British Tertiary Volcanic Province

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Chapter 7

Other Tertiary sites

INTRODUCTION

The British Tertiary Volcanic Province (BTVP) contains only a small proportion of the total igneous activity that occurred during the Palaeocene–Eocene opening of the North Atlantic. Within the Province, attention has been focused on the spectacular remnants of that activity in and around the central complexes and the majority of the sites described in this volume come from these areas and their immediate surroundings. Nevertheless, a number of important aspects of the igneous geology of the Province occur elsewhere and the sites described in this chapter cover them.

The NW- to NNW-oriented dyke swarms are a spectacular feature of the Province and examples of dense concentrations of dykes are described or noted close to the central complexes, for example, Kildonnan–Bennan Head, Arran and Loch Bà, Mull. The Cleveland Dyke of North Yorkshire is a far-flung, recently studied representative of the Mull swarm; this is described in the Langbaurgh Ridge–Cliff Ridge site. Mesozoic sediments filling basins adjoining the central complexes are often intruded by dolerite sill complexes. The Shiant Isles site is an excellently exposed, well-described example which exhibits a wide range of rock types attributed to multiple injection and magmatic differentiation. This site augments the information on differentiated sills from Dippin Head, Arran and Rubha Hunish, Skye. Two further sites, St Kilda and Rockall, lie in the North Atlantic to the west of Scotland (Fig. 1.1). St Kilda is formed by a central complex comparable in complexity with the other centres described; it consists of a succession of gabbroic and doleritic intrusions where basic and acid magmas frequently mingled, a later major granitic intrusion and many dykes and cone-sheets. The complex relationships of these bodies are magnificently exposed on the wave-washed cliffs of the islands in this archipelago. Further west, the isolated mass of Rockall provides one of the few examples in the BTVP of a peralkaline granitic intrusion, with a suite of rare minerals.

ROCKALL

Highlights

This is one of the few occurrences of alkali granite in the British Tertiary Volcanic Province and it is notable for its unusual mineralogy, including elpidite, leucophosphite and a Ba–Zr mineral 'bazirite'.

Introduction

The geological interest of Rockall lies in its relevance to the development of the North Atlantic Ocean and in its geochemistry and mineralogy which distinguishes it from the majority of intrusions in the BTVP. The island rises about 20 m above sea-level and consists entirely of peralkaline granite. Specimens were collected from Rockall early in the eighteenth century but the earliest detailed petrological and chemical descriptions were by Judd (1897) and Washington (1914). The geology has been described by Sabine (1960) and in accounts of expeditions to the islet in 1971 and 1972 (Harrison, 1975).

Description

Rockall is composed of moderately coarse-grained, aegirine/acmite-riebeckite granite with small segregations of finer-grained, peralkaline microgranite and xenoliths. Modal analyses of the granite gave the following mean (volume) percentage values: quartz 22%, feldspar 53%, ferromagnesian minerals 23% and accessory minerals 2%. Both felsic and mafic variants occur within the main body of granite; the variant with the highest modal percentage of ferromagnesian minerals (68%) has been termed rockallite (cf. Sabine, 1960). The granite contains drusy cavities which are lined by a variety of minerals including elpidite, leucophosphite and a barium–zirconium silicate (bazirite). Monazite may be embedded in the elpidite and apatite has been observed. Fine-grained, ovoid dark-coloured xenoliths up to 1 m by 0.3 m frequently carry quartz and feldspar megacrysts but otherwise have virtually identical mineralogy to the main mass of the granite. Sharp boundaries exist between the inclusions and the granite but no definite chilled contacts are present. The granite has been dated at *c.* 52 Ma (Harrison, 1975).

The Rockall Granite is apparently emplaced into the lavas and microgabbros of probable Cretaceous age which form Helen's Reef (Roberts *et al.*, 1974). The presence of continental crust is indicated by granulite-facies Precambrian rocks recovered from drill cores and bottom dredging

(Roberts *et al.*, 1972, 1973); the metamorphic rocks are similar to granulites exposed in the Outer Hebrides and north-west Scotland. The Helen's Reef microgabbro is associated with troctolites and they are probably responsible for a major negative magnetic anomaly in this area.

Interpretation

The Rockall Granite and the nearby microgabbro of Helen's Reef may be part of a central complex intruded into Cretaceous igneous rocks and Precambrian granulites. Although the Helen's Reef rocks have yielded a Cretaceous age in comparison with the Eocene age obtained from the Rockall Granite, it has been argued that the microgabbro could be of early Cenozoic age (Beckinsale, in discussion of Durant *et al.*, 1976). Harrison (1982) compares the composition of Helen's Reef microgabbro with (tholeiitic) non-porphyritic central magma-type rocks of the Inner Hebrides (for example, those of Centre 2, Mull), pointing out that the composition is unlike that of oceanic tholeiites; he also argues that there is no petrographic or chemical affinity with the Rockall Granite. However, this would not preclude both intrusions belonging to the same central complex, since both tholeiitic and (mildly) alkaline intrusions are well-documented from other centres, as, for example, on Skye (compare the mafic rocks of the Cuillin Centre with the mildly alkaline granite of Strath na Creitheach).

The Rockall Granite, with its suite of rare minerals, is compositionally comparable with the earlier, alkali-microgranite boss of Ailsa Craig (62 Ma; Harrison *et al.*, 1987) and with some members of the Eocene and younger alkaline complexes present along much of the East Greenland coastal belt (Nielsen, 1987; Upton, 1988). The Rockall Granite may have been formed by a small amount of partial melting in the upper mantle during the waning stages of igneous activity on the margins of a major hot-spot which existed over the area of the North Atlantic during the Tertiary (White, 1988).

Conclusions

Rockall is a small intrusion of granite which contains a suite of uncommon minerals. It appears to intrude lavas and metamorphic rocks which form the Rockall microcontinent. It was probably formed at a late stage in Tertiary igneous activity within the British Tertiary Volcanic Province and the North Atlantic, at a time when the upper mantle was cooling off after the main phase of magmatism during the Palaeocene.

THE SHIANT ISLES

Highlights

The Shiant Isles sill complex provides spectacular evidence for the differentiation of alkali-olivine basalt magma: basal olivine-rich picrites formed by accumulation under gravity outcrop on Eilean an Tighe–Garbh Eilean and analcite syenites, representing late differentiates, are present on Eilean Mhuire.

Introduction

The rocky Shiant Isles lie about 20 km north of Skye and 8 km south-east of Lewis. They consist of sheets of dolerite intruded into Jurassic sediments and form the exposed part of a sheet complex in the Little Minch. Their geological interest lies in the considerable textural, compositional and mineralogical variation exhibited by the dolerite which is magnificently exposed in the cliff sections (Fig. 7.1) and has been further explored by drilling.

Early accounts of the geology of the Shiant Isles were given by MacCulloch (1819), Judd (1878, 1885), Heddle (1884) and Geikie (1897), and

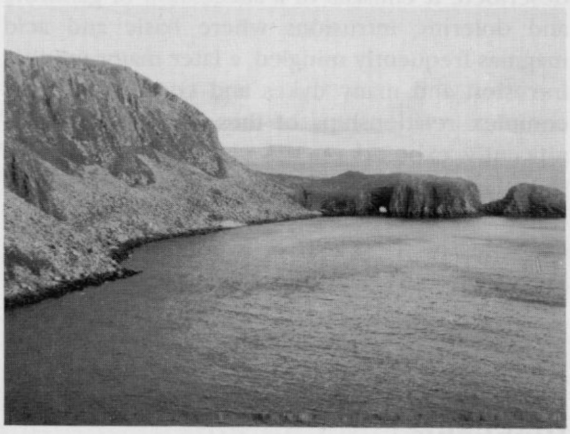

Figure 7.1 The north-west corner of Garbh Eilean, showing the main sill (left) and the lower sill (with natural arch), Shiant Isles. (Photo: F.G.F. Gibb.)

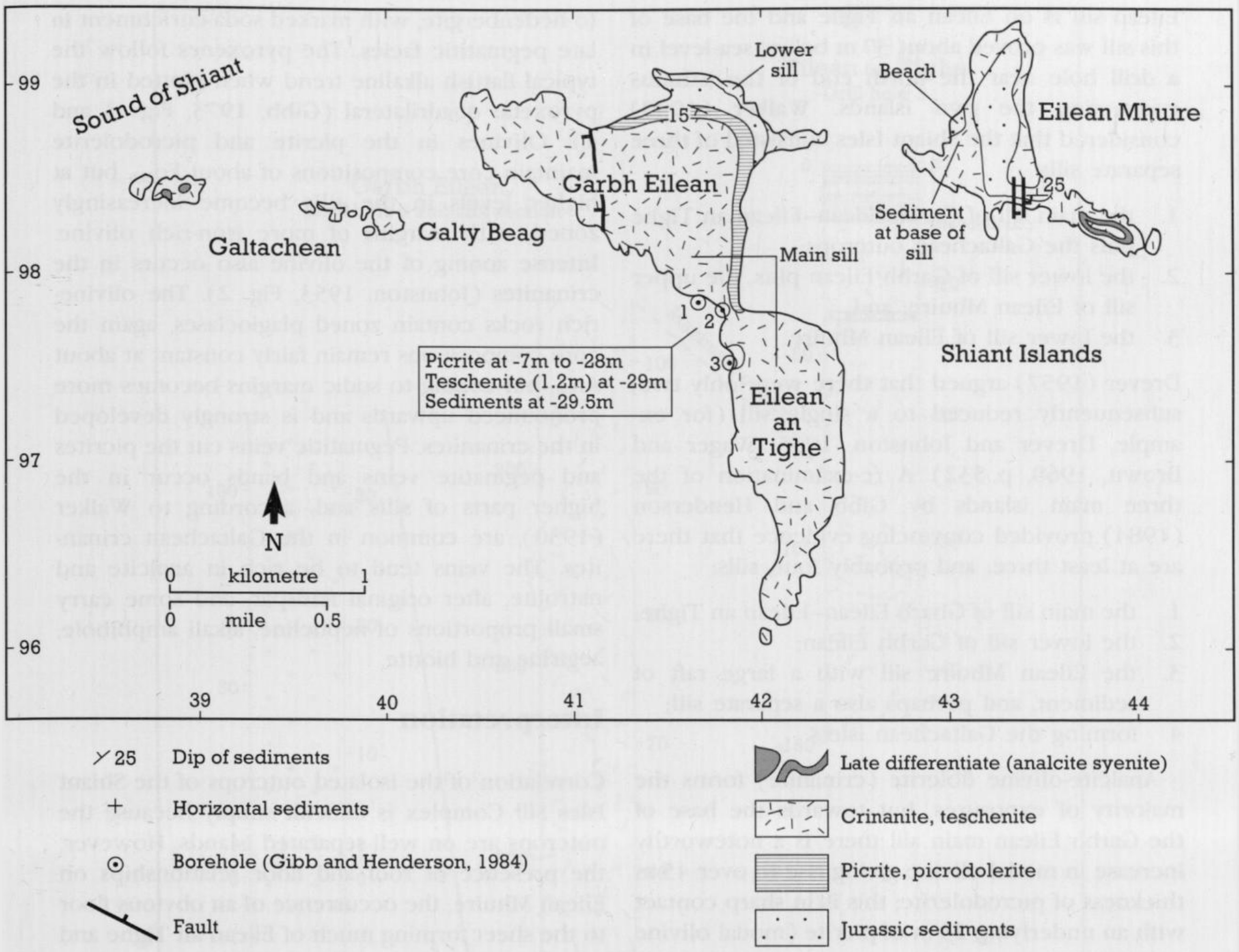

Figure 7.2 Geological map of the Shiant Isles (after Walker, 1930, plate 36, with additions from Gibb and Henderson, 1984, figure 1).

the picrites were figured in the classic *British Petrography* by Teall (1888, plate 3). The first detailed account was by Walker (1930) and subsequently, the mineralogy and petrology were investigated by Johnston (1953), Murray (1954), Drever (1953, 1957), Drever and Johnston (1958, 1965) and Gibb (1973). Reassessments of the structure of the sill complex has been provided by Gibb and Henderson (1984, 1989).

Description

The sills of the Shiant Isles are members of a major alkali-dolerite sheet complex intruding Jurassic sediments of the Little Minch Basin (Chesher *et al.*, 1983, Fig. 3) and probably represent an extension of the Trotternish sills of northern Skye (Rubha Hunish). Thick sheets of alkaline-olivine dolerite form the islands of Eilean Mhuire, Garbh Eilean, Eilean an Tighe and the Galtachean islets to the west. Jurassic (Lias) sedimentary rocks crop out on all three large islands although the outcrop on Eilean an Tighe is limited to a small coastal exposure. Fairly flat-lying contacts between sediments and dolerites, and the steep, massive columnar jointing of the dolerite (cf. Walker, 1930, plates 31, 32 and 33), indicate that the intrusions form sheets more or less conformable to the bedding of the sediments. The main body of sediments on Eilean Mhuire forms a major raft in the dolerite and the base of the sill is probably exposed on the west of the island, where Gibb and Henderson (1984) found sediments at sea-level. On Garbh Eilean, a lower sill on the north coast is separated by sediments from the main sill which is at least 130 m thick. The southern continuation of the main Garbh

Eilean sill is on Eilean an Tighe and the base of this sill was proved about 30 m below sea-level in a drill hole near the north end of the isthmus connecting the two islands. Walker (1930) considered that the Shiant Isles consisted of three separate sills:

1. the main sill of Garbh Eilean–Eilean an Tighe plus the Galtachean outcrops;
2. the lower sill of Garbh Eilean plus, the upper sill of Eilean Mhuire; and
3. the lower sill of Eilean Mhuire.

Drever (1957) argued that there were only two, subsequently reduced to a single sill (for example, Drever and Johnston, 1965; Wager and Brown, 1968, p. 532). A re-examination of the three main islands by Gibb and Henderson (1984) provided convincing evidence that there are at least three, and probably four, sills:

1. the main sill of Gharb Eilean–Eilean an Tighe;
2. the lower sill of Garbh Eilean;
3. the Eilean Mhuire sill with a large raft of sediment, and perhaps also a separate sill;
4. forming the Galtachean islets.

Analcite-olivine dolerite (crinanite) forms the majority of exposures, but towards the base of the Garbh Eilean main sill there is a noteworthy increase in modal olivine giving rise to over 45 m thickness of picrodolerite; this is in sharp contact with an underlying 23 m of picrite (modal olivine >40%). This in turn is separated from underlying sediments by a thin layer of fine-grained, olivine-free analcite dolerite (teschenite) (Drever and Johnston, 1965; Gibb and Henderson, 1984, Fig. 2). A thin picrite (*c.* 2 m) occurs in sharp contact with underlying crinanite at the top of the main sill (Gibb and Henderson, 1978a, 1984, Fig. 2; Fig. 7.3). Vesicular crinanite high on Eilean an Tighe, estimated to be from near the top of the sill, contains poikilitic nepheline. The upper part of the Eilean Mhuire sill, exposed towards the south-east end of the island, contains a layer about 20 m thick much enriched in alkali feldspar and alkali pyroxene; this is an analcite syenite with essexite segregations (Walker, 1930). It is therefore apparent that both the main sill of Garbh Eilean–Eilean an Tighe and the Eilean Mhuire sill show vertical variations suggestive of crystal fractionation and differentiation. Variation in modal mineralogy and texture, for example, is accompanied by variation in the mineral compositions (cryptic variation); clinopyroxenes range upwards in the sills from diopsidic augite to hedenbergite, with marked soda-enrichment in late pegmatitic facies. The pyroxenes follow the typical flattish alkaline trend when plotted in the pyroxene quadrilateral (Gibb, 1973, Figs 3 and 4). Olivines in the picrite and picrodolerite maintain core compositions of about Fo_{80}, but at higher levels in the sills become increasingly zoned, with margins of more iron-rich olivine. Intense zoning of the olivine also occurs in the crinanites (Johnston, 1953, Fig. 2). The olivine-rich rocks contain zoned plagioclases, again the core compositions remain fairly constant at about An_{80} but zoning to sodic margins becomes more pronounced upwards and is strongly developed in the crinanites. Pegmatitic veins cut the picrites and pegmatite veins and bands occur in the higher parts of sills and, according to Walker (1930), are common in the Galtachean crinanites. The veins tend to be rich in analcite and natrolite, after original feldspar, and some carry small proportions of nepheline, alkali amphibole, aegirine and biotite.

Interpretation

Correlation of the isolated outcrops of the Shiant Isles Sill Complex is difficult simply because the outcrops are on well-separated islands. However, the presence of roof and floor relationships on Eilean Mhuire, the occurrence of an obvious floor to the sheet forming much of Eilean an Tighe and Garbh Eilean, and a roof-like contact below sediments on the north of Garbh Eilean, make it fairly certain that we are dealing with a sheet complex with at least three and possibly four leaves.

The Shiant Isles sills were interpreted by Walker (1930) to provide a particularly clear example of magmatic differentiation through the *in situ* gravity settling of early-formed crystals within cooling magma: the picrites and picrodolerites represent rocks enriched through the settling of early-formed olivine, while the later-crystallizing and generally lower-temperature phases were concentrated towards the upper parts of the sill where the analcite syenite (syenoteschenite, of Gibb and Henderson, 1984, p. 29) and the alkaline segregations represent the extreme products of fractionation. The discovery by Drever and Johnston (1965) that the picrite had a sharp, undulating contact with the overlying picrodolerite rather than a gradational relationship, necessitated some reassessment of Walker's interpretation.

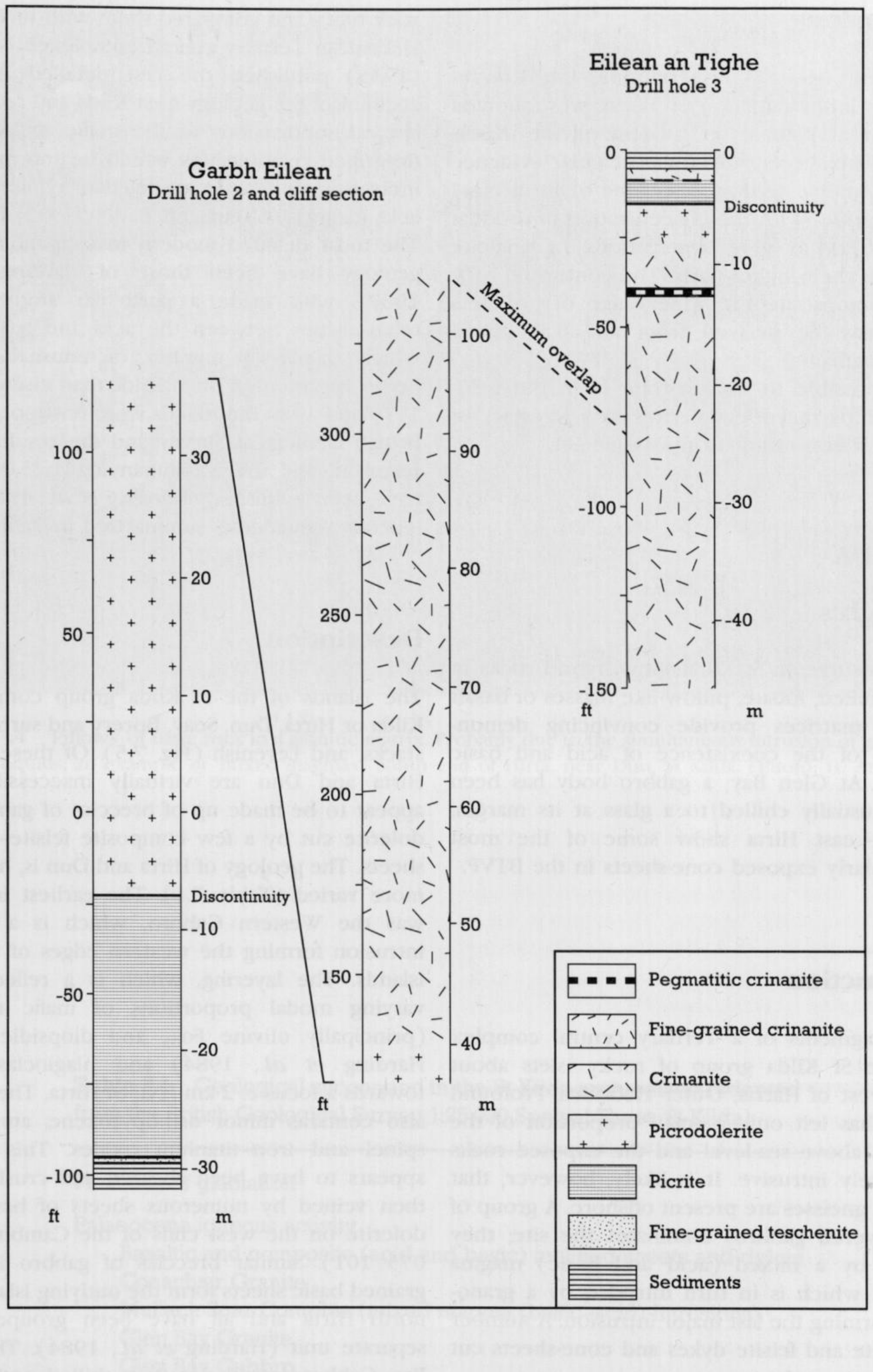

Figure 7.3 Simplified vertical sections through the main Garbh Eilean–Eilean an Tighe sill, Shiant Isles (after Gibb and Henderson, 1984, figure 2).

Conclusions

The Shiant Isles sill is a multiple intrusion in which an initial injection of picrite was followed by a large volume of analcite-olivine basalt magma. The sheets provide spectacular evidence for gravitational settling of olivine to form basal picrodolerites, with the concentration of residual differentiates to give segregations of analcite syenite in their higher parts. The contrasted rock types demonstrate the wide range of products which may be derived from an alkali-olivine basalt magma.

It is possible to demonstrate from the field-relationships that the dolerites form a series of separate sheets rather than a single sill.

ST KILDA

Highlights

The exposures on St Kilda show hybrid rocks in which chilled, lobate, pillow-like masses of basalt in acid matrices provide convincing demonstrations of the coexistence of acid and basic magmas. At Glen Bay, a gabbro body has been most unusually chilled to a glass at its margin. Cliffs in east Hirta show some of the most spectacularly exposed cone-sheets in the BTVP.

Introduction

Relict fragments of a Tertiary central complex form the St Kilda group of rocky islets about 80 km west of Harris, Outer Hebrides. Profound erosion has left only a small proportion of the complex above sea-level and the exposed rocks are entirely intrusive. It is likely, however, that Lewisian gneisses are present offshore. A group of early, layered gabbros dominates the site; they are cut by a mixed (acid and basic) magma complex which is in turn intruded by a granophyre, forming the last major intrusion. A number of dolerite and felsite dykes and cone-sheets cut the plutonic rocks.

The islands were visited by MacCulloch (1819) who recognized the presence of basic and acid rocks. Ross (1884) showed that acid rocks veined the basic intrusions and therefore considered them to be younger. Geikie (1897) described the rock types and compared them with those of the Hebridean Tertiary central complexes. Cockburn (1935) published the first detailed map and account of the geology of St Kilda and recognized several subdivisions to the mafic rocks. Wager described relationships which he interpreted as indicating that basic magma had chilled against acid magma (Wager and Bailey, 1953; Fig. 7.4). The most detailed modern investigations of the geology have been those of Harding (1966, 1967), who made a particular study of the relationships between the acid and basic rocks which display a number of unusual features better represented on St Kilda than elsewhere. In 1979 and 1980 the islands were remapped by the British Geological Survey and the results of this research, and the accompanying 1:25 000 map, have been published (Harding *et al.*, 1984). The igneous sequence is summarized in Table 7.1.

Description

The islands of the St Kilda group comprise St Kilda or Hirta, Dun, Soay, Borery and surrounding stacks, and Levenish (Fig. 7.5). Of these, all but Hirta and Dun are virtually inaccessible and appear to be made up of breccias of gabbro and dolerite cut by a few composite felsite–dolerite sheets. The geology of Hirta and Dun is, however, more varied (Table 7.1). The earliest intrusion was the Western Gabbro, which is a layered intrusion forming the western edges of the two islands. The layering, which is a reflection of varying modal proportions of mafic minerals (principally olivine Fo_{65} and diopsidic augite; Harding *et al.*, 1984) and plagioclase, dips towards a focus *c.* 2 km ENE of Hirta. The gabbro also contains minor orthopyroxene, amphibole, spinel and iron–titanium oxides. This gabbro appears to have been sheared and crushed and then veined by numerous sheets of basalt and dolerite on the west cliffs of the Cambir (*c.* NF 075 101). Similar breccias of gabbro in finer-grained basic sheets form the outlying islands and north Hirta and all have been grouped as a separate unit (Harding *et al.*, 1984). The Glen Bay Gabbro intrudes and is chilled against the basic breccias. The chilled contact on the east of Glen Bay is most unusual since there is complete textural gradation from a 10 mm border zone of splintery, glassy basalt to gabbro exposed on the east side of the bay. Fine, vertical banding occurs

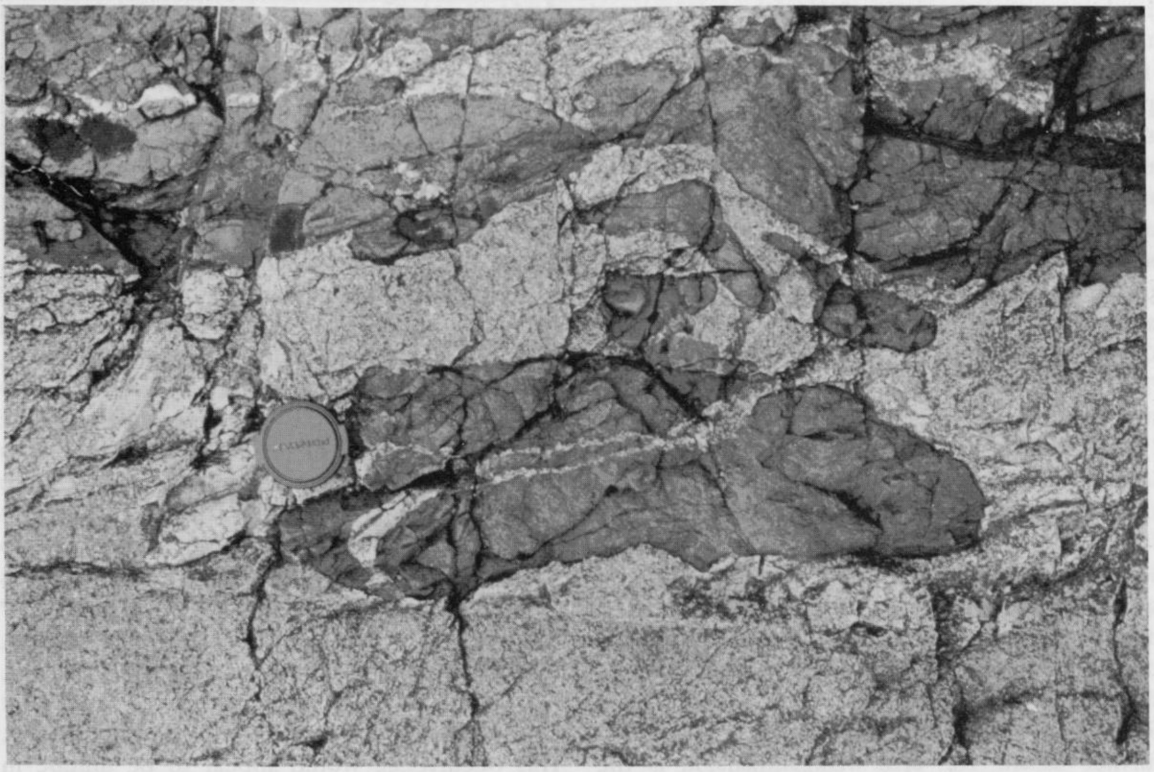

Figure 7.4 'Pillows' of basic rock in a granitic matrix. Probably due to the simultaneous intrusion of granitic and basaltic liquids; an example of 'mixed magmas'. South end of Hirta, near Dun, St Kilda. (Photo: H. Armstrong.)

Table 7.1 Geological succession in the St Kilda archipelago (adapted from the British Geological Survey 1:25 000 Special Sheet, St Kilda)

Pleistocene glaciation
Palaeocene igneous activity
Basaltic and composite (acid and basic) inclined sheets and dykes
Conachair Granite
Mullach Sgar Complex (mixed magma (basic–acid) intrusions)
Glen Bay Granite
Glen Bay Gabbro
Breccias of gabbro and dolerite
Western Gabbro (layered in places)

No pre-Palaeocene rocks are exposed, but the complex is thought to be intruded into Lewisian gneisses.

in the marginal zone parallel to the contact and the effects of chilling are estimated to extend for 100–120 m into the gabbro (Harding *et al.*, 1984, p. 12). Gabbro on the west of the bay is much sheared and granulated and is separated from the eastern outcrops by the oldest granite on Hirta, the Glen Bay Granite. This granite is chilled against the earlier gabbro and, like the gabbro, shows signs of fragmentation. The next intrusive phase involved four pulses of mixed basic and acid magmas which formed the Mullach Sgar Complex between Glen Bay and Village Bay (Fig. 7.5). This group of rocks includes dolerite, microdiorite, microgranite and rocks of hybrid (mixed dolerite and granite) aspect. Angular and lobate masses of marginally chilled basic rocks occur in more acid matrices and are veined by felsic material (cf. Fig. 7.4); a large amount of shattering of the dolerite and basalt has occurred, giving areas of complex net-veining (cf. Ardnamurchan Point to Sanna). Although extremely complex in detail, Harding *et al.* (1984) suggest that initial intrusions of basaltic magma were followed successively by granitic magma and further basalt. The final major intrusion is the Conachair Granite which forms the high ground north-east of Village Bay. This granite intrudes the Mullach Sgar Complex without notable chilling along the contact. The granite typically contains quartz, turbid, perthitic alkali feldspar and albitic plagioclase, with minor amounts of biotite and amphibole. Other accessory minerals include zircon, sphene, rutile, anatase, Ti-magnetite, fluorite and needle-like, deep-brown crystals of the rare-earth-bearing silicate chevkinite. The Conachair Granite characteristically has a microgranitic texture often with a considerable content of granophyrically intergrown quartz and feldspar. Some of the larger quartz crystals are interpreted as corroded, inverted high-temperature quartz. Radiometric age determinations on this granite give a date of *c.* 55 Ma, indicating a Palaeocene age.

Several generations of minor intrusions with compositions ranging from basalt to rhyolite have been recognized (Cockburn, 1935; Harding *et al.*, 1984). Frequently these are inclined sheets (Harding *et al.*, 1984, Figs 24c and 25c) whose disposition suggests that they once formed a classic cone-sheet complex. Many of the inclined sheets cut the Conachair Granite and are therefore the latest intrusions in St Kilda.

Interpretation

St Kilda is formed from the remains of a central complex of Palaeocene age which is situated towards the margin of the European continental shelf where it is probably emplaced into Lewisian gneisses. The earliest intrusions were coarse, layered gabbros which subsequently became crushed and shattered and were then intruded by a multiplicity of dolerite and basalt sheets and veins. Some of these must have been emplaced prior to complete solidification of the earlier, very variable-textured gabbros. The distinctly later Glen Bay Gabbro is most unusual among the gabbroic intrusions of the BTVP in possessing a glassy, chilled-margin which gradually grades into normal gabbro. Presumably the intrusion was emplaced into cold, solidified, earlier gabbro which itself had a high-melting point and was possibly effectively anhydrous. Normally, BTVP gabbros have complex contacts with earlier, relatively low-melting point acid rocks (cf. Rum, Harris Bay; Skye, Coire Uaigneich), or are not conspicuously chilled against other mafic bodies. This occurrence would appear to be unique in the Province.

The Mullach Sgar Complex provides a superb example of the coexistence of acid and basic magmas and their near simultaneous intrusion. Evidence for mixed basic and acid magmas occurs elsewhere in the Province (cf. Ardnamurchan Point to Sanna; Arran, Ard Bheinn and Drumadoon–Tormore; Skye, Marsco and Mheall a' Mhaoil, Kilchrist and Rubha' an Eirannaich; Mull, Cruach Choireadail, Allt Molach–Beinn Chàisgidle and Loch Bà–Ben More), but the pillowed exposures of chilled basaltic rocks in unchilled felsic matrices are exceptionally fine. The early recognition of their significance by Wager and Bailey (1953) has been crucial in elucidating some of the more puzzling field relationships within the Province, particularly where limited outcrops suggest that acid rocks veining and brecciating dolerite or gabbro are significantly younger than the mafic rocks, yet the broader relationships clearly show that this is not the case (cf. Rum, Harris Bay). The pervasive shattering of many of the St Kilda gabbros and dolerites is a striking feature of the complex and suggests that explosive release of water may have occurred towards the end of their solidification, followed by rapid injection of quickly cooled basaltic magma. It is also possible that the highly unusual

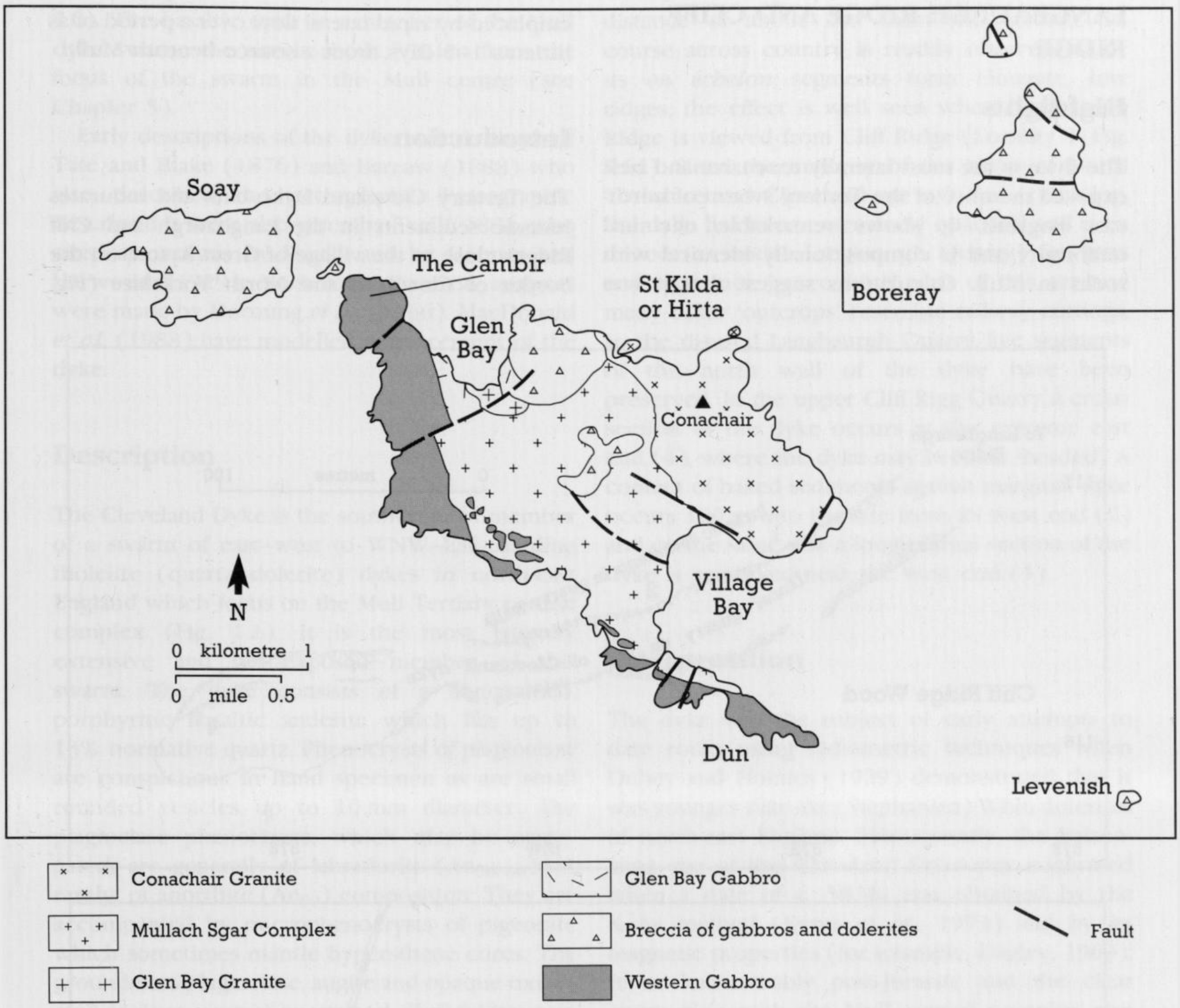

Figure 7.5 Geological map of the St Kilda archipelago (adapted from the British Geological Survey 1:25 000 Special Sheet, St Kilda).

glassy, quenched contact of the Glen Bay Gabbro may owe its origin to high-temperature, hydrothermal quenching.

Conclusions

An early layered gabbro intrusion forms much of the islands of the St Kilda archipelago. On Hirta and Dun, and to a lesser extent elsewhere, it underwent penetrative shattering and brecciation which may have been caused by explosive release of water as it completed crystallization. A further gabbro intrusion was quenched to a glassy rock against the breccias and itself intruded by granite. Basaltic and granitic magmas coexisted at this stage and the next intrusion consisted of several pulses of mixed basic and acid magmas. The last major intrusion, following soon after the mixed magma bodies, was a major body of granite in the east of Hirta. A final phase of basalt intrusion gave rise to a suite of cone-sheets which focuses to the north-east of Hirta.

LANGBAURGH RIDGE AND CLIFF RIDGE

Highlights

The dyke is the most laterally extensive and best exposed member of the Tertiary swarm of north-east England. It shows remarkable chemical uniformity and is compositionally identical with rocks in Mull. Calculations suggest that it was emplaced by rapid lateral flow over a period of as little as 1–5 days, from a source beneath Mull.

Introduction

The Tertiary Cleveland Dyke cuts and indurates Jurassic sediments in the Langbaugh and Cliff Ridges close to the village of Great Ayton, on the border of Cleveland and North Yorkshire (Fig.

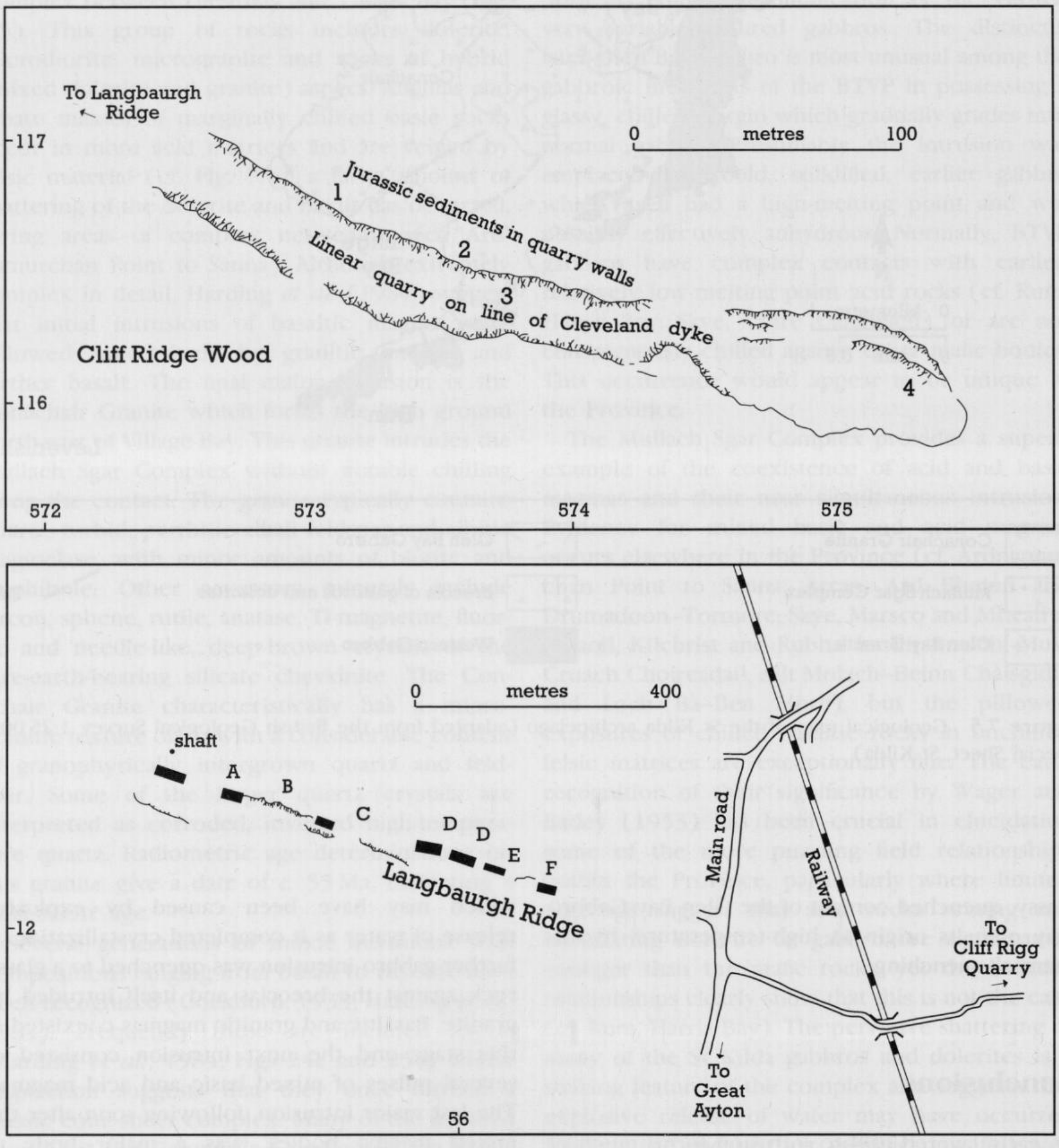

Figure 7.6 Sketch maps showing outcrops of the Cleveland Dyke near Great Ayton, North Yorkshire: (lower) Langbaugh Ridge. Localities A–F refer to points where the north margin of the dyke has been preserved. (upper) Upper part of Cliff Rigg Quarry. For explanation of localities 1–4 see text.

7.6). The basaltic dyke is a member of the Mull dyke swarm, the site is about 370 km from the focus of the swarm in the Mull centre (see Chapter 5).

Early descriptions of the dyke include those of Tate and Blake (1876) and Barrow (1888) who also described the petrography. Petrographic descriptions were also given by Teall (1884, who cited an analysis by Stock) and by Holmes and Harwood (1929). Numerous chemical analyses were made by Hornung *et al.* (1966). MacDonald *et al.* (1988) have modelled emplacement of the dyke.

Description

The Cleveland Dyke is the southernmost member of a swarm of east–west to WNW–ESE-trending tholeiite (quartz dolerite) dykes in north-east England which focus on the Mull Tertiary central complex (Fig. 1.1). It is the most laterally extensive and best-exposed member of this swarm. The dyke consists of a fine-grained, porphyritic basaltic andesite which has up to 13% normative quartz. Phenocrysts of plagioclase are conspicuous in hand specimen as are small rounded vesicles up to 10 mm diameter. The plagioclase phenocrysts, which may be aggregated, are generally of labradorite (An_{50-60}) or, rarely, of anorthite (An_{90}) composition. They are accompanied by microphenocrysts of pigeonite which sometimes mantle hypersthene cores. The groundmass plagioclase, augite and opaque oxides may enclose areas of quartz and alkali feldspar or, in the chilled margins, there may be intersertal areas of clear brown glass. Cognate basaltic inclusions up to 5 mm in diameter and derived from the margins are common. The vesicles contain quartz, calcite, chlorite and clay minerals (which may expand on exposure to the atmosphere causing disintegration of the vesicles' contents), rare epidote, pyrite, pectolite and mesolite (cf. Barrow, 1888). The basalt at the contacts with highly fossiliferous Middle Lias sandstones and ironstones is distinctly finer grained than the centre of the dyke, but tachylitic rock is not found. Subhorizontal, columnar jointing is developed in the marginal dolerite and has given rise to good examples of spheroidal weathering.

The dyke is up to 25 m in width and appears to have produced little alteration of the sediments apart from discoloration and induration for a distance of about 2 m from the contact. Its course across country is readily observed since its *en échelon* segments form elongate, low ridges; the effect is well seen when Langbaurgh Ridge is viewed from Cliff Ridge (Locality 3, Fig. 7.6a). Since the majority of the rocks of North Yorkshire and Cleveland are soft and crumbling, the dyke has been extensively quarried and even mined (as under Langbaurgh Quarry) for setts and aggregate; hence, both parts of this site and many other 'outcrops' resemble railway cuttings. In the disused Langbaurgh Quarry five segments of the north wall of the dyke have been preserved. In the upper Cliff Rigg Quarry a cross-section of the dyke occurs at the extreme east end (4), where the dyke may become 'headed'. A contact of baked sediments against marginal dyke occurs 100 m into the site from its west end (2) and on the same side a longitudinal section of the dyke is preserved near the west end (1).

Interpretation

The dyke was the subject of early attempts to date rocks using radiometric techniques when Dubey and Holmes (1929) demonstrated that it was younger than the (Stephanian) Whin dolerites of north-east England. Subsequently, the Palaeocene age of the Cleveland Dyke was confirmed when a date of *c.* 58 Ma was obtained by the K–Ar method (Evans *et al.*, 1973) and by its magnetic properties (for example, Dagley, 1969). It is demonstrably post-Jurassic and the clear connection with the Mull central complex also supports a Palaeocene age.

There has been debate whether the dyke was actually fed from a source in Mull, or rose vertically from subjacent mantle along a fracture system propagated from Mull. The considerable distance from Mull (*c.* 370 km) and the absence of any systematic increase in thermal metamorphism around the dyke when traced towards Mull have perhaps supported the suggestion that the magma rose vertically, but this does require a laterally extensive magma source beneath the dyke over its entire extent, for which there is little evidence (MacDonald *et al.*, 1988). MacDonald *et al.* have made a detailed examination of the petrology of the dyke which substantiates the earlier claims that it is extremely similar compositionally to some of the Mull non-porphyritic central magma-type intrusions. They have also carried out numerical modelling of the flow of magma through a dyke of this size from which they conclude that the dyke could have been fed by lateral flow from a large magma chamber beneath Mull, and that its emplacement could have taken place in the very short time of 1–5 days.

Conclusions

The Cleveland Dyke is a compositionally uniform quartz dolerite which closely resembles basaltic and doleritic rocks in the Mull central complex. It is a compact, fine-grained rock with scattered, small, plagioclase crystals and small vesicles. As it is the only durable rock in North Yorkshire and Teeside it has been extensively quarried and mined for aggregate.

Recent research has shown that the dyke was probably intruded laterally from a source beneath the Isle of Mull in western Scotland, and that lateral emplacement may have taken place in a few days.