British Tertiary Volcanic Province

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In 1987, Dr Emeleus and Dr M. C. Gyopari of the University of Durham were commissioned to write this volume for publication according to the format approved by the GCR Publications Management (now Advisory) Committee. Since that time, many others have contributed in various ways to the production of the volume; in particular, the editors wish to acknowledge the following: Professor Sir Malcolm Brown, FRS, who suggested several important improvements while refereeing the volume as a whole; Dr G. F. Marriner, Dr M. F. Thirlwall and Dr J. N. Walsh of Royal Holloway and Bedford New College, University of London, who commented helpfully on portions of the text; past and present members of the Publications Management and Advisory Committees for their support and advice; Dr D. O'Halloran, who has calmly managed this project on behalf of the Joint Nature Conservation Committee, and the GCR production team of Valerie Wyld (Sub-editor), Nicholas D. W. Davey (Scientific Officer) and Caroline Mee (Administrative Officer); the several Chief Wardens of the Rum NNR who over the years have greatly assisted Dr Emeleus in the field; Chapman & Hall for their help and advice at the final stages of publication; Lovell Johns Limited, Colwyn Bay, for cartographic drafting and David C. Davies for cartographic editing.

W. A. Wimbledon and P. H. Banham

Access to the countryside

This volume is not intended for use as a field guide. The description or mention of any site should not be taken as an indication that access to a site is open or that a right of way exists. Most sites described are in private ownership, and their inclusion herein is solely for the purpose of justifying their conservation. Their description or appearance on a map in this work should in no way be construed as an invitation to visit. Prior consent for visits should always be obtained from the landowner and/or occupier.

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Gwynedd LL57 2LQ.

English Nature,
Northminster House,
Peterborough PE1 1UA.

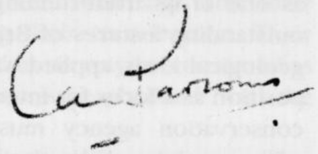
Foreword

When setting out to produce the Geological Conservation Review series the then Nature Conservancy Council rightly selected the British Tertiary Volcanic Province as one of its front-running topics. By any standards the Province is one of the outstanding features of British geology. It has contributed to the development of geological ideas, applied world-wide, over about 200 years, and holds a continuing position as a focus for international research. A prime earth science concern of any conservation agency must be to preserve the evidence on which scientific advances have been based, and to ensure that future generations have an opportunity to study the problems that remain. Of course, geological features are generally speaking pretty robust. Casual and thoughtless destruction on a grand scale, to which biological assemblages are so vulnerable, is not generally a serious problem. But geological knowledge depends on seeing the relationships between rock masses, the critical areas of outcrop may be few and far between, both in Highland Scotland with its peat moors and forests and in the agricultural lands to the south. It is documentation of these sites showing critical inter-relationships that is the business of the Geological Conservation Review series. This volume provides the NCC's successor body, Scottish Natural Heritage, with the scientific justification to safeguard the described sites, which are the highlights of the Province.

Reading this volume brought home to me the scale of the scientific resource provided by the volcanic rocks and associated intrusions which make up the British Tertiary province. To a geologist many of the place names ring out like the names of great battles: Waterloo, Trafalgar – Skye, Mull, Rum, Ardnamurchan! And lesser places have lent their names to rock types, used all over the world: benmoreite, allivalite, mugearite - to mention but a few. You can go to a scientific conference in California and hear American geologists talking about rocks named after tiny Hebridean hamlets, but also describing research, at the forefront of the international scene, which they are carrying out now on rocks from the Scottish Tertiary.

The province developed when the opening of the North Atlantic reached British latitudes about 65 million years ago. Truly vast outpourings of lava occurred, particularly in then-adjacent East Greenland, very probably associated with a 'hot spot' in the Earth's mantle which lives on to this day under Iceland. While the immense basalt fields of East Greenland are fearsomely inaccessible, the west of Scotland provides relatively easy access to the deeply eroded relics of the basalt pile and the frozen equivalents of the magma chambers (the central complexes) which lay beneath. Research on igneous rocks can take place at various scales, all admirably served by the Scottish Tertiary: in a regional setting, to understand problems such as the mechanisms and driving force behind ocean-opening, and the relationship between 'hot spots' and ocean formation; on the scale of a single volcano, to enable us to understand the processes of igneous intrusion, the evolution of magmas and the controls on episodic volcanic activity; and on the scale of the outcrop, where, for example, igneous layering, nowhere better shown than on Rum, still presents many totally enigmatic features.

Scotland's great natural laboratory is splendidly documented in this volume of the Geological Conservation Review. Henry Emeleus is an outstanding expert on the Tertiary igneous province, particularly with respect to the field relationships, at once the most fundamental and also the most difficult type of geological observation. He and his younger co-author, Mark Gyopari, have provided clear, crisp, beautifully illustrated accounts of sites, which will be of outstanding value to students, researchers, amateur geologists and professional conservationists. Because of its thematic character and style of presentation, placing local detail into a regional context, it provides an unmatched teaching resource. Finally, and most important of all, it sets out and values, for the first time, publicly and clearly, those sites which have contributed most in the past, and most probably will contribute in the future, to our enjoyment and understanding of one of the grandest events in the geological growth of Britain.



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Chapter 1

Introduction to the British Tertiary Volcanic Province

THE GENERAL SETTING

The north-western British Isles was the site of intense igneous activity during the Palaeocene and early Eocene (*c.* 63–52 Ma) which accompanied continental separation and lithospheric attenuation during the early stages of the opening of the North Atlantic. In Great Britain, volcanism was most vigorous in the Inner Hebrides and adjoining north-west Scotland but also extended to southern Scotland, north-east England and the Outer Hebrides. Intrusions of similar age in North Wales and the English Midlands are probably outlying representatives of contemporaneous activity in north-east Ireland; additional activity in the Bristol Channel centred on Lundy. The region encompassing this activity is known as the British Tertiary Volcanic Province (BTVP) or the British Tertiary Igneous Province (BTIP) (Fig. 1.1).

The igneous activity took many forms and involved a wide variety of magmas and rock types. The remains of large accumulations of dominantly basaltic lava flows cover extensive areas in Skye and Mull. Laterally extensive swarms of basaltic dykes are most intense near Skye, Rum, Mull, and Arran but extend to the Outer Hebrides, southern Scotland, Cleveland in north Yorkshire and parts of North Wales and central England. Central intrusive complexes consisting of granite, gabbro, peridotite and other rock types occur on a line from Skye to the Bristol Channel and at several places in the north-east Atlantic (Fig. 1.1); these are the deeply-dissected roots of major volcanoes.

The varied igneous rocks, together with associated sediments and metamorphic rocks have responded in different ways to the profound erosion of the last fifty million years. Gabbro and peridotite have given rise to the rugged mountain scenery of St Kilda, the Skye Cuillins and Rum. The considerable, but generally less-rugged, mountains of northern Arran and the Skye Red Hills are composed of granite, while the piles of flat-lying lavas form tabular, 'trap-featured' hills in northern Skye, rising sometimes to form high mountains, as at Ben More, Mull.

Geologists, mineralogists, mountaineers and others have been attracted to the Province for over two centuries by the spectacular mountain and coastal scenery, and by the abundance of fresh rock exposures from sea-level to over 1000 metres altitude. Pennant, Necker de Saussure, Ami Boué and MacCulloch were among early visitors; notable scientists who worked on the Province in later years included Judd, Geikie, Harker, Bowen, Holmes and Wager; and the area is one where at the present time research into fundamental problems of igneous geology is actively pursued. The intensity of scientific investigation has made the BTVP one of the most historically important and deeply studied igneous provinces in the world. Furthermore, it is acknowledged as one of the best areas in the British Isles in which to demonstrate igneous rocks in the field, and consequently it is visited annually by numerous groups from universities, schools and scientific societies from Britain and abroad.

GCR sites have been selected to cover the features of the BTVP within Great Britain. Additional sites have been identified in Northern Ireland, but these are outside the terms of reference of this published review. The sites vary considerably in importance, size and scope. Some are whole mountain groups (for example, the Skye Cuillin Hills); others may be merely stream sections or small quarries but all have been selected as scientifically significant examples of their kind, where the features described can be observed and appreciated at present and which should be preserved for future study and research.

The Tertiary igneous activity occurred in geographically well-defined areas which usually include a central volcano and surrounding lavas. These areas have been made the basis of individual chapters.

THE IGNEOUS SEQUENCE

Volcanism in the BTVP extended over a period of about twelve million years, largely within the Palaeocene Epoch, apart from the later intrusions within the Eastern Red Hills Centre of Skye (Dickin, 1981), the Sgurr of Eigg pitchstone (Dickin and Jones, 1983), the Lundy granite complex (Hampton and Taylor, 1983) and the youngest intrusion in the Mourne Mountains Western Centre, Ireland (Meighan *et al.*, 1988). The Palaeocene volcanism was preceded by Cretaceous igneous activity in the eastern Atlantic (Harrison, 1982) and it is also possible that the submarine central complex at the Blackstones, south-west of Mull, is Cretaceous in age (Durant *et al.*, 1982). Within the BTVP, the life span of individual central complexes was short, of the order of two or three million years (or even less) and the thick lava accumulations built up over even shorter periods (Table 1.1).

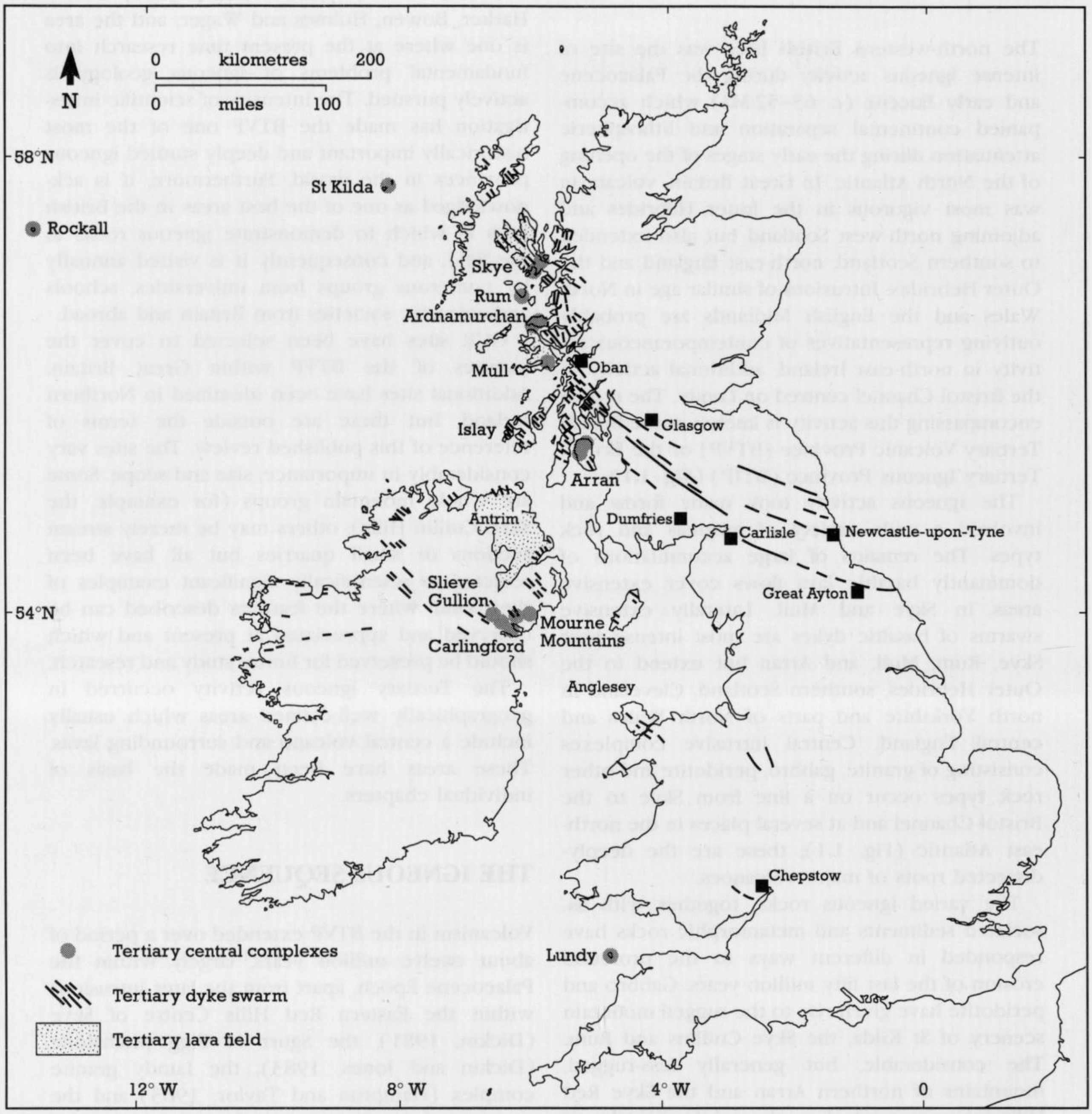
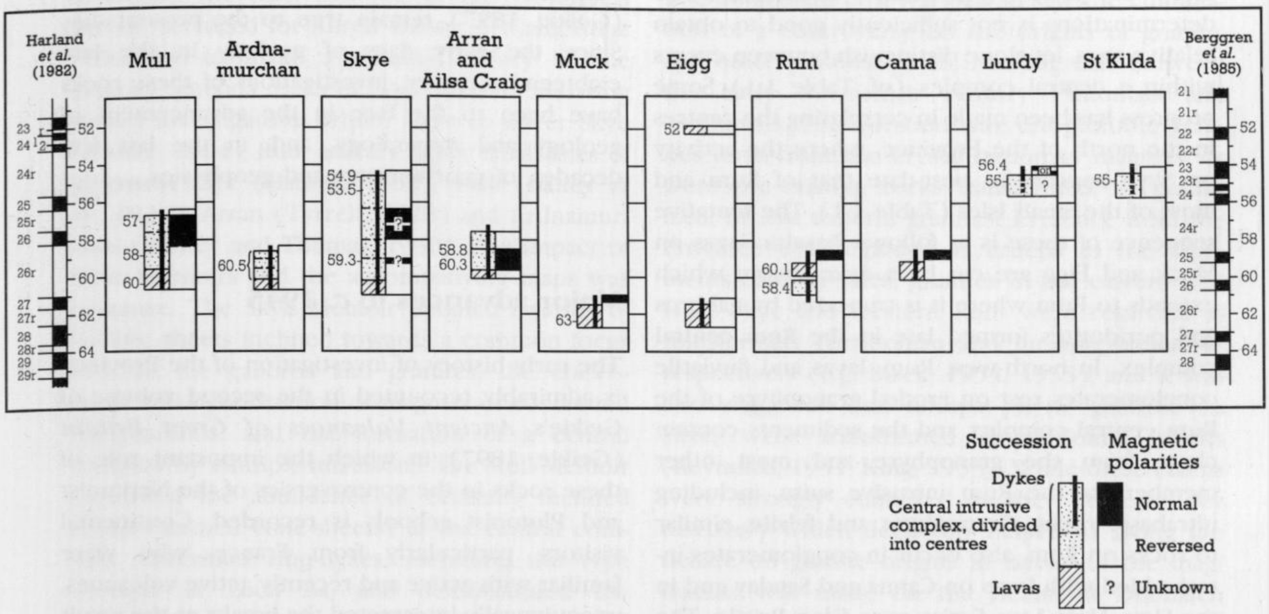


Figure 1.1 Map of the British Isles, showing the distribution of Tertiary central complexes, dyke swarms and lavas (submarine occurrences not shown). Modified from Emeleus, in Sutherland (1982, figure 29.1).

Volcanic activity in a given area often started with the formation of small amounts of basaltic ash and other volcaniclastic accumulations. These were quickly followed by voluminous subaerial eruptions of basaltic lavas which covered the peneplaned surfaces of older sedimentary and metamorphic rocks ranging in age from the Precambrian to the Cretaceous. Occasionally, the lavas covered landscapes of considerable relief, filling valleys, burying hills and sometimes flowing into shallow lakes, where pillow lavas and hyaloclastites formed. Sedimentary horizons are not common in the lavas, but fluviatile conglomerates, sandstones and fine-grained plant-bearing horizons do occur and provide valuable stratigraphic and palaeogeographical information. The lavas were often subjected to intense weathering between flow extrusion, with the

Table 1.1 British Tertiary Volcanic Province: summary of the geological successions, radiometric ages and magnetic polarities (after Mussett *et al.*, 1988, figure 2)



formation of bright red lateritic deposits. With increasing thickness of lavas, heated waters circulating through the flows altered the basalts and deposited distinctive suites of zeolite minerals, for which Skye and Mull are particularly noted.

The lavas were principally fed from fissure eruptions similar to those of present day Iceland. The actual feeders are among the multitude of dykes forming the swarms which extend across the Province; dykes intrude virtually all intrusions and extrusions in the BTVP, so it is likely that lava effusion also occurred throughout the life span of the Province. However, the thick sequences of lavas now preserved in Mull, Skye, and the Small Isles built up between about 63 Ma and 60 Ma, early in the life of the BTVP. Occasionally, lavas must have been erupted as the central complexes developed; there is good evidence from several centres that silicic and intermediate lavas were closely associated with central complexes but there are few substantiated examples of basaltic lavas, with the exception of pillow lavas within the Mull centre. Not all the (predominantly basaltic) magma reached the surface to form flows, some froze in conduits as dykes and plugs and quite large amounts spread laterally through the Mesozoic sediments beneath the lavas to form the prominent dolerite sills of northern Skye and Arran.

The central complexes generally post-date the adjoining lavas, but they were intruded by later members of the dyke swarms. Within the complexes the magmatic sequences were rarely straightforward: in Mull early granite intrusions were followed by numerous basaltic, intermediate and acid cone-sheets, by gabbros and peridotites and by further granites; in Skye, the sequence was apparently simpler, the gabbros and peridotites of the Cuillins were cut by numerous basaltic cone-sheets and subsequently by granites of the Red Hills. Thus, the central complexes record varied intrusive sequences in which basaltic and granitic magmas have been intimately associated. Occasionally, it may be shown that contrasted magmas must have co-existed, forming, for example, the composite basalt/quartz–porphyry sheets and dykes of the Province and the complicated intrusion breccias found in Ardnamurchan, Skye and other central complexes.

Within the central complexes, individual centres of activity are defined by arcuate intrusions – cone-sheets, ring-dykes and stocks – which have a common focus. In most central complexes, and in particular Ardnamurchan, Skye and Mull, the intrusions of one centre may cut those of an earlier one, recording movements in the focus of magmatic activity with time. Ardnamurchan provides an exceptionally clear and often cited example of this phenomenon.

The central complexes are generally spatially well-separated from one another. This has made correlation between centres difficult; furthermore, the present precision of radiometric age determinations is not sufficiently good to obtain relative ages, let alone distinguish between events within a central complex (cf. Table 1.1). Some progress has been made in correlating the centres in the north of the Province, where the activity on Skye appears to post-date that of Rum and most of the Small Isles (Table 1.1). The tentative sequence of these is as follows: basaltic lavas on Muck and Eigg are cut by a dyke swarm which extends to Rum where it is truncated by gabbros and peridotites formed late in the Rum central complex. In north-west Rum, lavas and fluviatile conglomerates rest on eroded granophyre of the Rum central complex and the sediments contain clasts from the granophyre and most other members of the Rum intrusive suite, including ultrabasic rocks. Granophyre and felsite, similar to rocks on Rum, also occur in conglomerates interbedded with lavas on Canna and Sanday and in the Skye Main Lava Series near Glen Brittle. The Skye lavas and sediments were, in turn, intruded by the Cuillin gabbros, the earliest members of the Skye central complex. The Skye central complex therefore post-dates the Rum central complex which had been deeply eroded and unroofed by the time the intervening lavas were erupted. This sequence also demonstrates that there were at least two periods when lava piles built up, one before and one after emplacement of the Rum central complex.

By combining the field evidence and the available radiometric age determinations with detailed palaeomagnetic measurements, Mussett *et al.* (1988) have been able to build up a stratigraphic framework for the BTVP, and at the same time have shown that intense igneous activity in any one lava field, or within a given centre, was usually of geologically short duration (cf. Table 1.1; Mussett *et al.*, 1988, Fig. 2); their pioneering approach is clearly of wide application.

A REVIEW OF RESEARCH

'The gradual development of opinion regarding the nature and history of volcanic rocks is thus in no small measure bound up with the progress of observation and inference in regard to the Tertiary volcanic series.' Sir Archibald Geikie's words, written nearly a hundred years ago about the fresh and extensive exposures of volcanic rocks in western Scotland and Northern Ireland (Geikie, 1897), remain true to the present day. Since the early days of geology in the late eighteenth century, investigations of these rocks have been to the fore in the advancement of geology and mineralogy, and, in the last few decades, of geochemistry and geophysics.

Major advances to *c.* 1945

The early history of investigation of the Province is admirably recounted in the second volume of Geikie's *Ancient Volcanoes of Great Britain* (Geikie, 1897), in which the important role of these rocks in the controversies of the Neptunist and Plutonist schools is recorded. Continental visitors, particularly from France, who were familiar with active and recently active volcanoes, unequivocally interpreted the basalts as the result of volcanic eruptions. Notwithstanding, others including Robert Jameson, the great Scottish mineralogist and Professor of Natural History at Edinburgh University, strongly advocated the Neptunists', or Wernerian, viewpoint and ridiculed any connection between these rocks and volcanic activity. The controversy continued well into the nineteenth century, with the gradual ascendency of the Plutonist viewpoint, partly through observations on the dykes of north-east England. Recognition of the Tertiary age of the rocks was due to the Duke of Argyll (1851) who discovered and described plant remains in sediments intercalcated with basalt flows on Mull, although arguments about the ages persisted and older dates were assigned to the rocks of Skye where difficulties were experienced in distinguishing sills in the Mesozoic rocks from true lava flows.

In the latter half of the nineteenth century very significant advances were achieved. The noteworthy investigations by A. Geikie (eg. 1888, 1894, 1897) and J.W. Judd (eg. 1885, 1886, 1889) were mainly concerned with the overall structure and mode of accumulation of the Hebridean lava plateau. Geikie drew on his experiences in the western USA and Iceland to assert that the lavas had built up by successive fissure eruptions, whereas Judd recognized that the central complexes were the eroded remains of major Tertiary volcanoes, and was strongly of the opinion that they were the sources of the lavas.

Partly in an attempt to resolve this controversy, A. Geikie, the then Director of the Geological Survey, arranged for Alfred Harker of Cambridge University to make a detailed survey of the Tertiary igneous rocks of Skye, thereby initiating Survey investigations which were to cover Skye (Harker, 1904), Rum and the other Small Isles of Inverness-shire (Harker, 1908), Mull (Bailey *et al*., 1924), Arran (Tyrrell, 1928) and Ardnamurchan (Richey and Thomas, 1930). The impact of these memoirs and the accompanying maps was immense. The Skye Memoir detailed swarms of basaltic sheets inclined towards a common focus beneath the gabbros and granites, the coexistence and hybridization of magmas of contrasted compositions, and the formation of a central complex by multiple intrusions. The Mull Memoir confirmed the abundance of centrally inclined sheets (termed cone-sheets) in the central complex, described ring-dykes, including the type example at Loch Bà, and demonstrated the migration of igneous activity within a central complex with time. The relatively large number of chemical analyses made on the Mull igneous rocks allowed the Memoir authors to introduce the concepts of distinct chemical lineages of igneous rocks forming 'Magma Types' and 'Magma Series'; the importance of crystal differentiation in the development of these associations was also stressed. Richey and Thomas's work on Ardnamurchan (1930) built on ideas generated in the Mull Memoir, numerous ring-dykes and several suites of cone-sheets were recognized and the presence of three distinct centres was demonstrated.

Research in the BTVP was relatively limited between the early 1930s and the mid 1940s. The lavas and sills of northern Skye were mapped by the Geological Survey (Anderson and Dunham, 1966). A reassessment of the composite Glen More ring-dyke of Mull by Holmes (1936) and by Fenner (1937) concluded that the upward passage from olivine dolerite to granitic rocks resulted from mixing of compositionally contrasted magmas rather than by crystal fractionation, as originally proposed by Bailey *et al*. (1924) and subsequently supported by Koomans and Kuenen (1938). Valuable theoretical contributions based largely on data from the BTVP were made by Kennedy (1931a, 1933) and Kennedy and Anderson (1938) on the possible origins of the basaltic magmas, and by Anderson (1936) on the conditions of formation of ring-dykes and cone-sheets.

Research in the post-war years

The immediate post-war period saw the culmination of a controversy on the origins of granite, and other plutonic rocks, rivalling that between the early nineteenth century Plutonists and Neptunists. The question was, did plutonic granites form from the crystallization of magmas, or were pre-existing rocks transformed, or granitized, *in situ* to form granites? Evidence from the Province was regarded as crucial to the arguments of both sides, granites in the eastern Red Hills, Skye and western Rum were regarded as transformed Torridonian and Jurassic sediments respectively (e.g. Black, 1954, 1955), and it was also suggested that feldspar-phyric gabbros on Skye, were transformed amygdaloidal basalts (Reynolds, 1951; King, 1953). While these claims were strongly contested as they arose, a key discovery which decisively helped to swing the debate on granite origins in favour of the magmatists was made on the Beinn an Dubhaich granite on Skye, where Tuttle and Keith (1954) conclusively demonstrated that the mineralogy of this granite had characteristics of *both* the problematical plutonic granites and extrusive rhyolites of undoubted magmatic origin. It, and other BTVP granites, provided the essential 'missing link'.

The layered rocks

N. L. Bowen's classic work *The Evolution of the Igneous Rocks* (1928), included arguments strongly favouring crystal fractionation as a major mechanism in determining rock compositions. He drew heavily on examples from the BTVP, in particular citing the Mull feldspar-phyric Porphyritic Central Magma-type rocks and the peridotite dykes of Skye as products of the process. The efficacy of this mechanism was brought into sharp focus by Wager and Deer's (1939) investigations of the East Greenland Skaergaard Intrusion. The strikingly layered rocks of Skaergaard were considered to have formed by the gravitational accumulation of crops of crystals from fractionating basaltic magma and its derivatives. The literature of the BTVP was already full of examples of banded peridotites and gabbros (for example, Geikie and Teall, 1894; Harker, 1904, 1908; Bailey *et al*., 1924; Richey and Thomas, 1930) and it was immediately recognized that there were at least superficial similarities to the

Skaergaard layering, especially in the Skye Cuillins and on Rum. Brown's (1956) study of the latter provided convincing evidence of crystal sorting and settling forming the layered rocks, but in contrast to Skaergaard, this was not accompanied by the systematic compositional ('cryptic') variations in rock and mineral chemistry. The explanation offered was that the Rum layered rocks built up from a succession of pulses (15) of basaltic magma, whereas there was only a single input of magma at Skaergaard. Thus Rum became, and remains, a classic example of an 'open' magma chamber, fed by successive batches of magma from each of which early, high-temperature crystals separated and accumulated to form the layered rocks of Hallival and Askival.

Minerals in layered igneous rocks frequently exhibit distinctive textural relationships thought to be due to the accumulation of some (cumulus) crystals and the precipitation of others from the liquid (intercumulus) trapped between sedimented crystals. The fresh, unaltered rocks of Skye and Rum provide type examples of the textures and structures found in these 'magmatic sediments' and the two centres are classic examples of layered igneous rocks and 'igneous cumulates' (Wager *et al.*, 1960; Wager and Brown, 1968). During the past decade, ideas on the origins of igneous rocks have undergone radical reappraisal (cf. McBirney and Noyes, 1979) and it has increasingly been recognized that *in situ* crystallization, double-diffusive convection and movement of trapped, high-temperature liquids through crystal mushes may contribute to the formation of layered igneous rocks or their modification, and that crystal fractionation aided by convection-driven magmatic currents may not always be applicable. The exceptionally well-exposed layered rocks of Rum have provided an excellent natural laboratory where the new hypotheses have been tested and developed (see for example, papers in the *Geological Magazine*, **122**, 1985).

The contribution from geochemical and isotopic studies

The 1950s and 1960s saw the extensive application of the analytical techniques of optical spectroscopy, spectrophotometry and X-ray fluorescence to geological and mineralogical problems. Geochemistry blossomed as a subject, as it became possible to analyse rocks rapidly, and to detect a whole range of hitherto geologically inaccessible elements in concentrations down to a few parts per million. Many of the pioneering applications of these techniques took place in the BTVP: trace element distributions in the Skye rocks were examined (Nockolds and Allen, 1954); the geochemistry of whole suites from the Province analysed and compared with other classic areas (Wager, 1956; Tilley and Muir, 1962, 1967); and detailed successions of lavas and intrusions were analysed (for example, the lavas of Skye, Thompson *et al.*, 1972), the Ardnamurchan cone-sheets (Holland and Brown, 1972) and the dykes of Skye (Mattey *et al.*, 1977). Several distinctive groups of basaltic and associated compositions were recognized in the Hebrides of which the Skye Main Lava Series and the Mull Plateau Group were the most abundant, including olivine basalts, hawaiites and mugearites which varied from transitional to mildly alkaline compositions (Fig. 1.2). Silica-rich, alkali-poor, tholeiitic rocks form late flows on Skye and are found as dykes on Skye and occur elsewhere in the Province; these were termed the Preshal More group (Table 2.2) after the type occurrence in south-west Skye. The BTVP lavas show significant differences in the compositional range when compared with lavas from another classic area, the Hawaiian Islands. The well-defined division into silica-poor, alkali-rich (alkali olivine basalts) and silica-rich, alkali-poor (tholeiitic) compositional fields found in Hawaii is not present in the Hebrides, signifying different conditions of both generation and transport to the surface of the magmas.

The geological application of mass spectrometry and the development of isotope geochemistry since the 1960s have provided crucial new information about the ages and origins of igneous rocks. The BTVP has figured prominently in the application of these techniques. The Skye granites, gabbros and lavas (Moorbath and Bell, 1965; Moorbath and Welke, 1969) yielded Palaeocene ages, together with strontium and lead isotopic data which showed that, whereas the basaltic rocks had distinct mantle signatures, the granites on the whole did not and were probably derived by partial melting from crustal sources. Lead derived from Lewisian sources was present and it was proposed that the granites came from partial melting of the gneisses. Subsequent oxygen isotope investigations (Taylor and Forester, 1971; Forester and Taylor, 1976, 1977) showed that the granites had been pervasively invaded by heated

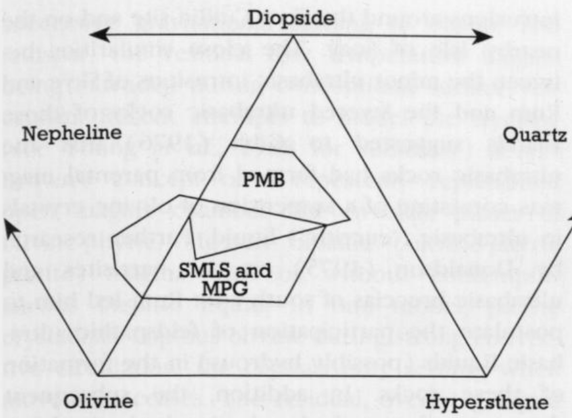


Figure 1.2 Diagram showing fields of the Preshal More Basalts (PMB), and the Skye Main Lava Series (SMLS) and Mull Plateau Group (MPG) when projected into normative nepheline–diopside–olivine–hypersthene–quartz (after Thompson, 1982, figure 2).

groundwaters as had the rocks around the central complexes. This raised the possibility of significant post-consolidation changes in the compositions of the rocks and consequently cast doubt on the validity of the earlier Sr- and Pb-isotope studies, with the added corollary that detailed elemental and isotopic studies of rocks from the BTVP (especially in and near central complexes) might be of very limited petrogenetic application. This crucial problem was specifically addressed by Pankhurst *et al.* (1978) who showed, by means of a careful study of the Loch Uisg Mull granite, that, provided that the samples were carefully selected, post-consolidation changes were in fact minimal.

Precision, accuracy and detection limits in elemental geochemistry have also been significantly improved in the past two decades, partly due to the introduction of induced neutron activation analysis (INAA) and inductively coupled plasma mass spectrometry (ICPMS). These, and other new and improved techniques, have been applied to the Province, notably to the problem of granite genesis. Both on Mull (Walsh *et al.*, 1979) and on Skye (Dickin, 1981) there is now a consensus that the granites contain variable, but always significant contributions from both mantle and crustal sources (for example, Dickin *et al.*, 1984). There is considerable compositional and isotopic variation within the basaltic rocks and their derivatives which has, for Mull, been attributed by Beckinsale *et al.* (1978) to variations in mantle sources. Essentially the same data are amenable to alternative interpretations: while agreeing with the ultimate mantle source, Morrison *et al.* (1985) and Thompson *et al.* (1986) suggest that a major factor contributing to the compositional variability is the extent to which a particular batch of magma has interacted with the lower and/or upper crust during its progress towards the surface. Using data obtained from flows low in the Skye and south-west Mull lava successions, they argued that each separate batch of magma may have had a distinctive and complicated history of intermittent ascent, ponding at different levels in the crust where rock types caused density traps, and reacting with the adjoining rocks to a greater or lesser extent. The Skye and Mull lavas have thus been used as geochemical probes to investigate the magmatic plumbing of part of the feeder system for the BTVP lavas.

A tholeiite dyke from the north of England was among the first intrusions to be dated radiometrically (Dubey and Holmes, 1929) and numerous age determinations have now been made on rocks from the BTVP (Table 1.1). As already mentioned, the time span for the Province is about eleven million years, between *c.* 63 Ma and 52 Ma (for example, Mussett *et al.*, 1988). Age-determination techniques have proved to be of somewhat limited application in the BTVP since individual igneous events, and groups of events, took place over very short times in geological terms. However, work is now well under way towards defining a reliable stratigraphy for the Province, using high-quality age data in combination with detailed determinations of remanent magnetization of rocks for which there are good geological data on relative ages. Table 1.1 provides a summary of some of the results to date (Mussett *et al.*, 1988).

Deep structure of the central complexes: the geological input

Studies of the gravitational field over the BTVP have yielded far-reaching and important results. In addition to regional surveys (by the British Geological Survey), much detailed local information has come from a series of investigations since the early 1950s (for example, Tuson, 1959). The central complexes are almost invariably the sites of positive Bouguer gravity anomalies which include some of the most pronounced in the British Isles (for example, the submarine Blackstones Bank complex; McQuillin *et al.*, 1975). The interpretations of the Skye, Mull and Ardnamurchan (Bott and Tuson, 1973), Arran and Rum (McQuillin and Tuson, 1963) anomalies show that each centre is underlain by dense rock (3.0–3.3 $g\,cm^{-1}$) of the composition of very olivine-rich gabbro or feldspathic peridotite. The masses of mafic rocks are broadly cylindrical or else steep-sided truncated cones, they extend for depths of 12 km or more through the crust, and they may be over 20 km in diameter (cf. Bott and Tuson, 1973, Figs 1 and 2). They are thus major features of the Hebridean crust and they underlie not only the mafic parts of centres but also the granites. The implications of the interpretations of the anomalies are far-reaching: mafic magmas must have dominated the BTVP igneous activity for, although areally extensive, the granites are only superficial bodies, perhaps only 2 km thick (Bott and Tantrigoda, 1987). The mafic rocks could have given rise to the granites by magmatic fractionation but equally they were heat sources capable of effecting melting in the surrounding crustal rocks, thus generating the granitic magmas, or a component thereof. The gabbroic and ultrabasic rocks of Rum are probably the upper tip of one of these mafic bodies.

The precise conditions governing the siting of the central complexes are not fully understood, but their location at or near the intersections of the basic dyke swarms with major faults has long attracted attention, and a causative connection has been suggested (Richey, 1937; Vann, 1978; Upton, 1988). If the major faults, such as the Great Glen and Highland Boundary Faults, have influenced siting of the central complexes, then that influence has extended to the base of the Palaeocene crust.

Modelling magmatic evolution

A major problem of the ultrabasic rocks of the BTVP, and elsewhere, has been to decide whether they formed from ultrabasic or basaltic magmas. Their frequent close association with rocks of basaltic compositions makes the latter an attractive proposition (Brown, 1956); however, the possibility that high-temperature ultrabasic magmas may have been present at upper crustal levels in the BTVP has become accepted in recent years. The idea was advanced by Drever and Johnston (1958) and Wyllie and Drever (1963) from examinations of minor ultrabasic intrusions around the Skye Cuillin site and on the nearby Isle of Soay. The close similarities between the minor ultrabasic intrusions of Skye and Rum and the layered ultrabasic rocks of those islands suggested to Gibb (1976) that the ultrabasic rocks had formed from parental magmas consisting of a suspension of olivine crystals in ultrabasic ('eucritic') liquid. Further research by Donaldson (1975) on the harrisites and ultrabasic breccias of south-west Rum led him to postulate the participation of feldspathic ultrabasic liquids (possibly hydrous) in the formation of these rocks. In addition, the subsequent discovery of quenched, aphyric ultrabasic dykes intruding the Rum layered rocks (McClurg, 1982), the recognition that some at least of the feldspathic peridotite layers in the Rum succession were intrusive (Renner and Palacz, 1987; Bédard *et al.*, 1988), and the presence of a quenched ultrabasic margin to this complex at Beinn nan Stac (Greenwood *et al.*, 1990), provided further strong supporting evidence for ultrabasic liquids. It thus appears inescapable from the evidence furnished by the BTVP that conditions in the central complexes and their immediate surroundings favoured the rise of hot, dense picritic liquids to within short distances (*c.* 1 km) of the Earth's surface. Although not unique, these examples are unusual and it appears that the special conditions involving rapid, strongly focused throughput of hot basaltic magmas, resulted in the formation of preheated pathways along which the ultrabasic liquids rose to high structural levels before crystallizing and congealing.

The availability of new, quantitative data on the physical and chemical properties of magmas and increasingly sophisticated computing techniques has made it possible to model magmatic processes. Noteworthy studies using examples from the BTVP have included examination of the emplacement of the Cleveland Dyke of north-east England and of the layering in the Rum ultrabasic rocks. MacDonald *et al.* (1988) demonstrated a close chemical similarity between the Cleveland Dyke tholeiite and rocks in the Mull central complex. They postulated that the dyke had been fed laterally from a source beneath Mull, flowing '. . . in a manner transitional between laminar and turbulent conditions'. It was calculated that the magma took between one and five days to reach North Yorkshire. Brown (1956) described contrasted olivine- and feldspar-rich layering in the Rum ultrabasic rocks, attributing the layering to successive gravitational settling of olivine and feldspar, the residual low temperature magma being extruded during concomitant surface volcanism. Recent attempts to model the layering (see Young *et al.*, 1988 for summary) accept Brown's concept of a repeatedly replenished open magma chamber but envisage pulses of olivine-phyric, Mg-rich basaltic (olivine-phyric picrite) magma with or without contemporaneous basaltic liquid. In one model, picrite crystallizes copious olivine during strong convective circulation, the crystals only settling when movement ceases. The residual, overlying liquid then crystallizes feldspar-rich cumulates by basalt fractionation (Huppert and Sparks, 1980; Sparks *et al.*, 1984; Tait, 1985).

An alternative view (Young *et al.*, 1988) is that simultaneous crystallization of olivine, and olivine plus plagioclase, occurs in a magma chamber zoned upwards from picritic to basaltic compositions. The model assumes a dipping floor to the magma chamber, corresponding more or less with the dipping layering observed on eastern Rum (cf. Brown, 1956; Volker and Upton, 1990). Simultaneous crystallization in picritic and basaltic liquids would result in the formation of peridotite at low levels on the magma chamber floor and of troctolitic (allivalitic) and gabbroic rocks at higher levels. The conspicuous major layering in eastern Rum would therefore result from variations in the rate of magma injection into the chamber, peridotite forming when this was high, and troctolite and gabbro when it waned and olivine precipitation depleted the picritic proportion of the resident magma. The model finds its support in the manner in which the proportion of peridotite in the layered rocks of eastern Rum increases towards the west where it has been suggested that the magma arose along the line of the present Long Loch Fault (McClurg, 1982; Volker and Upton, 1990).