The tertiary igneous geology of Strathaird, Skye

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THE TERTIARY IGNEOUS GEOLOGY OF STRATHAIRD, SKYE.

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ABSTRACT

This study is concerned with the Tertiary igneous rocks found within an area some twenty square miles in extent on the south-east side of the Skye central intrusion complex. The Tertiary rocks include basic lavas, a small intrusion of granophyre, the margin of the Cuillin Gabbro, and numerous minor intrusions.

Extrusive rocks occupy an area of some seven square miles, and have an aggregate thickness of about 1,000 feet. The greater part of the sequence consists of alkaline olivine basalts, but there is also one horizon of trachybasalt and a thin group of picritic flows. Pyroclastic rocks are rare, being limited to one small agglomerate vent and an isolated lens of tuff. It has been found possible to divide the sequence into several mappable units based on groups of flows possessing common petrographical features.

The lavas which lie within half a mile of the Cuillin Gabbro have been metamorphosed by that intrusion, while an outer zone of lower temperature alteration includes the whole of the Strathaird lava outcrop. Within the thermal aureole a narrow zone of pyroxene hornfels along the contact with the Gabbro is followed outwards by a broader zone characterized by the presence

of an actinolitic amphibole. Within the pyroxene hornfels zone the lavas have been thoroughly recrystallized to high temperature mineral assemblages, but within the amphibole zone equilibrium was only locally attained, and many of the lavas still possess much of their original texture and mineralogy. The transition from unmetamorphosed lava to pyroxene hornfels was not accomplished by progressive metamorphism, with minerals of higher grade succeeding lower ones, but each stage developed independently under its own particular pressure-temperature conditions. On the basis of both chemical and petrographical evidence it is considered probable that a small amount of silica was added to at least some of the lavas during metamorphism.

The internal structure and composition of the Cuillin Gabbro do not come within the provenence of this thesis, but some attention has been given to the relationships between the Gabbro and its country rocks, especially in the neighbourhood of Camasunary. In this latter area there is an extensive development of basic minor intrusions pre-dating the Gabbro, and metamorphosed in a similar manner to the nearby lavas. Most of these small intrusions are emplaced into Torridonian sandstones, which locally extend up to the edge of the Gabbro. For distances of up to several hundred feet from the contact, the Torridonian shows clear evidence of having been partially melted by the high temperatures induced by the intrusion of the gabbro magma, and many of the early intrusions are veined and broken into fragments by the mobilized material. The vein material is chemically more basic in composition than the sediments from which it was derived, partly due to reaction with the basic minor intrusions.

Parallel to the contact of the Cuillin Gabbro, in Strathaird, there is a series of irregularly shaped outcrops of granophyre which are thought to be parts of a single intrusion exposed in the vicinity of its roof. The granophyre is fine-grained, is unusual in containing paramorphs after tridymite, and differs chemically from other Skye granitic rocks. Though there is sometimes a well-defined, chilled margin, many of the contacts against sedimentary rocks are complex and highly xenolithic. The granophyre post-dates the Cuillin Gabbro, but is earlier than the large granitic intrusions which lie to the north and north-east of the area.

One of the most impressive features of the local geology is the great profusion of north-west dykes, all but a few of which are basic in composition. Most of the dykes are of later date than the Cuillin Gabbro, but their distribution shows that they are closely related to that centre. Other minor intrusions include a few acid and basic sills which are, in general, of earlier date than the dyke swarm, while basic cone-sheets occur in the vicinity of the Cuillin Gabbro and are later than most of the north-west dykes.

In Strathaird, erosion to a relatively deep level allows the structural relationships between lavas, intrusions, and pre-Tertiary sediments to be more easily examined than elsewhere in Skye. Most of the sediments are of Jurassic age, and these rest unconformably on Torridonian sandstones. There were several phases of warping in Mesozoic times, but the main period of deformation occurred after the outpouring of the lavas and gave rise to ~~the~~ large arcuate folds. It is believed that these folds are one result of the stresses set up by the intrusion of the Cuillin Gabbro.

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CHAPTER I

SCOPE AND METHODS.

(i) Scope of the Study.

In recent years a number of geologists have been engaged in making a new study of the igneous complex of Skye, for this area has received little attention since the first detailed work of Alfred Harker at the beginning of the present century. During the intervening years much new knowledge has been accumulated concerning the nature of igneous rocks in general and on the special features of the British Tertiary complexes in particular. Most of the new work on Skye is as yet incomplete and the greater part of it remains unpublished.

The peninsula of Strathaird, lying on the south-eastern margin of the Skye central intrusion complex (see Plate 1), was primarily selected because it contains a considerable area of extrusive rocks, and so offered the opportunity to study both a lava sequence and its relationships with the intrusive rocks, particularly the Cuillin Gabbro, which borders Strathaird on the north-eastern side. The Gabbro itself does not form a part of the subject matter studied, though the event of its intrusion had a considerable influence on various aspects of the geology. The two main subjects dealt with in this

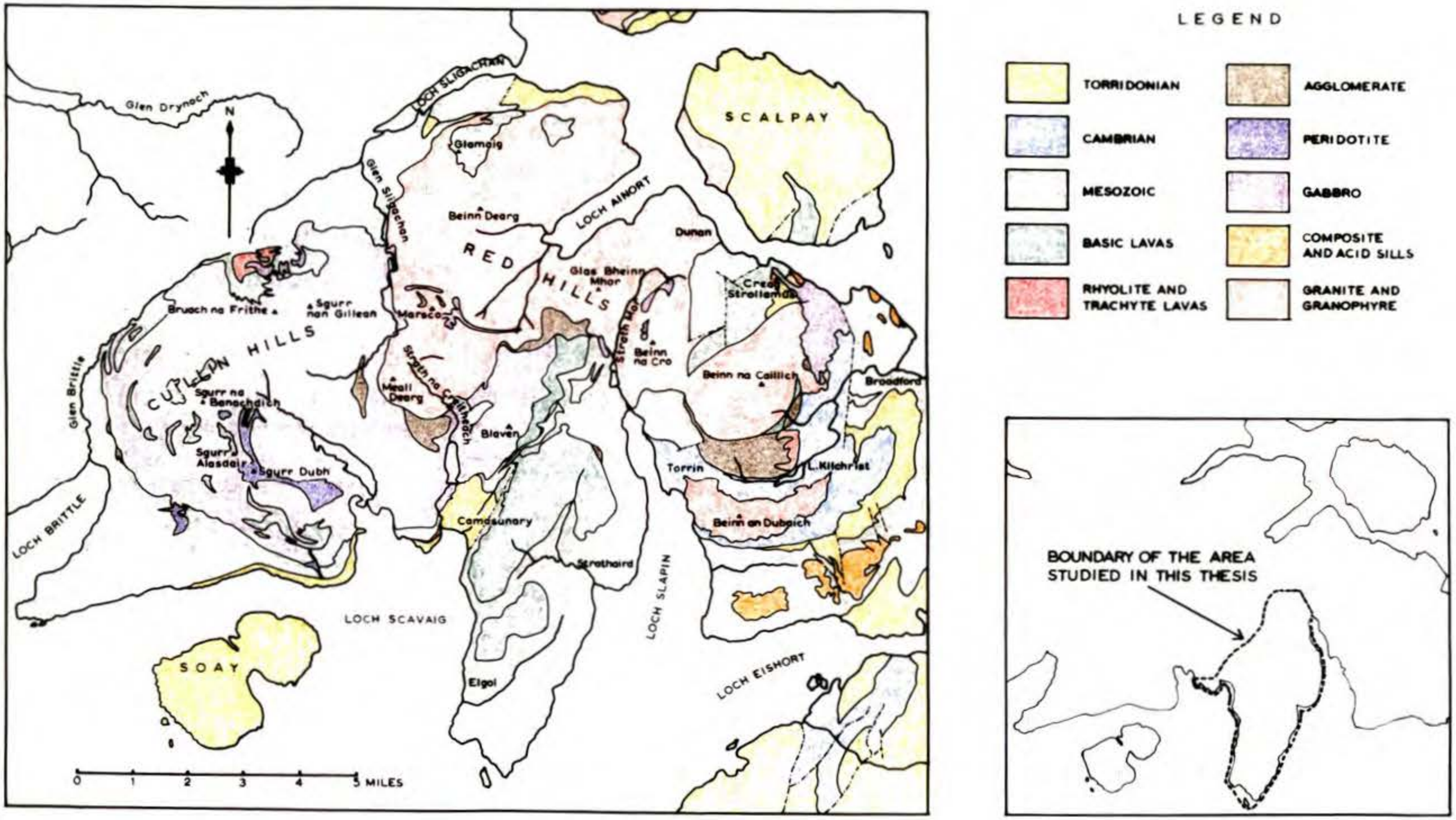


PLATE 1 SKETCH MAP OF CENTRAL SKYE, SHOWING THE GENERAL GEOLOGY

REDRAWN FROM GEOLOGICAL SURVEY OF SCOTLAND, 1 INCH TO 1 MILE, SHEETS 70 AND 71.

thesis are therefore a study of the lava and an examination of the contact zone of the Cuillin Gabbro. An account is also given of the other, mainly small, intrusions in the area, and of the tectonic and time relationships between the various elements.

For the purposes of this work the area of Strathaird has been taken to include the whole of the peninsula portion, together with the area around Camasunary, to the west, which forms the natural termination to this sector of the Gabbro contact. To the north the boundary approximately coincides with the edge of the Red Hills complex of granitic rocks and agglomerates.

(ii) Methods.

Mapping. The field mapping was carried out on a scale of six inches to one mile, using Ordnance Survey maps and a stereoscopic coverage of aerial photographs on approximate scales of 1:10,000 and 1:30,000 (provided by kind permission of the Air Ministry).

The final base map was prepared by using the most accurately surveyed lines of the Ordnance Survey maps and superimposing details from the aerial photographs. In this way the forms of crags, streams, and sea-cliffs were corrected, and topographical features of geological significance added.

The contour lines, placed at 100 ft. O.D., 250 ft. O.D., and 250 foot intervals thereafter, are derived from the O.S. 1 inch to the mile map via the O.S. 1:25,000 provisional edition, with corrections taken from form lines drawn on the aerial photographs. They are thus of only approximate accuracy. The names and spellings given by the Ordnance Survey have been generally adhered to, while two further names used locally have been added. The first of these refers to the corrie between the south ridge of Blaven and Slat Bheinn, which is called Coire Casteail, and the second to the corrie between Slat Bheinn and An Stac, locally named Coire Ballaig.

A copy of the base map with geological information added is provided in the back pocket of this volume.

In addition to the 6 inch maps, an area of about half a square mile along the contact of the Cuillin gabbro at Camasunary was mapped in greater detail on a scale of 1:1,250. A plane table was used for this work, the geological and topographical features being added at the same time. The large scale employed and the high degree of exposure enabled the method of "outcrop mapping" to be used, whereby the position and approximate shape of each exposure is individually delineated and the geological features actually visible entered on them. Conjectural boundaries can then be shown by broken lines between the exposures. On the copy of the map at the back of this volume lighter shades of colour are used for the conjectural portions than for the rocks exposed. The known facts are thus separated from the inferences and the relations between the two seen at a glance.

<u>Laboratory methods</u>. A large porportion of the time spent in laboratory work was occupied in routine petrographic examination of thin sections. To aid the precision of this work a large number of modal analyses were made using a Swift point-counter, and on each slice examined in this way about 2,000 points were determined. Many of the Strathaird rocks have been affected by low temperature alteration, but it was decided that only the proportions of primary minerals would be measured in the normal case. The primary texture was nearly always well enough preserved for the alteration products to be counted in with one or other of the primary minerals; olivine, for instance being always represented by pseudomorphs of characteristic form. The accuracy of the point counter method decreases rapidly as the grain becomes fine, and it is believed that the analyses of fine grained lavas, such as ophimottled basalts, are less reliable than those of the coarser lavas and intrusions.

Refractive indices of crushed mineral grains were determined by the immersion method, using a sodium vapour lamp to observe the Becke line in the final liquids. Results obtained by this method are usually said to be accurate to $\pm$ 0.002. Optic axial angles were measured directly on a Leitz four-axis universal stage, using the method described by Emmons (1943).

The general scheme for rapid silicate analysis developed by Shapiro and Brannock (1952) was employed in making the chemical analyses. In this method SiO_2, Al_2O_3, total iron as Fe_2O_3, TiO_2, MnO, and P_2O_5 are determined by measuring the optical density of coloured solutions of their compounds, alkalis are measured in a flame photometer, while CaO, MgO and FeO are determined by titrations. The total loss on ignition is used to obtain a summation. Several modifications of the scheme were used on the suggestion of Dr. R. A. Chalmers of the Durham Colleges Geological Department. Thus in the method for determining CaO and MgO, micro-titrations were carried out in a special cell fitting into the spectrophotometer, so as to determine the end-point more exactly (see Chalmers, 1954). In the determination of total iron an aliquot of Solution B was passed through a silver reductor column and then titrated with 0.01 N solution of ceric sulphate, using o-phenanthroline-ferrous complex as the indicator. Water below 105° C. was determined by drying in an oven for twelve hours, and combined water by the Penfield tube method.

CHAPTER II

GENERAL GEOLOGY.

(i) Topography and Rock Types.

The subject of this study is an area of some twenty square miles in central Skye. The whole of the peninsula of Strathaird and the immediately adjacent parts of the Cuillin Hills are included. Jurassic sediments and igneous rocks of Tertiary age form the bulk of the outcrops (see Plate 1).

The Strathaird Peninsula is bounded by Loch Scavaig to the west and Loch Slapin to the east. These two basins are continued to the north by deep valleys which cut right through to the east coast of the Island without rising to more than 250ft. O.D.. Strath Mor is the extension of Loch Slapin and Strath na Creitheach continues the line of Loch Scavaig. The silted nature of the floors of these valleys indicates that the retreating Pleistocene ice left them very much more flooded than at present.

Between the two straths the mountains rise steeply and culminate in the Blaven Range* of north Strathaird, which for some three miles has an elevation of over two thousand feet. Blaven itself (3,042 ft. O.D.) lies at the south end and is followed north by Clach Glas, Sgurr nan Each, Garbh Bheinn, and Belig. The

* Plate 2

PLATE 2 (opposite). The Blaven Range, seen from the east across the head of Loch Slapin.

In the centre of the panorama the peaks of Blaven, Clach Glas, and Sgurr nan Each rise steeply above Coire Uaigneich, with the contact of the Cuillin Gabbro situated about half way up the face. To the left, and in front, of Blaven is An Stac, built of lavas dipping towards the observer, while on the extreme left is the long ridge of An Carnach, in which the lavas dip away from the observer. Below the An Carnach lavas can be seen features produced by the Inferior Oolite sandstones (in sunlight.) Garbh-Bheinn lies to the right of Sgurr nan Each, but is largely hidden by it, while Belig stands isolated at the head of the loch. The contact of the Cuillin Gabbro passes below Garbh-Bheinn and crosses over Belig near the summit, while the lower parts of these mountains consists of lavas overlying sediments of Jurassic age. On the extreme right is Glas Bheinn Mhor, one of the summits within the Red Hills granitic complex.

eastern slopes are deeply embayed by corries, while the western flanks are relatively smooth. The summit ridge has been taken as the north-west boundary of the mapping area.

These mountains owe their precipitous character to their situation on the margin of the Cuillin Gabbro massif, the contact of which runs through the eastern slopes. Between Blaven and the Cuillin main ridge to the west the Gabbro has been deeply embayed by the later intrusion of a southward extending lobe of the Red Hills granophyres. To the north, the contact of these granitic rocks lies between Belig and Glas Bheinn Mhor and another group of similar intrusions forms Beinn na Cro and Beinn na Caillach on the east side of Strath Mor. All these late acid rocks lie outside the studied area. Their rounded, scree-covered slopes are in marked contrast to the bold hill-forms of northern Strathaird.

The country rocks into which the Gabbro was intruded occupy the peninsula south and east of the Blaven Range, and comprise a thick series of Mesozoic sediments overlain by Tertiary basic extrusives. They rest upon a basement of Torridonian sediments which is only seen where upthrown by a pre-Tertiary fault at Camasunary.

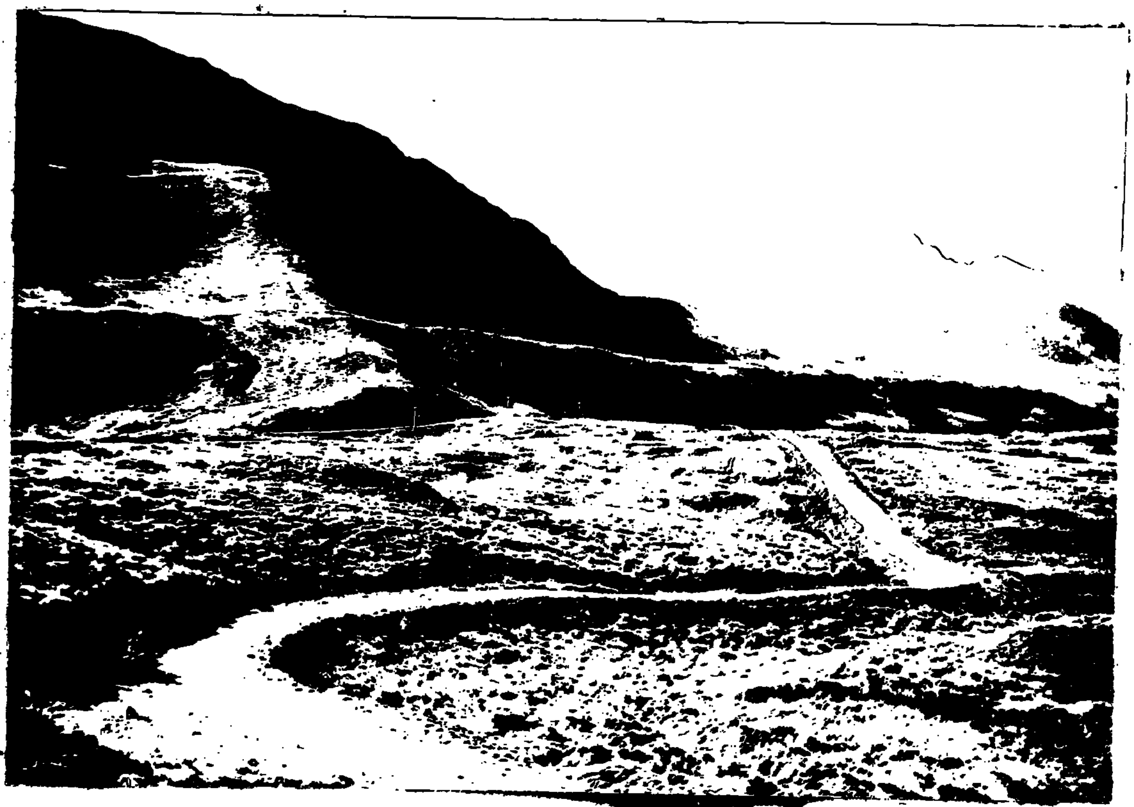
In the north, lavas and sediments occupy the eastern slopes of the Blaven Range below the Gabbro contact, and are there intruded by an elongate mass of granophyre. In the centre of the peninsula the main outcrop of lavas builds a south-facing horse-shoe of hills which rises 2,002 feet O.D. in Slat Bheinn, and also includes Beinn Leacach (888 ft. O.D.), An Stac (c.1,700 ft. O.D.) and An Carnach (c.1,100 ft. O.D.). This main outcrop is separated from a subsiduary lava area to the south by the Glen Scaladal-Kilmarie depression. South of it the lavas form a capping to Ben Meabost* (1,128 feet) and Ben Cleat.

The lava hills attain their greatest elevation and boldness of relief adjacent to Blaven, the cause of this being in part tectonic, and in part due to the hardening effects of thermal metamorphism.

The sub-lava sedimentary sequence is mainly of Jurassic age, and has its greatest spread on the east side of the Peninsula. In that area the thick Inferior Oolite sandstones outcrop in several north-south scarps while the shaly Estuarine Series forms a steep slope above. In western and northern Strathaird a wedge of sandy Corallian strata intervenes below the lava base. The sediments have a gently westerly dip which brings the Estuarines and Corallian down to sea-level on the

* Plate 3.

Frontispiece. Blaven from Loch Kilchrist, Strath.



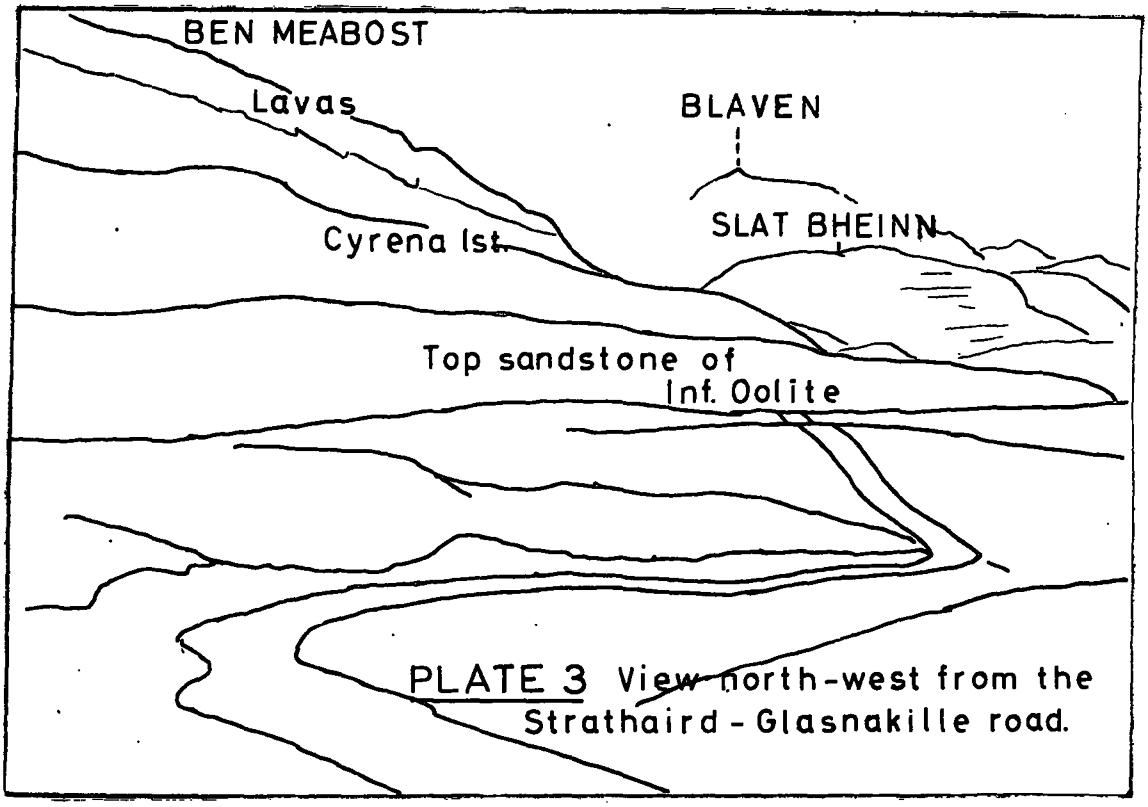


PLATE 3 View north-west from the Strathaird - Glasnakille road.

western coast, where the former is particularly well exposed in high cliffs.

The lavas and the Jurassics together constitute over ninety per cent of the outcrops in Strathaird. There is also present an extremely numerous series of Tertiary minor intrusions especially abundant in the southern half of the peninsula. They are mainly basic in character and most are dykes belonging to the north-west swarm of central Skye. Accompanying them are less numerous dykes of other orientations, a system of cone-sheets related to the Cuillin Gabbro, and a few sills, both acid and basic. The largest sill forms a marked feature near Elgol.

The chief rivers lie in the through-valleys to the east and west, but much of the drainage is by a small scale lattice pattern of streams developed in the Jurassics and emptying direct into the sea-lochs. The watershed lies towards the western side of the Peninsula.

(ii) Glaciation.

Land-forms. The influence of Pleistocene glaciation upon the land-forms of Strathaird is very marked and deserves a brief account.

Harker (1902) gives a general description of the glaciation of the Cuillin Hills and presents a map of the main directions of ice-flow. He and the authors of the Geological Survey memoir to Glenelg, Lochalsh and south-east Skye (1910) showed that the main Scottish ice-sheet, sweeping westwards, was bifurcated by a thick local ice-cap accumulated in central Skye. The boundary of this local sheet lay in the Sound of Scalpay in the north and curved round through the Broadford district to cross the foot of the Strathaird Peninsula. Thus the whole of Strathaird except the southern tip lay under local ice. Harker also considered that the thickness was not less than 3,000 feet at maximum and that the deepest accumulation probably lay over Strath na Creitheach.

While the great overdeepening of the north-south through valleys is probably to be referred to the period of maximum glaciation, when a great depth of ice pressed out along these channels, the detailed sculpturing of the Blaven range was affected during the valley-and corrie-glaciation stages. The alpine-type frost-shattered aretes and deeply gouged corries were carved out of the Gabbro and its contact aureole at this time. More easily eroded rocks to the south and east yielded a lower relief.

An interesting feature of the Strathaird corries is that they show a marked tendency to possess quadrangular rather than bowl-shaped forms due to the influence of the approximate rectangular arrangement of the joint and dyke systems. Coire Uaigneich, under Blaven's east face, illustrates this feature well, possessing upper and lower corries of this shape separated by a rock step. Coire Casteail and Coire Ballaig are again almost square in plan.

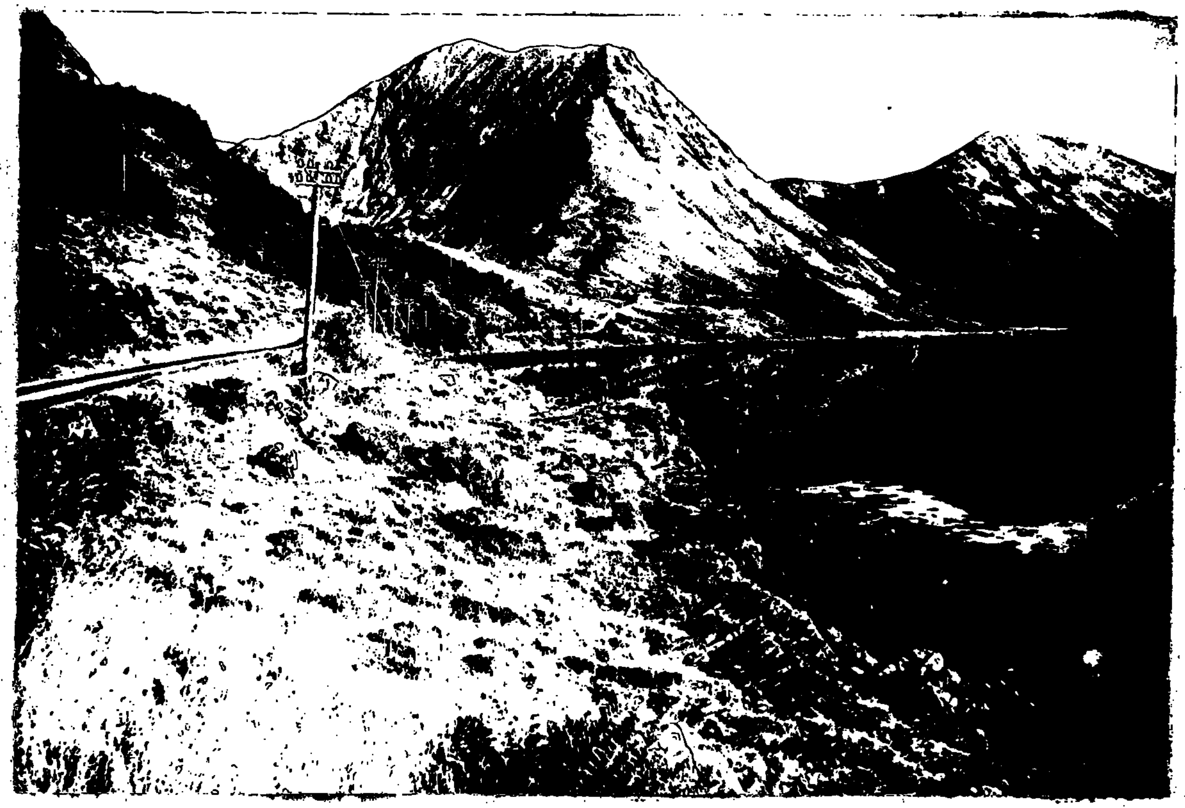
Corrie lakes are absent except for the unusually situated Loch Coire Uaigneich, which lies in a low col between Coire Uaigneich and the adjacent Coire Ballaig. The lake is confined by rock steps on both east and west. In Lower Coire Uaigneich a small alluvial flat suggests the former presence of a moraine-dammed lake.

According to Hobbs (1911) the position of the old bergshrund in a corrie is marked by a break between the frost-shattered cliffs above and ice-smoothed plinth of slabs below. This old "shrund-line" can sometimes be detected in the Blaven range, as on the east face of Clach Glas at about 1,500 feet. Down-stream the shrund-line passes into a similar feature marking the lateral extent of the valley glacier, as can be seen in the neighbourhood of Camasunary at some 500 feet O.D.. Horizontal grooving of the old glacier floor is there very strongly developed.

Narrow ridges are usual in the Gabbro hills and are especially spectacular on Clach Glas, while on Garbh-Bheinn three such aretes abut to form a fine example of a pyramidal peak. The lava-built hills however, exhibit great reluctance to form ridges and, where a thick sequence is present, have been eroded into stack-shaped, flat-topped hills. Where only a few flows are present they form rounded hills with a cliff-line marking the lava base.

The numerous joints and shatter belts, often followed by dykes and sometimes by faults, have been exploited by frost and streams, and so give character to the form of the hill sides. Most of the planes of weakness are orientated between N.W. and N.N.W. and this has given rise to the lineation of minor features in this direction. Deep gullies and chimneys divide otherwise smooth slopes, as, for instance, those which cleave Clach Glas's eastern face into several segments. In the lower hills the lineation is expressed as shallow depressions and parallel streams, while notches are formed in the edges of the lava capping.

The cone-sheets and their related joint system are found only in the vicinity of the Gabbro. They are marked by small terraces dividing the eastern faces approximately horizontally, and inclining to the W.N.W. in the northern and southern flanks. A complementary joint system dipping eastwards is also present, though



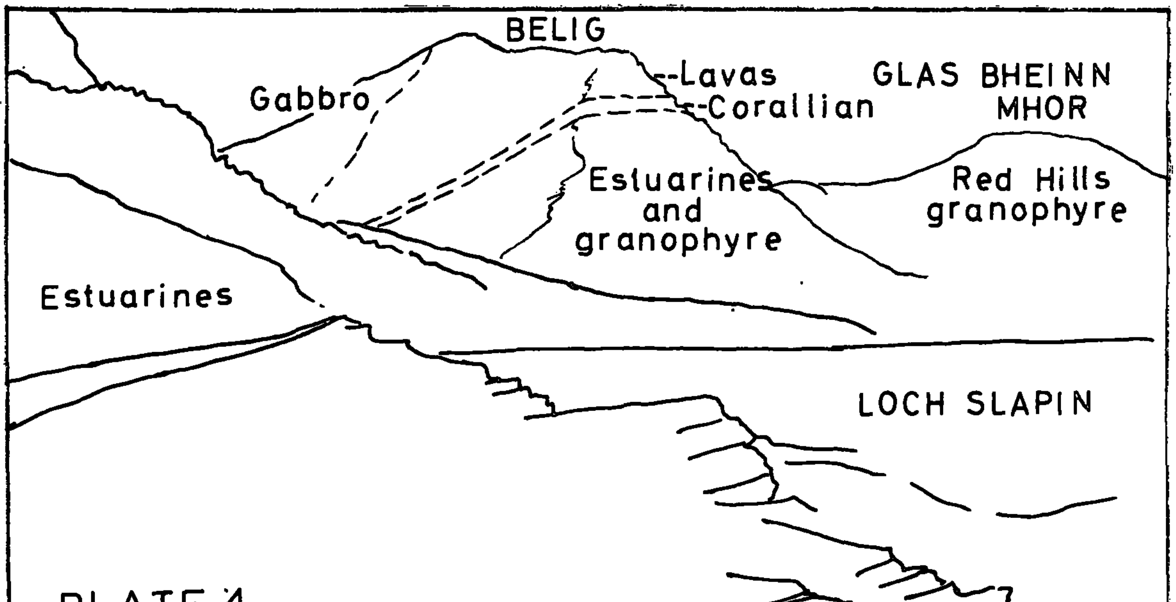


PLATE 4
View north from Faoilean.

rarely followed by intrusions, and this has similar effects on the weathering. Where the two sets intersect, as on the south face of Belig, a diamond-shaped crag pattern is produced.

Influence is also exerted by the bedding of the lavas and sediments. In close proximity to the Gabbro contact metamorphic welding has made this of little account in controlling erosion, but its role increases in importance outwards from the intrusion and terrace-featuring is characteristic of the lower hills.

The valleys are of typical U-shape, particularly the large north-south through-valleys, while the corries bear a hanging relationship to them. The east face of Belig* is a good example of a truncated spur bevelled by the Strath Mor ice-stream. The floors of the through-valleys are mainly obscured by lochs or their silted-up remnants, but rock emerges at Camasunary as a smoothed and grooved barrier separating the ninety-foot deep Loch na Creitheach from the sea in Loch Scavaig.

<u>The pattern of ice-flow</u> (see Plate 5) Three factors guided the directions of ice-flow (a) accumulation in the Blaven range, (b) restriction of the outlets by the two large southward-flowing glaciers of Strath Mor

* Plate 4

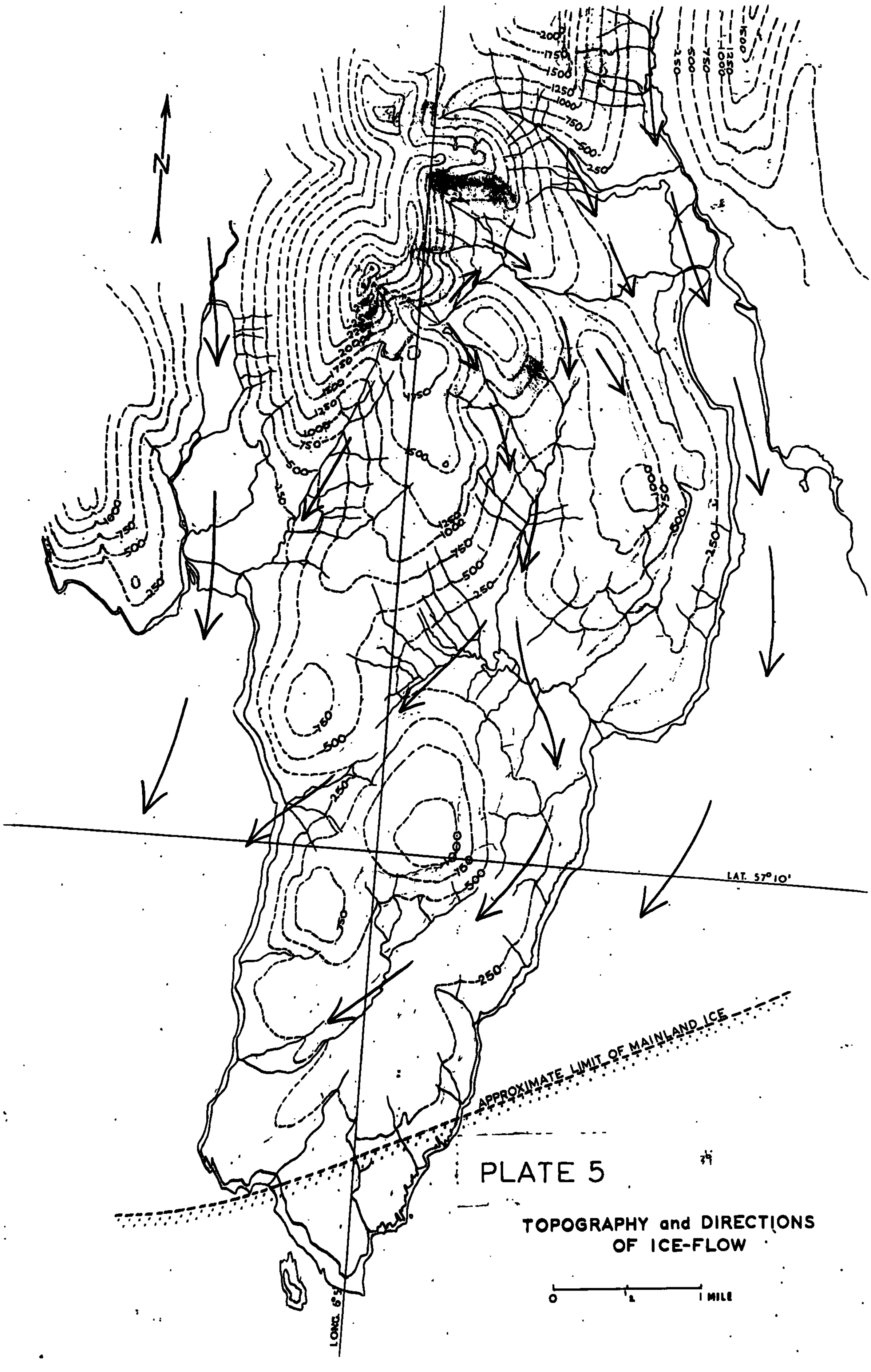


PLATE 5

TOPOGRAPHY and DIRECTIONS OF ICE-FLOW

and Strath Creitheach, and (c) overall pressure in a westward direction from the mainland ice in east and south-east Skye.

Ice-streams emerging from Blaven's eastern corries were forced to turn south by the Strath Mor glacier as they emerged from the protecting spurs. Thus in the north in Allt Aigeinn, flowing eastwards, was pressed into parallelism with the Strath Mor ice and truncated the eastern ridge of Sgurr na Each on its right bank. The combined ice-stream then blocked the outlet of the Coire Uaigneich ice which was forced to override the hills to the south, much of it passing over the An Stac-An Carnach col into the Kilmarie valley. Striae indicate that some of this ice also overrode the crest of An Carnach in a south-easterly direction. Moreover, ice accumulating in Upper Coire Uaigneich was inadequately drained through the Lower Coire and eventually spilled over the Slat Bheinn-An Stac col to be added to the ice in Coire Ballaig. This col must have been considerably lowered by the overflowing, for it is now little higher than the floor of the Upper Coire, and contains the small rock basin (Loch Coire Uaigneich) mentioned above.

The Kilmarie basin thus received most of the Blaven ice and had two outlets, firstly through the present valley of the Kilmarie River, and secondly to the south-west into the Scavaig Basin via Glen Scaladal.

The southerly flowing streams were again diverted in southern Strathaird, for here the pressure of the southern branch of the mainland ice forced re-orientation into a south-westerly direction. The striae on the bench of Inferior Oolite sandstones near Elgol trend around N.135°W..

Finally, ice-drainage from the south-east slopes of Blaven scoured out the present course of the Abhuinn nan Leac and joined the Strath na Creitheach glacier at Camasunary. It is noteworthy that the Camasunary River valley now contains two watercourses. The Camasunary River is bedded in rock against the western wall of the valley while the Abhuinn nan Leac is confined partly by rock and partly by drift along the eastern side. Moreover the centre of the valley contains a series of rocky knolls. It seems likely that these knolls represent the remnants of a spur which once separated two pre-glacial valleys in this area.

Depositional Features. Since the region was primarily one of ice accumulation, erosional features are predominant, and only late glacial deposits are present, chiefly dumped morainic material.

Well-marked terminal moraines in Upper Allt Aigeinn and Lower Coire Uaigneich represent the last stage of shrinking corrie glaciers. A lateral moraine lies below the east face of Belig, and at the termination of the south ridge of Blaven are the remains of a medial moraine which once separated the Abhuinn nan Leac ice from the Strath na Creitheach stream.

"Hummocky drift" or "kettle moraine", the dumped debris of melting ice sheets, occupies stretches of Strath Mor and the low ground to the west of the head of Loch Slapin, and this is also found in Abhuinn nan Leac. A valley-train of moraine and boulder clay fills Glen Scaladal to considerable depth.

Post-glacial modifications include the silting up of the through-valley floors and the formation of a 25 foot raised beach, the largest remnants of which are near the heads of Lochs Slapin and Scavaig (Camasunary). There is little trace of higher beaches, but some of the lower terracing in the Inferior Oolite near Glasnakille may be part of a 100 foot raised beach.

CHAPTER III

HISTORY OF RESEARCH.

The Tertiary igneous centre of Skye was the first area of this type to receive detailed attention from H.M. Geological Survey, and as early as 1904 a complete memoir, supported by 6-inch to the mile maps, was devoted to its complexities. This was the culminating work of a long period of discussion and controversy which concerned not only Skye but the whole of the Tertiary igneous province of western Scotland. The observations of Macculloch in the early years of the nineteenth century may be conveniently regarded as the beginning of this period.

Macculloch wrote several papers and two books, the first of which, "Description of the Western Islands of Scotland", appeared in 1819 and was followed by "The Highlands and Western Isles of Scotland" in 1824. At the time of his journeys the controversy between Neptunists and Volcanists was still active, and Macculloch, who supported the latter school, was concerned to show that irrefutable evidence of ancient volcanic activity was to be seen in north-west Scotland. Writing of columnar jointed sills on the coast of Skye he notes that they "belong to the trap famiby, as the mineralogists call it, or, as the vulgar do, to basalts" and elsewhere asserts, "Nothing can exceed the variety, the extent, and the number of their appearances, demonstrating the identity between trap and the produce of volcanoes ...". The great abundance of dykes also attracted his attention, and he describes the peninsula of Strathaird as consisting of "horizontal strata of sandstone, sometimes calcareous, and intersected by perpendicular trap veins. These are so numerous that the intervals are scarcely thicker than the veins themselves" (op. cit. 1819). Apart from his advocacy of the Vulcanists' views Macculloch's chief contribution was his demonstration that the intrusions pierce, and the lavas overlie, the rocks of Jurassic age. He was uncertain about the relative ages of the intrusive "Hypersthene Rock" (Gabbro) and the granites.

Von Oyenhausen and Von Decken (1829) wrote a brief account of a visit to Skye during which they followed the contact of the Cuillin Gabbro with the granites without however adding to the knowledge of their age relations.

The next publication of importance was a paper by J.D. Forbes in 1846. Forbes was the first to realise that the Cuillin Gabbro post-dated the basalt lavas, and he considered it a "vast bed", thinning both ways, and inclined at a moderate angle to the south-east.

Vital evidence on the age of the basalts resulted from the Duke of Argyll's discovery of plant remains in sediments between flows low down in the lava sequence of Mull. These were dated as Tertiary by Prof. E. Forbes (1851), but he nevertheless considered that at Staffin in Skye the lavas were partly interbedded with Jurassics. This view persisted until 1865, when Geikie demonstrated that all the basic rocks interbedded with the Mesozoics were in fact intrusions (as previously recognized by Macculloch). Judd (1874) followed this by showing that the lavas overlaid beds up to and including the Upper Chalk, and thus clinched the evidence for assigning a Tertiary age to the volcanicity.

Apart from the paper by Zirkel in 1871, applying the methods of microscopic petrography to the Skye rocks for the first time, the later part of the nineteenth century, is chiefly notable for a controversy which developed between J. W. Judd and Archibald Geikie. To Judd (1874) is due the concept that the Tertiary intrusion centres of north-west Scotland represent the dissected remnants of extinct volcanoes. He considered moreover that there was evidence of three phases of activity in these volcanoes, the first being characterised by acid lavas, tuffs, and plutonic granite, the second by basalt lavas and gabbros, and finally a minor phase of mixed lavas.

Geikie disagreed with Judd on both of these points. After a visit to the lava field of the Snake River area in Idaho, Geikie was convinced that fissure eruptions were the only form of volcanicity that could account for the Scottish Tertiary lavas. He put forward this view in Nature in 1880, and thereafter reiterated and amplified it. Geikie's work culminated with the publication of "Ancient Volcanoes of Great Britain" in 1897, covering the entire field of British igneous rocks. In this he draws analogies with the modern volcanoes of Iceland to support the idea of fissure eruptions in the Scottish Tertiary. In his view the sequence of events commenced with basaltic eruptions and was followed by gabbro, and finally by granophyre. Meanwhile, as Director of the Geological Survey, he had decided that a typical part of the Tertiary volcanic region should be studied in greater detail, and obtained the services of Alfred Harker to carry out this work.

Harker worked on the igneous rocks of central Skye during the years of 1895 to 1901, while Clough and others were working in the south-east part of the island and on the sediments around the igneous centre. The maps were published as one-inch sheets 70 and 71 and part of the sheets 80 and 81, while the complex central portion also received more detailed coverage in six-inch sheets, Inverness-shire 38, 39, 44 and 45. Harker's memoir was published in 1904 under the title "Tertiary Igneous Rocks of Skye", while Clough and Wedd supplied notes to that volume. Clough's main work was incorporated in the memoir to sheet 71, "The geology of Glenelg, Lochalsh, and the south-east part of Skye", published in 1910, and Clough and Harker collaborated in the memoir to West-Central Skye, published in 1904. Some of the material for Geikie's "Ancient Volcanoes" was obtained from visits to Harker in Skye.

Harker agreed with Geikie in assigning a fissure-eruptive origin to the lavas and also with the latter's broad sequence from basic to acid. The combined authority of Geikie and Harker ended controversy on Skye problems for some years, and Prof. Judd's views lost ground, especially since he was mistaken in supposing that the granites were the earliest plutonics. Harker's volume remains the standard work on the area, for he contributed much new material, including an expansion of the time sequence. An initial explosive phase was added to the eruptive period and an ultra-basic phase to the plutonic period, while most of the minor intrusions were relegated to late, post-granite times. The main sequence now reads;- 1. explosive phase (agglomerates) 2. lavas (basic to acid) 3. ultra-basic plutonics 4. basic plutonics 5. acid plutonics 6. minor intrusions. It is unnecessary to discuss Harker's work further, since many references to his work in the area covered by this thesis are given in the text.

"Tertiary Igneous Rocks of Skye" gave new impetus to British igneous petrology, and its tradition was carried on by the publication of the G.S. memoirs of Bailey, Richey and Thomas on Mull (1924) and Richey and Thomas on Ardnamurchan (1930). These authors showed that the sequences in these two centres were much more complex in detail than had been supposed, and more complicated too than Harker's straightforward sequence in Skye. It became evident that further work on Skye might well be profitable. In Mull evidence emerged that a central volcano existed during at least part of the lava period, thus vindicating to some extent the idea of Judd and casting new doubt upon the origin of lavas elsewhere in the province.

Although much work has been carried out on Skye in recent years, a great deal of it is as yet unpublished. Some of the material which has application to the problems of Strathaird is briefly reviewed below.

The lavas of Skye have received only slight attention in the literature published since Harker's memoir, and that which does exist is dealt with more fully in Chapter V. In the last half of the 1930's the Geological Survey mapped sheet 81, which covers much of the north Skye lava area, but the results are as yet unpublished except for notes in the G.S. Summary of Progress for 1935-1938 (G.V.Wilson, 1936-1939).

In a paper on Tertiary Ring Structures (1932), Richey made a critical resurvey of the evidence concerning the time sequence in Skye, and the structures of the plutonic intrusions. Richey had taken a prominent part in the survey of Mull and Ardnamurchan and the complexity of these centres led him to question the simplicity of Harker's sequence in Skye. Harker had followed the idea, first expressed by Forbes (1845), that the Cuillin Gabbro was intruded as a laccolith. Richey observed that the internal structure described in the memoir is not in accord with such a form, and thought that it may represent an early cone-sheet system deeply dissected. Richey also pointed out that the granophyre strip along the eastern slopes of Blaven (in Strathaird) is shown by

Harker as intersected by cone-sheets, unlike the Red Hills Granophyres with which Harker postulates a connection. Morover, Richey considered from his own observations that the cone-sheets are probably pre-Red Hills in age, and that some of the agglomerates are to be dated to the interval between the Gabbro and the Granite plutonic phases.

A different view point of Skye geology is taken by King (1953) in a paper on the Creag Strollamus area, north of Broadford. In this district Harker described a boss shaped mass of gabbro and an irregularly shaped granophyre (in places sheet-like, elsewhere transgressive). These pierce Cambrian limestone overlain by the thrust Torridonian, and capped by the basalt lavas. King writes that this area "presents in miniature all the formational and structural elements of the plutonic region of Skye". (op.cit p. 358). It should be noted however that the gabbro is unlike that of the Cuillins in being olivine-free, and though varying considerably in texture it is generally of finer grain. The granophyre is a member of the Eastern Red Hills complex. According to King the gabbro is derived from original basalts and the granophyre from Torridonian, both being transformations in situ. Thus the three-tiered structure:-

3. Basal Lavas

.... undulating surface

2. Torridonian

.... folded thrust plane

1. Cambrian Limestone

is thought to be transformed in parts of this area into:-

3. Gabbro

....

2. Granite

....

1. Cambrian Limestone

The gabbro-basalt structural level in places rests directly upon the Cambrian, due to pre-basalt erosion of the Torridonian.

Since a gabbro-basalt contact is one of the chief features of interest in Strathaird, it may be as well to summarise the most important of the evidence King uses to support the basalt-gabbro transition;

1. Gabbro and basalt are apparently mutually interchangeable in the same structural level, and the form of the outcrops is thought to suggest a sheet-like form for the gabbro, local steep contacts being interpreted as faults.

2. King finds that the texture of the gabbro varies in sheeted manner, and he interprets this as

derived from the basalt flows.

3. Transitional contacts between gabbro and basalt are to be found, and moreover "within all the gabbro areas fine grained rocks occur which are petrographically indistinguishable from typical basalts" (op. cit. p. 377).

4. Relict structure in the gabbro includes ophitic and porphyritic textures, while "ill-defined patches of plagioclase, actinolite and chorite, having an allotriomorphic texture, are not infrequent and suggest former amygdales" (op. cit. p. 378).

The paper also includes data upon the lavas, their alteration and their chemistry.

Though King is the first to interpret a section of the Skye centre on a transformation basis, it had been previously stated by Reynolds (1951 and 1952) that Harker's description of certain "amygdaloidal gabbros" of the western Cuillin implied that the basalts in Skye had been locally converted to gabbro and peridotite. Harker (1904 p. 95) had detected conspicuous amygdales in rocks with the appearance of normal gabbros and peridotites in the neighbourhood of metamorphosed lavas. Harker thought the only likely explanation was that the lavas had been locally fused and only the amygdales had remained intact, a process which is probably as Reynolds says, "quite impossible". Bailey (1952) however, upon re-examination of Harker's four slides of the disputed rocks, had come to the conclusion that their textures and composition suggested that they are not gabbros, but minor intrusions. Three of the rocks he describes as amygdaloidal tholeiitic dolerites, and the fourth as a dolerite with quartzo-feldspathic patches. Low grade thermal metamorphism has affected three of the specimens while the other shows no evident alteration of this kind. Reynolds, in reply (1952) doubts the value of Bailey's observations without further field work, and in any case regards the slice evidence as indecisive.

A paper by Wager, Weedon, and Vincent (1953), has particular application to Strathaird, since it describes some aspects of the petrology of the elongate granophyre mass east of Blaven which is referred to by Richey (1932). This rock contains the first recorded instance of tridymite (now inverted to quartz) in an acid intrusion from the Thulean Province. The paper is more fully discussed in Chapter X.

Finally it may be noticed that two as yet unpublished theses are concerned in part with the Strathaird area. That of J.M.Carr (submitted Oxford, 1952) gives the results of a detailed investigation of a representative sector of the Cuillin basic mass. He also describes some of the features of the contact rocks at Camasunary.

The second part of M. Wyatt's thesis (submitted, Cambridge, 1952) is an investigation of the metamorphism and metasomatism present at certain gabbro-limestone contacts in the Camasunary area. He elucidates the sequence of lime and magnesia silicates in the sediments and the contamination of the adjacent gabbro.

CHAPTER IV

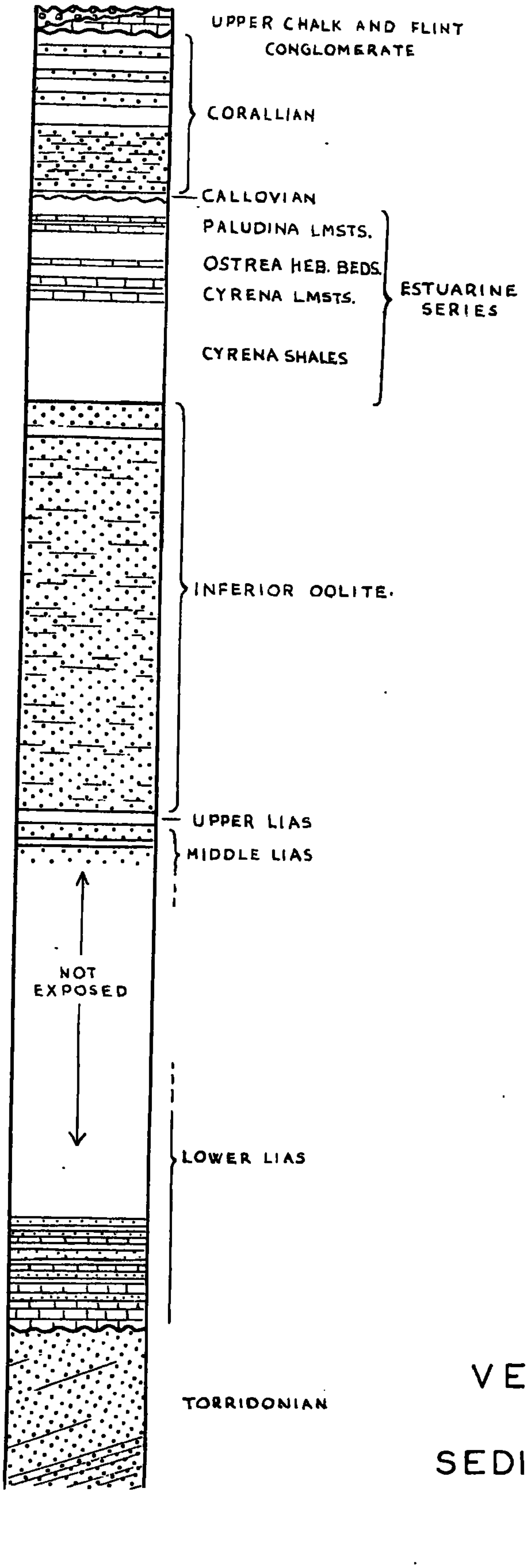
THE SEDIMENTARY SEQUENCE.

(i) Introduction.

Although the sedimentary rocks of Strathaird have not received detailed attention in this study the main formations were mapped as part of the field work in order to determine their structural relations to the igneous rocks. This aspect receives more detailed attention in a later chapter; meanwhile the notes which follow provide an outline of the general stratigraphy. A fuller account is given by Wedd (1910) in the Geological Survey memoir dealing with south-east Skye and the adjacent areas, while H.M.G.S. 6-inch Sheet 45 (Inverness-shire) delineates the sedimentary boundaries in north Strathaird and 1-inch Sheet 71 shows the whole peninsula.

Table 1 lists the main formations and indicates the lithologies by brief annotations. A vertical section is drawn on Plate 6. A considerable part of the information in this chapter is condensed from Wedd's work, the facts having been checked in the field by the writer and a few notes added.

It will be seen from Table 1 that there are several considerable gaps in the stratigraphical succession, the most notable of which is the entire absence of



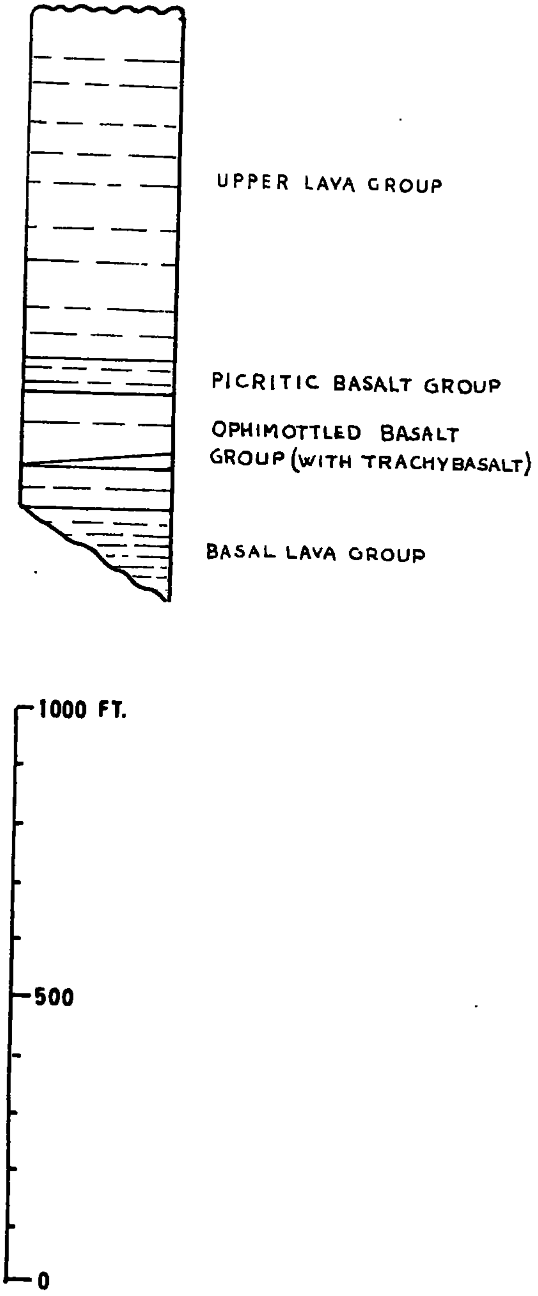


PLATE 6

VERTICAL SECTIONS
of the
SEDIMENTARY AND LAVA
SEQUENCES

TABLE I

THE SEDIMENTARY SEQUENCE OF STRATHAIRD.

	Base of the Tertiary Lavas
	------unconformity------
Early Tertiary (?)	Flint Conglomerate 0 - 15 ft.
	------unconformity------
Upper Cretaceous	Upper Chalk 0 - 10 ft.
	------unconformity------
Upper Jurassic (280 ft.)	Corallian - shales and sandstones Callovian - flaggy sandstones
	------non-sequence------
Middle Jurassic (1,100 ft.)	Great Estuarine Series (400 ft.) 6. Shaley marl. 30-40 ft. 5. *Paludina scotica* Limestone 37 ft. 4. Shales with mudstones and thin limestones 40 ft. 3. *Ostrea hebridica* Beds - calcareous shales and limestones. 17 + ft. 2. Cyrena Limestones - Limestones and calcareous sandstones. 70 ft. 1. Cyrena Shales - shales with thin limestones and calcareous sandstones. 200 ft. Inferior Oolite - thick calcareous sandstones and rare shales. 700 ft.
Lower Jurassic (c. 1,000 ft.)	Upper Lias - shales and thin limestones. Middle Lias - calcareous sandstones with doggers. Lower Lias - sandy shales and sandstones with limestones near the base.
	------unconformity------
Late Precambrian	Torridonian - flaggy arkosic sandstones.

Palaeozoic rocks. Only a few miles to the east, in Strath, a considerable thickness of Cambrian limestone is present which is not represented in Strathaird, and this is also apparently true of the Triassic strata which near Broadford are some fifty feet thick.

(ii) Torridonian

Rocks of this age are only to be found in the neighbourhood of Camasunary, at the head of the western arm of Loch Scavaig, where they lie on the upthrow side of the Camasunary Fault. The latter dislocation trends N.N.E. and has a downthrow to the east of about 2,000 feet on the shore of the loch, where it brings the Torridonian in contact with the Cyrena Limestone of the Great Estuarine Series. West of the fault the Torridonian occupies most of the low-lying ground around Camasunary bay and extends round the headland of Rudha Ban on the western side, where it is overlain by lavas. North-east of Camasunary the Torridonian passes beneath the Lias of Blaven and Abhuin nan Leac, but to the north it lies directly against the contact of the Gabbro.

As on the mainland of Scotland the Torridonian of Camasunary consists almost entirely of arkosic sandstones and grits, but these never have the characteristic red colour found on the mainland. West of the Camasunary River the bedding is flaggy and a few intercalated bands of shale are present. A fine lamination is often developed and ripple marks are common. East of the Camasunary River the rocks are more massive, coarser, and frequently contain quartz pebbles, while the weathering surface is a paler grey and without the brown tint to be seen to the west. These lithological differences are accompanied by a change of dip from 10° N.W. at Rudha Ban to between 30° and 45° N.W. at Camasunary, and it is probable that a fault separates the two areas along the line of the river.

Four miles W.S.W. of Camasunary is the island of Soay, between three and four square miles in area and built almost entirely of Torridonian rocks. Both there and at Camasunary there is no indication of the extensive shattering which affects rocks of the same age in Strath and south-east Skye, due to overthrusting at the time of the Caledonian earth-movements. It can therefore be assumed that the Torridonian is autocthonous in this area, and does not overlie Cambrian limestones along a tectonic surface, as in Strath.

Peach and Horne (1907) identify the Soay Torridonian as belonging to the Applecross Group, but consider that differences in lithology between there and Camasunary, and general direction of dip, suggest that the rocks of the latter area are older than those of Soay and may be a part of the Diabaig Group.

(iii) Jurassic

Strata of Jurassic age form the bulk of the exposed sedimentary sequence of Strathaird. The lower and middle divisions are each about 1,000 feet thick while the Upper Jurassic amounts to less than 300 feet and is eroded at the top. It also lacks an equivalent of the Oxford Clay which is developed at Staffin, in north Skye. Lias. Outcrops of Lower Lias are confined to the upthrow side of the Camasunary Fault where they are exposed in the south ridge of Blaven and the adjacent valley of Abhuin nan Leac. They are based upon Torridonian and owe their preservation to the rise of ground east of Camasunary and to a diminution of the throw of the Camasunary Fault to the north-north-east. About 250 feet of beds are exposed and form a north-easterly trending anticline cut by cross-faults. Metamorphism has hardened the sediments to such an extent that even shales produce a craggy topography.

Limestones are predominant at the base of the sequence and are followed by a group of mixed sediments and then by sandy shales. Wedd (op.cit.) correlates this succession with the Broadford Beds (the lower division of the Skye Lower Lias).

The calareous beds at the base can be seen at the waterfall in the Abhuin nan Leac (two-thirds of a mile N.E. of Camasunary House) where they consist of conglomeratic sandstone and blue limestone dipping south-east. On the south-western slopes of Blaven these same beds are seen to turn over the crest of the above-mentioned anticline and above An't Sron they dip north-west until cut off by the Gabbro. The outcrops are cut by several faults with downthrows to the west, so that there is a certain amount of repetition of beds uphill.

In the middle of the Camasunary valley, 750 yards N.W. of Camasunary House, is an isolated patch of limestone with minor shale and sandstone some forty feet long, dipping 50° N.W.. The field relations of this outcrop have been variously interpreted. Harker shows it as an outlier of Lower Lias exposed beneath lavas, while on Carr's map (1952) it extends up to the contact of the nearby Gabbro. The present author however considers it to be surrounded by Torridonian, implying that either it is an unusually large loose block or that it is faulted into place.

In the faulted outcrops above An't Sron mixed sediments are exposed above the basal limestones and these rocks are again found in Abhuin nan Leac and Coire Casteail, together with the sandy shales above, which are the highest beds exposed west of the Camasunary Fault. In the floor of the corrie the anticlinal disposition is clearly displayed and several faults are also exposed.

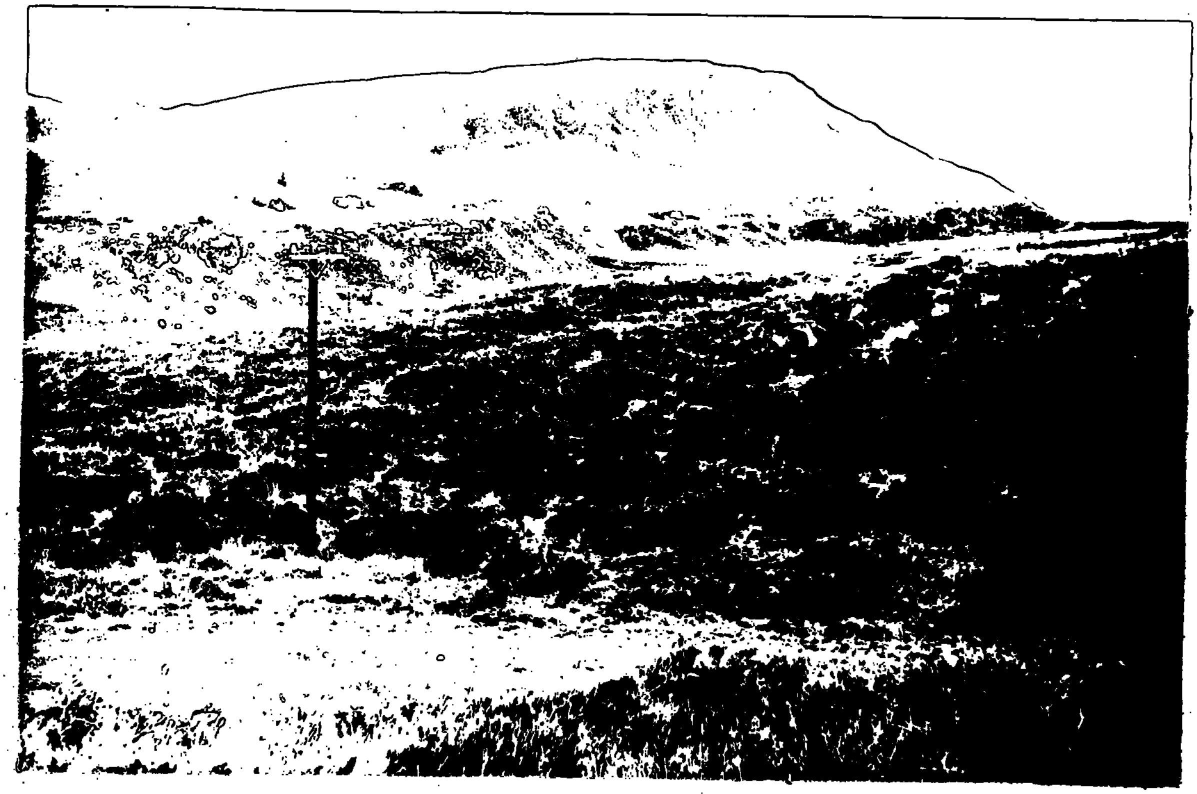
The Middle and Upper Lias appear at only two localities, both on the eastern coast of the peninsula, where they are brought up above sea-level by shallow domes. The more northerly of the two outcrops occupies about half a mile of the shore near Faoilinn, and the rather smaller southern outcrop is to be found between Dun Liath and Allt Mor. The Middle Lias consists of grey calcareous sandstones not unlike those of the Inferior Oolite, though they are distinguished by containing large dark brown doggers, and a shallow water fauna of lamellibranchs, brachiopods, and belemnites. The Upper Lias is thin, perhaps twenty feet, and consists of shales with a thin limestone.

Middle Jurassic. This division consists of a 700 foot thick sequence of Inferior Oolite sandstones followed by 400 feet of shaley beds with limestones belonging to the Great Estuarine Series. Both are well exposed in the belt of terraced country along the eastern side of the peninsula. Gentle cross-flexures superimposed on the general westerly dip are responsible for bringing up the base at two localities on the east coast.

The Inferior Oolite comprises a monotonous sequence of calcareous sandstones of grey or pale yellow colour. Massive horizons are marked by features while the more flaggy and calcareous layers weather back. Cross-bedding and doggers are common and belemnites are occasionally to be found. The 50 foot thick uppermost sandstone, flaggy at the base and massive quartzite at the top, is separated from the calcareous sandstones below by a 30 foot, black, nodular shale. A few plant remains at this top horizon suggest a transition to non-marine conditions (Wedd, op. cit.) Along almost the whole length of the peninsula streams have excavated the shale band and left the hard sandstone above forming a bold feature*. This is especially prominent at Elgol, and there also the shale below has been intruded by a large dolerite sill which also forms a strong feature. West of the head of Loch Slapin the Inferior Oolite has been involved in folding and faulting so that the regular form of the outcrop is destroyed.

On the eastern side of the peninsula the Great Estuarine Series has been eroded into a steep slope above the terraces of Inferior Oolite. Its preservation is due largely to the protecting capping of lavas, which it directly underlies in parts of the area. The

* Plate 7



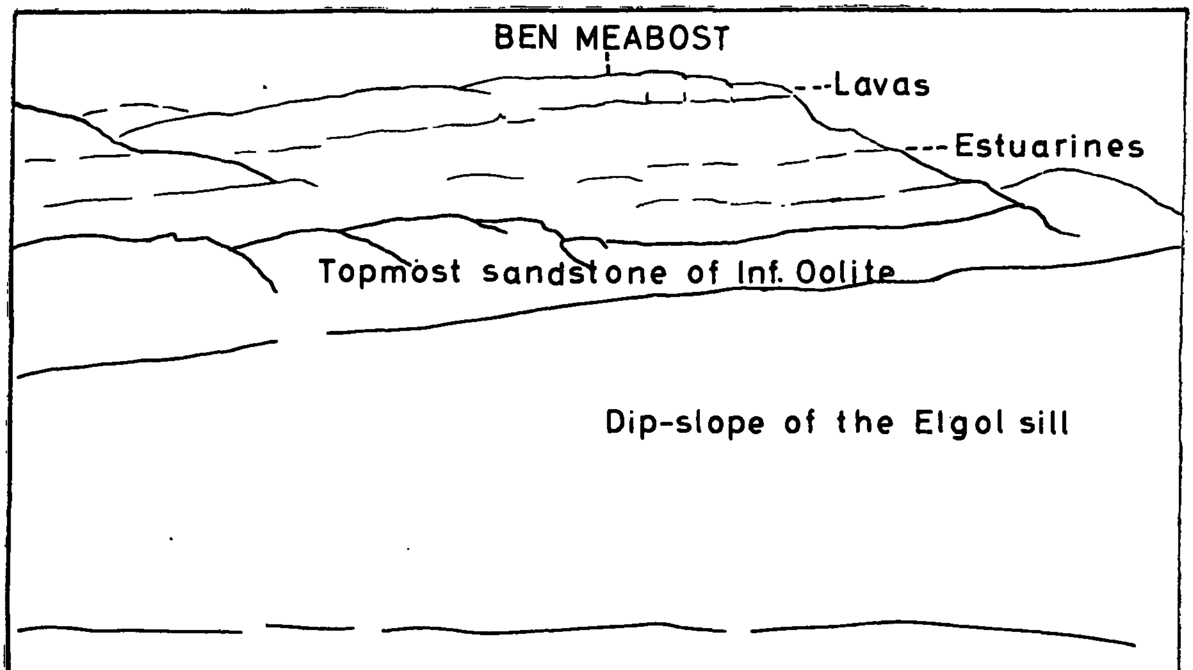


PLATE 7 View north from the Elgol - Glasnakille road.

most complete exposures however are situated on the west coast, north of Port na Cuillaidh (Elgol). A condensation of Wedd's sequence at that locality is incorporated in Table I. Of the three main calcareous horizons the Cyrena and Paludina Limestones normally form small but clear features while the Ostrea hebridica Beds rarely do so and have not been mapped separately. The Port na Cuillaidh sequence is less arenaceous than those recorded for the series in Eigg to the south and Raasay to the north. In north Strathaird there is again a considerable development of sandstones between the calcareous horizons, and since this area is faulted, folded, and partly obscured by drift it is often difficult to define the boundaries with the over- and under-lying groups.

Upper Jurassic. Over much of Strathaird a variable thickness of Upper Jurassic rocks intervenes between the top of the Estuarines and the base of the lavas, though in the areas around Coire Casteail and Allt Dunaiche they are entirely absent. The fullest development of Upper Jurassic is found in the Kilmarie Valley where it is rather less than 300 feet in thickness. Micaceous sandstones make up the lowest 80 feet, with a pebbley horizon at the base, and these are followed by about 200 feet of argillaceous beds with sandstone bands. The lower part of this sequence is best exposed in the cliffs of Carn Mor* on the west coast, while a section of the upper part is provided by the Kilmarie River and its tributaries. To the north the basal sandstones are again seen in Allt Aigeinn and on Belig.

Wedd (op. cit.) assigned the lower part of this sequence to the Oxfordian and the upper part to the Corallian, and also remarked that since several loose blocks in the scree below Carn Mor contain a Callovian fauna it is evident that at least local representatives of that formation are present as well. It is now thought (see review by Richey, 1948) that Oxfordian is absent and that most of the beds are to be correlated with the lower Corallian, with undifferentiated Callovian at the base. The absence of the Oxfordian thus indicates a non-sequence between Middle and Upper Jurassics, while pre-Upper Cretaceous erosion has removed any higher formations originally present above the Corallian.

(iv) Upper Chalk and Flint Conglomerates

Both of these formations are thin and are found in the two restricted areas on either side of the lavas of Am Mam (the saddle between Slat Bheinn and Beinn Leacach). It is believed that the two outcrops are

* Plate 8.

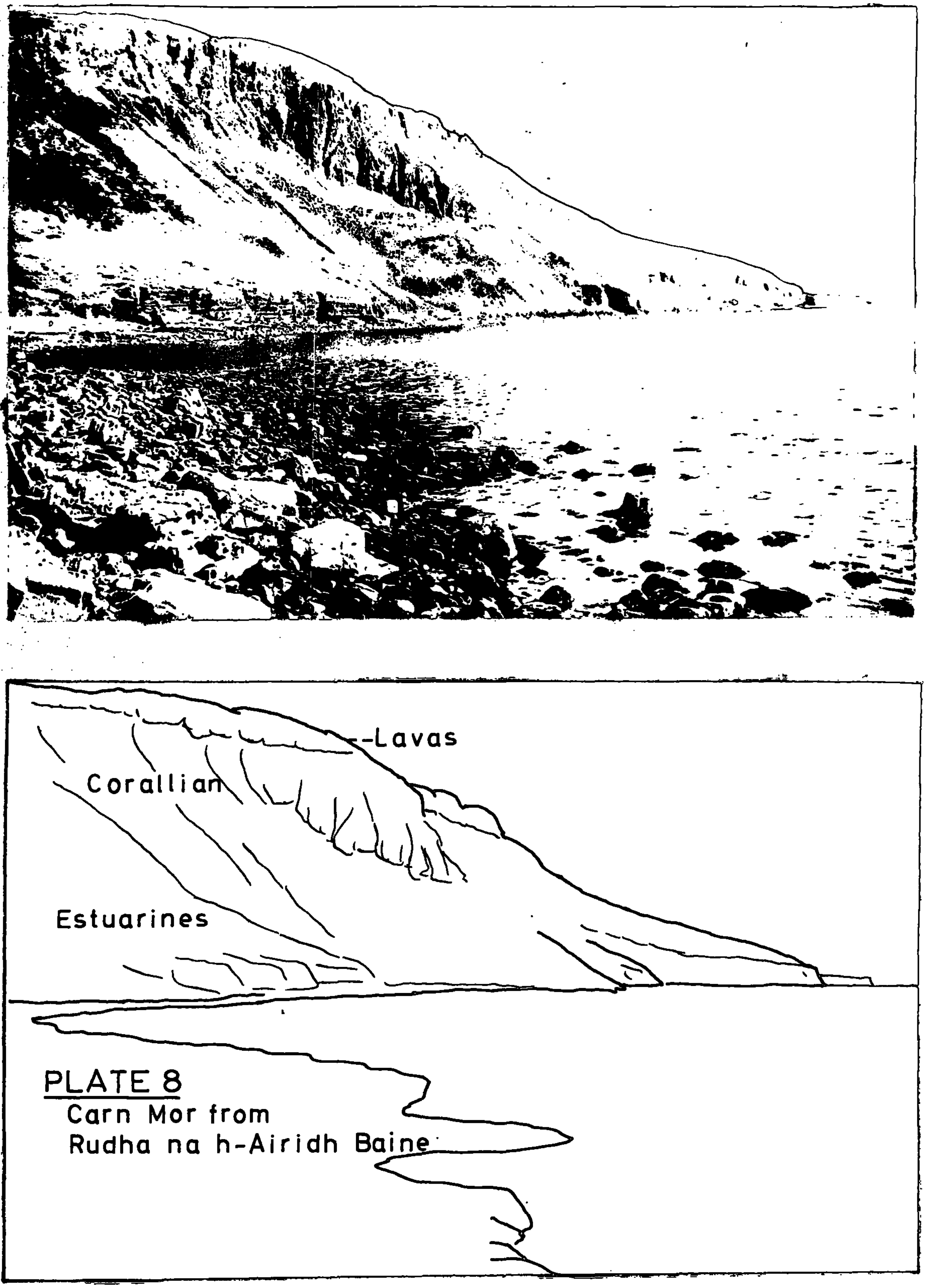


PLATE 8
Carn Mor from
Rudha na h-Airidh Baine

connected beneath the lavas and are preserved in the middle of a shallow basin of sediments. The exposure of Chalk on the eastern side of Am Mam was noted by Wedd, who dated it as Upper Cretaceous. The outcrop is about 300 yards long and lies on the north side of the Kilmarie - Camasunary pony track at the point where this crosses the base of the lavas. The Chalk consists of eight to ten feet of white limestone containing a few purple-edged flints and sub-rounded quartz pebbles. The Flint Conglomerate above is a ten foot thick conglomeratic sandstone containing angular fragments of Chalk and flint. It oversteps the outcrop of the Chalk on both sides and rests on the Corallian.

The exposure on the western side of Am Mam lies astride the track from Camasunary to Elgol about 1,100 yards S.S.E. of Camasunary House. It is about 600 yards in length and consists of the same rock types as the other exposure. Six feet of hardened grey Chalk form a small bench crossed by the track, and is overlain by a more extensive lens of Flint Conglomerate directly underlying the lavas. At the top and base the conglomerate is relatively fine, with pebbles not exceeding half an inch in diameter, but the centre is coarser, with purple-edged flints up to eight inches in length set in a grey, sandy matrix. The flints vary from angular to well rounded. This exposure is not shown on the Geological Survey maps, though it has certainly been noted by several geologists (F.H. Stewart and L.R. Wager, personal communications).

The conglomeratic material is likely to be a product of sub-aerial weathering of the Chalk, and may therefore date from the early Tertiary uplift of the area. Similar rocks have been described from Mull (Mull Memoir, 1924, pp. 53-58) where they precede the Basal Mudstones which there underlie the lavas in some parts of the island.

The relations of the lava base to the topography indicate that in Strathaird this surface is virtually planar, though flexed by post lava movements, so that a peneplanation stage evidently intervened between the Upper Cretaceous and the onset of vulcanicity. Though the pre-lava surface was generally flat in most parts of the Scottish Tertiary igneous field, a few cases of pre-lava valleys infilled by flows have been described (see Chapter V) and King (1953) describes the sub-lava surface at Creag Strollamus, Skye, as possessing considerable relief. Bailey (1954) however considers the irregu-larities in the latter area to be due to a "volcanic inbreak".

CHAPTER V

LAVAS - INTRODUCTION.

(i) General Characteristics of Thulean Lavas.

In mid-Tertiary times the area which is now the North Atlantic basin was the site of volcanic activity on a large scale. This region of Tertiary igneous action is usually referred to as the Thulean Province, and at the present time eroded remnants of the Thulean lavas are found in western Scotland, northern Ireland, the Faroes, Iceland, Jan Mayen, and both east and west Greenland. Tyrell (1949) estimates the total area of lavas now exposed as about 100,000 square miles. Of this only a small part lies in the Scoto-Irish sub-province, the chief outcrops being in Antrim (1,480 square miles), Skye (425 square miles), Mull (280 square miles), and Morvern (45 square miles).

Opinions differ as to whether vulcanicity was mainly centred round the areas in which the old lava fields are still partially preserved, or whether the larger part of the volcanic province is now hidden beneath the sea. It has been suggested that the submarine Wyville-Thompson ridge, linking Britain to Iceland, is composed of subsided basalt lavas.

<u>Features of individual lava flows.</u> In many Thulean

sequences the commonest rock type is olivine basalt, though olivine-free basalts are also numerous and there are lesser numbers of trachyte and rhyolitic flows.

A typical flow of olivine basalt is between ten and thirty feet thick and possesses upper and lower slaggy portions rich in vesicles and a central more massive layer. Normally the cavities have been filled by post-consolidation minerals and are then named "amygdales". The upper vesicular layer is commonly one to four feet thick and the basal layer somewhat thinner, perhaps between one and two feet. In a few lavas the vesicles are scattered more evenly throughout the flow ar are concentrated in streaks at several levels. Vesicles often vary in shape according to their position in the flow. Thus as the top of a flow they are round or ovoid, while at the base there is frequently a tendency for sub-vertical pipe-shaped cavities to form, and these may be bent over in the direction of primary flow of the lava. Under the microscope it can be seen that the vesicular parts of a flow are of finer grain than the massive portions, and the upper vesicular layer is often of sensibly finer grain than the basal layer. The open structure renders the top and base of a flow especially liable to alteration and weathering, and as a result lava outcrops give rise to a terraced topography.

In some extrusions a prefered shape orientation of minerals, especially feldspar, has been imposed by the primary flow of the lava, or the rock may be flow laminated by differential mineral streaking. In general the more basic the lava the less indication of flow structure it contains.

When cooling joints are present they are best developed in the massive centre of the flow. Many lavas have no regular joints, and these are all transitions from rough vertical fractures to an almost perfect hexagonal columnar structure, sometimes with vertical bases and curved tops (e.g. Staffa and the Giant's Causeway, Antrim). In other flows a close-spaced platy jointing is found, a feature especially typical of oligoclase basalts (mugearites).

The Thulean lavas, with few exceptions, were poured out into a land surface, so that reddening of the flow tops due to sub-aerial weathering is of common occurrence. When decomposition was incipient only a few scattered patches of haematite are to be found between the flows, but longer inter-flow periods have allowed the development of bright red, iron and alumina rich clays known as "boles". In north Skye these may be as much as five feet in thickness, while in Antrim the twenty-five foot thick Interbasaltic Zone is largely composed of this material. The break between a bole and the flow from which it derived is not sharp but involves a transition through bole with lava relics into reddened lava below. Cracks in the top of the lava often allow the clay to penetrate some way into the body of the flow.

Much more uncommon is the pillow structure which indicates extrusion into water. Examples in north Skye and Mull are believed to be the result of lava encroaching on small lakes.

The infilling of valleys by lava is another indication of the sub-aerial environment of the flows. Geikie (1897) ascribed the unusual shape of the Scuir of Eigg pitchstone to this cause, though Harker (1908) disagreed with this interpretation. Other examples have been described in north Skye (Wilson, 1938), and in Antrim (Tomkieff, 1940).

Sequence of lavas in the Scoto-Irish sub-province. The work of the authors of the Mull Memoir (1924) established that the lavas of that island are divisible into two main groups, each 3,000 feet thick. The lower division consists predominantly of olivine basalts, with horizons of mugearite and porphyritic basalt, while the upper division is mainly of olivine-poor tholeiites. The latter are most fully developed round the central Mull plutonic complex and are thought to have accumulated in a down-faulted lava caldera which spilled over at intervals. The two main lava types were named "plateau" and "central" from the respective areas in which they are now found. These authors also suggested that at a later date, coinciding with the intrusion of acid plutons, the old caldera became the site of a volcanic cone built of ash and acid lava.

Olivine basalts, grading locally into picrite basalts, are predominant in the lava sequence of Antrim. It was a long time thought (Charlesworth, 1935: Tomkeieff, 1940) that there was a simple, two-fold division in the Lower Basalts, consisting of up to 550 feet of olivine basalt, and the Upper Basalts, which are up to 600 feet thick and consist of olivine basalt in the south tholeiitic basalts in the north, the two being separated by a 25 foot Inter-basaltic Zone. The latter consists of laterite with patches of bauxite and lenses of lignite, and at Tardree Hill and elsewhere it also includes rhyolites. The laterites and bauxites have been studied in detail by Eyles (1952). However, Patterson (1950, 1955a and 1955b) has shown that in north Antrim the tholeiitic lavas form a wedge up to

450 feet thick, and are separated by Upper and Lower Interbasaltic Beds from olivine basalts above and below. The wedge of tholeiites thins out both to the south and west. Walker (1959) has pointed out that whereas a maximum of 1,000 feet of basalts is exposed at the surface, various boreholes have shown that greater thicknesses are present in the centre of the plateau, and at Langford Lodge, one such borehole passed through 2,590 feet of lavas. Both Patterson and Walker (op.cit., also Patterson, 1950b) favour a fissure eruptive origin for the Antrim lavas, and both authors have discovered rare cases of a direct connection between a dyke and a flow. Moreover, about thirty intrusive plugs are now known in the area, most of them composed of olivine basalt or crinanite, and Walker (op.cit.) suggests that they represent local enlargements of the fissures through which the lavas poured out.

In the Small Isles of Inverness-shire (Rhum, Canna, Eigg, Sanday and Muck) agglomerates and conglomerates are found near the base of the volcanic sequences (Harker, 1908), which otherwise are predominantly of olivine basalt. Mugearite lavas occur in several of these islands, and in Rhum they overstep the olivine basalts below. Tomkeieff (1942) points out that the analysis of one of the Rhum mugearites quoted in Harker's memoir (1908, and also quoted in Table 5 of this thesis) shows it to be intermediate in composition between the mugearites of Skye and the tholeiites of Mull, and he suggests that it would more properly classified as a trachybasalt. The Rhum lavas normally rest on a base of Torridonian sandstones, but at Orval they lie on top of a large granophyre intrusion. Judd (1874) considered that the granophyre pre-dated the lavas, but Geikie (1897) and Harker (1908) thought that the lavas were remnants of the granophyre's roof. More recently, Black (1952) has produced evidence in support of Judd's view, and if he is correct this is the only known instance in the Hebridean Tertiary of a large acid intrusion which pre-dates the basic lavas.

Published data on the large area of lavas in north Skye is as yet scanty. Geikie, and later Harker (1904, pp. 23-24) noted that over a considerable area in the Portree district the lavas lie on a base of tuff and agglomerates. The known outcrop of this "Palagonite Tuff" was later greatly extended by the mapping of the Geological Survey, and in the Summaries of Progress for 1935 (1936) and 1936 (1937) Wilson describes it as up to 100 feet thick, largely unbedded, and containing volcanic bombs, fragments of basalt, and small pieces of fossil wood. A Tertiary plant-bearing bed is some times associated with the tuff, and there are also several thin lava flows interbedded with it. The lava sequence above has not yet been fully described, but to quote Wilson (1936 p. 83)

> "In composition the lower flows consist in the main of olivine basalts ...... As the sequence is traced south-westwards from the neighbourhood of Portree some of the higher flows are found to consist of fine-grained, rather splinty, black basalt, which often weathers with a greyish crust and possesses mugearitic affinities. Still further south-west, in the Bracadale area, this type becomes more prevalent, and typical mugearites occur, together with big feldspar basalts, thus giving an association of rock types comparable to that noticed in Central Mull."

Later (1938) the same author remarks that the Bracadale lava types extend as far north as Edinbane.

Harker in central Skye estimated the total thickness of basalt lavas as not less than 2,000 feet (1904, p. 8). He also found a thick sequence of trachytes, andesites, rhyolites and rhyolitic tuffs on the northern flanks of the Cuillin Hills, and these he describes as interdigitated with some olivine basalts and overlain by others (1904, pp. 55-56). Since the dip of the lavas in north Skye is to the west it would seem from Wilson's description that there is a lower group of olivine basalts overlain by more acid alkaline lavas, while in the case of the acid lavas in the Cuillins a lateral change is implied.

The total thickness of the lava sequence in Skye is probably in excess of 3,000 feet.

Other Thulean lava sequences. The greater part of the Thulean lava field is much less well known than the Scoto-Irish sub-province. Tyrell (1949) provides a general account of the whole area, and some of the more important work is mentioned below.

Noe-Nygaard (1942) estimates the total thickness of lavas in the Svartenhuk Peninsula of West Greenland as some 10 kilometres. The base is marked by ash, breccia, and tuff, and is followed by olivine basalts, including some feldspar-phyric varieties, and then by an upper series of olivine free basalts, andesitic basalts, and trachytes. Drever and Game (1949) from their work on Ubekendt Island in the same region distinguish a Lower Lava Group of olivine basalts and picrites some 10,000 feet thick and a 4,000 foot Upper Lava Group which includes porphyritic tholeiites, rhyolites, trachytes, and monchiquitic basalts accompanied by some volcanic breccia.

In East Greenland Wager (1934a, 1934b) estimates the maximum thickness of lavas in the Angmagsalik-Kap Dalton area as 7½ kilometres, though thinning rapidly inland. Little is known of the sequence, though Anwar (1955) mentions a series of oligoclase and andesine basalts overlying the plateau lavas north-east of the head of Kangerdlugssuaq.

Walker and Davidson (1936) give a generalised sequence for the Faroe Islands consisting of, from the base upwards, 6,000 feet of mixed tholeiites and olivine basalts, 7,000 feet of tholeiites, and 2,000 feet of olivine basalts.

Recently Walker (1958) has described the Tertiary lavas of Reydarfjordur in eastern Iceland. In that area he found a volcanic sequence nearly 15,000 feet thick in which tholeiites, olivine basalts, and porphyritic basalts take the chief parts but without indications of a systematic distribution. Two main periods of acid vulcanism are represented by andesites, rhyolites, and tuffs, while two other acid phases are indicated only by tuffs in the area mapped. A fifth and final acid period built up a large central volcano on the top of the flat-bedded main series.

Finally, Tyrell (1926) has written of the lavas of

Jan Mayen as a "mildly alkaline series" consisting of alkaline olivine basalts and associated picrites, trachyandesites, and trachytes.

Most Thulean sequences outside Britain are thus very much thicker than those in Scotland and Ireland, though to what extent deeper erosion accounts for this is difficult to estimate. The sequences of Britain and Greenland have in common the tendency for the lower parts of the sequences to be built of olivine basalt and the upper parts of more acidic basalts and alkaline lavas, but in Iceland and the Faroes the sequences are more complex.

Chemical characteristics and petrogenesis of the Thulean lavas. Unlike most volcanic associations the lava fields of the Thulean Province are characterised by the close association of alkaline olivine basalts similar to those of oceanic regions and tholeiitic basalts which are analogous to the continental flood basalts. It is difficult to provide a rigid chemical definition of these two lava types, since an olivine basalt of one province may on analysis almost exactly match a tholeiitic basalt from another region. Turner and Verhoogen (1951, p. 181) define the differences as a tendency for SiO_2 to be higher and for Na_2O, K_2O and MgO to be lower in tholeiites than in olivine basalts in petrographic provinces containing both types. The norms of tholeiites always favour the appearance of normative quartz and exclusion of olivine and nepheline, whereas the majority of olivine basalts are distinctly undersaturated.

The authors of the Mull and Ardnamurchan Memoirs (1924 and 1930) distinguished on the basis of petrography and chemistry several magma types and series embracing both intrusive and extrusive rocks. In brief they suppose that an olivine basalt magma (plateau type) was the parent of all other types and series. Thus the tholeiitic magma (non-porphyritic central magma type) arose by removal of olivine and then by further fractionation the acid series came into being, the extrusive representatives of which are andesites and rhyolites. The alkaline series (mugearites and trachytes) were formed by the removal of late liquids enriched in alkalies and volatiles, while accumulative processes gave big-feldspar basalts and picrites.

Some of these ideas derived from Bowen's work (1928), but there are differences of opinion on the nature of the parent magma which are too complex to discuss here.

<u>Central and fissure volcanoes.</u> The form of the volcanoes which extruded the Tertiary lavas has been

in dispute since the advocacy of a fissure-eruption origin by Geikie and the counter argument for central volcanoes by Judd.

Geikie (1880, 1897), supported by Harker, compared the Tertiary basalts with those of the Columbia-Snake River plains and the historical fissure eruptions of Iceland. He imagined numerous small eruptive centres aligned over fissures, with the site of extrusion constantly changing. The fissures were believed to be preserved as members of the north-west dyke swarms which pass through the Scottish igneous centres, though Harker showed that the majority of these dykes are of later date than the exposed flows. The great volume and extent of the lava piles compared with the thinness of individual flows, and the rarity of pyroclastic rocks were held to support this view.

According to Judd's hypothesis (1874, 1878) the present plutonic centres represent the dissected interiors of large central volcanoes from which lavas were extruded at the same time as plutons of similar compositions were emplaced below. Geikie and Harker demonstrated that the large intrusions are later than all the lavas with which they came into contact, and that Judd's general igneous sequence, which commenced with acid activity and ended with basic intrusions and lavas, is certainly incorrect. Judd's ideas were therefore abandoned for some time.

The case was reopened when the Mull Memoir authors (1924) showed that a central volcano of lava caldera type had probably existed in Mull for at least the period of extrusion of the tholeiitic basalts. The plateau basalts may also have been poured out from this extrusion centre, for in Morven they thin northwards away from Mull, with overlapping of lower flows by higher ones (op. cit. p. 105-106). They also considered it likely that this volcano later persisted as a steep-sided ash and acid lava cone of Vesuvius type. Later Richey (1948) pointed out that a central volcano theory was favoured by the marked concentration of dyke swarms through the plutonic complexes, indicating that the latter were marked out as centres of igneous activity before the dykes were intruded. He also suggested that the basic and acid volcanic plugs found in Mull may be the remnants of local extrusive foci, analogous to the parisitic vents found on the flanks of modern volcanoes. About thirty basic plugs occur in Antrim (Walker, 1960) and others have been described in south-east Skye by Clough (1904, p. 101). The agglomerates vents of Skye are also indicative of localised activity, and though Harker thought most of them to be of pre-lava age it now seems that some of them were pre-cursors of much later acid igneous intrusion and possibly extrusion.

The evidence of centralised extrusion in Mull refers mainly to the second part of the basalt lava period, and while this volcano may have persisted into later times as an acid volcanic cone the origin of the olivine basalts (plateau type) which are so abundant here and throughout the rest of the province still remains in doubt.

Summaries of the evidence by Rastall (1931) and Richey (1937) favour a general theory of central eruption, while Tyrrell (1937) supports extrusion from fissures. The last author supposes that early eruptions along dykes were followed by a later localization of activity to specially favoured parts of the fissure network.

Direct evidence of dykes feeding lava flows is not entirely lacking. Walker and Davidson (1936) refer to two lava feeders in the Faroe Islands, though they are uncertain whether these are dykes or plugs. In Antrim both Patterson (1950b) and Walker (1960) have found individual instances of dykes feeding lava flows, and Walker (1958) in Iceland has found two cases of visible continuity between porphyritic dykes and similar lava flows.

It may be of interest to summarise some of the features of the Hawaiian shield volcanoes from the account given by Stearns and Macdonald (1946). This type of volcano is often quoted as characteristic of centralised eruption of olivine basalts. Five volcanoes build the island with a total area of a little over four thousand square miles. The fundamental feature of Hawaiian volcanic activity is that the lavas are nearly all erupted from narrow fissures confined to rift zones which intersect at the summit of each dome. A central vent may or may not be present, depending on the phase of development (op. cit. p. 24) which are as follows:-

1. Youthful - rapid outpouring of highly fluid, undifferentiated basalts builds up a shield dome over a fissure intersection, with a small crater at the top. Olivine basalts predominate.

2. Mature - continued activity and gradual collapse of the superstructure over the vent forms a caldera, and sometimes shallow grabens along the major rifts. The composition of the lavas is little changed.

3. Old-age - the lava poured out obliterate a part or whole of the caldera. The time interval between the flows become progressively longer and the composition

may change gradually to andesine basalts and picrites, or abruptly to mugearites and trachytes. The profile of the cone becomes steeper because of the shorter, thicker nature of the acid flows, while pyroclastic material becomes common.

4. Rejuvenated - proceeded by a long period of erosion, with nepheline basalts and porphyritic basalts as the chief products. No volcano in Hawaii has reached this stage though others in the archipelago have done so.

The undifferentiated olivine basalts pour from cracks which extend down the slopes, and may flow as far as thirty miles. Eruptions are characterized by many short flows from the upper part of the crack and a few long ones which extend downwards from the lower end of the fissure. Undifferentiated basalts average five feet in thickness near the summit and twenty feet near the periphery, and eruptions are spaced at two to four year intervals.

Crystal sinking is thought to be principal mechanism of differentiation in Hawaii (op. cit. pp. 207-208), and the type of evidence is shown in the following quotation:-

"An interesting example of gravitative crystal differentiation is furnished by the lavas of 1840.

Flows erupted at altitudes of 3,100 to 2,650 feet ... (on Kilauea) ... contain very few crystals of olivine; whereas lavas erupted a day or two later from vents at altitudes of 750 feet to 850 feet are picrite basalts ... It is believed that the difference results from the settling of olivine phenocrysts in the Kilauea magma columns" (op. cit. p. 191).

One of the significant features of Stearn's and Macdonald's account is that although this is a central volcano complex most of the lavas are erupted from fissures, so that visible connections between dykes and lavas are not conclusive evidence of the lack of central volcanoes. A comparison could be made between the Hawaiian volcanoes and those of western Scotland, for the order of size is the same, but it should be noted that the varieties of lava found in Scotland have a more extended range than those in Hawaii, possibly due to the difference in tectonic environment.

In summary it can be said that there is still considerable doubt about the form of the volcanoes which erupted the Thulean lavas. As far as the olivine basalts are concerned the choice appears to lie between shield volcanoes of Hawaiian type and eruption from a regional series of uncentralized fissures. In one case (Mull) there are indications that the lavas of tholeiitic type accumulated in a caldera, while in other areas where tholeiites are abundant, such as Iceland, no evidence of centralization has been found. In comparison, continental flood basalts (tholeiites) of other provinces appear to have poured out of regional fissure systems. One is tempted to think that the only significant difference between these two modes of eruption is whether the regional fissure systems were or were not insecting. Hawaiian shields and flood basalts might well co-exist in the same province. There is general agreement that many acid lavas, due to their greater viscosity and the association with local explosive activity, built up steep central volcanoes of Vesuvius type.

(ii) Introduction to the Lavas of Strathaird.

The total area of extrusive rocks exposed in Strathaird is seven square miles, amd is so a very small part of the 425 square miles of lava found on the Isle of Skye. Nearly all this area, however, is situated north of the Cuillins, and Strathaird contains the major part of the lava outcrop found on the south side of the central intrusion complex. There may be a tenuous connection under Loch Scavaig with the lavas of Glen Brittle to the west, and so with the north Skye lavas, but to the north the Red Hills intrusions cut out all but a few isolated patches of the volcanics (see sketch map, Plate 1.).

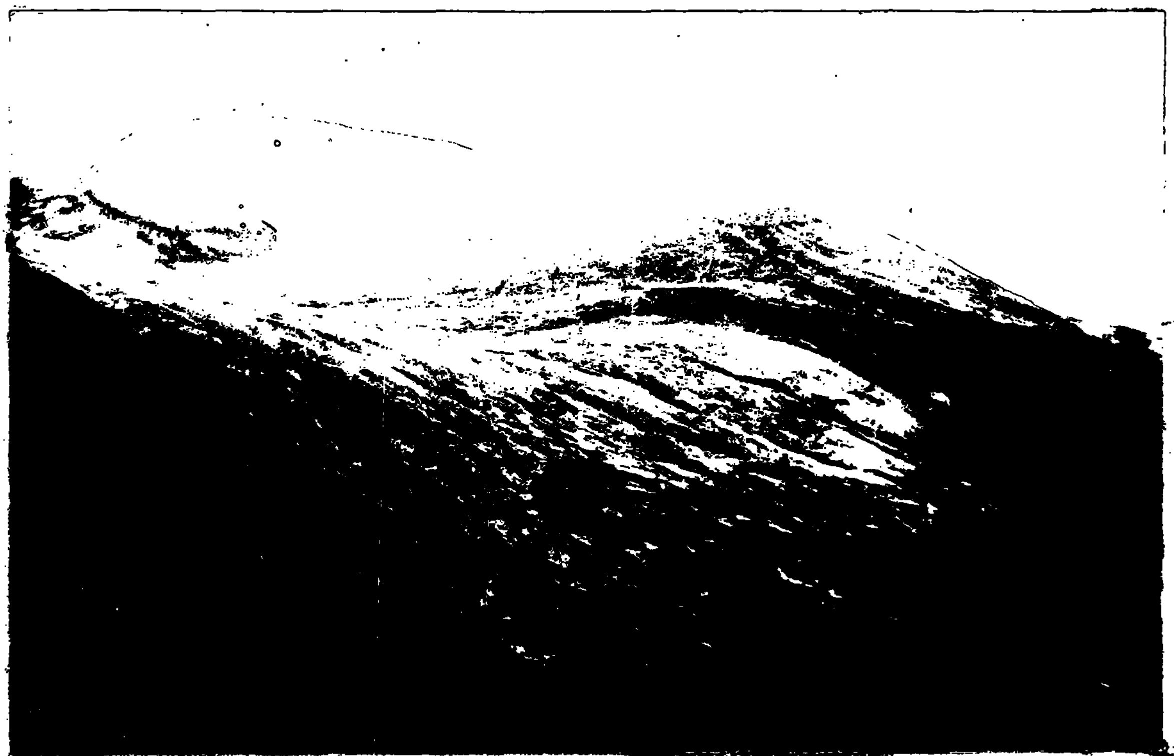
In Strathaird there is no representative of the Palagonite Tuff at the base of the lava sequence, and pyroclastic rocks are limited to a small agglomerate vent piercing the lowest flows on An Carnach and a small lens of tuff at a higher horizon on Slat Bheinn. The maximum thickness of flows exposed is 1,000 feet, and consists wholly of basalts of "plateau type" together with one horizon of andesine trachybasalt and a thin group of picritic flows. Both are common associates of olivine basalt throughout the Province, and represent the alkaline trend and olivine accumulative phases respectively. The olivine basalts show a range of textures varying from relatively coarse doleritic types to finer varieties with highly ophitic or granular pyroxenes. In the upper part of the sequence feldspar-phyric lavas became common but the phenocrysts are much smaller than the big-feldspar basalts of Mull.

Apart from the absence of a basal tuff the sequence is similar to that of the lower part of the north Skye lava pile.

PLATE 9 (opposite.) The lava hills.

Above:- Slat Bheinn (left) and An Stac seen from the road south of Strathaird. The terrace featuring of the Slat Bheinn lavas is very clear in this view, with the sunlight picking out the horizon of the Ophimottled Basalt Group.

Below:- View to the south-east from the south ridge of Blaven. The valley of Abhuinn nan Leac lies in the foreground, with Slat Bheinn and Beinn Leacach rising beyond it. In the background the Basal Lavas make a well-marked feature on Ben Meabost and Ben Cleat.



appear that they are most numerous near to the contact of the latter, and are especially well developed at Camasunary. Since the Cuillin Gabbro post-dates at least most of the Skye lavas it follows that if the flows were extended from fissures these should be preserved among the dykes of the early suite. Such a relationship is, however, difficult to establish. At Camasunary the earliest dykes intruded were of picrite and olivine gabbro, and these were followed by olivine-poor and olivine-free dolerites. This might correspond with a lava sequence which began with olivine basalts and continued with tholeiitic lavas. Harker (1904,p.12) describes as lava feed-channels some similar, irregular basic bodies which pierce the Torridonian sandstones near Creag Strollamus, north of Broadford, and King (1953), though considering that some of these bodies are outliers of the lavas, admits that some of them appear to have been emplaced by explosive drilling. Also of irregular form is the dyke in Antrim, described by Patterson (1950b), which can be seen to continue directly into the lava flow above. No direct connections between lavas and dykes have been detected during the present study. One possible lava feed channel in Strathaird is the small plug of gabbro which breaks through the Estuarine Series half a mile south of Ben

Meabost. This plug is about 150 yards in diameter, almost circular in plan, and is cut by several small dolerite dykes belonging to the north-west swarm.

Finally, it should be mentioned that one feature of Harker's (1904) description of the Skye lavas has been shown to be incorrect by later workers. This concerns his mistaken identification of the presence of numerous sills amongst the lava pile. Thus under the designation "Great Group of Basic Sills" (op. cit. pp. 235-237) he includes not only the undoubted intrusions in the sub-lava sediments but also most of the scarp-forming, massive centres of the lava flows, imagining that only the amygdaloidal layers were extrusive flows. Again under the heading "Minor Group of Basic Sills" (op. cit. pp. 256-269) composite sheets of "Roineval type", consisting of an upper layer of porphyritic dolerite and a lower layer of mugearite, are interpreted as intrusions. The lava sequences of the Small Isles were later described by Harker (1908) in a similar way. Bailey (1914) was the first to draw attention to Harker's mistake and pointed out that continuous gradations exist between massive doleritic horizons through amygdaloid into bole above, with sharp breaks below the overlying amygdaloid. Kennedy (1931) showed that the Roineval composite sheet in Skye is also a lava flow. Sills appear, in fact, to be extremely rare among the Thulean lava sequences, though inclined sheets of gabbro have been found locally in north Skye (Wilson, 1936).

CHAPTER VI

LAVAS - SEQUENCE AND PETROLOGY

(i) Distribution.

The present disposition of the Strathaird lavas in two belts approximately parallel to the margin of the Cuillin Gabbro is the result of erosion along the crest of an anticline of country rocks formed at the time of the latter's intrusion. The western, or inner, belt lies in direct contact with the Gabbro and the outer belt consists of two large outcrops on the watershed of the peninsula.

The inner belt is some six miles long, extending from Belig in the north to Sgurr na Stri in the south-west. North of Belig the lavas are cut off by the Coire na Seilg agglomerates and the granophyres of the Red Hills complex, while west of Sgurr na Stri they plunge beneath Loch Scavaig and are presumably continuous with the lavas of Gars-Bheinn on the Cuillin main ridge. The maximum width of the belt is half a mile and the average some 350 yards, while at Camasunary and in Coire Casteail the lavas are locally cut out altogether by the Gabbro. Though at sea level at Camasunary, the height of the outcrop rises rapidly to the north and reaches 2,500 ft. O.D. on the east face of Blaven.

In the outer belt the more northerly of the two outcrops has in plan the appearance of an inverted hook. It is some two miles across and three miles long. The shank of the hook lies parallel to the inner belt of lavas but is separated from it by erosion; on it lie the hills of Slat Bheinn* (2,000 ft. O.D.), An Stac** (1,700 ft. O.D.), and Beinn Leacach*** (888 ft. O.D.). The barb of the hook to the east is the ridge of An Carnach (1,100 ft. O.D.). The southern outcrop of the belt forms a bilobed capping, one and a half miles long, to the hills of Ben Meabost (1,128 ft. O.D.) and Ben Cleat.

(ii) Sequence.

An Stac and Slat Bheinn display the most complete succession of flows in the area with a total thickness of exposure of about one thousand feet. This includes between twenty-five and thirty flows, the average thickness of which is therefore between thirty and forty feet. Olivine basalts of plateau type predominate and pyroclastic rocks are rare.

It was found impracticable in the field to trace individual flows for any considerable distance laterally, except in the case of the few more distinctive varieties. The sequence can however be divided into several groups of flows, which have sufficiently characteristic

* Plate 9. ** Plate 10. *** Plate 11.

appearances to be mapped as units. Four such "flow-groups" have been distinguished. Their boundaries are indicated on the six-inch maps.

Flow-Groups.

Name	Average Thickness	Chief Characteristics
4. Upper Lava Group	600 ft.	Sub-ophitic to ophi-mottled olivine basalts, often with a feldspar-micro-phyric tendency.
3. Picritic Basalt Group	50 ft.	Upper and lower flows of olivine-rich basalt separated by a highly amygdular olivine basalt.
2. Ophimottled Basalt Group	200 ft.	Highly ophitic basalts, rarely porphyritic, with an intercalation of trachybasalt.
1. Basal Lava Group	150 ft. (sometimes absent)	Relatively coarse, olivine-micro-phyric basalts.

(iii) Field Relations.

The inner belt of lavas takes part in the rugged scenery of the Blaven Range and forms cliffs not notably different from those carved out of the Gabbro. Individual flows are difficult to distinguish, and even the plane of contact against the intrusive rocks is frequently unmarked by a feature. The south face of Sgurr na Stri is an exception in this respect, since a broad glacial bench cut in the top of the lavas above Rudha Ban is there backed by a steep slope of gabbro. The lavas of the inner belt dip in towards the centre of the Cuillin massif at angles varying from fifteen to forty degrees. They lie on the north-west limb of the fold hereafter referred to as the Coire Uaigneich anticline.

The outer belt of lavas form terraced hills neither so high nor so rugged as those of the Cuillins. These hills have a tendency to be oval in plan. The terraces are not flat, since this part of the lava tract is disposed in a shallow down-fold complementary to the Coire Uaigneich Anticline and here named the Strathaird syncline. Dips are as high as forty degrees on the western limb but rarely exceed ten degrees on the eastern limb.

Basal Lava Group. The lowermost flow-group of the sequence frequently outcrops in a line of cliffs, fifty to one hundred feet,high, overlooking a steep slope of Mesozoic sediments. These cliffs are especially prominent on the eastern side of the An Carnach ridge (see Plate 2) and on Ben Meabost (Plate 3). In the Kilmarie Valley the feature is more subdued, though a waterfall marks the lava base at c. 350 ft. O.D.. The Group is absent on the east face of An Stac and on Sgurr nan Each due to thinning away.

A close examination of the basal contact of the lavas where it is best exposed on An Carnach shows that the pre-lava surface was here almost flat, with only small irregularities a few feet high. The earliest flow thins out and sometimes disappears against these hillocks. Furthermore a consideration of the relations between lava-base and contours, with corrections for the post-lava folding, indicate that on the scale of the area under consideration the pre-lava surface can be regarded as a peneplain.

The Group consists of seven or eight flows thinner than the average for the area. Thin boles are occassionally seen between the flows and consist of brown or reddish-brown clay or black shale. The bright red colour of the north Skye boles is not found in Strathaird. Vertical jointing imparts a roughly columnar appearance to the cliffs, and all the flows contain conspicuous amygdaloids, forming narrow terraces. Dark grey with a tint of green or blue is the usual colouration of fresh specimens, while weathered surfaces vary from brown or grey to black. The grain size is comparable to that of a fine-grained dolerite.

Ophimottled Basalt Group. Unlike the previous group the Ophimottled Basalts rarely form cliffs, though usually giving rise to a good feature. This part of the sequence consists of upper and lower leaves of

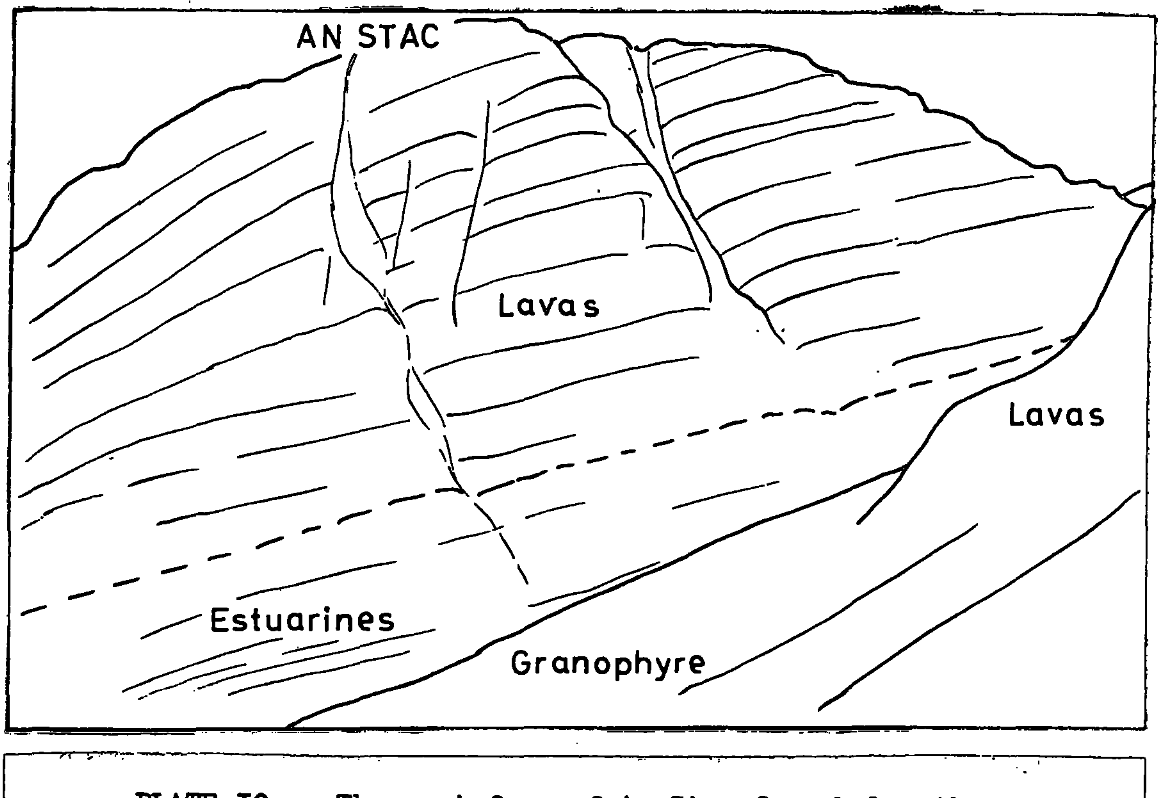


PLATE IO The west face of An Stac from below the cliffs of Clach Glas.

ophitic olivine basalt separated by an horizon of trachybasalt up to thirty feet thick. Being more easily eroded than its neighbours the latter flow now forms a bench between two steep features of ophitic lava.

The Ophimottled Basalts are extensively exposed on the broad ridge of An Carnach, and the trachybasalt contributes a broad terrace to the dip slope on the western side. However, this flow, when traced round the southern end of the hill, rapidly thins and four hundred yards south-east of the summit is reduced to a chilled tongue wedging out between the upper and lower divisions of ophitic lava.

Followed round the upper end of the Kilmarie Valley the Group continues across the col at its head as a broad outcrop and then passes under the higher flows of An Stac and Slat Bheinn, forming a plinth to those mountains. At the mouth of Coire Ballaig the trachybasalt is well exposed of the sides of the outlet gully. On Ben Meabost the Ophimottled Basalts underlie much of the summit plateau.

The highly ophitic type of lava characteristic of the Group tends to form series of rounded rock knolls rather than continuous crags, and the poor development of vertical jointing is seen in the lack of columnar structure. Flow partings and amygdaloids tend to be thin and inconspicuous, so that while there is evidence that the hundred-foot upper division on An Carnach consists of at least two flows, it is uncertain whether the seventy-foot lower division is also multiple.

Southwards, on Ben Meabost, the Group again has a three-fold division, but to the west, on Beinn Leacach, the sequence is rather different, with several flows of Basal Lava type interspersed amongst the ophitic lavas and no ophitic flows above the level of the trachy-basalt. Such lateral variation may be the result of the flows being poured out from more than one contemporaneous vent.

The term "ophimottled" refers to a marked textural division into areas of highly ophitic clinopyroxene, one to three millimetres across, and interstitial feldspathic areas. The relative ease with which weathering attacks the latter produces a characteristic pimply surface, usually reddish brown in colour. Frequently such lavas exhibit flow lamination, with about six laminae to the inch. These features, together with the rounded, craggy nature of the outcrops, readily distinguishes flows of this type in the field.

The rocks of the trachybasalt horizon possess a markedly different appearance to the above, for they are dark grey, fine grained, and fracture easily along numerous, flat lying, platy joints.

<u>Picritic Basalt Group.</u> This horizon is best displayed on the eastern slopes of An Stac and Slat Bheinn, while on Carnach, Meabost, and Leacach it forms small outliers, and on Ben Cleat is altogether absent.

Though only fifty feet thick the Group contains three flows, the lowermost of which is a true picrite containing rather more than fifty per cent olivine. The uppermost flow, though not a picrite, also contains a high proportion of olivine, while the middle flow is a normal olivine basalt.

The picrite is a dark green-grey, friable rock forming a flow only five feet thick. It is commonly eroded into a recess below the overlying basalt. The possibility that this sheet is an intrusive sill was considered and rejected on the grounds of petrographic affinity with the two flows above, constancy of horizon, and the presence of a reddened top on An Carnach.

The thirty-foot olivine-phyric basalt which overlies the picrite is also of distinctive appearance in that numerous streaks and rafts of amygdaloidal material occur throughout its thickness, their predominantly white contents contrasting with pale green and reddish tints of the matrix.

Many of the features of the picrite are repeated in the uppermost flow, but containing rather less olivine, (amounting to some 35 per cent,) it is classed as an olivine-rich basalt.

Upper Lava Group. This, the highest and thickest of the flow groups defined in Strathaird, is also the most variable and might have been further divided were the variation less irregular. Most of the flows have characters which ally them either with the Ophimottled or the Basal Lava Group, but there is also a common tendency for the constituents, especially feldspar and olivine, to build porphyritic crystals. The phenocrysts occupy only a small proportion of the bulk in most cases, and they are not large; feldspars, for instance, rarely exceed five millimetres in length. The local association of feldspar and olivine in small cognate xenoliths suggests that the phenocrysts were probably derived from an already consolidated rock.

Flows belonging to this Group build the higher parts of An Stac and Slat Bheinn, the base lying at c. 800 ft. O.D. on the eastern slopes and rising to c. 1750 ft. O.D. on the western side of Slat Bheinn. They must also occur, in altered form, on Sgurr nan Each, in the inner belt of lava outcrops, where an eight hundred foot sequence starts with lavas of the

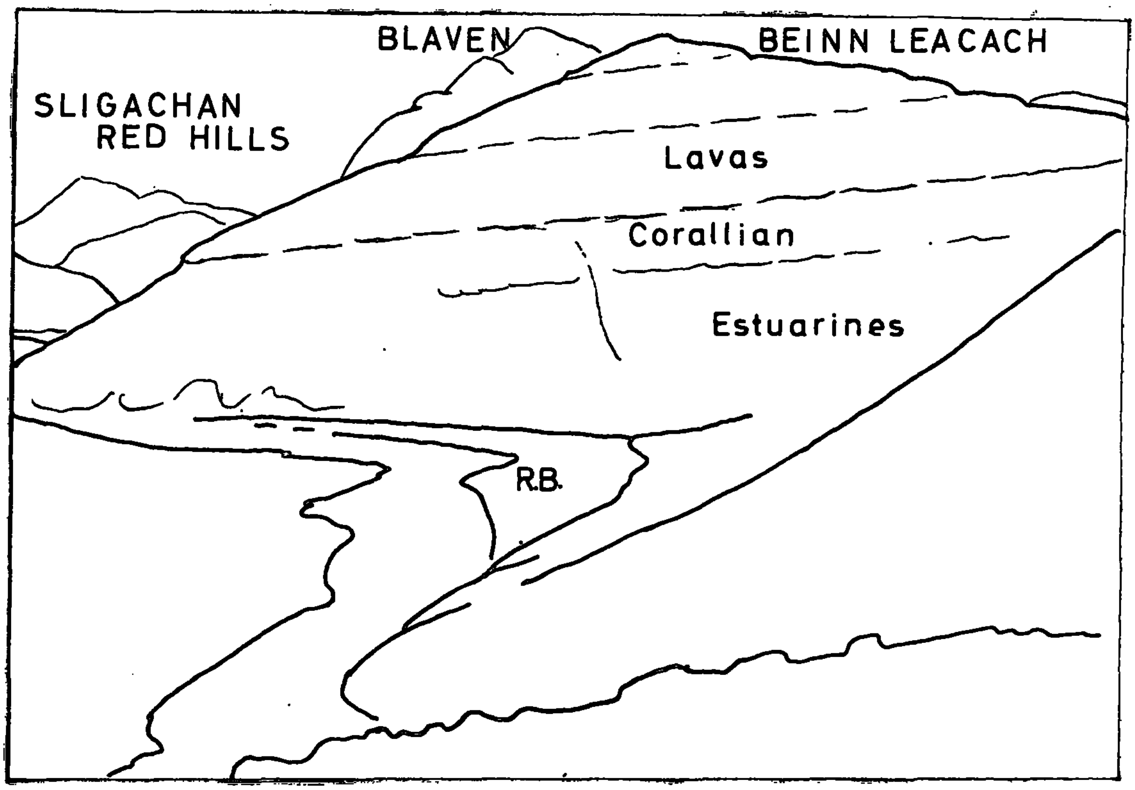


PLATE II View to the north from Carn Mor

Ophimottled Group. Elsewhere in the Peninsula they have been removed by erosion.

The sequence is displayed to its best advantage on the eastern face of An Stac. Above the line of crags marking the Picritic Basalt Group the face rises another seven hundred feet to the top of the exposed sequence. Four prominent steps mark the most resistant flows. The topmost of these steps also underlies the eastward-tilted summit plateau and is formed of distinctive flow of ophimottled type. The same horizon also underlies the upper part of Slat Bheinn. At least eleven flows are present within the total thickness of about six hundred feet.

Pyroclastics. Fragmental volcanic rocks are rare in Strathaird. There is no representative of the tuff horizon found over a widespread area at the base of the north Skye sequence.

Pyroclastic rocks have, however, been found at two localities in the area. The first and larger occurrence is situated at the northern end of the An Carnach ridge, and forms a part of the cliff feature facing the head of Loch Slapin. At this point a small explosion vent, one quarter of a mile across, has been drilled through the lowest four or five flows of the Basal Lavas but is overlaid by the uppermost flows of that Group. The cliff exposes the vent in section and it is seen to be bounded by a steep and irregular wall having a tendency to incline inwards. About one hundred feet of unbedded tuffs and agglomerates are displayed, with angular fragments up to fifteen feet across set in a black, muddy, basaltic matrix. The latter is cut by a number of variously inclined, slickensided displacements, which probably originated by slumping of partially consolidated material within the vent. Most of the fragments were derived from the adjacent Basal Lavas, while the remainder are of Jurassic sandstone, shale, and limestone, all of which can be matched less than fifty feet below the base of the volcanics. The vent is probably the result of only one eruption, the greater part of the debris thrown up having fallen back into the crater. This event can clearly be dated to the period of extrusion of the Basal Lavas.

The second occurence of fragmental material is situated on a small exposure between flows lying near the top of the sequence on the summit plateau of Slat Bheinn. It is only a few feet thick, and cannot be traced many yards laterally. A sliced specimen shows fragments up to an inch or two across set in a dark, powdery matrix. Some of the fragments are evidently olivine basalts, but others are of coarse dolerite. The presence of porphyritic elements and cognate xenoliths in the Upper Lavas may be related to the explosive fragmentation of intrusive rocks evidenced by this rock.

(iv) Petrography.

<u>The zone of alteration</u>. Before commencing an account of the petrography of the various flow-groups described in the previous section, it should be made clear that almost all the lavas in the Strathaird area have suffered a varying degree of low temperature alteration. Pneumatolytic or hydrothermal agencies associated with the emplacement of the central Skye plutonic complex are thought to be responsible for this condition.

The existence of a zone of alteration was first suspected when a visit to the Portree area of northern Skye made obvious several megascopic and microscopic differences between the lavas of that area and those of Strathaird. These differences are summarized below:-

North Skye (Portree)	Strathaird
1. Lavas when fresh are black or dark brown, and break with a rough fracture.	1. Fresh surfaces are dark green or blue; fracture is compact.
2. Weathering is deep and produces a brown, friable surface.	The weathering crust is usually less than 1 cm. thick and has a hard grey surface.

3. Trap-featuring is well developed.	3. Trap-featuring becomes progressively more obscure towards the central intrusive complex.
4. Columnar joints are often well displayed.	4. Columnar joints tend to be sealed.
5. Bright red boles are frequent and conspicuous between flows.	5. Boles are apparently few, thin, and inconspicuous brown or black.
6. Fresh or slightly decomposed olivine is common, and is often visible in hand specimen.	6. Fresh olivine is very rare.
7. Zeolites abound in the vesicles, while chlorite is sparse both in vesicles and groundmass.	7. Chlorite, albite and epidote are the commonest vesicular minerals and are abundant in the groundmass. Zeolites are rare.

The authors of the Mull Memoir (1924) ascribe similar changes of appearance and mineralogy in the Mull Lavas to the presence of a pneumatolyzed aureole surrounding the central intrusion complex (op. cit. p. 94-97). A brief reconnaissance suggested that the Strathaird lavas lie in a similar aureole of alteration surrounding both the Cuillin gabbro and the later Red Hills granophyres.

The processess of decomposition appear to have continued intermittently over a long period, probably related to successive phases of major intrusion. In southern Strathaird the hornfelsed lavas adjacent to the Gabbro are fresh, apart from a few thin veins of uralitic amphibole, while the lavas outside the thermal aureole contain abundant chlorite and albite. Evidently in this part of the area the alteration was not later than the intrusion of the Gabbro, and was most probably a result of that event. Nevertheless in some of the hornfels thin stringers of pyroxene are seen to cut the feldspars, and pyroxene is common in the amygdales, so that some chlorite may have been present prior to the metamorphism. North of the Blaven-Slat Bheinn col the hornfels themselves are frequently decomposed, often to a high degree and with associated crushing. Moreover, as in Mull the later dykes and cone-sheets have also been affected, though to a lesser extent than the lavas which they intrude. It seems reasonable to suppose that this later phase of alteration was associated with the emplacement of the Red Hills granophyres and the explosive activity which preceded it.

Some parts of the southern Strathaird lava outcrop are as much as two miles distant from margin of the Gabbro, while the altered hornfels of the Blaven-Slat Bheinn col, are situated one mile from the Sligachan Centre granophyres in Strath Creitheach and two miles from the Broadford Centre granophyres north of Loch Slapin. The zone of alteration is thus of considerable width, but owing to the lack of unaffected lavas in the area the situation of the outer margin is unknown.

Basal Lava Group. (see Plate I2) Many of the rock slices used to describe this group were taken from specimens collected from An Carnach and Ben Meabost. A good section is provided by a steep gully cutting through the cliff feature on the southern slope of Ben Meabost, 600 yards south-west of the summit. The succession is as follows:-

Flow	Thickness	Microscopic Appearance
7	?	Poorly exposed, grey lava, speckled with dark red olivine pseudomorphs.
6	15 ft.	Green tinted grey lava.
5	15 ft.	Coarse grained, green tinted black lava.
4	14 ft.	Grey, coarse grained lava.
	6 in.	Black shale.
3	20 ft.	Black lava with green tints, amygdular throughout.
2	20 ft.	Dark green and grey, coarse grained lava.
	1 ft.	Dark grey shale.
1	25 ft.	Black, compact, fine to medium grained lava with whitened base.

-------- Corallian Sandy Shales --------

A very similar sequence is exposed in the western

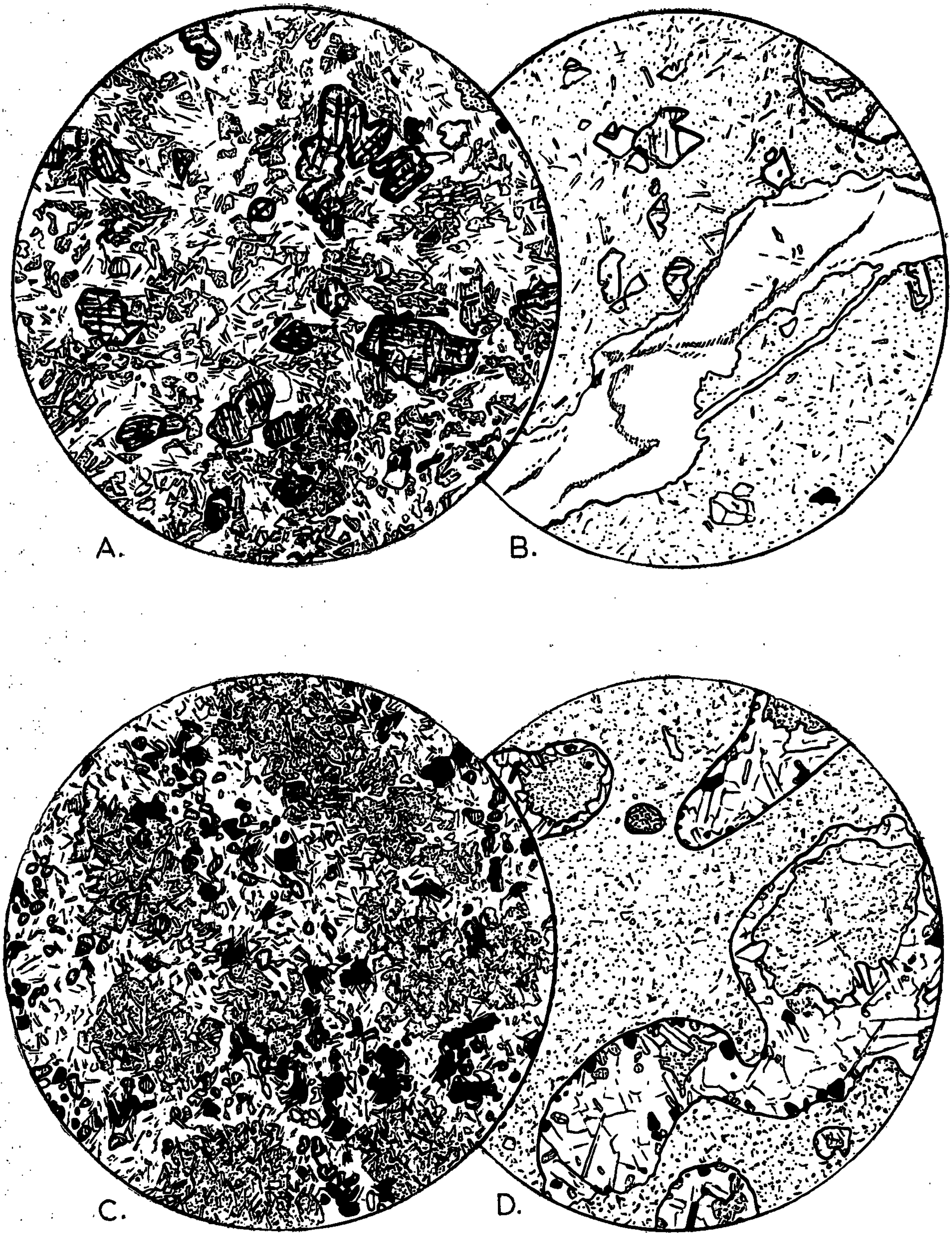
<u>PLATE I2</u> (opposite.) Microsections: Basal Lavas and Ophimottled Basalts.

A. (Spec. 7I) ×9. Centre of a flow from the Basal Lava Group, An Carnach. Altered phenocrysts of olivine in a groundmass of plagioclase, intersertal clinopyroxene, chlorite, and ore.

B. (Spec. 70) ×9. Lower amygdaloid of the same flow as A. The groundmass has been largely replaced by chlorite, and the amygdales contain quartz, chlorite, and calcite.

C. (Spec. 88) ×20. Ophimottled basalt from Slat Bheinn. Con--taining plagioclase, ophitic clinopyroxene, small altered olivines, and abundant ore.

D. (Spec. I5) ×9. Lower amygdaloid of an ophitic lava, from the col between An Stac and An Carnach. The vesicles are largely filled by pegmatitoid, consisting of albitic plagioclase, titaniferous clinopyroxene, ore, and apatite, while the remaining spaces are occupied by chlorite. The groundmass is fine grained, with granular pyroxene.


A.
B.
C.
D.

cliff of An Carnach, but with the addition of a thin basal flow. The latter is a pale green, vertically jointed rock weathering into a recess at the foot of the feature. In places it is as much as six feet thick, while elsewhere it thins and disappears against minor irregularities of the pre-lava surface. This flow has not been recognised elsewhere in the area.

Modes.

Modal analyses for five Basal Lavas are given below in terms of primary constituents. All are from sections of the massive centres of the flows.

Constituents	Volume Percentages				
	Spec. 42	Spec. 43	Spec. 44	Spec. 479	Spec. 20
Plagioclase	45.3	45.3	46.0	49.2	49.3
Clinopyroxene	31.6	26.7	33.4	27.9	23.3
Olivine	15.9	19.4	16.3	19.6	23.1
Ore	7.2	8.6	4.3	3.3	4.3
	100.0	100.0	100.0	100.0	100.0

Spec. 42 - Flow 1, Ben Meabost.

Spec. 43 - Flow 2, Ben Meabost.

Spec. 44 - Flow 3, Ben Meabost.

Spec. 479- Flow 5, Ben Meabost.

Spec. 20 - Flow 1, western slope of An Carnach.

Plagioclase.

The plagioclase is always a labradorite. The range in average composition in the slices examined is from An 54 to An 62. It builds well formed, narrow, twinned laths varying in average lengths from 0.25 mm. to 0.6 mm.. Normal, continuous zoning over a small compositional range is usually present. In one slice (Spec. 43) a single phenocryst (or xenocryst) of labradorite-bytownite was seen. It showed a corroded core and marked zoning in which an inner and outer envelope normally zoned are separated by a reversed layer. The feldspar laths occasionally are arranged in a poorly developed flow orientation which moulds round the olivines.

Clinopyroxene.

The pyroxene is a titaniferous augite, colourless to pale brown, non-pleochroic. There are often indications of continuous zoning in titanium content in that the outer parts of the crystals are more coloured than the cores.

There are all variations in mode of occurrence between small granules, 0.1 mm. across, up to crystals 2 mm. across ophitically enclosing plagioclase. The former is particularly to be found in the chilled amygdaloidal layers. An intersertal texture is most common.

Pyroxenes from three of the An Carnach Basal Lavas were examined to determine their optical properties. The results are tabulated below, together with their calculated compositions in terms of Ca-Fe-Mg molecules derived fr_om the optical data, using the triangular diagrams of Hess (1949).

Spec. No.	Type	$n\alpha$	$n\beta$	$n\gamma$	2V(+)	Composition
9.	Sub-ophitic, titaniferous	1.697	1.701	1.722	$51.\frac{1}{4}^{o}$	Ca41 Mg34 Fe25
72.	Granular, titaniferous	1.697	1.702	1.723	$53.\frac{1}{4}^{o}$	Ca43 Mg32 Fe25
78.	Intersertal & granular, titaniferous.	1.696	1.700	1.722	$52.\frac{1}{4}^{o}$	Ca42 Mg34 Fe24

Olivine.

This mineral is never found fresh in the Basal Lavas, but is represented by pseudomorphs of unmistakable appearance.

Olivine originally formed subhedral and anhedral phenocrysts, sometimes embayed by resorption, varying in length from one tofour millimetres. In some lavas it also occurs sparsely in the groundmass. (43,476). Plagioclase and pyroxene mould round the olivine, which is clearly the earliest formed mineral in the rock, apart from a few small euhedral grains of ore enclosed within it.

Olivine exhibits a variety of decomposition products of which the commonest are, in order of abundance, chlorite, bowlingite, talc, secondary ore, and carbonate. In Flow 7 on Ben Meabost the pseudomorphs are red in hand specimen, and in this case a slice (481) shows that the outer shell is composed of iddingsite.

Ore.

There is an average content of about five per cent primary ore in these lavas. A small amount occurs as euhedral grains enclosed within olivine, while the later formed groundmass ore has a subhedral, or even intersertal, relationship to the plagioclase. Alteration to leucoxene is not uncommon. Apatite is the only other common accessary mineral.

Differentiation.

Slight vertical mineral differentiation is occasionally detectable within the flows. It is marked by changes in the ratio of feldspar to pyroxene, in texture, and in olivine content. Flow 2, An Carnach, provides an example. This lava is fifteen feet thick, with upper and lower amygdaloids of two or three feet each. The modes (primary constituents) of specimens collected from the lower amygdaloid, centre, and upper amygdaloid are given below:-

Constituents	Volume Percentages		
	Base (70)	Centre (71)	Top (72)
Plagioclase	47.8	42.7	54.4
Clinopyroxene	32.3	37.8	33.6
Olivine	15.8	15.3	8.6
Ore	4.1	4.2	3.4
	100.0	100.0	100.0

It will be noted that the ratio of feldspar to pyroxene is greatest at the top and least at the centre. This corresponds with textures mainly ophitic in the centre, granular at the top, and intersertal at the base. With the exception of olivine the grain size of the constituents also varies, as is indicated by the average length of the feldspars; 0.3mm. at the base, 0.5 mm. at the centre, and 0.4 mm. at the top. This last effect is the result of chilling.

These variations are explainable in terms of gravitative settling of olivine and, to a lesser extent the early-formed pyroxene, after the lava was extruded. Crystallization of pyroxene in the centre must have continued after the base had become too viscous to allow settling, thus building up an ophitic texture locally. The constant size and textural relations of olivine suggests that it crystallized either before extrusion, or very soon after.

Amygdaloids and Alteration.

Most flows possess upper and lower amygdaloidal layer one or two feet thick, and in some (e.g. Flow 3, Ben Meabost) amygdaloidal streaks extend throughout the entire thickness. The vesicles at the base of a flow are frequently pipe-shaped and sub-vertical, while those at the top are ovoid. A well exposed example of the former is found at the base of Flow 2, An Carnach, half a mile north of the summit. Here over half of the rock bulk is composed of vesicle fillings.

The degree of alteration is always highest in the amygdaloidal parts of the flows, while the proximity of water-rich sediments also seems to have had some influence, so that the lowermost flows are more decomposed than those higher up. Thus a slice taken from the whitened basal portion of Flow 1 (Spec. 41), Ben Meabost, is unusual in that most of the pyroxene is now represented by a fine grained, dirty brown clay mineral, white in reflected light. Fine grained carbonate has been introduced into the olivine pseudomorphs, and the slice also contains some nineteen per cent chlorite in irregular, intersertal masses.

The thin, amygdular Flow 1 on An Carnach is the most altered flow in the Group. Colourless serpentine and pale green chlorite are the chief products of decomposition, speckled with fine particles of carbonate. Chlorite also fills many of the vesicles, while others are occupied by clear quartz, tending near the walls to form inwardly directed sub-hedra. Small radiating sheaves of chlorite associated with the quartz differ from that elsewhere in being almost colourless and possessing an anomalous blue interference colour.

Quartz is again plentiful in the basal amygdaloid of the next flow, and is clearly a late addition, replacing the pale green chlorite, filling veins, and having a colourless chlorite associated with it.

Quartz is lacking in the amygdales of the higher flows, which contain instead mosaics of altered, dusty albite, patches of rosetted chlorite, interstitial calcite, prehnite, and epidote. The optical properties of two albites from Ben Meabost (476 and 477) were found to be :- $n\alpha$ 1.528; $n\gamma$ 1.575; 2V large, sign positive; maximum extinction on (010) cleavage flakes 14 - 15 degrees. Twinning is absent from about one third of the grains, and when present tends to be wedge shaped.

Zeolites are rare, and are thought to be now represented by albite. A small amount of stilbite and laumontite (?) were observed in specimens from

An Carnach. The laumontite (?) was found in Flow 3 (Spec. 73) as remnants in an amygdale otherwise occupied by albite. The clear prismatic fragments are monoclinic, have a negative 2V with moderate axial angle, while the refractive indices are :- $n\alpha$ 1.506; $n\gamma$ 1.516 ; and $C^\wedge\gamma$ is c.40 degrees.

A tentative depositional-replacement sequence for the amygdular minerals of An Carnach is given below:-

chlorite --
zeolites----------- albite + calcite
quartz---

Boles.

Thin boles, often shaly, are sometimes seen between the flows, but frequently there is only a slight decomposition of the lower lava.

Two specimens have been sliced. The first (77) is from a brown, shaly layer, six inches thick, resting on Flow 2, An Carnach, at a site on the eastern cliffs immediately below the summit. It consists almost entirely of limonite, with relic crystals of plagioclase and small masses of chlorite and talc. The plagioclases are somewhat larger than those found in the flow below, and it is possible that this rock is a decomposed crystal tuff.

The second slice (74) is from the same horizon, about half a mile north of the summit. In this case the specimen was collected from pockets of reddish material filling cracks in the top of the flow. Perhaps owing to this protected position it is more like a normal bole than any other specimen found in the area. It consists largely of hematite, though the zone of transition into the lava is highly vesicular, and contains carbonate, chlorite, and a little analcite.

Ophimottled Basalt Group. (see Plate 12). This group comprises upper and lower divisions of ophitic olivine basalt separated by a thirty foot flow of trachybasalt. The latter is related by several characteristics to the other members of the Group, but it possesses a sufficiently different appearance to merit a separate description at the end of this section.

Modes.

The modes of five representative specimens of the Group are given below in terms of primary constituents.

Constituents	Volume Percentages				
	Spec. 23	Spec. 18	Spec. 14	Spec. 452	Spec. 456
Plagioclase	45.8	50.9	49.2	46.1	60.9
Clinopyroxene	33.2	33.5	25.1	27.2	26.6
Olivine	16.2	10.4	16.4	9.7	4.0
Ore	4.6	5.2	9.3	17.0	8.5
	100.0	100.0	100.0	100.0	100.0

Spec. 23 - Typical ophimottled lava from near the base of the Group, Kilmarie Valley. Non-porphyritic; highly developed ophitic clinopyroxene.

Spec. 18 - From lower part of upper division An Carnach; not ophimottled; granular to intersertal pyroxene, locally elongate; continuous gradation of olivine up to 1 mm. phenocrysts.

Spec. 14 - Upper part of lower division, An Carnach. Highly ophitic pyroxene; contains more than average ore, and accessory brown hornblende.

Spec. 452 - From fifty feet above the base on Slat Bheinn. Ophimottled lava very rich in ore grains, many of which are rodded.

Spec. 456 - From the upper part of the Group, Slat Bheinn. Clinopyroxene moderately ophitic and tending to elongate.

In comparison with the modes of Basal Lavas these basalts show a slightly higher ratio of feldspar to pyr_oxene and a more variable content of olivine. Some contain almost as much of the latter mineral as a typical Basal Lava, others a great deal less. Ore percentages also fluctuate, and some rocks are very rich in this constituent.

Textures.

Although the typical member of the Group contains highly ophitic pyroxene, in a few flows this mineral is granular, especially near the base and top, and there are all gradations between. In general, ophitic textures are better developed below the horizon of the trachybasalt than above it. The grain size of the plagioclase becomes less and that of the pyroxene greater as the degree of ophitic enclosure increases. Thus in the ophimottled Spec. 23 the plagioclase laths average 0.25 mm. in length and the pyroxenes 2 mm. in diameter, while in the granular to intersertal Spec. 18 the plagioclase averages 0.4 mm. and the pyroxene 0.3 mm.

In the typical ophimottled texture there is a well marked division into ovoid pyroxene areas, one to two millimetres across, enclosing a considerable number of plagioclase laths with some olivine and ore, separated by interstitial areas containing the bulk of the plagioclase, olivine and ore. A well marked flow orientation of the plagioclases is always evident, and the laths enclosed in the pyroxene are as well orientated as those outside. The enclosed laths are moreover, very little different in size to those in the interstitial areas, though a slight tapering off from the point of entry is occasionally seen in laths lying across the pyroxene boundaries.

The textural features suggest that an orientation of incipiently formed plagioclases was already established before flow in the lava ceased. Whether embryonic pyroxene was also present at this stage is unknown, but certainly the growth of the large enclosing crystals must have been at a later date, for they freeze the flow structure. Some overlap of the plagioclase-pyroxene crystallization is indicated by the tapering of plagioclase laths entering pyroxene. The rarity of olivine phenocrysts and the greater abundance of this mineral in the interstitial areas may mean that crystallization of olivine was relatively later than was the case in the Basal Lavas.

Plagioclase.

This mineral forms laths varying in length from 0.15 mm. to 0.4 mm., with an average of about 0.2 mm.. Composition of specimens ranged between An56 and An64, sometimes with a continuous zoning to andesine externally. Partial alteration to a dusty albite is not uncommon in the inner parts of the zone of alteration (Slat Bheinn and An Stac).

Clinopyroxene.

The pyroxene is either colourless or, more commonly, a pale titaniferous purple. In highly ophitic textures most of the pyroxene ovoids consist of single anhedral crystals, but occasionally they are composed of two or more crystals, or of a single twinned crystal. Granularity ranges from 0.3 to 1 mm. in non-ophitic textures and from 1 mm. to 2 mm. in ophitic varieties. In the former case pyroxene sometimes tends to elongate and occasionally becomes subhedral.

The pyroxenes of two ophimottled lavas from the Kilmarie Valley were examined in detail in order to determine their optical properties. The results, together with the calculated compositions in terms of Ca-Fe-Mg molecules are tabulated below.

Spec. No.	Type	$n\alpha$	$n\beta$	$n\gamma$	2V(+)	Composition
23.	Ophimottled, titaniferous.	1.696	1.700	1.721	53°	$Ca_{43}Mg_{34}Fe_{24}$
14.	Ophimottled, titaniferous.	1.698	1.703	1.724	51°	$Ca_{40}Mg_{33}Fe_{27}$

Olivine.

Olivine is now represented by pseudomorphs consisting of chlorite, bowlingite, ore and talc, in various combinations. These indicate that olivine was originally to be found in most lavas as 0.1 to 0.2 mm.

granules scattered in the groundmass. More rarely an isolated phenocryst is seen (Spec. 24) or there is a continuous gradation from small groundmass grains to 1 mm. phenocrysts (Spec. 18).

Ore.

In many lavas ore forms a few per cent of the rock bulk, building grains ranging from 0.2 to 0.5 mm. across which sometimes partly enclose feldspars but end sharply against pyroxene. This ore evidently crystallized relatively late. It is not uncommon, however, for ore to take a more prominent part, and there are indications that an iron and titanium rich late-stage solution was active at the end of the magmatic phase. The mode of one ore-rich lava (Spec. 452) has already been quoted, and the building of rodded grains by part of the opaque constituents of this rock probably signifies the presence of ilmenite. More remarkable is the 25% ore content of a flow from Beinn Leacach. This ore is largely disseminated as subhedral grains, but there are also a number of larger individuals up to 1 mm. across, several of which can be seen replacing olivine in progressive stages.

Accessories.

A brown hornblende is commonly accessory in these lavas. It is found in the interstitial areas and forms grains up to 0.3mm. across. In one rock (Spec. 14) it amounts to over half of one per cent of the bulk, but usually it is much scarcer. Since it occurs in similar, but fresher, rocks in north Skye it is probably a late magmatic mineral and not an alteration product.

Apatite in small amount is the only other common accessory mineral.

Pegmatitoid.

Near the stream at the head of the Kilmarie Valley the basal amygdaloid of the topmost flow in the Group is exposed in a small feature. This rock is noteworthy in that a late magmatic "pegmatitoid" phase lines the walls of some of the pipe vesicles and completely fills others.

The pegmatitoid consists marginally of inwardly-growing, half-millimetre plagioclase laths, short prisms and granules of titanaugite (av. 0.3 mm.), and ore (0.25 mm.). The original composition of the plagioclase is difficult to determine, since albitization is extensive. The centres of the vesicles are filled by anhedral alkali feldspar, at least part of which is albite, pierced by acicular titaniferous ores and needles of apatite, some of which are as much as 2 mm. long. Granular sphene is common in some of the vesicles, and brown hornblende is also occasionally present. In contrast to the relatively coarse grain of the pegmatitoid the groundmass basalt is considerably chilled, with the granular clinopyroxene averaging only 0.1 mm. in diameter.

Similar pegmatitoids have been described by the authors of the Mull Memoir (1924; Chapters VII and X) and by Walker in Antrim (1960). In Mull the late-stage material is found in veins, vesicles, and patches. Outside the "Limit of Pneumatolysis" the pegmatitoids contain analcitic centres amd the marginal plagioclases are partly analcitized. The presence of albite in the centres of the Strathaird example is almost certainly due to replacement during the regional alteration. M'Lintock (1915) refers to vesicle linings of albite pierced by titanaugite in the Ben More lavas, which are within the Mull alteration aureole.

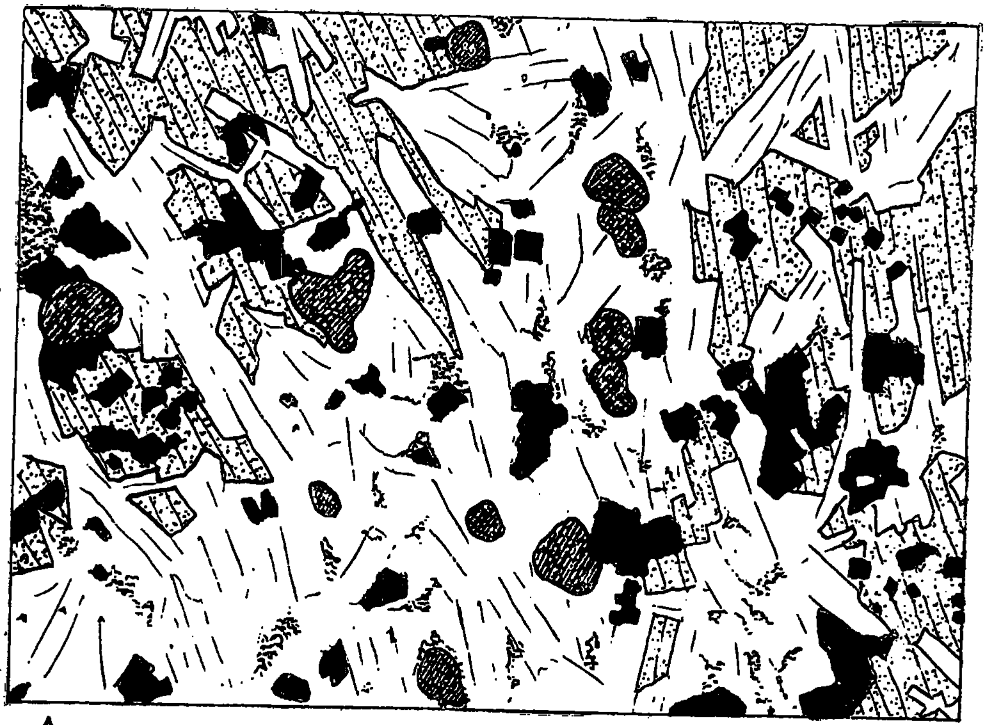
Trachybasalt (see Plate I3)

Separating the upper and lower divisions of the ophimottled lavas is an horizon of trachybasalt up to 30 feet thick. On An Carnach the flow is fine-grained, with granular pyroxenes, and flow-orientated feldspar which appears in slice to have a composition close to the oligoclase-andesine boundary. There are also a few micro-phenocrysts of more basic feldspar. The flow thins eastward and ends as a chilled tongue south

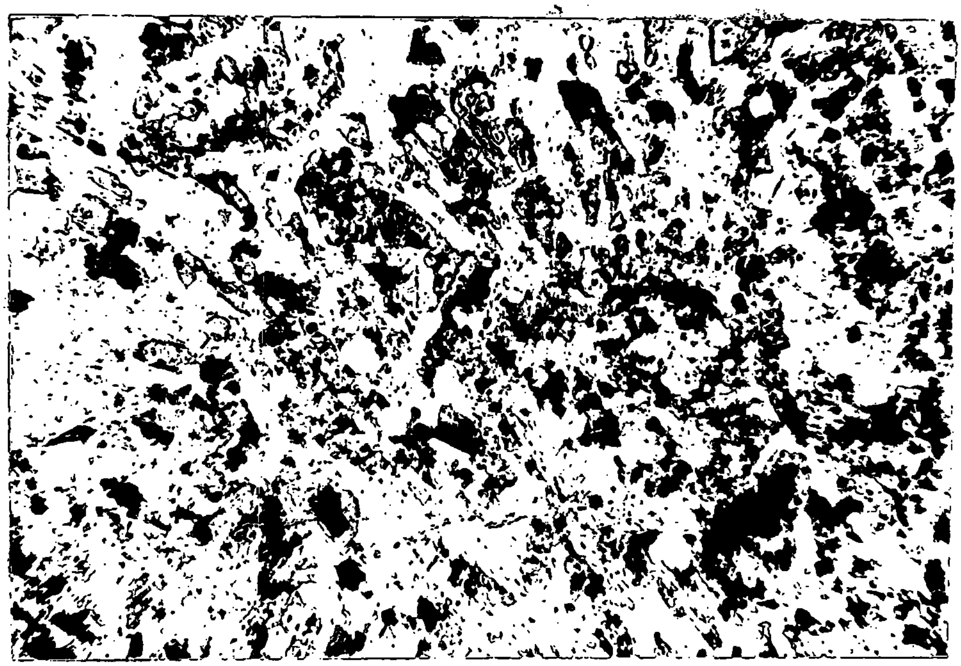
PLATE I3 (opposite.) Microsections: Trachybasalts.

A. (Spec. I7) ×I50. Trachybasalt, An Stac. Contains flow-orientated laths of andesine, sub-ophitic clinopyroxene, granules of altered olivine, abundant ore, and chlorite.

B. (Spec. 30) ×I50. Finer in grain than Spec. I7, and with granular pyroxene.



A.



B.

Constituents	Volume Percentages	
	Spec. 30	Spec. 17
	Trachybasalt, An Carnach	Trachybasalt, An Stac
Plagioclase	59.5	59.4
Clinopyroxene	31.7	22.5
Olivine	?	6.4
Ore	8.8	11.7
	100.0	100.0

Specimen 30 is dark grey, fine grained, and possesses a marked platy jointing. In thin section it is seen to be feldspathic, the jointing following from the well developed flow orientation of the laths. The latter average 0.3 mm. in length, and their extinction angles indicate a composition around the oligoclase-andesine boundary. Rare porphyritic feldspars up to 1 mm. long are rounded off by corrosion, and consist of andesine, now partly albitized. Fine grained clinopyroxene is scattered throughout in the form of 0.1 mm., subhedral prisms and granules. Olivine is either absent or represented by small chloritic patches. Ore is abundant in fine euhedral grains, and flecks of reddish hornblende are also to be seen.

The slice contains several angular areas in which the ore and clinopyroxene are of considerably finer grain than in the body of the rock. They are thought to be fragments resulting from the autobrecciation of an early chilled crust. If this is so, most of the feldspar crystallized before the main phase of pyroxene separation commenced. A slice of the chilled tongue from south of An Carnach summit (Spec. 31) has a similar texture to that of the fragmentary material mentioned above, yet this rock encloses fragments of still finer grain in which oligoclase laths are set in a largely cryptocrystalline groundmass, with fine pyroxene and ore barely visible.

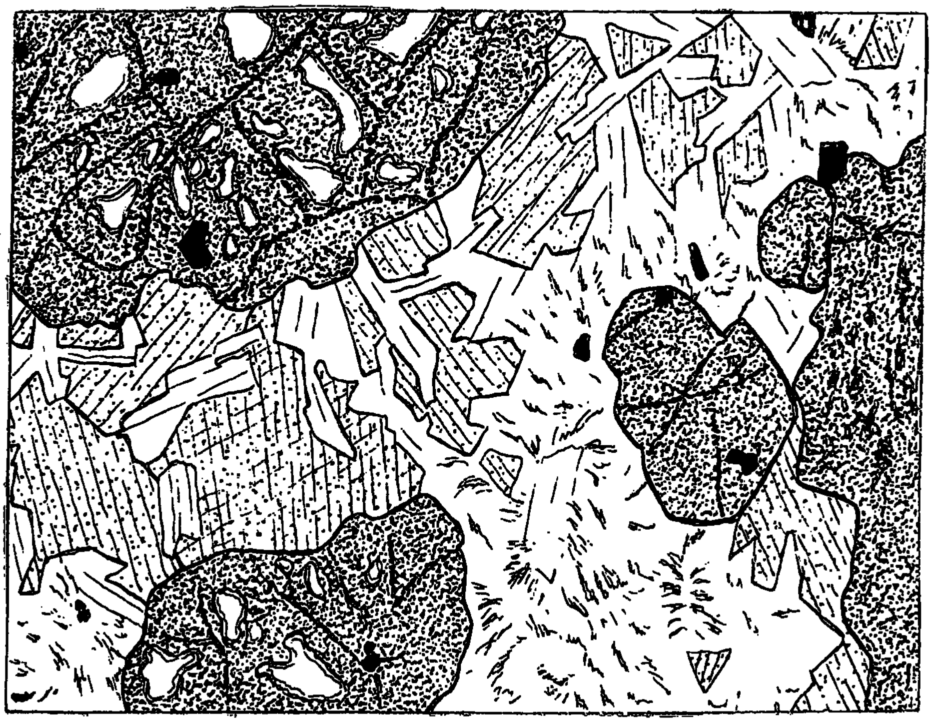
Granular sphene is scattered throughout the groundmass of both the above specimens, and is also occasionally found in the amygdales. Most of the latter are small, rounded, and filled with chlorite and calcite.

A hand specimen of the flow on An Stac (17) looks very similar to the An Carnach rock. A section shows it to consist of 0.4 mm. andesine laths, moderately well flow-orientated, together with partly ophitic clinopyroxene, abundant ore, and sparse pseudomorphs after olivine. The feldspars average An40, though normally zoned to oligoclase externally. A few of the larger laths are labradoritic. Several rounded and albitized feldspars are also present and are rich in secondary inclusions of ore, chlorite, and a little brown hornblende and pyroxene. One of these individuals is bordered by a reaction rim of mixed green and brown hornblendes in 0.2 mm. grains. Flecks of brown hornblende are also seen in the groundmass. The moderately ophitic pyroxenes are in some cases elongated up to a length of 1 mm., but the average size is nearer 0.5 mm.. The optical properties are as follows:-

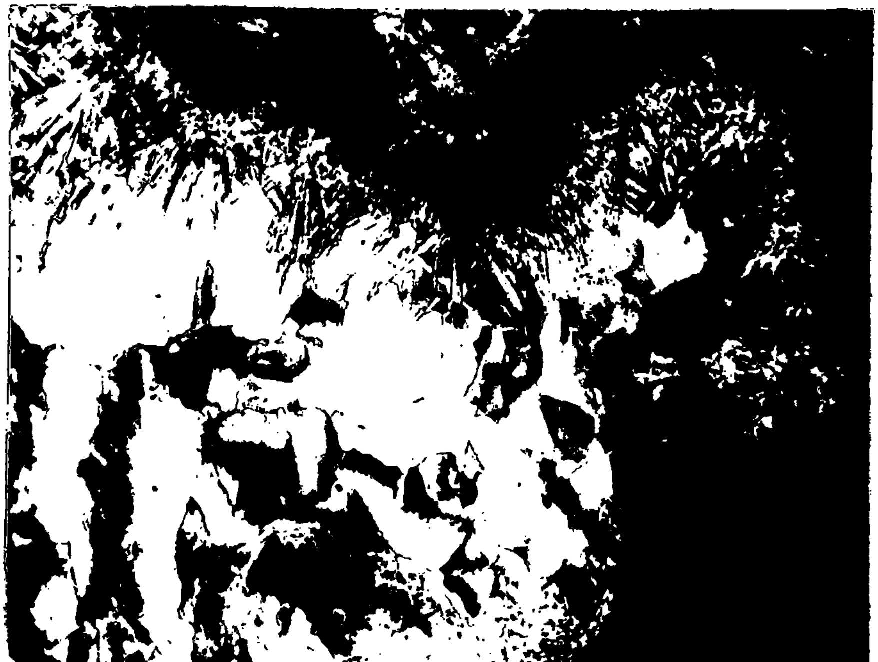
Spec. No.	Type	$n\alpha$	$n\beta$	$n\gamma$	2V(+)	Composition
17.	Moderately ophitic, titaniferous	1.698	1.703	1.724	54°	$Ca_{43}Mg_{31}Fe_{26}$

The olivine pseudomorphs (0.2 mm.) are of chlorite and secondary ore. Both subhedral and euhedral ore grains occur, and are sometimes enclosed by pyroxene. Accessories include fine needles of apatite and numerous minute granules of sphene.

Picritic Basalt Group (see Plate I4) These lavas are best exposed on the summit ridges of An Carnach and at the foot of the eastern face of An Stac. The Group consists of only three flows; a thin picrite at the base is followed by a highly amygdaloidal olivine basalt, which in turn is topped by an olivine-rich basalt with similar features to the picrite.



A.



B.

Modes.

The modal percentages of the primary constituents in the three flows as developed on An Carnach are given below.

Constituents	Volume Percentages		
	Spec. 25 (picrite)	Spec. 26 (olivine basalt)	Spec. 27 (Olivine-rich basalt)
Plagioclase	34.0	55.3	41.7
Clinopyroxene	13.9	26.8	19.2
Olivine	50.6	14.7	35.4
Ore	1.5	3.2	3.7
	100.0	100.0	100.0

Textures.

Olivine builds phenocrysts up to 3 mm. long in the olivine-rich lavas, while plagioclase and intersertal or sub-ophitic clinopyroxene form the groundmass, the latter tending to wrap round the olivines.

The textures of the middle flow are akin to those found in the Basal Lavas, though with a second generation of olivine in the groundmass.

Plagioclase.

In the olivine-rich flows the plagioclase forms rather stout laths between 0.5 and 0.6 mm. in length, and these are partly enclosed by the pyroxene. Continuous normal zoning is usually present, with a mean composition ranging from An62 to An64. The feldspar of the picrite has been largely altered to a pale green flaky material which may be a clay mineral.

In the middle flow the laths are shorter and slimmer and are often albitized, sometimes with a chloritic core.

Clinopyroxene.

The pyroxene of the picritic flows is almost colourless, and forms both intersertal grains of 0.5mm. granularity and more ophitic grains reaching 1 to 2mm. The pyroxene of the middle flow is finer (0.2 mm.), and has the purple tint of titanaugite.

The optical properties of two clinopyroxenes from this Group were determined; the results are given below.

Spec.No.	Type	$n\alpha$	$n\beta$	$n\gamma$	2V(+)	Composition
25.	Sub-ophitic, from picrite	1.692	1.696	1.717	$52\frac{1}{2}^{\circ}$	Ca43Mg37Fe20
26.	Intersertal, from olivine basalt.	1.699	1.703	1.725	53°	Ca42Mg32Fe26

Olivine.

The olivine of the picrite and the olivine-rich basalt builds euhedral, nearly equant grains up to

3 mm. long, with an average length of 1 mm.. They are sometimes corroded. Small cores of fresh olivine still remain in the An Carnach lavas, a feature unique among the unmetamorphosed basalts of Strathaird.

The olivine phenocrysts of the middle flow are very similar to those in the picrite, but there is also a second generation of groundmass grains averaging 0.25 mm. in length.

Ore.

Primary ore is sparse in the picrite and is there found chiefly as 0.1 mm. euhedra enclosed in the olivine, though a few rods of ilmenite are present in the groundmass. Ore is more abundant in the upper flow as subhedral to intersertal grains, and this is also true of the olivine basalt, in which a few ilmenite rods also occur.

Accessories.

Apatite is the only common accessory.

Amygdaloids and alteration.

In the two olivine-rich flows sparse amygdales are found throughout, and are filled by chlorite, a little albite, and a dusty brown clay mineral. The latter grows as fibrous sheaves, white in reflected light. It is nearly isotropic, and the refractive index exceeds that of balsam. An X-ray powder photograph (kindly taken by Mr. R. Phillips) exhibits a well marked 7 angstrom line, while the other spacings suggest that the mineral is a member of the kaolinite group.

The middle lava of the Group is very rich in vesicles, hardly any part of the rock containing less than five per cent, and this increases to fifty per cent in the richer streaks. The most important minerals filling the vesicles are chlorite, albite, epidote, and prehnite, and the commonest arrangement consists of chlorite with rosettes of epidote deriving from it. The largest amygdale in a slice from An Carnach (Spec. 26) is 5 mm. across and consists marginally of euhedral prisms of epidote and a few squat prisms of dusty albite resting on a thin wall lining of chlorite. The centre is filled by feathery prehnite and a small amount of late anhedral epidote. The optical properties of the marginal epidote are as follows:-

prisms length slow; moderately pleochroic, with α green $>$ γ colourless; 2V small, sign positive; $n\alpha$ 1.696, $n\gamma$ 1.707; slightly anomalous blue interference colour of the 1st. order.

These properties are indicative of zoisite, though this mineral usually lacks pleochroism (Winchell, 1951). The later, central anhedra are of epidote in the strict sense, with pleochroism γ green-yellow $>$ α pale yellow; $n\alpha$ 1.726; bright second and third order colours. Marginal zoisites are common in other vesicles, and central fillings may be of albite or epidote, the latter being the later formed. In one slice (Spec. 215) from An Stac the albite exhibits a sheaving structure marginally and is matted within, perhaps indicating a textural inheritance from zeolites.

The evidence from the vesicles has been interpreted as providing the depositional-replacement sequence below:-

chlorite ------------------------------ epidote

(Zeolite ?) ---------- albite

Zoisite ------

-- prehnite --

Chlorite and some albitization are found in the groundmass of these lavas, but pyroxene usually remains fresh. Olivine, as always, is represented by a large variety of alteration products, including chlorite, bowlingite, talc, small spindles of carbonate (?), ore, cross-fibre serpentine, and sometimes iddingsite along the cracks.

Upper Lava Group (see Plate I5) The eastern face of An Stac presents a well exposed sequence of this Group. A summary of the external appearances and microscopic textures of the flows there seen is given below:-

Flow	Megascopic	Microscopic Texture
10.	Dark grey; weathering reddish brown and pimply.	Sparsely feldspar-olivine-phyric; ophimottled groundmass.
9.	Dark grey; brown weathering.	Sparsely feldspar-olivine-phyric; intersertal to sub-ophitic pyroxene.
8.	Dark grey; fine grained.	Sparsely feldspar-olivine-phyric; intersertal pyroxene.
7.	Blue grey; medium grained.	Sparsely feldspar-olivine-phyric; intersertal to sub-ophitic. pyroxene.
6.	Blue grey; fine grained.	Non-porphyritic; ophimottled groundmass.
5.	Dark blue; medium grained.	Feldspar-olivine-phyric; ophimottled.
4.	Blue grey; coarse grained.	Olivine-phyric; intersertal pyroxene.
3.	Dark blue; medium grained.	Feldspar-olivine-phyric; ophimottled.
2.	Blue grey; fine grained.	Feldspar-phyric; ophitic pyroxene.
1.	Dark grey; coarse grained.	Sparsely olivine-phyric; ophitic pyroxene.

Several of these flows possess features recalling those of the basal Lavas, while others are not unlike me_mbers of the Ophimottled Basalt Group except in

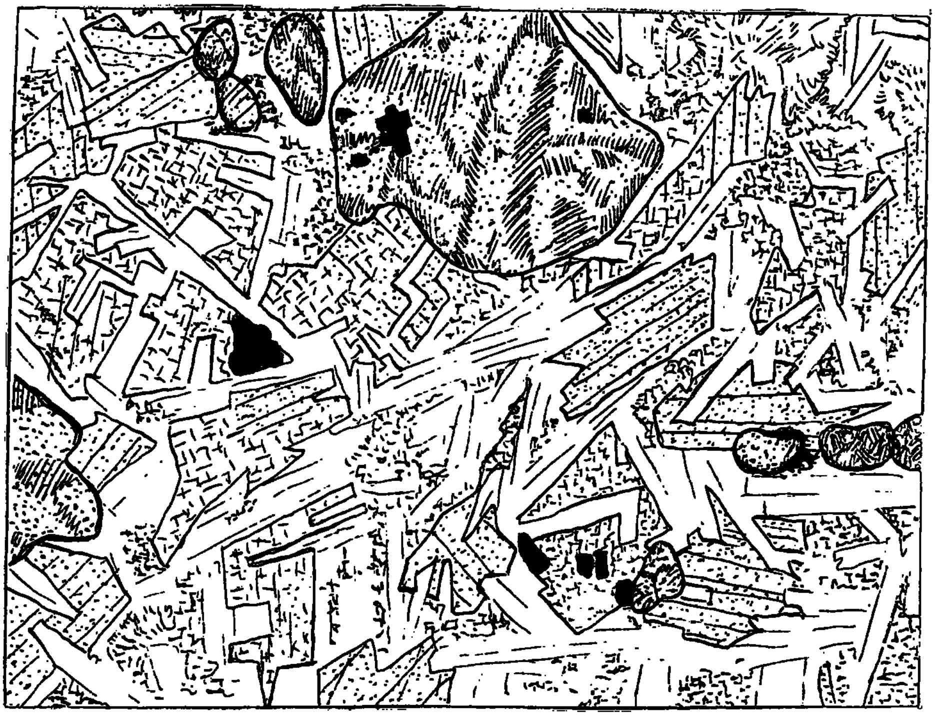


PLATE I5. Microsection: Upper Lava Group. (Spec.300) × I00. Olivine-phyric basalt, An Stac. Olivine occurs in two generations, and is completely altered to chlorite and ore. Clinopyroxene is intersertal to plag--ioclase, and has been partly altered to chlorite.

containing porphyritic feldspars and olivines.

Modes.

The seven modes quoted below attempt to cover most of the variations found in the Group. The first four are from the An Stac sequence and represent the most common types. The three below are more exceptional rocks and are taken from the Slat Bheinn sequence.

Constituents	Volume Percentages			
	Spec. 298	Spec. 299	Spec. 304	Spec. 306
Plagioclase	51.3	44.8	48.8	45.6
Clinopyroxene	29.8	34.6	25.6	32.3
Olivine	12.6	17.3	21.2	19.1
Ore	6.3	3.3	4.4	3.0
	100.0	100.0	100.0	100.0

	Spec. 103	Spec. 111	Spec. 102
Plagioclase	52.3	41.1	50.6
Clinopyroxene	28.7	44.2	31.2
Olivine	5.7	9.3	14.1
Ore	13.3	5.4	4.1
	100.0	100.0	100.0

Spec. 298 - Flow 2. An Stac. Feldspar-phyric, ophitic.

Spec. 299 - Flow 3. An Stac. Feldspar-olivine phyric; ophimottled.

Spec. 304 - Flow 8, An Stac.	Olivine-phyric; intersertal pyroxene.
Spec. 306 - Flow 10, An Stac.	Feldspar-olivine-phyric; ophimottled.
Spec. 103 - Slat Bheinn.	Sparsely feldspar-olivine-phyric; granular pyroxene.
Spec. 111 - Slat Bheinn.	Non-porphyritic basalt rich in sub-ophitic pyroxene.
Spec. 102 - Slat Bheinn.	Coarse, non-porphyritic; sub-ophitic pyroxene.

Plagioclase.

Phenocrysts of feldspar occur in about two-thirds of the specimens examined, and are most common in those lavas which possess ophitic pyroxene in the groundmass. They form thick tablets up to 6 mm. long which align themselves with any flow orientation which may be present. In one lava (Spec. 22) they occupy as much as fifteen per cent of the rock bulk, and there are all gradation from this down to rocks containing only a few, isolated phenocrysts. In Specimen 109 rounded olivines are embedded in the large feldspars in the manner found in troctolitic gabbros.

The feldspar phenocrysts vary in composition from basic labradorite (An68) to acid bytownite. Slight zoning, sometimes oscillatory, is common. Though usually euhedral, cracking and corrosion is a common fe_ature, and in one case (Spec. 306) it was noted that adjacent to the corrosion channels the composition had been altered to medium labradorite. Penetrating albitization has attacked some of these lavas, and in one of the Slat Bheinn rocks (Spec. 109)* several stages in the alteration of phenocrysts can be observed in the slice, starting with albitization along cracks and ending with a fine grained mosaic of albite interspersed with granular epidote.

The groundmass laths are of labradoritic composition and vary in average length between 0.2 mm. in the ophimottled lavas to 0.5 mm. in those with intersertal textures. Flow orientation is well marked in the former.

Clinopyroxene.

The pyroxenes of the ophimottled type of lava are very similar to those present in the Ophimottled Basalt Group. They average 1 to 2 mm. across and are almost colourless. Titaniferous purple tints are more common in lavas in which the pyroxene is intersertal or granular. The grain size decreases to a minimum of c. 0.3 mm. in the latter.

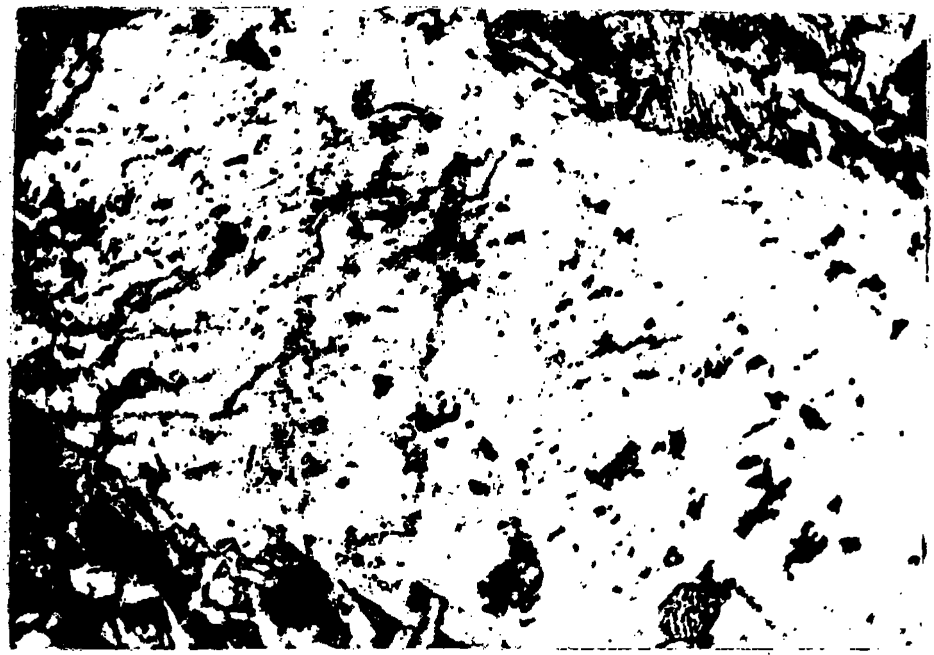
The optical prope_rties of two pyroxenes from the Group have been determined and are as follows:-

*Plate I6.

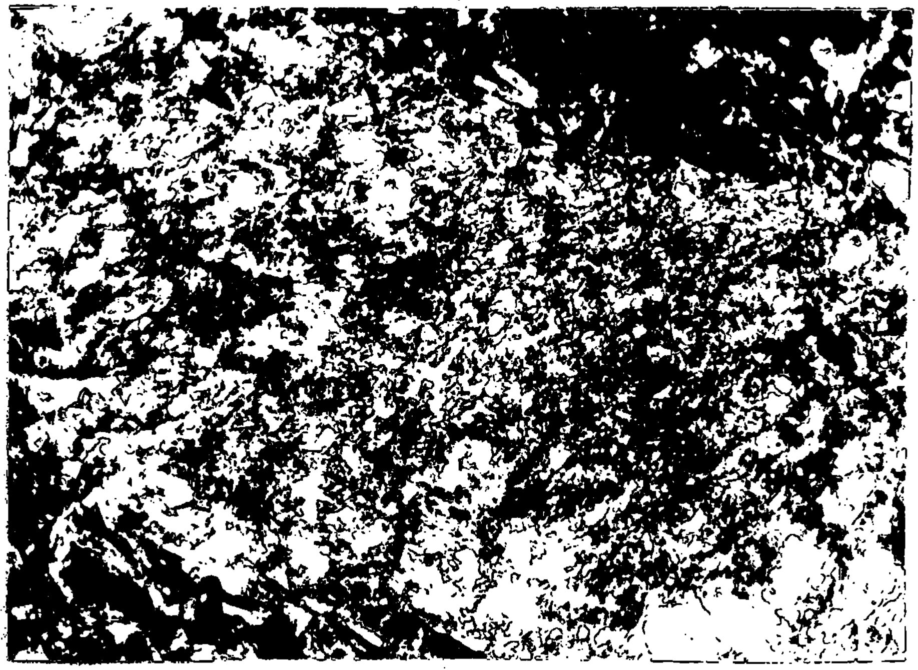
PLATE I6 (opposite.) Microsection: An albitized plagioclase phenocryst.

(Spec.I09) $\times$ I00. A phenocryst from a flow in the Upper Lava Group, Slat Bheinn. The original basic plagioclase has been completely replaced by an aggregate of albite, interspersed with granules of epidote.

A. ordinary light ; B. crossed nicols.



A.



B.

Spec.	Type	nα	nβ	nγ	2V(+)	Composition
300.	Intersertal to sub-ophitic.	1.692	1.697	1.717	53.½°	Ca44Mg36Fe20
304.	Intersertal to sub-ophitic.	1.693	1.698	1.718	53.½°	Ca44Mg35Fe21

Olivine.

Phenocrysts of olivine are present in about eighty per cent of the rocks examined, and in two thirds of these they are accompanying more abundant phenocrysts of plagioclase. The maximum size reached by the larger olivines is about 3 mm., and there is always a second generation in the groundmass around 0.2 mm. in average size. The usual alteration product is a fine grained chlorite. Talc and ore form the pseudomorphs in one lava (Spec. 306).

Ore.

Though usually found in the groundmass as late-crystallized anhedra, ore occasionally attains a porphyritic status, as in Specimen 113, in which several 1 mm. ores are partly resorbed along rounded, irregular boundaries; and in Specimen 107, where the 0.75 mm. ores often enclose laths of plagioclase.

Accessories.

Apatite and infrequent minor amounts of brown hornblende were noted as accessory.

Amygdales.

In Coire Ballaig the lowest flow of the Group (Specs. 307, 308) contains interesting amygdales up to five or six centimetres across largely filled by silica; chalcedonic marginally and coarsely crystalline quartz within. Some of the quartz is shot through by long needles of green amphibole and was therefore probably deposited at the same time as the Gabbro metamorphism. In other vesicles prismatic epidote and coarse calcite are associated with the quartz, together with earlier spherules of chlorite partly or wholly replaced by the quartz, leaving remnental outlines defined by inclusions. Adjacent to the amygdales the groundmass is chloritized and silicified.

Fine grained chlorite is the most common amygdular mineral elsewhere, with grains of epidote and needles of amphibole developed at its expense. Less abundant are albite, calcite, and quartz. In Specimen 103 the chloritic vesicles are pierced by basal plates of calcite anchored to the walls and sometimes intersecting in a loosely reticulate structure.

(v) Notes on the Alteration of the Lavas.

The case for the existence of a zone of low temperature alteration surrounding the central Skye plutonic massif was argued earlier in this chapter. For comparative purposes several lavas were collected from the Portree area of north Skye. Slices show that the olivine they contain is largely in a fresh state, though not infrequently altered along cracks to bowlingite or iddingsite. In a few exceptional cases complete decomposition to a bowlingite or chlorite has occured. The groundmass of these lavas often shows a sparse, patchy development of chlorite, while the vesicles are filled by a large variety of zeolites, with chlorite in some of the smaller amygdales.

None of the specimens examined, however, showed alteration on the scale which is common in the Strathaird lavas, a fact which was expected from the very much fresher appearance of the hand specimens.

<u>Alteration of Olivine</u>. In contrast to specimens from North Skye, the Strathaird lavas contain partially fresh olivine in only two observed cases, both from the Picritic Basalt Group, in which the mineral is present in unusually coarse grains. Elsewhere olivine is completely decomposed to one or more of the following products, arranged in approximate order of abundance:-

chlorite - bowlingite - iron ore - talc - serpentine -

carbonate - iddingsite - epidote - fibrous green amphibole - quartz.

The last three in the above list replace chlorite, and so are secondary alterations.

There is some suggestion of a zonal distribution in that bowlingite, talc and carbonate are most common in the outer parts of the aureole (Ben Meabost and An Carnach), where they accompany chlorite and ore. On Slat Bheinn and An Stac, chlorite, with or without ore, is usually the only product, and it is, moreover a variety with very low birefringence, unlike that found in pseudomorphs in the outer areas.

Iron ore is most abundant in association with talc, since the latter contains no iron itself. There is of course also a variation dependant on the original composition of the olivine. A few ophimottled lavas contain olivines which are largely or wholly replaced by iron ore, which is clearly in excess of the amount present in the primary mineral, indicating an introduction of iron from late-stage magmatic solutions.

Iddingsite has a sparse and erratic distribution and appears to be a relatively early alteration. Since it is commonly present in otherwise unaltered lavas from north Skye, its formation is probably unconnected with the main pneumatolytic period.

Bowlingite is a very common product of olivine decomposition, and the optical properties of two typical specimens are appended below:-

a. Spec. 43 (Basal Lava Group, Ben Meabost) Olivine pseudomorphs are pale green in thin section, but dark red in hand specimen. Most of the pseudomorphing material is a bowlingite, with well developed lamellar structure parallel to the slow ray direction, which in turn is orientated parallel with the fast direction in the original olivine. Thin linings of iron ore mark the cracks, and are followed inward by a layer of cross-fibre serpentine. Occasional small cores of talc are also seen.

The pleochroism of the bowlingite is moderately strong, with α pale yellow = β greenish yellow = γ pale green. 2V is small (c. 5 degrees), and the optic sign negative, while the refractive indices are as follows:-

$$n\alpha\ 1.541\ ;n\beta\ 1.565\ ;n\gamma\ 1.569$$

$$\gamma-\alpha\ = 0.028$$

b. Spec. 75 (Basal Lava Group, An Carnach) Bowlingite after olivine, with similar associate minerals and structure to the above.

Pleochroism moderately strong, with α pale yellow $<$ β greenish yellow $<$ γ pale green. Refractive indices:-

$n\alpha$ 1.557 ; $n\beta$ 1.580 ; $n\gamma$ 1.585

$\gamma - \alpha = 0.028$

Ot_her bowlingites show some variation in the strength and colour of pleochroism. In Spec. 25 the optic axial angle is very small and the pleochroism formula is α honey yellow $>$ γ pale straw yellow.

Well developed talc pseudomorphs are exemplified by Spec. 28 (Basal Lava Group, Kilmarie Valley), in which the mineral is accompanied by a thin envelope of chlorite and a little ore. The optical properties are as follows:-

colourless ; 2V small (c. 10 degrees), sign negative ; flakes length slow ; $n\alpha$ 1.549 ; $n\beta$ 1.590 ; $n\gamma$ 1.590 ; $\gamma - \alpha = 0.041$.

Alteration of other constituents. The percentage of chlorite in the groundmass of the Strathaird lavas greatly exceeds that commonly found in those from north Skye, and is frequently accompanied, especially in the inner part of the alteration zone, by albitization of the feldspars. The permeability of the rock to the alteration solutions has been the chief factor in controlling these processes, so that while the amygdaloids are always considerably decomposed, the massive centres vary in their state of alteration. Where an ophimottled texture is present the interstitial areas proved relatively easy of access, while the ophitic areas remain almost free of chlorite and albitization. Nevertheless, small olivines that are sometimes enmeshed by the pyroxenes have not thereby escaped decomposition. In an even-textured lava the chlorite is typically erratic in distribution, some pyroxenes being strongly attacked, while others remain unaffected.

Feldspar, where not albitized, usually remains fresh, but in one rock (Spec. 41) it is converted to a clay mineral. Scattered grains of epidote and calcite in feldspar, the alteration of titaniferous ores to leucoxene, and the development round them of granular sphene, are also referred to the period of alteration.

Vesicular minerals. The processes of alteration also had a considerable influence on the constitution of the amygdular assemblages. It has already been remarked that, as in Mull, zeolites are virtually absent from the lavas within the alteration zone, their place being taken by albite.

The approximate order of abundance of vesicular minerals is given below:-

chlorite - albite - epidote - prehnite - calcite - quartz - zoisite - fibrous green amphibole - clay minerals - hematite.

Chlorite may be rosetted, vermicular, feathery, or in bladed sheaves or hemispherically layered structures. Two or more generations are often to be detected, differing in structure and optical properties. Chlorite which was introduced with quartz is usually distinctive in forming small radiating masses of very low, anomalous blue, birefringence.

Albite is usually dusty, anhedral, and with only poorly developed twinning. It may have replaced original zeolites, though there is little direct evidence. The structure of marginal sheaves sometimes seen is suggestive of zeolite mode of occurrence, and in a lava from An Carnach (Spec. 73) remnants of laumontite (?) are present in an amygdale otherwise of albite.

The commonest epidote is the yellow-green variety which is so abundant in the middle flow of the Picritic Basalt Group. It is usually anhedral and post-dates albite. In many cases it replaces chlorite. Zoisite is much rarer than common epidote and is found as marginal euhedra of early date.

Prehnite commonly fills in spaces between albite, or zoisite and albite.

Quartz was one of the latest minerals to be introduced, and in certain cases can be seen to replace chlorite.

Needles of green amphibole developed from chlorite in response to the higher temperatures near to the thermal aureole. It has an erratic distribution in the inner parts of the zone.

Veins of epidote, albite, and quartz have been noted cutting the lavas in a few instances but they are apparently less common than in the analogous rocks of Mull (Bailey and others, 1924).

Date of the alteration. In vesicles from Coire Ballaig (Specs. 307, 308; see reference in previous section) it seems that amygdular quartz was there introduced contemperaneously with the metamorphism induced by the Cuillin Gabbro. There is no direct evidence that the other minerals of the amygdular paragenesis, and those formed by alteration in the body of the rock, were originated during the same period. Indeed there is reason for thinking that chloritization took place over a much wider time span. Nevertheless suitable conditions for alteration would inevitably arise after the emplacement of the Gabbro;

conditions of elevated temperatures and circulating hydrous solutions; and it is difficult to resist the conclusion that this was the major period of lava decomposition.

Probably both pneumatolytic and hydrothermal processes were involved. Albite, for instance, is usually considered a stable phase under conditions of pneumatolysis (c. 400° to 600° C.) while the carbonate and talc may be hydrothermal (c. 100° to 400°C.). The temperature would vary in time and space, and it is significant that albitization is much more common in the inner parts of the zone (Slat Bheinn and An Stac). Continuing further towards the Gabbro contact there is no real break in continuity between the zone of alteration and the outer parts of the thermal aureole, the presence of new amphibole after pyroxene being taken as the arbitrary outer limit of the latter. There is however a sharper transition as the contact rocks themselves are approached. This marks off that part of the thermal aureole that owes its features almost entirely to high temperature, from the outer portion in which circulating solutions were also a decisive factor.

Chlorites. Chlorite plays the most important role among the secondary minerals in the zone of alteration,

TABLE 2

OPTICAL PROPERTIES OF CHLORITES

(n.b. optic sign in all specimens is negative).

Spec.	Occurrence	Pleochroism	nγ	Biref.
8.	Lowest flow, An Carnach. Two types of chlorite present;-			
	a. Yellow-green rosettes in discrete vesicles.	moderate γ green-yellow $>\beta>\alpha$ pale yellow	1.622	0.006 normal
	b. Later introduced, associated with quartz.	weak	1.630	0.002 anomalous blue.
17.	Andesine basalt, Slat Bheinn. Coarse folia, radiating from the walls of vesicles.	strong; γ grass green $>\beta>\alpha$ pale straw yellow.	1.632	0.003 anomalous purple.
19.	Picritic Basalt Group, An Stac. Folia, tending to vermicular structure; in amygdales with later albite and epidote.	moderate; γ medium green $>\beta>\alpha$ pale straw.	1.610	0.004 normal
70.	Basal Lava Group, An Carnach. Pale green chlorite in quartz amygdales.	weak	1.630	0.003 anomalous
71.	Basal Lava Group, An Carnach. Vermicular masses in dendritic amygdales.	strong; γ turquoise $>\beta>\alpha$ pale yellow-green.	1.597	0.008 normal
72.	Basal Lava Group, An Carnach. Pale brownish green folia, coarse at vesicle margins.	weak	1.630	0.008 normal

TABLE 2

(cont.)

Spec.	Occurrence	Pleochroism	$n\gamma$	Biref.
76.	Basal Lava Group, An Carnach. Rosettes, vermicular masses, and fine-grained spherulitic accretions.	moderate	1.615	0.010 normal
91.	Ophimottled Group, Slat Bheinn. Coarse amygdular sheaves (cf. Spec. 17).	strong; γ brown green > β yellow green > α pale yellow	1.632	0.014 normal
102.	Upper Basalt Group, Slat Bheinn. Vesicles filled by large feathery aggregates.	strong; γ green > β pale yellow-green > α pale straw.	1.597	0.005 normal
109.	Upper Basalt Group, Slat Bheinn. Fine aggregates of folia in vesicles.	moderate; γ pale green > β pale green > α colourless.	1.622	0.002 anomalous blues and purples
Chlorites after Olivine				
8.	Basal Lava Group, An Carnach. Cross-fibre veinlets in serpentinous pseudomorphs.	moderate	1.627	0.006 normal
71.	Basal Lava Group, An Carnach. Fine, yellow-green aggregates.	v. weak	1.583	0.005
87.	Basal Lava Group, Slat Bheinn. Coarse folia aggregates.	moderate; γ pale yellow-green > β v. pale yellow > α colourless.	1.610	0.003 anomalous

TABLE 2

(cont.)

Spec.	Occurrence	Pleochroism	nγ	Biref.
96.	Ophimottled Group, Slat Bheinn. Coarse folia parallel to c-axis of original olivine.	strong; γ pale green > β > α pale yellow-green.	1.619	0.005 normal

<u>Chlorites in the Coire Uaigneich Granophyres.</u>

Spec.	Occurrence	Pleochroism	nγ	Biref.
50.	Bright green folia pseudomorphing prismatic ferromag. mineral, probably orthopyroxene.	strong γ grass green > β green > α green-yellow	1.637	0.005 normal
81.	Chlorite after biotite.	strong; γ bluish green > β > α pale straw.	1.630	0.003 anomalous browns, purples.

and the optical properties of a number of specimens were determined. Table 2 gives a summary of the results.

M.H. Hey (1954) classifies chlorites into an unoxidised series (orthochlorites) and an oxidised series (leptochlorites), the latter containing more than four per cent ferric oxide. These groups are subdivided into species on the basis of total FeO, Si, and the ratio Fe : Fe + Mg in the unit cell (recalculated to an anhydrous basis of fourteen oxygens). Hey derives simple, straight-line variations of optical properties in the orthochlorites, but in the leptochlorites the properties vary with the degree of oxidation of the iron.

Four of the Strathaird chlorites, the optical properties of which are given in Table 2, were analysed for iron content. The results are as follows:-

Spec. No.	17.	91.	96.	109.
FeO %	13.7	11.5	7.4	14.0
Fe_2O_3%	11.8	11.3	11.8	9.6

All four are thus considerably oxidised and can be classified as leptochlorites, though not more exactly defined without extended analysis. It would seem reasonable to suppose that leptochlorites rather than orthochlorites are stable products under alteration conditions of this type.

The table of optical properties shows that the chlorites with the highest indices are those associated with free silica in the amygdales of the basalts and those which are found in the granophyres (where free silica is again available). This is unexpected, since Hey's diagrams show that increase in refraction is chiefly a function of rising iron and falling silica.

Anomalous birefringence is present in about one third of the chlorites examined, and appears when the birefringence is less than c. 0.004. According to Winchell (1951. Part II, p. 382), such anomalies are probably due to an isotropic state for part of the spectrum and an anisotropic condition for another part.

(vi) Chemistry of the Lavas.

Four lavas from Strathaird were chemically analysed by the author. One is a typical member of the Basal Lavas; the second is of the characteristic ophitic basalt from the Ophimottled Basalt Group; the third and fourth are of picrite and trachybasalt, representing the most extreme variations found in the area.

The specimens to be analysed were taken from the freshest flows available and from parts of the rock lacking amygdales, but it was nevertheless impossible not to include some groundmass alteration products as well as the pseudomorphous representatives of the olivine. Since most of these secondary minerals are hydrous the combined water contents in the analyses are inevitably high. It is hoped that otherwise the alterations were sufficiently isochemical to not radically affect the results.

Olivine basalts. The oxide percentage figures obtained for the specimens from the Basal Lava Group and the Ophimottled Basalt Group are set out in the first part Table 3, together with comparative data which include four analysis averages from various sources and three other analyses of Skye lavas. The modes and norms for the Strathaird rocks are given in the seeond part of Table 3.

TABLE 3.

CHEMICAL ANALYSES OF TWO OLIVINE BASALTS WITH COMPARISONS.

	Strathaird		Comparisons		
	42	23	1.	2.	3.
SiO_2	46.0	48.1	45.78	46.77	45.5
TiO_2	1.65	1.65	2.63	3.00	3.1
Al_2O_3	13.7	15.1	14.64	14.65	15.0
Fe_2O_3	3.6	2.0	3.16	3.71	3.5
FeO	7.1	8.2	8.73	7.94	10.4
MnO	0.27	0.21	0.20	0.15	0.2
MgO	10.2	6.3	9.39	6.82	8.1
CaO	11.1	11.6	10.74	12.42	8.7
Na_2O	2.4	2.7	2.63	2.59	2.6
K_2O	0.5	0.6	0.93	1.07	0.4
$H_2O(+)$	2.8	3.9	0.76	0.51	1.7
$H_2O(-)$	1.1	0.2			1.0
P_2O_5	0.05	0.05	0.39	0.37	0.3
Total	100.5	100.6	99.98	100.00	100.5

Comparisons

	4.	5.	6.	7.
SiO_2	46.61	45.6	46.38	45.68
TiO_2	1.81	1.1	1.04	1.65
Al_2O_3	15.22	14.6	16.77	14.66
Fe_2O_3	3.49	2.8	3.22	2.88
FeO	7.71	8.2	8.03	9.67
MnO	0.13	0.18	0.24	0.22
MgO	8.66	11.5	8.83	9.82
CaO	10.08	10.0	10.68	9.37
Na_2O	2.43	2.0	1.94	2.14
K_2O	0.67	0.25	0.10	0.19
$H_2O(+)$	2.07	2.2	2.46	3.43
$H_2O(-)$	1.10	1.4	0.37	0.36
P_2O_5	0.10	0.22	0.08	0.07
Total	100.08	100.05	100.14	100.14

TABLE 3
(cont.)

Origin of analyses:-

Strathaird.

42. - Massive centre of Flow 1, Basal Lava Group, Ben Meabost. Micro-phyric olivine; with granular and intersertal pyroxenes in the groundmass. Analyst D. C. Almond.

23. - Massive centre of lowest flow, Ophimottled Basalt Group, Kilmarie River. Non-porphyritic, olivine basalt with highly developed ophitic pyroxene. Analyst D. C. Almond.

1. - Average of 96 analyses of 'normal alkaline basalts', Green and Poldervaart (1955).

2. - Average of 22 analyses of alkaline basalts without olivine, Green and Poldervaart (1955).

3. - Average of 3 analyses of basalts of plateau type, Mull (Mull Memoir, 1924, p. 15).

4. - Analysis by W. Pollard of olivine basalt lava, Drynoch, Skye (Harker, 1904, p. 31).

5. - Average (by present author) of 5 analyses of olivine basalts, Antrim, by Patterson (1952, p. 286, nos. 1, 3-6).

6. - Analysis of fine-grained ophitic olivine basalt, Strollamus, Skye, by King (1953, p. 365, no. 1).

7. - Analysis of ophitic olivine basalt, Strollamus, Skye, by King (1953, p. 365, no. 2).

TABLE 3
(cont.)

MODES, NORMS, AND RATIOS

Normative Minerals		42.		23.	
Orthoclase			2.8		3.3
Albite			20.4		23.1
Anorthite			25.0		27.2
Diopside	Wo.	12.5	23.9	12.8	25.0
	En.	9.0		7.2	
	Fs.	2.4		5.0	
Hypersthene	En.	1.3	1.7		-
	Fs.	0.4			
Olivine	Fo.	10.9	14.2	6.0	10.7
	Fa.	3.3		4.7	
Magnetite			5.3		3.0
Ilmenite			3.2		6.2
Apatite			0.1		0.3
Water			3.9		4.1

MODES

Constituents	Weight Percentages 42.	23.
Plagioclase	38.3	39.4
Clinopyroxene	33.6	35.9
Olivine	16.4	17.1
Ore	11.7	7.6

Normative Compositions and Ratios.

	42.	23.
Plagioclase	Ab45 An55	Ab46 An54
Diopside	Wo52 En38 Fs10	Wo51 En29 Fs20
Hypersthene	En78 Fs22	--
Olivine	Fo77 Fa23	Fo56 Fa46
$\frac{FeO+Fe_2O_3 x100}{MgO+FeO+Fe_2O_3}$	51	62
$\frac{Fe_2O_3 x100}{FeO+Fe_2O_3}$	34	20
$\frac{K_2O x 100}{Na_2O+K_2O}$	21	18

The analysis of the flow from the Basal Lava Group (42) is comparable with those for many mildly alkaline olivine basalts. It matches fairly closely the average for the Mull plateau type (cf. 3) and Green and Poldervaart's (1955) average of 96 "normal alkaline basalts" from various parts of the world (cf. 1). The chief departure is that the Strathaird rock is somewhat low in alumina. It is also noteworthy that the low content of K_2O in this rock is in keeping with other olivine basalts from the Scoto-Irish Tertiary Province (cf. 3,4,5, and 6). Titania and P_2O_5 are also in small amount, a feature also shared with other analyses from this Province (cf. 4. 5. and 6). Combined water is, as expected, somewhat high.

The analysis of the lava from the Strathaird Ophi-mottled Basalt Group (23) shows, in comparison to the Basal Lava flow, increases in silica and alumina percentages and a marked drop in magnesia. This corresponds in the norm (Table 3) to a change towards more iron-rich olivine and pyroxene while the normative composition of the feldspar remains almost the same. Thus while the modes of the two rocks indicate that the same minerals are present in approximately equal amounts in both rocks, the textural differences (see section (iv) of this chapter) reflect the slight difference in chemistry. The texture of 23 and similar ophimottled lavas suggests that olivine and pyroxene crystallized rather later in respect to plagioclase than was the case in the Basal Lavas. This might well be the result of the higher iron content of the dark minerals delaying their final crystallization to a lower temperature.

A reduced magnesia content and slightly raised silica percentage are also characteristic of Green and Poldervaart's average for 22 olivine-free basalts (cf. 2).

Picrite. The oxide percentages, mode, and norm of the picrite analysis are set out in Table 4. The chemical composition of this rock is similar to that of other picrites, including that found as an olivine-rich accumulation in the Shiant Isles main sill (Walker, 1930) and a picrite basalt from Antrim (Patterson, 1955). The characteristic features are low silica, calcium, and alkalis, with very high magnesia. Combined water is also high in the Strathaird rock due mainly to the alteration of the olivine to hydrous minerals.

Trachybasalt. Details of an analysis of the trachybasalt flow on An Carnach are given in Table 5, where it is compared with a mugearite from north Skye (Harker,

TABLE 4

CHEMICAL ANALYSIS OF THE STRATHAIRD PICRITE LAVA, WITH COMPARISONS.

	25.	1.	2.
SiO_2	41.5	41.9	41.69
TiO_2	0.85	0.8	0.52
Al_2O_3	8.2	9.1	8.89
Fe_2O_3	3.8	0.6	2.76
FeO	7.0	12.9	8.56
MnO	0.24	0.4	0.19
MgO	24.0	26.7	23.53
CaO	6.5	5.8	6.69
Na_2O	1.1	1.4	1.04
K_2O	0.5	0.2	0.14
$H_2O(+)$	6.0		4.00
$H_2O(-)$	0.6		1.78
P_2O_5	0.14	0.2	0.13
Total	100.4	100.0	99.92

25. - Picrite lava from An Carnach, Strathaird, Skye. Analyst D. C. Almond.

1. - Picrite from Shiant Isles, main sill. Walker (1930)

2. - Picrite basalt, Antrim. Patterson (1955, p.162)

Mode, Norm, and Ratios of the Strathaird Picrite.

Orthoclase		2.8
Albite		9.4
Anorthite		15.9
Diopside	Wo. 6.5; En. 5.0; Fs. 0.8	12.3
Hypersthene	En3.1; Fs. 0.5	3.6
Olivine	Fo. 36.1; Fa. 5.7	41.8
Magnetite		5.6
Ilmenite		1.7
Apatite		0.3
Water		6.6

Mode (Wt.%)

Plagioclase	29.3
Clinopyroxene	14.9
Olivine	53.2
Ore	2.6

Normative Compositions & Ratios

Plagioclase	Ab37 An63
Diopside	Wo53 En41 Fs6
Hypersthene	En87 Fs13
Olivine	Fo86 Fa14

$$\frac{FeO+Fe_2O_3 \times 100}{MgO+FeO+Fe_2O_3}=31 \qquad \frac{Fe_2O_3 \times 100}{FeO+Fe_2O_3}=35$$

TABLE 5

CHEMICAL ANALYSIS OF THE STRATHAIRD TRACHYBASALT,

WITH COMPARISONS.

	30.	1.	2.
SiO_2	49.5	49.24	50.70
TiO_2	1.50	1.84	1.89
Al_2O_3	13.2	15.85	14.60
Fe_2O_3	7.0	6.09	5.23
FeO	5.1	7.18	7.68
MnO	0.19	0.29	0.42
MgO	8.4	3.02	4.15
CaO	7.6	5.26	7.20
Na_2O	3.6	5.21	3.71
K_2O	1.4	2.10	1.33
$H_2O(+)$	3.2	1.61	1.15
$H_2O(-)$	0.2	1.08	2.08
P_2O_5	0.04	1.47	0.49
Total	100.9	100.23	100.63

30. - Trachybasalt from An Carnach, Strathaird, Skye. Analyst D. C. Almond.

1. - Mugearite from near Portree, Skye. Harker (1909, p. 263).

2. - Trachybasalt from Rhum. Analyst E. G. Radley (quoted in Harker, 1908, p. 130). This rock also contains 0.08 BaO.

Mode, Norm, and Ratios of the Strathaird Trachybasalt.

Orthoclase		8.3
Albite		30.4
Anorthite		15.6
Diopside	Wo. 9.2 En. 7.2 Fs. 0.9	17.3
Hypersthene	En. 8.6 Fs. 1.2	9.8
Olivine	Fo. 219 Fa. 0.4	3.3
Magnetite		10.4
Ilmenite		2.9
Apatite		0.1

Mode (Wt. %)	
Plagioclase	51.1
Clinopyroxene	34.3
Olivine	?
Ore	14.6

Normative Compositions & Ratios

Plagioclase	Ab_{66} An_{34}
Diopside	Wo_{53} En_{42} Fs_5
Hypersthene	En_{88} Fs_{12}
Olivine	Fo_{88} Fa_{12}

$$\frac{FeO+Fe_2O_3 \times 100}{MgO+FeO+Fe_2O_3} = 59 \qquad \frac{Fe_2O_3 \times 100}{FeO+Fe_2O_3} = 58$$

$$\frac{K_2O \times 100}{Na_2O + K_2O} = 39$$

1904) and a trachybasalt from the Tertiary lavas of Rhum (Tomkeieff, 1942). It will be seen that the Strathaird lava contains higher magnesia and lime, and lower alkalies, than the north Skye mugearite. It compares more closely with the Rhum trachybasalt, though magnesia is still relatively high. The highly oxidised state of the iron in the Strathaird rock is probably a consequence of low temperature alteration.

(vii) Petrogenesis of the lavas.

The small volume of lavas available for study in Strathaird, the lack of an extended sequence, and the state of alteration of the rocks make it unwise, or impossible, to attempt broad conclusions concerning the petrogenesis of the lavas, especially in the face of the great volume of literature already devoted to the origin of similar lava suites.

The whole of the Basal Lava Group and about one third of the Upper Lava Group are typical olivine basalts of "plateau type" (Mull authors, 1924) or in other words "alkaline olivine basalts" (Tilley, 1950). The ophimottled lavas vary slightly, and the picritic and trachybasaltic flow more markedly, from this possible parent type. Interpreted in the classical manner (Mull authors, 1924; Kennedy, 1938; Tilley, 1950) the mugearite falls on the "alkaline trend" from olivine basalt through mugearite to trachyte, with the ophimottled lavas as a possible intermediate stage, while the picrite represents an olivine accumulative phase. Since picritic and trachybasaltic flows occur within one hundred feet of each other in the Strathaird sequence it is tempting to speculate whether they represent the accumulative and residual portions of the same differention cycle, starting with the Basal Lavas. The Upper Lava Group, might represent another and more extended cycle in which either differentiation was less extreme, or in which strong differentiates were extruded but have now been removed by erosion.

Wager (1956) has defined fractionation stages for various types of lava association on the basis of the iron ratio $\left(\frac{Fe'' + Mn}{Fe'' + Mn + Mg}\right)$ and the albite ratio $\left(\frac{\text{normative molecular albite}}{\text{normative molecular albite + anorthite}}\right)$. Since these two ratios are generally thought to increase simultaneously as fractionation proceeds, the graphical plotting of one against other provides a means of defining successive stages of fractionation. Part of one of Wager's graphs is reproduced on Plate I7 , and shows how lavas of the Hebridean alkaline magma series can be divided into early, middle, and late stage fractionated basalts, with trachytes, the most extreme products

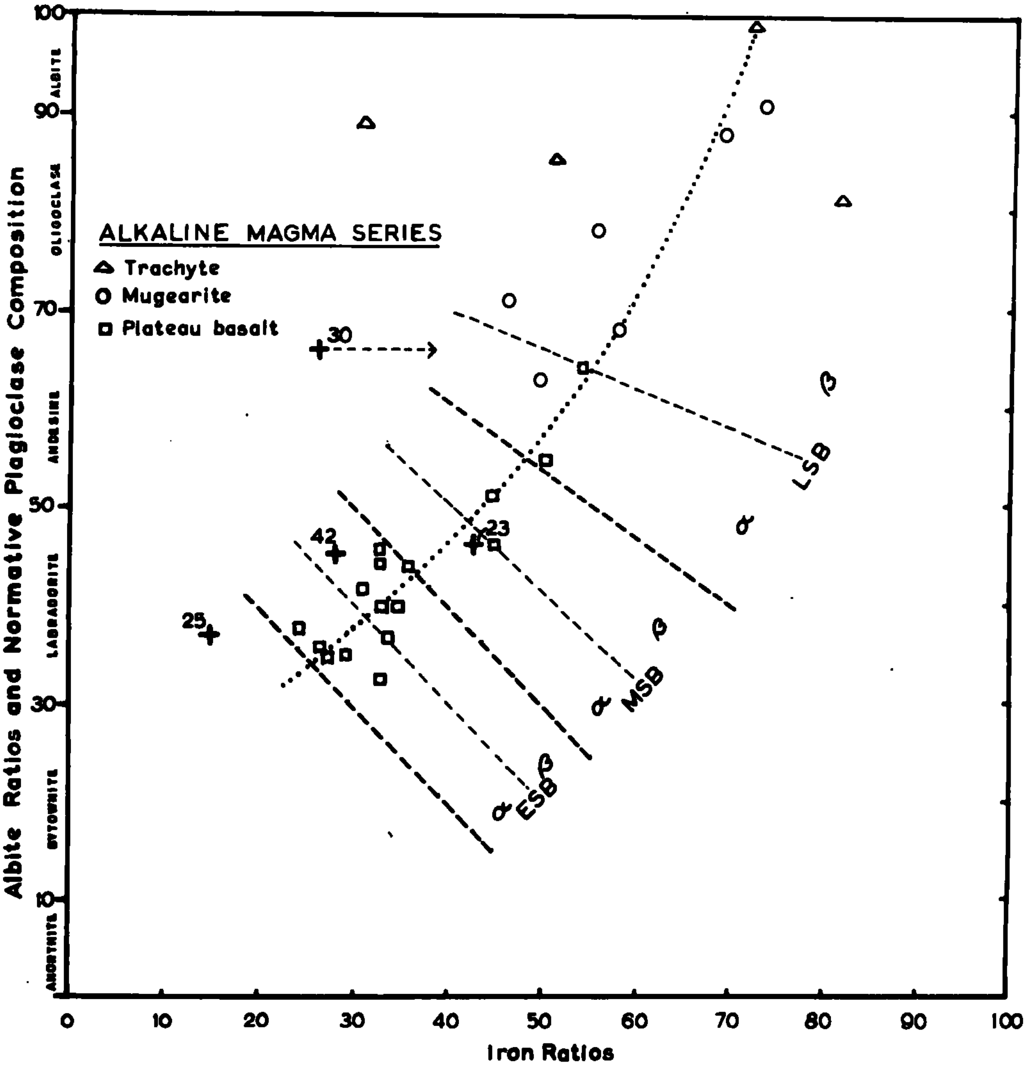


PLATE 17. FRACTIONATION STAGES OF THE HEBRIDEAN ALKALINE MAGMA SERIES, AFTER WAGER (1956)

Wager distinguishes "early stage basalts"(ESB),"middle stage basalts"(MSB), and "late stage basalts", each subdivided into α and β sub-stages.

Superimposed on Wager's diagram are the plots of the four Strathaird lavas quoted in Tables 3, 4, and 5; +25, picrite; +42, basal lava group; +23, ophimottled basalt; +30, trachybasalt. The iron of the trachybasalt appears to have undergone post-consolidation oxidation, and the probable position of its plot for its original state is indicated by an arrow.

of the process, situated at the top of the diagram. Plots for the four analysed lavas from Strathaird are also shown on this graph. Although these rocks are not ideally suited to this purpose, owing to interference with the original ferrous/ferric ratio during low temperature alteration, it can be seen that the lava from near the base of the Strathaird sequence can be defined as an early stage basalt. The ophimottled lava is a middle stage basalt, and the trachybasalt as a late stage basalt. This supports the impression, gained from petrographic examination, that the ophimottled lavas occupy a position of intermediate fractionation between the olivine-phyric basalt of Basal Lava Group type, and the more alkaline, olivine-poor trachybasalts. The picrite is an accumulative phase characterised by a high content of magnesian olivine, and so lies well to the left of the diagram; it is a by-product of the fractionation process. The dotted line on Plate 7 represents the liquid line of descent along which fractionation proceeds by the removal of accumulative phases.

CHAPTER VII

LAVAS - METAMORPHISM

(i) Introduction

The aureole of thermal metamorphism surrounding the Cuillin Gabbro has an average width of half a mile in Strathaird. Thus the lavas affected are chiefly those which lie in the "inner belt" of outcrops along the Gabbro contact, though the outer part of the aureole also includes a strip of the Slat Bheinn and An Stac lavas on the eastern side of Coire Uaigneich.

Within the aureole two main zones are distinguished. The external appearance of the lavas in the outer and wider zone differs little from those further from the Gabbro, though they are rather more resistant to weathering and are cut by numerous joints sealed by epidote and amphibole. In thin section however they are characterized by the presence of a green, fibrous amphibole which has grown at the expense of primary pyroxene, and this appears to have been the stable mineral under the conditions of metamorphism. It is nevertheless evident that equilibrium was rarely attained, for the distribution and abundance of the amphibole vary erratically. The primary texture of the lavas often remain largely intact.

Approaching nearer to the Gabbro a marked change of appearance takes place in the lavas at distances varying between 100 yards and 400 yards from the contact, and this marks the outer edge of the second zone. The terrace featuring which is characteristic of the unmetamorphosed lava outcrops finally disappears and the indurated lavas form rugged cr ags which from a distance cannot easily be distinguished from those carved out of the adjacent gabbros. In hand specimen these rocks present a finely granulated appearance and their even grey colouration is in contrast with the dark greens and browns of the unmetamorphosed lavas. Thin sections show these rocks to have undergone extensive recrystallization, and the new minerals and textures so produced are typical of rocks formed under the conditions of the pyroxene hornfels facies (Eskola, 1939).

The boundaries of the thermal aureole and its zone are indicated on the sketch map, Plate I8 .

(ii) Petrography of the Amphibole Zone Lavas.

Amphibole outside the main zone. The occurrences of amphibole which are most remote from the Gabbro are those in which the mineral develops at the expense of chlorite in the amygdales. In a specimen from

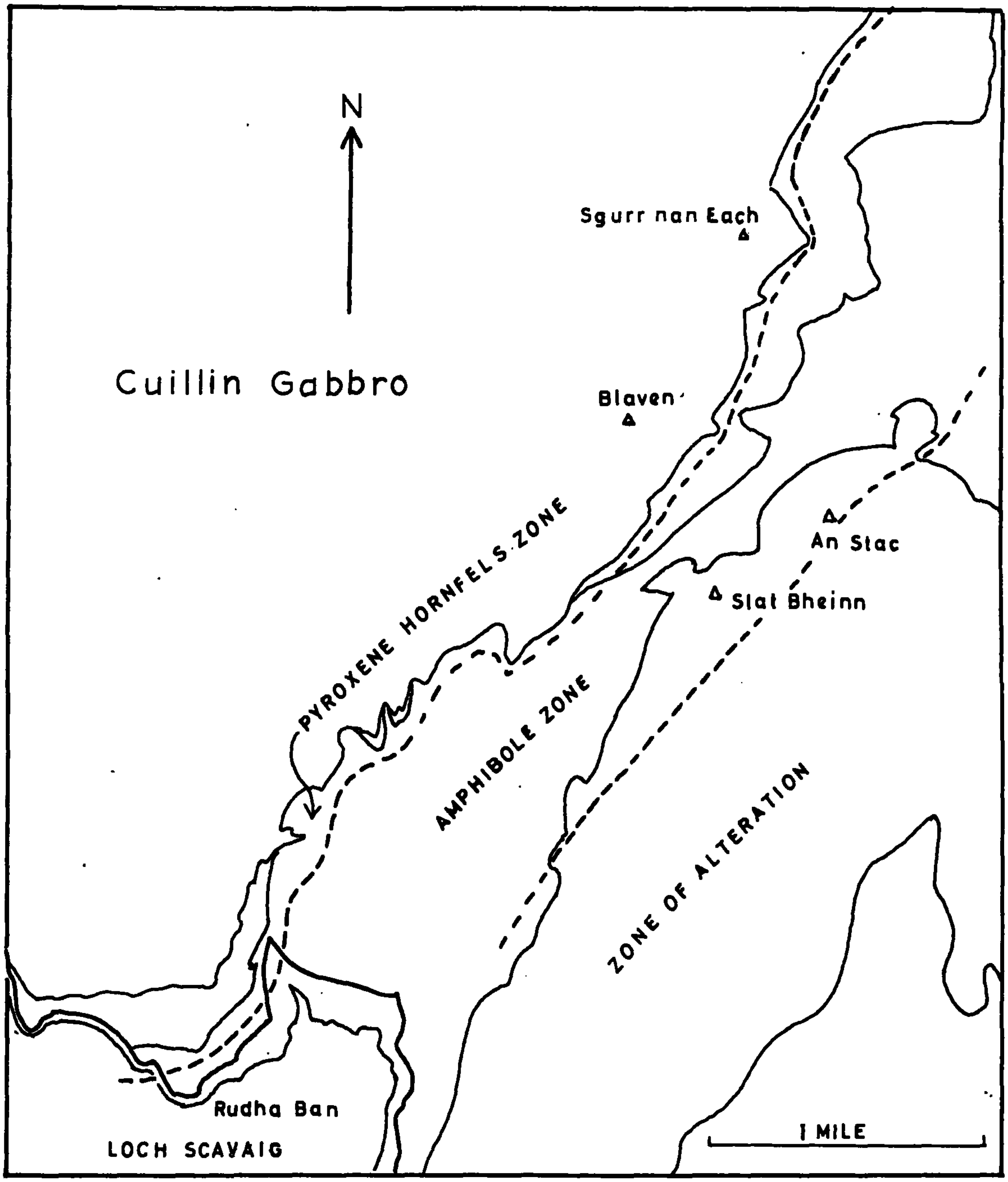


PLATE 18. THE ZONES OF THE CUILLIN GABBRO AUREOLE, AS DEFINED IN THE LAVAS AND EARLY MINOR INTRUSIONS.

LAVA OUTCROPS SHADED GREEN

Coire Ballaig (307), fibres and raggedly-terminated prisms of green amphibole partly or wholly replace chlorite in the vesicles while the groundmass pyroxene is unaffected. The contact of the Gabbro lies one mile to the west.

<u>Early stages of uralitization</u>. Under the microscope a slight fuzzing of the outlines of the groundmass pyroxenes is the first indication of incipient uralitazation. A high magnification reveals the development of minute pleochroic fibres parallel with the slow ray of the host. Other features typical of the zone also develop at this stage. An overall dusty appearance results from advanced albitization of the feldspars and from marginal dissemination of the ore grains. The primary olivine is nearly always pseudomorphed by a fine textured chlorite of very low birefringence, usually accompanied by ore and sometimes by amphibole.

Incipient uralitization is not limited to the outer portions of the zone, for rocks of this type are widely scattered and frequently lie in close proximity to more highly altered lavas.

A specimen (342) from the base of the volcanics in Sgurr nan Each provides an example of the early stage. The lava is of medium grain, with 0.6 mm.

clinopyroxenes ophitically enclosing the 0.25 mm. plagioclases. Sparse olivine pseudomorphs are up to 0.5 mm. across. All the pyroxenes show narrow alteration rims of palely pleochroic amphibole and sometimes larger segments are replaced. The fibre length rarely exceeds 0.2 mm. and is usually much less. Albitization has affected the feldspars in patches and along cracks, and there are many inclusions, the larger grains being identifiable as flakes of amphibole and granules of epidote and calcite. The olivine is represented by a chlorite of anomalous blue interference tints and a little iron ore. Diffusion has occurred at the boundaries of the primary ores and minute sphene granules have been formed there. Intersecting the slice is a narrow vein of amphibole and chlorite.

<u>Advanced uralitization</u> (see Plate 19) As adjustment to metamorphic conditions proceeded the fibrous amphibole ate back into the body of the host pyroxene, reducing the latter to a central kernel and finally replacing it altogether. Many of the stages are often to be seen in a single slice. The end products are dirty greenish rocks containing albite, amphibole, chlorite, and ore. Little remains of the primary texture. This ultimate stage was, however, rarely

A.

B.

attained.

Two specimens from Sgurr nan Each are representative. The first (344) is a coarse lava poor in ferromagnesian constituents. The whole of the latter is now replaced by sheaves of green uralite which occasionally have a brown-tinted core. The almost completely albitized feldspars are turbid with inclusions of calcite, epidote, chlorite and amphibole. In contrast, Specimen 439 is rich in ferromagnesians and the amphibolitization has extensively encroached upon the feldspars, which may imply the removal of felsic constituents to form epidote and albite elsewhere. The amphibole pleochroism is usually weak but gains in strength in the vicinity of amygdales. The latter are occupied by dusty albite anhedra and colourless sub-prismatic epidote. Veins and pockets of epidote are also found in the groundmass and the relatively late emplacement of this mineral is demonstrated by one of these veins feeding an amygdular epidote cluster.

A lava from the east face of Blaven is even more drastically modified. At the locality at which this was collected a broad tongue of gabbro runs out from the main contact and, traversing the hornfels zone, enters the amphibole zone. The adjacent volcanics are reddened, a feature which in slice is seen to be due to the preservation of an original olivine-phyric texture by a pseudomorphing, fine-grained chloritic mineral of reddish-brown tint. No primary texture remains in the groundmass however, which consists of little else but finely fibrous sheaves of uralite. There are a few euhedra of leached brown ore grains, but no indication of the fate of the feldspar. Veins of late amphibole cut both lavas and gabbro. Evidently the intrusive tongue contained insufficient heat to granulitize the adjacent lavas but acted instead as a locus of severe amphibolitization.

<u>Amygdales in the amphibole zone.</u> (see Plate I9) Good exposures of amygdaloidal lavas are to be seen in the bed of Allt Dunaiche, near to the high waterfall below the lip of Coire Uaigneich. Five specimens (245 - 248, and 268) from this locality all show advanced stages of amphibolitization, while their vesicles contain various combinations of albite, epidote, chlorite, amphibole, and calcite. The amphibole situated within or near to the amygdales forms large fibres, poorly terminated prisms, and fibre bundles, and has a notably stronger pleochroism than the groundmass amphibole. Chlorite always exhibits anomalous birefringence colours; blues, purples, and tawny browns; and much of

the epidote and amphibole appears to have been derived from it. Calcite fills up the centres of albite vesicles, and veins of epidote, mixed amphibole and chlorite, and calcite are numerous. One of these rocks (268) has been heavily carbonated, the calcite attacking especially the amphibolitized pyroxenes.

Well developed amygdales are also seen in a specimen (358) from near the top of the lava sequence on the south ridge of Sgurr nan Each. Albite is the chief constituent, together with ore, epidote, chlorite, and green amphibole needles. The latter are, as usual more strongly pleochroic than the amphibole in the groundmass, and there is a clear dependence of this feature upon iron content, for those needles which are nearest to the ore grains possess the deepest colouration. Occasionally there is zoning within the crystals, with the strongest colours externally.

<u>Optical properties of the amphiboles.</u> The main optical properties of seven amphiboles from Strathaird are set out below. The properties often vary within the same rock and the figures in the table refer to most persistent type in each case. The optic sign is negative in all cases.

	Colour	Strength of Pleochroism	$n\alpha$	$n\gamma$	Extinction
1.	Green	very strong	1.661	1.687	23°
2.	Green	moderate	1.642	1.664	18°
3.	Green	weak to strong	1.639 to 1.643	1.659 to 1.664	24°
4.	Green	strong	1.632	1.657	12½°
5.	Green	moderate	1.640	1.654	22°
6.	Green	strong	1.622	1.642	13°
7.	Brown	strong	1.661	1.681	24°

1. (Spec. 114) Aggregates of fibre groups pseudomorphing olivine in a lava outside the amphibole zone. The high indices correspond to strong colouration.
2. (Spec. 245) Fibrous groups replacing groundmass pyroxene in a lava from Allt Dunaiche.
3. (Spec. 246) Prisms and fibres associated with epidote in an amygdale in the amphibole zone, Allt Dunaiche. Variability of colour and index is marked in this setting.
4. (Spec. 275) Coarse fibres of late amphibole altering from clinopyroxene in a quartz-bearing contact gabbro from Sgurr nan Each. Associated with chlorite of low birefringence.

5. (Spec. 276) Late amphibole from vein in pyroxene hornfels, Sgurr nan Each.

6. (Spec. 128) Coarse fibres altered from hypersthene in marginal gabbro, Camasunary. Associated with late vein-amphibole.

7. (Spec. 165) Brown hornblende derived from pyroxene in a hornfels, Camasunary. Probably a product of waning metamorphism.

All the green amphiboles detailed above (1 - 6) can be approximately classified as members of the tremolite-actinolite series. There are no generally accepted divisions within this group at present. Winchell (1951) terms the end members 'tremolite' and 'ferrotremolite' with the formulae $Ca_2Mg_5(OH)_2Si_8O_{22}$ and $Ca_2Fe_5(OH)_2Si_8O_{22}$, and assigns the general formula $Ca_2(Mg,Fe)_5OH_2Si_8O_{22}$ to actinolite. His optical property diagram is based chiefly on points at the magnesia end of the series. Rogers and Kerr (1942) give an optical property range for 'tremolite-actinolite' which corresponds to Winchell's series up to 20% of the ferro-tremolite molecule. Sundius (1946) tentatively suggests that 'tremolite' should refer to the magnesian members of the series up to 15% of the iron-bearing molecule, with a similar range for ferrotremolites at the other end, and actinolite in between. The Strathaird amphiboles correspond in optical properties to members of the series containing between 20 % and 50 % of the iron molecule, and are best termed 'actinolites'. The least ferriferous is that which is an alteration product of hypersthene (6). The extinction angles in several cases are higher than those usually quoted for the series (10° to 20°), probably due to the presence of some alumina substituting for silica.

The brown amphibole (7) is evidently a common hornblende formed under different physical conditions to the above.

<u>The mineralogy of the amphibole zone in relation to the facies classification.</u> The following quotation is from Turner and Verhoogen (1951 p.466) and refers to the distribution of rocks belonging to the greenschist facies:-

"Owing to the extremely low velocity of chemical reaction between crystalline minerals throughout the lower range of metamorphic temperatures, chemical adjustment of a rock to such temperatures seldom proceeds beyond an incipient stage unless under the accelerating influence of synchronous deformation or intense hydrothermal activity. For this reason there is virtually no equivalent of the greenschist facies among the hornfelses of simple contact aureoles ... "

It is certainly true of the Strathaird amphibole zone lavas that they have seldom achieved equilibrium, but it would appear that it was towards a greenschist facies type of mineralogy that the rocks tended, and on occasions attained. It is relevant to compare the mineralogy of these amphibolitized lavas with that of the low-zone greenschists (epidiorites) of the Scottish Highlands described by Wiseman (1934), with which there is a striking resemblance. Comparable epidiorites are found in the chlorite and biotite zones of regional metamorphism; at higher grades the mineralogy is not like that of any Strathaird rocks. The commonest mineral assemblage in the epidiorites is green hornblende - chlorite - epidote - albite; this was also the stable assemblage of the Strathaird lavas. Moreover the optical properties of the amphibole and chlorite are similar in the two areas. The chlorite of the epidiorites is of low birefringence (anomalous browns and violets) except when hornblende is not present, reflecting a similar relation between lavas inside and outside the Strathaird amphibole zone. Wiseman discovered that the refractive indices of the chlorite and hornblende varied sympathetically, probably indicating some sort of regular partition of magnesia and iron. The amphiboles also have properties like those in Strathaird, and one of them was analysed and shown to be a tremolite-actinolite with a small amount of alumina substitution.

It therefore seems that around large basic intrusions, with their correspondingly long cooling periods, the outer parts of the metamorphic aureole may include rocks of greenschist facies type. Equilibrium is, however, only locally attained under these conditions. Moreover, in Strathaird the capricious distribution of uralitization and especially its concentration in the amygdaloidal parts of the lava flows suggests that the chemical reactions included were largely dependent on the circulation of hot, aqueous solutions.

(iii) Field Relations of the Hornfelsed Lavas.

Adjacent to the Cuillin Gabbro the lavas have suffered a high temperature metamorphism which has converted them into hard, fine grained, grey rocks of granular appearance, very different in texture to the amphibolitized lavas. The distribution of the hornfels zone is shown in the sketch map, Plate 18 . This account of the field relations follows the outcrop along the contact of the Gabbro from south-west to north-east.

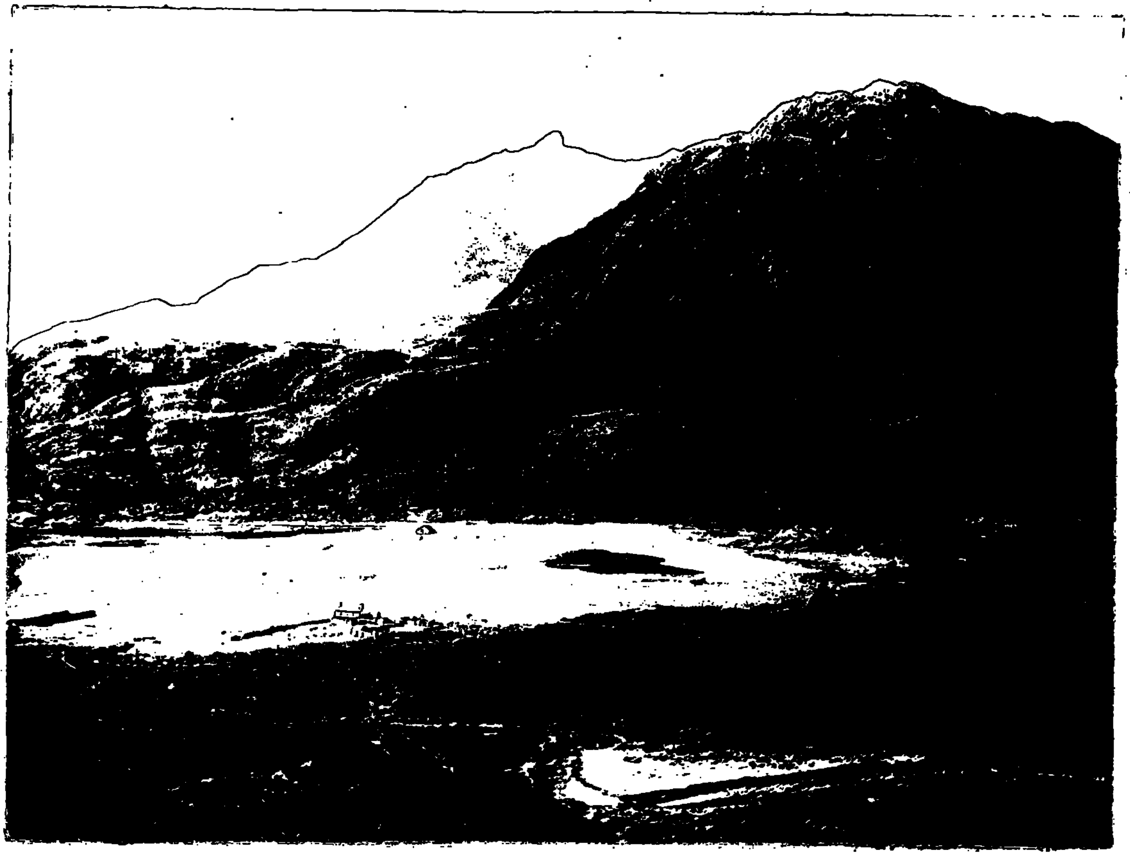
Sgurr na Stri.* A broad outcrop and clean exposures display the hornfels zone to its best advantage on the southern and eastern slopes of Sgurr na Stri. The outcrop extends from Rudha Buidhe on the shore of Loch Scavaig for some fifteen hundred yards eastwards to the Camasunary River. Above Rudha Ban the outcrop reaches its maximum width of four hundred yards, the whole of which is within the hornfels zone.

The lavas rest on Torridonian arkoses, with a narrow and irregular granophyre along the contact. The flows dip to the north-west at about 40°, and are cut off in this direction by the often-irregular junction of the Gabbro.

The lavas are pierced by a number of pre-Gabbro minor intrusions of various shapes which range in composition from peridotites to olivine-free dolerites, and are also cut by straight-coursed post-Gabbro dykes and a few granophyric veins.

Camasunary. In the Camasunary valley exposures of meta-lavas are limited to two small outcrops. The first lies on the eastern bank of the Camasunary River in continuity with the Sgurr na Stri exposures. Some 500 feet north-east of the stream the lavas are cut

*Plate 20.



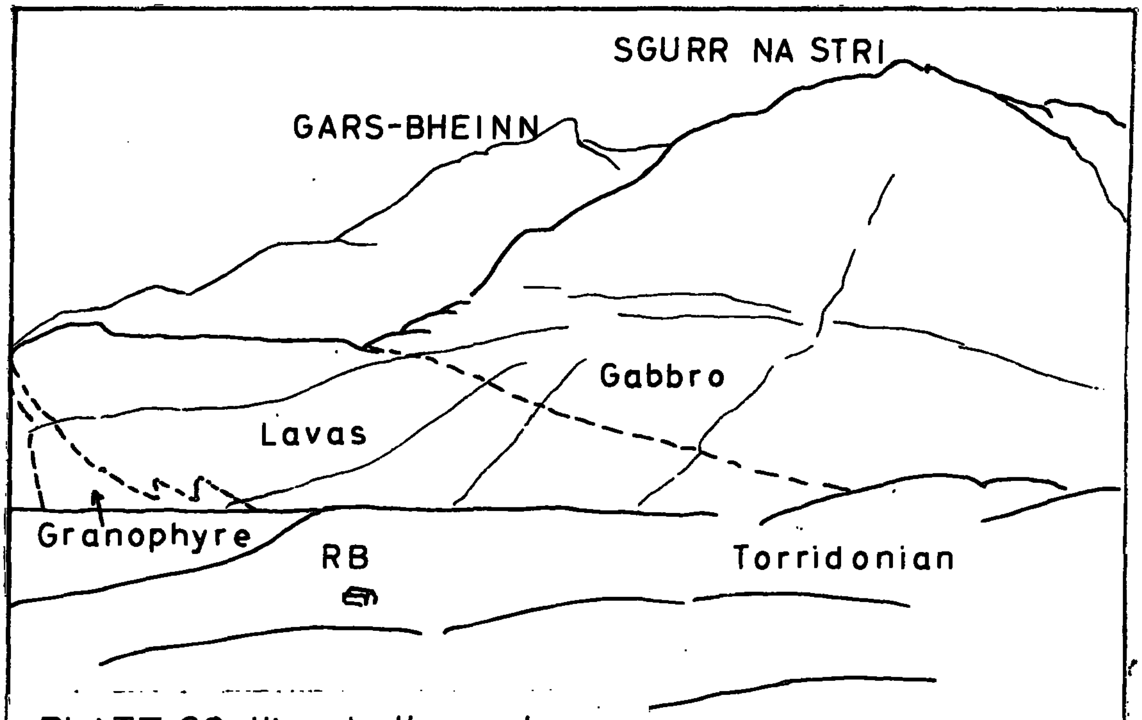


PLATE 20. View to the west from Am Mam.

intervenes, while elsewhere the lavas are seen to rest on Jurassic sediments. On Slat Bheinn the lavas are metamorphosed in the style of the amphibole zone, while on the Blaven side of the col, and some one hundred and fifty yards from the Gabbro contact, the metamorphism is of a transitional character, with the hornfels zone itself beginning at a distance of between one hundred and one hundred and forty yards from the contact. A similar, though variable, width of hornfels continues across the eastern face of Blaven and onto Clach Glas and Sgurr nan Each*, with a narrow transitional zone into the lavas of amphibole zone type, which occupy the rest of the inner belt of outcrops. The exact delineation of the outer margin of the zone is however impossible in the field.

Throughout this stretch the lavas continue to dip inwards towards the Gabbro at angles between 20° and 30°.

(iv) Petrography of the Hornfelsed Lavas.

<u>General discussion.</u> The manner in which a thermally metamorphosed rock of high grade differs from one of lower grade has often been regarded as the result of "progressive metamorphism" in the sense that the higher grade rock has passed through low grade stages

* Plates 2I & 22.

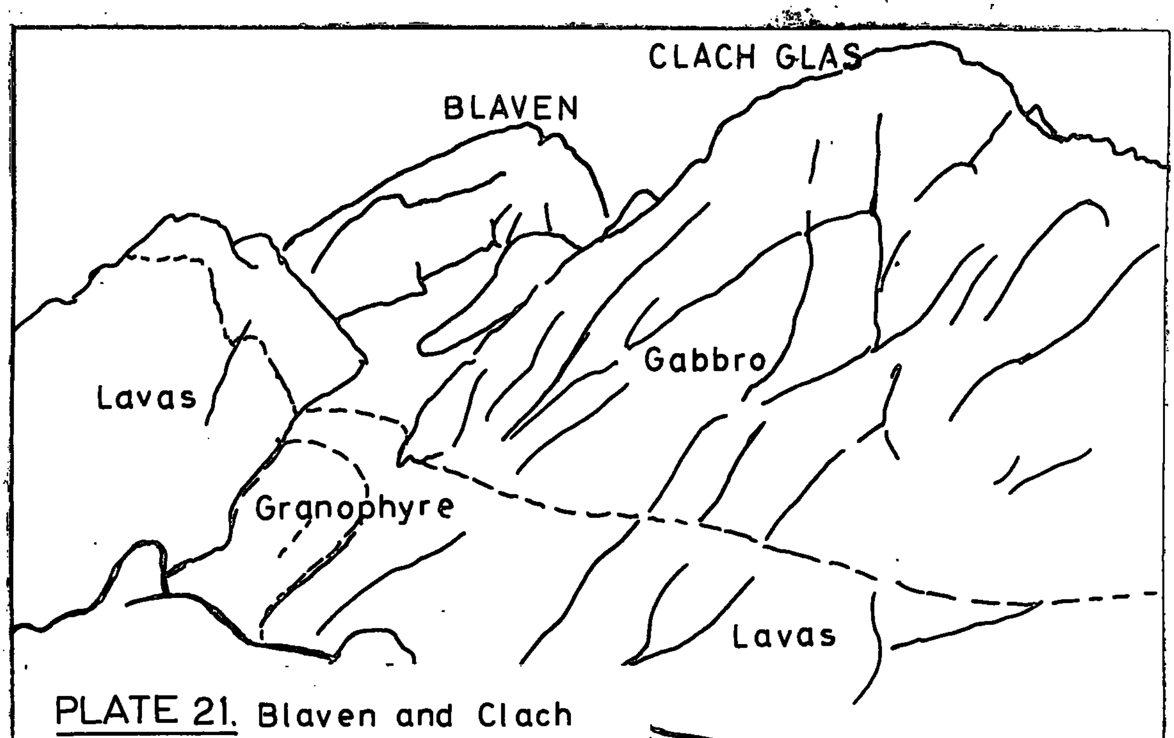


PLATE 21. Blaven and Clach Glas from the south-east spur of Sgurr nan Each.

before attaining its present constitution. The grade finally reached by a rock is therefore thought to depend both on its position in space in relation to the source of heat and on the time that it was subjected to high temperatures. This concept is developed in Harker's book "Metamorphism" (3rd. ed., 1950). To quote:-

"The reconstruction of a rock in metamorphism proceeds with rising temperature, and all the facts go to show that, at least in any advanced stage in the process, adjustment of equilibrium in general keeps pace with the rise of temperature. Minerals formed at an earlier stage are, potentially at least, parties to the reactions which succeed at higher temperatures." (op.cit.,p.30).

"The highest grade of metamorphism in ordinary basic igneous rocks is marked by the total obliteration of all original structures except those of a large order ...... Mineralogically the most notable feature is the reappearance of augite ...... The uralitization effected at an earlier stage is thus reversed ..." (op.cit.,p.110).

The length of time during which high temperatures are maintained is of undeniable importance in aiding thermal reactions. A field demonstration of this fact is the frequent lack of thermal affects in any but the most sensitive rocks (e.g. silecious limestones) bordering quite large basic dykes. However in cases where a field of elevated temperatures has been established by the emplacement of a large body of hot magma, heating of the immediately adjacent country rocks would be relatively rapid and high temperatures long maintained. It would not seem necessary to assume a progressive metamorphism of such rocks without further evidence from within the rocks themselves. In the context of regional metamorphism Read (1949, p.105) has said:-

"... the preservation of original sedimentary textures ... in the higher grade rocks of a so-called progressive series and their obliteration in the low grade rocks ... indicate that the observed series is not one of time; the high grade rocks did not pass through the low grade stage."

The evidence in Strathaird clearly indicates that the relationship of the hornfels zone to the amphibole zone is not a progressive one. The hornfels' textures and mineralogy were impressed directly on unmetamorphosed basalts.

In Strathaird, olivine basalt lavas were locally brought into direct contact with a magma of gabbroic composition. These two phases, the one essentially liquid and the other essentially solid, were of similar chemical composition. In volume the hornfels were a mere skin on the surface of the gabbro magma and must have cooled at much the same rate as the latter. In these circumstances it is not surprising that the mineralogies of the gabbros and hornfels have much in common, though their textures remain distinct. The gabbros underwent primary crystallization, and the slow fall of temperature allowed large mineral grains to grow up round relatively few centres. The basalts already possessed a close-set, multicomponent system of crystallization centres, and these formed the textural basis of the new rocks. It is evidently easier for high temperatures, acting alone, to reorganize the internal structure of minerals than to overcome the barriers to diffusion and allow aggregation into larger grains. This limitation is largely removed when strong deformation or circulating fluids are also involved, as in regional metamorphism. The resulting texture in the hornfelsed basalts consists of a fine grained mosaic of rounded grains, the well-known "granoblastic" texture. The mineralogical changes are the result of the adjustment of extrusive rocks, originally rapidly cooled, to plutonic conditions

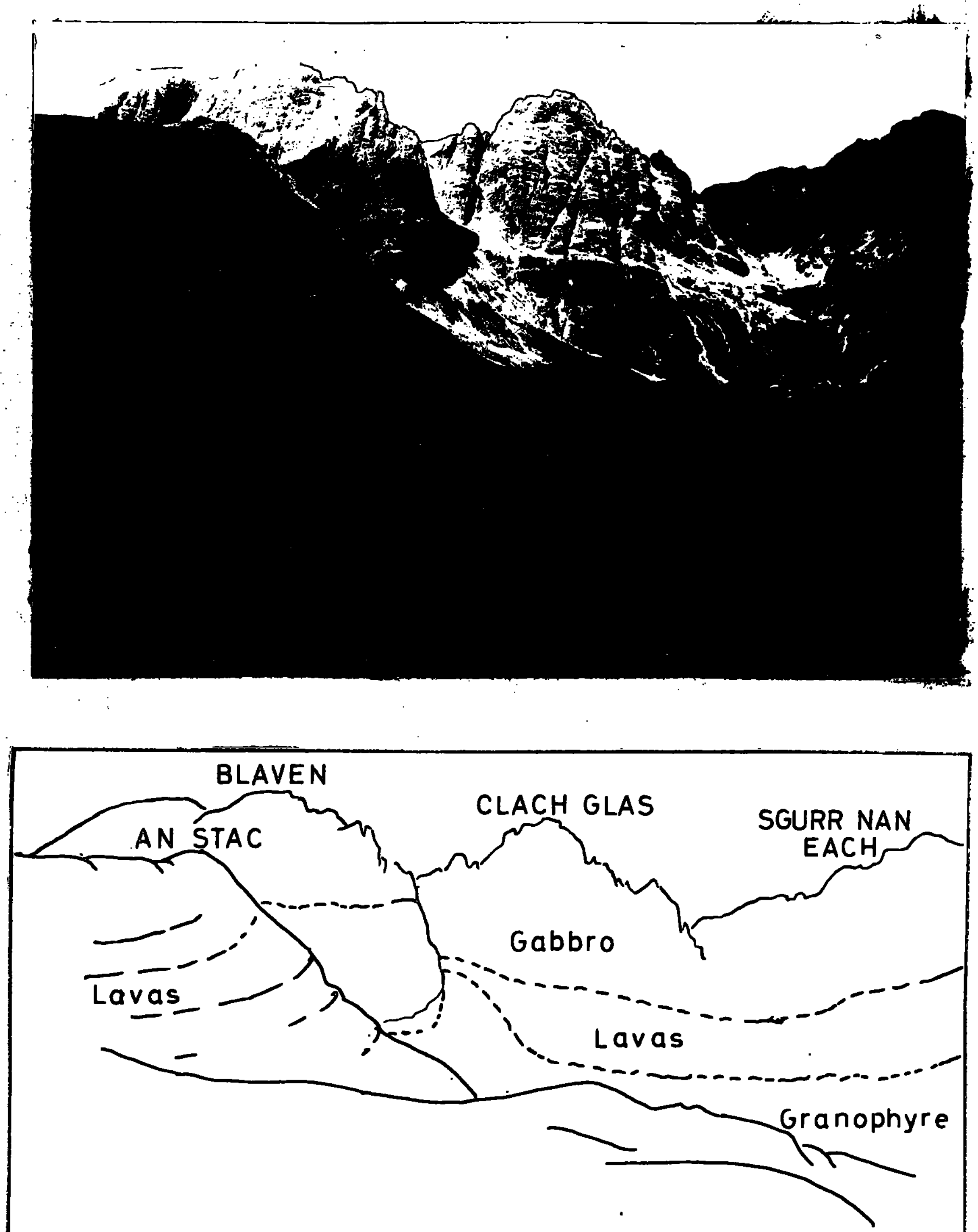


PLATE 22. View to the west from the northern end of An Carnach.

of slow cooling. The chief results are the homogenization of feldspars; the exsolution of a calcium-free (orthorhombic) pyroxene and of some iron oxide from the primary high-temperature clinopyroxene, leaving the latter enriched in calcium and magnesium; and the adjustment of pyroxene and olivine content to the stoichiometric ratio.

Gradation within the hornfels zone. The outer margin of the hornfels zone is here arbitrarily defined as the surface within which new pyroxene has developed at the expense of the old. Between this outer boundary and the lavas of the amphibole zone lies a narrow belt of transitional rocks, the characters of which foreshadow those of the hornfels zone but do not include the growth of new pyroxene.

Within the hornfels zone ~~the~~ three grades of metalava have been distinguished, differing in the manner and degree of their adjustment to the metamorphic temperatures. In general the most complete reconstruction of texture and mineralogy has occurred adjacent to the Gabbro, and the lavas become gradually less modified outwards. However the grain size of the original rock has had a considerable influence on these changes; the finer the grain of the rock the more readily it has reacted to the changed conditions.

The chief characteristic of the three grades of lava hornfels are summarized below:-

1. Low grade hornfels - The original texture remains almost unchanged. Very fine granules of new-formed pyroxene - mainly orthorhombic - develop round the margins of the primary pyroxene and sometimes round olivine; their distribution is patchy. Extremely fine grained exsolved ore makes the primary pyroxene appear dusty. Original ore is partly recrystallized and diffused at the edges. The contents of vesicles are completely recrystallized to new minerals.

2. Medium grade hornfels - The primary pyroxene is entirely replaced by granules of new pyroxene, of larger size than at low grade. Both monoclinic and orthorhombic varieties are usually present, and the granules are more or less confined to the sites of the primary pyroxene, though characteristically they tend to encroach upon the margins of the feldspars and produce a "scalloped lath" texture.

3. High grade hornfels - Pyroxene, feldspar, and ore are all completely recrystallized to an equigranular, granoblastic texture. Two pyroxenes are normally present, with the monoclinic variety predominating. Olivine may be partly or wholly recrystallized, or absent from the assemblage. Relict structures are

usually limited to recrystallized amygdales and occasional feldspar phenocrysts. The latter commonly retain their identity except for marginal dentation by the granulitic groundmass. A primary ophimottled texture or flow orientation are partially preserved in some hornfels.

Biotite and brown hornblende are common accessories in rocks of all grades. There is a gradual increase of grain size in the recrystallized minerals from low to high grade, but even the coarser hornfels, with a granularity of c. 0. 2 mm., are finer than most unmetamorphosed basalts. The colour tends to be dark at low grade due to fine grained dispersion of the ore, but at high grade the latter forms granules of comparable size to the other constituents, and the colour is of a lighter grey.

<u>Transitional rocks.</u> The petrographic features of the meta-lavas which lie between the hornfels and the amphibole zone can be illustrated by two slices (439 and 440) from rocks lying some hundred and fifty yards from the Gabbro contact on the western side of the Blaven - Slat Bheinn col. In these two slices the intersertal clinopyroxene is of dirty appearance due to the development of fine, exsolved ore grains, and there is a considerable growth of granular brown

hornblende round the rims. The feldspar is partially albitized, and dusty with inclusions, while olivine is represented by pseudomorphs of low-birefringence chlorite and ore. Primary ore is recrystallized to minute granules scattered throughout the groundmass.

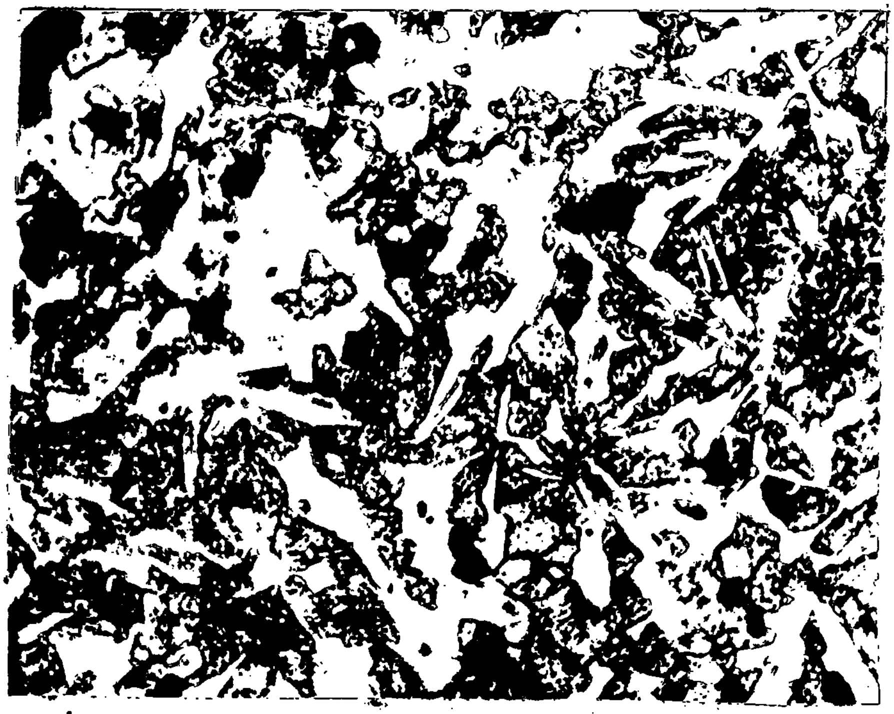
One of the slices (439) is amygdular, and chlorite fills many of the vesicles, but one large cavity about 1 cm. across contains an assemblage of higher temperature type. In this a half-millimetre thick outer layer consists of finely granular, green diopsidic clinopyroxene interspersed with plagioclase and resting on an ore-rich vesicle wall. A second layer is of spongy anhedral garnet embedded in feldspar and enclosing cores of clear prehnite. Several large grains of sphene are associated with this layer, and where this mineral is in contact with the garnet both develop a brown marginal zone. The centre of the vesicle is filled by acid plagioclase, variously granular, sheaved and spongy in form, with a few enclosed grains of clinopyroxene, both green-tinted and colourless. The garnet of this amygdale is reddish brown in hand specimen and pale brown in thin section. It is completely isotropic and has a refractive index greater than 1.83, indicating the calcium-iron variety, andradite. The cores of prehnite suggest a derivation from this mineral, probably with iron derived from ilmenite, leaving the excess titanium in sphene. M'Lintock (1915) ascribed the origin of the grossular found in some Mull amygdular meta-lavas to metamorphism of scolecite-bearing vesicles, intermediate stages giving prehnite and epidote.

<u>Low grade hornfels.</u> (see Plate 23) A representative specimen (428) is that collected from the Rudha Ban headland below Sgurr na Stri, and 350 yards from the Gabbro contact. The primary texture is that of a rather coarse, sparsely feldspar-phyric basalt. The groundmass feldspars tend to form radiating groups, and the pyroxene is intersertal. The feldspar phenocrysts retain their identity and even their zoning, which consists of an anhedral sodic envelope discontinuous with the slightly zoned, euhedral calcic core. The groundmass laths (An64) contain small areas made cloudy by extremely fine indeterminate inclusions, and also enclose a few larger grains of new-grown pyroxene and apatite. The primary clinopyroxene is rich in fine exsolved ores, many of which are rod-shaped and aligned in (010) and (001) planes. Small (0.05 mm.) granules of new pyroxene, mainly orthorhombic, develop from the margins of the grains and also replace some sectors entirely. Clusters of coarser

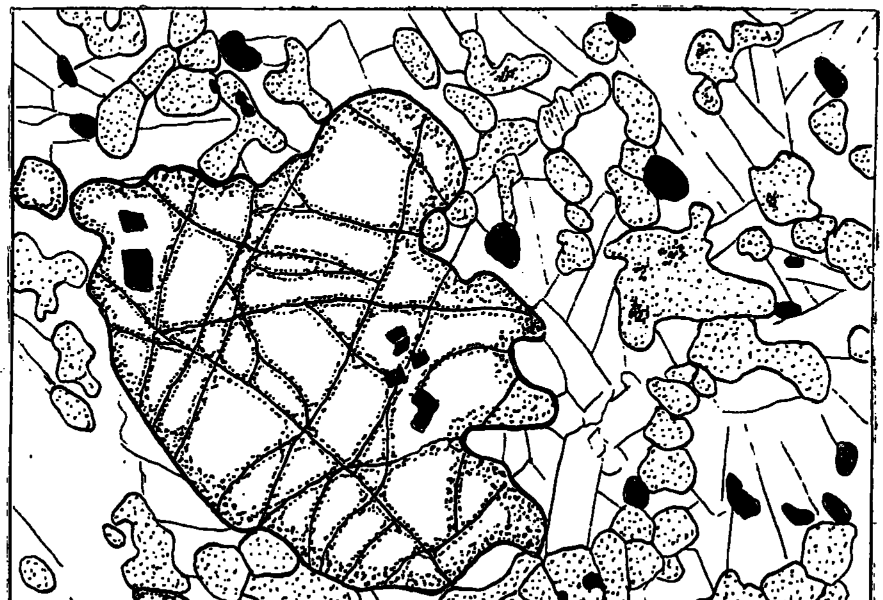
PLATE 23 (opposite.) Microsections: Low and medium grade lava hornfels.

A. (Spec.428) × IOO. Low grade hornfels, Rudha Ban. The prim--ary texture is largely retained, but granules of new pyroxene (mainly orthorhombic) have developed round the margins of the igneous clinopyroxenes, which now contain numerous inclusions of ore.

B. (Spec.224) × IOO. Advanced medium grade hornfels from An t-Sron, Camasunary. A relict phenocryst of fresh olivine containing euhedral ores is seen to the left of the field. The groundmass consists of granular pyroxene (predominantly monclinic) and ore, set in basic plagio--clases which still retain much of their primary, elongate form.



A.



B.

orthopyroxene may be replacements of primary olivine, which is otherwise not represented. The primary ore has been recrystallized and is now scattered as 0.15 mm. sub-rounded grains. A little red biotite is associated with it and also coats joint surfaces. The rock is of fresh appearance except for slight marginal alteration of the orthopyroxene and the presence of a few thin uralite veins. The mode is as follows:-

Constituents	Volume Percentages
Plagioclase	42.2
Pyroxene (predominantly primary, plus new-formed fine granules)	39.7
Orthopyroxene (coarse clusters, after olivine?)	12.7
Ore	4.4
Biotite	1.0
	100.0

Another low grade rock was collected from the east side of the large gully on the south face of Sgurr na Stri and 370 yards from the Gabbro contact. The slice (212) has the same general metamorphic features as that described above, but differs in that olivine has been recrystallized into indefinite patches of granules (av. 0.05 mm.) which remain fresh. Brown hornblende is locally abundant both as coarse crystals filling irregular veins and more sparsely as coatings to the ore grains. The slice contains several amygdales which consist of an outer layer of equidimensional (0.3 mm.) clinopyroxene and a core of coarse prisms of wollastonite with slivers of calcite along the cleavages. Some of the pyroxene abutting against the calcic core is weakly pleochroic from pale green to yellow.

A rock collected from the gully between Blaven and Clach Glas (270) has low grade textures in which the primary olivine is again represented by new-grown granules together with ore. In many cases the clusters preserve the shapes of the original crystals, but sometimes the grains are more dispersed.

Medium grade hornfels. (see Plate 23). A specimen (427) collected some 270 yards from the Gabbro contact on the south side of Sgurr na Stri is representative of this grade. The plagioclase (An60) forms 0.3 mm. laths, largely clear but with a few patches dusty with inclusions. The ferromagnesian minerals indent and are sometimes enclosed within the laths. Almost the whole of the primary augite is recrystallized to granules of monoclinic and orthorhombic pyroxene. The distribution of the former roughly preserves the primary ophitic texture of the lava and the grains contain orientated inclusions of exsolved ore. The orthopyroxene is found between these relict ophitic areas as small pink prisms which sometimes enclose small clinopyroxenes. Associated with it is a small amount of olivine in clear granules averaging 0.1 mm. across. Over two per cent of red-brown biotite is present in this rock and mainly centres round the ore grains. It also builds several poeciloblastic metacrysts up to 2 mm. long which enclose grains of pyroxene and olivine. The refractive index of this biotite was found to be 1.651, indicating the variety "lepidomelane", containing according to a diagram of Winchell (1951, p.374) a content of between 55% and 75% of the iron-bearing molecules.

The modal percentages of the above rock and of several other medium grade hornfels are given below.

Constituents	Volume Percentages				
	427	136	224	225	336
Plagioclase	42.0	44.1	51.2	49.3	46.5
Clinopyroxene	25.6	36.1	32.2	23.3	38.3
Orthopyroxene	21.5	13.4	9.3	22.3	2.1
Olivine	5.0	-	4.4	-	10.4
Ore	3.5	3.4	2.9	5.1	2.7
Biotite	2.4	3.0	-	-	-
	100.0	100.0	100.0	100.0	100.0

Spec. 427 - From Rudha Ban headland, Sgurr na Stri; 270 yards from the Gabbro contact.

Spec. 136 - From the east bank of the Camasunary River; 80 yards from the Gabbro contact.

Spec. 224 - From the hillock north-east of An't Sron, Camasunary; situated 2 yards from the Gabbro contact.

Spec. 225 - Same locality as 224; 4 yards from the Gabbro contact.

Spec. 336 - From the gully between Clach Glas and Sgurr nan Each, Blaven Range; 10 yards from the Gabbro contact.

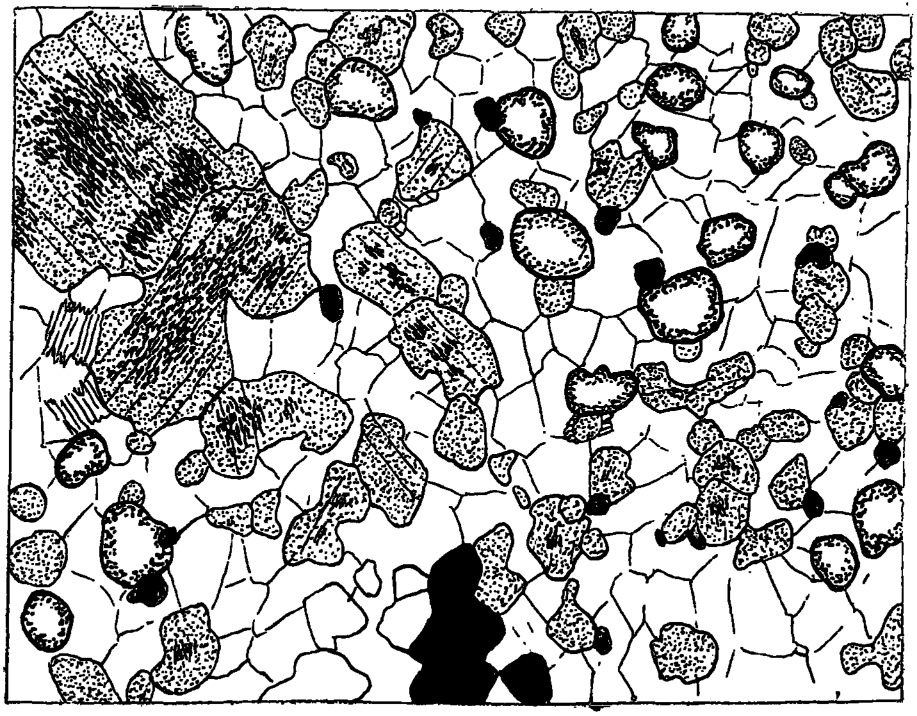
It will be seen from these modes that orthopyroxene is in some rocks almost as abundant as clinopyroxene, while in others it is much subordinate to it. Olivine is not always present, and is always less abundant than in the unmetamorphosed lavas. One of the specimens (224) contains primary phenocrysts of bytownite (An76) and olivine, neither of which have been recrystallized although the rock was collected only two yards from the Gabbro contact. A small amount of recrystallized olivine is found in the groundmass however.

<u>High grade hornfels.</u> (see Plate 24) The extent to which complete recrystallization of the lavas to high

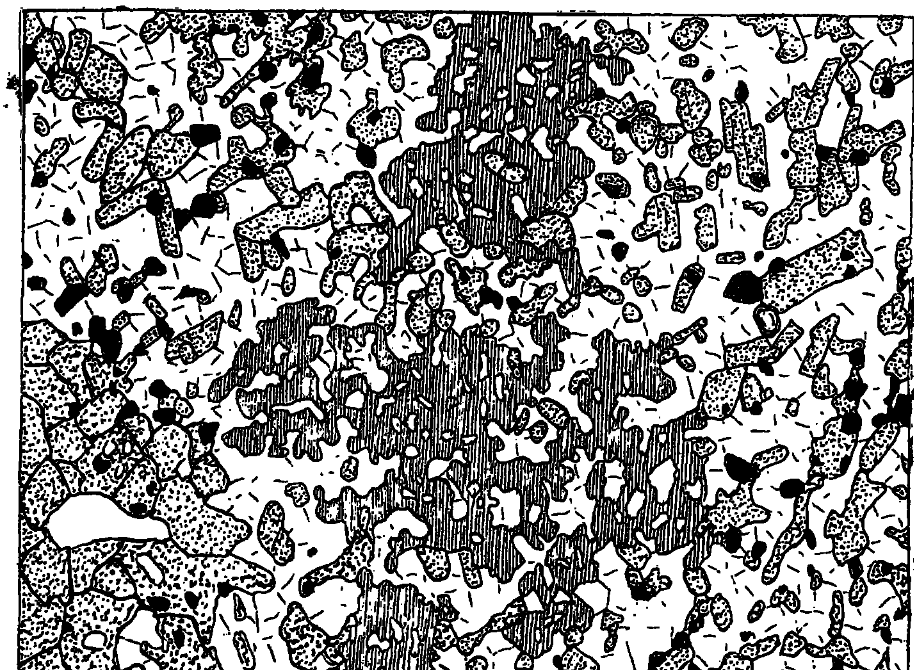
PLATE 24 (opposite.) Microsections: High grade lava hornfels.

A. (Spec.205)X IOO. High grade hornfels from Sgurr na Stri. Large,poeciloblastic biotite metacrysts occupy the centre of the field,and part of a recrystallized amygdale is seen to the bottom left,and consists largely of ortho--pyroxene. The rest of the field consists of small granules of pyroxene,ore,and occassional olivine,set in a mosaic of eqüidimentional plagioclase. Orthopyroxene predominates over clinopyroxene in the upper right corner of the field,and there shows a characteristic tendency to be prismatic.

B. (Spec.I83)X IOO. High grade hornfels,Sgurr na Stri. The large clinopyroxenes in the top left corner of the field probably mark the site of a large primary crystal. The rock otherwise consists of granular clinopyroxene,olivine, and ore,together with a little biotite,set in an equi--granular mosaic of plagioclase.



A.



B.

grade textures occurs varies from place to place along the contact of the Gabbro pluton. In general this sub-zone is very much wider on Sgurr na Stri than elsewhere. On the western shoreline below this hill high grade rocks are found as much as 300 yards from the contact, but on the eastern slopes, above Camasunary, the sub-zone has narrowed to about 150 yards. In parts of the Camasunary valley and on the Blaven Range high grade rocks are altogether absent along the contact, but on the Blaven - Slat Bheinn col they occupy a width of 20 yards, and in the gully between Clach Glas and Sgurr nan Each are found up to 8 yards from the margin of the Gabbro.

In the petrographic descriptions which follow the hornfels are subdivided into four groups, the first including the most undersaturated hornfels, containing abundant olivine, while the other three deal with successively less undersaturated rocks.

Hornfels with abundant olivine.

This type is not common, and the three rocks the modes of which are quoted below were the only ones found belonging to this category.

Constituents	Volume Percentages		
	165	334	443
Plagioclase	47.8	35.5	47.2
Clinopyroxene	1.3	32.8 (Clinopyroxene + Orthopyroxene)	31.2
Orthopyroxene	-		-
Olivine	21.1	29.3	18.9
Ore	2.6	2.4	2.8
Biotite	0.4	-	trace
Brown hornblende	26.8	-	-
	100.0	100.0	100.1

Spec. 165 - From An't Sron, Camasunary valley.

Spec. 334 - From the gully between Clach Glas and Blaven; 1 yard from the Gabbro contact.

Spec. 443 - From the Blaven - Slat Bheinn col; 1 yard from the Gabbro.

Apart from the relative abundance of olivine, the absence of orthopyroxene in two of the rocks is noteworthy. This mineral is present in 334, but unfortunately the grain size is too small for it to be accurately separated from the clinopyroxene.

The presence of abundant brown hornblende is the most unusual feature of Specimen 165, although smaller amounts of this mineral are found in several other meta-lavas. The amphibole has developed at the expense of the clinopyroxene and is probably a retrogressive product of waning metamorphism. Olivine is found both as small granules and as larger irregular grains up to half a millimetre across. Granular olivine is especially common round amygdales.

Most of the olivine in the rock from the Clach Glas gully (334) retains its primary porphyritic mode as crystals up to 2 mm. across, with a minor amount of granular olivine in the groundmass. Conversion to orthopyroxene occurs marginally and along the cracks of the larger grains. A granular mosaic of plagioclase (An52), clinopyroxene and orthopyroxene fills in the groundmass. The appearance suggests that this hornfels was derived from a lava of picritic affinity.

All the olivine of 443 occurs in 0.25 mm. rounded grains now altered to uralitic material associated with the uralite veins which cross the slice. The metamorphic clinopyroxene was evidently derived from an ophitic parent, and now consists of rounded lobes tenuously connected over areas some 2 mm. in diameter. It contains numerous exsolved ore rods.

Hornfels with moderate olivine contents.

Hornfels containing between 10 and 15 per cent olivine are rather more common than olivine-rich varieties. A selection of modes is given below.

Constituents	Volume Percentages			
	182	420	183	332
Plagioclase	53.6	61.0	51.1	50.4
Clinopyroxene	20.6	19.8	22.4	29.4
Orthopyroxene	8.5	1.0	9.6	1.5
Olivine	11.9	13.9	13.8	14.6
Ore	4.1	4.3	2.1	4.1
Biotite	1.3	trace	1.0	-
	100.0	100.0	100.0	100.0

Spec. 182 - From an inclusion of lava in the Gabbro, 16 yards within the contact; Sgurr na Stri.

Spec. 420 - From an inclusion within the Gabbro, 250 yards within the contact; Sgurr na Stri.

Spec. 183 - From the Gabbro contact; eastern face of Sgurr na Stri.

Spec. 332 - From the gully between Clach Glas and Sgurr nan Each; at the contact of the Gabbro.

It will be noted from these modes that the content of orthopyroxene, though sometimes considerable, is always much less than that of clinopyroxene.

An interesting feature of 182 is that the feldspar, though thoroughly recrystallized to an equidimensional mosaic, nevertheless possesses a marked preferred orientation as revealed by the twinning. Whether this is an inherited or a newly imposed feature (the inclusion from which this specimen was collected is in fact a lens-shaped streak) is not known. The clinopyroxene and ore of this rock are also granulitic, but the orthopyroxene frequently forms poeciloblastic anhedra up to 2 mm. across. Olivine builds small granules and a few rounded half millimetre grains which are probably the remnants of primary phenocrysts. Amygdales present in the slice contain mosaics of clinopyroxene and poorly-twinned plagioclase. Around the more feldspar-rich amygdales the groundmass is enriched in olivine.

The grain size of another gabbro-enclosed lava (420) is coarser than that of most hornfels, with the plagioclase (An62) anhedra averaging 0.3 mm. and occasionally reaching 1 mm.. Groups of clinopyroxene granules often have a common optical orientation suggesting derivation from large parent crystals. Schiller structure is often present. Olivine again forms both large irregular grains and small granules, and adjacent to a uralite - chlorite vein is altered to talc, amphibole and ore. This and other xenoliths from the margin of the Gabbro show no notable mineralogical or textural differences from meta-lavas outside the contact, though the grain is sometimes a little coarser and schiller structure is common in the clinopyroxenes.

Specimen 183 contains recrystallized cores of primary clinopyroxene up to 0.75 mm. across, though most of the pyroxene is found as granules. Olivine also occurs both as granulaes and as larger remnental grains. In 332 the texture is fine grained and equigranular.

Hornfels poor or lacking in olivine and with dominant clino-pyroxene.

Rocks falling into this category are more numerous than those in any other group. Seven modes are quoted below.

Constituents	Volume Percentages						
	441	423	125	126	205	333	335
Plagioclase	41.2	44.7	50.8	62.1	47.6	45.2	52.4
Clinopyroxene	18.2	25.5	25.3	17.9	18.9	43.4	21.5
Orthopyroxene	16.5	17.2	18.6	10.4	14.4	-	14.0
Olivine	-	1.8	-	-	7.3	7.6	8.2
Ore	5.3	8.2	5.3	9.6	7.5	3.8	3.9
Biotite	18.8	2.6	traces	-	4.3	-	-
	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Spec. 441 - From the Blaven - Slat Bheinn col; 17 yards from the Gabbro contact.

Spec. 423 - Sgurr na Stri; 6 yards from the Gabbro contact.

Spec. 125 - East bank of the Camasunary River; 1 yard from the Gabbro.

Spec. 126 - East bank of the Camasunary River; 6 inches from the Gabbro.

Spec. 205 - Sgurr na Stri; 170 yards from the Gabbro contact.

Spec. 334 - Gully between Clach Glas and Sgurr nan Each; 2 yards from the Gabbro.

Spec. 335 - Gully between Clach Glas and Sgurr nan Each; 4 yards from the Gabbro.

One feature of the above modes is that with one exception (333) these rocks contain a considerably higher percentage of orthopyroxene than is found in lavas with more abundant olivine. Several of them also have a high ore content.

Textural variations in this group do not vary from those already described; suggestions of a primary ophimottled pyroxene mode are detectable in 441 and 423; remnents of porphyritic olivine are to be seen in 333, and a well-defined preferred orientation of the feldspars is present in 126. The abundant biotite of 441 forms numerous poeciloblastic plates.

Metamorphosed amygdales are well represented in one of the slices (205) and there consist chiefly of both varieties of pyroxene, some plagioclase, a little ore and olivine. The subhedral prisms of orthopyroxene are sometimes very coarse (2 mm.). When olivine is present it is set in plagioclase, and the surrounds of such amygdales are commonly enriched in olivine at the expense of the pyroxenes.

Hornfels poor or lacking in olivine with dominant orthopyroxene.

Three modes suffice to represent this small group.

Constituents	Volume Percentages		
	442	162	186
Plagioclase	63.5	64.0	57.0
Clinopyroxene	1.3	-	6.7
Orthopyroxene	27.1	25.6	23.0
Olivine	-	-	7.4
Ore	8.1	8.4	4.3
Biotite	traces	2.0	1.6
	100.0	100.0	100 .0

Spec. 422 - From Sgurr na Stri above Rudha Ban; at contact of Gabbro.

Spec. 186 - Eastern face of Sgurr na Stri; at contact of Gabbro.

Spec. 162 - From An 't-Sron, Camasunary.

All three modes show high percentages of feldspar, while clinopyroxene is either greatly reduced or absent.

The rock from above Rudha Ban (422) has an equigranular and relatively coarse texture. Clinopyroxene is only a minor constituent but ore is abundant and of similar grain size (c. 0.25 mm.) to the other dark minerals. The plagioclase (An58) matrix has an average granularity of 0.35 mm.; individual grains are often slightly elongated parallel to the c-axis. are clear, and are free from zoning.

Specimen 162 is interesting in that it provides evidence of reaction between the meta-lava and several veins of acid material which transect it. The feldspar of the basalt is andesine and the crystals often show normal zoning. Clinopyroxene is entirely absent and the orthopyroxene has a more marked pleochroism than usual and is most abundant adjacent to the veins. Ore is abundant and apatite common. The veining material consists of potash feldspar, andesine, quartz, and a little orthopyroxene and biotite. Apatite prisms are numerous and large.

Specimen 186 is unlike the other two in containing granules of olivine, and these are again especially common in the vicinity of meta-amygdales. The latter are filled by coarse grains of the two pyroxenes together with subordinate plagioclase.

(v) Pyroxenes and Metamorphism

Clinopyroxenes of unmetamorphosed lavas. In the basalts lying outside the thermal aureole only one pyroxene is present, and it is always a clinopyroxene with a titaniferous purple tint varying in intensity in different lava types. The optical properties of this mineral were investigated in ten rocks distributed throughout the sequence, and the results are given in the previous chapter (section (iv) Petrography).

When plotted on Hess's triangular diagram of 2V and $n\beta$ plotted against composition (1949, p. 634) these pyroxenes form a cluster in the Ca-Mg corner of the augite field, with an average calculated composition of $Ca_{42}Mg_{34}Fe_{24}$ (see Plate 25). The most magnesian member of this group is that taken from the picrite flow (Ca43 Mg_{37} Fe_{20}) and the most iron rich is that found in a strongly ophitic lava from the Ophimottled Basalt Group (Ca_{40} Mg_{33} Fe_{27}).

There is reason for believing, however, that these

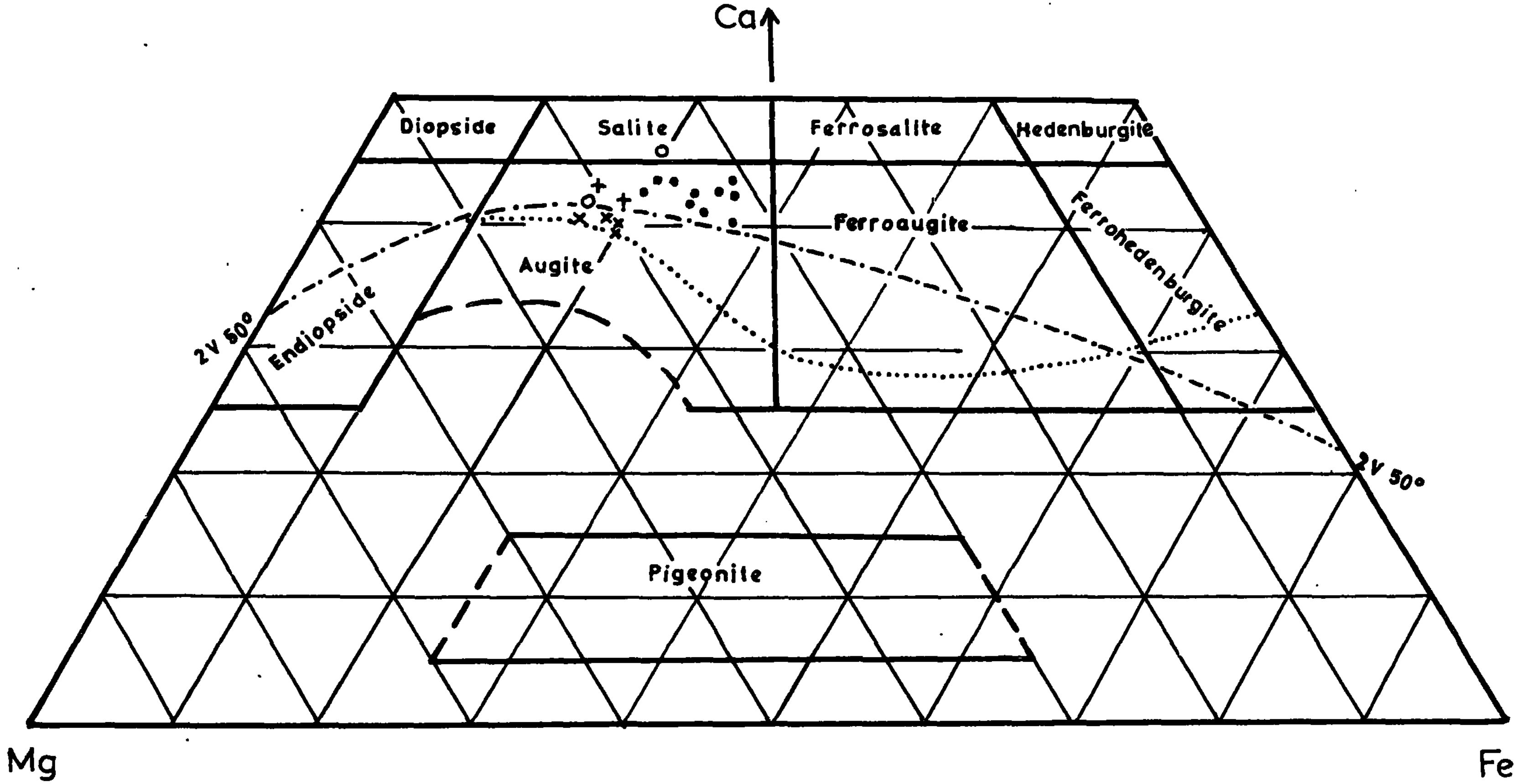


PLATE 25. COMPOSITIONS OF CLINOPYROXENES FROM LAVAS AND HORNFELS, BASED ON OPTICAL PROPERTIES.

PYROXENES FROM UNMETAMORPHOSED LAVAS •
PYROXENES FROM METAMORPHOSED AMYGDALES o
PYROXENES FROM LOW GRADE PYROXENE HORNFELS +
PYROXENES FROM HIGH GRADE PYROXENE HORNFELS x
HESS'S NORMAL CRYSTALLIZATION CURVE FOR IGNEOUS PYROXENES ·······

calculated compositions do not more than approximate to the true proportions of Ca : Mg : Fe ions in these pyroxenes. It will be noted that their plots all lie well above the "normal crystallization curve" constructed by Hess from a study of clinopyroxenes in basic plutonic rocks. Moreover, using Hess's curves, the birefringence is between 0.001 and 0.003 lower than that which would be expected from the 2V - $n\beta$ plots. Part of the explanation may be that titania is almost certainly present in excess of the figure of 0.4 % used by Hess in constructing the curves, and an increase in titania content also causes a substitution of alumina for silica in the proportion of two Al^{3+} for Si^{4+} ions for every Ti^{4+} ion in the structure. There is a great deal of uncertainty concerning the effect of minor constituents on the optical properties, and recent workers in this field (Wilkinson, 1956; Brown, 1957; Muir and Tilley, 1958) are unanimous in concluding that the simple Ca : Mg : Fe diagram cannot adequately represent the relations between optical properties and chemical composition in complex clinopyroxenes. Wilkinson (1956), for instance, finds that the optical properties of titanium-rich pyroxenes in a sill of alkaline olivine dolerite indicate a higher Fe and lower Ca content than is revealed by analysis.

Muir and Tilley (1958) discovered that the optical plots of clinopyroxene from the metamorphosed basic rocks studied by them generally lie on the iron side of the position based on chemical analysis.

Clinopyroxenes of hornfelsed lavas. The optical properties of two clinopyroxenes from low grade hornfels and three from high grade hornfels were determined together with a clinopyroxene from a dolerite dyke which has been metamorphosed to high grade. In addition, measurements were made on two pyroxenes found in the metamorphosed amygdales of two high grade meta-lavas. The results are set out below.

		$n\alpha$	$n\beta$	$n\gamma$	2V(+)	Composition (Hess)
Low grade hornfels						
425.		1.689	1.694	1.717	$51\frac{1}{2}^{\circ}$	$Ca_{42}Mg_{39}Fe_{19}$
426.		1.687	1.692	1.713	$52\frac{1}{2}^{\circ}$	$Ca_{43}Mg_{40}Fe_{17}$
High grade hornfels - groundmass						
126.		1.688	1.694	1.716	$47\frac{1}{2}^{\circ}$	$Ca_{39}Mg_{41}Fe_{20}$
335.		1.689	1.693	1.715	49°	$Ca_{40}Mg_{41}Fe_{19}$
438.		1.690	1.695	1.716	48°	$Ca_{40}Mg_{40}Fe_{20}$
519.	(metadol.)	1.686	1.690	1.711	$48\frac{1}{2}^{\circ}$	$Ca_{40}Mg_{43}Fe_{17}$
High gr_ade hornfels - amygdales						
423.	(granular, colourless)	1.686	1.691	1.713	50°	$Ca_{41}Mg_{42}Fe_{17}$
435.	(granular, pale green)	1.691	1.697	1.719	56°	$Ca_{46}Mg_{35}Fe_{19}$

The pyroxenes from the two low grade hornfels still retain much of their primary texture, but that some recrystallization has occurred is indicated by the presence of small exsolved bodies of ore and by the loss of titaniferous colouration. Marginally they have been notched by the formation of minute granules of new pyroxene, mainly orthorhombic. In comparison with unmetamorphosed pyroxenes their indices are lower, but 2V remains about the same.

The completely recrystallized and re-formed clinopyroxenes of the high grade hornfels have both lower indices and lower values for 2V when compared with the igneous pyroxenes.

Of the two pyroxenes from metamorphosed amygdales, the first (424) is of similar properties to the groundmass pyroxenes, but the green, pleochroic mineral is considerably more calcic and can be provisionally classified as a salite. The meta-amygdale from which it was derived contained a highly calcic assemblage including wollastonite and calcite.

In all the metamorphic clinopyroxenes there is good correspondence between the measured birefringence and that predictable from the plotting of $n\beta$ and 2V on Hess's curves. This may mean that their optical properties agree more closely with those of the plutonic igneous pyroxenes studied by Hess than do the pyroxenes of the unmetamorphosed lavas. In this respect it is significant that during metamorphism the titaniferous colouration disappears, evidently due to the exsolving of titanium oxide, so that the optical interference caused by this constituent must be considerably reduced. Moreover, the hornfels crystallized under much the same pressure-temperature conditions as did the adjacent gabbros, so it would not be surprising if the properties of their pyroxenes agreed more closely with those of plutonic basic rocks than do the pyroxenes of the extrusive rocks from which they were derived. Nevertheless, Muir and Tilley (1957, 1958) examined similar clinopyroxenes in metamorphosed picrite basalts from Hawaii and found that their optics suggested a higher content of iron than is revealed by chemical analysis.

It is unfortunate that the inability to correlate optical properties with chemical composition accurately make it impossible to define clearly the changes which metamorphism induced in the composition of the Strath-aird clinopyroxenes. Optically, the clinopyroxenes in the hornfels show both lower refractive indices and lower values for 2V than do the clinopyroxenes in unmetamorphosed lavas. There are also some optical differences between the clinopyroxenes of low grade and high grade hornfels. The average values of 2V and $n\beta$ given below show the general nature of these differences.

	2V(+)	$n\beta$
Clinopyroxenes in lavas	$52\frac{3}{4}^{\circ}$	1.700
Clinopyroxenes in low grade hornfels	52°	1.693
Clinopyroxenes in high grade hornfels	48°	1.693

At low grade the clinopyroxenes retain their external form almost intact, but are rich in exsolved opaque minerals, and there is a certain amount of marginal recrystallization to orthopyroxene and clinopyroxene. At high grade the clinopyroxene is entirely recrystallized, but still contains some exsolved opaque mineral, while orthopyroxene is separately crystallized. Despite the uncertainties it does seem likely, both from the optical and petrographic evidences that one of the major changes in the composition of the clinopyroxenes on metamorphism was the loss of a considerable part of the iron and titanium content.

Orthopyroxenes of high grade hornfels. All the hornfels orthopyroxenes are optically negative and show moderate to weak pleochroism in pale pinks and greens. Thus they are all either hypersthene or bronzite. The optical properties of only one specimen were completely determined. The results are set out below.

		$n\alpha$	$n\beta$	$n\gamma$	2V(-)
422.	Prismatic granules; moderate pleochroism, α pale pink > γ pale green	1.690	1.699	1.704	64°

This specimen was obtained from an orthopyroxene rich hornfels, and according to the optical property diagram of Poldervaart (1947) it is a bronzite containing 27% of the orthoferrosilite molecule. The orthopyroxene of another hornfels (335), in which clinopyroxene is dominant, possesses a 2V of 60°, suggesting a composition near to the bronzite - hypersthene boundary (Or 30).

(vi) Chemistry of the Hornfelsed Lavas.

Four high grade hornfels were chemically analysed, one rock being selected from each of the four mineralogical groups described in the petrographic section of this chapter. Although these are metamorphic rocks the norms were nevertheless calculated in order to better compare them with the analyses of unmetamorphosed lavas given in section (vi) of Chapter VI. The oxide percentages of the hornfels are given in the first part of Table 6, and the modes and norms in the second

TABLE 6

CHEMICAL ANALYSES OF FOUR HIGH GRADE LAVA HORNFELS.

	165.	183.	205.	162.
SiO_2	48.8	47.8	48.1	53.4
TiO_2	1.26	1.00	1.37	1.32
Al_2O_3	12.1	15.5	13.2	15.9
Fe_2O_3	3.3	3.8	4.9	5.8
FeO	7.6	7.2	7.8	6.4
MnO	0.13	0.11	0.10	0.24
MgO	12.7	10.5	11.6	7.3
CaO	10.5	10.2	8.7	4.4
Na_2O	2.8	2.2	2.8	4.2
K_2O	0.44	0.26	0.41	1.07
$H_2O(+)$	0.50	0.50	0.18	0.17
$H_2O(-)$	0.28	0.16	0.25	0.28
P_2O_5	0.10	0.25	0.19	0.12
Total	100.5	99.5	100.6	100.6

165. - An't-Sron, Camasunary. Rich in olivine and brown hornblende.

183. - Hornfels adjacent to the Gabbro contact plane, eastern face of Sgurr na Stri. Moderately high olivine content.

205. - Collected 170 yards from the Gabbro contact, Sgurr na Stri. Moderately low olivine content.

162. - From An't Sron, Camasunary. Lacking in olivine and clinopyroxene; contains abundant ortho-pyroxene; feldspar andesine. Has reacted with acid veins during metamorphism.

Analyst D. C. Almond.

TABLE 6
(cont.)

MODES AND NORMS OF FOUR HIGH GRADE LAVA HORNFELS.

Normative Minerals		165.		183.		205.		162	
Quartz			-		-		-		2.46
Orthoclase			2.78		1.67		2.22		6.12
Albite			23.58		18.86		23.58		35.63
Anorthite			19.46		31.41		21.04		21.41
Diopside	Wo	13.46	25.63	7.44	14.22	8.35	16.00		-
	En	9.40		5.20		5.80			
	Fs	2.77		1.58		1.85			
Hypersthene	En	0.80	1.06	12.80	16.76	14.00	18.22	18.20	23.35
	Fs	0.26		3.96		4.22		5.15	
Olivine	Fo	15.12	20.02	5.88	7.72	5.04	6.88		-
	Fa	4.90		1.84		1.84			
Magnetite			4.87		5.57		7.19		7.75
Ilmenite			2.43		2.28		2.43		2.58
Apatite			0.23		0.57		0.34		0.27
Water			0.78		0.65		0.48		0.45

Modes.

Constituents	Wt. %	
	165.	183.
Plagioclase	43.3	45.2
Clinopyroxene	1.4	25.0
Orthopyroxene	-	10.1
Hornblende	26.7	-
Olivine	23.5	15.1
Ore	4.8	3.6
Biotite	0.3	1.0
	205.	162.
Plagioclase	41.0	56.7
Clinopyroxene	20.3	-
Orthopyroxene	14.6	26.9
Olivine	7.1	-
Ore	12.4	14.4
Biotite	4.1	2.0

part of Table 6.

The major chemical constituents of the first three hornfels (165, 183, and 205) approximately agree in amount with those in the Basal Lava Group olivine basalt (Table 3, 42), excepting that silica is higher in the hornfels. The predominance of magnesia over lime and low alumina of 165 and 205 may mean that these lavas were originally olivine rich varieties of picritic affinity, since these features are also found to a more marked extent in the analysis of a picrite (Table 4). The high silica content is expressed in the norms and modes of 183 and 205 by the appearance of a notable amount of orthopyroxene and a much lower content of olivine than is normally found in unmetamorphosed lavas. Specimen 165 remains a heavily undersaturated rock with a high content of olivine.

The fourth analysis (162) is a special case in that its petrography shows that at the time of metamorphism reaction occured between the lava and intruded acid material. The effects of this are indicated in the analysis by the low magnesia and lime values and high contents of silica, soda, and potash. These features find expression in the norm, as in the mode, by the presence of a notably sodic plagioclase and the absence of any ferromagnesian silicate apart from orthopyroxene. A similar hornfels might have been formed by the metamorphism of a trachybasalt lava, with which this analysis has many similarities (see Table 5), but the examination of thin sections makes it clear that the present composition has largely been determined by the loss of lime and magnesia to the invading acid material and a gain in silica and alkalies.

(vii) A Metamorphosed Bole.

Metamorphosed representatives of the thin shales and red clays which are sometimes found between the flows of the lava sequence are surprisingly hard to find in the hornfels zone. Even where there are continuously exposed sections through several of the metamorphosed flows the partings are only indicated by amygdale rich horizons.

One sedimentary parting was, however, detected not far from the base of the lavas on Sgurr na Stri and 520 yards north-north-east of Rudha Ban. It outcrops as a thin black vein, never more than 2 inches thick, crossing a slab of lava hornfels.

In hand specimen this rock (211) is black, fine grained, and vitreous. It weathers to a dark reddish

TABLE 7

CHEMICAL ANALYSIS OF A BOLE FROM CAMASUNARY, WITH A COMPARISON.

	1.	2.
SiO_2	41.8	38.8
TiO_2	3.0	3.2
N_2O_3	32.1	32.8
Fe_2O_3	3.2	23.6
FeO	11.3	1.1
MnO	0.19	-
MgO	2.0	0.09
CaO	1.3	0.19
Na_2O	2.5	tr.
K_2O	2.0	tr.
H20(+)	0.93	-
$H_2O(-)$	0.09	-
P_2O_3	0.32	0.22
	100.7	

1. Metamorphosed bole from Sgurr na Stri, Camasunary (spec. 211). Analyst: D. C. Almond.

2. Analysis of a basaltic lithomarge from Glenavon, Co. Antrim, recalculated to 100 omitting H_2O. The original analysis contains $H_2O(+)$ 12.63 %; $H_2O(-)$ 8.15 %. From Eyles (1952, p. 14, analysis RS/18).

brown surface with projecting bands of black ore. In thin section a rough compositional banding is seen consisting of various combinations of cordierite, ore, potash feldspar mullite (?), plagioclase, and a little biotite apatite and zircon.

The cordierite predominates over all the other constituents, and varies in habit from subhedral prisms to anhedral aggregates. A few of the prisms are more than half a millimetre across in transverse section, but a granularity of about 0.1 mm. is more usual. Sector and polysynthetic twinning are well developed, and in some the core of the crystal is rich in fine, opaque inclusions. Most of the cordierite is fresh, but in a few patches there has been alteration to pinite. The value of $n\beta$ is 1.555, suggesting that the cordierite contains some 40 % of the iron-bearing molecule (Winchell, 1951; Miyashiro and others, 1955). Ore is abundantly scattered throughout the rock in the form of sub-rounded grains and aggregates, and it is also frequently concentrated into bands of irregular thickness. In some bands potash feldspar is abundant as large, poeciloblastic anhedra up to 2 mm. across, enclosing subhedral cordierites. It is usually fresh but is occasionally partly altered to a clay mineral and muscovite. The optical properties ($n\beta$

1.525 and 2V(-) small) suggest that this feldspar is a sanidine. Plagioclase occurs in some bands in a granulitic mosaic interspersed with cordierite. In composition it is an andesine, and it shows slight normal zoning marginally. Needles of a sillimanite type of mineral are abundant in the cordierite-rich bands, and in view of the high temperature paragenesis this mineral may well be mullite. Among the minor constituents apatite prisms are the most common, and there is also a small amount of biotite and zircon. Muscovite occurs in patches as an alteration of the aluminous minerals. ~~This analysis~~ A chemical analysis of this rock is compared, in Table 7, with a normal red bole (lithomarge) from Antrim (Eyles, 1952), and for this purpose the Antrim analysis has been recalculated to 100 %, omitting water. It will be seen that the two rocks are similar in containing high percentages of alumina and iron, and are both relatively poor in silica, but while the Skye rock contains significant amounts of magnesia, lime, and alkalies, these constituents are almost completely lacking in the lithomarge from Antrim. The high potash content of the Skye rock is especially puzzling, since few basalts contain more than 0.5 % of this oxide. According to Eyles (op. cit.), the formation of lithomarge from basalt is brought about by the breaking up of the complex silicates into their constituent oxides, with the almost complete elimination in solution of magnesia, lime, and alkalies, and the partial elimination of silica. The silica and alumina thus freed combine with water to form kaolinite or halloysite, and the resultant rock consists essentially of these clay minerals, together with oxides of iron and titanium. It is possible that before metamorphism the Skye rock was similar in composition to the Antrim lithomarge, and has gained magnesia, lime, and alkalies by metasomatism. The source of these constituents, especially alkalies, is unlikely to have been in the surrounding basalts, but they might have been gained from the para-metamorphic acid veins which are common in this area. Alternatively, these chemical peculiarities may have been inherited from the pre-existing sediment. It is conceivable, for instance, that the Camasunary rock was derived from a shaley sediment, deposited in a shallow pool of water on top of the weathering basalts. In such a situation potash may have been concentrated, and taken up into clay minerals of the illite type, while the clays weathered from basalt contributed kaolinite and iron oxide, giving as a final product a ferruginous and aluminous clay.

(viii) The Distribution of Combined Water in the Lavas.

Hydrous solutions played an important part in forming the present mineralogy of the Strathaird lavas. The conversion of basalts adjacent to the Cuillin Gabbro into hornfels was a "dry metamorphism", but in the amphibole zone there is a clear relationship between degree of uralitization and permeability, and many of the new minerals formed are hydrous. This is also true of the broad belt of alteration outside the amphibole zone in which all the olivine and some of the pyroxene have been degraded to chloritic minerals and lime has been carried away from some of the feldspars to be deposited in epidote.

To give an approximate idea of the present distribution of combined water fifty-four determinations were made on lavas from all parts of the area. The figures obtained are expressed below as averages for the three main zones. For comparison it may be noted that both Nockolds (1954) and Green and Poldervaart (1955) show a combined water content of 0.76 % in their averages of "normal alkaline basalts".

Hornfels zone (17 determinations)	0.41% $H_2O(+)$
Amphibole zone (13 determinations)	2.49% "
Zone of alteration (24 determinations)	2.99% "

In the almost completely fresh hornfels of the Camasunary area all the values are below 0.5 % and one is as low as 0.1 %. North of the Blaven - Slat Bheinn col there is an increasing degree of alteration in the zone, and four specimens from Sgurr nan Each contained between 1.7 and 3.0 % combined water.

The lavas from the amphibole zone all contain more than 1 % $H_2O(+)$, and the highest value was 3.5 %. The range in the zone of alteration is from 1.5 % to nearly 7 %, the latter being the figure for the highly altered basal flow on An Carnach.

The emplacement of the Cuillin Gabbro and later of the Red Hills Granophyres probably initiated the circulation of the hot aqueous fluids which were the agents of the mineralogical changes. It is however obvious that this was not merely a process of redistribution of water amongst the lavas. The amount of water driven off from the hornfels zone is insignificant compared with that added to the outer areas. The intrusions themselves may have provided some of the fluids, but the quota is not likely to have been large, especially in the case of the Gabbro. The bulk of the water must, then, have come from below, and there is an obvious source in the sandstones and shales of Jurassic age which underlie the lavas. Shales situated up to a mile or more from the margin of the Gabbro are significantly indurated and must have been considerably dried by the metamorphism. This idea gains support from the observation that the lowermost flows of the lava sequence are the most altered.

(ix) General Features of the Metamorphism.

Facies considerations. The following is a summary of the mineral assemblages found in the hornfels zone:-

Assemblage	Derived from
1. Plagioclase - clinopyroxene - olivine - ore.	Basalt
2. Plagioclase - clinopyroxene - orthopyroxene - olivine - ore.	Basalt
3. Plagioclase - clinopyroxene - orthopyroxene - ore.	Basalt
4. Plagioclase - orthopyroxene - ore.	Basalt
5. Clinopyroxene - orthopyroxene - (plagioclase).	Amygdales
6. Clinopyroxene - wollastonite - calcite.	Amygdales
7. Cordierite - potash feldspar - ore - plagioclase - mullite (?).	Shaley bole

Such assemblages are typical of the pyroxene - hornfels facies of Eskola (1939). The most common assemblages include plagioclase, and the two pyroxenes as their chief members. Ore is always present. In silica - poor varieties olivine is added to the assemblage, and orthopyroxene is successively reduced as olivine increases. Excess lime is expressed by assemblages such as 6, found only locally in an amygdular setting, while 7 is derived from a highly aluminous rock. If however the potash feldspar of this latter hornfels is sanidine, as is suspected, the assemblage becomes characteristic of the sanidinite facies (Eskola, 1939; Turner and Verhoogen, 1951). Wyatt's (1952) discovery that spurrite, rankinite and other high temperature calc-silicates occur in limestones adjacent to the Gabbro at Camasunary also suggests that the temperatures characteristic of the pyroxene-hornfels facies were locally exceeded in this thermal aureole.

On a previous page the mineralogy of the Strathaird amphibole zone has been compared with that of the low grade epidorites of the Scottish Highlands, and the conclusion reached that these rocks are best classified as tending towards a greenschist facies. Rocks of intermediate grade would therefore be expected between the pyroxene-hornfels and the low grade rocks. In these the pair albite-hornblende would first become stable (albite - epidote - amphibolite facies), as the pyroxene hornfels zone was approached, a more basic plagioclase would be associated with the hornblende (amphibolite facies). If such zones are present in Strathaird they must be very compressed, since the only rocks which might be referable to these facies lie in the narrow transitional belt on the outer margin of the hornfels zone. Lavas in this situation have not developed two pyroxenes, though there appears to have been some internal reconstitution of the primary augite. The original plagioclase has remained stable, and a brown hornblende is sometimes abundant, while an amygdale contained clinopyroxene, andradite, sphene, and relict prehnite. These hornfels might, therefore, be regarded as a thin zone formed under the conditions of the "amphibolite facies".

<u>Mineralogical and chemical changes in the derivation of hornfels from olivine basalts</u>. The most important mineralogical differences between the Strathaird olivine basalts and their hornfelsed equivalents are the presence of one pyroxene in the former and two in the latter, and the lower content of olivine in metamorphosed as compared with unmetamorphosed lavas. Between 40 % and 45 % of the bulk of both basalts and hornfels consists of ferromagnesian silicates. In the unmetamorphosed basalts this is made up of about 28 % clinopyroxene and 16 % olivine, while in the

hornfels the percentages average clinopyroxene 22 % orthopyroxene 13 %, and olivine 9 %. These figures would suggest that about one half of the metamorphic orthopyroxene is derived at the expense of the primary clinopyroxene and the other half at the expense of the primary olivine. This dual origin of the orthopyroxene is also apparent from the textural relations of the new grown minerals, for in many thin sections orthopyroxene can be seen developing simultaneously from both clinopyroxene and olivine.

In high grade thermal metamorphism of basic igneous rocks it is not uncommon for primary clinopyroxene to recrystallize as new clinopyroxene together with a lesser amount of orthopyroxene. If no other minerals are involved this must result in the new clinopyroxene being more calcic than the old, unless sufficient lime is taken into the plagioclase to counter balance the loss of iron and magnesia. Unfortunately, uncertainties as to the correlation of optical properties with chemical composition make it impossible to state definitely whether the hornfels clinopyroxenes are more, or less, calcic than those in unmetamorphosed lavas, but it does seem probable that a loss of iron, without notable change in the Ca : Mg ratio, was the dominant change which accompanied metamorphism. Another possibility is a three-cornered redistribution of ions involving olivine, so that the latter contributed more of the magnesia and less of the iron to the new orthopyroxene than did clinopyroxene.

A more important question is why olivine should have been converted to orthopyroxene at all, instead of merely recrystallized, for the reaction requires the addition of silica. There are two possible sources of this silica, the first being the oxidation of part of the iron and titanium contained in the clinopyroxenes, and the second in the addition of silica from some external source. Oxidation of some of the iron contained in an augite leaves the pyroxene richer in lime and magnesia, and releases silica, as can be expressed in a general way by the following equation:-

$$6\ Ca\ Mg\ Fe\ (SiO_3)_3 + O_2 \quad 6\ Ca\ Mg\ (SiO_3)_2 + 2Fe_3O_4 + 6\ SiO_2$$

Since the petrographic examination of the hornfelsed lavas shows that exsolution of iron and titanium from clinopyroxene was a usual feature of the metamorphism, it seems evident that some silica was made available in this way. However, if this process alone was responsible for reducing the average content of olivine from 16 % in the lavas to 9 % in the hornfels, it would be expected that the modal content of one would be significantly greater in the hornfels than in the unmetamorphosed lavas. In fact, this is not so, for the average ore content of 21 lavas was found to be 6.2 % (by volume), and that of 17 high grade hornfels, 5 %. Although ore is more abundant in those hornfels which are poor in olivine than in those containing a considerable amount of that mineral, this is also true of the unmetamorphosed lavas, as is shown below:-

Modal Olivine (vol. %)	Modal Ore (vol. %)	
	Lavas	High grade hornfels
>18	4.7 (7)	2.6 (3)
10 - 18	5.4 (9)	3.6 (4)
<10	9.5 (5)	6.4 (10)

Since the modal ore content of the lavas has been reduced, rather than increased, during metamorphism, it seems necessary to assume that silica has been added, to at least some of the hornfels, from some external source. This is supported by the chemical evidence, for in Table 6 it will be seen that three of the high grade hornfels (nos. 165, 183, and 205) contain two or three per cent more silica than is present in an unmetamorphosed olivine basalt (Table 3, no. 42) of the type for which these hornfels are thought to be derived.

If silica has been added to many of the lavas during metamorphism there follows the further problem of its origin. One possibility that was considered is that before metamorphism the lava amygdales contained excess silica which was redistributed throughout the rock during recrystallization. Such evidence as exists indicates that the opposite process was often operative however, for in many vesicular rocks (e.g. 182, 186, 205) it was noted that the surroundings of metamorphosed amygdales are richer in olivine than the rest of the groundmass, presumably because silica has been removed. This is especially the case when the meta-amygdales contain a high propertion of plagioclase, perhaps because the original amygdular contents include silica-poor zeolites such as analcite. A more likely explanation is that the lavas gained silica by reaction with intruding acid magma. One of the hornfels already described (162) provides petrographic and chemical evidence that such reactions did occur. Silica and alkalis were added to the lava in exchange for lime and magnesia, and the resulting hornfels contains an acidified plagioclase, and orthopyroxene as its only ferromagnesian silicate. A less extreme process on a broader scale may have affected many of the other hornfels. Siliceous veins of parametamorphic age are common in the lavas, though only numerous in the Camasunary area. Some of these may have arisen directly from the Gabbro, but in the Camasunary area at least, most of them are thought to be products of rhe_omorphic mobilisation of sediments, a subject more fully discussed in a later chapter. It seems significant that entirely olivine-free hornfels are more common in the Camasunary area than elsewhere.

CHAPTER VIII

THE GABBRO CONTACT ZONE - GENERAL FEATURES.

(i) Introduction

The margin of the Cuillin Gabbro forms a convenient limit to the western side of the area covered by this thesis. No attempt has been made to carry out a systematic study of the gabbroic rocks themselves, but since their contact with the country rocks is the most important igneous boundary plane in Strathaird it deserves some description.

The general shape of the Cuillin Gabbro as it appears on a map (see Plate 1) approximates to an oval, with the longer axis east-west and some eight miles long, and a north-south width of six miles. The symmetry of this plan form has been destroyed however by the encroachment of a lobate mass of younger granophyres and agglomerates from the north-east. This tongue of later rocks is some two miles wide and extends as far south as the north end of Loch na Creithach, leaving on its south-east flank the mile-wide belt of the Blaven gabbros as a promontary of the main mass forming the Cuillin Hills. The granophyres and agglomerates of which the tongue is composed are a part of the Western Red Hills centre of acid intrusion.

The Gabbro itself is far from being a homogeneous mass. Apart from both large and small enclosures of basalt lava there is an arcuate belt of peridotitic rocks three mile long to the west of Loch Coruisk, and the gabbros themselves have a sheeted structure inclined towards the centre of the intrusion, with textural and mineralogical variation both between the sheets and as banded structures within them. The best description to date of the complexities within the Gabbro is contained in a thesis by Carr (submitted 1952) dealing with the gabbros of Sgurr na Stri and Druim Hain.

Where not encroached on by later intrusions the margin of the Gabbro is nearly everywhere in contact with basalt lavas at the present level of erosion. For a short distance in the neighbourhood of Camasunary the sediments of Torridonian and Jurassic age which underlie the volcanics can be seen resting directly against the contact of the Gabbro.

(ii) External Form of the Cuillin Gabbro

Forbes (1845) was the first to speculate on the external shape of the Cuillin Gabbro, suggesting that it was essentially a thick sheet, thinning marginally and inclined at a small angle to the south-east. Later Harker (1904) also subscribed to this view and describes the Gabbro as laccolithic in form with an inwardly sloping and undulating floor. Its emplacement occurred, he supposed, by the repeated injection of centrally inclined sheets fed through dyke conduits. He considered the textural and mineralogical banding within the sheets, first noted by Geikie and Teall (1894), to be some kind of flow structure. Harker arrived at these conclusions because his field work suggested to him that the contact always dips inwards, often at a low angle, and that the floor of the intrusion never descends far below sea-level. Harker's construction of a structure contour map on the base of the Gabbro makes use of these assumptions together with the trace of the contact on the topography and its dip where observable (op.cit.p.86). The resulting map shows a deep sycline underlying Loch Coruisk, anticlinal rises under Bruach na Frithe and Marsco, and synclines below Glen Sligachan and Blaven. The Marsco anticline was taken to be a secondary feature resulting from the intrusion of the later granophyres. It should be noticed that these structures are features of the supposed base and are not paralleled by the observed sheeting or banding; indeed the general lack of correspondence between internal structure and the external form proposed by Harker is one of the chief reasons for doubting the validity of the latter's theory (Richey, 1932). The evidence from the attitude of the contact plane is also equivocal, for steep junctions are probably as numerous as shallow ones, as Harker's maps show, though it is true that the inclination is usually appears to be inward. Shallow contacts would seem to be most common on the western and southern margins, though exposures are few, while steeper contacts ar_e to be found on the north and east. Moreover Harker's assumption that the intrusion was floored at no great depth forced him to assume that synclines underlay the valleys while anticlines lay beneath the hills, a circumstance that he attempts to account for by even more insecurely based suppositions regarding the shape of the top of the intrusion and its consequent effect upon erosion (op.cit.p.442).

Richey (1932) has made the suggestion, based on his experience of the igneous complexes of Mull and Ardnamurchan, that the Cuillin Gabbro may be a deeply dissected cone-sheet system. In support of this idea he refers to Harker's description of the Gabbro as consisting of centrally inclined sheets, and to a tendency shown on Harker's maps for these sheets to dip more steeply as the centre of the mass is approached. The larger enclosures of basalt lava, which

Harker describes as separating some of the sheets, are compared with the screens of basalt or other country rock which are frequently present between closely spaced cone-sheet systems elsewhere. Post-Gabbro doleritic cone-sheets ("inclined sheets") were described by Harker. Their distribution conforms fairly closely with the outcrop of the Gabbro and they incline towards the same area as do the banded structures within the gabbro sheets, though focussing at a lesser depth. (Harker, op. cit. pp. 91 and 367). Richey's theory would appear to reconcile internal and external structure better than that of Harker. The increase of inclination of the banded structures inwards as shown on Harker's maps, would seem to be rather less regular than would be expected, though possibly the presence of more than one system focussing to different depths could account for this irregularity. If Richey is correct, the external shape of the Gabbro might be expected either to conform to the inclination of the outermost cone-sheets or to consist of a feather edge of tapering sheets. The field evidence would seem to fit into this interpretation except where, as on Blaven. the contact is steep and smooth.

Stewart and Wager (1947) have observed that some of the banding in the Cuillin Gabbro shows gravity stratification. At Skaergaard, in East Greenland, Wager and Deer (1939) had previously interpreted similar banding of gabbros as due to rhythmic crystal accumulation in a large body of magma. Apart from the banding this process has also given rise to a saucer-shaped layering structure and regular variations from below upwards in rock type and mineral composition. Using Wager's methods Carr (thesis, 1952) has interpreted the Sgurr na Stri-Druim Hain sector of the Cuillin Gabbro as part of a large intrusion differentiated in place. As at Skaergaard the sheet structure and banding are regarded as a result of the differentiation in mineral composition from below upwards also exists in Skye, though in the rocks at present exposed the range is more limited than at Skaergaard. The nature of the external contact on Sgurr na Stri is considered by Carr, who comes to the conclusion that it is probably steeply inclined inwards. Though the Skaergaard intrusion has the shape of an inverted and tilted cone there seems no necessity to suppose that other intrusions with related internal histories have similar external forms, but if Carr is correct in his interpretation it may well be that the sub-surface extension of the Cuillin Gabbro is deeper than has previously been supposed.

Recent geophysical work by Tuson (unpublished thesis, 1960) provides strong evidence that basic rocks continue to great depth, not only below the Cuillins, but also beneath the granitic rocks of the Red Hills. The following is a quotation from Tuson's thesis (p. 56):-

"The high positive Bougher Anomalies (73 mgals.) over Central Skye are interpreted in terms of a basic vertical cylinder of radius five miles extending into the Intermediate layer at a depth of 17 Kms.. Departures from the cylindrical form indicated by the gravity residuals suggest that the anomalous mass is slightly eccentric with its major axis trending NE-SW.. This is consistent with the three main plutonic centres being underlain by three interacting basic vertical cylinders representing original magma chambers. There is also a possibility that the basic mass widens towards the base ...... "

Both Reynolds (1952) and King (1953) have suggested that in some parts of Skye, at least, gabbroic rocks have arisen in situ by the transformation of basaltic lavas. Some support for this theory might be gained if it could be shown that the base of the lavas passed continuously into the base of the Gabbro, and that between gabbros and basalts there was some sort of transitional zone. In fact, at the few places where the base of the lavas is exposed the contact of the Gabbro continues downwards below that horizon, while contacts between gabbro and basalt are nearly always sharp. A study of the metamorphosed basalts adjacent to the Gabbro has shown no indication of a transition between the two rock types (see Chapter VII), and though lavas metamorphosed to high grades often contain similar minerals to those in the gabbros, texturally they remain quite distinct. Also, if the sheeted structure of the Gabbro is considered to be an inheritance from pre-existing lava flows the central inclination of these sheets would seem to pose a very difficult structural problem. Some of these objections might be circumvented by assuming the existence of faults for which there is no other evidence, but in general there is little to be said in support of such a theory as far as the Cuillin Gabbro is concerned.

(iii) The Gabbro Contact in Strathaird.

The general features of the contact of the Cuillin Gabbro, as it is exposed in Strathaird, are described below, while in the succeeding chapter a more detailed treatment is given to a small sector of the contact in the vicinity of Camasunary.

The contact enters the western margin of the area on the south flank of Sgurr na Stri, crosses Strath na Creitheach a mile north of Camasunary House, and then ascends steeply into the flank of the south ridge of Blaven. From there it traverses the east face of the Blaven range at heights between 1,000 ft. and 2,000 ft. O.D., and is finally cut off to the north, on Belig, by the agglomerates of Coire na Seilg. On the map the general shape of the contact is arcuate towards the south-east, though this is modified in detail by variations in the style of intrusion and by the relief.

Sgurr na Stri. Sgurr na Stri is a low but rugged mountain built of gabbro, but on the headland of Rudha Ban and the flanking shores of Loch Scavaig on the south side of the hill is a belt of country rocks consisting of Torridonian sandstones, and basalt lavas intruded by a thin sheet of granophyre. Only the basalts lie directly adjacent to the gabbros. To the west, near Rudha Buidhe, the contact passes beneath an arm of the loch, while to the east it crosses the Camasunary River about 300 yards above its outlet. The contact is at its highest above Rudha Ban, in the middle of the sector, where it lies some 400 feet above the sea, and the general convexity of the contact trace as it passes over the headland may be the expression of an inclination to the north.

The line of juncture between gabbro and basalt lavas varies in its nature from clean cut and smooth to vëined and irregular, though however complex the contact, the two rocks types retain their separate identities; there are no transitional rocks. Near Rudha Buidhe the irregular type of contact prevails but it is nevertheless possible to see, in a section of the shore on the west of the headland, that the general dip of the contact plane is a gentle one, and is inclined to the north. Several flat lava xenoliths up to tens of feet long are enclosed within the gabbro and are similarly inclined to the north. East of Rudha Buidhe the gabbros continue to form a veining contact for some 600 yards, and several irregular and isolated masses of gabbro lie outside the contact, sometimes as far as 300 feet from it. These gabbroic masses intersect similarly irregular intrusions of feldspar-phyric dolerite and are themselves cut by thin sheets of biotite microgranite.

The line of contact becomes smoother as it traverses the promontary above Rudha Ban, but there is some repetition of the veining on the descent to Camasunary. The margin of the gabbro is embayed at several points and a number of lava xenoliths are enclosed within it, the largest noted being 40 yards in length. Two small exposures of the contact plane provided dip readings of 12° and 7° to the N.N.W.. ~~(see photo Plate~~

).

Dykes with N.N.W. orientations are numerous throughout the Sgurr na Stri exposures. Most of them cross the Gabbro contact without deviation, but there are also a considerable number of early dykes which are cut short by the Gabbro and have been metamorphosed together with the enclosing basalts. Such dykes characteristically follow irregular courses. An exposure on the Camasunary side of the hill (c. 100 ft. O.D., directly west of Celtic Cottage) shows an early dyke, 15 feet in width, which has been completely hornfelsed and veined by gabbro but nevertheless continues its course for several yards within the contact.

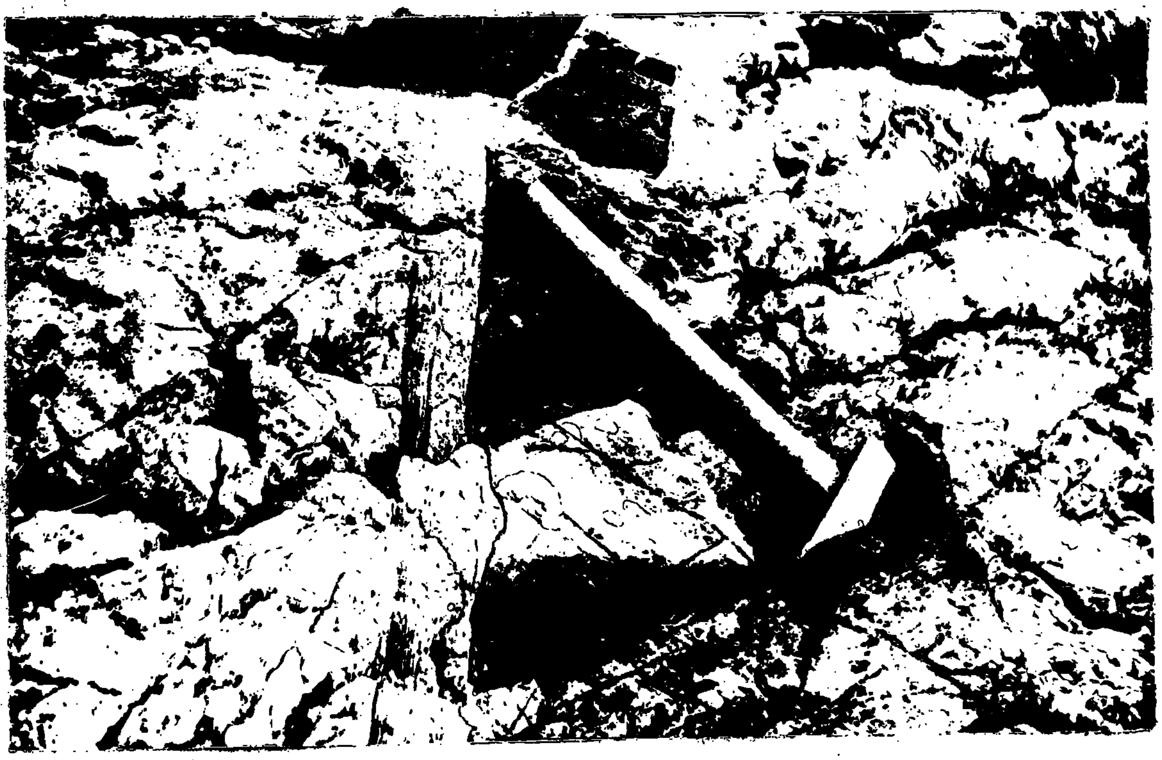
On the western side of the large gully which cleaves the middle of the south face of Sgurr na Stri these dykes serve to demonstrate an interesting feature of this part of the contact. At this point several of the early dykes are seen to cut Torridonian sandstones, but in places the dykes themselves have been broken up into echeloned angular fragments, and the bedding of the adjacent parts of the Torridonian partly broken up and disturbed. There is no indication that the fragmentation was caused by external addition of material and it appears that the Torridonian itself became partially mobilised and intruded the dykes (see photo Plate 26). The same process has been operative in the neighbourhood of Camasunary, where the evidence is even clearer and is more fully discussed in the following chapter.

Thin, highly leucocratic veins are common in the contact zone and within the gabbros. They follow various jointing directions and are sometimes numerous enough to form net-veining patterns. The veins precede in age the post-Gabbro N.N.W. dykes and were probably intruded soon after the emplacement of the Gabbro itself. They are not to be confused with the earlier veining which breaks up the pre-Gabbro dykes. The establishment of a close-spaced system of N.N.W. joints guided the courses of the late dykes and these joints transect all the other rock types. A number of narrow belts of crushing also follow this direction and are often slickensided. These belts now lie in linear depressions up to 25 feet wide.

Retrograde metamorphism of some of gabbroic and metamorphic pyroxene to amphibole is the latest event

PLATE 26 (opposite.) Fragmentation of early dykes in the Torri--donian, west of Rudha Ban.

The two photographs show metamorphosed pre-Gabbro dykes veined and broken into fragments by the partial rheo--morphism of the enclosing Torridonian arkoses.



recorded. The process has been especially active along joint planes and crush belts, and the contact itself also appears to have had a controlling influence for in its vicinity (i.e. usually within 30 feet) it is common for whole leaves of the gabbro to have been altered to greenish, rotted looking rocks.

Carr (1952) is of the opinion that the Sgurr na Stri sector of the Gabbro probably possesses a steep margin, but the writer considers that the field evidence is more in favour of a north-north-westerly inclination not exceeding 25°. The vertical interval directly observable is, however, limited to 400 feet, and it may well be that the low inclinations of the exposed contacts are only local incidents on a generally steep margin.

In Chapter VII it was pointed out that the width of the hornfels zone in the lavas is broader on Sgurr na Stri than elsewhere along the contact in Strathaird. This may partly be due to a low inclination of the contact plane. Such an attitude would not only increase the apparent surface width of the zone in the horizontal plane, but might also lead to higher temperatures than usual being attained outside the contact due to the retention of heat below ahanging wall of hot gabbro.

<u>Camasunary</u>. Between Loch na Creitheach and Camasunary bay the contact zone is well exposed in glacially-smoothed hillocks. The country rocks consist of a complex of Torridonian arkoses, basalt lavas, and numerous early dykes. The nature of the contact is similar to that on Sgurr na Stri; in places sharp and planar and elsewhere with veins and projections of gabbro extending into the country rocks.

Xenolithic enclosures of lava and metadolerite are common, and near the Camasunary River several small banded schlieren are probably of sedimentary origin. Pegmatitic patches of gabbro, sometimes with granophyric cores, have been attributed by Carr (1952) to enclosure and subsequent melting of fragments of quartzose sedimentary rock, with resulting contamination giving rise to coarse-grained envelopes of quartz-gabbro. He compares these bodies to certain inclusions at Skeargaard (Wager and Deer, 1939). Most xenoliths are found within a marginal zone of gabbro characterized by variable textures and grey weathering surfaces. About 100 yards within the contact these variable gabbros are succeeded by later, more massive and homogeneous gabbros with a reddish weathering crust (Carr, 1952).

An exposure situated 250 yards south of the S.E. corner of Loch na Creitheach shows a contact of gabbros against Torridonian which gave a value of 30° N.N.W. for the local dip of the contact plane.

Blaven. In the locality of the 300 foot hill of An t-Sron, which lies at the base of the south ridge of Blaven, the homogeneous gabbros cut out the variable gabbros along a contact plane which dips 15° N.W. Variable gabbros reappear for a short distance on the north side of An t-Sron but are cut out once more as the angle of the contact steepens and rises rapidly to a height of 1,250 ft. O.D. on the western flank of the south ridge of Blaven. The inclination again becomes shallow as the margin of the Gabbro passes over the crest of the ridge into Coire Casteail, where dip values between 12° and 45° N.W. were obtained. The angle soon becomes steep once more as the Blaven-Slat Bheinn col is approached (c. 1,800 ft, O.D.) and the contact continues across the east face of the mountain with a W.N.W. inclination of about 80°. Over most of the Blaven section the contact is sharp and smooth, though a broad, dyke-like projection extends outwards from the contact in upper Coire Uaigneich.

Over most of the distance between An t-Sron and the Blaven-Slat Bheinn col the Gabbro is in direct contact with Liassic sediments, which, as a result, have been indurated by metamorphism. Most of these sediments are shaley, but on the hillside above An t' Sron, at a height of c. 800 ft. O.D., the basal limestones of the Lias are in contact with the gabbros. At this point metasomatic exchange has led to the development of an interesting suite of calc- and magnesium-silicates in the limestones and of a calcium-soda rich facies in the adjacent gabbro, which have a whitened appearance (see also Wyatt, 1952).

From the Blaven-Slat Bheinn col northwards the country rock at the contact is basalt lava. Unlike the Sgurr na Stri and Camasunary sectors the gabbros here enclose only very rare fragments of lava, a fact which is possibly related to the increased steepness of the contact plane. Pegmatitic streaks and patches are, however, still common within the marginal gabbros, but leucocratic veining is sparse. Amphibolitization of the gabbroic and metabasaltic pyroxenes is locally severe, as at the Blaven-Slat Bheinn col.

Clach Glas to Belig. North of Blaven the ridge continues through Clach Glas, Sgurr nan Each, Garbh-bheinn, and Belig, all of which lie on or near the edge of the Gabbro pluton. Deep gullies separate the peaks and so expose the contact through a considerable vertical relief, amounting in the Allt Aigeinn, between Sgurr nan Each and Belig, to about 1,000 feet. This section of the contact therefore provides a considerable amount of evidence on the local attitude of the contact plane. Between Blaven and Clach Glas the inclination is steep; about 60° to the W.N.W.. As the contact crosses the ridge of Sgurr nan Each the dip lessens to 45°, but again steepens on the descent to Allt Aigeinn, which it crosses without deviation. On the rise to the summit ridge of Belig the angle again decreases to about 50°.

As on Blaven the contact surface is in general smooth, and there are few enclosures of country rock within the gabbros. Several dyke-shaped projections of the contact are again present, and sometimes small lenses of gabbro with steep contacts continue their lines in the country rock. The two largest examples of such bodies are found in the gully between Clach Glas and Sgurr nan Each and in Allt Aigeinn. The latter, which lies at a height of 1,300 ft. O.D. on the south face of Belig, is some 350 yards in length, and since it dips steeply in the same direction as the slope it shows a deceptively wide outcrop on the map.

The marginal gabbros of this section are more variable than on Blaven, crushing and amphibolitization reach their maximum, and on the col to the north between Belig and Glas Bheinn amphibolitization, epidotization, and the injection of acid veins have all acted strongly on the crushed gabbros. It seems probable that shattering of the gabbros accompanied the formation of the adjacent Coire na Seilg agglomerates, while the processes of alteration followed the emplacement of the granophyre plutons.

Summary. That part of the contact of the Cuillin Gabbro which was mapped in the course of this study provides evidence of two contrasted styles of marginal relationship. On the south side of the pluton, between the western arm of Loch Scavaig and Camasunary, the contact plane is apparently inclined at a moderate angle inwards, the contact surface is often highly irregular in detail, and there is frequent enclosure of the country rocks, particularly lavas. In the Blaven range, on the south-east side of the pluton, the contact surface becomes much steeper, though still dipping inwards. The junction is nearly always smooth, and there is little enclosure of country rock. From Harker's maps it would appear that the shallow type of contact continues west of Loch Scavaig into the Glen Brittle area, on the western side of the Gabbro, and in this section there are frequent large enclosures of lava within the gabbro. Accompanying these differences in contact attitude there is another which concerns the attitude of the surrounding country rocks. It will be shown in a later chapter that in Strathaird the Gabbro appears to have exerted a strong outward push during intrusion, so that the country rocks have been gently folded on arcuate axes parallel to the margin of the Gabbro, and small faults have been formed in various orientations. There are no indications of similar structures on the western side of the intrusion, where the country rock lavas apparently continue their gentle westward dip right up to the contact. It would seem therefore, that on the eastern side the gabbro magma was forced both upwards and outwards, while on the western side it gained its position by gently levering open the flat-lying sheets of lava and inserting itself between them.

(iv) Petrography.

Variable gabbros of Camasunary. The narrow zone of variable gabbros along the contact at Camasunary range in composition between olivine gabbros and quartz gabbros, and also includes some noritic types. Many of the variations are probably due to contamination by quartzose sedimentary rocks.

Carr (1952) has remarked that these rocks sometimes show slight chilling, unlike most of the contact gabbros. This feature can be observed in exposures situated about

300 feet east of the Camasunary River, where the granularity at the contact (Spec. 128) is 0.5 mm., while 40 yards within the contact (Spec. 129) this has increased to 0.8 mm.. Both of these rocks are quartz gabbros typical of the contaminated facies. When freshly broken they present a more leucocratic appearance than a normal gabbro, and in thin section the texture is seen to include felsic patches with a coarser grain than the body of the rock. These may represent the positions of the original contaminating material. Most of the feldspar in the rock is found as 0.75 mm. subhedral prisms, but in the felsic patches the grains are larger and irregularly bounded. Zoning indicates that the early formed plagioclase was bytownite, for a core of this material is present in most grains and carries a normally zoned mantle with the composition of sodic labradorite at the outside. The accretion has continued longest in the felsic patches, where interstitial quartz amd rare micropegmatite are also to be found. Clinopyroxene is the predominant dark mineral, but orthopyroxene assumes a greater importance than in the normal, uncontaminated gabbros. In this case it is an optically positive variety without pleochroism and it contains blebs of exsolved clinopyroxene. The clinopyroxene forms 1 mm. grains with

an intersertal relation to the feldspar. Basally-orientated exsolution lamellae and faint zoning are not uncommon. Ore is the most abundant accessory, most of it building late crystallized, ramifying masses up to 2 mm. across, although smaller and better shaped grains are also present. Other accessories include granular sphene and small plates of biotite, both as coatings to ore grains, while apatite prisms up to 0.5 mm. in lengths are sparsely scattered. Secondary minerals include uralite (sometimes associated with late quartz), chlorite, epidote, and a clay mineral.

A common feature of the variable gabbros is that their feldspar frequently shows strain twinning and bending, a characteristic shared with many of the rocks immediately outside the contact, but not with the more homogeneous gabbros found at the contact elsewhere. This, together with the variability and contamination of these rocks, their marginal chilling, and the fact that the homogeneous gabbros appear to be later, suggests that the variable gabbros are a part of an early gabbroic intrusion, which probably immediately preceded the injection of the main mass of magma.

Homogeneous marginal gabbros. The marginal gabbros along the greater part of the contact are homogeneous, poorly banded olivine gabbros and eucrites. Typical of the eucrites is a specimen (251) collected from west of An t-Sron, Camasunary, from the belt of rocks which cuts across the local variable gabbros. The texture is allotriomorphic, and the granularity about 1.5 mm.. The early plagioclase forms half-millimetre prisms while later anhedra up to 4 mm. across have grown interstitially. The twinning of these larger feldspars is complex, and many of them are normally zoned, with an average composition of about An 77. Clinopyroxene is the predominant dark mineral, and is partly ophitic to the early plagioclases, often with lamellar exsolutions parallel to (001) which are presumably of orthopyroxene. The latter mineral also forms discrete grains, and in one case a partial mantle of clinopyroxene is wrapped round an orthopyroxene and is in optical continuity with vermiform clinopyroxene exsolutions within it. The orthopyroxene is faintly pleochroic, optically negative, and partly altered to bastite. Olivine is pseudomorphed by rounded masses of talc and chlorite averaging 1 mm. across. Ore occurs sparsely in the slice as well-formed grains, but the hand specimen shows that most of the oxides are gathered into large aggregates several millimetres across.

Of similar constitution to the rock described above, but with a less basic feldspar, is a specimen (117)* collected from the dyke-like projection of the contact in Coire Uaigneich. The mode is as follows:-

Constituents	Volume Percentages
Labradorite	55.5 %
Clinopyroxene	33.9 %
Orthopyroxene	4.8 %
Olivine	5.3 %
Ore	0.5 %
	100.0

In hand specimen this rock presents a dark reddish-grey, rough surface when weathered, and fresh is coarse grained and grey, with pale green tints due to alteration. In thin section the texture is seen to be allotriomorphic, with over 50 % labradorite (An64), most of which is in large anhedra up to 5 mm. across, while the smaller grains tend to be subhedral. Zoning is slight and normal, with a discontinuity against a euhedral, calcic core. Clinopyroxene occurs in colourless anhedra of similar size to the feldspar, with fine, basal exsolution lamellae which are absent

* Plate 27

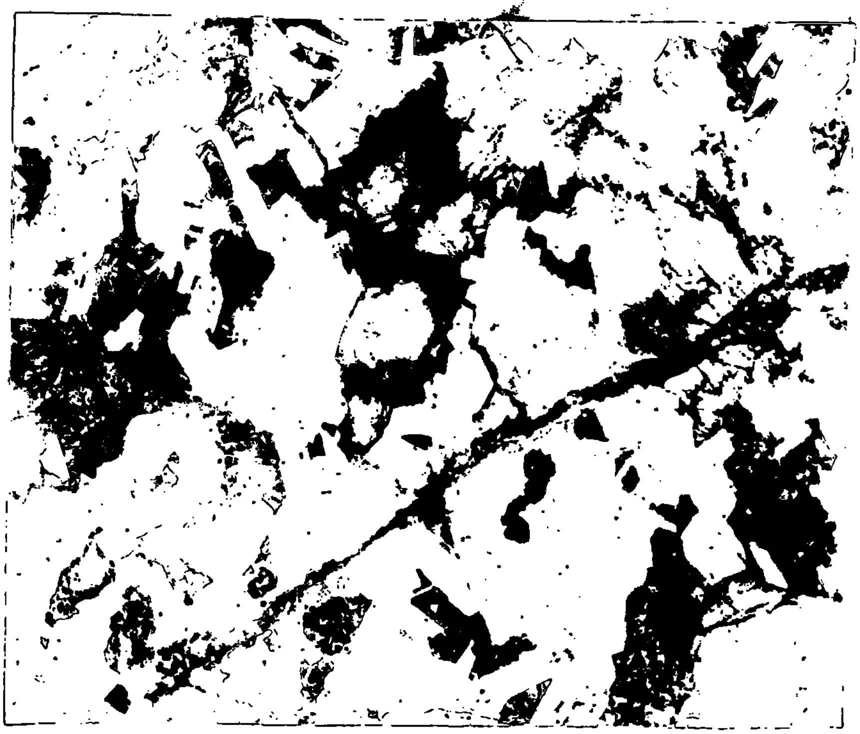


PLATE 27 Microsection: A specimen from the margin of the Cuillin Gabbro on Blaven.

(Spec. II7) × 6. The slice contains plagio--clase, both in large anhedra and smaller subhedral laths, partly schillerized clino--pyroxene, altered olivine, ore, and a little interstitial orthopyroxene. It is crossed by a narrow crush zone containing chlorite and fibrous amphibole.

in the cores of the grains. The orthopyroxene has grown interstitial to the feldspars and also wraps round olivine. It is usually altered to either uralite or bastite, and frequently contains unaltered blebs of exsolved clinopyroxene. The rounded olivines are now converted to mixtures of chlorite, serpentine, and ore.

Similar gabbros form a zone several hundred feet thick along the contact both north and south of Coire Uaigneich, but new types appear higher up on Blaven. One example of these (Spec. 232) will suffice here. It is a red weathering rock with a spotted appearance on fresh surfaces. The slice shows it to be a feldpathic eucrite with a troctolitic tendency. Large poecilitic augites reach 6 mm. in diameter and enclose tablets of plagioclase and rounded olivines. Around the augites are feldspathic areas in which are set rounded olivines, sometimes with a thin rim of orthopyroxene, and a little interstitial clinopyroxene. The feldspar ia s bytownite (An83) and has an average granularity of 0.75 mm., with occasional phenocrysts up to 3 mm.. The mode of this rock is as follows:-

Constituents	Volume Percentages
Bytownite	68.2 %
Olivine	20.5 %
Clinopyroxene	8.7 %
Orthopyroxene	1.7 %
Ore	0.9 %
	100.0

North of Coire Uaigneich the gabbros become progressively more altered and crushed. In an olivine eucrite (Spec. 275) collected from the contact plane on the crest of Sgurr nan Each uralitization is far advanced, and narrow crush zones of comminuted fragments traverse the slice. An interesting primary feature of this rock is the presence of late-stage pegmatitic material similar to the pegmatitoids found in the basalt lavas. It forms a small patch rich in large, poeciloblastic ore grains, apatite, and sphene.

Even more complete reconstitution is seen in parts of the large, curving, dyke shaped mass of gabbro which is situated on the north-eastern slopes of Belig, on the northern margin of the area. This rock has been almost completely crushed, and while fragments of recognizable plagioclase remain there is no trace of pyroxene. Instead, a green hornblende has grown in the crushed material, some of it in small (0.1 mm.) grains scattered throughout, and the rest forming clusters as much as 6 mm. across, with individuals up to 2 mm. long. A few of these large crystals are bent, probably indicating that the stresses which caused the crushing were still operative at the time of their growth.

<u>Xenoliths.</u> Almost all the inclusions in the contact gabbros are recognizable as meta-lavas and metadolerites. The petrography of these xenoliths is essentially similar to that of their in situ counterparts already described in Chapter VII. Inclusions of sedimentary origin are rare, though if Carr (1952) is correct, the quite common pegmatitic patches with granophyric cores have their origin in the melting of sedimentary enclosures. There are also, at Camasunary, a number of small xenoliths which may be modified sedimentary rocks. They are found as leuticular schlieren, a foot or two in length, and most are strongly banded in a manner which suggests derivation from a laminated rock. In thin section (Specs. 130 - 132) their unusual composition is revealed, for they consist almost entirely of a basic plagioclase mosaic, usually fine grained (0.2 mm.) but with some bands of coarser,

tabular grains (0.5 mm.), and scattered euhedral individuals up to 3 mm. long. These larger grains are crowded with inclusions, some of which are identifiable as quartz. The latter mineral also occurs sparsely in the groundmass and in late-stage veins. Strong zoning is present in many of the plagioclases, both large and small, with reversals against euhedral cores. Dark minerals include ore, in streaky bands of cubic and acicular grains, a few plates of biotite, and sparse clusters of small, pleochroic granules, possibly orthopyroxene. A large amount of secondary micaceous material is found in some of the bands. It attacks plagioclase and in one case was noted as replacing a squat, prismatic mineral embedded in the feldspar, perhaps cordierite. Similar rocks were described in the same area by Carr (1952), who found that they sometimes develop a noritic phase adjacent to the enclosing gabbro. He compares them with the banded inclusions found in the hypersthene gabbro of Ardnamurchan by Wells (1951), who considers them to be of sedimentary origin, though modified of reaction with the gabbros. Brown (1955), however, suggests that the Ardnamurchan inclusions are thermally metamorphosed, layered ultrabasic rocks carried up by the gabbro magma from a deeper level in the intrusion.

In the opinion of the present author, the textures of the banded inclusions at Camasunary suggest that they are derived from a layered anorthosite, and that they are only slightly metamorphosed, for it seems unlikely that the large euhedral plagioclase and the complex plagioclase zoning could arise by thermal metamorphism.

Post-gabbro acid veins. All the specimens from acid veins which transect the gabbros possess a similar constitution, and the same material can be recognized in veins penetrating the country rocks for a few hundred feet outside the contact. The sheets of biotite microgranite which occur on Sgurr na Stri, between Rudha Buibhe and Rudha Ban, belong to this group.

In hand specimen (e.g. 405,412) the material of the veins is white or pale grey and speckled by fine chlorite. The grain is fine to medium. Thin sections contain between 40 and 60 per cent quartz together with feldspar and sparse altered biotite, while the average granularity varies between 0.3 and 0.5 mm.. The quartz is largely discrete but also forms rudimentary intergrowths with orthoclase. Laths and short prisms of oligoclase are common and are strongly zoned to albitic exteriors. Both feldspars occasionally build phenocrysts up to 2 mm. across. The sparse biotite is crystallized in ragged, half millimetre plates, sometimes poecilitic. When fresh it is reddish-brown, but for the most part it is replaced by chlorite and epidote. Accessories include rare grains of ore, apatite and sphene.

CHAPTER IX

THE GABBRO CONTACT ZONE - A DETAILED STUDY AT CAMASUNARY

(i) Introduction.

During the period devoted to general mapping it was noted that one of the best localities for making a detailed study of a small sector of the Cuillin Gabbro contact zone lies in the small area of hillocks between Loch na Creitheach and Camasunary bay. The favourable factors include a high percentage of exposure and the presence of a representative selection of rock types. Moreover, whereas along the greater part of the contact the gabbros only seen where it is emplaced into basalt lavas, at Camasunary deeper erosion has reached the top of the sub-lava surface and the relations of the underlying sediments to the intrusion are displayed.

As related in the preceeding chapter, the contact plane of the Gabbro in the Camasunary area appears to be a rather irregular surface with an apparent dip at a moderate angle towards the N.N.W.. Small exposures of the surface have inclinations between 15° and 30° N.N.W., while the general trend of the contact trace across the valley suggests an average dip of about 25°. Small patches of north-westerly dipping lava lie against the Gabbro on both sides of the valley, but in the centre the underlying Torridonian arkoses are seen to continue right up to the edge of the Gabbro. A small mass of Lower Lias limestone overlies the Torridonian, but is probably bounded by faults. There is an unusually abundant development of pre-Gabbro minor intrusion piercing the arkoses and lavas, while a later swarm of dykes transects both country rocks and Gabbros.

A representative strip of the Camasunary contact zone was mapped on a scale of 1:1,250 (50 inches to 1 mile), the area covered being about one third of a mile in length and 200 to 250 yards in width. A copy of this map will be found in the back pocket of this thesis, and the reference numbers given in the succeeding discussion refer to the grid drawn on the map to facilitate the finding of localities.

Two aspects of the local geology are of particular interest. The first of these is that good exposures allow the structure, sequence, and composition of the pre-Gabbro suite of minor intrusions to be easily examined. Harker (1904) does not refer to these early intrusions, and his mapping of Camasunary suggests that he supposed that nearly all the dykes in the neighbourhood post-dated the Gabbro. He does, however, show a number of dyke-shaped "feeders" which he thought to be contemporaneous with the intrusion of the Gabbro. It became evident during this study that a considerable variety of small igneous bodies were intruded prior to that event. Moreover their present distribution suggests that they were probably most numerous within the same general area that is now occupied by the main body of gabbro, and they may have been the precursors of large scale intrusion.

The field work also revealed an interesting relationship between the pre-Gabbro intrusions and the Torridonian arkoses into which they were emplaced. The evidence strongly suggests that at the time of intrusion of the Cuillin Gabbro the temperatures in the country rocks became high enough to allow local melting of the acid sediments, while the igneous intrusions, being more basic, remained essentially solid.

A discussion of these two aspects of the geology occupies the greater part of this chapter.

(ii) The Pre-Gabbro Minor Intrusions - Field Relations.

Intrusions belonging to the pre-Gabbro suite are numerous along the Camasunary contact, and can be distinguished with certainty from the post-Gabbro dykes as far as Abhuinn nan Leac, which lies parallel to the contact and is about three-quarters of a mile distant from it. In the exposures of that stream the early dykes are much rarer than at the contact itself, and are completely overshadowed by the later swarm.

The early group of intrusions is entirely basic in character, but there are all variations from picrites and gabbros to fine-grained olivine-free dolerites. Adjacent to the contact in the centre of the Camasunary outcrop is a mass of metamorphosed dolerite some 600 yards in length and 50 to 100 yards in width. This is shown on the 1:1,250 map as a broad belt aligned in a direction slightly east of north and lying in the centre of the sheet. Further to the east is a complex of early minor intrusions cutting the Torridonian, and including several composite dykes.

Although many of these intrusions are dykes, others are irregular, sometimes branching masses. Both pre- and post-Gabbro intrusions possess a preference for north-north-westerly orientations, but the two groups are easily distinguished by the following criteria:-

1. Form - many of the early intrusions are highly irregular, but even those which show a definite dyke habit are prone to rapid thickening and thinning and to frequent offsetting. The post-Gabbro dykes, however, follow straight or slightly curved courses and possess parallel walls. They rarely offset, and when this does occur the two terminations are symmetrically

thinned and there is frequently an exposed bridge between. The irregularity of the early dykes is a consequence of a sparsity of joints at the time of their intrusion. Most of the fractures in the area are of post-Gabbro age, and from this follows the second criterion.

2. Jointing - both country rocks and early intrusions are cut indiscriminately by a close-spaced N.N.W. joint set. Many of these fractures have been later sealed by uralite, quartz, and epidote so that they form ridges on weathered surfaces (see photo, Plate 3I). The early intrusions are sometimes also affected by small N.E. faults with shifts of a few inches to a foot or so in the horizontal plane.

3. Metamorphism - over the inner half of the hornfels zone of metamorphism, which at Camasunary is about 300 yards wide, indications of a metamorphic fabric are usually visible in hand specimens of the early intrusions. These include a granulated appearande and, in some cases, the presence of biotite metacrysts. Such features are not easily detected in the coarser grained rocks however.

4. Weathering - thermal metamorphism has welded together the early intrusions and their Torridonian surrounds so that they weather as a unit. The later

dykes, on the other hand, often give rise to ridges or channels. Moreover the prismatic and longtitudinal joints usually present in the latter are not seen in the early dykes, probably because they have been obliterated by the welding.

<u>The smaller intrusions</u>. Under this head are included all the dykes and masses intruded into the Torridonian with the exception of the large mass of dolerite along the Gabbro contact.

In shape, most of these small intrusions are dykes, averaging about a foot across, though varying from veins up to a width of four feet. There are also a number of irregular and rectangular bodies to which no morphological name can be applied. Dolerites of fine and medium grain are the most common rock types, but gabbros and peridotites are not uncommon.

Cross-cutting and marginal chilling provide evidence for three main phases of injection:-

1. N.N.W. dykes and masses of gabbro and picrite. Examples of dyke-form are to be seen on the map in sections H 14 and 15 (picrite) and in J 4 (gabbros). In J 15 is a ramifying mass of gabbro possessing a central nucleus 100 feet long and 30 feet wide which sends out dyke prolongations to the N.N.E. and S.S.W.. In contrast, the mass of similar material in G 16 has

a smoothly rectangular outcrop measuring 70 feet by 20 feet.

2. N.N.W. dykes and masses of fine and medium grained dolerites, sometimes macro-porphyritic. These injections form the bulk of the dyke complex, and the map shows them to have a more or less evenly spread throughout the Torridonian outcrop. In three cases, however, they group together to form large composite dykes with the earlier gabbros and picrites. These dykes can be seen on the map passing through J 4, J 12, and J 16, respectively. They are as much as 50 feet wide, but are not so regular in form as the large multiples seen on the lava plateau.

3. N.E. dykes and cone-sheets (?). N.E. dykes, generally less than a foot in width, are locally numerous and cut all other pre-Gabbro intrusions. Some of them dip at moderate angles to the N.N.W. and may be members of a cone-sheet complex. Carr (1952) refers to a remnant of an early cone-sheet enclosed within the Cuillin Gabbro itself.

Although there are numerous other intersections to illustrate the above intrusion sequence the composite dykes provide the best examples. The most southerly of the three composites is composed of brown weathering picrite sliced up into lenses by dark grey dykes of fine dolerite running N.N.W., and the whole dyke is cut across by several of the small N.E. dykes. The central member of the group of composites is basically a multiple injection of N.N.W. dolerite dykes intersected by N.E. dykes, while an apparently connected prolongation to the north-east (in J 11) consits of gabbro cut by dolerite. The northern composite dyke includes both gabbro and picrite on its north-east flank, while on the western side it is built predomanantly of fine dolerites containing numerous xenoliths of gabbros and others of medium grained dolerite. By analogy with the other dykes these inclusions are considered to be remnants of earlier intrusions, derived almost in situ, rather than of intratelluric origin. The xenolithic rocks and flanking gabbros can be traced right up to the contact of the Cuillin Gabbro and are seen to be truncated by it. Thus Harker's view (1904, p.42, and H.M.G.S. 6 inch Sheet XLV, Inverness-shire) that this dyke is a feeder of the Gabbro receives no direct support from the field relations, though by Harker's hypothesis the dyke could still be a feeder of a higher, and earlier, sheet in a composite body.

<u>The massive dolerite.</u> Dolerites similar to those which form the dyke complex build an apparently massive intrusion some 600 yards in length along a part of the

Gabbro contact. Although a few cases of internal cross-cutting relations have been detected the metamorphic welding and the presence of numerous acid veins somewhat obscure the evidence, and it is possible that this structure is not truly massive, but consists of contiguous minor intrusions. The exceptions to the lack of discernable internal structure are as follows:-

1. In two places a N.E. dyke was seen cutting a coarse variety of dolerite.

2. There are a number of small areas in which xenoliths of gabbro and picrite are numerous, probably representing remnants of earlier dyke intrusions. The shape of the contact between the dolerite mass and of the Torridonian is not clear from the field evidence, but it is certainly highly irregular and it seems likely that a feather edge of N.N.W. dykes and prolongations extends out into the country rock (see 1:1,250 map). In any case the body does not appear to have the form of a simple sheet.

Carr (1952) supposed this dolerite mass to be a patch of meta-lava, though he notes an unusual paucity of amygdales. Since it is frequently difficult to discriminate between meta-lavas and meta-dolerites in the field, the evidence in favour of an intrusive origin for this body is summarized below:-

1. No amygdales have been detected in these rocks, whereas close examination of the apparently similar meta-lavas on Sgurr na Stri and east bank of the Camasunary River has never failed to reveal local concentrations of these structures.

2. The shape of the outcrop, as far as it can be determined, suggests that the dolerite mass has an irregular form and is not a simple sheet.

3. Gabbro and picrite xenoliths are rare in the lavas of the area but are of common occurrence in the early dolerite dykes around Camasunary.

4. The petrography of the dolerite is similar to that of many of the early dolerite dykes, and differs from nearby basalt lavas in containing only sparse olivine and a more basic feldspar (often bytownite).

The dating of the massive dolerite in relation to the intrusion sequence given on a previous page is uncertain. The presence of two cross-cutting N.E. dykes and the enclosure of gabbro and picrite xenoliths suggests that it was intruded at the same time as the system of early N.N.W. dykes. The two N.E. dykes referred to above are, however, seen only in two isolated exposures and are there cutting relatively coarse dolerites which may themselves to xenoliths. If they are, then the massive dolerites may be the

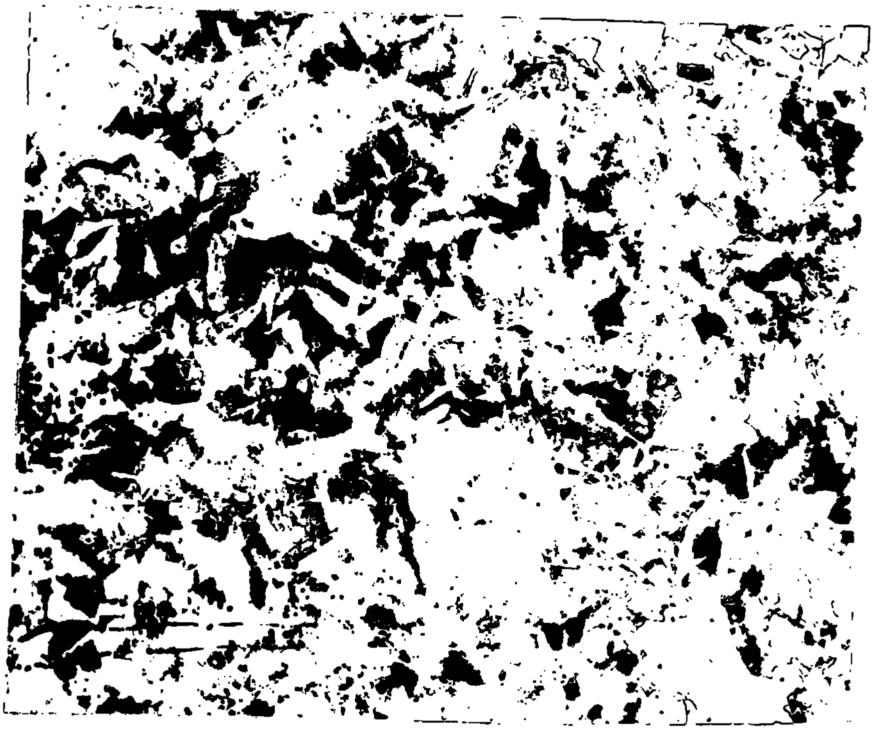


PLATE 28 Microsection: Early gabbro, Camasunary.

(Spec.506) 6. Large, equidimentional plag--ioclase anhedra in a matrix of tabular plagioclase, intersertal pyroxene, and ore. Quartz occurs sparsely in this rock. Part of the pyroxene has been recrystallized to clusters of orthopyroxene granules and ore.

last stage in the sequence of early intrusions.

(iii) The Pre-Gabbro Minor Intrusions - Petrography.

Since the whole of the area covered by the detailed map lies within the pyroxene hornfels zone of thermal metamorphism all the early intrusions have been modified by high temperatures. The coarse grain of the picrites and gabbros has, however, allowed them to resist complete recrystallization, so that they are often less changed in appearance than the doleritic members of the suite. The terms low-, medium-, and high-grade hornfels, which were used in Chapter VII to describe the textural and mineralogical variations of basalts within the pyroxene hornfels zone, are here applied in a similar manner to the metamorphosed intrusive basic rocks.

Picrites. The most southerly of the three composite dykes is composed largely of this rock type. Several individual N.N.W. dykes compose this mass, and form distinctive rounded outcrops of dark reddish-brown material (1:1,250 map, I 16.). These dykes, each some three to six feet wide, have been later sliced up into lenticles by the dolerites which later followed the same direction.

When fresh (Spec. 499)* the picrite is dark grey

* Plate 29.

and of vitreous appearange, and the overlying weathering crust rarely exceeds a millimetre in thickness. Thin sections indicate that this specimen has been metamorphosed to a low grade pyroxene hornfels, but the original constituents remain predominant. The most abundant of these is an optically positive olivine in euhedral, slightly rounded grains with a size range from 0.25 mm. to 5 mm., and an average of c.1 mm.. Augite and laths of plagioclase compose the interstitium with the former interstitial to the plagioclase and tending to mantle the olivine. The feldspar is never more than a millimetre in length and averages less than half a millimetre. Pericline twinning accompanies the albite and carlsbad lamellae, and the determination of composition on albite-carlsbad twins shows it to be a basic bytownite (An 88). Small euhedral octahedra of ore are common, and there are also present a few larger ore grains which, being a translucent brown marginally, are probably picotite.

The effects of metamorphism are superimposed upon these original features. The most obvious changes have occurred in the interstitial areas, where about one third of the primary pyroxene has been recrystallized to fine granules and a biotite and brown hornblende have been added to the assemblages. The pyroxene

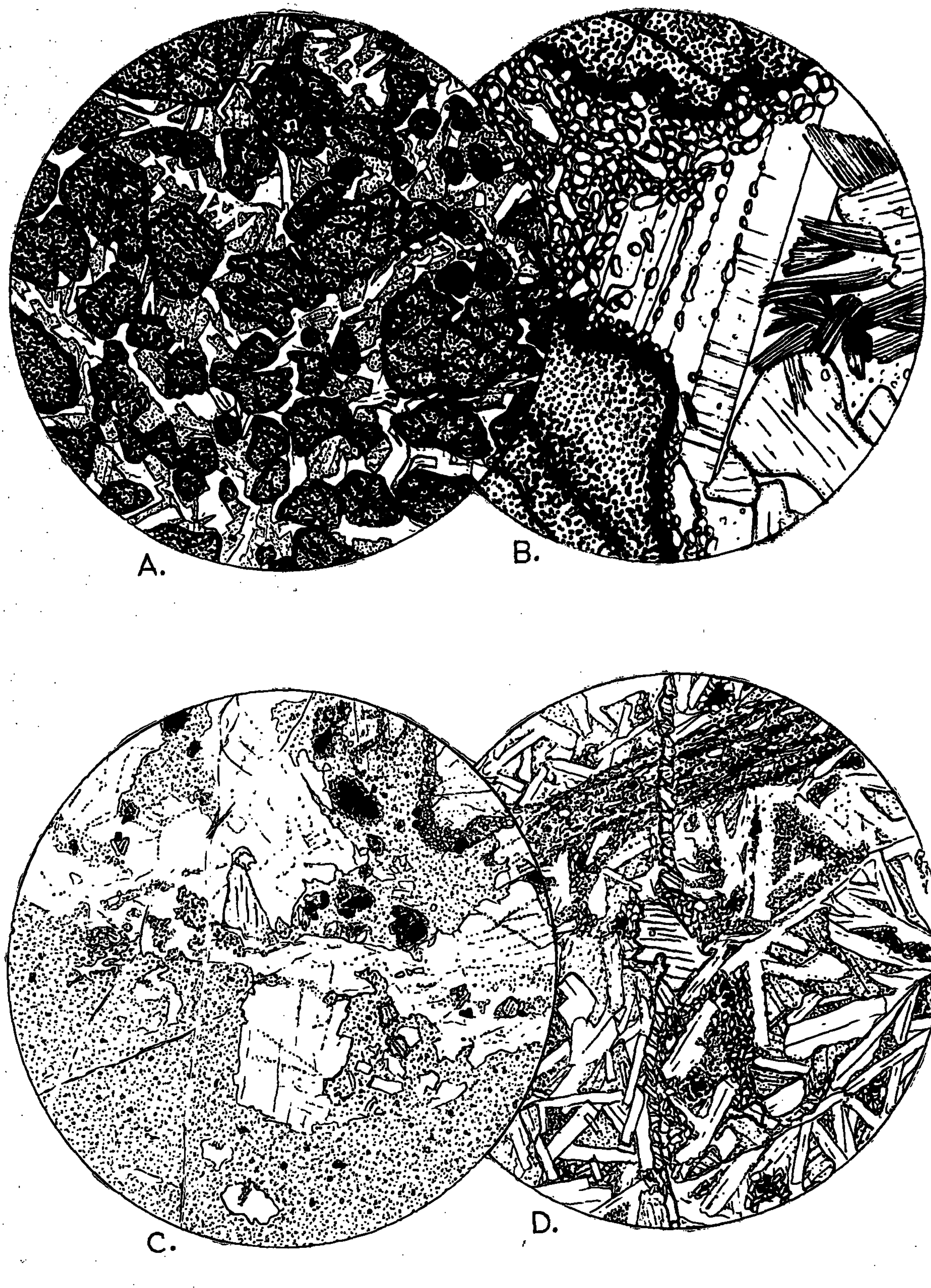
PLATE 29 (opposite.) Microsections: Early basic minor intrusions, Camasunary.

A. (Spec.499) ×18. Picrite dyke rock. Porphyritic olivine in a groundmass of plagioclase laths and interstitial clinopyroxene.

B. (Spec.499) ×300. The same slice as A, under high magnif--ication, showing the manner in which part of the clino--pyroxene and the margins of olivine have been recryst--allized by metamorphism to minute granules of new pyroxene. To the right of the field is a cluster of brown hornblende and biotite.

C. (Spec.159) ×10. The margin of a gabbro xenolith enclosed in fine dolerite. The dolerite has been completely recrystallized to a fine grained pyroxene hornfels, while the gabbro feldspars retain their original form, though containing stringers of pyroxene granules. Biotite has developed round ore grains, and there are rims of new pyroxene around the primary gabbroic pyroxenes.

D. (Spec.151) ×45. Early dolerite dyke metamorphosed to a low grade pyroxene hornfels. Part of the primary pyrox--ene has been recrystallized to fine granules, and a small crush zone crosses the upper part of the field. Brown hornblende occurs in clusters after pyroxene and also fills a vein crossing the field from north to south.


A.
B.
C.
D.

granules are of minute dimensions, c. 0.015 mm., and so cannot be determined. While a few of the primary augite crystals have been completely recrystallized, others have been left untouched. This capricious distribution is typical of thermal granulitization in its earlier stages. Not only pyroxene has been attacked, for the edges of olivines often show fine scalloping and a rim of fine pyroxene granules which also form stringers through the body of the crystal. Some of the new material no doubt derives from alteration products. Many other hornfels of low grade show an abundant development of exsolved ores within the primary pyroxene, and the fact that it is lacking in this rock is perhaps a result of the primary clinopyroxene being more magnesian than usual. Brown hornblende is the most conspicuous new mineral produced by the metamorphism. It builds small, discrete grains which sometimes enclose granules of new pyroxene, while elsewhere it clusters with biotite, or grows at the expense of primary augite and olivine. The fine grained aggregates of biotite are usually found surrounding primary ore gr ains. Both these minerals are probably the products of waning metamorphism. In the modal analysis of Spec. 499 given below the primary and metamorphic pyroxene have been counted together:-

Constituents	Volume Percentages
Olivine	58.1 %
Bytownite	17.1 %
Pyroxene	16.5 %
Hornblende and biotite	6.5 %
Ore	1.7 %
	99.9

Other rocks of similar appearance are less rich in olivine. Thus in Spec. 512, collected from a lens shaped body situated some 50 feet from the contact of the Gabbro, and within the outcrop of the massive dolerites (E 16), the content of olivine is less than forty per cent, the complete mode being as follows:-

Constituents	Volume Percentages
Olivine	38.9 %
Bytownite	33.3 %
Pyroxene	23.4 %
Hornblende and biotite	2.4 %
Ore	2.0 %
	100.0

The olivine of this rock is much embayed and fractured, and in rare cases a euhedral olivine is enclosed within a porphyritic plagioclase. The mineral is fresh apart from a little ore and serpentine along the cracks. The plagioclase is fresh in appearance, and though apparently largely recrystallized it still retains part of its original elongate habit. The composition is about An 85. Similarly, although most of the pyroxene has been reconstituted into 0.15 mm. granules, it still partly preserves the primary sub-ophitic form. Among the new-formed granules, palely pleochroic orthopyroxene predominates over clinopyroxene, and is of coarser grain (0.25 mm. as compared with 0.1 mm.) Granular ore is interspersed with the pyroxene, and small plates of biotite are commonly associated with it. The complete recrystallization of the pyroxene implies that this has attained the medium-grade hornfels stage.

Gabbros. Typifying this group is a specimen (156) from the most northerly of the composite dykes (J 4). It was collected from a xenolith embedded in a very fine grained variety of meta-dolerite. These xenoliths are angular, average one foot in diameter, and compose about one third of the entire rock.

In hand specimen the gabbro is dark grey when fresh and weathers almost black, with a rough surface upon which green pyroxene and metallic-grey ores form the rugosites. The slice reveals a texture consisting of approximately equal amounts of plagioclase and pyroxene with mutually interfering boundaries. The granularity is c. 1.5 mm.. The moderately abundant ore has a size range from 0.2 mm. to 1.5 mm..

The metamorphic influences which affected this rock were both thermal and dynamic in nature. The latter caused fracturing and crushing of the feldspars and so aided recrystallization. Most of the feldspar has not been recrystallized, but bending, strain-twinning, and strain-shadows are common, and there are numerous enclosures of new pyroxene granules and ore. Many of the primary pyroxenes have been granulitized, and most of the new material falls into a size range between 0.01 and 0.1 mm.. There is also a sporadic distribution of coarser orthopyroxene (0.1 - 0.3 mm). Unrecrystallized pyroxene is dusty with exsolved ore grains, and fine ore is interspersed amongst the new pyroxene. Brown, spongy hornblende is a common accessory, both replacing clinopyroxene and as discrete grains, which together with biotite form rims round some of the primary ore grains. Metamorphically this rock is classified as an advanced low-grade hornfels.

Another rock from the same locality (Spec. 159)* illustrates some of the relationships between the

*Plate 29.

xenoliths and their matrix. The latter is seen to be very fine grained and completely recrystallized to a granoblastic texture. The contact between xenoliths and matrix is in places sharp and elsewhere highly irregular, with floated-off xenocrysts in the matrix. The slice is traversed by several veins of uralitic amphibole, and these are observed to cut discontinuous veins of brown hornblende of the type commonly present in the hornfels of the neighbourhood. This hornblende tends to form granules with the cleavages disposed at high angles to the direction of the vein, while adjacent pyroxenes are converted to the same material. Whereas this mineral is probably to be dated to a late stage in the Gabbro metamorphism, the uralitic amphibole post-dates the N.N.W. jointing and at least most of the dykes which follow this direction. It was probably deposited by the circulating hot solutions which are thought to have arisen after the emplacement of the large granophyre intrusions to the north.

Quartz gabbros are also found in the neighbourhood and are exemplified by a specimen (506)* from the oblong mass intruded into Torridonian arkoses in G 16 (1:1,250 map). The margin of this intrusion is of fine dolerite carrying xenoliths of the gabbro, and is presumably of later date. The specimen was taken from the centre

*Plate 28.

of the intrusion, and a thin section provided the following mode:-

Constituents	Volume Percentages
Plagioclase (labradorite-bytownite)	49.9 %
Unrecrystallized pyroxene	30.9 %
Recrystallized pyroxene	12.2 %
Ore	6.4 %
Quartz	0.6 %
	100.0

Two thirds of the feldspar has crystallized in subhedral tablets averaging 1 mm. in length, while the remainder forms rather larger, equidimensional anhedra. Discontinuous, normal zoning is usual, and the average composition is c. An 70. Stress effects are again seen in the cracking and crushing of some of the feldspar, while completely crushed zones up to a millimetre wide cross the whole slice. Along these zones the feldspar is partly fragmental, partly recrystallized, and is accompanied by granular pyroxene. In the body of the rock the greater part of the primary pyroxene retains its original shape, though rich in exsolved ore. New grown granules are almost wholly of orthopyroxene, and the way in which these granules collect into compact groups suggests that they may replace primary orthopyroxene. Both granular and primary symplectic ore are present. The quartz is found in a few interstitial pools which frequently contain an alkaline plagioclase and coarse prisms of apatite. A few large plates of biotite complete the assemblage.

Dolerites. This group composes over 90 per cent of the early intrusions and includes many dykes as well as the massive dolerite mass along the Gabbro contact. They are uniform in character, poor or lacking in olivine, and contain a basic plagioclase. Approximately one third are feldspar-phyric.

In hand specimen the dolerites are dark grey when fresh and weather to a light grey crust up to 2 mm. thick; smooth-surfaced except for upstanding amphibolitized joints. Laths of plagioclase are visible in many of the hornfels which lie some distance from the contact, but in the vicinity of the Gabbro the colour becomes paler and the texture granular.

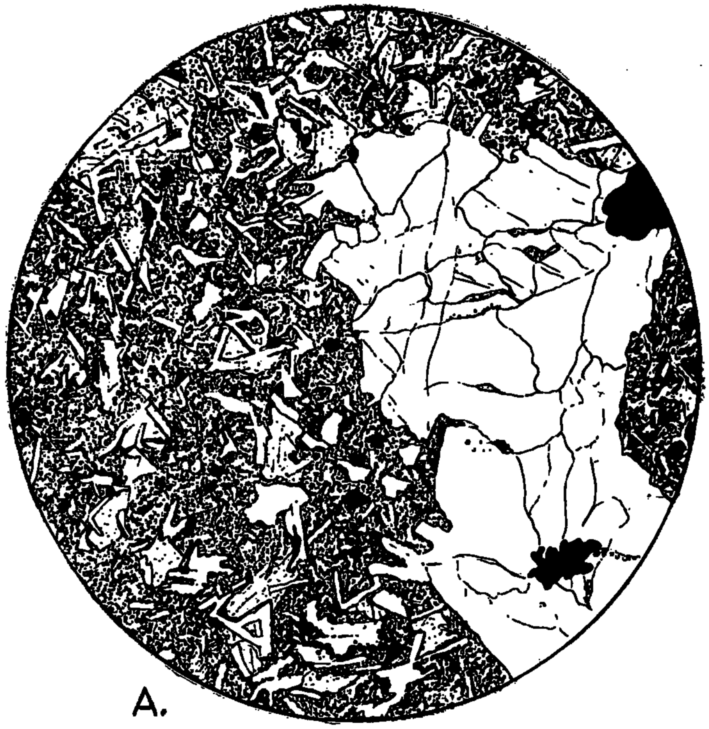
Specimen 151* is a typical non-porphyritic fine dolerite and was obtained from a small N.N.W. dyke in Torridonian sandstones 700 feet from the contact.

* Plate 29.

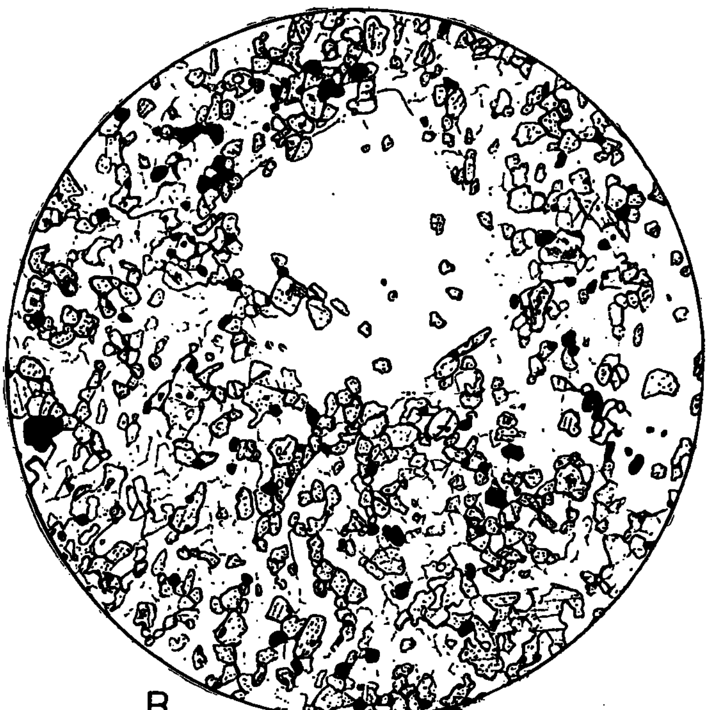
It possesses an intersertal texture and is metamorphosed to only a low grade. Plagioclase takes the form of slender, 0.4 mm. laths of bytownite, with pericline twinning commonly accompanying the albite lamellae. Metamorphism has produced a dusty brown appearance varying considerably in intensity, while bending and micro-shearing have affected a number of crystals. A crush zone, 1.5 mm. wide, crosses the slice, and along it the feldspar is comminuted but not recrystallized. About half of the primary clinopyroxene retains its primary form, while the remainder is now finely granulated, though still largely concentrated within the original boundaries of the crystals. Along the crush zone granulitization is complete. Brown hornblende and biotite have grown in moderate quantity, the former attacking pyroxene and building thin lenses along the crush zone. Felted borders of biotite rim the primary ores, and these have been marginally indented.

Specimen 504* may be taken as exemplifying the porphyritic type of dolerite. It comes from a dyke on the south-west flank of the large composite dyke in H 15. The slice shows the groundmass to be similar to that of the previous rock except in the lack of brown hornblende and the greater abundance of biotite.

*Plate 30.



A.



B.

The feldspar phenocrysts are numerous and occupy one fifth of the bulk. Most are anhedral, embayed, are slightly zoned, and possess both albite and pericline lamellae. They show varying degrees of shattering, some being unaffected, others cut by small slip fractures, while a few are completely broken up and have started to recrystallize. Included stringers and clumps of granular pyroxene, ore, and biotite are typical, and in one case appear to have been derived from an enclosure of olivine. Crush zones are again present.

Dolerites metamorphosed to high grade are exemplified by a specimen (517)* collected 150 feet from the edge of the Gabbro (G 11). The modal percentages are as follows:-

Constituents	Volume Percentages
Plagioclase	52.4 %
Clinopyroxene	29.7 %
Orthopyroxene	13.8 %
Ore	4.1 %
	100.0

In this rock the groundmass plagioclase (An 60) is completely recrystallized to an anhedral mosaic, with a few grains inheriting an elongate form, while the

*Plate 30.

sparse phenocrysts range in size from 0.5 to 2 mm., and retain their individuality, though notched by recrystallized groundmass constituents. Some of these large feldspars exhibit a "sheath-and-core" structure ~~(see Plate)~~ in which the cores are of bytownite and the sheaths of basic labradorite. This probably resulted from a tendency for the compositional difference between phenocrysts and groundmass to be reduced during metamorphism. Clinopyroxene, with a granularity of 0.1 mm., predominates among the ferromagnesian constituents, and is accompanied by somewhat coarser orthopyroxene and ore.

Summary and discussion of the petrography. This early suite of minor intrusions comprises an early group of gabbros and picrites, and a later and more abundant group of olivine-poor dolerites.

The earliest intrusions were of picrite containing between 30 and 60 per cent porphyritic olivine set in a groundmass of bytownite plagioclases and interstitial clinopyroxene. These rocks are very similar to some of the ultrabasic dykes of the lava plateau, which are thought to be the latest manifestation of intrusion in central Skye.

Gabbro minor intrusions include both olivine-bearing and olivine-free varieties, and some of the latter contain quartz.

Small phenocrysts of feldspar are present in about one third of the doleritic members of the suite, but they are rarely abundant. The composition of the groundmass feldspars range from An 54 to An 80, with an average composition of basic labradorite, while the phenocrysts are always of bytownite. The feldspars are thus usually more basic than those in the basalt lavas. The primary clinopyroxene is intersertal or sub-ophitic, and is coloured a pale titaniferous brown. Definite olivine pseudomorphs have only been detected in one specimen (82), but it is possible that the clusters of orthopyroxene often seen at medium and high grade may be derived from this mineral.

As in the case of the metamorphosed lavas (see Chapter VII), the features imposed by thermal metamorphism can be described in terms of high-, medium-, and low-grade hornfels, both textures and mineralogies being embraced by these terms. Where, at Camasunary, both coarse and fine varieties of early intrusion are found in juxtaposition, and have therefore demonstrably undergone the same degree of metamorphism, it is found that the coarser rock has resisted granulitization to a greater extent than the finer rock, so that while the former might show textural features which are typical of low-grade hornfels, the finer rock may possess a medium, or even high-grade texture. The grade stages which have been defined for the metamorphosed lavas and basic intrusions cannot, therefore, be directly corelated with temperatures of formation. It is believed, however, that an approximate temperature equation can be made between metabasic rocks in which the grain size of the new-formed pyroxene is similar. Thus in a slice (159) which contains both coarse gabbro xenoliths and a fine doleritic matrix, the grain size of the metamorphic clinopyroxene averages about 0.015 mm. throughout. In using this criterion it should be noted that metamorphic orthopyroxene is commonly rather coarser than clinopyroxene, and also the comparison can only be applied to rocks of similar, original composition.

<u>Effects of stress.</u> Almost all the collected specimens of the early intrusions exhibit signs of stress. In the outer parts of the hornfels zone this is largely a matter of mechanical bending and breaking of crystals, while in the inner parts of the zone these effects have been accompanied, or followed, by recrystallization. The feldspars commonly show local micro-faulting, cracking, crushing, and the development of strain-shadows and strain-twinning. Phenocrysts are

especially susceptable, presumably because there is less possibility of small, intergranular adjustments. Narrow zones of crushing are often detectable in the dolerites, and tend to strike N.E., as do the small faults mentioned earlier. Within these zones the feldspars are completely comminuted, but are not, at low grade, recrystallized. Pyroxene is sometimes partly recrystallized, and together with brown hornblende forms small lenses within the crush zones.

In the medium grade hornfels the crushing appears to have locally accelerated the process of granulitization, and in the crush zones the feldspars are completely recrystallized to granular mosaics, while the nearby groundmass feldspar is unaffected. At the highest grades, complete granulitization of all the constituents tends to obscure the effects of crushing, but the latter is still sometimes detectable in the phenocrysts.

Since the thermal metamorphism has tended to obliterate, or be modified by, the stress effects, the latter cannot be post-metamorphic, as is the crushing on Sgurr nan Each and elsewhere in the north (see Chapter VII). In a later section of this chapter it is shown that at the height of metamorphism the Torridonian arkoses were in an incompetent state, and thus any stress applied would tend to be taken up by the more rigid basic intrusions. The crushing and micro-faulting are probably one aspect of a compensatory adjustment enforced on the country rocks by the intrusion of the Cuillin Gabbro. Other aspects include the folding and faulting described in the chapter on tectonics.

(iv) Chemistry of a Pre-Gabbro Dolerite.

One specimen (159) of a pre-Gabbro dolerite dyke has been chemically analysed. It was obtained from the most northerly of the three composite dykes (J 4), and is a very fine-grained, non-porphyritic, variety which has been completely recrystallized by thermal metamorphism to a granoblastic mosaic of plagioclase, clinopyroxene, orthopyroxene, and ore. At the same locality this rock also encloses xenoliths of gabbro, as has been described in the foregoing section, but the analysis refers to the fine-grained portion only. Oxide percentages and norm are set out in Table 8. The rock is too fine-grained to allow a modal analysis to be made, and for the same reason it is possible that olivine is present and was not distinguished from pyroxene.

Compared with typical alkaline olivine basalt lavas (see Table 3, Chapter VI) the analysis of the meta-

TABLE 8

CHEMICAL ANALYSIS OF A PRE-GABBRO DOLERITE

FROM CAMASUNARY.

	159.	Norm		
SiO_2	49.6	Orthoclase		0.89
TiO_2	1.0	Albite		20.44
Al_2O_3	14.2	Anorthite		27.80
Fe_2O_3	3.9		Ca 13.46	
FeO	7.2	Diopside	Mg 9.20	25.83
MnO	0.17		Fe 3.17	
MgO	9.4			
CaO	12.0		Mg 7.60	
Na_2O	2.4	Hypers-		10.24
K_2O	0.16	thene	Ca 2.69	
$H_2O(+)$	0.06			
$H_2O(-)$	0.21		Mg 5.40	
P_2O_5	0.10	Olivine	Fe 2.04	7.44
Total	100.4	Magnetite		5.57
		Ilmenite		1.98
		Apatite		0.34
		Water		0.29

Normative Compositions and Ratios

Plagioclase	Ab 42.5 An 57.5
Diopside	Wo 52 En 36 Fs 12
Hypersthene	En 73 Fs 27
Olivine	Fo 73 Fa 27

$$\frac{FeO+Fe_2O_3 \times 100}{MgO+FeO+Fe_2O_3} = 54 \qquad \frac{Fe_2O_3 \times 100}{FeO+Fe_2O_3} = 30$$

$$\frac{K_2O \times 100}{Na_2O+K_2O} = 6$$

-morphosed dolerite shows similar contents of the basic oxides, though containing rather more lime than most rocks of this type. Silica, however, is definitely higher than is typical olivine basalts, and this is reflected by a considerable amount of hypersthene accompanying olivine in the norm. These characteristics are also shown by some of the lava hornfels (e.g. 183 in Table 6), and it was suggested in Chapter VII (section ix) that silica may have been gained by the basic hornfels during metamorphism, probably by reaction with the adjacent Torridonian sediments.

(v) Field Relations of the Torridonian Sediments and their Rheomorphosed Equivalents.

At Camasunary, the country rocks into which the pre-Gabbro complex and the Gabbro itself were intruded are well exposed, but have nevertheless been differently interpreted by each of the geologists who have been concerned with them. Harker's map shows the whole of this area as a belt of basalts extending outwards from the Gabbro contact for a width of about 1,000 feet, and overlying Torridonian rocks which are continuous with similar rocks on the east flank of the valley. The small patch of limestone and shale near the centre of the exposures (D 18 on the 1/1250 map) is interpreted as an outlier of Lias, resting unconformably on the Torridonian, and revealed below the base of the lavas. The latter appear to have low and variable dips.

In a recent thesis, which refers mainly to the Cuillin Gabbro, Carr (1952) recognized that only a part of the rocks which Harker shows as basalts are, in fact, lavas. He limits the outcrop of the latter to a patch in the centre of the exposures (this patch is described in a previous part of this chapter as an intrusion of dolerite), and also shows the basalts on the east flank of the Camasunary River which are also mentioned in this chapter. Carr remains doubtful of the identity of the rocks lying between Harker's lava boundary and his own, and while remarking that they are very similar to the Torridonian he prefers to designate them "undifferentiated hornfels". Carr also mentions the presence of pre-Gabbro dykes.

The present study has shown that apart from the pre-Gabbro intrusions and the small patch of Lias, the whole of the country rock in the centre of the valley is Torridonian. The evidence is as follows:-

a. There is no sharp break in rock type between the Torridonian at Camasunary House and the country rocks in the neighbourhood of the Gabbro. Dips of 25° to 35° N. continue throughout this distance, though there is local disturbance in the contact zone. Sedimentary features, such as bedding laminae and pebbly bands can be detected in all parts of the outcrop, though becoming less obvious towards the contact.

b. Thin sections of the disputed rocks have many similarities with the Torridonian in other parts of the Camasunary valley, though becoming progressively more metamorphosed towards the contact. The stages of this metamorphism are similar to those that can be traced in the Torridonian of Rudha Ban, to the west.

Harker's misidentification was probably due to the fact that as the Torridonian is traced into the zone of high temperature metamorphism it loses its light colour and obvious sedimentary character and becomes a dark-coloured, dense, flinty rock, not unlike a meta-basalt in general appearance. However, careful examination usually reveals a lamination or traces of flaggy bedding, especially on weathered surfaces, while the texture is less granulitic than that of the meta-basalts and presents a more vitreous appearance. Metacrysts of biotite are not uncommon, as in the metamorphosed basic rocks.

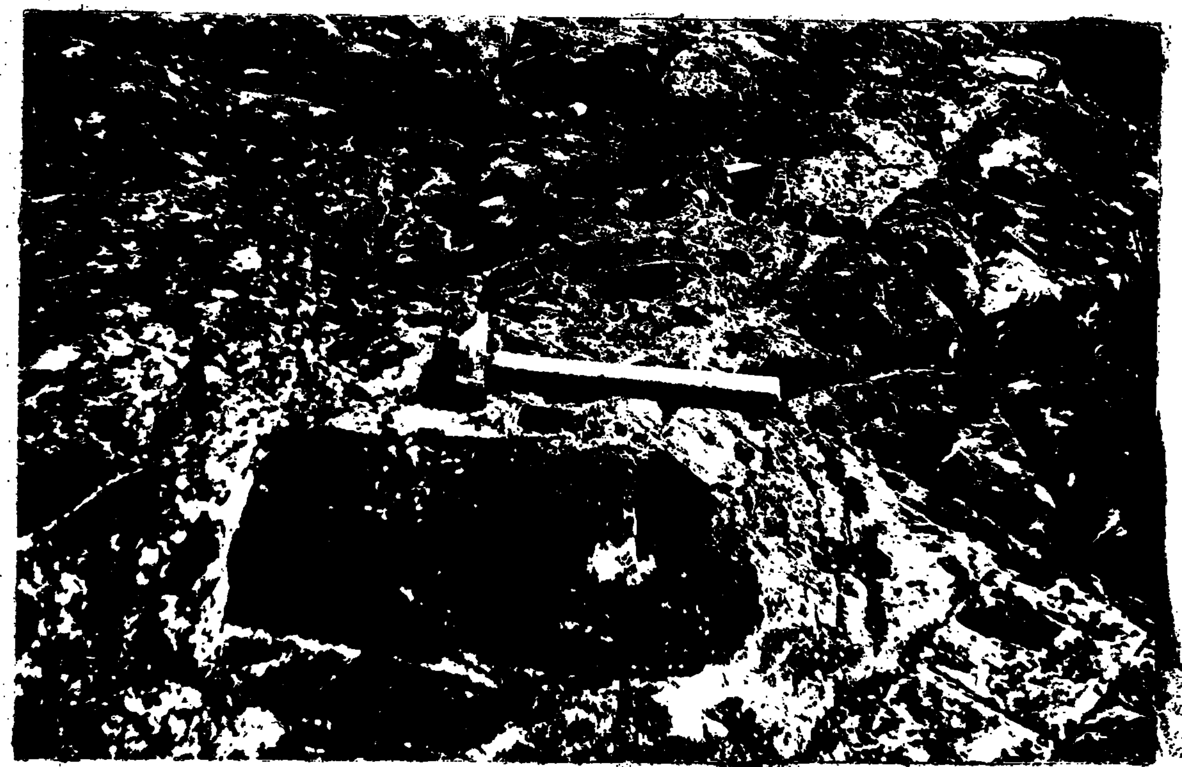
The regular structure of the Torridonian is continuous through the outer parts of the hornfels zone, but at distances varying from 50 to 400 feet from the edge of the Gabbro it begins to become broken-up and sometimes contorted, at first without any other obvious change in appearance. Such irregular structure is well seen on An t-Sron, some 50 feet from the Gabbro contact, where anomalous dips up to 80° north are found. As the pre-Gabbro dykes are traced into this broken-up zone they show signs of disturbance, being at first bent and then fracturing across, the breaks being sealed by acid material which appears to derive from the enclosing Torridonian.* Inwards towards the contact this brecciation rapidly increases, and patches occur in which the "Torridonian" is full of disoriented basic "xenoliths", varying in size from a few inches to several feet across, and evidently derived from broken-up basic dykes. The basic fragments are sometimes accompanied by a lesser number of acid fragments in which Torridonian lamination is still discernable. All the stages in this process of fragmentation can be followed on the ground, and in no case is there evidence of external intrusion, apart from the later, and distinct, leucocratic veins which are found everywhere along the edge of the Gabbro. The breaking-up also affects the edges of the lava outcrop on the east bank of the Camasunary River, and the outer margin of the "massive dolerite" in the centre of the exposures,

*Plate 31.

PLATE 3I (opposite.) Rocks from the vicinity of the Cuillin Gabbro contact, north of Camasunary.

A. Exposure situated 250 feet from the Gabbro contact, showing metamorphosed early dolerites veined by acid material derived by rheomorphism of the Torridonian arkoses.

B. Exposure situated 700 feet from the Gabbro contact. A slab of metamorphosed Torridonian intruded by a small dyke of early dolerite (left) is crossed by close-spaced north-west joints (parallel to the hammer handle.)



A

B

but the main masses of these two bodies remains unaffected except for a few irregular acid veins.

The evidence appears to indicate that the brecciation of the pre-Gabbro intrusions was a consequence of rheomorphic mobilization of the acid Torridonian sediments under conditions of high temperature and moderate stress. The material which forms an interstitium to the fragments can be traced outwards into rocks of typical Torridonian appearance, while sometimes there is a centimetre-thick skin of relatively coarse acid material around the basic blocks which grades out into rocks of sedimentary aspect. This last feature is probably due to local melting along the thermal discontinuity represented by the surface of the basic blocks. Examples of the break-up of basic dykes, and the formation of "xenolithic" rocks, can be examined in the areas represented by squares G 14, 15; H 13, 14, and 15 on the 1/1250 map. Similar features can also be seen in the Torridonian exposures on the coast, west of Rudha Ban (see also photographs on Plates 26 & 31).

The rheomorphic processes were probably aided by stress. The imprint of N.E. lines of crushing and small-scale shear-faulting in the meta-basic rocks has already been remarked in the previous section. Similar crush-lines and faults can occasionally be discerned in the Torridonian lying in the outer parts of the hornfels zone, though they have usually been sealed by recrystallization. Towards the outside of the mobilized zone pieces of brecciated Torridonian containing relicts of bedding can sometimes be seen drawn out into spindle shapes elongated in a north-easterly direction, and the longer axes of some of the basic fragments also have this orientation. The evidence strongly suggests a plastic flow of unequally mobilized rock under a compressive force acting along N.W.-S.E. lines. Near the contact the mobilization was evidently more complete, and has resulted in a melée of basic fragments lying in a swirled acid matrix.

It may be noted that the post-Gabbro dykes pass through the zone of mobilized rocks entirely undisturbed.

Carr (op.cit.) has already suggested that the complexities of the country rocks in the Camasunary area are best explained by rheomorphism, and he considers that this process was related to a hypothetical extension of hypersthene granophyre beneath Camasunary, connecting the outcrops of granophyre on Rudha Ban and the Blaven-Slat Bheinn col. Carr dates the granophyre as pre-Gabbro on evidence discussed elsewhere (see Chapter X). The present writer would agree that such an underground extension of granophyre is likely, and that in a general sense the rheomorphism and the emplacement of the granophyre may be related, but he disagrees with the suggestion that the presence of an underground granophyre is the cause of the rheomorphism. It does not seem likely that an acid mass of such moderate dimensions could, by its intrusion, create the widespread, very high temperatures which would appear to be indicated by the partial melting of the Torridonian. Indeed, the exposed portions of the granophyre have induced only low-grade metamorphism in their contact rocks. The high grade metamorphism of the lavas and pre-Gabbro basic intrusions is clearly related to the intrusion of the Cuillin Gabbro. Turner and Verhoogen (1951, p. 441) estimate the probable temperature of the amphibolite facies - pyroxene hornfels facies boundary as about 700 to 750 degrees centigrade, and the rheomorphic features described appear well within the outer limit of the pyroxene hornfels zone, and moreover in an area where the latter reaches its maximum development. The intrusion of the Cuillin Gabbro, then, with its great size, its high internal temperature, and the demonstrable high temperature effects on the basic country rocks, would seem just the sort of event which would be expected to cause local melting of the contact rocks, where these are of acid composition. The writer also disagrees with Carr's dating of the granophyre intrusions as pre-Gabbro, and considers that these bodies were emplaced soon after the intrusion of the Cuillin gabbro, but this point is more fully discussed in Chapter X.

Actual melting was the ultimate stage in the metamorphism of the Torridonian, but there were also induced a wide range of states between merely-heated rocks, through plastic rocks to almost completely mobile rocks. Although there is a general progression towards ultra-metamorphism as the contact is more closely approached, a certain amount of mixing between rocks in different states must have occurred, as is witnessed by inclusions of recognizable Torridonian within an acid matrix. Apart from the probability of differential melting between layers of somewhat different composition, it is quite possible that material melted by proximity to the Gabbro was squeezed outwards into less mobile rocks, or that some of this material rose upwards under pressure. At the same time, such processes must have been on a small scale at the present level of exposure, because most structures in the zone can only be explained on the assumption that the constituent rock types are nearly in situ. A more tentative extrapolation that may be put forward is the suggestion that at deeper levels the rheomorphic mechanism gave rise to a reservoir of magma, which was then pressed upwards after the cooling of the Gabbro to form the Rudha Ban and Coire Uaigneich granophyres. In the Rudha Ban Torridonian there is again evidence of rheomorphism, but in this case the disturbed zone has been broken through, and to the east entirely destroyed by, the uprise of the granophyre. There are sufficient chemical and mineralogical similarities between the granophyres and the metamorphosed Torridonian to give some support to this view. Wager, Weedon, and Vincent (1953) draw attention to this in their paper on the Coire Uaigneich granophyre, and a further discussion is to be found in Chapter X.

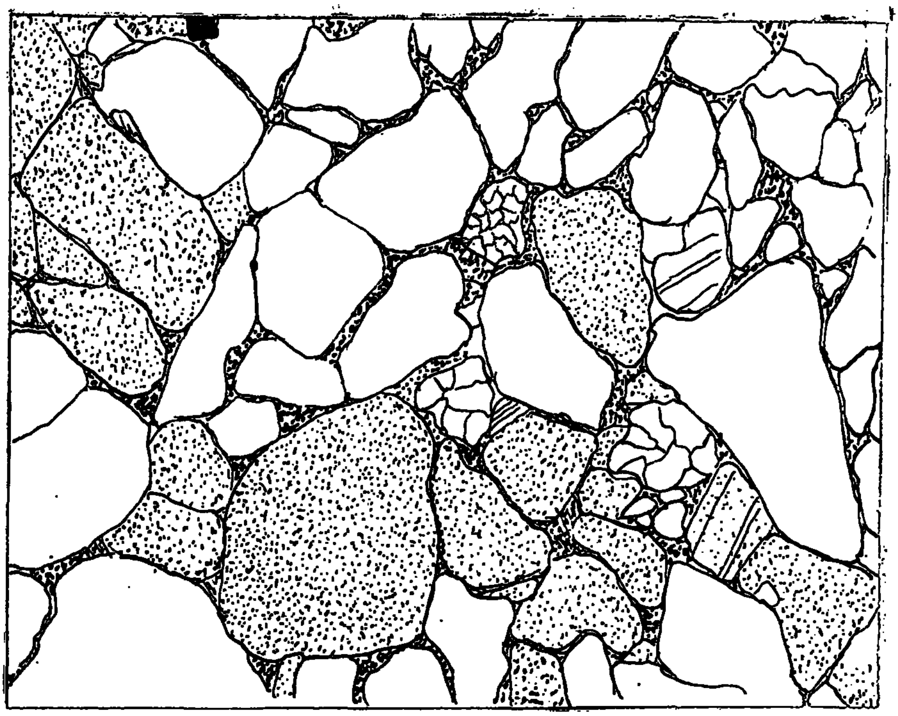
(vi) Petrography of the Torridonian Sediments and their Rheomorphosed Equivalents.

The field evidence indicates that the intrusion of the Cuillin Gabbro raised the temperature in its immediate vicinity to such a degree as to allow local mobilization of the Torridonian arkoses. This section attempts to trace the metamorphism of the latter from almost unmodified sediments through to intrusive acid veins. As with the basalts, however, it cannot be assumed that this series is a progressive one.

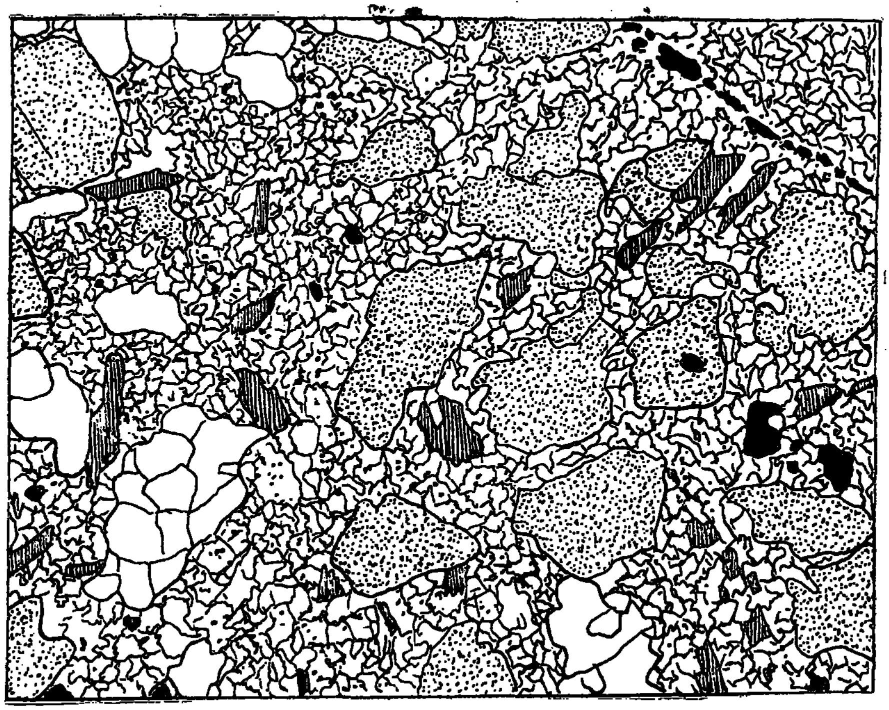
<u>Metamorphosed Torridonian</u>. No part of the Camasunary Torridonian is far enough from the Gabbro to be sure that it is entirely unaffected by the latter's metamorphic aureole. Indeed, the lack at Camasunary, of the reddish colouration often seen in Torridonian of other areas is probably due to the reduction of haematite to magnetite by low-grade metamorphism. Apart from this, it is thought that in the neighbourhood of Camasunary House and on the north-east side of the bay the arkoses are almost unaffected by thermal metamorphism.

A typical specimen from east of Camasunary House (525)* is a pale-grey, coarse sandstone which in thin section is seen to ba a feldspathic grit, with sub-angular constituents and a granularity of 0.5 mm.. More than half the bulk is quartz, and most of the rest feldspar, and there is a little ore, chlorite, and muscovite interstitially. The quartz is strained and occurs both as discrete detrital grains and in small pebbles of quartzite up to a few millimetres across. A small amount of secondary silica occurs in the cement. Among the feldspars, perthite predominates over acid

*Plate 32.



A.



B.

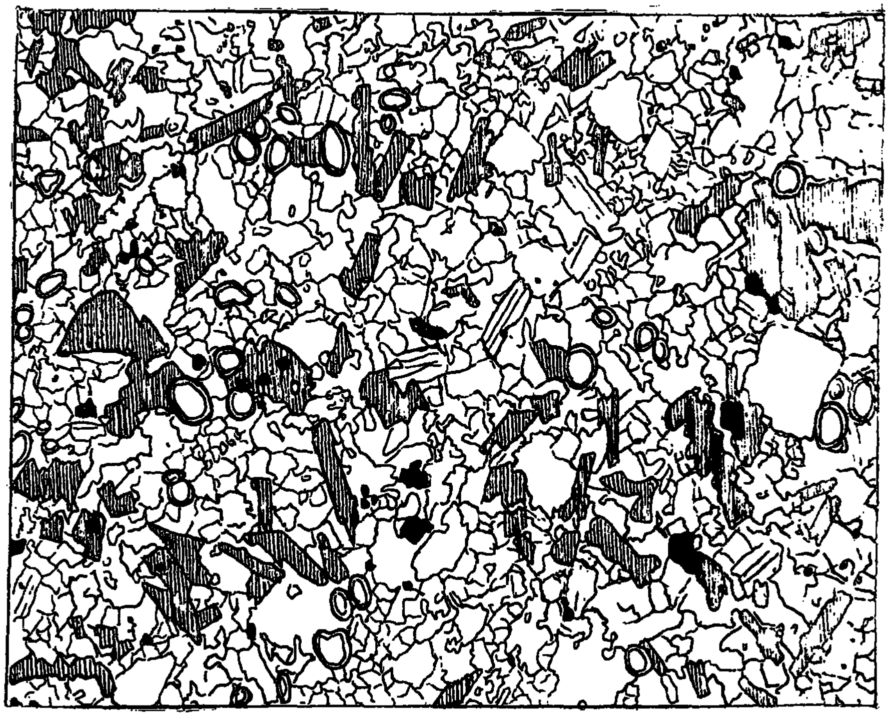
plagioclase, some of which are bent, and both feldspars are dusty. An analysis of this rock appears in section (vii) of this chapter.

Thermal effects begin to be discernable in a specimen (81b) from the stream on the east side of An 't-Sron, and 350 feet from the Gabbro contact. It should be remarked that the hornfels zone is here rather narrow, so that the grade is lower than in similarly-placed rocks further west. The rock is a fine-grained arkose, with a few phenoclasts of quartz and pink feld-spar visible in hand specimen. The quartz is sub-angular and strained, with a granularity of 0.25 mm., and is set in a groundmass of very dusty feldspar, the larger grains of which retain their individuality, while the remainder has been recrystallized to feathery aggregates. Ore, chlorite, and a little zircon are concentrated in thin bands which appear to be of depositional origin. Most of the ore is leucoxenized.

Further stages are found in specimens taken from the outer boundary of the hornfels zone (as defined in the meta-basic rocks). A rock (134) from an exposure 700 feet from the Gabbro in the centre of the Camasunary valley is dark-grey in colour, weathers to a light sandy grey, and is cut by numerous N.N.W. joints and a few N.E. joints. A polished surface shows the bedding to consist of half to two millimetre thick laminations, chiefly defined by ore content. The basis of the rock is a fine-grained, recrystallized arkose, consisting of a mosaic of almost fresh orthoclase and quartz with a granularity of 0.15 mm.. The quartz tends to be interstitial and spongy. Reddish-brown biotite forms small poikiloblastic plates associated with ore, and is often altered to a pale chlorite containing patterns of exsolved rutile needles. Most of the ore is fine grained and well-formed, and apatite is a common accessory. Specimen 147, from the same locality, contains rather less ore and is crossed by thin veins of quartzo-feldspathic material. Plagioclase is a notable constituent of this rock. Specimen 497* has marked fine and coarse bands, the latter consisting of poorly-sorted material varying from small pebbles of quartzite and feldspar to a finely recrystallized quartzo-feldspathic interstitium. These bands are also rich in minute ore grains, and half-millimetre biotite metacrysts are not uncommon.

Within a distance of about 500 feet from the Gabbro contact, a pink orthopyroxene makes its appearance in the assemblage, while biotite becomes more abundant and is easily visible in hand specimen. A rock (498)** collected 550 feet from the gabbro consists of an equigranular

* Plate 32. ** Plate 33.



A.

B.

(0.2 mm.) mosaic of quartz and feldspar, with a considerable amount of oligoclase accompanying the orthoclase. The constituents tend to intergrow. Biotite is abundant as plates up to a millimetre across, and is most abundant in the ore-rich streaks. The sparse granules of hypersthene are strongly pleochroic and are most abundant in the finer parts of the light coloured bands. Specimen 155, situated 500 feet from the contact, possesses a similar petrography, but there is a more marked differentiation into coarse and fine bands, the latter richer in biotite and ore, and the former in hypersthene, which always shows a preference for quartzose areas.

Rheomorphosed Torridonian. In banded Torridonian it was apparently in the more leucocratic layers that mobilization commenced. Thus a polished surface of Specimen 507 (300 feet from the contact) reveals the presence of vaguely-defined dark patches in a lighter coloured matrix, and a section shows that the dark patches are of similar constitution and texture to the more biotitic layers of banded Torridonian, while the matrix contains a higher proportion of quartz and feldspar, and most of the hypersthene. One large grain of plagioclase with lobate boundaries has clearly grown at the expense of the groundmass. It would seem reasonable to suppose that the dark patches have been derived from the breaking up of a banded rock due to the incipient mobilization of the more leucocratic layers. This rock is undoubtedly Torridonian, but similar features can be traced in some of the intrusive veins within meta-basic rocks. One such specimen (150)* is pale grey in colour, contains sharply-defined xenoliths of metadolerite, and has a granularity of 0.2 mm.. Quartz is interstitial to the feldspar, which includes a high proportion of slightly-zoned, subhedral oligoclase, while several porphyoblastic feldsaprs intergrow with the groundmass along lobate boundaries. Biotite is slightly more abundant than the granular hypersthene, and tends to concentrate in areas of relatively fine texture, and also builds spongy porphyroblasts up to one millimetre or so across. Apatite is a common accessory. It is evident that the enclosed fragments of basic rock have reacted to some extent with their matrix, for while both clinopyroxene and orthopyroxene are present in their cores, the external two millimetres contains only orthopyroxene, and moreover, some of the feldspars have grown sodic outer envelopes. A few flakes of biotite lie along the contact of xenoliths and matrix. In another vein of this type (Spec. 505) biotite is entirely lacking, and the

*Plate 33.

hypersthene is a little coarser than usual. Reaction of basic fragments with matrix is again in evidence, and in this case biotite, which is found in the centres of the fragments, is absent from their margins.

In view of the fact that tridymite is present in the metamorphosed Torridonian adjacent to the basic intrusions of Rhum (Wager et al, 1953), in acid xenoliths enclosed in a basic dyke on Blaven (see Chapter XI), and in parts of the granophyre of Coire Uaigneich, it is perhaps rather surprising to find that this mineral is absent from the rheomorphosed Torridonian at Camasunary. Walker and Poldervaart (1949) note the lack of tridymite in the mobilized sediments, adjacent to certain of the Karoo dolerite sills, which are referred to in the following section.

(vii) Chemistry of the Rheomorphism.

The first column of Table 9 sets out the results of a chemical analysis of the almost unmetamorphosed Torridonian feldspathic grit found in the vicinity of Camasunary House. Compared with the average of three analysed Torridonian sandstones from Skye quoted by Kennedy (column 3), the Camasunary rock is higher in silica and lower in calcium and sodium. Neither of these analyses has much in common with the composite

TABLE 9

CH EMICAL ANALYSES OF THE TORRIDONIAN

AND ITS RHEOMORPHOSED EQUIVALENTS, WITH COMPARISONS.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	80.8	65.3	75.58	73.6	76.92	61.84	62.64
TiO_2	0.30	0.83	0.42	0.78	0.20	1.51	1.53
Al_2O_3	10.4	14.0	11.39	11.9	12.38	10.52	13.96
Fe_2O_3	1.0	2.2	0.82	1.6	1.39	3.66	1.12
FeO	1.0	3.1	1.63	2.4	1.45	9.24	6.54
MnO	0.05	0.14	0.05	0.07	tr.	0.23	0.13
MgO	0.42	5.5	0.73	1.3	0.22	0.56	1.83
CaO	0.26	2.9	1.69	1.4	0.28	4.97	3.91
Na_2O	1.3	2.6	2.46	3.5	2.17	2.83	5.02
K_2O	3.0	3.1	3.36	2.8	3.88	2.58	1.90
$H_2O(+)$	0.25	0.57	1.07	0.75	0.77	1.82	1.02
$H_2O(-)$	0.31	0.40	0.05	0.16	0.39	0.19	0.28
P_2O_5	0.04	0.15	0.30	0.19	tr.	0.34	0.11
Total	99.1	100.8	99.55	100.45	100.05	100.29	99.9

1. Composite chip-sample of Torridonian east of Camasunary House; D. C. Almond.

2. Composite sample of two acid veins (spec. 150 505) in metadolerite; D. C. Almond.

3. Average of three analyses of Torridonian arkoses from Skye; Kennedy (1951, p. 258, nos. A(1) - A(3).)

4. Average of four analyses of the Coire Uaigneich granophyre; D. C. Almond (see Chapter X, Table nos. 1-4).

5. Unaltered centre of sandstone xenolith in Karoo dolerite; Walker and Poldervaart (1949, Table 15, p. 646, no. 108).

6. & 7. Granophyre margin of sandstone xenolith in Karoo dolerite; Walker and Poldervaart (1949, Table 15, p. 646, nos. 92, 93).

TABLE 9
(cont.)

	1.	2.	3.	5.	6.	7.
Quartz	61.2	21.78	42.72	48.06	22.08	13.38
Orthoclase	17.79	18.35	20.02	22.80	15.57	11.12
Albite	10.49	21.99	20.43	18.34	24.10	41.92
Anorthite	1.39	14.18	6.67	1.39	8.06	10.01
Corundum	4.28	1.12	1.63	4.18	-	-
Diopside	-	-	-	-	13.79	7.52
Hypersthene	2.95	16.65	3.65	1.79	6.01	9.37
Magnetite	1.39	3.25	1.16	2.09	5.34	1.62
Ilmenite	0.61	1.52	0.76	0.30	2.70	2.85
Apatite	0.10	0.34	0.67	-	0.67	0.33
Water	0.56	0.97	1.07	1.16	2.01	1.3

Note: For norms of Coire Uaigneich granophyre see Table 10.

sample determination of two acid veins which were chosen to represent the product of rheomorphism (column 2). The vein material contains much less silica than the sandstones, while magnesia, iron oxides, and lime are all notably higher in the latter. Moreover, compared with the Camasunary Torridonian, the veins show a less well-marked predominance of potash over soda. When the analysės are recalculated in terms of normative minerals, the rheomorphic vein is seen to contain a great deal less quartz and much more plagioclase and hypersthene than the Torridonian sandstones.

Selective fusion and the reaction of the fused material with basic rocks are the two processes most likely to account for the chemical differences between the sediments and their rheomorphosed equivalents. As is well known from the work of Bowen (1928) and others, fusion of a sediment gives rise, in its early stages, to the liquefaction of a low-melting point mixture approximately in composition to a granite, leaving a recrystallized residue representing the "excess" of silica, alumina, or lime originally present in the sediment. If this liquid is then squeezed out from the residue it may crystallize elsewhere as a granite. This may well have occurred at Camasunary, for in that area the rheomorphic material is found veining the early basic intrusions and forming a matrix of blocks derived from both the intrusions and the Torridonian sediments. In Plate 34 normative quartz, albite, and orthoclase for the Torridonian and rheomorphic vein material are plotted as part of Schairer's (1950) dry-melt phase diagram for the system SiO_2 - $NaAlSiO_4$ - $KAlSiO_4$. It will be seen from this that the plot for the rheomorphic rock (2) lies near to the "low temperature trough", whereas those for the sandstones lie well outside the trough towards the SiO_2 corner of the diagram. This lends some support to the hypothesis that the veins are a product of selective fusing. It is also of interest that the rheomorphic material plots much nearer to the positions of four typical Skye granitic rocks (quoted by Wager, Weedon, and Vincent, 1953) than do the analyses of the Coire Uaigneich granophyre (see also Chapter X).

However, the high content of basic oxides in the vein rock, as compared with unmetamorphosed Torridonian, cannot be explained on the basis of selective fusion. There is petrographic evidence that reaction has occurred between the veins and the basic rocks into which they are intruded, for at the contact the latter is enriched in orthopyroxene at the expense of clinopyroxene, and some of the plagioclase possess a sodic

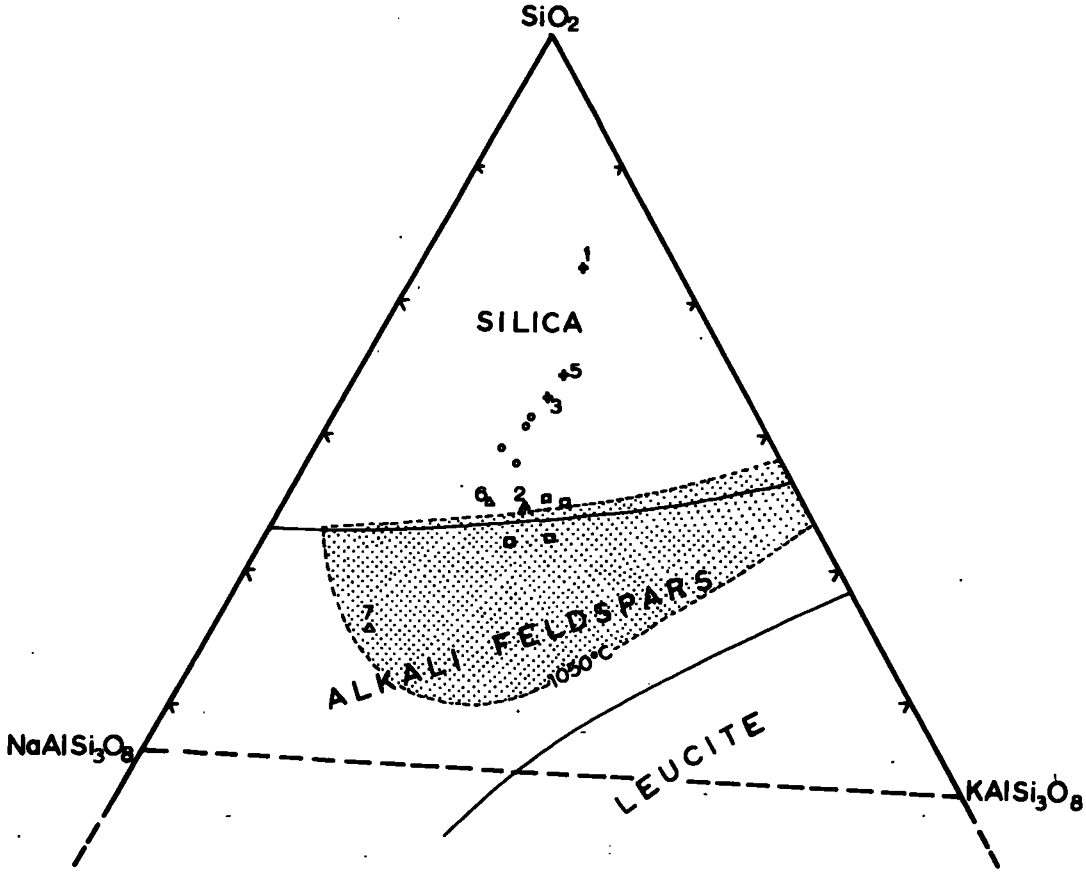


PLATE 34 PLOTS OF NORMATIVE QUARTZ, ALBITE, AND ORTHOCLASE IN RHEOMORPHOSED SANDSTONES, WITH COMPARISIONS

Phase diagram after Shairer (1950.) "Low temperature trough" shaded.

Numbering as in Table 9 ✦ - feldspathic sandstones (Torridonian and Karoo)

▲ Rheomorphosed sandstones (2, at Camasunary, 6 & 7, in Karoo dolerite.)

• Coire Uaigneich granophyre, Blaven (see Plate 39)

▫ Four other Skye granitic rocks (see Plate 39) outer envelope, while the veins themselves contain a higher proportion of ferromagnesian minerals than the in situ metamorphosed Torridonian rocks. The analysis of a hornfelsed lava adjacent to an acid vein (Table 6, specimen 162) shows this rock to be relatively enriched in silica, soda, and potash, mainly at the expense of lime and magnesia. It therefore seems reasonable to suppose that reaction with early basic intrusions and lavas is responsible for the high magnesia, iron oxide, and lime content of the veins compared with the Torridonian sediments. In return, the veins must have lost silica, soda, and potash.

It is not easy to decide the relative importance of selective fusion and assimilative reaction in producing the present composition of the rheomorphic veins, but it does seem likely that both processes were operative. Selective fusion can account for the present ratio of normative quartz, albite, and orthoclase in the veins, but not for their high content of basic oxides. On the other hand, had reaction between basic rocks and completely fused Torridonian been the only factor, then it would be expected that the veins would be impoverished in potash and soda, as well as in silica. This, however, is not the case, for potash is as abundant in the veins as in the Torridonian, and soda is higher in the veins.

Walker and Poldervaart (1949) have made a study of the rheomorphism of sandstones and siltstones which sometimes occurs adjacent to the large Karoo dolerite sills, and around xenoliths enclosed within the sills. In this case shaly sediments have been more susceptible to melting than sandstones. Analyses of transfused sediments and their unaltered equivalents show that there is a general tendency for the affected sediments to be enriched in titanium, iron, magnesium, and calcium, while the surrounding basic rocks show a gain in silicon, aluminium, and potassium. The analyses in columns 5, 6, and 7 illustrate these features as they occur in a sandstone xenolith caught-up in one of the sills. There seems to be a close parallel with the situation at Camasunary.

Walker and Poldervaart (op. cit., p. 675) consider that there is no evidence of especially high magmatic temperatures in the areas where melting occurred, and suggest that an excess of water diffusing from the magma, together with that already in the sediments, may have provided a favourable medium for metasomatism and mobilization. The present writer considers that in Skye a prolonged period of high temperature was probably the controlling factor. Within the area mapped, rheomorphism has only occurred in the Camasunary area, which not only lies in the most deeply-eroded sector of the Gabbro contact, but also in a situation where the contact plane is believed to incline inwards at an unusually low angle, and may well have formed a favourable trap for the development of prolonged high temperatures in the country rock. In the melting of rocks available heat is of more importance than the highest temperature attained, and the rate of heat loss would be lowest in places where the contact dipped most gently inwards.

(viii) Post-Gabbro Minor Intrusions at Camasunary.

At some time following the consolidation of the Cuillin Gabbro the area was subjected to stresses which resulted in the formation of vast numbers of joints trending around N.N.W., and so closely spaced that in some exposures the intervals between them hardly exceed one quarter of an inch. Some of these fractures were utilized by uprising basic magma, and so a swarm of dykes was built up, transecting both the country rocks and the Gabbro.

At Camasunary most of the post-Gabbro dykes are less than three feet wide, and are not shown on the six-inch maps, but rather more than one hundred are indicated on the 1:1250 map, their average width being two feet, and the maximum, six feet. The dykes are few in number near to the Gabbro and ~~to~~ increase rapidly outwards from the contact. They are parallel sided, follow straight or slightly curving courses, and make occasional side steps. Chilled margins are commonly present, and a few contain phenocrysts or amygdales. The mean strike of the swarm is N. 30°W., but there is a variation of about ten degrees on either side of this direction, and a few dykes follow entirely aberrant courses. Of the 100 dykes on the map, 68 were classed in the field as fine dolerites, 10 as porphyritic fine dolerites, 20 as medium-grained dolerites, and 2 as coarse dolerites. There are no acid dykes in this sector.

At a time when a few N.N.W. dykes were still being intruded, a new set of stresses produced the inwardly-dipping joints which guided the cone-sheet injections. Harker has said "In the interior valleys of Sligachan and Camasunary .... there is only a small thickness of gabbro free from inclined sheets ..." (1904, p. 368), and his maps show a break in these intrusions along the line of the Camasunary valley. However, over a dozen cone-sheets were found within the area covered by the large-scale map, and a total of twice that number over the whole valley between An t-Sron and the river, so that in fact they are hardly less numerous there than on Blaven. Their thickness is between one and six feet, and they incline N.N.W. at around 45°. Both fine and medium-grained dolerites occur, and are sometimes texturally banded parallel to the contacts. One prominent sheet (1:1250 map, D 12 - K 12) can be traced from the point where it cuts the Gabbro contact, in the west, for nearly half a mile to the track between Camasunary House and Loch na Creitheach, and in this distance it varies in thickness from three to six feet. All intersections between cone-sheets and dykes shown on the large-scale map indicate that the latter are older, but several instances of dykes cutting cone-sheets were observed in the ground south of An t-Sron, and in one these cases the dyke involved is a gabbro which Harker shows on his map as a part of a feeder to the Cuillin Gabbro.

CHAPTER X

THE COIRE UAIGNEICH GRANOPHYRE

On the eastern slopes of the Blaven Range outcrop two elongated masses of fine-grained granophyre, and on the headland of Rudha Ban, west of Camasunary, is a third intrusion of similar material. The three outcrops have so many features in common that it is likely that they are continuous at depth, and are therefore here referred to collectively as the Coire Uaigneich granophyre, after the location of the largest of the three outcrops.

Harker supposed these granophyres to be essentially sheet intrusions, dipping north-west beneath the Blaven gabbros and connecting directly with the granophyres of the Red Hills. He thought of them as the frayed-out edge of a large granitic laccolith (1904, pp. 120-129 and 139). This view was later questioned by Richey (1932), who pointed out that whereas Harker's maps show the Coire Uaigneich granophyre to be cut by cone-sheets, the Red Hills themselves are apparently not intersected by any of these intrusions. Richey's own observations led him to suggest that the cone-sheets were in fact cut off by the Red Hills intrusion, so that the latter must have been emplaced some time after the Coire Uaigneich granophyre.

Carr (1952, thesis) has briefly described the outcrop at Rudha Ban, and dates it to the period prior to the intrusion of the Cuillin Gabbro, but after the injection of the early dyke suite.

A paper by Wager, Weedon, and Vincent (1953) is largely concerned with the discovery of paramorphs after tridymite in exposures of granophyre at the Blaven-Slat Bheinn col, and its bearing on the petrogenesis. They give an account of the petrography and chemistry of this part of the intrusion.

(i) Field Relations

All three outcrops of granophyre are irregular in shape, but as a group they can be said to be aligned sub-parallel to the contact of the Cuillin Gabbro. No part of the outcrop is situated more than one mile from the contact of the latter intrusion, and the granophyres follow an arcuate line which approximately corresponds with the axis of the Coire Uaigneich anticline. Over most of its length, the granophyre is separated from the Gabbro by a screen of Jurassic sediments and basalt lavas, but tongues of acid material cut into this screen and may locally penetrate the gabbros themselves.

The northern outcrop. The northernmost of the three outcrops has the shape of an irregular triangle with its western apex pointing up the Allt Aigeinn valley. The northern apex is drawn out into a series of tongues along the east face of Belig, while to the south the granophyre terminates bluntly on the north-east slopes of Sgurr nan Each. On the south face of Belig there is a tongue-shaped extension to the north-west, and two isolated lens-shaped masses lie off the western apex in Allt Aigeinn. The main outcrop is some 800 yards across from east to west, and has a north-south extension of 1,500 yards, while the vertical interval between the highest and lowest exposures is 550 feet.

Harker's maps show the northern end of the granophyre as passing continuously into the Red Hills intrusion below Glas Bheinn, but this is not confirmed by the present mapping. The granophyre tongues fade out northwards amongst Jurassic quartzites, which are of very similar general appearance to the fine-grained, pale-grey granophyre.

The main body of granophyre is everywhere in contact with Inferior Oolite and Estuarine sediments, now mostly quartzites. The attitude of the contact plane on the eastern side can be examined on the south-east spur of Belig, and is there seen to be vertical up to the point where the granophyre reaches the crest; then at a height of about 750 ft. O.D. the contact reappears below a flat roof of Estuarine shaly and calcareous sediments, and a few hundred feet to the west turns abruptly down again towards Allt Aigeinn. At this point the north-westward tongue alluded to above continues the line of the flat roofed portion. The granophyre is markedly chilled below the roof, but this feature does not occur elsewhere in the northern outcrop. The attitude of the granophyre in Allt Aigeinn is not easy to determine, but the stream exposes a steep contact at the western apex of the main outcrop, and a few veins extend upstream into the base of the lavas, and form a tenuous connection with the two isolated, lens-shaped outcrops. The more southerly of this pair is partly emplaced into lavas, against which the contact is highly irregular, with enclosure of lava and local basification of the granophyre, and the whole is cut by unhybidized, lighter-coloured acid veins.

The granophyre is cut by a number of basic dykes trending north-west and west, and on Belig a solitary cone-sheet was noted.

<u>The central outcrop.</u> The northern outcrop is separated by only a few hundred yards of Jurassic, on the crest of Sgurr nan Each's south-east spur, from the northern end of the central outcrop. Granophyre occupies most

of the floor of Coire Uaigneich, and crosses the Blaven-Slat Bheinn col to the south as a narrow neck, before dying out on the western side of Coire Casteail. Over most of its length the granophyre has the shape of a sinuous dyke some 800 feet across, but in two places the outcrop expands rapidly to more than twice that width. Steep contacts are well seen in the region of the Blaven-Slat Bheinn col*, where they descend through 200 feet of lavas with a dip of 80° to the S.E.. The stream in upper Coire Uaigneich is eroded along the eastern contact against Jurassics, and the inclination is again to the S.E. at not less than 50°, while on Clach Glas the western contact dips 60° in the same direction. A thin sheet offshoot which arises from the western side of the main mass, to the north of the gully between Clach Glas and Sgurr nan Each, has a dip of 15° to the east.

Marginal chilling is better developed in the central outcrop than elsewhere, though it is not always present. It is most marked against lava contacts, as for example at the Blaven-Slat Bheinn col, where a dark-grey, flinty marginal facies is developed over a width of between three inches and one foot. Chilling becomes progressively less obvious as the contact is followed southwards into the Jurassics of Coire Casteail, but continues

* Plate 35.

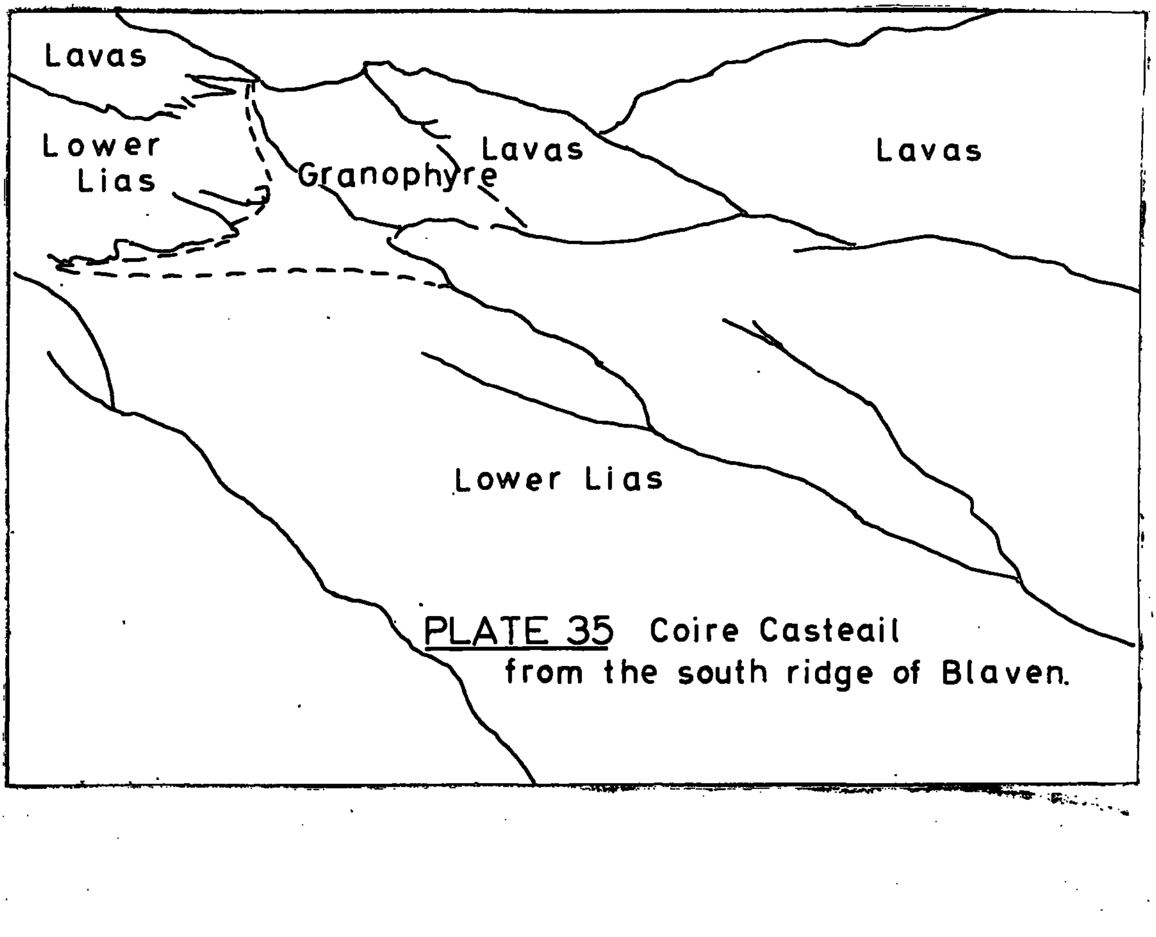


PLATE 35 Coire Casteail from the south ridge of Blaven.

to be a feature of the western contact against the lavas on the north side of the col. At one exposure on Clach Glas the margin carries sub-horizontal bands of spherulites in a fine-textured matrix. Along the northern termination of the outcrop, and in the sheet offshoot in the gully to the west, a moderate degree of chilling has occurred against Jurassic quartzites, and a small exposure of chilled granophyre is found wit_hin the gabbros at a height of 2,600 ft. O.D. in the large gully which descends from between the two summits of Blaven.

In the region of the Blaven-Slat Bheinn col the granophyre contains a well-defined system of platy jointing striking N. 65°E., and dipping 50° to 80° north-west, so that it trends sub-parallel to the contacts but inclines in the opposite direction.

A number of north-west basic dykes cut the granophyre, especially in upper Coire Uaigneich, but several dykes which traverse the lavas of An Stac are cut short at the contact. A few small cone-sheets also cross the granophyre, and are later than at least most of the dykes.

<u>The southern outcrop.</u> Between the southern end of the central outcrop and the western side of the Camasunary valley is a gap of one mile and a half without grano-

phyre, except for a few thin sheets which intrude the top of the Torridonian and the overlying base of the Lias on the south-west flank of Blaven. West of the mouth of the Camasunary River the granophyre reappears in an outcrop some 300 yards wide, but followed westwards over the Rudha Ban headland this width is rapidly reduced, and finally the intrusion becomes merely an irregular series of veins along the lava-Torridonian unconformity. In view of the considerable width of the granophyre at the Camasunary River the outcrop probably extends some way north-east beneath the sand and gravel of the Camasunary raised beach.

The south-west contact, against Torridonian, is a highly irregular one, passing inwards through a zone of veins into granophyre full of xenoliths, and then into granophyre with only a few inclusions. The metamorphosed Torridonian is of similar colour to the granophyre, but can be distinguished, especially on weathered surfaces, by its finely-laminated character. A well-defined chilled margin is not found at Rudha Ban, but at the mouth of the Camasunary River the centre of the mass is of relatively coarse grain, with acicular pyroxenes up to 4 mm. long set in a mottled yellow and grey matrix. This phase grades outwards into more typical, fine-grained, homogeneous, pale-grey granophyre. To the south-west the coarse phase disappears entirely, and the granophyre becomes progressively more crowded with xenoliths of Torridonian and meta-basic rocks.

The north-west contact, against lavas, is well-exposed in a cliff one third of a mile W.S.W. of the Camasunary Celtic Cottage, and is there seen to be irregular but sharply-defined, dipping at about 80° to the south-east.

The manner in which the outcrop of granophyre follows the unconformity between the lavas and the Torridonian gives the impression that it is a sheet dipping at a moderate angle north-west, but the highly-inclined contact against the lavas mentioned above may be an indication that the body as a whole is in fact steeply inclined to the south-east.

Shape of the granophyre. Some of the most important field characteristics of the granophyre are summarized below:-

(i) The outcrops are irregular in shape.

(ii) Where the contact is exposed it is usually dipping steeply outwards from the Gabbro, but in places the granophyre forms thin sheets inclined at much shallower angles.

(iii) Xenolithic enclosure of country rocks is very common. Although the process of enclosure is only seen in operation at such localities as the south-east contact at Rudha Ban, slices of apparently homogeneous granophyres taken from areas with sharp contacts often reveal the presence of enclosed quartzose sedimentary material, which, being of similar external appearance to the granophyre, is not easily detected in the field.

(iv) A definite roof to the intrusion can be seen on Belig, and the sediments which separate the northern and central outcrops on Sgurr nan Each are probably also in this situation.

(v) The granophyre as a whole presents a fine-grained, felsitic appearance, and chilling along the contacts is most marked at the highest levels exposed.

These facts suggest that the intrusion as a whole is exposed near to its roof, and that its basic shape is that of a dyke dipping steeply outwards away from the margin of the Cuillin Gabbro. The top of the intrusion varies considerably in altitude, and sends out a number of thin, sheet-shaped offshoots on its north-western side. The irregular shape of the outcrop is thus a result of erosion cutting right through some of these sheets, so that they appear as tongues on the map, while only reaching the top of others, so that they form broad expansions of the outcrop.

The field evidence is not in accord with Harker's idea of the granophyre as a low-angled sheet extending beneath the Blaven gabbros, while Wager, Weedon, and Vincent (1953) have suggested that the intrusion is a ring-dyke, a view with which the evidence agrees except in so far as the ring is a very incomplete one.

Age relations. It has been shown that Harker's suggestion that the Coire Uaigneich granophyre is a part of the Red Hills complex is not supported by the field evidence. Carr (1952, thesis) has dated the Rudha Ban portion of the intrusion to pre-Gabbro times, on the grounds that in two five-foot dolerite sills which transect it, the feldspars have been "schillered" by thermal metamorphism, and that therefore these sills are pre-Gabbro. The present writer considers that these two sills are part of the post-Gabbro cone-sheet system, for the degree of metamorphism which they show is in no way comparable to that in the nearby basalt lavas and pre-Gabbro dykes. The "schiller" is probably an intratelluric effect which may be consequent on the enclosure of feldspars from a consolidated gabbro within a still-liquid magma. The following points of evidence establish that the granophyre is of post-Gabbro age:-

(i) In Coire Uaigneich the granophyre cuts short north-west dykes which have not been metamorphosed by the Gabbro.

(ii) The granophyre has not undergone the same degree of metamorphism as many of the rocks which it intrudes. On Rudha Ban most of the granophyre lies within the pyroxene hornfels zone, and at the Blaven-Slat Bheinn col it is situated along the boundary between the pyroxene hornfels and amphibole zones, yet only low grade alteration of the dark minerals has occurred within it. On the other hand, xenoliths of lava enclosed within the granophyre at Rudha Ban possess all the metamorphic features of the adjacent outcrops of hornfelsed lavas. Carr suggests that the granophyre itself has contributed to the granulitization, but there are no similar effects in the amphibole zone lavas intruded on Blaven.

(iii) A small mass of chilled granophyre which is probably an offshoot of the main body was found intruding gabbros on the east face of Blaven.

An upper age limit to the granophyre is given by the fact that all but a few of the north-west dykes cut the intrusion, as do the still later cone-sheets. Those dykes which are earlier than the granophyre may in part or whole belong to the suite of dykes which Harker (1904, p. 365) describes as distributed radially to the Cuillin centre. This suite cannot, in Strathaird, be clearly distinguished from the north-west suite, since their trends are similar.

(ii) Petrography

Chilled rocks. Strong chilling is locally present along the margin of the granophyre, put a more gradual decrease in grain size towards the contacts is more common. Against some arkosic and quartzitic sediments even this change is barely perceptible.

The localities described by Wager and others (1953) at the col between Blaven and Slat Bheinn are the best in the area for examining strong chilling. Lying against the lavas at the contact is a zone of dark-grey, flinty rock, some three to twelve inches in depth, traversed by a few thin veins of quartz and epidote. Polished surfaces show a flow orientation of micro-phenocrysts parallel to the contact plane, and a few small veins of granophyre penetrate the lava.

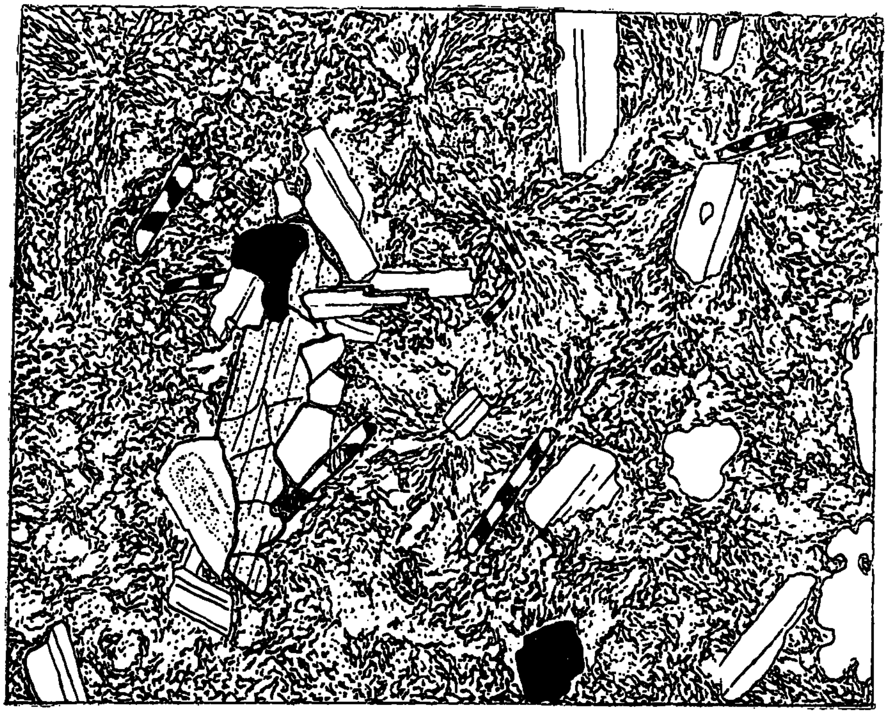
Thin sections of the chilled rocks from the Blaven-Slat Bheinn col (Specs. 217,* 218, 219) contain some 5% phenocrysts set in a dark-coloured, feathery, crypto-crystalline groundmass. The phenocrysts are of plagio-clase, inverted tridymite, orthopyroxene and ore, and they are accompanied by rare enclosed fragments of sedimentary quartz and quartzite. The 1 mm. long

* Plate 36.

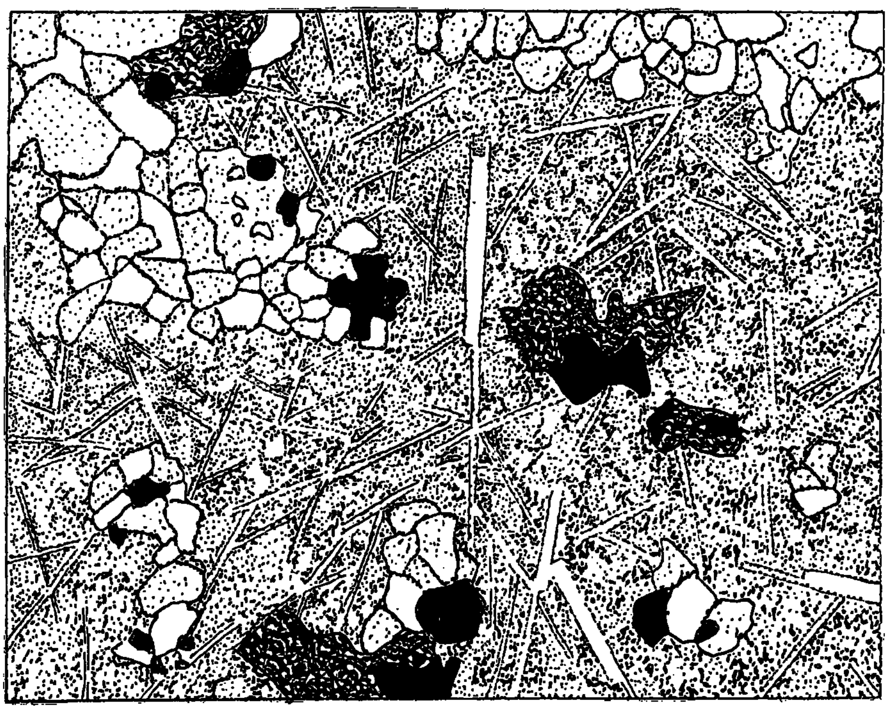
PLATE 36 (opposite.) Microsections: Coire Uaigneich granophyre at the Blaven - Slat Bheinn col.

A. (Spec.2I7) × 60. Chilled margin, half an inch from the contact. Phenocrysts of plagioclase, orthopyroxene, tridymite, and ore, in a cryptocrystalline groundmass. Note the glomeroporphyritic group in the left centre of the field, and the corroded quartz xenocryst in the bottom right corner.

B. (Spec.22I) × 60. Granophyre from the middle of the outcrop, showing micrographophyric and microgranitic textures. The micrographophyre contains a plexus of second generation tridymite crystals, some of which grow as terminal outgrowths to the tridymite pheno--crysts. The field also contains several patches of chlorite.



A.



B.

plagioclases are tabular in shape and occasionally euhedral, but they are frequently somewhat corroded by the groundmass, and in the vicinity of the contact plane broken crystals are not uncommon. Prominent carlsbad twinning, faint albite lamellae, and occasional pericline twins are present, and the extinction angles on albite-carlsbad twins show the composition to be in the region of the andesine-labradorite boundary. There is some alteration to a more alkaline feldspar along transverse cracks. Zoning is usually weak, continuous, and of normal type, but two individuals showed reversals outside the core and near to the margin. The plagioclases are sometimes associated with orthopyroxene in glomeroporphyritic aggregates, and in these cases the pyroxene moulds around the feldspar. The plates of inverted tridymite appear as thin, half millimetre laths in sections at right angles to the flow planes, with prism faces well-defined but terminations poor. Each original tridymite crystal is paramorphed by several anhedral quartzes, and these are frequently rich in inclusions. Orthopyroxene builds prisms up to 1 mm. long, and is often rounded by corrosion and altered along margins and cracks to a pale-green chloritic substance. The pleochroism is marked, and from the optical properties (2V 51°, n γ 1.716) Wager et al. (op. cit.) calculate the composition as 58% $MgSiO_3$. Porphyritic ores are always rounded and frequently carry a thin rim of biotite. The groundmass has the appearance of a devitrified glass, and varies in depth of colouration from almost black where the products of devitrification are of extremely fine grain, to pale grey in areas where crystallization is rather more advanced. In specimen 219 variations in the type of devitrification has given rise to banding parallel to the contact plane, with a pale grey zone 4 mm. wide followed inwards by a black zone, which in turn gives way to a band in which spherules of cryptocrystalline material are set in a finely crystalline matrix containing a few small biotites. The spherulites become smaller and fewer in number as the degree of chilling decreases, while at the same time acicular crystallites make their appearance and the phenocrysts of hypersthene and plagioclase become increasingly altered. Quartz xenocrysts often develop a second generation of tridymite paramorphs around their margins.

The thin sheet of granophyre which penetrates the lavas on the north side of the gully between Clach Glas and Sgurr nan Each (Spec. 12) is also strongly chilled, but contains only rare phenocrysts, of which only plagioclase can be definitely identified. Certain acicular green crystallites are probably pseudomorphous after orthopyroxene. The groundmass consists of an acid cryptocrystalline intergrowth in which are set abundant dark crystallites with aborescent, crescentic, and acicular forms. Interstitial quartz patches, thin quartz veins, and a little chlorite and epidote complete the assemblage.

Spherulitic texture is well developed in the chilled granophyres adjacent to the lavas of Clach Glas, and is clearly visible in hand specimen (Spec. 269). The spherules are between one and two millimetres across, and consist of dusty, cryptocrystalline and finely granophyric quartzo-feldspathic intergrowths, set with acicular and crescentic microlites which have been altered to chlorite and ore. They also occasionally include minute slivers of quartz which may be representative of the second generation of tridymite found at the Blaven-Slat Bheinn col. Between the spherules is finely crystalline quartz and feldspar, containing occasional nests of coarser quartz. Chlorite is common in this interstitium, and probably replaces biotite. Phenocrysts are again rare, being limited to a few altered tablets of plagioclase, and one chlorite pseudomorph which may be after hypersthene or biotite.

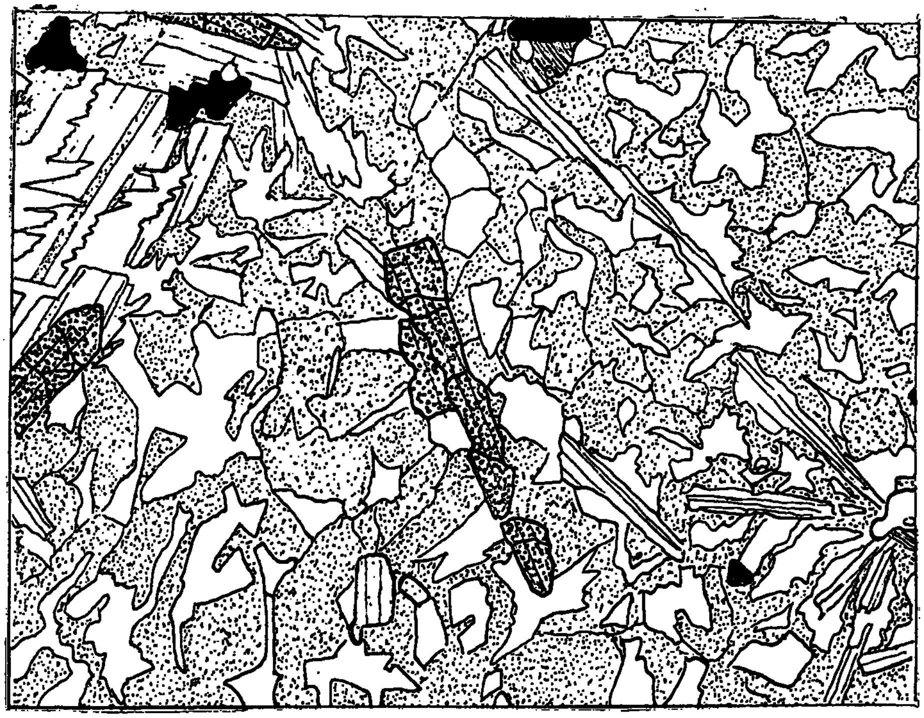
<u>Unchilled rocks</u>. As Wager et al. (1953) point out, the texture of the central part of the granophyre at the Blaven-Slat Bheinn col is an unusual one in showing "areas having two generations of tridymite crystals side by side with other areas having the typical microgranitic structure of the normal Tertiary acid rocks of Skye" (ibid. p. 268). In a slice of this rock (Spec. 221*) about one third of the area is microgranitic (granularity 0.1-0.2 mm.) and contains chlorite pseudomorphs after biotite, with a little sphene and epidote. The remaining two thirds of the rock consists of a finely granophyric intergrowth of quartz and alkali feldspar, in which are set phenocrysts of plagioclase, orthopyroxene, inverted tridymite, and ore. The plagioclase is largely altered to a more sodic feldspar, and the orthopyroxene is pseudomorphed by chloritic material. Apart from the larger inverted tridymites there is also a second generation of this mineral forming a criss-cross pattern of thin plates set in alkali feldspar, and also represented by terminal outgrowths of the porphyritic crystals.

A similar dual texture is also found in the central parts of the granophyre in Coire Uaigneich and Coire Casteail, and is most coarsely developed at the Camasunary end of the Rudha Ban outcrop. At this

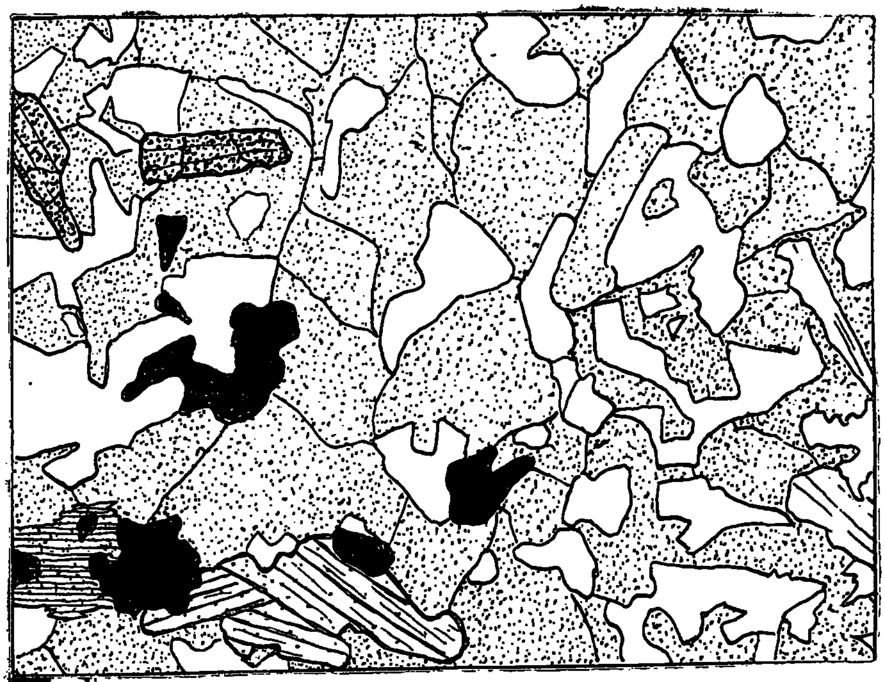
*Plate 36.

last locality the rock (Spec. 189,* 208) is mottled pale yellow and grey, and contains abundant acicular pyroxenes up to 4 mm. long. The grey patches mark areas of granophyric intergrowth, while the yellow portions are microgranitic. Dark minerals include a brownish-green hornblende and a ferriferous biotite as well as hypersthene and ore, but hypersthene is the most abundant as subhedral prisms without marked pleochroism. Hornblende and biotite are associated with ore, and can be sometimes observed to have developed at the expense of the pyroxene. As on Blaven, a plagioclase with a composition near to the andesine-labradorite boundary was the earliest of the felsic minerals to crystallize. It forms slender laths between 0.5 mm. and 1 mm. in length, and often contains pericline lamellae as well as carlsbad and albite twins. Much of the plagioclase is embedded in the granophyric areas and there forms radiating patterns. The granophyric quartz often corrodes the laths and sometimes separates them into several segments, whereas in the microgranitic areas accretion of a more sodic plagioclase has made the laths broader and anhedral. An analysis of this rock (Table 10, column 1) shows that the normative composition of the plagioclase to be An_{23}. The granophyric areas consist

*Plate 37.



A.



B.

of intergrown quartz and alkali feldspar moulded round the radiating groups of plagioclase laths referred to above, and are of much coarser texture than the analagous intergrowths on Blaven. In the microgranitic parts of the rock the granularity is less than half a millimetre, and the constituents are quartz, dusty, perthitic alkali feldspar, plagioclase, ore, and a little apatite and sphene. In specimen 189 there is a small amount of secondary chlorite and epidote, while in specimen 208 most of the plagioclase has been replaced by a dusty, sodic feldspar with $n <$ balsam, and the hypersthene is largely replaced by chlorite.

Paramorphs after tridymite have not been detected in any part of the granophyre at Rudha Ban. It is possible that tridymite was originally present but became incorporated into the quartz of the granophyric areas, which is more coarsely developed than on Blaven.

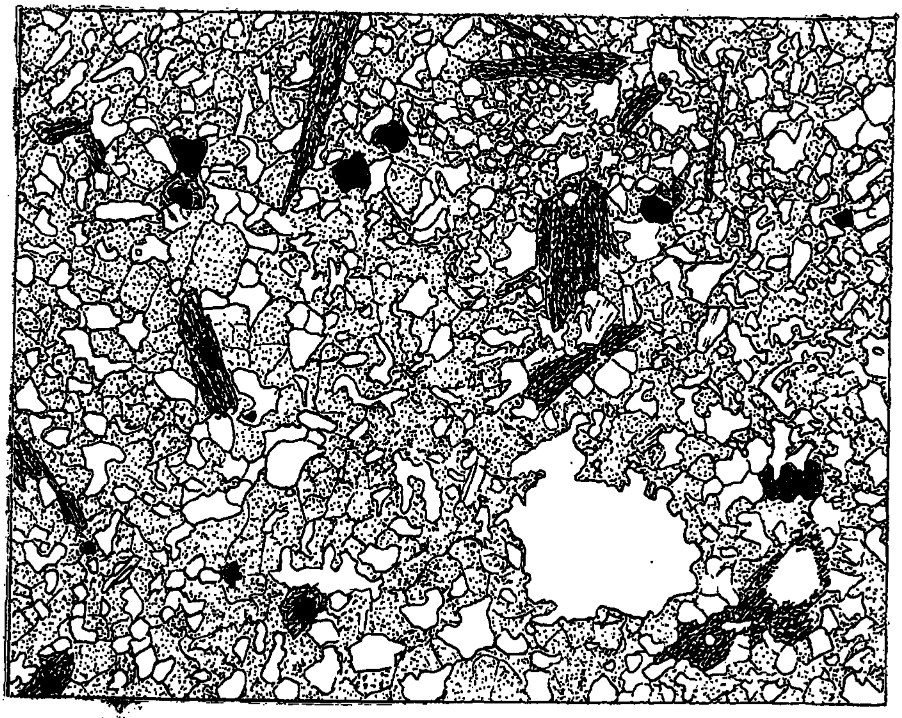
At Rudha Ban there is no distinctive chilled zone, though the rocks do become finer towards the margins, and are there crowded with xenolithic material - quartz, quartzite, arkose, and basic igneous rocks. The interstitial material consists of large, anhedral alkali feldspars averaging 1 mm. across, and these are full of fine intergrowths of quartz. Altered biotite and secondary muscovite are present in small amount. A laminated xenolith of Torridonian collected from well within the granophyre resembles the higher grades of metamorphosed arkoses from north of Camasunary, with granular hypersthene, spongy biotite, and a considerable amount of ore are set in a finely granular quartzo-feldspathic matrix. The relative abundance of dark minerals varies between the laminae. Lobes of granophyre have penetrated along some of the bedding planes, and possess a microgranitic texture, with granular hypersthene derived from the sedimentary rocks. In the field the granophyre can be seen to insinuate itself along the bedding planes, prising these apart, and finally enclosing the fragments.

The metamorphic effects of the granophyre upon the adjacent lavas is almost negligible, being limited to local amphibolitization of the pyroxenes in the higher grade hornfels. A slice (219) from across the contact plane at the Blaven-Slat Bheinn col shows no effects upon the lavas which can be distinguished from the local uralitization.

The rocks from the northern outcrop of granophyre are very variable in texture, some approximating to types already decribed, others being predominantly microgranitic, and many containing a very high proportion of quartzose sedimentary material. A specimen (48) from the south-east spur of Belig possesses a texture similar to that of the coarse phase at Rudha Ban, but is somewhat finer in grain. Relics of inverted tridymites phenocrysts are detectable, though partly masked by the granophyric texture, and there is also evidence of a second generation of this mineral, sometimes deveøloped as small, thin plates around quartz xenoliths. Hypersthene and biotite are both altered in this rock, but remain fresh in specimens from near the contact (e.g. Spec. 52, 62). In one of these (62) areas of fine granophyre are set in a background of highly quartzose rock which contains a few large, dusty, and albitized plagioclases up to 2 mm. in length. It seems likely that this texture represents the chilling of a small amount of magmatic material injected into a sedimentary rock, with concomitant growth of feldspar porphyroblasts in the latter.

Another contaminated granophyre (Spec. 11*) collected in Allt Aigeinn, has the texture of a quartzose microgranite, though locally the quartz forms crude intergrowths with the feldspar, and some of the larger quartz xenoliths are intergrown at the margins. There

*Plate 38



<u>PLATE 38</u>. Microsection: Coire Uaigneich
granophyre in Allt Aigeinn.
(Spec.II) 60. Specimen from the centre of the northern granophyre outcrop. Contains chloritized biotite and orthopyroxene, set in a microgranitic base, together with several grains of ore and xenocrysts of quartz.

are a few chloritized biotites, and a number of elongate pseudomorphs crowded round with ore, which are probably after hypersthene.

In the more southerly of the two isolated granophyre outcrops in the upper part of the Allt Aigeinn valley the textures are wholly micrograniti c, and biotite is the chief ferromagnesian constituent. A typical example (Spec. 340) has a granularity of half a millimètre, and contains some 40% quartz, 55% feldspar, and 5% dark minerals, mostly chloritized biotite, and a little sphene, apatite, and ore. About half the feldspar consists of subhedral albite-oligoclase. Some of these Microgranites have been hybridized with basic lavas, are darker in colour, and contain about twice the usual amount of dark minerals. In Specimen 338 about half of the ferromagnesian element is xenocrystic pyroxene, partly altered to a brown-green hornblende, the rest being made up of chloritized biotite and ore. The leucocratic constituents are similar to those in unhybridized microgranite, except that the plagioclases show marginal reversed zoning. Lavas adjacent to, and within, the granophyre are light in colour, and a slice (339) reveals the presence of interstitial quartz and the development of biotite and hornblende at the expense of pyroxene.

<u>Discussion of the petrography.</u> Wager, Weedon, and Vincent (1953) concluded that at the Blaven-Slat Bheinn col the Coire Uaigneich magma contained over 5 % crystals at the time of intrusion, made up in one specimen (op. cit. p. 270) as follows:-

(Vol. %) feldspar 2.7; pyroxene 0.6; ore 0.7; tridymite 1.7; total phenocrysts 5.7 %. They consider that close to the margin the magma was rapidly chilled to a glass, which later devitrified at lower temperature. Chilling was less rapid in the centre of the intrusion, and there was time for a second generation of tridymite to form before the magma cooled below the inversion temperature. While about two thirds of the liquid crystallized this second generation of tridymite was precipitated in the vicinity of the original tridymite phenocrysts, giving the criss-cross tridymite texture. In the later stages the remaining third crystallized as quartz, feldspar, and chlorite, giving the areas of microgranitic texture.

Other parts of the intrusion show notable differences from the rocks of the Blavên-Slat Bheinn col. Strongly chilled margins are by no means everywhere found, but they do seem to be commonly developed against lavas in other parts of the central outcrop, as are Clach Glas and Sgurr nan Each. At these localities, however, the chilled rocks contain only a very low proportion of phenocrysts. Specimens collected from the contact on Clach Glas contain only occasional phenocrysts of plagioclase, and no tridymite, ore, or hypersthene. The chilled tongue in the gully between Clach Glas and Sgurr nan Each again contains only a few plagioclase crystals, together with some small, acicular orthopyroxenes. In the centre of the intrusion a textural division into granophyric and micrograngitic portions is found at Rudha Ban and in the higher parts of the outcrop on Belig, but in Allt Aigeinn, below Belig, the textures are predominantly micrograngitic. In the Rudha Ban rock the large, acicular hypersthenes, elongate plagioclases, and large ore grains are probably equivalent to the phenocrysts found at the Blaven- Slat Bheinn col, but they are more abundant than at the latter locality:- orthopyroxene occupies 3 % of the volume; plagioclase 7 %; and ore 1.5 %. Inverted tridymite has not been detected at Rudha Ban, but it has been found in rocks of similar, though finer, texture near the roof of the intrusion on Belig. It is therefore evident that when the magma was intruded it was not homogeneous in respect to the crystalline content. This may indicate that the magma did not originate in a single magma chamber, but arose from an interconnected series of magma bodies which differed slightly in physical environment and possibly also in composition. Differences in internal vapour pressure, for instance, may have influenced the appearance or non-appearance of tridymite. Thus Tuttle and Bowen (1958, p.70) show that in the system Na Al Si_3O_8-K Al Si_3O_8-SiO_2-H_2O the stability field of tridymite at the liquidus decreases in size with increase in pressure of water vapour, and eventually, at high pressure, it becomes an unstable phase. Similarly, increase of hydrostatic pressure with depth of burial raises the inversion temperature of tridymite and eventually inhibits its formation altogether (Bowen and Tuttle, op.cit. p.29). Black (1955) calculates the depth at which tridymite becomes unstable as being between 3850 and 2650 metres. It is therefore possible that tridymite only crystallized from some of the less deeply situated portions of the magma body which later was intruded to form the Coire Uaigneich granophyre.

(iii) Chemistry.

Table 10 shows the results of five chemical analyses made on various types of granophyre, together with one analysis of a Jurassic quartzite collected from outside the contact on Belig, and the average of three analyses of Torridonian rocks from Skye quoted by Kennedy (1951). For comparative purposes two analyses of granophyre from Coire Uaigneich by Vincent (Wager, Weedon, and Vincent, 1953) are set out in Table 11, together with several other analyses of Skye granitic rocks quoted by these authors. It will be seen that the analyses of the chilled and semi-chilled granophyre from the Blaven-Slat Bheinn col in Table 10 (2 and 3) made for the present study compare fairly closely with Vincent's results on granophyres from the same area, except in that soda is somewhat higher and silica a little lower in the new analyses. On the other hand an analysis made on a specimen of the relatively coarse-grained type of granophyre found in the centre of the Rudha Ban outcrop (Table 10, 1) is notably different from the Blaven rocks in that silica, ferric iron and potash are much lower, and lime and soda, higher in the Rudha Ban rock. These differences are reflected by a higher ratio of normative plagioclase to normative orthoclase:- 48 % plagioclase and 8 % orthoclase, as against 33 % plagioclase and 19 % orthoclase in the specimens from Blaven. Similarities of field relations and petrography make it unlikely that the two rocks are of different

TABLE 10

CHEMICAL ANALYSES OF THE COIRE UAIGNEICH GRANOPHYRE.

	1.	2.	3.	4.	5.	6.	7.
SiO_2	71.9	73.8	73.1	75.0	77.0	75.58	83.4
TiO_2	0.82	0.73	0.80	0.77	0.56	0.42	0.34
Al_2O_3	13.1	11.7	11.4	11.5	10.1	11.39	6.8
Fe_2O_3	0.9	2.1	2.1	1.3	0.07	0.82	0.7
FeO	2.5	2.2	2.4	2.3	1.9	1.63	1.4
MnO	0.06	0.06	0.09	0.07	0.05	0.05	0.01
MgO	1.4	1.3	0.8	1.5	1.0	0.73	1.5
CaO	2.2	1.4	1.5	0.7	1.3	1.69	trace
Na_2O	4.4	3.4	3.4	2.9	2.7	2.46	1.2
K_2O	1.3	3.2	3.6	3.2	3.3	3.36	3.6
$H_2O(+)$	0.80	0.60	0.20	1.40	0.60	1.07	0.80
$H_2O(-)$	0.15	0.21	0.13	0.15	0.06	0.05	0.08
P_2O_5	0.16	0.27	0.26	0.09	0.07	0.30	0.03
Total	99.69	100.97	99.80	100.88	99.34	99.55	99.86

1. Spec. 189 Central facies of Rudha Ban granophyre. D. C. Almond.
2. Spec. 218. Semi-chilled granophyre from the Blaven-Slat Bheinn col; D. C. Almond.
3. Spec. 217. Chilled margin of granophyre from the Blaven-Slat Bheinn col; D. C. Almond.
4. Spec. 11. Moderately contaminated granophyre from centre of northern outcrop, Allt Aigeinn; D. C. Almond.
5. Spec. 52. Contaminated granophyre from near margin on the south-east spur of Belig; D. C. Almond.
6. Average of three analyses of Torridonian arkoses from Skye; Kennedy (1951, p. 258).
7. Spec. 55. Jurassic quartzite from near granophyre, Belig; D. C. Almond.

TABLE 10

(cont.)

NORMS.

	1.	2.	3.	4.	5.	6.	7.
Quartz	33.30	36.96	35.40	41.58	43.50	42.72	60.18
Orthoclase	7.78	18.90	21.13	18.90	19.46	20.02	21.13
Albite	37.20	28.82	28.82	24.63	23.06	20.43	9.96
Anorthite	10.84	5.00	5.56	3.06	5.56	6.67	-
Corundum	0.41	0.82	-	2.14	-	1.63	1.02
Diopside	-	-	-	-	0.68	-	-
Hypersthene	6.14	4.75	3.32	5.32	4.28	3.65	4.66
Magnetite	1.39	3.02	3.02	2.09	0.93	1.16	0.93
Ilmenite	1.52	1.37	1.52	1.52	1.06	0.76	0.46
Apatite	0.34	0.67	0.67	0.20	0.17	0.67	-
$H_2O(+)$	0.80	0.60	0.20	1.40	0.60	1.07	0.80

TABLE 11

CHEMICAL ANALYSES OF THE COIRE UAIGNEICH GRANOPHYRE AND OTHER SKYE GRANITIC ROCKS

(as quoted in Wager, Weedon and Vincent, 1953, p. 270).

	1.	2.	B.	C.	D.	E.
SiO_2	74.47	74.22	74.88	76.41	71.68	70.34
TiO_2	0.67	0.77	0.18	0.14	0.38	0.46
Al_2O_3	11.32	11.07	12.73	11.71	12.55	13.18
Fe_2O_3	2.06	1.75	0.53	1.68	2.29	2.65
FeO	2.22	2.43	1.33	0.77	2.40	2.24
MnO	0.06	0.06	0.02	0.002	0.05	0.19
MgO	0.78	0.74	0.25	0.17	0.24	0.40
CaO	1.69	1.56	1.12	0.42	0.92	1.24
Na_2O	2.79	2.95	3.33	3.62	4.28	3.61
K_2O	3.44	3.42	4.99	4.92	4.37	4.90
$H_2O(+)$	0.47	0.90	0.79	0.50	0.64	0.76
$H_2O(-)$	0.04	0.04	0.16	0.12	0.25	0.46
P_2O_5	0.06	0.09	0.05	0.04	0.03	0.10
Total	100.07	100.07	100.36	100.50	100.08	100.53

1. Chilled marginal granophyre, Coire Uaigneich, Blaven, Skye. Analyst: E. A. Vincent.

2. Granophyre near centre of intrusion, Coire Uaigneich, Skye. Analyst: E. A. Vincent.

B. Biotite-hornblende-granite, Kilchrist, Skye. Analyst: Geochemical Laboratories (Tilley, 1949).

C. Porphyritic felsite, Harker's Gully, Marsco, Skye. Analyst: E. A. Vincent.

D. Pyroxene-granophyre, G2, S.E. face of Beinn Dearg Mhor, Skye. Analyst: E. A. Vincent.

E. Hornblende-granophyre, Druim Eadar da Choire, Skye. ANALYST: W. Pollard (Harker, 1904).

origins, but the chemical differences are not easily explained. Contamination of the Rudha Ban granophyre by assimilation of basic inclusions can hardly be the cause, for if that was the case not only soda and lime, but also iron oxides and magnesia would have been increased. The sinking of plagioclase phenocrysts through the newly-injected magma might provide the answer - Rudha Ban is about 1,800 feet lower in altitude than the Blaven-Slat Bheinn col - but it would be expected that the hypersthene phenocrysts would also have been involved in such a process.

Wager, Weedon, and Vincent (op.cit.) have made the following points concerning the chemistry of the granophyre:-

1. The bulk chemical composition is significantly different from that of other Skye granitic rocks. The Coire Uaigneich granophyre has a high silica content, roughly equivalent to the more acid types of British Tertiary granite, but the latter are poorer in lime and magnesia. Less acid types of Tertiary granite, including most other Skye granophyres, have iron and magnesia contents comparable to the Coire Uaigneich granophyre, but silica is lower.

2. One aspect of these chemical peculiarities is made evident when normative contents of quartz,

orthoclase, and albite are plotted on a triangular diagram. The thermal relationships in the system SiO_2-K Al SiO_4-Na Al SiO_4 in dry melt are known from Schairer's (1950) work. The phase diagram contains a low-temperature "trough" within the stability field of the alkali-feldspars, and Barth (1951), by plotting normative quartz, orthoclase, and albite for various granitic rocks upon the phase diagram has shown that the majority fall in or near the area of this trough. Wager et al (op.cit) show that whereas other Skye granites also fall in or near the trough, the analyses of the Coire Uaigneich granophyre show it to be outside the trough towards the SiO_2 corner (Plate 39.). The Coire Uaigneich magma was therefore unlikely to have been the late residue from a crystal fractionation process, but may have been formed by fusion of a quartz-rich material, with little subsequent fractionation.

To these comments may be added some observations on the present work. It is evident from the petrographic descriptions and the chemical analyses that the Coire Uaigneich granophyre is variable in both mineralogy and chemistry, and this may be a reflection of the fact that the intrusion is exposed in its roof zone. The field relations indicate that enclosure of

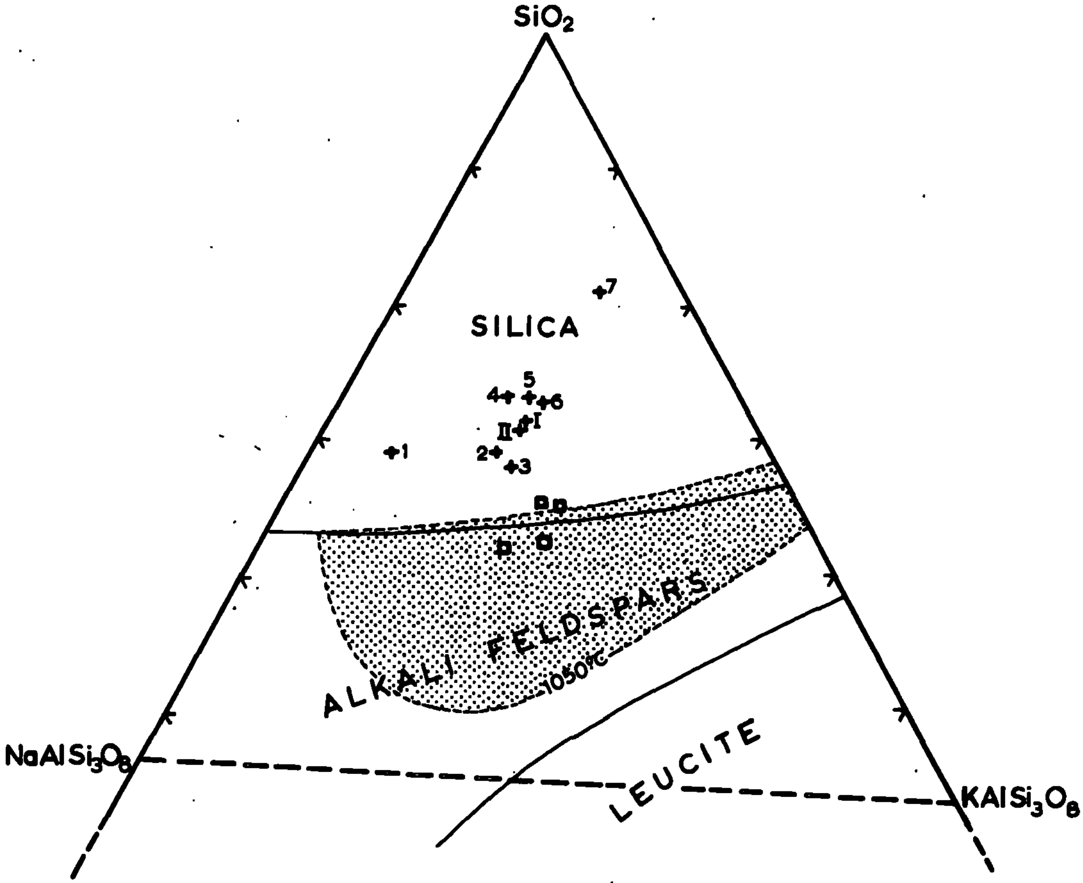


PLATE 39. PART OF THE PHASE DIAGRAM SiO_2-$KAlSiO_4$-$NaAlSiO_4$

(AFTER SCHAIRER, 1950)

THE "LOW TEMPERATURE TROUGH" IS SHADED

+ 1 - 7 ANALYSES QUOTED IN TABLE 10

+ I and II ANALYSES QUOTED IN TABLE 11 (from Wager, Weedon, and Vincent, 1953)

□ ANALYSES OF FOUR OTHER SKYE GRANITIC ROCKS (from Wager, Weedon, and Vincent, 1953) country rock fragments was a common feature of the intrusion process, and few thin sections of the granophyre are entirely free from foreign material. Most of the enclosures are evidently derived from quartzose sediments, but fragments of basaltic rock are common at Rudha Ban and in the upper part of Allt Aigeinn. Although most of this material remains as xenoliths and xenocrysts, the presence of granophyric reaction rims round some of the foreign quartz seems to indicate that there was also a certain amount of assimilation. Two analyses of granophyres containing significant amounts of quartzose sedimentary material are shown in Table 10 (4 and 5), together with the analysis of a Jurassic feldspathic quartzite from Belig, and the average of the three analyses of Torridonian arkose from Skye given by Kennedy (1951). The chemical composition of the Torridonian shows a general resemblance to that of the chilled granophyre (Table 10, 3), though containing rather more silica, and less ferric iron. The granophyres which enclose sedimentary material show similar features, but the Jurassic sediment differs considerably from both Torridonian and the granophyres in containing almost no lime, low soda and a very high proportion of silica. When the normative quartz, albite, and orthoclase of these rocks is plotted on the SiO_2-K Al SiO_4-Na Al SiO_4 phase diagram (Plate 39), it is seen that the Torridonian and the granophyres containing quartzose sedimentary material plot nearer to the SiO_2 corner than the chilled granophyres (I, II, 2 and 3 on Plate 39), but in the same general area. It seems quite feasible that the Coire Uaigneich magma originated by fusion, or partial fusion, of a feldspathic sediment or acid gneiss, as suggested by Wager et al (op. cit.), but it also seems probable that the magma, whether it originated in this way or not, was modified by enclosure and reaction with the country rocks during intrusion.

CHAPTER XI

MINOR INTRUSIONS.

The sequence of minor intrusions spans the whole of the igneous period, the earliest injections probably being contemporaries of the basic lavas, while some of the latest north-westerly dykes are among the youngest igneous rocks exposed in the area.

Most of these minor intrusions can be classified as sills, dykes or cone-sheets, and the dykes far out-number the other two groups. The majority are basic in composition, but a few acid and ultrabasic varieties also occur.

(i) Sills

In Strathaird sills are neither numerous nor large, for over most of the igneous period tension joints were abundantly available and exploited by the uprising magma. This circumstance appears to be especially associated with central Skye, and in the northern and north-eastern parts of the island sills are more common.

The sills of Strathaird include both acid and basic types, and they range in thickness from only a few inches to over forty feet. Sills less than three feet in thickness are not indicated on the six-inch maps. No sills have been discovered within the lava pile, and Harker's supposition that the lava flows of Skye are interbedded with numerous sills has since been shown to be incorrect (see Chapter V).

The magma which formed the sills tended to exploit shaly members in the sedimentary sequence, and consequently this type of intrusion is most common along the eastern side of the Strathaird Peninsula, where both the Estuarine Series and the shale near the top of the Inferior Oolite form favourable horizons. The Lower Lias to the north-east of Camasunary and the well-bedded Torridonian rocks at Rudha Ban also contain a number of small sills.

Both acid and basic sills are cut by nearly all the dykes with which they came into contact. Rare instances of the reverse relationship have been noted, a clear example being situated on the shore north of Rudha na h-Airidh Baine ~~Rudha Ban na h'aindh~~ (west of Ben Leacach). At this point a six-foot dolerite sill is seen to cut one of the early members of a basic multiple dyke and is itself cut by the later members. Although it is unlikely that all sills belong to any one special epoch, it has been found that at least most of them are transected by the close-spaced north-north-westerly jointing system, and by faults which follow a similar direction. Since these structures are known to have been formed soon after the intrusion of the Cuillin Gabbro, it is almost certain that most sills were injected before or during the latter event. The intrusion of sills into the sediments may well have accompanied extrusion of the lavas above. It is not known whether acid and basic sills are of dissimilar age; judging by other igneous sequences in the British Tertiary it is not unlikely that acid intrusion followed a basic phase, but in composite sills elsewhere in Skye the acid centres were injected after the basic margins, with very little time interval between (Harker, 1904, Chapter XII).

The Elgol Sill. The largest of the Strathaird sills is a sheet of coarse dolerite intruded into the Inferior Oolite shale horizon at Elgol. The sill thickens to the south-west and is cut off by the sea south of Port na Cuillaidh, while to the north-east it thins out, and finally disappears near Elgol Post Office. At the coast the thickness is 40 feet, but this is reduced to 30 feet at the Elgol-Glasnakille road, and 700 yards north of the road a rocky knoll reveals the full thickness to be only 15 feet. On the north side of this knoll a depression marking the line of a fault cuts across the feature, and beyond this point the scarp formed by the sill is only a few feet high and soon disappears altogether.

The sill everywhere rests on shales and in well-exposed on the coast and on the south side of the Glasnakille road. At a locality 400 yards south-west of the road the base is seen to step down some 15 feet to the south-west, transgressing the bedding of the shales. Shales are again seen above the sill at several points along Allt Port na Cuillaidh, and the contact of dolerite and shale is well exposed in this stream opposite Elgol School.

The dolerite itself is best displayed in the sea-cliffs south of Port na Cuillaidh (see Plate 40) and is there seen to possess a layered structure. At the southern end of these exposures the layering comprises:-

Layer 3. 6 feet of hard, grey, angular-weathering coarse dolerite with crude columnar jointing.

Layer 2. 12 feet of deeply-weathered, dark-brown dolerite.

Layer 1. 12 feet of brown-weathering dolerite containing several thin, lighter-coloured layers which appear to be late injections. Rough columnar joints are present.

At the northern end of the cliffs an undulating basal

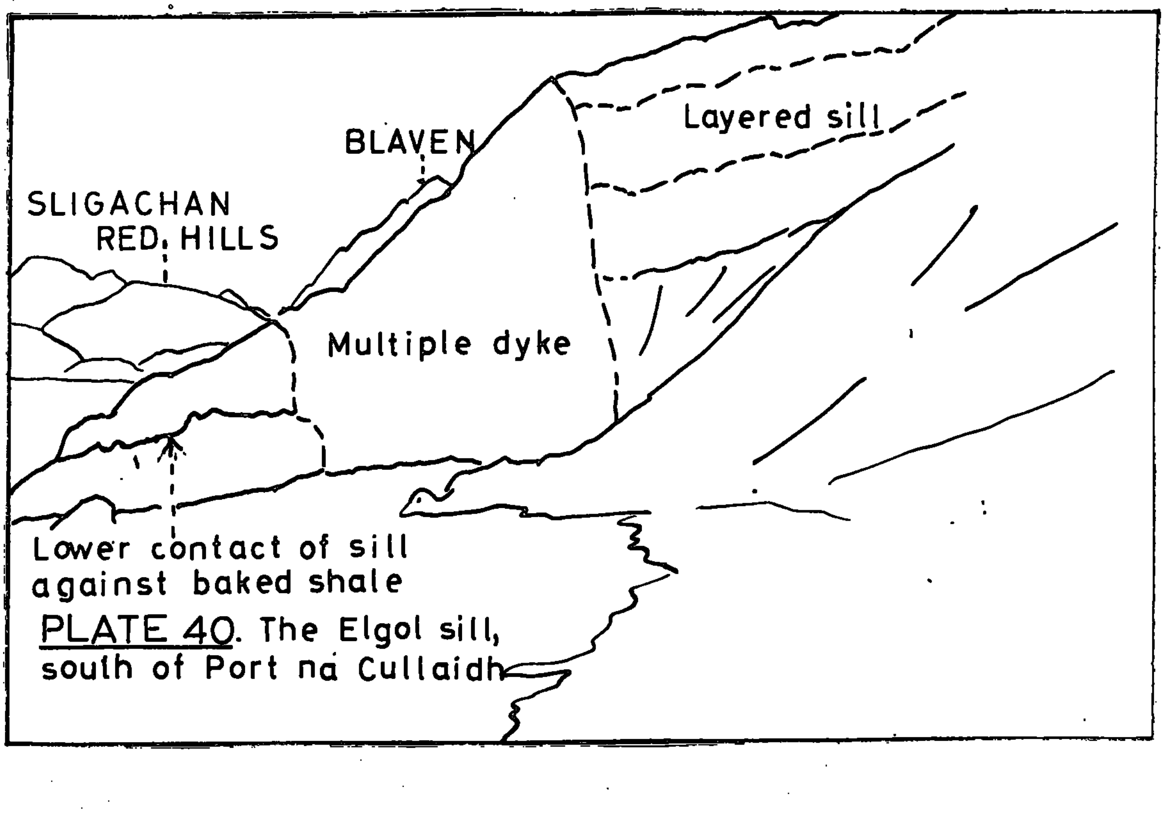


PLATE 40. The Elgol sill, south of Port na Cullaidh

contact is exposed on the south-west side of a large multiple dyke. Below the contact the shales are contorted to a depth of five feet and cut by small sheets of dolerite parallel to the main body. There is a well-marked chilled margin zone six inches thick, and Layer 1 is here 15 feet thick, Layer 2 is 20 feet thick, and Layer 3 ~~only~~ 8 feet thick. There is thus considerable lateral variation in the thickness of the layers within the 300 yards which separate the northern and southern ends of the exposure. Late-stage injections form net-veining patterns at the base of the sill but form regular layers at higher levels.

Slices from different layers of the Elgol sill showed less petrographic variation than was expected from their appearance in the field. All the rocks collected show a considerable degree of alteration. A slice of the upper chilled margin (494) at Elgol School shows it to be a fine-grained dolerite possessing an intersertal texture. The laths of feldspar average 0.3 mm. in length and the pyroxenes 0.35 mm. across, and these minerals are accompanied by a few olivine pseudomorphs. A specimen from Layer 1 (487) is ophitic in texture, and consists principally of 0.4 mm. labradorite laths (An62) enclosed by titaniferous clinopyroxene 2 mm. across. Ore is common in small subhedra, and a part of the chloritic material in the groundmass appears to be pseudomorphous after olivine. The base of Layer 2 (488) is rather finer in grain than the previous specimen, the plagioclase laths being only 0.3 mm. in length and most of the ophitic pyroxenes less than 1 mm. across. Small pseudomorphs of olivine are again present. The upper part of the same layer (489) is coarser and more leucocratic, with broad feldspar laths, largely altered to a clay mineral, and large (2-3 mm.) sub-ophitic clinopyroxenes. Olivine is present in moderate amount, but is now represented by bowlingite, while the ore builds large grains which tend to be skeletal or elongate. Large pyroxenes are again found in Layer 3 (490) with thick plagioclase laths (0.7 mm.) and a higher proportion of altered olivine than is present in the lower layers. The late-stage veins (492, 493) are highly feldspathic rocks consisting largely of thick plates of plagioclase (An 54) averaging half a millimetre in length. The subordinate clinopyroxene is in part sub-hedral and elongated, and in part intersertal. The pyroxenes of specimen 493 exhibit a green tint and the margins are sometimes composed of aegerine-augite, a mineral which also occurs in a few discrete needles. Analcitic patches.

altered partly or wholly to albite, are found in both specimens. Olivine pseudomorphs are rare, while rods of ilmenite and needles of apatite are common accessories.

The compositional differences between the various layers of the Elgol sill are thus relatively slight, and there is no regular variation with height in the sill to suggest that fractional crystallization after intrusion was the cause of the layering structure. The sill appears to be a multiple injection, though some differentiation within individual layers may be postulated to account for an increase of feldspar upwards to Layer 2. Slight differentiation must also have preceded intrusion, for the late stage veins which occur in Layers 1 and 2 evidently crystallized from a magma enriched in soda, titanium and phosphorous and poor in magnesium and iron.

Other Basic Sills. Most of these small sheets are composed of medium-grained dolerite which may or may not contain subordinate olivine. The olivine-bearing varieties are exemplified by a six-foot sill intruded into the Corallian north of Rudha na h-Airdh Baine. This rock consists of labradorite, granular clinopyroxene, olivine altered to chlorite and bowlingite, and skeletal ores. A notable amount of uralitic amphibole has developed at the expense of chlorite. Typical of the olivine-free sills is a four-foot thick sheet intruded into the Cyrena shale east of An Carnach. It is sparsely feldspar-phyric, and the clinopyroxene is sub-ophitic, while chlorite fills small amygdales and occurs patchily in the groundmass. The labradorite in this rock has been partly altered to albite.

Several dolerite sills make prominent features amongst the Estuarine shales north of Elgol, but none are more than ten feet in thickness. One of these sheets forms the summit of Bidein an Fhithich and passes northward into the flank of Ben Cleat.

The Allt Aigeinn Felsite. The largest acid sill in the Strathaird area is a sheet of felsite which can be traced for over a mile within the Estuarine shales west of the head of Loch Slapin. In the north the sill is first seen in Allt Aigeinn, 1000 yards south-west of Loch na Sguabaidh, and is from that point intermittently exposed for some 600 yards south from the stream. The dip is between 15 and 25 degrees to the east, in conformity with the attitude of the adjacent shales. At the southern end of this section the outcrop is offset some 150 yards to the west, a feature which is probably due to displacement along a north-west trending fault. To the south of these exposures the geology is obscured by drift, but the sill reappaers at a height of 350 feet O.D. in Allt Dunaiche, and in there faulted out on the south side of the stream. The sill is last seen in a small stream below the An Carnach cliffs, 1000 yards north-west of Faoileàn. Over the length of its outcrop the sill varies between fifteen and twenty-five feet in thickness.

The felsite is a distinctive rock in the field since it weathers pale grey, and is almost pure white when freshly broken. Spherulitic texture is frequently developed, especially near the contacts, white spherules are set in a pale grey, opharitic matrix. In Allt Dunaiche the spherules define a banding parallel to the contacts. In the centre of the sill more advanced crystallization has produced a fine, even-grained appearance not unlike that of a limestone. Sparse phenocrysts of quartz are not uncommonly present, and at an exposure 300 yards south of Allt Aigeinn the felsite contains numerous phenocrysts of both quartz and feldspar.

Thin sections of the spherulitic contact rock in

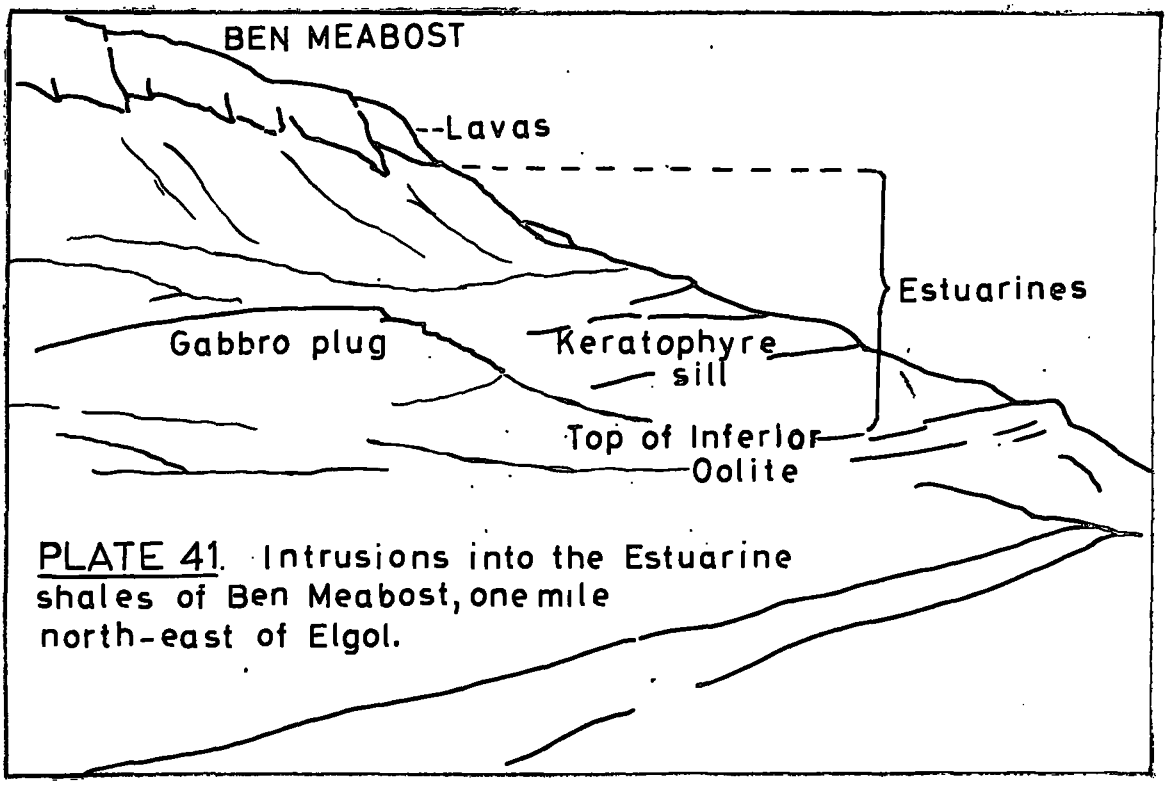


PLATE 41. Intrusions into the Estuarine shales of Ben Meabost, one mile north-east of Elgol.

Allt Aigeinn (240) shows the Spherules to consist of fine, radiate intergrowths of quartz and feldspar, while the groundmass is cryptocrystalline except for patches of coarse, strained quartz within which grow small quartz-feldspar rosettes. Thin veins of quartz have been noted to traverse the spherules but stop short against the groundmass. No dark minerals are present. This rock has been thoroughly carbonated after consolidation and nearly half the bulk now consists of ragged carbonate crystals half a millimetre across. Much of this material forms rounded groups which evidently replace the spherules and contain zones of brown inclusions. The carbonate displays a very distinct twinkling from colourless to grey, but since the refractive index is less than 1.66 it is evidently a calcite. The centre of the sill at the same locality (239), shows more advanced, but still immature, crystallization. Feathery quartzo-feldspathic intergrowths alternate with patches possessing micrographic texture. Set in this variable groundmass are slender, dark-coloured microlites with straight extinction, probably orthopyroxene. This rock bears a marked resemblance to some of the semi-chilled phases of the Coire Uaigneich granophyre.

A specimen of the porphyritic variety of felsite*

* Plate 42.

found in a stream south of Allt Dunaiche is rich in quartz and feldspar phenocrysts averaging 1.5 mm. and 3.0 mm. in length respectively. The quartz occurs as squat, slightly-corroded euhedra surrounded by granophyric rims, while the feldspars are largely altered but appear to be mainly of acid plagioclase. It is possible that this local abundance of phenocrysts indicates proximity to a feeder. Slices from the felsite of Allt Dunaiche (243b) have textures similar to those in the rocks from Allt Aigeinn, while a specimen from the exposure east of An Carnach contains well-developed spherulites 2 mm. across which sometimes contain a quartz phenocryst in the core. This rock also carries altered needles of orthopyroxene (?) up to 1 mm. in length.

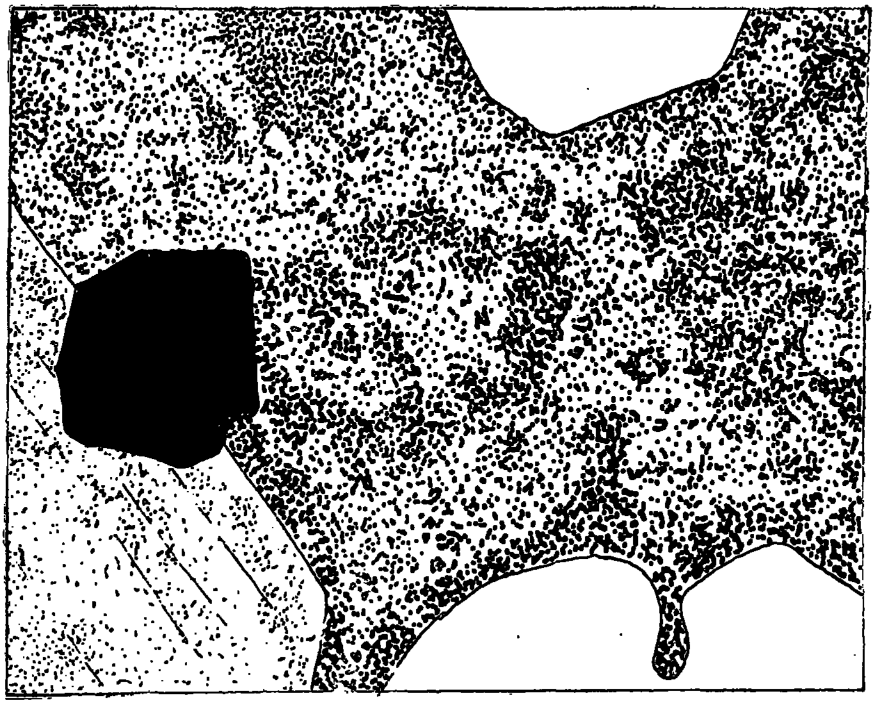
Petrographic similarities between the Allt Aigeinn sill and some of the chilled phases of the Coire Uaigneich granophyre suggests that the two are genetically related and perhaps in physical continuity at depth. Harker's (1904) maps show the Allt Aigeinn felsite as an outlier of the granophyre, though the occurrence in Allt Dunaiche is indicated as a felsite dyke.

The Quartz-Keratophyre of Ben Meabost. The only other

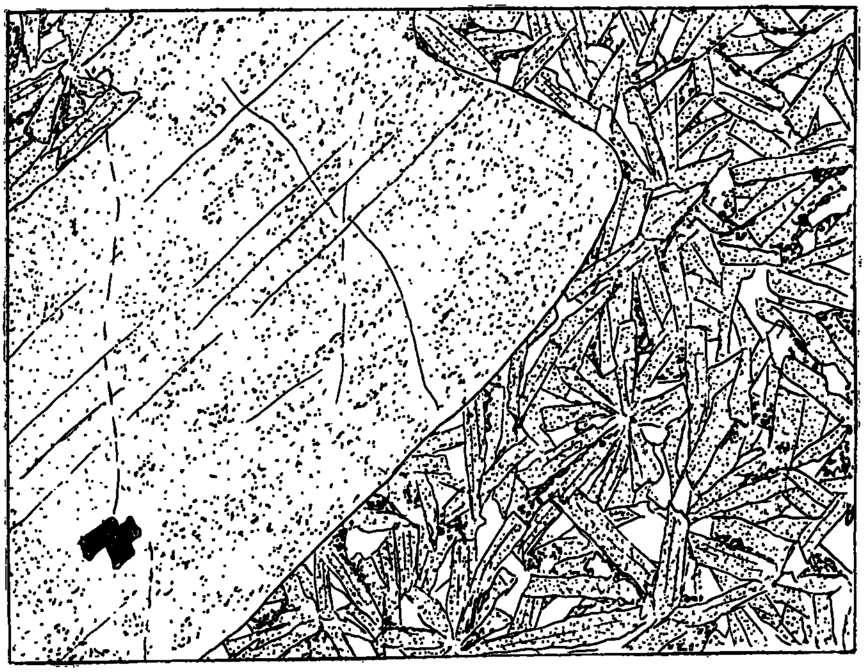
PLATE 42 (opposite.) Microsections: Acid sills.

A. (Spec.241) × 60. Porphyritic variety if the Allt Aigeinn felsite sill. Euhedral phenocrysts of quartz(sometimes corroded),serictized acid plagioclase,and ore,in a cryptocrystalline groundmass.

B. (Spec.486) × 60. Quartz keratophyre sill,Ben Meabost. Euhedral phenocrysts of acid plagioclase,partly sericit--ized,in a groundmass of dusty acid plagioclase laths and interstitial quartz.



A.



B.

acid sill of note in Strathaird is found in the Cyrena shales south of the Ben Meabost lava capping, and is marked by an arcuate feature zone 400 yards in length.* Several north-north-west dykes can be seen to intersect the sill, including a 50 foot wide multiple dolerite intrusion. In hand specimen the rock of the sill is greenish-grey, feldspar-phyric, and contains a few vesicles lined with chlorite but otherwise empty. In thin section it is seen to consist principally of thin laths of acid plagioclase, a few phenocrysts of the same mineral, and some 10 % of interstitial quartz. Dark minerals are limited to rare elongate microlites of indeterminate nature, a little ore, and chloritic patches. The feldspar laths average 0.4 mm. in length and tend to form sub-radiate groups, while the phenocrysts are euhedral and up to a centimetre long. All the feldspars are cloudy. No extinction angles greater than 15 degrees were noted, and the refractive index is less than that of balsam, so the composition evidently falls within the albite range. This rock may be classified as a quartz-keratophyre, and is similar in composition to a dyke and a sill described by Harker (1904, pp. 227 and 289) and classified by him as bastonite, or bostonite porphyry.

*Plate 41.

(ii) Dykes - Field Relations.

Distribution. In his account of the minor intrusions of Skye, Harker (1904, Chapters XVII-XXIV) distinguishes two main elements in the dyke distribution pattern, the first being a regional swarm of dykes orientated between north-west and north-north-west, and the second comprising several systems of dykes and sheets confined to the general area of the central intrusion complex. The north-west swarm includes a vast number of individual intrusions, the average trend of which is N. 37° W., and Harker points out that dykes concentration is greatest in the strike zone which includes the central intrusions. In the lateral parts of the swarm the dykes swing inwards towards the central intrusions so as to tend towards a radiate pattern.

In the immediate vicinity of the Cuillins are found the localised sets of minor intrusions which Harker (1904, p. 305) classified as follows, in order of age:-

1. A set of basic dykes tangential to the Cuillin centre.
2. A set of basic dykes radial to the Cuillin centre.
3. A set of inclined sheets dipping inwards towards the Cuillin centre (i.e. cone-sheets).

4. A set of ultrabasic dykes radial to the Cuillin centre.

Since Strathaird lies on the south-east side of the Cuillin intrusion centre it lies in the zone of maximum development of the north-west swarm. Dyke concentration is related particularly to the Cuillin Gabbro, rather than to the central intrusion complex as a whole, and since the strike N. 37° W. which passes through the centre of the Gabbro also cross southern Strathaird, the latter part of the Peninsula is richer in dykes than the northern part of the area. Moreover, the strike of the swarm swings gradually from north-north-west in southern Strathaird to north-west in northern Strathaird in response to the radiate tendency mentioned above. This is illustrated by considering the following average dyke trends in various parts of the Peninsula:-

1. Belig.	N. 55° W.
2. Coast east of Keppoch, An Stac, and Blaven.	N. 47° W.
3. Ben Meabost and Beinn Leacach.	N. 35° W.
4. Elgol to the southern tip of the Peninsula.	N. 30° W.

Members of the radial dyke suite of Harker cannot be distinguished in Strathaird from the main swarm, since in that area there is a coincidence of strike.

A few dykes which may belong to a tangential suite have been noted in Coire Uaigneich and Abhuinn nan Leac, but they are certainly not well developed in this part of central Skye. A set of small, north-east dykes which parallel the Gabbro margin at Camasunary are of pre-Gabbro age, unlike the tangential suite of Harker. There are also several ultrabasic dykes in the Peninsula, but within the limits of the area they cannot be shown to have a radial tendency.

Harker considered that within the general framework of the distribution pattern, frequency of dykes depends on the nature of the country rock. He remarks particularly on the paucity of minor intrusions within the granitic rocks of the Red Hills, and, to a lesser extent, within agglomerates and the overthrust Torridonian of Strath. Although the nature of the country rock no doubt does have some effect upon dyke distribution, Harker was partly misled in that he thought that virtually all dykes post-dated all other varieties of igneous rock in Skye. The sequence which is now emerging from recent work makes it clear that periods of dyke intrusion alternated with phases of major intrusion, so that abundance of dykes is often a reflection of age relationships. It must be admitted, however, that the sparsity of dykes within the overthrust Torridonian of Strath is best explained by supposing that the rock was resistant to penetration by dykes. The autochthonous Torridonian at Camasunary is cut by no fewer dykes than adjacent rock types.

Injection of dykes must depemd both on the availability of magma under high pressure and the presence of a set or sets of high-angled tensions joints. The form of a dyke suite is therefore a reflection of the tectonic events which preceded or accompanied the uprise of magma. At Camasunary there is a marked contrast between the irregular forms of the pre-Gabbro intrusion and the rectilinear courses followed by the later dykes of the main swarm, and this is because the north-west jointing patterns only became well established after the intrusion of the Gabbro. It also follows that a major intrusion emplaced after a period of joint formation but before the injection of the dyke magma will tend to be penetrated by fewer dykes than the adjacent formations.

Field Characteristics of Dykes. Harker has provided an excellent description of the field characteristics of Skye dykes (1904, pp. 291-314), and the notes given here refer to some of the special features as developed in Strathaird.

The dykes vary in width from a few inches to several feet or more, but only those over three feet wide are indicated on the six-inch maps. Dykes of six feet and over are generally multiple injections, and the average width of individuals is between three and four feet. However, a few "solitary" dykes are among the largest of all, and these are always composed of coarse dolerite, gabbro, or peridotite.

Individual dykes can rarely be traced far laterally especially in the dense swarm of southern Strathaird. The large solitary dykes can, however, sometimes be followed for a considerable distance, as in the case of a coarse dolerite found north of Loch Coire Uaigneich, which can be traced south-eastwards through Coire Ballaig and into the Kilmarie Valley, a distance of over a mile. This dyke is in places over 90 feet wide, and though essentially solitary it is followed by a few minor dykes of fine-grained dolerite. A number of the larger dykes which cross the south ridge of Blaven (at c. 1000 feet O.D.) can be followed for half a mile. Most dykes cannot be traced beyond one exposure.

A feature of the swarm in southern and western Strathaird is the presence of several large multiple injections. A dyke of this type situated half a mile south of Camasunary House has a total width of 59 feet and consists of fourteen separate injections varying from coarse dolerite to extremely fine-grained dolerite. Followed along the strike the members separate, come together, and cross over each other, and are sometimes separated by lens-shaped screens of country rock. Other large multiples on the coast between Camasunary and Elgol have widths of 25 to 75 feet, and a few include felsite members and may then be termed "composite multiples" (Harker, 1904, p. 297).

Dykes exposed in vertical section show similar coalescence and bifurcations to those seen in horizontal sections, as is well seen in the 300 feet cliff of Carn Mor, on the western side of Ben Cleat. The dyke swarm can thus be regarded as a plexus of sub-parallel, gently-curving individuals, joining together and parting company in both horizontal and vertical planes. Bifurcations of individual injections are rare except at dyke terminations, but an older dyke is not infrequently split by a later one.

Occasionally a dyke can be seen to make an abrupt step to the side, the two ends thinning out and often joined by a narrow bridge. Sometimes the joint planes adjacent to a side-step are slightly diverted from their courses, and this is one of the rare indications of active deformation by intrusion pressure.

Whereas most dykes are parallel-sided and follow nearly straight courses, in a few localities in eastern Strathaird the pattern is noticeably curved. Two areas which exhibit this feature particularly well are situated on the coast one mile south-south-east of Elgol School, and one hundred yards north-east of Glasnakille, respectively. At these localities the strike of dykes changes through 20° within a few hundred yards. Curving patterns of this type have usually been noted in places where the country rock is Inferior Oolite sandstone, so that the jointing which caused them may be the result of some property peculiar to this type of rock.

Minor features of dykes in the field include joints, chilled margins, amygdales, phenocrysts, and xenolithic material. Joints may be absent altogether, but where present they are most commonly of the cross-dyke, prismatic pattern. In other cases jointing is parallel to the walls, and in rare instances both types of joint are present. Chilled margins are best developed in the finer-grained dykes, and may contain a separate micro-jointing system. Phenocrysts and amygdales are usually most abundant in the central portion of a dyke and give rise to a pitted appearance on weathering. Phenocrysts are often aligned parallel to the walls, and in some acid dykes flow orientation is also shown by the banded nature of the groundmass. Amygdales are not uncommon, but the majority of dykes are free from them. According to Stearns and Macdonald (1946, p. 22), dykes found close to the surface of extrusion in Hawaii are commonly vesicular and vertically-jointed, whereas these features disappear at depth and the rock becomes cross-jointed. Unfortunately for its use as a criterion of depth, vesiculation is complicated by variations in vapour pressure of volatiles in the magma of different dykes. In the Spanish Peaks region of Colorado, Knopf (1936) found vesiculation in dykes of variable composition to extend through a vertical interval of 5,000 feet.

While most dykes followed joints planes, a few were intruded along small faults; several instances of this were found in the cliffs of An Carnach. Most dykes are sub-vertical, but a small proportion possess a marked hade which, as Harker has remarked (1904, p. 305) is most commonly into the north-east quadrant. The suggestion by the same author that the hade results from tilting of early dykes which were once vertical does not appear to be borne-out by the age relationships observed at dyke intersections, and it is more likely a result of local idiosyncrasies of the jointing system.

The marked concentration of dyke trends into the north-west quadrant has been an important influence on the development of the present day topography. Reference to the six-inch maps will show that among such features as sea-cliffs, streams, gullies, and depressions a north-west orientation is the most common one. The deep, sheer-walled gullies which diversify the rock faces of the Blaven range are notable instances of erosion along dykes. Where the country-rock is igneous, dykes usually weather back, but in the shaly rocks of the sedimentary sequence wall-like exposures are common.

Density of the North-West Dyke Swarm.

The table below provides some data on dyke-frequency in the north-west swarm, as revealed by a number of well-exposed sections across the strike. Individual members of multiple intrusions are not calculated separately.

Locality	Length of section	Number of dykes	Total thickness	Crustal expansion
Camasunary; shore north-east of Rudha Ban. 600 yards from margin of Cuillin Gabbro.	900 yds.	23	240 ft.	1 in 10
Camasunary; half a mile south of Camasunary House. One mile from margin of Cuillin Gabbro.	600 yds.	39	426	1 in 4
Camasunary; Abhuinn nan Leac 1000 yards from Gabbro contact.	1800 yds.	121	791	1 in $6\frac{1}{2}$
Kilmarie River. One and a half miles from the Gabbro contact.	1500 yds.	35	352	1 in 13
Shore north of Kilmarie House. Three miles from the Gabbro contact.	2300 yds.	59	379	1 in $16\frac{1}{2}$
Allt Dunaiche. One and a quarter miles from the Gabbro contact.	900 yds.	26	194	1 in 13
Shore west of Elgol. Three miles from the Gabbro contact.	1800 yds.	61	558	1 in $9\frac{1}{2}$

The three sections in the Camasunary district and that from near Elgol all lie along the zone of maximum concentration in the centre of the swarm, and have ultilised to construct a profile of dyke density along the strike (Plate 43). Plots representing the density in the other sections referred to in the table are also shown in this diagram, but lie well outside the zone of maximum concentration. Plate 43 illustrates

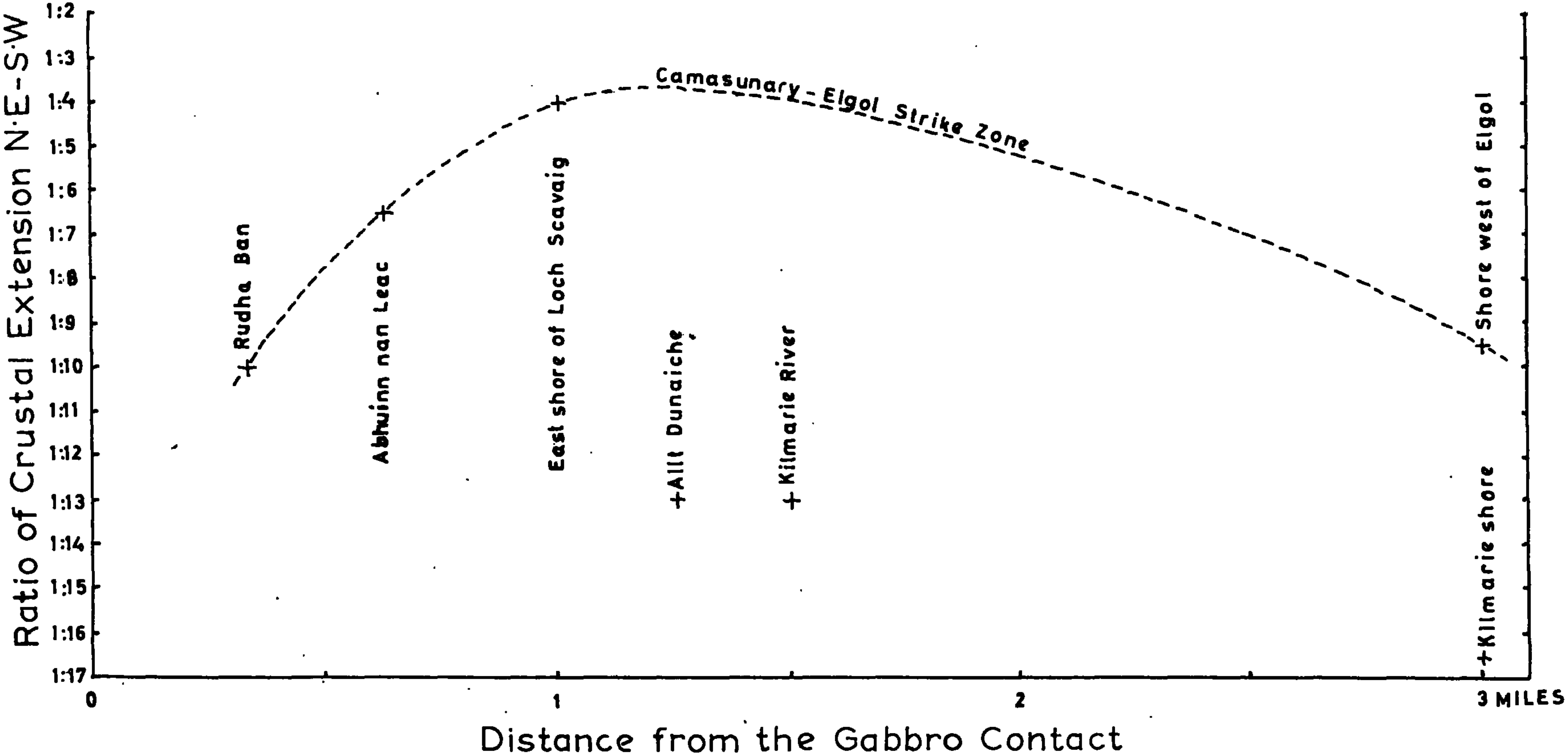


PLATE 43. DISTRIBUTION OF DYKES ALONG THE STRIKE OF THE NORTH-WEST SWARM.

the fact that dyke density increase rapidly away from the edge of the Cuillin Gabbro, and after reaching a maximum one mile from the contact gradually falls off with increasing distance.

A general decrease in number of dykes away from the Gabbro might be expected on the grounds that the main source of magma was probably situated somewhere below that body; the relative paucity of dykes near to the edge of the Gabbro (and in the Gabbro itself) is more puzzling. It may be that the Gabbro and its aureole of hornfelsed rocks was relatively resistant to penetration of the dyke magma, but the author considers it more likely that variations in the tensional stress across the north-west joints was a more probable cause.

One final characteristic of dyke distribution within the swarm remains to be mentioned. In sections across the strike it is noticeable that apart from a general increase in density towards the centre of the swarm there are also smaller, but regular variations which give rise to zones of relative concentration spaced at intervals of about 300 to 400 yards. The large multiple dykes are usually to be found along the middle of these zones of minor concentration.

It is not known to what extent the distribution characteristics found in that part of the north-west swarm within the Strathaird area can be applied to the swarm as a whole. The author believes that dyke density depends on the availability of joints and variations in the tensional stress across those joints. The structure of the swarm will only be understood when more is known of the dynamics of fracture systems of the type represented by the north-west joints, and especially their relationship to the central intrusion foci.

(iii) Petrography of the Dykes.

The dykes can be divided into the following petrographic types:-

Acid and intermediate	Micrographitic rhyolite Microgranophyric rhyolite Trachyte Quartz keratophyre
Basic	Olivine dolerite Dolerite without olivine or quartz Quartz dolerite Gabbro
Ultrabasic	Olivine-rich gabbro Picrite Dunite

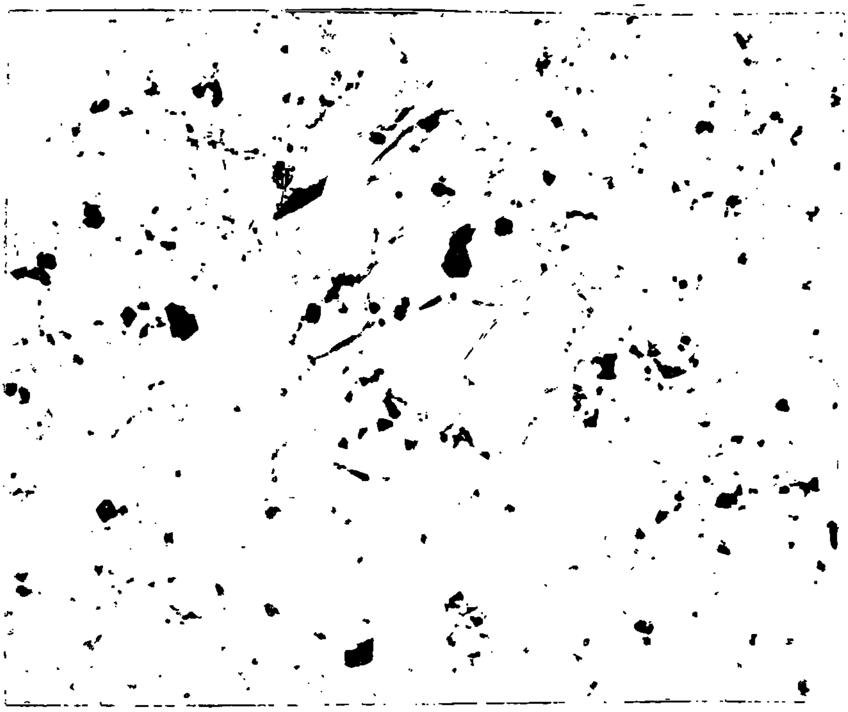
Basic Dykes. Dykes of basic composition are greatly predominant over all other types. Most are fine-grained dolerites, and of the dolerites examined in slice over half are olivine-bearing, while the remainder are more or less equally divided into quartz-bearing and quartz-free varieties. Many of the dolerites are porphyritic but the phenocrysts are usually small and few in number.

Olivine dolerites.

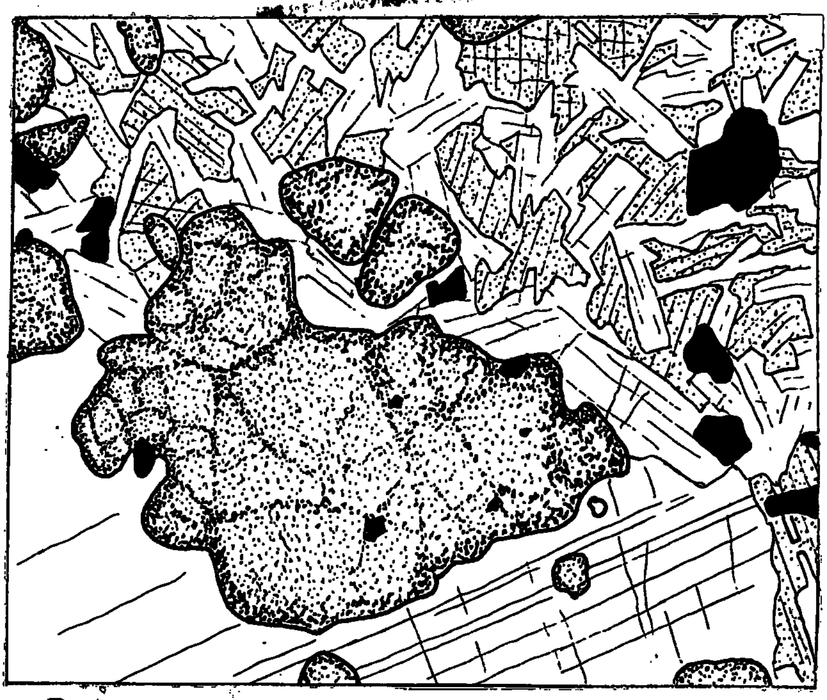
Most of the members of this group contain porphyritic elements, but in most cases they are of a type recognisable as derived from a consolidated gabbroic rock, and are therefore more truly cognate xenocrysts. There is a complete transition from dykes containing a few discrete feldspar phenocrysts to those in which xenoliths and xenocrysts constitute up to half the bulk of the rock, and the latter type is indistinguishable in the field from a true gabbro, and usually builds large solitary dykes. A typical example is the 90 foot wide dyke on the north side of Coire Ballaig. This rock (16) weathers reddish-brown, and fresh surfaces show feldspars up to 5 mm. across set in an dark-grey matrix. A slice shows that over 40 % of the bulk consists of fragments of gabbro, while the matrix is of fine dolerite. The gabbroic fragments consist principally of anhedral bytownite (An 84) crystals, ~~anhedrals completely~~ complexly twinned, and containing rounded inclusions distributed in zones. Some of the feldspathic clusters enclosed fresh, rounded olivines up to 2 mm. across, but there is no clinopyroxene. The doleritic matrix comprises 0.3 mm. laths of labradorite, granules of pyroxene, and large ore anhedra. The fresh nature of this dyke suggests that it is a relatively late intrusion. Another large solitary dyke found cutting the base of the lavas on the west face of Ben Meabost (45)* is of similar type, but the olivines are larger and more abundant within the xenoliths. Clinopyroxene is also present, and the feldspars are zoned from labradorite to bytownite. The matrix is of olivine dolerite possessing an intersertal texture. One of the large dykes at Camasunary which Harker regards as a feeder of the Cuillin Gabbro (149) was also found to be of xenolithic type. The fragments are of olivine-eucrite, while the doleritic matrix is highly ophitic.

With decrease in the number of xenoliths and increasing fragmentation of those that remain a porphyritic doløerite is produced, but the feldspar phenocrysts remain typically gabbroic in appearance. A three-foot dyke (193) situated half a mile south of Camasunary contains a few gabbro xenoliths up to 6 inches in length, but the bulk of the rock is a fine dolerite containing sparse anhedral plagioclses up to 2 mm. across, sometimes collected into glomero-

*Plate 44.



A.



B.

porphyritic groups. Phenocrysts of bytownite up to 4 mm. long, accompanied by altered olivines 1 mm. across, appear to be of similar origin in an ophitic dolerite (215) from Rudha Ban. A dyke of this type on Belig is unusual in containing small pegmatitoid patches consisting of inwardly-growing laths of acid plagioclase enclosing titanaugites, brown hornblende and apatite needles, with a central filling of prehnite.

Transitional to the non-porphyritic type of olivine dolerite are certain dykes which carry only rare feldspar phenocrysts. Such a rock is 139, collected from a three-foot dyke which cuts the Gabbro contact 150 yards north-east of the Camasunary River. In this, a groundmass of labradorite laths, granular pyroxene, and a few altered olivines, is set with sparse phenocrysts of bytownite up to 7 mm. in length.

Completely non-porphyritic olivine dolerites are not common, but include a coarse-grained dyke (219) situated one quarter of a mile north-east of Rudha Ban, in which the 1 mm. feldspar laths exhibit a well-marked, sub-horizontal flow orientation.

Olivine-free dolerites without quartz.

This group includes porphyritic and non-porphyritic varieties, but xenolithic types have not been found. Typical of the porphyritic variety is an early member of a small multiple dyke found on the shore north of Rudha na h-Airdh Baine (194). The phenocrysts are of bytownite and form small glomeroporphyritic clusters set in a groundmass of 0.3 mm. labradorite laths and intersertal clinopyroxene. There is a tendency for the feldspar to form radiating groups. Ore is the only other constituent, and all the larger grains are enclosed within the phenocrysts.

The non-porphyritic type is exemplified by a specimen (2) from a three-foot dyke in Allt Dunaiche (700 yards above the mouth). The grain is fine, with 0.25 mm. labradorites and abundant granules of clino-pyroxene and ore. A similar dyke (244) from the same stream carries thin veins of calcite and stringers of pyrite along the vertical jointing. Both these minerals are common in dykes intruded into the Jurassics.

Quartz dolerites.

A north-east trending dyke (Spec. 1) from Allt Dunaiche, which is cut by several north-westerly dykes, was found in slice to possess interstitial patches of quartz up to half a millimetre across. It is a non-porphyritic dolerite consisting principally of slender, 0.5 mm. labradorite (An 60) laths, granular titan-augite and abundant ore. Another quartz-bearing dyke from Allt Dunaiche (3) contains fractured phenocrysts of plagioclase up to 2 mm. long, and also a few large, altered olivines. The groundmass comprises of 0.6 mm. labradorite laths, intersertal titanaugite, and ore, with quartz occurring as interstitial pools up to 1 mm. across, partly intergrown at the margins. A dyke from the Kilmarie River (324) was also found to contain both olivine and quartz. In hand specimen this rock presents a close-textured, greenish-grey appearance, with white, platy feldspar phenocrysts up to half a centimetre long. In thin section these feldspars are accompanied by smaller phenocrysts of euhedral clinopyroxene, ores, and olivine (now altered), and all these minerals have the appearance of being true intratelluric phenocrysts, rather than cognate xenocrysts. The groundmass is extremely finer-grained, with barely-discernable feldspar and clinpyroxene, and abundant interstitial quartz.

In rather a different category is a large dyke rich in sedimentary quartzose xenoliths found on Blaven. This dyke, which trends north-west and crosses the south ridge of the mountain at a height of 1200 feet O.D., was referred to by Harker (1904, pp. 351-353).

The foreign material consists of quartz and quartzite fragments probably derived from the Torridonian rocks which outcrop a few hundred feet lower down the hill. On the crest of the ridge the dyke is 24 feet in width and contains xenoliths averaging one inch across but occasionally as large as six inches, but followed down the crags to the south-east the dyke narrows and the fragments become smaller. The dyke is cut by several cone-sheets but is not metamorphosed. Slices (408)* indicate that while most of the quartz is coarse and strained, it has been locally recrystallized to smaller, unstrained grains. Reaction at the borders with the groundmass has taken one of two courses, the less common being the development of a thin rim of granular pyroxene, which appears to have inhibited further mixing. More frequently there is a broad reaction rim of sheaved, and fibrous alkali feldspar ($n <$ balsam) which makes broad embayments into the quartz, and in places these shears give place to better-crystallized acid plagioclase ($n >$ balsam). Quartz also occurs in the reaction zones as slender needles or plates, often in optical continuity with uncrystallized grains, and sometimes forming a thick fringe to the latter. It seems likely that these quartz plates are paramorphs after tridymite. The

* Plate 45.

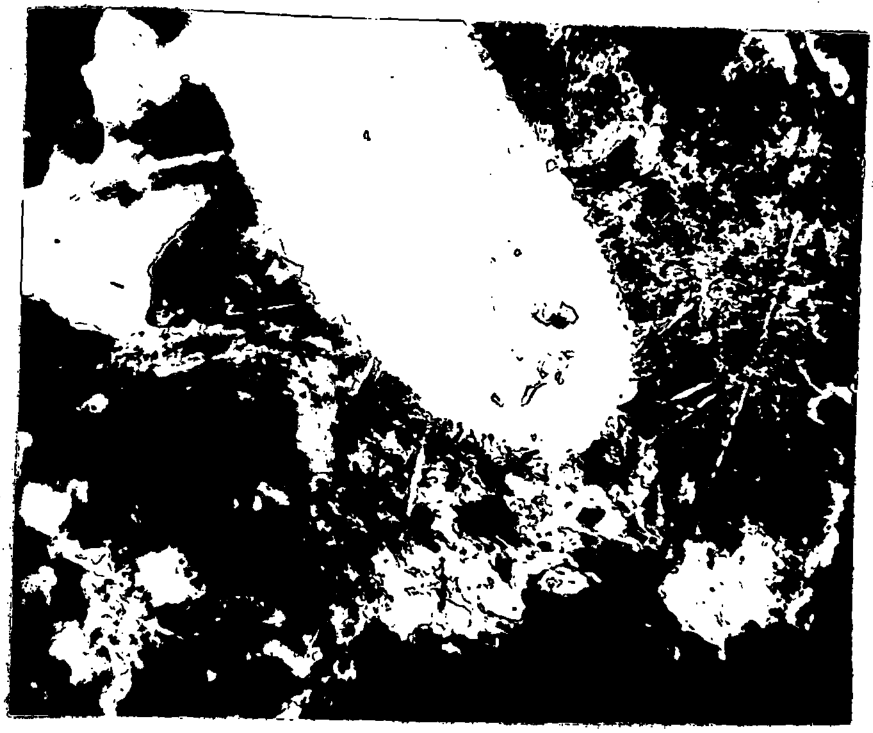


PLATE 45. Microsection: Quartz xenolith in a dolerite dyke.

(Spec.408) × 100. A section from a dolerite dyke full of quartzose xenoliths, south ridge of Blaven. The rounded xenocryst of quartz in the upper part of the field is surrounded by a reaction rim of cryptocrystalline alkali feldspar in which are set elongate quartzes, probably inverted from tridymite. A fringe of similar material borders the xenocryst itself.

alkali feldspar of the reaction rims is probably derived at least in part from the xenolithic material, for the in situ Torridonian consists largely of arkosic rocks. The doleritic matrix of the fragments consist of tabular labradorites zoned externally to andesine, and partly albitized, together with both clinopyroxene and orthopyroxene in sub-hedral prisms. The presence of orthopyroxene is presumably a result of the contamination. Ore is very sparse.

Gabbros.

The term gabbro is here restricted to medium- and coarse-grained basic rocks in which the feldspar is for the most part anhedral and equidimensional, whereas in coarse dolerites the feldspar is mainly lathy. The two rock types are not easily distinguished in the field from each other, or from the type of dolerite which is rich in gabbroic xenoliths and xenocrysts.

A nine-foot wide dyke which cuts the base of the lavas 600 feet south of the summit of Beinn Leacach consists of a thick central member of gabbro flanked by fine dolerite. The gabbro is of medium-grain, but contains xenoliths of coarser material. Slices (181) show it to be an olivine-bearing variety in which the plagioclase is a bytownite forming anhedra between one and two millimetres across and a lesser number of smaller, subhedral laths. Most of the clinopyroxene is interstitial, but there are also some clusters of coarse grain which are probably xenolithic. Chloritic pseudomorphs of olivine up to 2 mm. across are enclosed by the other minerals. Ore is subhedral. Rather similar to the above, but containing only subordinate olivine, is a specimen (157) obtained from a ten foot dyke which crosses the Camasunary-Loch na Creitheach track 600 yards north of Camasunary House. This dyke is shown on H_arker's map as part of a feeder of the Cuillin Gabbro, but since it can be shown to intersect a post-Gabbro cone-sheet it is evidently a relatively late intrusion.

A broad, curving, dyke-like mass of gabbro which intrudes the Jurassics north-west of Loch na Sguabaidh is cut by veins of granophyre originating from the Red Hills intrusions. Moreover in slice it is seen to be thoroughly shattered and largely recrystallized to green hornblende and epidote. The shattering is almost certainly a result of proximity to the Coire na Seilg agglomerate, and the recrystallization a metamorphic effect of the Red Hills granophyres.

It may be noted in passing that the plug of basic rock which pierces the Jurassic sediments south of Ben Meabost is also of gabbro. It contains a few fresh cores of olivine and a rather higher proportion of lathy plagioclase than the gabbros previously described. The plug is cut by at least one north-west dyke.

Ultrabasic Dykes.

The ultrabasic dykes of Strathaird were included by Harker in his group of "later peridotites" (1904, p. 374), which mainly comprises a set of large dykes distributed radially around the Cuillin Gabbro. Harker's sketch map and description show that in Strathaird he found three dykes of this type, all in the area around Ben Cleat. One dyke lies in the col between Ben Cleat and Ben Meabost, and the others lie within 100 yards of the summit of Ben Cleat. During the present study ultrabasic dykes have also been found at several other localities, both at Camasunary and in eastern Strathaird. Carr (1952, thesis) has already pointed out that ultrabasic dykes at Rudha Ban, west of Camasunary, are metamorphosed by the Cuillin Gabbro, and are therefore early members of the intrusive sequence. Other ultrabasic dykes (olivine-rich gabbros and picrites) have been found by the present author in the Camasunary valley and on the south ridge of Blaven, and their field relations show them to be the earliest intrusion in the area. In eastern Strathaird two newly-found occurrences of ultrabasic dykes are, firstly, a 30 foot wide dyke intruded into the Estuarine sediments west of Keppoch, and secondly, a 20 foot dyke piercing the Inferior Oolite on the shore, 350 yards east-north-east of the T-junction at Glasnakille. This latter dyke is in line with the dykes on Ben Cleat. All the dykes in this part of the area are too far from the margin of the Cuillin Gabbro to determine whether or not they were emplaced before or after that intrusion. However, they can nowhere be seen to be cut by later dykes, whereas the Camasunary ultrabasic rocks are often intruded by later dolerites. It must therefore remain uncertain whether there are one or two ages of ultrabasic dyke in Strathaird. Harker refers to some of the later peridotite intrusions in the western Cuillins cutting gabbros and cone-sheets, so it appears that there certainly was a late episode of ultrabasic intrusion. The Ben Cleat dykes pierce altered lavas and yet themselves contain fresh olivine, a fact which favours the supposition that these dykes are late intrusions.

The petrography of the pre-Gabbro ultrabasic dykes of the Camasunary Valley has been described in a previous section (see Chaptér IX). There remains to be mentioned an outlying member of the group found on the south ridge of Blaven at c. 900 feet O.D.. This rock (444)* contains some 47 % olivine, and can be classified as a picrite. The olivine has a marked tendency to be elongate parallel to the c-axis, and is accompanied by clinopyroxene, colourless orthopyroxene, and basic plagioclase. The rock has a dusty appearanne due to metamorphism, but there has been no significant recrystallization.

The ultrabasic dykes of peninsula Strathaird vary from olivine-rich gabbros through picrites to dunites, picrite being the commonest rock type. Some dykes vary considerably within themselves. Between Ben Meabost and Ben Cleat a line of hummocks composed of reddish-brown, rough weathering material marks the line of one of these dykes. Numerous xenoliths add to the rugosity, for some are highly mafic and weather into depressions, while others which are feldspathic form projections. The matrix is a dark, sub-vitreous rock (482a) which possesses a mode of 31.2 % plagioclase, 24 % clinopyroxene, 42.6 % olivine, and 1.6 % ore, and is therefore a picrite. Olivine occurs in two generations, forming both subhedral phenocrysts 1 mm. across and 0.2 mm. grains in the groundmass.

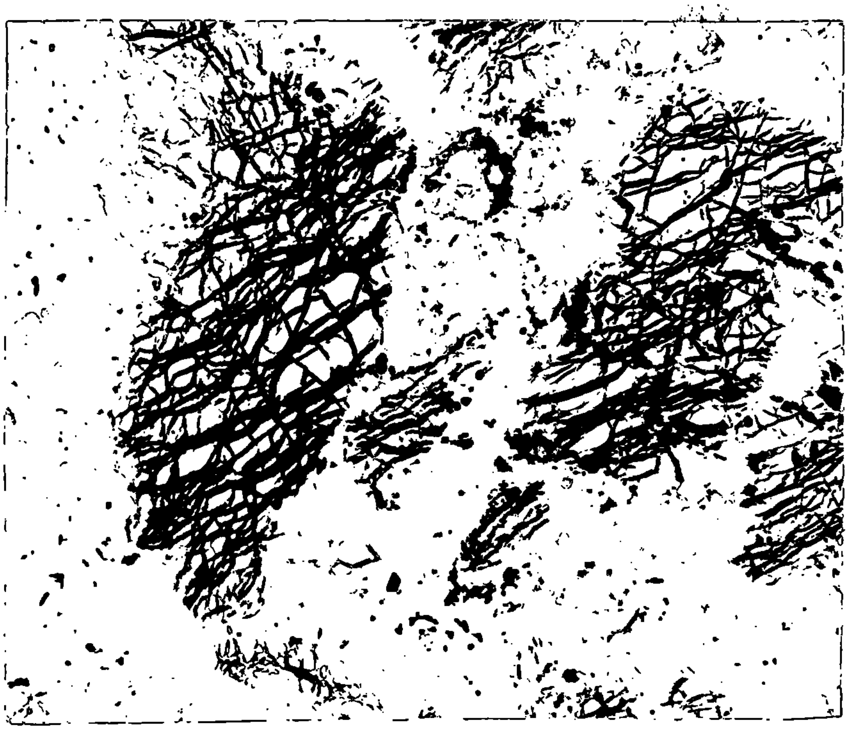
* Plate 46.

<u>PLATE 46</u> (opposite.) Microsections: Picrite dykes.

A.(Spec.444)×IO. Early picrite dyke,south ridge of Blaven,comsisting of olivine,laths of plagioclase, and intersertal clinopyroxene. The olivine tends to and elongate habit,and is dusty due to exsolution of ore during metamorphism.

B.(Spec.496)×IO. Picrite dyke,east of Glasnakille. Large,corroded olivine phenocrysts in a groundmass of sub-equidimentional plagioclase,clinopyroxene,and olivine. There are also a few pools of chlorite and a little ore,and the olivines are altered to serpentine and ore along cracks.

A.



B.

There is only a slight degree of alteration to serpentine and ore. The feldspar is of bytownitic composition (An 76) and forms a mosaic of anhedral tablets. The clinopyroxene is intersertal and sometimes wraps round olivine. The euhedral cubes of ore show the translucent brown colour of picotite in the thinner parts of the slice. A little biotite is associated with it.

A slice from one of the light-coloured xenoliths in the same dyke (482 b) shows it to be a feldspathic troctolite, with 77.7 % bytownite (An 78) in half-millimetre tablets, 19.8 % olivine in rounded grains, 2.2 % clinopyroxene, and 0.3 % ore. In hand specimen the distribution of the olivine imparts a roughly-banded appearance to the rocks and in slice the feldspar tablets show a preferred orientation parallel to this banding.

A third specimen, collected from a mafic portion of the same dyke (F. H. Stewart, H. 1009) is a dunite, and contains 90 % olivine in close-packed, rounded grains and occasional bipyramidal prisms. The size range is from 0.3 to 2 mm.. Plagioclase predominates over clinopyroxene in the interstitium, and there is also present some 2 % picotite.

The two dykes from the summit of Ben Cleat are of picritic type, that to the north-east (283) having a modal composition of 24.0 % plagioclase, 13.2 % pyroxene, 60.5 % olivine, and 2.3 % ore. The south-westerly dyke contains 63 % olivine (F. H. Stewart, H. 1011). Most of the olivine is contained in a porphyritic generation, with grains up to 4 mm. across. It remains largely fresh.

The Glasnakille dyke* is also a picrite, with 20.8 % plagioclase, 11.5 % clinopyroxene, 66.3 % olivine, and 1.4 % ore. The porphyritic texture is more marked than in the Ben Cleat rocks, with olivine phenocrysts up to 6 mm. long and a second generation in the groundmass. The plagioclase is coarse grained (average 2 mm.). The Keppoch dyke is similar but contains rather less olivine (57.5 %).

Acid and Intermediate Dykes. Dykes belonging to the acid and intermediate groups are present in relatively small numbers, some two dozen having been noted during the mapping. They are usually deeply weathered, and when fresh are commonly pale-grey and aphanitic. Phenocrysts of feldspar are frequent, and are accompanied by quartz in the rhyolites.

Microgranitic rhyolite.

Only one dyke of this type has been found. It is

* Plate 46.

of north-westerly orientation, sixteen feet wide, and outcrops in a small waterfall in Allt Dunaiche (c. 1000 yards above the mouth). It is contiguous with, and later than, a porphyritic dolerite. In hand specimen the dyke (Spec. 6) is pale grey and carries numerous small cubes of pyrite. In slice the latter average half a millimetre across and are accompanied by rectangular-sectioned quartz and occasional cognate xenoliths of coarse granophyre. Some of the quartz carries rims of granophyre. The micrograniti ground-mass has an average granularity of 0.1 mm., and includes a subordinate amount of plagioclase. Flakes of muscovite are scattered throughout, together with a little chlorite.

Micrographophyric rhyolites.

This type is represented by two dykes cutting the Jurassics of Belig some seven hundred yards west-north-west of the head of Loch na Sguabaidh. Specimens 364 and 365 were collected from the more southerly of the pair, a dyke 36 feet wide carrying numerous small quartz and feldspar phenocrysts in a pale greenish-grey groundmass. The quartz is euhedral, but corroded, and up to 2.5 mm. across. The feldspars are also well formed, and both coarse perthites and andesines are present in grains of up to 2 mm.. The albitic portions of the perthites form up to 40 % of the crystal volume, growing as angular patches 0.4 mm. across. The andesines are sometimes discrete, but in other cases are surrounded by a thick mantle of orthoclase or perthite, also with euhedral outlines, but sometimes corroded. The groundmass is of immaturely-crystallized, intergrown quartz and feldspar set in a glassy base, the latter increasing in amount towards the margins of the dyke. A few small ocelli contain flakes of green hornblende, acicular ore, and quartz. A minor amount of allanite and zircon are to be found in the groundmass.

In the other Belig dyke (Spec. 61), phenocrysts of orthoclase are accompanied by small quartz grains and granophyre xenoliths. Two elongate, brown, pseudomorphs in the slice are probably after biotite.

The position of these dykes, only a few hundred yards from the contact of the Glas Bheinn Mhor granophyre, suggests that they are related to that intrusion.

Trachytes.

The rocks possess a finely felted groundmass of alkali feldspar, and flow structure is often emphasised in the hand specimen by colour bands. In a four foot dyke found at the base of the lavas on the northwestern slopes of Ben Meabost (Spec. 47) alternate bands are dark blue and white, and define sinuous, sometimes folded, flow-laminae, sub-parallel to the dyke walls. The darker bands are seen in section to contain a higher proportion of glass than the lighter coloured laminae. The groundmass otherwise consists of minute, flow-orientated laths of alkali feldspar, a few small ores, and granules of unidentifiable dark mineral. Infrequent phenocrysts and segregations of quartz are also present, while locally the groundmass has been partly devitrified.

Banding is only poorly developed in an eight-foot dyke (180) from the western slope of Glen Scaladal (2,000 feet south of the summit of Bheinn Leacach). Phenocrysts include perthites up to 2 mm. long, several rounded masses of some mafic mineral now replaced by limonite, chlorite, and sphene, and rare plates of chloritized biotite. The groundmass is of felted feldspar laths together with scattered interstitial quartz. A probable continuation of the same dyke on the south side of Glen Scaladal possesses a similar petrography, and there the biotite is largely fresh. There are also some clusters of coarse biotite and apatite, usually associated with, and sometimes enclosed within, the feldspar phenocrysts.

Quartz Keratophyres.

Two dykes of quartz-keratophyre have been found, one on the western shore of the Peninsula, 130 yards south of the Scaladal Burn, and the other on the eastern shore, half a mile south of An Reidhean. A dyke of similar composition has been described by Harker (1904, p. 289) from south-east of Elgol.

The dyke from the western shore (463) is a medium-grained rock with dark grey rectangular feldspar phenocrysts, greatly decomposed, but evidently originally of acid plagioclase. The most conspicuous feature of the groundmass is the presence of numerous 0.2 mm. laths of similar feldspar, while potash feldspar and a moderate amount of quartz occurs in the interstices. Dark minerals are limited to a little fine-grained ore. Calcite has been introduced in coarse groups and sometimes replaces the phenocrysts.

The An Reidhean dyke (495) contains numerous glomeroporphyritic groups of altered alkali feldspar up to 1 cm. across. The groundmass is more coarsely crystalline than that of the 463, and the bulk is of rectangular, square-sectioned ~~orthoclase~~ acid plagioclase laths averaging 0.3 mm. in length. A few clots of chlorite represent the dark minerals, and a small amount of interstitial quartz is also present.

The keratophyre dykes are probably related to the sill of similar material which is emplaced in the Estuarine shales south of Ben Meabost.

(iv) Cone-sheets.

The system of cone-sheets (Harker's "inclined basic sheets of the Cuillins") has a close spatial relationship to the Cuillin Gabbro complex, and most of the intrusions lie within the limits of the gabbro outcrop. Harker (1904, Chapter XXI) showed that these sheets are present in great numbers, but are individually of small dimensions. They incline inwards at angles which become progressively steeper towards the centre of the gabbro, and can be ideally regarded as a series of inverted cones possessing a common apex. By extrapolation of the dips this apex, or focus, of the cone-sheet system can be shown to be below the hill of Meall Dearg at a depth of about three miles. Harker, however, thought of these intrusions as inclined sills, fed by dykes and dying out downdip. He states that as a result, the lower levels of the gabbro "laccolith" are relatively free from these intrusions.

Only a small portion of the cone-sheet complex comes within the province of the present study, but

Harker's supposition that the cone-sheet die-out downwards is not supported by the field evidence in this area at least. At Camasunary, where the Gabbro contact is not far above sea-level, cone-sheets are hardly less common than on Blaven, 3,000 feet above, but it is true that certain zones are richer in cone-sheets than others at all levels in the complex. It appears that some angles of inclination were more favoured than others. Work on other cone-sheet complexes, notably those of Mull and Ardnamurchan, and led to a better understanding of their structure, and according to Anderson (1936) cone-sheet fractures result from a localised upward thrust, probably originating in a deep magma chamber, from which source the fractures are then sealed by injection of magma. Harker's maps show that the main zone of cone-sheet concentration has an average radius of about two miles, with Meall Dearg as the centre. Since the sheets incline inwards, the radius of this zone varies with the depth of erosion, and so on the higher ground it is nearer the contact than in the deeply-eroded valleys. In the Camasunary Valley the belt is displaced inwards and passes beneath Loch Creitheach, and half a mile within the contact, whereas the elevation of the Blaven Range carries the concentration zone into the vicinity of the contact, and many cone-sheets also occur in the country rocks. Cone-sheets have been found up to 1000 yards from the edge of the Gabbro in the lavas of An Stac and Slat Bheinn, and these intrusions are also common within the sediments and granophyre of Coire Uaigneich and Abhuinn nan Leac. Within the contact on Blaven they become very frequent, some 20 to 30 individuals being counted on the eastern buttress of the mountain within a vertical interval of 1,000 feet. The dip is this area is between 45° and 50° north-west. Most cone-sheets are small, generally between one and three feet in thickness, and most are single injections. Fine-grained dolerite is the predominant rock type, but a few coarser-grained, thicker sheets also occur. The sheets have had a marked influence on the form of the crags, for most of them are less resistant to weathering than the gabbros or metamorphosed rocks which they intrude, and so give rise to terraces which vary from horizontal to inclined, depending on the orientation of the cliff in relation to the dip of the sheets.

Harker regarded the cone-sheets as the product of a single epoch of intrusion which occurred when all the central intrusions, both basic and acid, were already in place, and also post-dating the majority of the dykes in the north-west swarm (op.cit. pp.365, 427). It has been found during the present mapping that most cone-sheets are certainly later than the Cuillin Gabbro, the Coire Uaigneich granophyre, and most of the dykes in the north-west swarm. However there are, at Camasunary, a number of small intrusions which have the attitude of cone-sheets but are of pre-Gabbro age, and Carr (1952, thesis) has noted metamorphosed remnants of cone-sheets enclosed within the Gabbro itself. It seems therefore, that there were at least two phases of cone-sheet injection, though the later of the two was the more important. Richey (1932) has even suggested that the Cuillin Gabbro is a deeply-dissected cone-sheet system, and has also observed that the post-Gabbro cone-sheets appear to be earlier than the Red Hills granophyres, not later as Harker supposed. A glance at Harker's own map will show that cone-sheets are absent from the granophyres even where they have encroached upon the gabbro in Strath Creitheach, though the gabbros themselves do contain these intrusions. This can only be explained using Harker's time scale by assuming that the character of the country rock had an all-important control on the distribution of minor intrusions. Added to this is the evident spatial relationship of the cone-sheet system to the Cuillin Gabbro, and not to either of the later intrusion centres of Sligachan and Broadford.

It may be noted that nowhere in Skye does the density of cone-sheets reach the level found in Mull, where in places (e.g. Ben Buie) the intrusions are actually contiguous over most of their contacts. Nor, apparently, is there in Skye a sequence of cone-sheets related to successive intrusion centres, and varying regularly in composition through time.

Petrography. Harker divided the cone-sheets into the following petrographic types (op.cit. pp. 370-372):-

1. Olivine-free fine dolerites - the commonest type.
2. Dolerites with xenocrystic feldspars.
3. Porphyritic, olivine-free dolerites.
4. Olivine-phyric dolerites - a rare type.
5. Olivine dolerites - with basic feldspars.

Most of the pre-Gabbro cone-sheets (?) at Camasunary consist of fine-grained, olivine-free dolerite, but a three-foot sheet (148) collected 700 yards north-north-west of Camasunary House is an olivine-rich dolerite carrying xenoliths of picrite. It has a texture similar to those of metamorphosed basic rocks in the neighbourhood, most of the pyroxene being recrystallized to small granules and accompanied by a little brown hornblende and biotite.

The majority of the post-Gabbro cone-sheets are also close-textured dolerites lacking olivine. A typical example (53) collected from a sheet cutting granophyre on Belig, contains 0.2 mm. labradorite laths, granular clinopyroxene, and some chloritic and epidotic alteration products. The thicker cone-sheets are usually of coarse olivine-dolerite, distinctive because they weather yellowish-brown and form upstanding feature even among gabbros. In a sheet of this type outcropping in the hillocks north of Camasunary (see 1:1250 map, D. 12 - K. 12) contains zoned bytownites (An 76), half to two millimetres in length, sub-ophitic clinopyroxene, and olivine pseudomorphed by chlorite and uralitic amphibole. Sphene is an abundant accessory to a neighbouring sheet of similar composition (153). In another coarse-grained sheet from the summit plateau of An Stac (319), alteration to chlorite and uralite, with albitization of the feldspars, is far advanced. A cone-sheet from near the top of Slat Bheinn (108) possesses a gabbroic texture, with 2 mm. anhedral, equidimensional feldspars.

Among the more unusual rock types is a specimen collected from a cone-sheet 800 yards north of Camasunary House. It contains phenocrysts of clinopyroxene up to 2 mm. across which intergrow with the groundmass at the margins, and there are also several large masses of mixed chlorite and uralite which may represent primary olivine. The groundmass is medium-grained, with 0.4 mm. plagioclase laths, sensibly pleochroic granules of clinopyroxene, abundant subhedral ore, and a little interstitial quartz.

(v) Conclusions.

At the beginning of this chapter it was stated that phases of minor intrusion occurred throughout the whole of the igneous period in Strathaird. The form which these intrusions assumed varied with time, mainly as a result of changes in the structure of the area. Although the sequence is not known in detail, it is probable that the earliest minor intrusions came into place at a time when the outpouring of basic lavas at the surface was the chief manifestation of igneous activity. At this period the fracture systems which later had such an important influence on the style of intrusion were either absent or developed in only rudimentary form, so that magma injected into the substratum was forced to assume the form of irregular dykes, or else exploit the bedding planes of the sediments and solidify as sills. Even at this early date the area which is near the Cuillins was marked out as a centre of activity, for the early dykes are most numerous in this vicinity. It is, of course, ~~also~~ possible that the Cuillins was also a centre of extrusion at this time.

There followed the intrusion of the Cuillin Gabbro, and it was following this event that the regional stresses were set up which produced the remarkable system of north-west joints. There is clearly a close relationship between this fracture system and the Cuillin centre, which lies in the middle of the fracture zone and to some extent focuses the joint-planes towards itself. It is not known, however, whether the stresses which produced the joints had their origin in magmatic pressures generated at the centre itself, or whether the structural rigidity of the Cuillin intrusion merely caused the fracturing to be most severe in its vicinity. Certainly the joints followed by the radial dykes and the later cone-sheet fractures, are directly related to the intrusion centre, and are presumably due to such factors as cooling stresses and the fluctuation of pressure within an active body of magma below the consolidated basic mass. The continued existence of such a body is evidenced by the exploitation of each fracture system, as soon as it was formed, by uprising magma.

Throughout the whole of the igneous period, the magma which was tapped and channelled by the fracture systems was predominantly basic in character. While only about twenty dykes of acid and intermediate composition have been found during the mapping, the basic dykes number many hundreds and the cone-sheets are wholly basic in character. No acid lavas are to be found in Strathaird at the present level of erosion, but they may well have once been present at higher horizons. Apart from this the dykes show the same general compositional range as do the lavas, but the frequency of the different types is not the same. As far as can be judged from petrographic examination of representative specimens, the bulk composition of the minor intrusions as a whole inclines more towards the silica-saturated end of the series than does the bulk composition of the lava sequence. Among the minor intrusions, the rock type which predominates over all others is the dolerite with little or no olivine, whereas nearly all the members of the lava sequence are significantly undersaturated rocks. There are, of course, a number of olivine-rich, ultrabasic rocks amongst the dyke swarm, but these hardly redress the lavas. Moreover the lavas themselves are disposed in broad fold structures. In order to explore these relationships, three structure contour diagrams have been prepared to show:-

1. The present structure of the lavas; constructed with the lava base as datum (Plate 47)
2. The present structure of the Jurassic sediments, using the base of the Cyrena limestone as datum (Plate 48)
3. The structure of the Jurassic sediments before the lavas were extruded, derived by subtracting the contour values for the base of the lavas from the values for the Cyrena limestone (Plate 49). This construction assumes that

the surface onto which the lavas are poured out was virtually flat, an assumption which seems to be justified by the field observations.

Owing to the approximate nature of the topographical contours available, the structural maps are not of a high degree of accuracy but it is believed that on a small scale they provide a close approximation to the truth.

(i) Structure of the Lavas.

Plate 47 illustrates the manner in which the balance because there is also a roughly equal volume of acid rock. Normal alkaline olivine-basalt (Plateau magma type) is considered by many petrologists to represent the parent magma type of at least most of the rocks of the Thulean province. If this is provisionally accepted, then the almost-saturated dolerites which form the bulk of the minor intrusions must be the product of a partial fractionation. It may be significant in this respect that so many dykes contain cognate xenoliths and xenocrysts derived from eucritic and troctolitic gabbros. It may well be that the dyke magma was squeezed out of the interstices of a partially-crystallized gabbro, leaving behind most of the early-formed, basic plagioclase and olivine, which now, presumably, are present somewhere in the deep-seated basic mass, the presence of which is indicated by the geophysical work of Tuson (1960).

CHAPTER XII

TECTONICS

Since late Precambrian times central Skye has had a relatively tranquil tectonic history. During the Caledonian orogeny the Hebridean area lay on the edge of a stable block of ancient rocks which acted as a foreland to the intensely deformed belt to the east, though overthrust slices of Torridonian and Lower Palaeozoic rocks overrode the edge of the block and reached at least as far west as the Broadford area. The Torridonian rocks at Camasunary and the neighbouring island of Soay are, however, autochthonous, and are probably underlain at no great depth by Lewisian gneisses similar to those found in south-east Skye.

The almost complete absence of Palaeozoic sediments, and the presence of important breaks in the Mesozoic succession, suggest that the area was often exposed above sea-level. At the time when the first outpourings of basic lavas initiated the Tertiary igneous epoch, central Skye was part of a landmass of low relief.

The rocks of Strathaird have nevertheless undergone gentle folding at several periods, as evidenced by the presence of angular unconformities at the base of the Jurassics and between the Jurassics and the

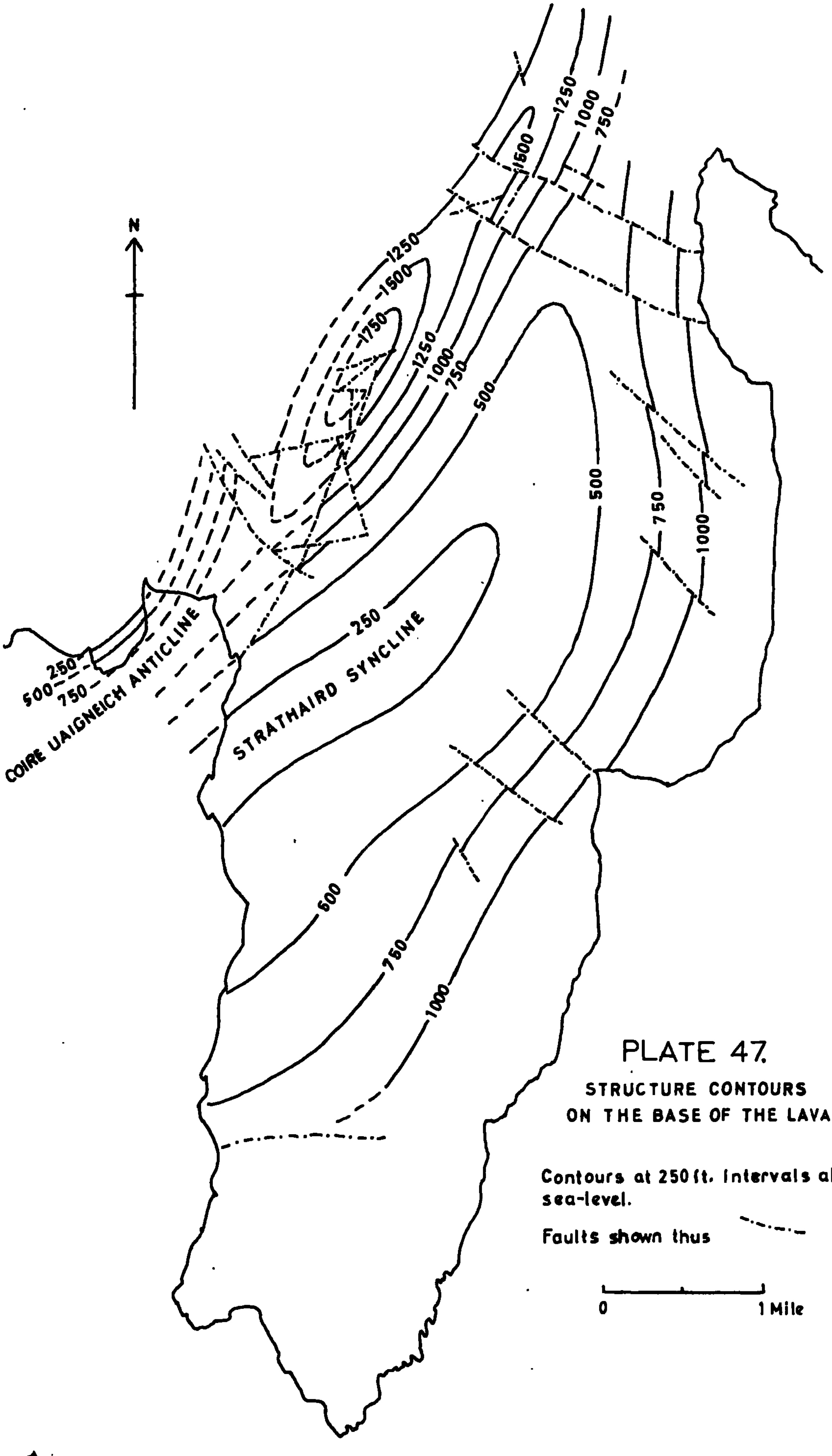


PLATE 47.

STRUCTURE CONTOURS
ON THE BASE OF THE LAVAS

Contours at 250 ft. intervals above sea-level.

Faults shown thus

0 1 Mile

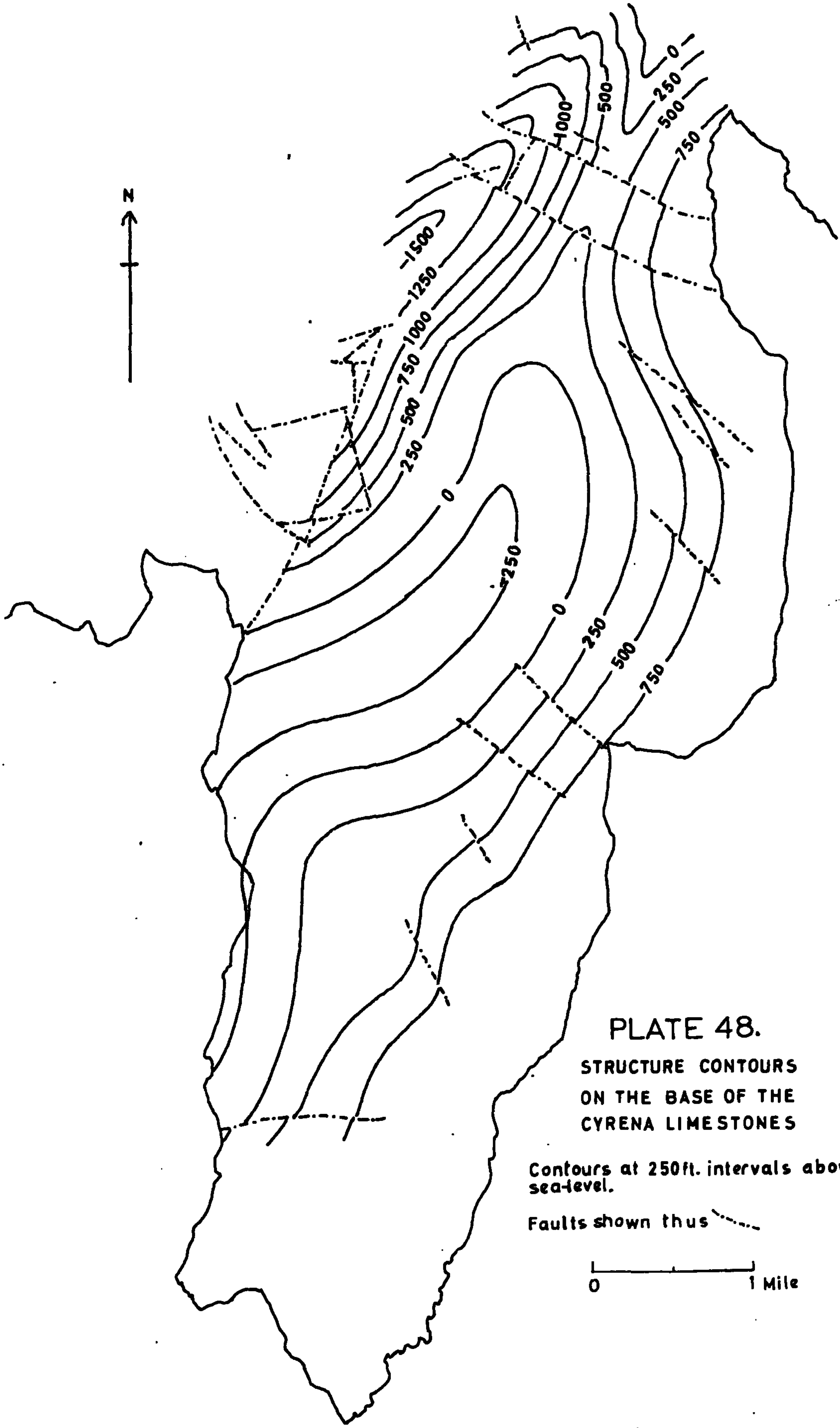


PLATE 48.

STRUCTURE CONTOURS ON THE BASE OF THE CYRENA LIMESTONES

Contours at 250 ft. intervals above sea-level.

Faults shown thus

0 1 Mile

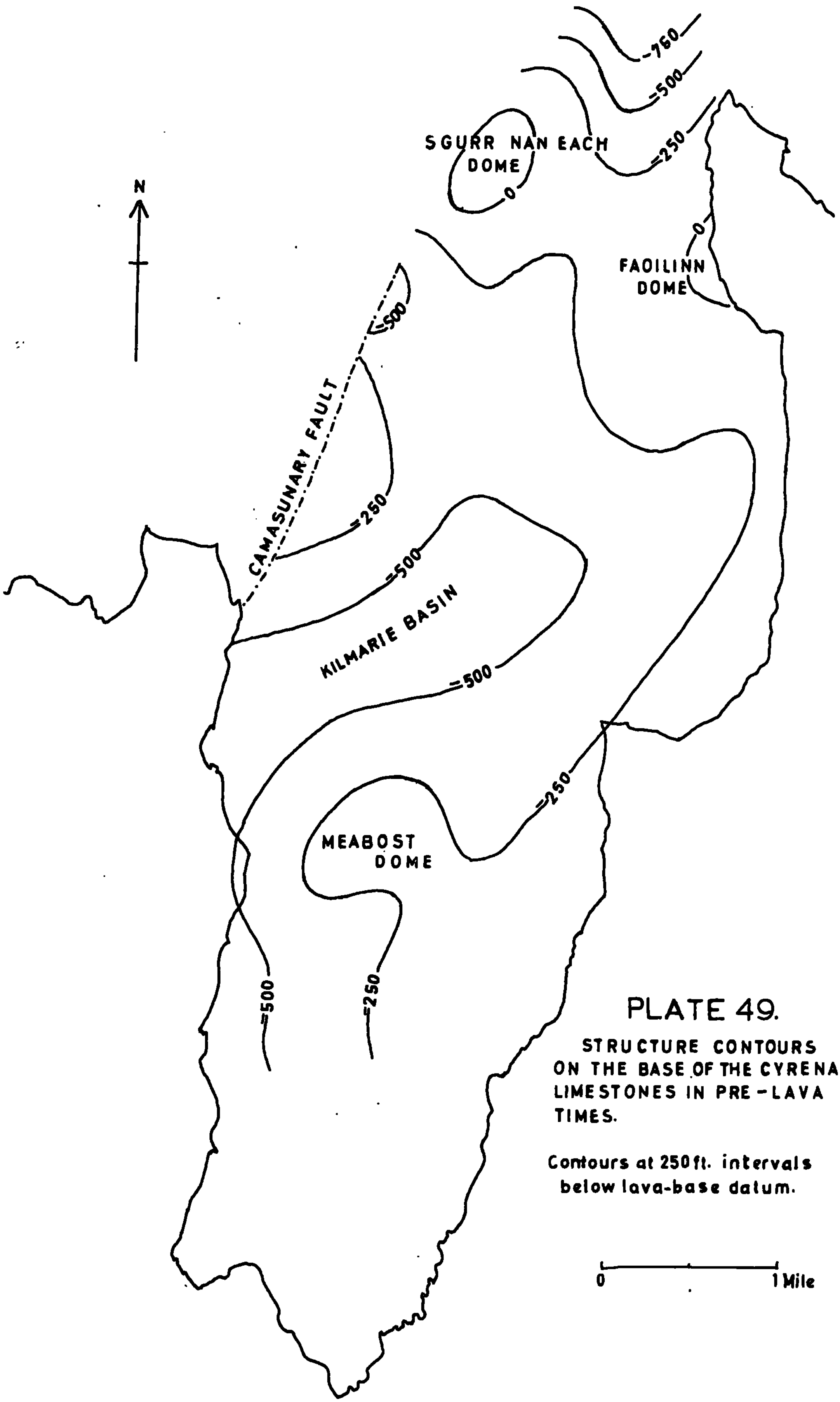


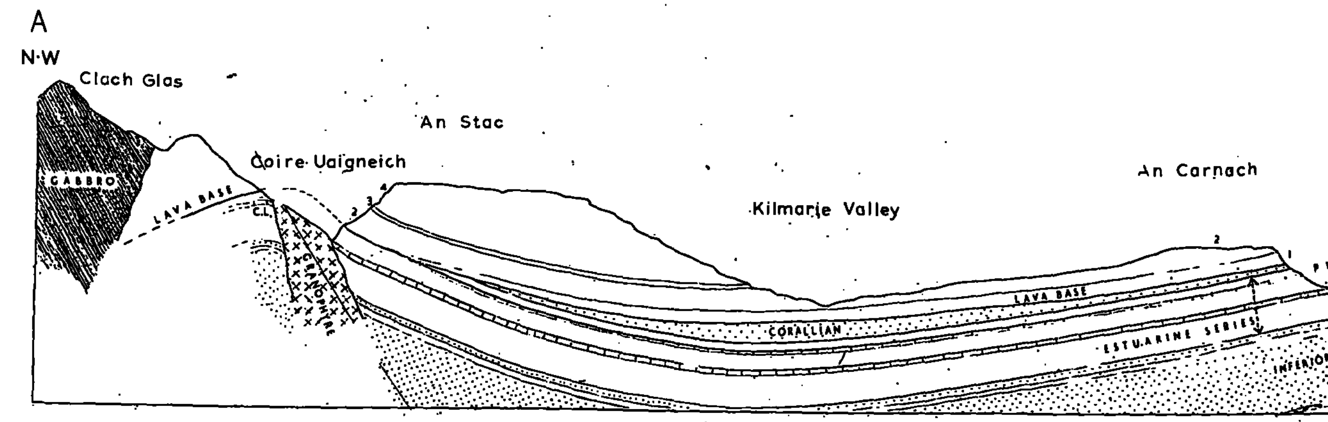
PLATE 49.

STRUCTURE CONTOURS ON THE BASE OF THE CYRENA LIMESTONES IN PRE-LAVA TIMES.

Contours at 250 ft. intervals below lava-base datum.

lavas are disposed in a pair of folds parallel to the margin of the Cuillin Gabbro. Adjacent to the contact of the intrusion the structure is anticlinal, while the complementary syncline to the south-east occupies the greater part of the Strathaird Peninsula. The anticline is a more compressed structure than the syncline, and has a closure angle of about 120°. Its north-west limb is largely cut out by the margin of the Gabbro, but where visible it has a dip of about 40° N.W.. The middle limb of the two folds possesses an average inclination of about 18° S.E., though locally the dips are as high as 45°. The eastern limb of the syncline has a shallow and constant dip of between 6° and 8° to the north-west. A cross-section of these folds is given in Plate 50, When viewed across Loch Slapin the Strathaird lavas appear to dip away from the gabbroic rocks of Blaven, as can be seen in the photographic panorama on Plate 2. This, however, is an illusion due to the resistant nature of the meta-lavas nearest the intrusion, which makes them almost indistinguishable from the gabbros, and so conceals the inward dip of the lavas immediately outside the contact.

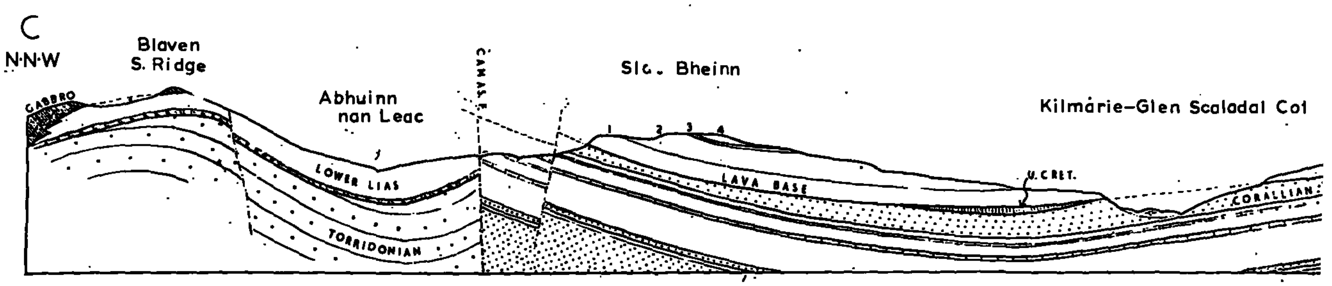
The two folds, which are mentioned by Wedd in the Geological Survey of Scotland Memoir to sheet



DIP SECTION —— NORTH STRATHAIRD

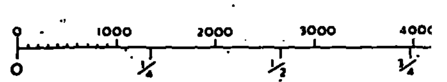
PLATE 50.

see six inch map fo



DIP SECTION —— SOUTH STRATHAIRD

VERTICAL AND HORIZONTAL S



71 (1910, p. 11), are hereafter referred to as the Coire Uaigneich anticline and the Strathaird syncline. At the horizon of the lava base, the anticline culminates at 1250 feet O.D. in the region of the Blaven-Slat Bheinn col, while at its lowest point in the syncline the lava base is below 250 feet O.D.. A significant feature of these folds is the parallelism of their axial traces with the contact of the Cuillin Gabbro, so that while the trend of the folds at Camasunary is north-east, it swings gradually anti-clockwise to become north-north-east in the neighbourhood of Belig.

The folds are cut by a number of north-westerly cross-faults. Two of these dislocations are situated in the ground between Allt Aigeinn and Allt Dunaiche, and strike N. 70° W.. Both throw down to the south, the more northerly of the pair up to 100 feet, and the more southerly not more than 50 feet. The northerly fault is exposed in the gorge near the outlet of Allt Dunaiche, and there brings Inferior Oolite shale on the south against the topmost sandstone of the same series on the north. Followed north-westward the same fault can be seen to affect the lavas on Sgurr na Each, though with a lesser throw. The southerly member of the pair displaces the Allt Dunaiche felsite sill, which may be an offshoot of the Coire Uaigneich granophyre (see Chapter XI), but the relationship of these faults to the main body of granophyre is obscured. Several small, north-west faults affect the lowermost lavas in the eastern cliffs of An Carnach, and one of them (exposed to the west of Faoilean) depresses the lava base some 40 feet to the north. Two basic dykes follow the line of this fault, and since they show no signs of crushing they are probably post-faulting. Faults of a similar nature have been found at Strathaird and on Ben Meabost, while at Elgol there is an east-west fracture which probably post-dates the lavas but cannot be directly observed to affect them. Movement on this fault has brought the base of the Paludina limestones on Bidein an Fhithich down to the level of the Cyrena limestone to the south, indicating a downthrow of about 100 feet. The fault is dated as Tertiary because its continuation to the east depresses the Elgol sill a few feet to the north, but the possibility that these have been movements of more than one age along this fault cannot be ruled out. There are excellent exposures of the fault breccia (comminuted sedimentary rocks) on the shore west of Elgol, the breccia weathering into a wall-like mass some 20 feet in thickness and inclined steeply north. A large multiple basic dyke crosses the breccia unaffected.

(ii) Structure of the Jurassic Sediments.

Since the post-lava deformation was more severe than any which had previously affected the Mesozoic sediments, the structure contour map based on the Cyrena limestone (Plate 48) bears a general resemblance to that constructed on the base of the lavas (Plate 47), the chief features being an anticline adjacent to the Cuillin Gabbro, and a syncline to the south-east. There are, however, significant differences in the shape of these folds at the two horizons, owing to the presence of pre-lava fold structures in the sediments. In order to determine the nature of these early folds, plates 47 and 48 were superimposed, and the values for the lava contours subtracted from those based on the Cyrena limestone; the resulting figures are contoured as depths of the Cyrena limestone below the lava base (Plate 49). The picture that emerges shows the pre-lava structure to consist of shallow domes and basins, with datum horizon rising up to, or near, the pre-lava surface in three areas - Ben Meabost, Faoilean, and Sgurr nan Each - while a basin occupies the Am Mam-Kilmarie area, and there is a steep falling-away towards the northern boundary of the map. The average dip on these structures is only three or four degrees.

Over part of northern Strathaird, rocks of Estuarine age outcrop directly below the base of the lavas, but in the Kilmarie basin, where the Cyrena limestone descends up to 500 feet below the lava base, sandy Corallian rocks supervene, and below Am Mam is a small area of Upper Cretaceous rocks on top of the Corallian. Since about 200 feet of beds intervene between the base of the Cyrena limestone and the base of the Corallian, it can be shown from Plate 49 that the latter should outcrop at the surface, below the lavas, in three other areas - the Blaven-Slat Bheinn col, upper Allt Dunaiche, and on Belig - though rocks of this age do not appear at the localities on the Geological Survey map (6 inch sheets, Inverness-shire, XLV). Arenaceous rocks which may be of Corallian age have been found, during the present study, in Allt Dunaiche and on Belig, but the area around the Blaven-Slat Bheinn col is not well exposed. The problem of definitely identifying these rocks is made difficult by metamorphic recrystallization at these localities. Moreover, it is known that the arenaceous content of the Estuarine Series increases northward, so that the lithological distinctions which exist in the south become much vaguer in the critical area. Wedd (1910, p. 126) mentions the possibility that beds higher than the Estuarines may be present in the Allt Dunaiche-Belig area. The prominent quartzite overlying baked quartzose shales at c. 600 feet O.D. in Allt Aigeinn certainly bears a lithological resemblance to the base of the Corallian near Kilmarie, and since its appearance there is conformity with the structural evidence, it has been taken as the base of the Corallian for the purposes of the present mapping.

Metamorphic hardening and obscuring drift also make difficult the detailed structural interpretation of the low ground between Allt Dunaiche and Allt Aigeinn. The positioning of faults and of the Inferior Oolite-Estuarine Series boundary on the writer's map are not in entire agreement with Wedd's mapping (6 inch sheet, Inverness-shire, XLV), though the general interpretation is the same. Differences include Wedd's classification of all the beds in Allt Aigeinn below the contact of the Coire Uaigneich granophyre as Inferior Oolite, whereas the presence of limestone bands with mixed shales and sandstones, 300 feet below the contact, is here taken to indicate the re-entry of the Estuarine Series dipping eastward off the Coire Uaigneich anticline.

Over most of its length, the axial zone of the Coire Uaigneich anticline has been exploited by erosion,

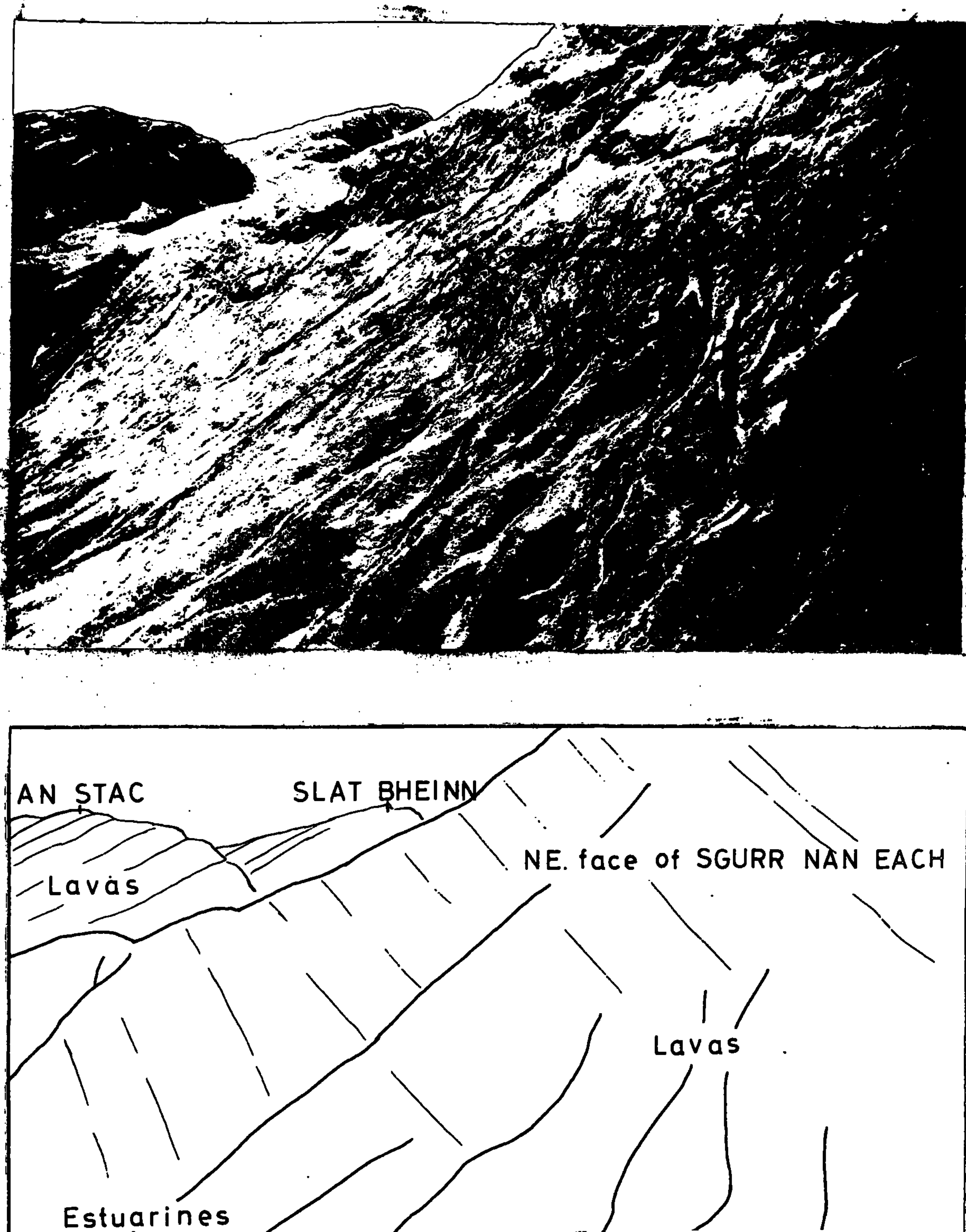


PLATE 51. The two limbs of the Coire Uaigneich anticline, as seen from the south face of Belig.

exposing the sedimentary core of the fold. The axial zone possesses two features of structural interest, the first being the presence of a system of small faults oblique to the axial plane of the anticline, in addition to the long north-west faults which cross the whole area. In Abhuinn nan Leac at least one of these small faults is cut short by the Coire Uaigneich granophyre, while another is followed for a short distance by the south-east contact of that intrusion. Evidently the faults can be dated to the same period as the folding, and were probably a result of the same stresses. A second feature of the anticlinal structure revealed in the sedimentary core is the presence of small subsidiary folds parallel to the main fold. Two small anticlines are exposed in the Jurassics on the south face of Belig, another was found on the south-east spur of Sgurr nan Each, and a third can be traced from Coire Casteail into the south ridge of Blaven. Similar structures have not been detected in the lavas above, which may have been too rigid to yield in this way.

Superimposition of the structure contours constructed from the base of the lavas and the Cyrena limestone shows that the axial traces of the Coire Uaigneich anticline at the two horizons do not coincide. This is a result of the original discordance of dip between the Jurassics and the lavas. In areas where the pre-lava dip of the Jurassics was to the west, the anticlinal axis (or strictly, the "crestal line") is displaced to the east relative to that in the lavas.

(iii) Structural Features of the Camasunary Area.

At Camasunary, deep erosion has removed the greater part of the lava pile, so that the form of the post-lava folding in the area has to be largely inferred. The disposition of such lava remnants as remain, and the attitude of the sedimentary rocks below, leave little doubt that the Coire Uaigneich anticline continues across the Camasunary valley to Rudha Ban, but the Strathaird syncline passes below Loch Scavaig and is seen no more. The eastern side of the valley is bounded by the Camasunary Fault, a structure of pre-Tertiary age downthrowing some 2,000 feet to the east, so that the sediments exposed in the core of the anticline at Camasunary are older rocks than are found elsewhere in the area.

The structure of the Camasunary area can best be understood by considering the view along the axis of the folds as seen from Camasunary House, looking towards Blaven (Plate 52). At the foot of Blaven, and flooring the valley below, are Torridonian arkoses.

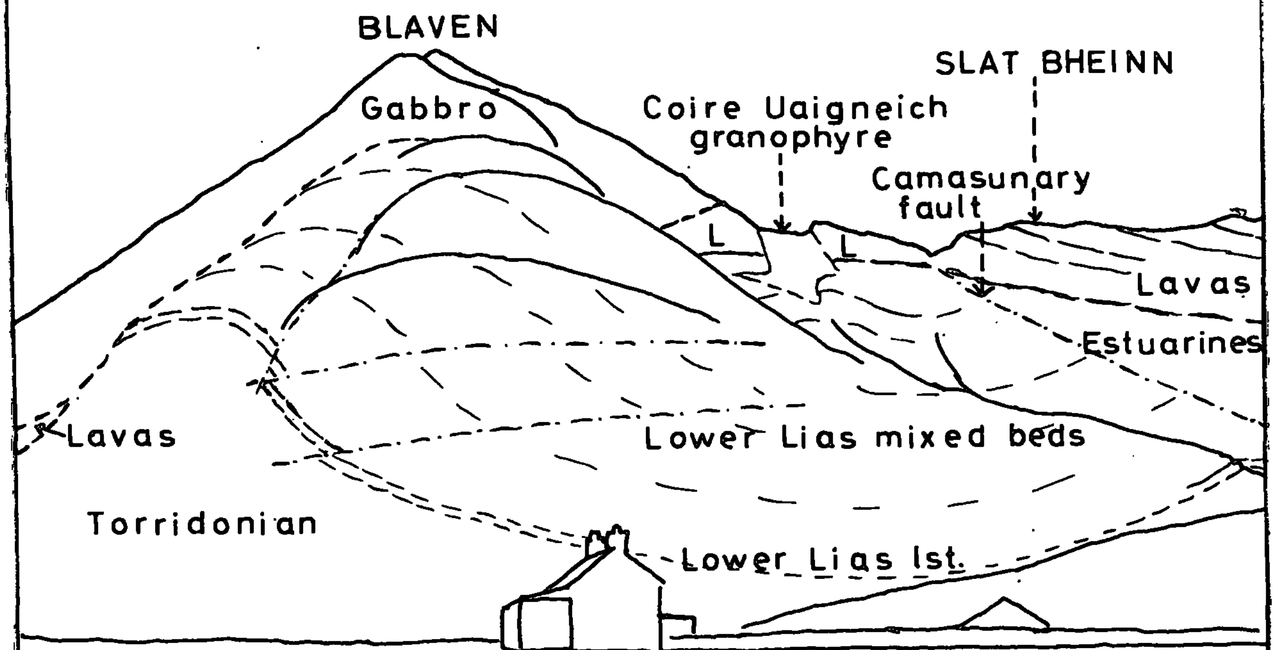


PLATE 52. A sketch showing the structure of Blaven and Coire Casteail, as seen from Camasunary House.

These are unconformably overlain by a thick sequence of Lower Lias sediments which builds most of the south ridge of the mountain and underlies the Abuinn nan Leac valley to the east. The structure of the Lias can be discerned by following the line of its unconformable base. This horison is seen to the north abutting against the north-westerly dipping contact of the Cuillin Gabbro, at a height of c. 850 feet O.D.. It then rises south-eastward as an arch in the south ridge of Blaven, descends as a synclinal structure north-west of Abhuinn nan Leac, and ascends again until cut off by the Camasunary fault below Slat Bheinn. East of the fault are eastward-dipping sediments of Estuarine age. If the lavas are followed in the same way, from north to south, they are first seen low down on the western flank of Blaven, dipping north-west and wedged between Torridonian below and to hanging-wall of the Gabbro contact above. Higher up, on the ridge, the lavas are cut out altogether at the contact, but reappear as a flat capping to the Lias on the col between Blaven and Slat Bheinn. Eastward, they cross the Camasunary fault and lie on the Estuarine, with a gentle dip to the south-east. The lavas thus form a simple arch, with a part of the north-west limb cut out by the edge of the gabbros, whereas the Lias sediments below contain both an anticline and a syncline. The structure as a whole plunges gently south-west, and is further depressed in this direction by several north-west faults, the most important of which is marked by a linear depression along the foot of Blaven's south ridge. The Geological Survey map (Inverness-shire, Sheet XLV, 6 inches to one mile) show these faults continuing into the gabbros, but the field evidence seems inconclusive on this point. In Abhuinn nan Leac and Coire Casteail there are also a number of small faults oblique to the Coire Uaigneich fold axis, and the Camasunary fault there underwent some degree of rejuvenation in post-lava times, for at the Blaven-Slat Bheinn col it shows a reversal of its main throw and lets down the lavas a few feet to the north-west.

The floor of the Camasunary Valley is underlain by Torridonian arkoses dipping at angles between 25° and 45° N.N.W.. The patches of lava which overlie the Torridonian at An't-Sron and on the banks of the Camasunary River, dip at between 10° and 20° in the same direction. On Rudha Ban, west of Camasunary, this relationship is reversed, with the Torridonian inclined zone 10° N.W., and the lavas dipping more steeply at angles up to 40°. It is thus apparent that the pre-lava dip of the Torridonian was to the south-east at Rudha Ban and to the north-west at Camasunary, and it is therefore likely that a pre-lava fault separates the Torridonian of these two localities. Other faults are almost certainly present within the Torridonian outcrop, but are not easily detected in this situation. The small patch of Lower Lias limestone situated 900 yards north-west of Camasunary House must be faulted into place because it dips 50° N.W. and yet is surrounded on all sides by Torridonian. A north-west shatter-belt passes through the south-east corner of Loch na Creitheach and affects both gabbros and Torridonian, and another belt was found on the east face of Sgurr na Stri. They are probably to be dated to the period preceding intrusion of the Red Hills granophyres, when extensive crushing occurred in northern Strathaird.

The subject of jointing has already been discussed in those sections dealing with the minor intrusions, and the relationships of the Cuillin Gabbro to its country rocks (Chapters IX and XI). In brief, the most important structure of this type is the regional system of close-spaced tension-joints, orientated between north-west and north-north-west. This system only became fully developed after the intrusion of the Cuillin Gabbro. There are also more localised joint systems related to the gabbro intrusion centre itself, including tangential and radial fractures, inwardly-dipping cone-shaped joints, and outwardly-dipping joints complementary to the latter.

(iv) Summary of the Tectonic History.

It has been shown that the peneplaned surface upon which the lava pile was built up consisted at the surface of strata ranging in age from late Precambrian to Upper Cretaceous. The sediments were folded into gentle domes and basins, and cut across in a north-north-easterly direction, by a large fault in the neighbourhood of Camasunary. East of the fault outcropped sediments belonging to the Estuarine Series, the Corallian, and the Upper Cretaceous, while to the west were exposed Torridonian arkoses and overlying shales of Lower Lias age. At the present time the Camasunary fault can be traced from the Scavaig shore as far north as the Blaven-Slat Bheinn col, where it becomes obscured by overlying lavas and intrusive granophyre. Although the downthrow decreases northward, the fault must continue for some distance beyond the col, but is hidden by the lavas of the Blaven Range. Recently, Bailey (1954) has remarked that to the north the fault must, in a sense, separate the Upper Jurassics of Scalpay and Strollamus from the Lias of Sligachan, which directly underlies the lavas. Wedd (South-east Skye Memoir, 1910,

p. 151) has suggested that to the south the fault may continue between the islands of Eigg, where Tertiary lavas rest on Upper Jurassic sediments, and Rhum, where the lavas lie directly on the Torridonian. Wedd considered the fault to be of pre-Cretaceous age, since the Chalk rests on Upper Jurassics in Strathaird and upon lower lias in the Sound of Scalpay, some three miles to the west. The domes and basins which flank the fault may also have been initiated at this time, but they were certainly re-emphasized after the deposition of the Cretaceous, for in Strathaird the Chalk is now confined to the centre of the Kilmarie basin, and was removed by erosion before the onset of vulcanicity. The pre-lava sequence can therefore be summarised as follows:-

1. Deposition of the Jurassics on a base of Torridonian (and Cambrian?).
2. Formation of the Camasunary fault.
3. Subaerial erosion.
4. Marine transgression and deposition of the Chalk.
5. Folding into domes and basins.
6. Subaerial erosion to a peneplain.
7. Onset of vulcanicity in mid-Tertiary.

After the Strathaird lavas were extruded the rocks of the area were folded into an arcuate anticline and syncline, with associated faulting. An upper limit to the age of these structures is provided by the non-deformation of the cone-sheets, and of the dykes of the main north-west swarm. The folding must, therefore, date to the same general period as that in which the Cuillin Gabbro and, later, the Coire Uaigneich granophyre were intruded. There is some evidence that the granophyre post-dates the folding, since chilling of that intrusion occurs against one of the faults (in Coire Casteail) thought to be associated with the folding, and the granophyre cuts short a number of north-west dykes which do not appear to have been affected by the folding. There are good arguments, however, to support the view that the Cuillin Gabbro was intruded at the time of folding and was, in fact, the source of the deforming stresses. These arguments may be summarized as follows:-

1. At any time after the intrusion of the Gabbro the rocks in the vicinity of its contact would be in a thoroughly indurated state, and therefore unlikely to yield to deformation by folding.

2. Crushing and flowage of the country rocks near to the Gabbro contact at Camasunary indicate that considerable outward pressures were developed at the time of intrusion.

3. The arcuate form of the folds parallels the

contact of the Gabbro.

4. The inner of the two flexures (Coire Uaigneich anticline) is considerably more compressed than the outer one (Strathaird syncline).

The post-lava tectonic sequence is envisaged as commencing with crustal tensions over the future site of the Cuillin Gabbro. These were relieved by the development of tension fractures in north-north-westerly and north-easterly orientations, now followed by early dykes at Camasunary. The intrusion of the gabbroic magma followed, shouldering aside the country rocks, with crushing of the contact passing outwards into folding and faulting. The folding was to some extent guided by pre-existing flexures in the sediments, so that, for instance, the pre-lava basin at Kilmarie became incorporated into the Strathaird syncline.

The development of radial and tangential joints in the immediate vicinity of the Cuillin centre was probably related to the cooling of the gabbro magma. This phase was followed by the establishment of strong regional stresses and the formation of north-west joints, and it was early in this period that granophyre was intruded into the core of the Coire Uaigneich anticline. Continued regional stresses, localised by the Cuillin massif, brought into being vast numbers of north-west joints, many of which were soon exploited by dyke intrusions. In its later stages this process was accompanied by a final upward push from the Cuillin centre, resulting in the formation of the cone-sheets and related fractures.

The final event of tectonic significance in Strathaird involved localised crushing and shattering of the Gabbro and its country rocks, especially in the north. This phase was an accompaniment to the explosive activity which initiated new centres of igneous activity to the north and north-east.

(v) The Tectonic Setting of Strathaird.

West of Camasunary the country rocks of the Cuillin Gabbro are hidden beneath Loch Scavaig, and north of Strathaird they have been destroyed by later intrusions. To the west and north of the intrusion the lavas which lie against the contact show no sign of folding, though a gentle westerly dip indicates that tilting occurred at some period after their extrusion. It therefore seems that pressure folds were formed round only a limited sector of the Gabbro margin.

To the east of Loch Slapin, in Strath, lavas are absent, but the Mesozoic sediments are folded by the east-west, Beinn an Dubhaich anticline. This fold has an arcuate form reminiscent of the Strathaird post-lava flexures, but in this case the concavity faces towards the middle of the Broadford intrusion centre. The core of the anticline is of Cambrian limestone intruded by a large granite. Harker (1909, p. 414), and Wedd (1910, p. 10) have pointed out that folding was initiated early in the Mesozoic, for in the south limb the Trias is overlapped by the base of the Jurassics, and this in turn by progressively higher zones of the Lias. Any Tertiary movement on this axis must have been in the nature of a re-emphasis and re-moulding of a pre-existing flexure.

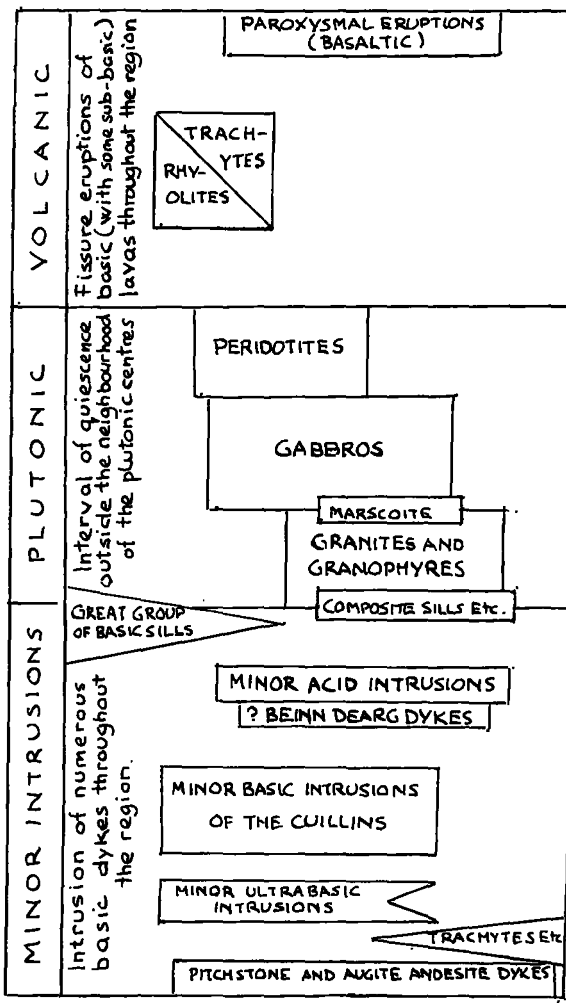
Pre-Tertiary folding on the Beinn an Dubhaich axis finds its continuation, in Strathaird, in the Faoilean dome (see Plate 49). However, the distribution of the formations on opposite sides of Loch Slapin suggest the presence of structural discontinuity in this area. There appears to be insufficient room for the eastward-dipping Estuarine sediments on Belig to rise again above the Lower Lias on the eastern side of Strath Mor, and it is also surprising that the broad spread of Cambrian limestone east of Loch Slapin has entirely disappeared on the western shore, less than half a mile distant. A fault trending a little west of north along the line of Loch Slapin and Strath Mor, with a downthrow to the west, might be the cause of these anomalies. The relatively thick Jurassic sequence in Strathaird may therefore owe its preservation to being situated in a graben between two pre-Tertiary faults - the Camasunary fault on the west, and a fault along Loch Slapin to the east.

Instances of marked structural disturbances of the country rocks in the vicinity of large intrusions have been described from other centres of the Scoto-Irish sub-province, but they are more usually associated with acid, rather than basic, intrusive masses. The authors of the Mull Memoir (1924) describe arcuate folds which they believe to be due to pressures set up by the intrusion of early granophyres into the ring-fracture of the south-eastern caldera. Folding is locally associated with the updoming of the sediments around the north Arran granite (Tyrrell, 1928), while at Slieve Gullion doming is again associated with granitic rocks (Bailey and McCallien, 1956). In Ardnamurchan, however, Richey and Thomas describe the country rocks as domed around Centre 2, which consists largely of quartz-gabbros.

CHAPTER XIII

TIME SEQUENCE

The age relations deduced from evidence described in previous chapters are summarized in Table I2. For comparative purposes, Harker's sequence for the igneous rocks of central Skye is reproduced below (from Tertiary Igneous R_ocks of Skye, p. 432).



The local episodes are indicated by separate tablets in the Table above, their vertical spacing representing diagrammatically the time-intervals between the successive groups.

TABLE I2

TIME SEQUENCE

Sedimentation and Igneous Activity.	Tectonism and Erosion.
JURASSIC	
Deposition of 2500 + feet of sediments, partly marine, partly estuarine, on a basement of Torridonian and Cambrian(?) rocks.	Slight warping and erosion led to a disconformity between the Estuarine Series and the Corallian.
LOWER CRETACEOUS	Formation of the Camasunary fault, downthrowing to the east; slight warping of the whole area into broad flexures. Subsequent erosion laid bare the basement rocks on the west side of the fault.
UPPER CRETACEOUS	
A marine transgression was followed by deposition of the Chalk.	
EARLY TERTIARY(?)	
Laying-down of the Flint Conglomerate in depressions (on land?)	Re-emphasis of the pre-existing flexures was followed by uplift and peneplanation.
MIDDLE TERTIARY	
Extrusion of basic lavas, with minor explosive phases locally. Some sills and dykes were probably intruded at the same time.	
Irregular north-west dykes of picrite and gabbro, followed by dolerites, were intruded into the general area now largely occupied by the Cuillin Gabbro at Camasunary.	Poorly-developed system of north-west jointing.

TABLE I2
(cont.)

Narrow, north-east dykes and a few cone-sheets, mainly of fine dolerite.	Upward pressure, probably originating in the mass of magma destined to form the Cuillin Gabbro, led to the formation of north-east joints and a few cone-sheet fractures in the Camasunary area.
Emplacement of the Cuillin Gabbro, and consequent metamorphism and alteration of the country rocks.	Intrusion pressure remoulded the Mesozoic flexures into arcuate folds. Faulting in various directions affected rocks near the Gabbro contact.
Radial and tangential basic dykes in the Cuillin area.	Radial and tangential joints arose in the Cuillin area, possibly due to cooling stresses.
Period of intrusion of the north-west dyke-swarm commenced.	Regional stresses resulted in a close-spaced system of north-west joints.
Intrusion of the Coire Uaigneich granophyre.	Formation of north-west joints continues.
Main phase of intrusion of the north-west dykes.	
Main period of cone-sheet injection, followed by a few north-west dykes.	Renewed upward pressure from below the Cuillin Gabbro formed cone-sheet joints and a related set of outward-dipping joints.
Explosive activity forms masses of agglomerate to the north of the area.	Shatter belts and irregularly jointing, especially in the northern part of the area.
Emplacement of the Red Hills granophyres to the north and north-east of the area was accompanied by a second wave of alteration, most severe in northern Strathaird. Some of the acid north-west dykes in the area may be of this age.	

TABLE I2
(cont.)

QUATERNARY	Development of an ice-cap in Skye. Sculpturing of the main features of the present topography. Raised beaches formed during and after the retreat of the ice.
RECENT	Silting up of lochs in Strath Creitheach and Strath Mor.

BIBLIOGRAPHY

ANDERSON (E. M.), 1936. The Dynamics of the Formation of Cone-sheets, Ring Dykes, and Cauldron Subsidences. Roy. Soc. Edinburgh, Proc., vol. 56, pp. 128-157.

ANWAR (Y. M.), 1955. Geological Investigations in East Greenland, Part V. The Petrography of the Prinsen af Wales Bjerge Lavas. Meddel. om Grønland, vol. 135, no. 1.

ARGYLL (DUKE OF), 1851. On the Tertiary Leaf Beds in the Isle of Mull. Geol. Soc. London, Quart. Jour., vol. 7, pp. 89-103.

BAILEY (E. B.), 1914. The Sgurr of Eigg. Geol. Mag., dec. 6, vol. 1, pp. 296-305.

———————, CLOUGH (C. T.), WRIGHT (W. B.), RICHEY (J. E.), WILSON (G. V.), and others, 1924. Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban. Geol. Surv. Scotland Mem..

———————, 1952. So-called Amygdaloidal Gabbro in Skye. Geol. Mag., vol. 89, pp. 369-375.

———————, 1954. Contact of Tertiary Lavas with Torridonian near Broadford, Skye. Geol. Mag., vol. 91, pp. 105-115.

———————, and McCallien (W. J.), 1956. Composite Minor Intrusions, and the Slieve Gullion Complex. Liverpool and Manchester Geol. Jour., vol. 1, pp. 466-501.

BARTH (T. F. W.), 1952. Theoretical Petrology. New York. 387 p.

BLACK (G. P.), 1952. The Age Relationship of the Granophyre and Basalt of Orval, Isle of Rhum. Geol. Mag., vol. 89, pp. 106-112.

———————, 1954. The Significance of Tridymite in Igneous and Metamorphic Petrogenesis. Min. Mag., vol. 30, pp. 518-524.

BOWEN (N. L.), 1928. The Evolution of the Igneous Rocks. Princeton University Press.

BROWN (G. M.), 1954. A Suggested Igneous Origin for the Banded Granular Hornfelses within the Hypersthene-gabbro of Ardnamurchan, Argyllshire. Min. Mag., vol. 30, pp. 524-533.

——————, 1957. Pyroxenes from the Early and Middle Stages of Fractionation of the Skaergaard Intrusion, East Greenland. Min. Mag., vol. 31, pp. 511-543.

CARR (J. M.), 1952. An Investigation of the Sgurr na Stri - Druim Hain Sector of the Basic Igneous Complex of the Cuillin Hills, Isle of Skye. Unpublished thesis for Ph.D., Univ. Oxford.

CHALMERS (R. A.), 1954. Spectrophotometric Microtitration of Calcium. Analyst, vol. 79, pp. 519-521.

CHARLESWORTH (J. K.), and others, 1935. The Geology of North-east Ireland. Geol. Assoc., Proc., vol. 46, pp. 441-486.

CLOUGH (C. T.), and HARKER (A.), 1904. The Geology of West-central Skye. Geol. Surv. Scotland, Mem..

——————, WEDD (C. B.), and others, 1910. The Geology of Glenelg, Lochalsh, and the South-east Part of Skye. Geol. Surv. Great Britain, Mem..

DREVER (H. I.), and GAME (P. M.), 1949. The Geology of Ubekendt Island, West Greenland. Part 1. A Preliminary Review. Meddel. om Grønland, vol. 134, no. 8.

EMMONS (R. C.), 1943. The Universal Stage. Geol. Soc. America, Mem. 8.

ESKOLA (P.), BARTH (T. F. W.), CORRENS (C. W.), 1939. Entstehung der Gesteine. Berlin.

EYLES (V. A.), 1952. The Composition and Origin of the Antrim Laterites and Bauxites. Geol. Survv. N. Ireland, Mem..

FORBES (E), 1851. On the Estuary Beds and the Oxford Clay at Loch Staffin, in Skye. Geol. Soc. London, Quart. Jour., vol. 7, pp. 104-113.

FORBES (J. D.), 1846. Notes on the Topography and Geology of the Cuchullin Hills in Skye, and on the Traces of Ancient Glaciers which they Present. Edinburgh New Phil. Jour., vol. 40, pp. 76-99.

GEIKIE (A.), 1865. The Scenery of Scotland, Viewed in Connexion with its Physical Geology. London and Cambridge.

————, 1880. The Lava-fields of North-western Europe. Nature, vol. 33, pp. 3-5.

————, and TEALL (J. J. H.), 1874. On the Banded Structures of some Tertiary Gabbros in the Isle of Skye. Geol Soc. London, Quart. Jour., vol. 50, pp. 645-659.

————, 1897. Ancient Volcanoes of Great Britain. 2 vols. London.

GREEN (J.), and POLDERVAART (A.), 1955. Some Basaltic Provinces. Geochim. et Cosmochim. Acta, vol. 7, pp. 177-188.

HARKER (A.), 1902. Ice-erosion in the Cuillin Hills, Skye. Roy. Soc. Edinburgh, Trans., vol. 40, part 2, pp. 221-252.

————, 1904. Tertiary Igneous Rocks of Skye. Geol Surv. Scotland, Mem..

————, 1908. Geology of the Small Isles of Inverness-shire. Geol. Surv. Scotland, Mem..

————, 1950. Metamorphism. 3rd. edition, revised by C. E. Tilley. London.

HESS (H. H.), 1949. Chemical Composition and Optical Properties of Common Clinopyroxenes. Part 1. Am. Min., vol. 34, pp. 621-666.

HEY (M. H.), 1954. A New Review of the Chlorites. Min. Mag., vol. 30, pp. 277-292.

HOBBS (W. H.), 1911. Characteristics of Existing Glaciers. New York.

JUDD (J. W.), 1874. The Secondary Rocks of Scotland. Second Paper. On the Ancient Volcanoes of the Highlands and the Relations of their Products to the Mesozoic Strata. Geol. Soc. London, Quart. Jour. vol. 30, pp. 220-302.

————————, 1878. The Secondary Rocks of Scotland. Third Paper. The Strata of the Western Coast and Islands. Geol. Soc. London, Quart. Jour., vol. 34, pp. 660-673.

KENNEDY (W. Q.), 1931. On Composite Lava Flows. Geol. Mag., vol. 68, pp. 166-181.

————————, and ANDERSON (E. M.), 1938. Crustal Layers and the Origin of Magmas. Bull. Volcan., series 2, vol. 3, pp. 23-82.

————————, 1951. Sedimentary Differentiation as a Factor in the Moine-Torridonian Correlation. Geol. Mag., vol. 88, pp. 257-266.

KING (B. C.), 1953. Structure and Igneous Activity in the Creag Strollamus Area of Skye. Roy. Soc. Edinburgh, Trans., vol. 62, pp. 357-401.

KNOPF (A.), 1936. Igneous Geology of the Spanish Peaks Region, Colorado. Geol. Soc. America, Bull., vol. 47, pp. 1727-1785.

MACCULLOCH (J.), 1819. A Description of the Western Islands of Scotland, including the Isle of Man. 3 vols. London.

————————, 1824. The Highlands and Western Isles of Scotland .... in Letters to Sir Walter Scott, Bart.. 4 vols. London. (Skye, vol. 3, pp. 370-484.)

M'LINTOCK (W. F. P.), 1915. On the Zeolites and Associated Minerals from the Tertiary Lavas around Ben More, Mull. Roy. Soc. Edinburgh, Trans., vol. 51, pp. 1-33.

MIYASHIRO (A.), IIYAMA (T.), YAMASAKI (M.), and MIYASHIRO (T.), 1955. The Polymorphism of Cordierite and Indialite. Am. Jour. Sci., vol. 253, pp. 185-208.

MUIR (I. D.) and TILLEY (C. E.), 1957. Contributions to the Petrology of Hawaiian Basalts:- 1. The Picrite-basalts of Kilauea. Am. Jour. Sci., vol. 255, pp. 241-253.

MUIR (I. D.) and TILLEY (C. E.), 1958. The Compositions of Co-existing Pyroxenes in Metamorphic Assemblages. Geol. Mag., vol. 95, pp. 403-408.

NOCKOLDS (S. R.), 1954. Average Chemical Composition of some Igneous Rocks. Geol. Soc. America, Bull., vol. 65, pp. 1007-1032.

NOE-NYGAARD (A.), 1942. On the Geology and Petrography of the West Greenland Basalt Province. Part 3. The Plateau Basalts of the Svartenhuk Peninsula. Meddel. om Grønland, vol. 137, no. 3.

PATTERSON (E. M.), 1950 a. Preliminary Note on the Tertiary Lava Succession in North Antrim. Geol. Soc. London, Quart. Jour., vol. 106, pp. 134-135.

——————, 1950 b. Evidence of Fissure Eruption in the Tertiary Lava Plateau of North-east Ireland. Geol. Mag., vol. 87, pp. 45-52.

——————, 1952. A Petrochemical Study of the Tertiary Lavas of North-east Ireland. Geochim. et Cosmochim. Acta, vol. 2, pp. 283-299.

——————, 1955 a. The Tertiary Lava Succession in the Northern Part of the Antrim Plateau. Roy. Irish Acad., Proc., vol. 57, pp. 79-122.

——————, 1955 b. The Tertiary Volcanic Succession in the Western Part of the Antrim Plateau. Roy. Irish Acad., Proc., vol. 57, pp. 155-178.

PEACH (B. N.), HORNE (J.), GUNN (W.), CLOUGH (C. T.), and HINXMAN (L. W.), 1907. The Geological Structure of the North-west Highlands of Scotland. Geol. Surv. Scotland, Mem..

POLDERVAART (A.), 1947. The Relationship of Orthopyroxene to Pigeonite. Min. Mag., vol. 28, pp. 164-172.

RASTALL (R. H.), 1931. The Tertiary Igneous Geology of the British Isles: An Essay Review. Geol. Mag. vol. 68, pp. 121-126.

READ (H. H.), 1949. A Contemplation of Time in Plutonism. Geol. Soc. London, Quart. Jour., vol. 105, pp. 101-156.

REYNOLDS (D. L.), 1951. The Geology of Slieve Gullion, Foughill, and Carrickcarnan: An Actualistic Interpretation of a Tertiary Gabbro-Granophyre Complex. Roy. Soc. Edinburgh, Trans., vol. 62, pp. 85-143.

—————————, 1952. So-called Amygdaloidal Gabbros, Skye: Comments on a Paper by E. B. Bailey. Geol. Mag., vol. 89, pp. 376-379.

RICHEY (J. E.), THOMAS (H. H.), and others, 1930. The Geology of Ardnamurchan, North-west Mull, and Coll. Geol. Surv. Scotland, Mem..

RICHEY (J. E.), 1932. Tertiary Ring Structures in Britain. Geol. Soc. Glasgow, Trans., vol. 19, pp. 42-140.

—————————, 1937. Some Features of Tertiary Volcanicity in Scotland and Ireland. Bull. Volcan., series 2, vol. 1, pp. 13-34.

—————————, 1948. British Regional Geology. Scotland: The Tertiary Volcanic Districts. 2nd. edition, H. M. S. O., Edinburgh.

ROGERS (A. F.), and KERR (P. F.), 1942. Optical Mineralogy. New York and London.

SCHAIRER (J. F.), 1950. The Alkali-feldspar Join in the System Na Al SiO_4 - K Al SiO_4 - SiO_2. Jour. Geol., vol. 58, pp. 512-517.

SHAPIRO (L.), and BRANNOCK (W. W.), 1952. Rapid Analysis of Silicate Rocks. U. S. Geol. Surv., Circ. 165.

STEARNS (H. T.), and MACDONALD (G. A.), 1946. Geology and Ground-water Resources of the Island of Hawaii. Hawaii Division of Hydrography, Bull. 9.

STEWART (F. H.), and WAGER (L. R.), 1947. Gravity Stratification in the Cuillin Gabbro of Skye. Geol. Mag., vol. 84, p. 374.

SUNDIUS (N.), 1946. The Classification of the Hornblendes, and the Solid Solution Relations in the Amphibole Group. Arsbok Sveriges Geol. Undersok., vol. 40, pp. 1-36.

TILLEY (C. E.), 1949. An Alkali Facies of Granite at Granite-dolomite contacts in Skye. Geol. Mag., vol. 86, pp. 81-93.

——————, 1950. Some Aspects of Magmatic Evolution. Geol. Soc. London, Quart. Jour., vol. 106, pp. 37-61.

TOMKEIEFF (S. I.), 1940. The Basalts of the Giant's Causeway District of Northern Ireland. Bull. Volcan., series 2, vol. 6, pp. 89-143.

——————, 1942. The Tertiary Lavas of Rhum. Geol. Mag., vol. 79, pp. 1-13.

TURNER (F. J.), and VERHOOGEN (J.), 1951. Igneous and Metamorphic Petrology. New York, Toronto, and London.

TUSON (J.), 1960. A Geophysical Investigation of the Tertiary Volcanic Districts of Western Scotland. Unpublished thesis for Ph.D., Univ. Durham.

TUTTLE (O. F.), and BOWEN (N. L.), 1958. Origin of Granite in the Light of Experimental Studies in the System Na Al Si_3O_8 - K Al Si_3O_8 - SiO_2 - H_2O. Geol. Soc. America, Mem. 74.

TYRRELL (G. W.), 1926. The Petrography of Jan Mayen. Roy. Soc. Edinburgh, Trans., vol. 54, pp. 747-765.

——————, 1928. The Geology of Arran. Geol. Surv. Scotland, Mem..

——————, 1937. Flood Basalts and Fissure Eruptions. Bull. Volcan., series 2, vol. 1, pp. 89-111.

——————, 1949. The Tertiary Igneous Geology of Scotland in Relation to Iceland and Greenland. Meddel. af Dansk Geol. Foren., vol. 2. no. 4, pp. 413-440 von OEYNHAUSEN (C.), and von DECKEN (H.), 1829. Die Insel Skye. Karsten's Achiv fur Min., vol. 1, pp. 56-104.

WAGER (L. R.), 1934. Geological Investigations in East Greenland, Part 1. General Geology from Angmagsalik to Kap Dalton. Meddel. om Grønland, vol. 105, no. 2.

——————, 1935. Geological Investigations in East Greenland. Part 2. Geology of Kap Dalton. Meddel. om Grønland, vol. 105, no. 3.

——————, and DEER (W. A.), 1939. Geological Investigations in East Greenland. Part 3. The Petrology of the Skaergaard Intrusion, Kangerdlugssuaq, East Greenland. Meddel. om Grønland, vol. 105, no. 4.

——————, WEEDON (D. S.), and VINCENT (E. A.), 1953. A Granophyre from Coire Uaigneich, Isle of Skye, Containing Quartz Paramorphs after Tridymite. Min. Mag., vol. 30, pp. 263-276.

——————, 1956. A Chemical Definition of Fractionation Stages as a Basis for Comparison of Hawaiian, Hebridean, and other Basic Lavas. Geochim. et Cosmochim. Acta, vol. 9, pp. 217-248.

WALKER (F.), 1930. The Geology of the Shiant Isles. Geol. Soc. London, Quart. Jour., vol. 86, pp. 355-398.

——————, and DAVIDSON (C. F.), 1936. A Contribution to the Geology of the Faroes. Roy. Soc. Edinburgh, Trans., vol. 58, pp. 869-897.

——————, and POLDERVAART (A.), 1949. Karoo Dolerites of the Union of South Africa. Geol Soc. America, Bull., vol. 60. pp. 591-706.

WALKER (G. P. L.), 1958. Geology of the Reydarfjordur Area, Eastern Iceland. Geol. Soc. London, Quart. Jour., vol. 114, pp. 367-482.

——————, 1959. Some Observations on the Antrim Basalts and Associated Dolerite Intrusions. Geol. Assoc., Proc., vol. 70, pp. 179-205.

WELLS (M. K.), 1951. Sedimentary Inclusions in the Hypersthene-gabbro, Ardnamurchan, Argyllshire. Min. Mag., vol. 29, pp. 715-736.

WILKINSON (J. F. G.), 1956. Clinopyroxene of Alkali Olivine-basalt Magma. Am. Min., vol. 41, pp. 724-743.

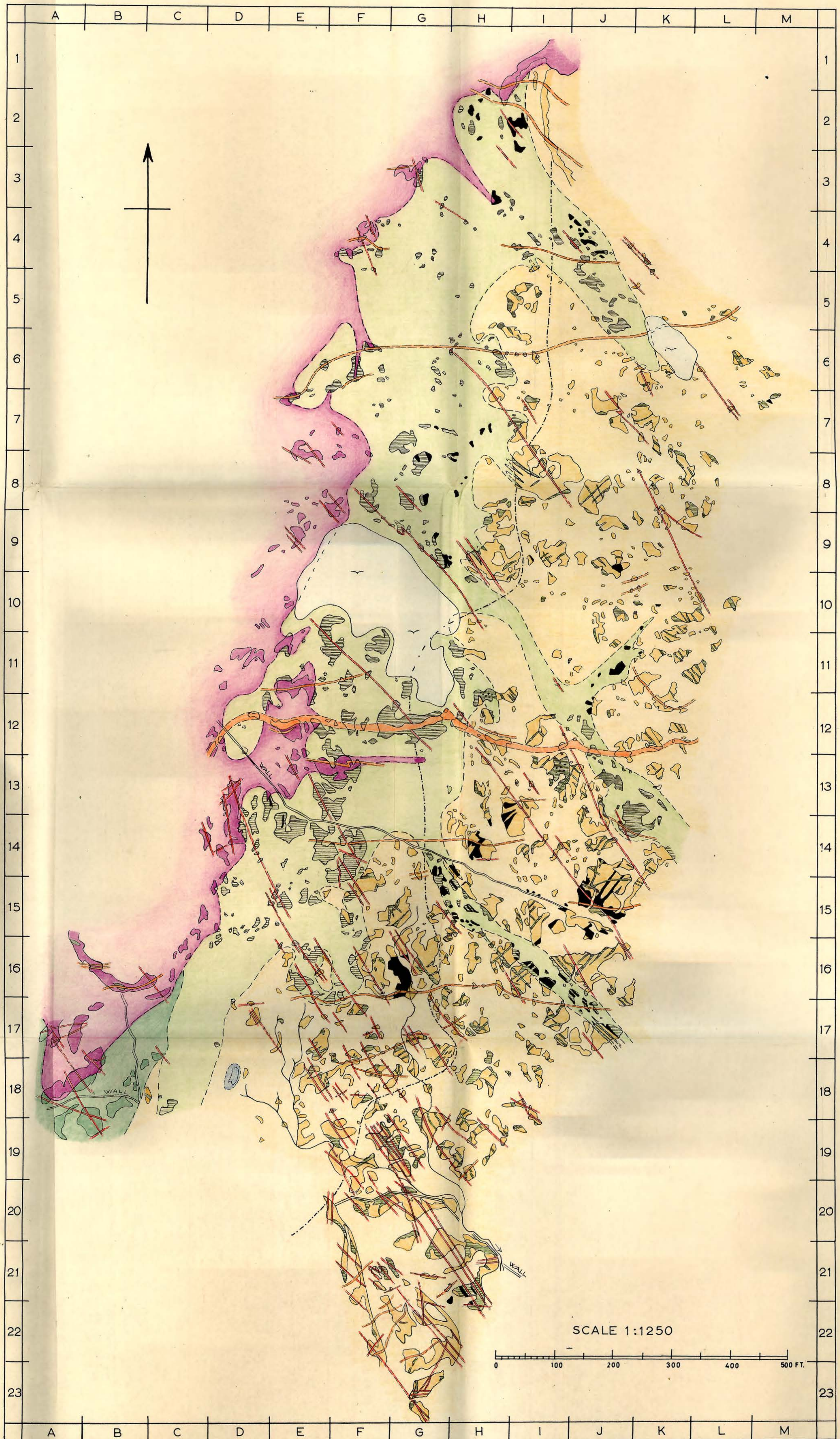
WILSON (G. V.), 1936 -1939. Sheet 81, Scotland. Geol. Surv. Great Britain, Summaries of Progress for 1935 (pp. 81-84), 1936 (pp. 77-79), for 1937 (pp. 73-74), for 1938 (pp. 74-76).

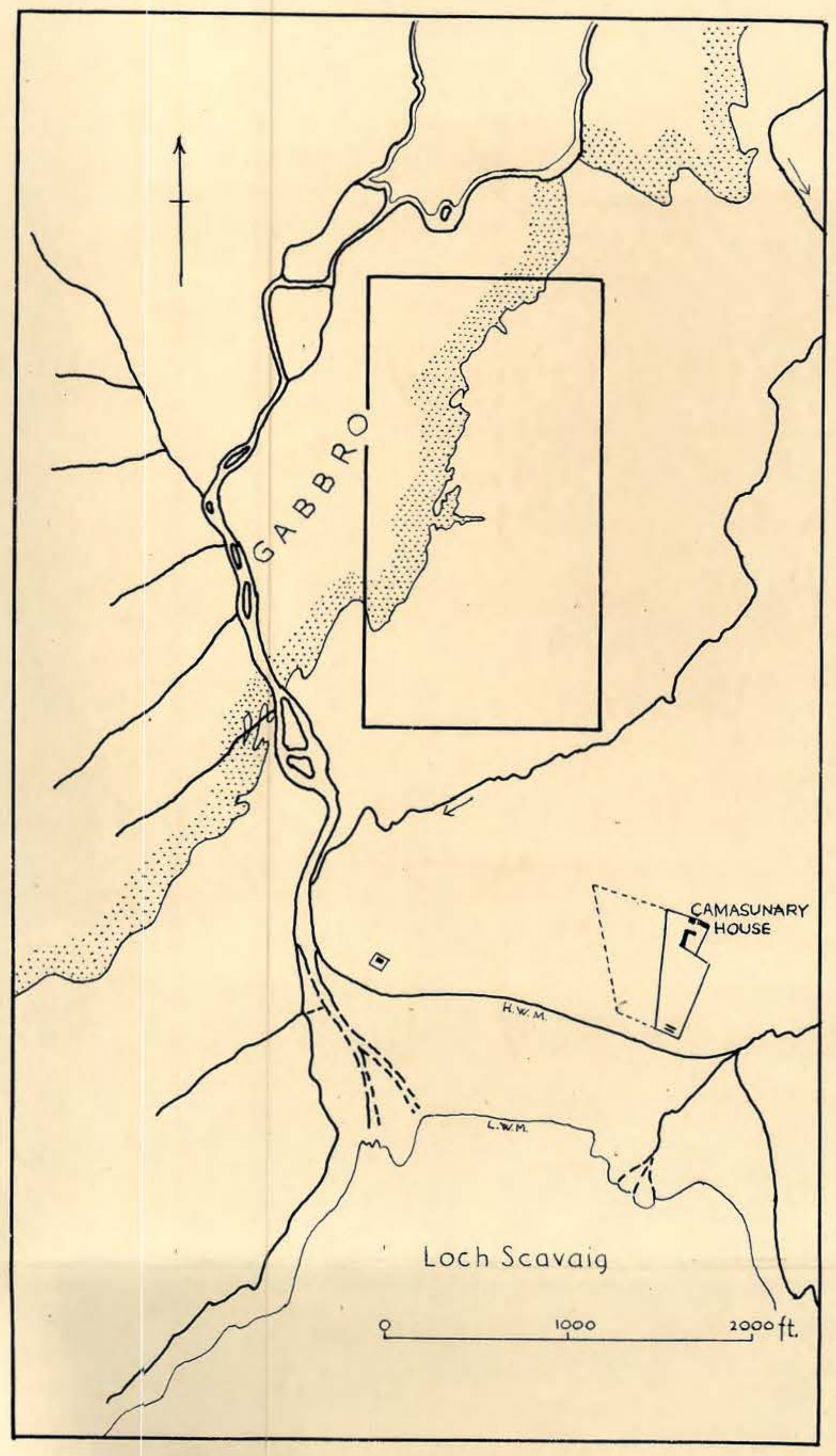
WINCHELL (A. N.), 1951. Optical Mineralogy. 4th. edition. Part 2. Description of Minerals. New York and London.

WISEMAN (J. D. H.), 1934. The Central and South-west Highland Epidiorites: A Study in Progressive Metamorphism. Geol. Soc. London, Quart. Jour., vol. 64, pp. 245-270.

WYATT (M.), 1952. The Camasunary (Skye) Gabbro-limestone Contact. Second part of an unpublished thesis for Ph.D., Cambridge.

ZIRKEL (F.), 1871. Geologische Skizze von der Westkuste Schottlands. Zeits. dents. geol. Ges., vol. 23, pp. 1-124.





SKETCH MAP OF CAMASUNARY, SHOWING THE LOCATION OF THE AREA MAPPED AT 1:1250

LEGEND

- Approximate limits of individual exposures.
- Lake alluvium.
- Cone sheets.
- Basic dykes which post-date the Cuillin Gabbro.
- Cuillin Gabbro.
- Intrusions of dolerite which pre-date the Cuillin Gabbro. Exposed portions shaded.
- Intrusions of gabbro and picrite which pre-date the Cuillin Gabbro. Only exposed portions are indicated
- Basalt lavas
- Lias limestone
- Torridonian

Between the line marked thus, -·-·-·-·-·-, and the contact of the Cuillin Gabbro, the early basic rocks are commonly veined by acid material which had its origin in the rheomorphism of Torridonian arkoses.

D.C. ALMOND, DURHAM, 1960.

GEOLOGY OF THE CUILLIN GABBRO CONTACT ZONE NORTH OF CAMASUNARY


GEOLOGICAL MAP
of the
STRATHAIRD PENINSULA, SKYE
SCALE : SIX INCHES TO ONE MILE
0
1 Mile
LEGEND
TERTIARY IGNEOUS INTRUSIONS
CUILLIN GABBRO (MARGIN) G
COIRE UAIGNEICH GRANOPHYRE Gr
BASIC SILLS BS
BASIC PLUG BP
EARLY BASIC INTRUSIONS (CAMASUNARY) EB
BASIC DYKES
ACID AND ULTRABASIC DYKES A U
CONE SHEETS
ACID SILLS AS
RAISED BEACH
RIVER AND LAKE ALLUVIUM
LANDSLIP LS
TERTIARY VOLCANICS
LAVAS (GROUP UNSPECIFIED) L
UPPER LAVA GROUP UL
PICRITIC BASALT GROUP PB
OPHIMOTTLED BASALT GROUP OB
TRACHYBASALT TB
BASAL LAVA GROUP BL
AGGLOMERATE
PRE-LAVA SEDIMENTARY ROCKS
FLINT CONGLOMERATE FC
CHALK C
CORALLIAN Co
ESTUARINE SERIES
PALUDINA LIMESTONE Pal. Lst.
OSTREA HEBRIDICA BEDS Ost. Lst.
CYRENA LIMESTONE Cy. Lst.
CYRENA SHALE Cy. Sh.
INFERIOR OOLITE
SHALE Inf. Sh.
SANDSTONE Inf. Sst.
UPPER AND MIDDLE LIAS UML
LOWER LIAS
MIXED BEDS LL
LIMESTONE LL Lst
TORRIDONIAN T
ROADS
ROUGH TRACKS
FOOTPATHS
CRAGS AND CLIFFS
LINEAR TOPOGRAPHICAL FEATURES
CONTOURS
GEOLOGICAL BOUNDARIES, CERTAIN TO INFERRED
FAULTS, WITH DOWNTHROW
DIPS OF BEDDING AND IGNEOUS CONTACTS
A–B, C–D are the lines of horizontal sections shown in Plate 50.
D.C.ALMOND, DURHAM, 1960
STRATH MOR
Loch na Sguabaidh
GARBH BHEINN
2649
SGURR NAN EACH
CLACH GLAS
BLAVEN
3042
3031
Coire Uaigneich
AN STAC
Coire Ballaig
LOCH SLAPIN
Loch na Creitheach
SLAT BHEINN
AN CARNACH
SGURR NA STRI
1623
Camasunary
Rudha Buidhe
Rudha Ban
LOCH SCAVAIG
Strathaird
Kilmarie
BEINN LEACACH
888
Glen Scaladal
BEN MEABOST
1128
1119
BEN CLEAT
Elgol
Port na Cullaidh
Glasnakille
Dun Liath
An Reidhean
Dykes not mapped
Rudha na h-Easgainne
Eilean na h-Airde
57°13'
57°12'
57°11'
57°10'
57°9'
57°8'
6°2'