D E C L A R A T I O N .

I hereby declare that the following Thesis is based on the results of investigations carried out by me, that the Thesis is my own composition, and that it has not previously been presented for a Higher Degree.

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THE GEOLOGY OF THE SHIANT ISLES.

Being a Thesis presented by

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to the University of Edinburgh

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C O N T E N T S .

I. PHYSICAL FEATURES.

The Shiant Isles form a small archipelago in the North Minch some five miles S.E. of the Park district of the Island of Lewis Though grouped with Ross and Cromarty, they are twenty miles distant from Rudh Re -- the nearest point of the mainland. Geologically, the islands are connected with the Trotternish district in the North of Skye, showing as their principal feature thick dolerite sills intruded into relatively thin Mesozoic sediments. The Shiants are, in fact, the most northerly representatives of the 'trap isles' of the Hebrides. The group contains three comparatively large islands -- Garbh Eilean (the rough island), Eilean an Tighe (the island of the house), and Eilean Mhuire (Mary Isle). Of these the first two are the largest, both being about a mile in length, with a maximum breadth of about half that distance. They are connected by a shingle beach -- except during unusually high tides -- one side or other of which provides a safe landing-place even in rough weather. Garbh Eilean, the northern island, rises to a height of 528 feet, and is bounded to the north and east by high cliffs. Those of the north face are particularly impressive, showing at one point a sheer wall 500 feet high (PLATE VI) rising out of the sea. To the north-east and east the bottom of the cliffs is buried under great scree slopes which, being partly over-

grown, form the nesting place of countless puffins. Eilean an Tighe is 410 feet in height and is bounded on the east by similar high cliffs together with occasional scree slopes. Both islands consist almost entirely of a single dolerite sill having a visible thickness of over 500 feet and dipping S.W. at an angle of 10 - 15°. Thus the S.W. side of Garbh Eilean and the W. side of Eilean an Tighe have moderately gentle dip slopes which are easy of access in calm weather. When a west wind is blowing, however, the summit of Garbh Eilean can be reached only by following a very steep route from the shingle beach which forms the one safe landing place in these circumstances.

Eilean Mhuire lies about half-a-mile to the east of Garbh Eilean and is surrounded by high cliffs on every side, although its height of 290 feet is inferior to that of the other two islands. Measuring seven-eighths of a mile in length by one-third of a mile in breadth, it can only be scaled by landing below the grassy slopes to the east of Bid na Faing, or on the rocky platform at the extreme east of the island whence its smooth green top is reached by a steep pull up crumbling rock. Eilean Mhuire is made up of several almost horizontal dolerite sills separated by thin Jurassic sediments.

About half-a-mile to the west of Garbh Eilean is the easternmost of a string of nine small islands (some of which are mere

rocks) stretching towards the west and extending over a mile in length. These are named the Galtachean, and the two largest are known as Galta Mor and Galta Beg. These islands also consist of dolerite, the sill or sills of which they are composed dipping to the south at a variable angle. The southerly dip slopes of the two Galtas are grass-clad and easily scaled, although a landing is difficult to effect except in the calmest weather. None of the Galtachean exceeds 200 feet in height, while Galta Mor, the largest, is about 300 yards long and 150 yards broad.

The rocky islet named Seann Chaisteal lies off the extreme east of Eilean Mhuire, being separated by a channel of only a few yards breadth. It is slightly over a hundred yards long and about fifty yards broad. A somewhat smaller rock, Sgeir Mhianuis, lies off the extreme south of Eilean an Tighe.

A large part of Garbh Eilean, Eilean an Tighe, Eilean Mhuire and the two Galtas is covered with rich grass providing excellent pasturage for the three hundred sheep which inhabit the group. Gulleries abound on the grassy slopes, while the nesting holes of the puffin riddle the ground wherever excavation is possible. Doubtless the excrement of these birds contributes to the extraordinary fertility of the islands, which forms a marked contrast to the utter sterility of the gneiss in the

neighbouring Park district. The cliffs of the islands are inhabited also by thousands of razor-bills, guillemots and kittiwakes. One or two hollows in Garbh Eilean and Eilean an Tighe are filled with thick peaty deposits. The only stream of any size on the islands is that flowing down the middle of the south-west slope of Garbh Eilean, but springs occur on all the islands, usually near the junction of the igneous rock and the Jurassic strata.

In view of the richness of their soil, it is not surprising to find evidences that the islands have been inhabited from the earliest times. During the last century, however, only a single family remained in occupation, and eventually the inconveniences attendant on the inaccessibility of the group led to its abandonment some thirty years ago, since when it has remained uninhabited. In 1922 the islands passed into the hands of Mr. Compton Mackenzie, who has leased it until last year to Mr. Malcolm Macsween of Tarbert, and it is mainly due to the kind assistance of these two gentlemen that the field work of this research was carried through.

II. PREVIOUS LITERATURE.

Although Martin[1] devotes over a page to the Shiant Isles in his 'Description of the Western Islands', the first geological account of the group is that of the indefatigable Macculloch[2] in 1819. In dealing with the Shiants Macculloch shows his customary acute observation, and describes many of the important geological features. He recognised that the islands are formed of sheets of remarkably ophitic 'augit' trap rock, and records the presence of Jurassic shales and 'siliceous schist' between the sheets of Garbh Eilean, and again on Eilean Mhuire. The curious botryoidal or spherical structure of some of these sediments did not escape his attention, nor did the impressions of belemnites which prove their 'secondary' or Mesozoic age. Amongst the minerals found by him were natrolite, stilbite, and wavellite, this last mineral occurring in the joint-cracks of the 'siliceous schist'. He gives, too, a graphic account of the cliffs of Garbh Eilean, and of the natural arch which penetrates the easterly horn of that island. The resemblance of the geological structure of the Shiants to that of parts of northern Skye and Raasay was also noticed by him.

(1) 'Description of the Western Islands of Scotland', 1703, pp.26-7

(2) 'Description of the Western Islands of Scotland', 1819, pp.435-444.

After the appearance of Macculloch's account the Shiants were neglected by geologists for nearly sixty years, although Lord Teignmouth[1] gives a good general description which was published in 1836. It was not, however, until 1878 that Judd's[2] classic paper on the Secondary Rocks of Scotland appeared in print. In this publication he gives a short description of the Jurassic strata of the Shiants, but does not mention on which islands they are found, although a section illustrating their occurrence on Garbh Eilean is printed. He was successful in finding Am. Murchisonae, Sow., and Am. corrugatus, Sow., besides the hollow casts of belemnites mentioned by Macculloch, and on these grounds assigned the strata to the lowest part of the Inferior Oolite series.

Shortly afterwards Heddle[3] visited the islands, and in 1884 his account of their geology appeared in print. His description of the group shows few advances on that of Macculloch, but he confirms the presence of wavellite and also records analcite and mesolite as occurring in the dolerite. He appears to regard the wavellite as permeating the spherules developed in the Jurassic strata. A fairly extensive account of the glaciation

[1] 'Sketches of the Coasts and Islands of Scotland', 1836, pp.166-172.

[2] Q.J.G&S., 1878, pp.660-743.

[3] Trans. Norfolk Nat. Soc. vol.III, 1884, pp.61-68.

of the group is given, his main conclusion being that the ice-flow was from the west! He was unable to land on Eilean Mhuire owing to bad weather, but accomplished this on a subsequent visit which led to a more detailed account including that island.[1] In this later account he records nepheline from a 'dolerite' occurring in a sea-cave at the east end of Eilean Mhuire -- a significant and suggestive discovery.

In 1885 Judd's[2] well-known paper on the 'Tertiary and Older Peridotites of Scotland' appeared. He gives in it petrological descriptions of the dolerites (probably from Garbh Eilean) commenting upon the beautifully developed ophitic structure of the augite. He also records for the first time the presence of ultrabasic rocks on the islands, but as most of his specimens were collected from fallen blocks he was unable to make out the mutual relationship of the two types. All varieties from felspathic dolerite to olivine rock were found, but even in the most basic specimens felspar and augite were present. Thus the term 'dunite' applied to them by Judd is a little misleading. Slightly less basic varieties were named picrite by him. He comments upon the yellow colour of the olivine in thin section and considers it to be highly ferriferous. The 'dunite', pic-

[1] 'A Vertebrate Fauna of the Outer Hebrides', Harvey-Brown and Buckley.

[2] Q.J.G.S., 1885, pp.354-418.

rite, and the augite from the dolerite are figured in plates. Like Heddle, he was prevented from landing on Eilean Mhuire by bad weather.

Sir Archibald Geikie[1] was the next geologist to turn his attention to the islands and he gives a good description of their geology in 'Ancient Volcanoes' based on three visits to the group. He has several new observations to make on Eilean Mhuire. Specimens from one of the thick sills of this island were submitted to Dr. Harker, who found that they were coarse gabbros without olivine and with a peculiar pleochroic augite. Geikie notes the occurrence of "schlieren" of light and dark rock on Eilean Mhuire, and finds that the thickest gabbro sill is intruded by veins and sheets of olivine ranging from an inch to twenty feet in thickness. These basaltic intrusions were found to show marked chilling against the gabbro. Specimens of the basalt are also described by Dr. Harker. Geikie was unable to find the ultrabasic rocks recorded by Judd, but suggests with characteristic perspicacity that they have accumulated at the base of some of the sills 'like the picrite in the Bathgate diabase'.

Dr. Harker, who makes several references to the Shiant Isles

[1] 'Ancient Volcanoes of Great Britain', 1897, vol. II, pp. 307-311.

in his memoir on the'Tertiary Igneous Rocks of Skye', visited the group five years ago, but was unfortunately unable to examine its geology through illness. He succeeded in securing, however, a specimen from the eastern end of Eilean Mhuire which proved to be a most interesting alkali syenite. On learning that the writer thought of making a geological survey of the islands, Dr. Harker with great kindness placed this and other important information at his disposal, and afforded him every encouragement in the work.

III. PRESENT RESEARCH.

The survey of the group was begun in July 1927, when the writer and his wife spent three weeks on the islands. They were able, through the kindness of Mr. Macsween, to occupy the small bothy which is used by him on his occasional visits to the islands. The shepherd's cottage, which is not a "black house" like the bothy, has fallen into ruins, but is being rebuilt by Mr. Compton Mackenzie at the time of writing.

During the time spent on the group, almost uninterruptedly good weather prevailed and a complete survey was made of Garbh Eilean and Eilean an Tighe. Eilean Mhuire was visited only on two days when the motor fishing-boat which provided the transport from Tarbert was at hand, as the aid of the crew was required to haul even a small dinghy up the very steep eastern

side of the shingle beach. The small size of this boat and the great strength of the tides in the group prevented visits to the Galtachean on these occasions.

The writer returned to the islands with a larger dinghy in May 1928, and spent four days on them in company with Mr. Macsween, Mr. Donald Morrison,of Scalpay, and his colleague Dr. Welch. They were not, however, favoured by good weather, for north-east winds blew with gale force during the whole period. In spite of this, landings were made on both the Galtas, and on Eilean Mhuire, but only through the expert seamanship of the first two gentlemen, both of whom have a lifelong knowledge of the group. The survey was thus successfully completed, and a more representative collection of fossils made with the help of Dr. Welch.

IV. SUMMARY OF GEOLOGICAL STRUCTURE.

The geological structure of Garbh Eilean and Eilean an Tighe is exceedingly simple, the great bulk of both the islands being made up of a single sill of crinanite which passes gradually in to picrite as the base is reached. This sill has a visible thickness of at least 500 feet, and is therefore one of the largest in the country. The picrite base of the sill is seen

only at the south-east of Garbh Eilean, but its presence all along the east and north-east coast of the island may be proved by the great numbers of boulders of that rock in the scree slopes. The western extremity of Garbh Eilean is let down by a large normal fault running north and south across the island, and clearly visible on the north cliff-face where the rock adjacent to it shows marked brecciation. This fault throws the picrite base of the sill far below sea-level, and gives rise, by denudation, to a very marked hollow which can be traced across the island from north to south (PLATE IVb). A similar fault, running N.E.- S.W. with downthrow to the south-west, probably occurs between Garbh Eilean and Eilean an Tighe, for the picrite base of the sill is not exposed at all in the latter island. If no dislocation were present the picrite would certainly be found at the south end of the shingle beach.

The great crinanite-picrite sill rests on some 30 feet of Upper Lias (Whitbian) shales with siliceous bands, exposed on the north-east of Garbh Eilean, and these are followed downwards by another crinanite sill of which only the top is seen. A small patch of similar sediments occurs on the north-west shore of Eilean an Tighe. These strata do not exceed 15 feet in thickness and have probably been caught up by the sill, for

they end abruptly to the north against dolerite without any trace of a faulted junction.

The Galtachean appear to be made up of a sill of crinanite petrologically identical to that of Garbh Eilean and Eilean an Tighe with which it is ,possibly, to be correlated. The rock of Galta Mor contains, however, numerous thick bands of alkaline pegmatite which do not occur to the same extent on the two larger islands. While the dip of the 500 foot sill is generally to the south-west, and never exceeds 15°, that of the Galtachean is to the south, being often much greater and exceedingly variable as is shown by the disposition of the columns.

The structure of Eilean Mhuire is slightly more complex. The summit of the island is made up of a crinanite sill very similar to that below the Jurassic strata of Garbh Eilean. This sill rests on at least 60 feet of almost horizontal Upper Lias shales and siliceous strata, again very much like those of Garbh Eilean. The Jurassic beds cover a large part of the top of the island, and are well exposed in the highest parts of the cliffs. They are underlain in their turn by a dolerite sill which is crinanitic, or even teschenitic, in places, and has been split by numerous basaltic bands of distinctly later age.

This sill contains numerous 'schlieren' of alkaline composition towards the eastern extremity of the island. About 200 yards south-west of the summit two N.-S. faults with downthrow to the east are clearly seen on the cliff face, and the Jurassic strata to the east of them dip to the north at a much higher angle than elsewhere.(25°).

V. JURASSIC STRATA.

(1) GARBH EILEAN.

The Jurassic strata of Garbh Eilean occur along the north-east shore of the island and are readily accessible, especially at low water. Passing from east to west, they are first encountered a few yards to the west of the natural arch named Toll a' Roimh, which cuts through the promontory of Bidean a' Roimh. At the south end of this arch they are indifferently exposed on the grassy slope, and are seen to dip south-west at 25°. Just to the west of the north end of the arch they appear at the top of the cliffs dipping at a somewhat smaller angle, and descend the cliffs as one passes west until they reach the shore level below Airidhean n a' Bhaigh. Here they are split by an offshoot from the lower doleritic sill of Garbh Eilean, and have suffered slight dislocation. Westward from this point they are exposed on the inner side of Sgeirean a' Bhaigh (PLATE IIIa) and, less perfectly, in intermittent low bluffs along the shore opposite the reef. At the west of Sgeirean a' Bhaigh the dip has swung round to due south and is at an angle of 15°.

The strata appear to be about 30 feet in thickness and consist of baked shales and more arenaceous beds which were probably originally siliceous mudstones, but have undergone such

profound contact alteration that they are referred to by Macculloch as 'siliceous schist'. In places they resemble porcellanite, being greyish-black in colour, and often breaking with a conchoidal fracture. Under the microscope their siliceous character becomes at once apparent. The shales are dark in colour, seem to be less altered, and still to a certain extent retain their lamination. The marked botryoidal structure which is occasionally developed in them will be considered below.

Macculloch[1] and Heddle[2] both record the occurrence of wavellite as "dead white flattened spheres of radiating crystals" along the joint cracks of these sediments, Heddle giving the locality as "near Sgeirean a' Bhaigh". A careful search revealed at the east end of this reef bodies whose occurrence and appearance correspond exactly with the above description. They failed, however, to give the characteristic phosphate precipitate with ammonium molybdate, after digestion with nitric acid. Fragments of undoubted wavellite gave an abundant yellow precipitate under similar conditions. The mean refractive index of the supposed wavellite was found by oils to be 1.498 ± .003, and the fibres are elongated in a positive direction. A flame

Op. cit. p.444.

'Mineralogy of Scotland', 1st edition, 1901, vol.II, p.164.

test showed a strong sodium reaction with a trace of calcium and potassium, while the genuine wavellite showed only the slightest signs of these elements. These results indicate a zeolite (probably stilbite) rather than wavellite whose mean refractive index according to Larsen[1] is 1.534. No trace of any other mineral resembling wavellite was found.

The botryoidal or pseudo-pisolitic structure occasionally developed in the shales is best seen in the low bluffs mentioned above, and appears to be a weathering phenomenon as the spheres are conspicuous only on weathered surfaces. Broken fragments which have undergone wave-action show the structure to perfection being almost entirely composed of spheres ¼-inch in diameter with rare infillings of greenish saponitic material in the interspaces. The spheres are distinctly harder than the normal rock, but their structure is too fine to be made out even under the microscope. It seems unlikely, however, that wavellite has entered into their composition as has been suggested. In view of Macculloch's[2] excellent account of the phenomenon further description is unnecessary.

There is no regular order in the succession of argillaceous and arenaceous beds, but the shales seem to be more abundant

[1] Bulletin 679, U.S. Geol. Survey, pp. 156, 211.
[2] Op. Cit., pp. 441-4.

towards the top of the sequence. The siliceous bands appeared to be unfossiliferous, except for obscure traces of belemnites, but during the second visit to the islands the shales yielded several fragmentary ammonites. Mr. J. W. Tutcher, M.Sc., very kindly examined these for the writer and identified amongst them:-

Elegantuliceras c.f. elegantulum (Y. and B.) sp. Harpoceratan. This fossil was found in a somewhat arenaceous shale.

[2] EILEAN AN TIGHE.

About 15 feet of highly altered siliceous strata very similar to those of Garbh Eilean are exposed on the north-west shore of Eilean an Tighe, in the bay just south of Sgeirean Mol na h-Althadh. They dip south-west at 10°, but are folded and faulted at their southern extremity where they pass under beach material and drift. To the north they end abruptly against the dolerite, the actual contact being well exposed (PLATE Vb). It seems probable that these beds were floated up from the bottom of the sill, partly by their lower specific gravity, and partly by the rush of gas which was evolved in their reaction[1] with the magma. Unmistakable signs of this ebullition are seen in the abundant spherical cavities in the overlying dolerite, now

[1] [Without perceptible assimilation]

filled by radiating zeolites. The sinuous pegmatite veins with their abundant black mesostasis, which are so prominent here in the dolerite, doubtless have some connection with this reaction. No fossils were observed in the sediments of Eilean an Tighe, except for some imperfect impressions of belemnite guards.

[3]EILEAN MHUIRE.

The development of Jurassic strata on Eilean Mhuire is considerably greater than on the other two islands, a thickness of at least 60 feet being attained. Proceeding southwards from Clach Uaine at the extreme north of the island, one encounters the sediments at the top of the cliffs which tower above the eastern shore line. They may be traced along the summit of these cliffs for 400 yards, after which they pass inland under drift.[1] They are again seen on the eastern cliffs, however, just east of the summit of the island. From this point they may be traced by intermittent exposures across the island to the southern cliffs above whose summits they are seen for over 300 yards. They are dislocated here by two small N.-S. faults (shown on the map) which throw them down to the west. Just north of the reef Sgeir na Ruideag they again pass inland where they are poorly exposed in one or two scrapes situated about

[1] There is no evidence for the continuation of the Jurassic beds below the grass of the eastern margin of Airidh Mhuire, and it is therefore possible that the 'Upper' and 'Lower' Sills of Eilean Mhuire belong to the same intrusion, as indicated on the map.

200 yards west of the summit of the island. They reappear along the top of the cliffs above Cudha na Gaoidhaich, being well exposed here (PLATE IX b), but are finally lost to view some 300 yards to the north.

The lithology of the strata is exactly the same as in Garbh Eilean, baked shales alternating with more siliceous flinty bands. As in the larger island, the shales are more abundant towards the top of the series, and occasionally show the same pseudo-pisolitic structure. No mineral resembling wavellite was found in any of the beds. The strata are at least 60 feet in thickness and dip at a very low angle, especially in the northern part of the island where they are practically horizontal. South of the summit, however, a northerly dip of 25° was measured, and the beds have probably undergone dislocation at this point.

In 1927 fossils were found only at one locality, viz., the scrapes 200 yards west of the summit. Here several ammonites were discovered in shales near the top of the series, one being in very fair preservation. They were submitted to Mr. S. S. Buckman, who very kindly determined them as below:-

Anguidactylites anguiformis, S.B.

Orthodactylites directus, S.B.

Elegantuliceras (near to elegantulum Y. and B.) sp.

During the second expedition to the islands a careful search was made of the strata above the cliffs north of Sgeir na Ruideag, these beds being easily accessible. No determinable ammonites were found, but a brachiopod was obtained from the shales near the top of the series and was identified by Mr. Tutcher as:-

Inoceramus dubius, Sow. U. Lias.

On the shore below the cliffs at this point several pebbles of arenaceous shales containing ammonites were found, and these also were determined by Mr. Tutcher as below:-

Tenuidactylites c.f. tenuicostatus Y.and B. sp.Harpoceratam.

Dactylioceras c.f. annulatum J.Sow. sp. Harpoceratan.

[4] CONCLUSIONS.

With the exception of one specimen of Elegantuliceras, the fossils discovered have suffered crushing, but Mr. Buckman and Mr.Tutcher agree that they all represent a very low position im the Upper Lias (Whitbian). Thus the strata of Garbh Eilean may be correlated with those of Eilean Mhuire, this conclusion being confirmed by the strikingly similar lithology of the two series. Judd[6] assigned the strata of Garbh Eilean (presumably) to the lowest part of the Inferior Oolite series, having dis-

[6] Q.J.G.S., 1878, p.721.

covered flattened impressions of ammonites which he identified as "Am. Murchisonae, Sow., and Am. Corrugatus, Sow." Mr. Buckman, however, in a private communication to the writer, points out that "if Judd only saw the Harpocerate (Elegantuliceras) it would not be surprising if he took that for an Inferior Oolite specimen: it has considerable likeness to Inferior Oolite forms."

Owing to the considerable thermal metamorphism which the strata have undergone, their original lithology is somewhat conjectural, and it is therefore difficult to compare them satisfactorily with the Upper Lias of neighbouring districts. They seem, however, to be somewhat similar to the Upper Liassic beds near the entrance of Portree Bay in north-east Skye[1]. Here the strata consist of dark micaceous shales with harder bands containing, amongst other fossils, Elegantuliceras elegantulum (Y. and B.), a species found both on Garbh Eilean and Eilean an Tighe. Natural exposures are poor, most of the information being obtained from boring records. There is no trace of any oolitic ironstone like that of Raasay on the Shiants.

[1] Mem. Geol. Survey, 'Mesozoic Rocks of Applecross, Raasay, and N.E. Skye', 1920, pp.38-39.

VI. IGNEOUS GEOLOGY.

[1] THE CRINANITE-PICRITE SILL OF GARBH EILEAN AND EILEAN AN TIGHE.

(a) FIELD CHARACTERS.

The great sill which forms the major part of Garbh Eilean and Eilean an Tighe is the most prominent feature of the Shiant Isles. The dip of 10° - 15° swings round in direction from south at the western extremity of Garbh Eilean to almost due west in the southern portion of Eilean an Tighe. The scarp slopes to the north and east of these islands present almost vertical cliffs or exceedingly steep rocky slopes towards the sea, but the bottom of both is frequently covered by vast accumulations of large boulders which have fallen from higher parts of the sill. This is to be seen particularly along the shores of the north-east of Garbh Eilean (PLATES III b, VII a) where the Jurassic strata occur, with the result that the lower junction of the sill is completely buried. Elsewhere the lower contact is below the sea, while the upper junction of the sill has been removed by denudation. The thin Jurassic strata to the north-west of Eilean an Tighe are seen in contact with the crinanite, but these beds have probably been floated up by the sill while

the junction between them and the igneous rock is abnormal, as will be explained below.

Exposures on the dip slopes of the islands are naturally less perfect than on the scarp slopes, but rocky projections rise up through the grass very frequently, and there are distinct walls of overhanging columns on the north-west slopes of Eilean an Tighe and the south-west slopes of Garbh Eilean. Along the western shore line the exposures are almost uninterruptedly perfect.

Columnar structure is well developed throughout the sill, and attracted the attention of all the previous observers. The columns do not display the perfect symmetry of those of Staffa, but have a certain rugged grandeur of their own, being both greater in diameter and very much longer. Though generally quite straight, they show slight curvature near the summit of Eilean an Tighe and on the north face of Garbh Eilean west of Glaic na Crotha. Round the latter locality some of the columns reach a height of 350 feet at least, while their average diameter is over five feet. They are usually hexagonal in form, but pentagonal and even heptagonal examples are frequent. The great scree slopes on the north-east face of Garbh Eilean are formed of the broken fragments of such columns which have cleaved along joints parallel to the plane of intrusion. The

boulders in most cases thus retain the characteristic polygonal outline of the original columns (PLATE VIIa). A white zeolitic substance sometimes fills the joint-cracks between the columns, and has been identified as mesolite by Heddle.(1)

Besides the ordinary columnar jointing, there is a series of vertical major joints running, for the most part, N.N.E.-S.S.W. They are well seen on the cliff face to the west of Glaic na Crotha where the rock has broken off in huge parallel slabs instead of column by column. On the south-west slope of Garbh Eilean, which is very steep, there is a similar series of major joints, and also a tendency for the columns to overhang and topple into the sea. This has caused some of the major joints to open out, and they now form straight gaping fissures in the grassy slopes, partly choked by soil and vegetation and with slab-like walls (PLATE Va). The absence of tachylitic selvages and slickensiding on the sides of these fissures shows that they do not find their origin in the rapid weathering of a basic dyke, or of crush rock along a line of movement. On the south-west shore of Garbh Eilean there are numerous caves and fissures running into the rock in a northerly direction, and these are probably due to the waves eroding along lines of weakness formed by such major joints. The N.- S. fault which lets down

(1)Trans. Norfolk Nat. Soc. vol.III, 1884, p.65.

the west part of Garbh Eilean, and the hypothetical fault between Garbh Eilean and Eilean an Tighe letting down the latter island, have already been mentioned and require little further comment. The hade of the former fault is approximately 30°, but no estimate can be formed of its throw.

Microscopic examination of sections taken from all parts of the sill shows that, apart from local segregations of pegmatitic phases, the composition of the rock does not vary laterally but is solely a function of the height of the locality above the base of the sill. Hence a description of the various types encountered when passing from bottom to top of the most complete vertical section available will apply in fact to any portion of the intrusion.

The best and most complete section is seen on the southern face of Garbh Eilean, which rises with great steepness from the shingle beach, has numerous excellent exposures, and is accessible to even moderate climbers at nearly every point (PLATE VIb).

The lowest visible part of the sill is exposed to the east of the shingle beach where great columns rise out of the sea at high tide. The rock here is a picrite which has almost the appearance of a dunite in the hand specimen, so numerous and fresh are the grains of yellowish-green olivine, but examination with a hand lens reveals the presence of white plagioclase

and plates of black poecilitic augite surrounding the orthosilicate. Where the rock is exposed to wave-action, there is no weathered crust, while elsewhere it is covered by a very thin dark-coloured skin or by lichen. The differential resistance to erosion of the plagioclase and augite causes pronounced carious weathering (PLATE VIIIa). The picrite is of medium grain, and us well exposed along the shore to a point 300 yards north of the shingle beach where it becomes buried under debris from which it does not again emerge. It is surprising that such acute observers ~~such~~ as Macculloch and Heddle should have failed to detect the presence of this striking ultrabasic rock. Veins of coarse pegmatite composed mainly of augite and felspar traverse the ultrabasic rock nearly everywhere, assuming a more or less vertical trend, and vary from one inch to ten in breadth (PLATE VIII).

As we pass upwards from the shingle beach, the rock is seen to assume a grey colour on the weathered crust, while examination of fractured surfaces shows that olivine becomes less abundant with every upward step, while augite and plagioclase show a complementary increase. There is, in fact, a gradual transition upwards from picrite at the beach, through dolerites rich in olivine (15 - 45 feet above the beach), into normal

olivine dolerite (or, more correctly, crinanite) above 45 feet. As we go still higher the olivine falls off steadily, but much more gradually, and is still quite recognisable in hand specimens from the highest visible portions of the sill. Not a trace of "schlieren" or other discontinuous variation is to be seen in the very complete exposures available. Continuing upwards from basic olivine dolerite into crinanite, we see that the augite begins to exhibit marked ophitic structure which becomes more pronounced the higher we ascend. In the upper parts of the sill huge ophitic plates measuring three inches across are of no uncommon occurrence, the crystals of felspar and of olivine being minute in comparison. Cavities filled with radiating fibres of zeolites are rare. All the other exposures of the sill in situ consist of crinanite like the above, showing no change other than a slight upward decrease in olivine.

The veins of pegmatite cutting the ultrabasic rock, but absent from the olivine-dolerite and crinanite of the type vertical section, have been already mentioned; there are, however, others occurring in the crinanite on the north-west shore of Eilean an Tighe near the rock named Sgeirean Mol na h-Aithadh. These latter veins are similar in appearance to the ones cutting the picrite, but follow a more sinuous course, and are

confined for the most part to the immediate neighbourhood of the Jurassic strata. Neither the normal crinanite nor the pegmatite shows chilling against the sediments. At this locality spherical cavities filled with acicular radiating zeolites are developed in strong force.

All the rocks of the sill are obviously exceedingly fresh, but it is a matter of some difficulty to collect satisfactory hand-specimens as the rock is seamed with irregular cracks in every direction, and tends to split along them. So numerous are these cracks that the preparation of thin sections is far from easy, the slice tending to break up, especially during mounting.

(b) PETROGRAPHY.

Picrite.[1] Under the microscope the picrite presents a very striking appearance. Rounded grains of olivine make up the bulk of the rock (50 - 75%), and except for occasional anastomosing veins of serpentine and magnetite the mineral is unaltered. The grains have an average diameter of 0.5mm., but vary

[1] Although the rock described below contains over 20% of felspar the name 'picrite' has been given to it as the most suitable. The rocks are distinctly more basic than 'kylite' which appears to be the only other alternative name.

considerably in size and sometimes form large composite groups, though these are not common. In sections of normal thickness the mineral is practically colourless, but may, in thicker slices, show faint greenish-brown tints. The mineral is optically negative and has an axial angle of nearly 90°. The average refractive index was found by oils to be in the neighbourhood of 1.68, while $\gamma - \alpha$ measured by the Berek compensator gave the value .032. These results indicate a normal olivine containing 11 -13% FeO. The norm of the analysed rock confirms this determination (p.44). Numerous fluid inclusions are visible in the olivine, and occasional rounded grains of iron ore (usually about .05 mm in diameter) which is probably magnetite, as no chromium was recorded in the analysis.

The olivine is enclosed poecilitically by large crystals of augite and basic plagioclase, the felspar being the more abundant. The pyroxene is purplish-brown in colour with very feeble pleochroism; $\gamma - \alpha$ is .024 by the Berek compensator, while the extinction angle $Z \wedge c$ is 44°. This augite forms large crystals measuring up to 1 cm. in length, which show idiomorphic boundaries towards the felspar.

The plagioclase crystals are equal in size to those of the pyroxene, and though usually perfectly fresh, may be partly replaced by serpentinous matter derived from the incipient decom-

position of the olivine. The twin lamellae extinguish symmetrically at angles well over 40°, and β was found by oils to be 1.575 - .005, which indicates bytownite (Ab_3An_4).

Except for a few rounded grains of magnetite, and small needles of apatite, the only other constituents are doubly refracting zeolites forming thin veinlets in the rock, and which will be considered with the pegmatite veins.

Although the average section contains about 60% of olivine, the proportion may increase locally up to 75%, and this more basic variety is probably the one referred to as dunite by Judd the resemblance to that rock in the hand-specimen being quite striking. A complete analysis of the average picrite together with the mode is given below.(p.44)

Olivine dolerite. The picrite gradually gives place upwards to a basic olivine-dolerite containing on an average about 30% of olivine, the transition from this rock to picrite being complete in about 10 feet. This decrease in the proportion of the orthosilicate is accompanied by a striking change in the habit of the augite and felspar.

The pyroxene in the dolerite assumes a very marked ophitic habit, and encloses numerous laths of the plagioclase, but the size of the augite crystals and their optical properties remain unchanged, apart from a tendency towards zonary banding. The

felspar, however, is considerably less calcic, the symmetrical extinction angles of the albite lamellae corresponding with a basic labradorite (Ab_1 An_3). The laths are elongated and much smaller than those in the picrite, rarely exceeding .5 mm. in length.

In the case of the olivine no change is seen in the optical properties, and it is often enclosed poecilitically by augite, but the crystals vary greatly in size though they always retain their rounded outline. The largest and smallest grains measure respectively 3mm. and .05mm. in length and the mineral still contains both fluid inclusions and rounded grains of magnetite. Some crystals of the iron ore, which is probably titaniferous, have, however, assumed a skeletal habit.

The only other constituents of the rock are apatite in inconspicuous needles, a few patches of interstitial analcite, and still rarer crystals of reddish-brown barkevikitic amphibole usually associated with the zeolite or iron ore.

While the rock is ordinarily very fresh, there may be slight alteration of the olivine to magnetite, serpentine and iddingsite. A complete analysis and mode of this transition type between picrite and crinanite is given below.(p.44). The rock seems to correspond fairly well with the published description

of the type named kylite by Dr. G. W. Tyrrell[1], but is somewhat less alkaline, and contains zeolites instead of nepheline.

Crinanite. The picrite at the south of Garbh Eilean begins to pass into olivine-dolerite ten feet above the shingle beach, and the latter rock persists upwards with a steadily diminishing proportion of olivine for 75 feet, above which level it is best described as 'crinanite'. This crinanite extends, with a very gradual upward decrease in the proportion of olivine, to the highest visible part of the sill, and is the only type encountered on Eilean-an-Tighe. The lower part of the crinanite contains 12 - 16% of olivine of very different appearance from that in the olivine-dolerite and picrite. In the crinanite, the mineral is often decicedly ophitic, enclosing numerous laths of plagioclase (PLATE X fig.4), while widely separated fragments have the same optical orientation. Some crystals, too, are greenish-brown in colour, and it was thought at first that they were highly ferriferous and a variety of hyalosiderite, if not of fayalite[2]. The coloured mineral is optically negative with an axial angle of nearly 90°, but $\gamma - \alpha$ measured by the Berek compensator proved to be .032, which is exactly

[1] Geol. Mag., 1912, p.121.

[2] c.f. Judd, Q.J.G.S., 1885, p.394.

the value obtained for the colourless mineral of the picrite and olivine-dolerite, and indicates an olivine of quite normal character. The colour, then, is not due to a high content of ferrous oxide, but probably to incipient general serpentinisation. Some crystals are colourless at one end, while the other is a distinct greenish-brown. In view of the high titania content of the rock (2.86%) it is just possible that the coloured olivine may be a variety of titanolivine such as is described by Lady McRobert[1] from the analcite dolerite of Penal Heugh, but this is unlikely, as numerous Tertiary basalts and dolerites with even higher proportions of titania contain perfectly normal olivine. The percentage of olivine falls off to 8% in the upper parts of the sill, and occasionally the serpentinisation is more advanced there (PLATE XI fig.6), but the mineral is never completely altered. It is invariably enclosed by augite when the two minerals come into contact.

The ophitic relationship between plagioclase and augite is even more pronounced than in the olivine-dolerite. In some cases the ophitic 'clusters' of pyroxene measure 6 - 7cm. in length and frequently occupy the whole of a section (2 by 3cm.) These pyroxene 'clusters' scarcely ever exhibit crystal boundaries, but often show well-marked zoning changing from a pale

[1] Trans. Edin. Geol. Soc. vol.XI, p.101.

purplish-brown tint at the centre to a strong purple-madder or reddish- brown at the margin. Where outlying portions of the clusters come into contact with acid plagioclase or zeolites, the aegirene molecule enters into their composition and they assume a greenish tinge. The maximum extinction angle of the titanaugite is 43° (Z ∧ c), and when the mineral is viewed under the highest powers, the fluid inclusions figured by Judd[1] become visible.

The plagioclase has the same habit as in the underlying olivine-dolerite, but the symmetrical extinction angles of 35°, and mean refractive index by oils (1.565 ± .003) indicate a medium labradorite ($Ab_2 An_3$). A very few phenocrysts of plagioclase with the above properties may also occur. Zoning is always present, but varies in amount, oligoclase ($Ab_1 An_1$) being the most acid variety detected. Orthoclase was not found, a fact which is not surprising when the small proportion of potash in the rock is considered (.40%). Analcite and natrolite are, however quite common, and fill many of the interspaces between the felspars outside the pyroxene clusters. The analcite is generally fresh, but sometimes shows alteration to brown decomposition products, and in many cases possesses stronger anomalous double refraction than usual. It presents idiomorphic boundaries to-

[1] Q.J.G.S., 1885, plate XI fig. 1.

wards the natrolite when the two minerals come into contact. The natrolite occurs in radiating fibres with positive elongation, and double refraction slightly above that of quartz. Analcite is usually the more abundant of the two zeolites.

The iron ore of the crinanite appears to be ilmenite, which is both conspicuous and abundant, forming large skeletal crystals up to 3mm. across; and small needles of apatite are ubiquitous.

The ophitic structure of the augite in the crinanite seems comparable with the 'ophimottling' described by Mr. E. B. Bailey[1] in the early basic cone-sheets of Mull. There is the same zoning of the augite, refusal of the mineral to exhibit crystal boundaries, and confinement of the olivine to areas between the augite-felspar clusters. The felspars within the clusters are less zonal than those in the interspaces, and it is probable that here, too, "the relatively early date of the augite is obscured by its almost complete refusal to show crystal boundaries The crystallisation of the olivine is also thought to be coeval with that of the felspar, in spite of its ophitic habit, and the significance of these conclusions will be discussed when the cooling-history of the intrusion is considered below.

[1] Mem. Geol. Survey Scotland; Tertiary Geology of Mull, 1924, p. 240.

Eilean an Tighe. Crinanite practically identical with that of Garbh Eilean makes up almost the whole of Eilean an Tighe, but the pyroxene occasionally shows minor differences. Sections from the summit of the island contain an almost colourless augite, while others from a lower position in the sill show a strongly coloured zonal mineral which is pleochroic in tints of reddish-brown and purple. Greenish soda-pyroxene is, on the whole, commoner than on Garbh Eilean, and a fibrous zeolite may be observed in places towards which the analcite is idiomorphic. It is brownish in colour, has lower double refraction and a higher refractive index than natrolite, and is probably stilbite.

A specimen of the crinanite taken from the south face of Garbh Eilean 125 feet above the shingle beach has been analysed by Mr. Radley, and the result is given below (p.44), together with the mode of the rock.

Pegmatite Veins in Picrite. The pegmatite veins which traverse the picrite of the sill exhibit great variety both in texture and in mineralogical composition. Several distinct rock types may be encountered in a single vein, presumably representing infillings at different stages during the crystallisation of the sill, for there is nowhere any trace of chilling of one variety against another. The felspathic portion of all the veins has suffered more or less decomposition through hydrothermal processes.

The first infilling, which occupies the margins of some of the large veins, crystallised out as a coarse-grained teschenitic rock rich in titanaugite. In this modification the pyroxene is idiomorphic, but has the same optical properties as that of the crinanite. It builds large prisms ranging up to 5mm. in diameter and 2cm. in length. These are accompanied by skeletal crystals of ilmenite, often .5cm. across, which have reacted with the magma to form flakes of biotite, and by a few elongated crystals of serpentinised olivine. The felspathic portion of the rock has been completely replaced by zeolites, amongst which analcite and natrolite are conspicuous, the former being invariably the first to crystallise. Apatite is a conspicuous accessory, forming needles up to 1mm. in length. This variety of infilling, before it underwent zeolitisation, must have been very similar to the veins, described below, near the Jurassic strata of Eilean an Tighe.

The second variety to be described sometimes occupies the centre of the composite veins along with the third. It is clearly of later date than the first variety, is distinctly finer in grain, and poorer in dark minerals. Augite similar to that of the first type is the most conspicuous constituent. Sometimes, however, it assumes a decidedly pink tinge and shows zoning with well developed hour-glass structure.

This pyroxene comprises about 20% of the rock, builds elongated idiomorphic prisms up to 3mm. in length and .8mm. in diameter, the crystals sometimes radiating outwards from a common termination. Rare elongated prisms of olivine also occur, but have generally undergone almost complete alteration to serpentine. Skeletal crystals of ilmenite make up over 5% of the rock and are exceedingly conspicuous. The felspar is mainly plagioclase (andesine-labradorite), frequently showing pericline twinning, in tables up to 2mm in length, but a good deal of soda-orthoclase is also present. Clear analcite is abundant and frequently replaces felspar, the alteration being, however, much less complete than in the previous variety. Apatite is an abundant, but not very conspicuous, accessory.

The third variety is still more felsic, and probably of later infilling, than the second. Augite, similar in habit to that in the preceding modification but considerably paler in colour, is the chief mafic constituent. Occasional idiomorphic crystals of olivine, generally serpentinised, are to be seen, as well as small crystals of titaniferous magnetite. The felspar is recognisable only as 'ghosts' up to 5mm in length, but was probably acid plagioclase: it has been completely replaced by analcite and natrolite, which also occur in interstitial areas; the former mineral, as always, being the first to crys-

tallise. Natrolite has also replaced analcite in some cases, and occurs as well defined icositetrahedra composed of radiating fibres.

There are, however, several other exceedingly alkaline constituents in the rock. Characteristic hexagonal or rectangular pseudomorphs after nepheline are of frequent occurrence, and occasionally a scrap of the fresh mineral with its straight extinction, low double refraction, and negative sign, may be observed. The mineral varies in its relations towards the felspar, but is generally idiomorphic. There are also small scraps of soda-bearing ferromagnesian minerals such as biotite, aegirine, barkevikite, and arfvedsonite, which appear to have been formed by reaction of the ~~zeolites~~ sodic residuum with the iron ore, as they are commonly associated with the latter. Large needles of apatite are usually very conspicuous.

The zeolitisation which all the infillings have undergone probably occurred during the last stage in the crystallisation of the crinanite, when the aqueous residuum was expelled through the picrite, using the pegmatite veins as channels. This will be discussed later, however, under the differentiation of the sill. Traces of this expulsion may be noticed in the thin zeolitic veins so often seen in sections of the picrite, and seldom measuring over .3mm across. These have been forced through

the ultrabasic rock under pressure, as olivine crystals are often seen to have broken in two, one half remaining on either side of the vein. Occasionally, in the neighbourhood of these veinlets, the picrite is seen to contain pyrites, and the presence of rare crystals of reddish-brown soda-hornblende may be accounted for by reaction between the sodic residuum and olivine[4].

The profound alteration which these pegmatitic modifications have undergone renders the measurement of their percentage mineral composition unprofitable. They are all extremely felsic in character, the dark minerals varying from 30% to 10%.

P Pegmatite veins in crinanite of Eilean an Tighe. Numerous pegmatite veins, usually not more than two inches across, pursue sinuous courses through the crinanite of Eilean an Tighe adjacent to the Jurassic beds in the bay south of Sgeirean Mol na h-Athadh. These veins are coarse in texture, containing large prisms of augite which reach a length of 2cm or more. Under the microscope this mineral is the most conspicuous constituent of the rock. It is sub-ophitic towards the equally large plagioclase laths, and is purplish-brown in colour like

[4] c.f. G. W. Tyrrell, Arran Memoir, 2nd edition, 1928, p.120, slice 24356.

the pyroxene of the crinanite. The pleochroism is usually quite distinct, the tints being: X purple, Y greenish-brown, Z brownish-purple. Occasionally a small content of the aegirene molecule imparts a greenish tinge to this pyroxene, and traces may be seen of the early crystallisation of an almost colourless diopsidic pyroxene presenting sharp boundaries towards the surrounding pink variety, both, however, having the same optical orientation. Elongated crystals of fresh, or partially serpentinised, olivine are also conspicuous, and measure up to 1cm in length, but are surpassed in size by abundant crystals of skeletal ilmenite.

The felspar occurs in long laths which may be as calcic as acid labradorite ($Ab_1 An_1$) at the centre, but become progressively acid towards the margin, which is usually oligoclase. This felspar is replaced by analcite along many of the cracks. The interspaces between the felspars are filled partly by clear isotropic analcite, and partly by dark brownish indeterminable mesostasis which probably consists largely of devitrified glass and is extremely sporadic in its occurrence: it contains microlites of felspar, and appears also to be rich in iron oxide. Natrolite and analcite are rare constituents occupying spherical cavities in the mesostasis; while apatite is an abundant accessory. Both the pegmatite and crinanite show ill-defined, un-

chilled boundaries against the adjacent Jurassic strata. In the neighbourhood of the pegmatite veins the crinanite is spotted with spherical cavities up to half an inch in diameter filled with radiating fibres of natrolite, while close to the junction with the Jurassic strata the olivine assumes a definitely granular habit.

(c) MODES OF VARIOUS TYPES.

The percentage mineralogical composition, or mode, of many of the types described above was calculated by means of the Shand recording micrometer, the results being quoted below:-

	A	B	C	D	E	F	G
Olivine	59	31	20	12	11	8	6
Augite	10	17	21	24	29	24	38
Plagioclase	26	50	54	60	54	61	38
Iron ores	2	2	3	3	4	4.5	11
Zeolites	3	-	2	1	2	2.5	7[a]

A. Picrite from base of cliffs at extreme south of Garbh Eilean, see PLATE X Fig.1.

B. Basic olivine-dolerite, 30 feet higher in sill than A, see PLATE X Fig.2.

[a] Includes mesostasis.

C. Crinanite, 70 feet higher in sill than A, see PLATE X Fig.3.
D. Crinanite, 125 feet higher in sill than A, see PLATE X Fig.4.
E. Crinanite, 250 feet higher in sill than A, see PLATE XI Fig. 1.
F. Crinanite, 400 feet higher in sill than A, see PLATE XI Fig.2.
G. Pegmatite vein in crinanite in bay south of Sgeirean Mol na h-Athadh, see PLATE XI Fig.3.

The large size of the ophitic minerals in most of the above types renders micrometric analysis somewhat unreliable, especially in the case of the crinanites, where a crystal of augite may extend over an entire section. For this reason the results have been given only to the nearest integer, and apatite, which does not make up one per cent of any of the rocks, has been omitted.

Note for the Author.

The "norm" of III, containing both nepheline & hypersthene, cannot be correct. Nepheline & hypersthene are equivalent to albite & olivine.

ANALYSES.

	I	A	II	B	III	C	D
SiO_2	47.83	47.64	45.07	43.30	40.62	40.90	45.8
TiO_2	2.86	1.27	.83	2.44	.82	1.70	2.4
Al_2O_3	15.31	14.15	14.43	12.71	8.93	7.56	15.0
Fe_2O_3	1.15	5.18	.80	2.35	.57	3.01	3.8
FeO	9.22	7.96	10.69	7.60	12.61	7.31	9.5
MnO	.36	.33	.33	.19	.39	.34	.3
(Co,Ni)O	.02	tr.	.02	-	.03	-	-
MgO	6.60	7.38	14.61	14.65	26.31	29.63	8.2
CaO	12.38	11.71	9.74	10.50	5.64	5.40	9.4
BaO	n.f.	n.f.	.01	-	n.f.	-	-
Na_2O	2.53	2.38	1.75	.96	1.32	.98	2.5
K_2O	.40	.71	.34	.22	.13	.37	.5
H_2O+	1.28	1.44	1.05	4.27	2.19	2.98	1.8
H_2O-	.28	.19	.35	.33	.61	.13	.9
P_2O_5	.16	.09	.10	.11	.15	.10	.2
CO_2	.05	-	.02	-	.03	-	.3
Cl	.01	-	-	-	.01	-	-
etc.	-	.10	-	.08	-	.11	-
Totals	100.44	100.53	100.14	99.71	100.36	100.52	100.3

NORMS.

	I	II	III
Orthoclase	2.2	1.7	.6
Albite	21.0	14.7	-
Anorthite	29.5	30.6	18.1
Nepheline	-	-	6.0
Diopside	25.4	13.5	7.3
Hypersthene	6.2	.8	9.1
Olivine	7.1	33.9	53.6*
Magnetite	1.9	1.2	.9
Ilmenite	5.5	1.5	1.5
Apatite	.3	.3	.3

* forsterite 39.5
fayalite 14.1

I. Crinanite; south face of Garbh Eilean, 125 feet above shingle beach. Anal. E.G.Radley. (PLATE X fig.4.)

A. Dolerite Cone-Sheet; Cuillins, Skye. Anal. W.Pollard. Quoted from Mull Memoir, p.15.

II. Olivine-dolerite; south face of Garbh Eilean, 30 feet above shingle beach. Anal. E.G.Radley. (PLATE X fig.2.)

B. Olivine-dolerite apophysis from peridotite dyke; Sgurr na Banachdich, Skye. Anal. M.G.Keyes. Quoted from N.L.Bowen, 'Evolution of Igneous Rocks', 1928, p.154.

III. Picrite; south face of Garbh Eilean at shingle beach. Anal. E.G.Radley. (PLATE X fig.1.)

C. Peridotite dyke; Coir' a' Ghreadaidh, Skye. Anal. M.G. Keyes. Quoted from N.L.Bowen, loc. cit. supra.

D. Average plateau-basalt magma-type. Quoted from Arran Memoir 2nd edition, 1928, p.121.

Of the above analyses, I, II, and III were made for the writer by Mr.E.G.Radley through the good offices of Sir John Flett and Dr.H.H.Thomas, who very kindly interested themselves in the work. A fourth analysis of a type from Eilean Mhuire was also made by Mr.Radley, and it is scarcely necessary to point out that these four excellent analyses have proved a valuable addition to the petrology of the group.

The crinanite of Garbh Eilean is distinctly more acid than any example hitherto analysed, and finds its nearest analogue in analysis A of the dolerite cone-sheet from the Cuillins. In spite of its slightly higher magnesia content, the Skye rock does not appear to contain olivine.[1]

[1] Skye Memoir; p.370.

Analysis II, of the olivine-dolerite, can be matched only by a slightly more basic type, also from the Cuillins, stated, however, by Bowen, to contain only 16% of modal and normative olivine[1].

Analysis III, of the picrite, can be matched alone, fairly closely, by a peridotite -- again from the Cuillins -- which contains 55% of normative olivine[2].

The average composition of the 'plateau-basalt magma-type' has been calculated by Dr.Tyrrell, and is given under D. On comparing this average with analyses I, II, and III, it will be seen that the orinanite is more acid, while the olivine-dolerite and picrite are more basic than the plateau magma-type. It is further apparent that the sinking by gravity of iron ore and olivine crystals of normal composition from a magma corresponding in composition to the more acid examples of the plateau-magma type[3] could produce the basic types of analyses II and III, while the upper part of the magma basin might well correspond in composition to analysis I, except in the case of the alkalies which would be lower in I. This deficiency in alkalies in the case of the Shiant rock might well be caused by the expulsion of the last alkaline residuum of the magma through the picrite in the manner described above.

[1] Op. cit., p.155. [2] Bowen, op. cit., p.153.

[3] e.g. analysis A, and Mull Memoir, p.15, D.

The case for gravitational differentiation in the great Shiant sill will be considered in detail below.

SPECIFIC GRAVITIES.

Eilean an Tighe	Summit (400 feet)	2.95
	Lowest visible point of sill . .	2.98
	Pegmatite by Jurassic strata . .	2.92
Garbh Eilean, S.face; heights above shingle beach.	400 feet	2.94
	250 feet	2.95
	125 feet	2.97
	70 feet	3.00
	45 feet	3.02
	30 feet	3.03
	15 feet	3.09
	0 feet	3.11

All the above measurements were made with exceedingly fresh material, and are therefore trustworthy. The heights given, in the case of 45 feet and above, were obtained by aneroid, and are accurate to the nearest ten feet. Those below 45 feet were interpolated by visual estimation with a probable error of ±5ft.

(d) DIFFERENTIATION OF THE SILL.

The writer believes that the picrite-crinanite sill of Garbh Eilean and Eilean an Tighe provides a singularly clear demonstration of crystallisation differentiation unique in the British Tertiary province at least. The gravitational settling of early-formed olivine crystals is thought to be the first and most important phase, and will now be considered.

Although the theory of gravitational differentiation of a magma through the settling of early formed crystals was initiated by Charles Darwin, it gained little support until the present century, notwithstanding its favourable consideration by such eminent petrologists as Teall and Loewinson-Lessing. During the last twenty-five years, however, numerous examples of the settling in igneous masses of early formed minerals, such as olivine and augite, have been described from all parts of the world; while in 1915 the theory received a distinct fillip through the brilliant experimental work of Dr.N.L.Bowen, who was able to demonstrate the settling of olivine and pyroxene in artificial melts in a platinum crucible[1]. An examination of the literature of natural occurrences indicates that even the best known type examples possess some features which prevent

[1]Amer. Jour. Sci., 1915, vol.XXXIX, pp.175-191.

them from being entirely convincing. Other processes of differentiation, or subsequent intrusions, may, for instance, conspire to confuse the issue. The brief consideration of a few cases will demonstrate this point, and will form a useful introduction to the discussion of the Shiant sill.

The Palisade Diabase sill of New Jersey and New York is generally considered to be one of the best examples of differentiation through the settling of early formed olivine and pyroxene. This great intrusion reaches a maximum thickness of 1000 feet, is excellently exposed mainly in railway tunnels and cuttings, and has been admirably described by Professor J.V. Lewis[1]. The bulk of the sill consists of a granophyric quartz-dolerite without olivine, which becomes more basic downwards until scattered olivines make their appearance and quartz fails. This latter modification shows (generally) a sharp junction with a 'ledge' of dolerite 10 - 20 feet in thickness containing over 15% of olivine. The olivine-dolerite ledge gives place downwards to a contact facies 40 - 50 feet thick, the two phases having, usually but not always, a sharp junction. A similar contact facies, passing gradually into coarse quartz-dolerite, is seen at the top of the sill, and both contain scattered crystals of olivine. Lewis' descriptions are accompanied

[1] Annual Rep. of State Geologist of N.J. for 1907, pp. 103-137.

by a series of excellent photographs, chemical analyses, and modes.

The olivine-dolerite ledge is considered by Lewis[1] to have been formed by the sinking by gravity of olivine crystals, the increasing viscosity of the magma preventing any considerable movement of the pyroxene and felspar after crystallisation. Fenner[2] attributes the sharp junction of the ledge and the upper dolerite to the sudden cessation of the crystallisation of olivine; while Bowen[3] argues convincingly from Lewis' figures that augite was also concentrated by gravity towards the bottom of the sill. None of the three petrologists attempts to explain why the contacts of the ledge should be sometimes sharp and sometimes more gradual, nor accounts for the presence of irregular streaks and masses of rock similar to the contact facies, and also of quartz-dolerite, within the olivine-dolerite ledge[4]. Apparently the possibility of the olivine-dolerite ledge being introduced by subsequent intrusion before the normal dolerite had cooled has never been considered.

The great Moyie Sills of British Columbia show a striking variety of composition from biotite granite to hypersthene or

[1]Op. cit., pp.130-31.

[2]Jour. Geol., 1926, pp.747-48.

[3]Op. cit., p.73.

[4]Lewis: op. cit., p.126.

hornblende gabbro, and have been described by Professor R.A. Daly,[1] and later by Dr.S.J.Schofield[2]. These two authors are, however, at variance as to the part which assimilation has played, and to the number of intrusions in the group, though they unite in ascribing a large part of the differentiation to settling of ferromagnesian minerals by gravity. The gabbros, however, often show a good deal of banding. Schofield's evidence, which is against appreciable assimilation, appears to be the more convincing.

The Triassic lava flows of Cape d'Or, Nova Scotia provide an interesting case of differentiation carefully studied by Drs. S.Powers and A.C.Lane[3] under almost ideal conditions, for two bores were sunk through the series, the entire journals being available for examination. The lowest, or Cape Spencer, flow is 556 feet thick, and has received the most attention. The magma is a basalt without olivine, except at the rapidly cooled top, and the authors find that there is a concentration of augite in the lower part of the flow. This, they consider, is brought about by sinking of ~~olivine~~ augite crystals and floating of felspar; but in the discussion of the paper, Bowen attributes the differentiation to the settling of the pyroxene alone. A

[1] Geol. Survey Can., Ann. Rep. 1904, p.91 A et seq.

[2] Geol. Survey Can., Museum Bull. No.2, 1914, pp.1-34.

[3] Trans. Amer. Inst. Min. Eng., Bull.110, 1916, pp.535-48.

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series of five analyses of specimens from different levels in the sill is given, but their uniformly low summation is to be regarded with suspicion; and a very complete set of modes has been made by Rosiwal measurements. These show 'tendencies' only, and are not of great quantitative value, for the gravitational settling of olivine is confused and obscured by flow banding, the occurrence within the flow of schlieren, and of engulfed portions of the crust. The range of silica percentage is very small, being less than 1.5%.

The Iniszwa and Tabankulu intrusions of Pondoland, South Africa[1] show a marked increase of basicity from top to bottom. The first named is a sheet 2000 - 3000 feet in thickness, and varying from olivine-free gabbro at the top to picrite at the b bottom. Veins of granitic composition traverse the lower part of the gabbro in all directions, and are sometimes mineralised. The slides are stated by Dr.A. du Toit, who has described the sheet, to show, with one exception, a gradual decrease in basicity from bottom to top. This exception appears to be the occurrence together, 500 feet above the base, of foliated olivine-gabbro (S.G.3.06) with parallelism of felspars and ferromagnesian minerals, and augite-picrite (S.G. 3.23) with over 50% of olivine. This would appear to indicate movement in the

[1] Cape of Good Hope: Department of Mines, Ann. Rep. 1910. p iii.

mass during crystallisation. Four unsatisfactory analyses accompany the description. Du Toit attributes the differentiation to gravitational settling of early-formed crystals, but although this is the dominating factor, other processes seem also to have been in evidence.

The Tabankulu and Tonti masses, which have also been described by Dr. du Toit, are relics of a huge irregular sheet, and the former shows strikingly the effects of gravitational differentiation. A 800 foot picrite zone at the base is sometimes separated by 100 - 150 feet of olivine norite from the underlying sediments, or may rest directly upon them. This ultrabasic rock passes gradually upwards into olivine-gabbro and olivine-norite, which become more felspathic towards the top. The mass is veined by acid material and contains numerous "schlieren," again indicating movement during crystallisation, while the specific gravity varies from 2.915 in the case of the summit norite, to 3.275 in the picrite. No analyses are given.

The Ring-dyke of Glen More provides the most striking of the eleven instances of gravitational differentiation described in the great Mull Memoir[6]. On the slopes of Cruach Choireadail a gradual transition is seen from granophyre at the summit, with over 68% SiO_2, to olivine-bearing quartz-gabbro (with under 50%

[6] Mull Memoir, pp. 323-330.

SiO_2) in the valley 1500 feet below. There is also a marked downward increase in apecific gravity from 2.55 to 3.08. The description is accompanied by a very complete chart of specific gravities and by four excellent analyses[1]. The only case of discontinuous variation is the occurrence of horizontal acid veins, sometimes 3 or 4 feet thick, intersecting the more basic lower portion of the mass. It will be noticed, however, that the specific gravities given in the map (fig.54) do not increase regularly downwards, but show curious oscillations, e.g. a specimen from 1300 feet gives the value 2.92, while one from 1125 feet gives 2.69. These variations, of which no explanation is given, are possibly due to the inclusion of occasional altered specimens in the suite.

The authors (Dr.H.H.Thomas and Mr.E.B.Bailey) ascribe the differentiation to the gravitational settling of early formed crystals followed by an extensive upward migration of acid residuum. This migration of the residual fluid appears from the description to have been accompanied by a good deal of auto-intrusion in the lower part of the mass.

The Picrite-Teschenite Sill of Lugar in Ayrshire has been admirably described in great detail by Dr.G.W.Tyrrell[2], who makes out a strong case for gravitational differentiation

[1] Mull Memoir, p289. [2] Q.J.G.S., 1917, pp.84-131.

through settling of olivine and augite crystals in the central portion, which shows sharp junctions with teschenitic margins above and below. In the central portion a gradual transition downwards from theralite (S.G.2.84) through picrite to peridotite (S.G.3.01)is seen. The remarkable analcitic rock, lugarite, forms a band intrusive into the picrite, while all types occur in 'schlieren' indicating movement during crystallisation. Dr.Tyrrell evidently considers that much of the differentiation took place prior to intrusion, postulating liquation to account for the teschenitic margins; but it is doubtful how many successive intrusions form the sill. A very complete series of modes and excellent analyses of the theralite and peridotite accompany the description. Although the gravitational settling is confused by other factors, it is interesting to note that it can take place in an intrusion only 140 feet in thickness when the magma is sufficiently aqueous and mobile.

Several other picrite-teschenite sills in the Central Valley of Scotland show a similar type of differentiation which has recently been accounted for convincingly by Mr.Bailey[1].

The above examples, which may be taken as representative of the literature of gravitational differentiation, display some

[1] N.L.Bowen: 'Evolution of Igneous Rocks', 1928, pp.173-4.

features in common. All the intrusions or flows, except the Lugar sill whose magma was abnormally aqueous and mobile, are exceedingly thick; and slow cooling, ensuring a long period of fluidity, appears to be a sine qua non of this type of differentiation. It will also be noted that all six examples show discontinuous variation, usually by the occurrence of 'schlieren' or banding. This may be due, as in the Lugar sill, to differentiation prior to intrusion or more probably, as Bowen[1] has suggested, to intrusion during crystallisation of the more liquid portions of the magma into rifts in the crystal mesh. Tyrrell has recently developed this latter hypothesis in connection with the crinanite-analcite-syenite sills of Ayrshire[2], and it is applicable with equal pertinence to a similar sill on Eilean Mhuire, as will be seen below. There can be no doubt, at any rate, that the above processes tend to obscure the variation caused by the gravitational settling of early-formed crystals, and the ideal case of this type of differentiation is one where the magma has been intruded (or extruded) in a completely liquid condition, and where no deformation of the mass takes place during cooling. Such a case is, of course, impossible of realisation, for in a lava flow there will always be movement during crystallisation, while in an intrusion there will always

[1] Jour.Geol., 1919, pp.417-22.

[2] Q.J.G.S., 1928, pp.565-6.

be deformation due to the pressure exerted by the overlying cover. It is hoped, however, to show that the crinanite-picrite sill of Garbh Eilean and Eilean an Tighe makes a close approximation to the ideal.

A continuous variation should be shown in all cases of gravitational differentiation (the chilled contacts being excluded) unless the sinking constituents ceased to crystallise at an early stage while the magma was still quite fluid. In this latter case a layer consisting chiefly of the sinking minerals would be formed at the bottom of the mass and would have a relatively sharp contact with the upper part, as in parts of the Palisade 'diabase'. If, however, the heavy minerals continued to crystallise until the magma became (gradually) too viscous to permit of further sinking, then a continuous increase of specific gravity, together with a corresponding rise in the proportion of the sinking minerals, would be seen from top to bottom of the mass. This is beautifully illustrated in a microphotograph of a vertical section of the melt in which Bowen[1] demonstrated gravitational sinking of crystals in the laboratory. No contacts are seen in the Shiant sill, but the most complete section of the intrusion, whose lowest exposures must closely approach the lower contact, shows a wonderfully con-

[1] Amer.Jour.Sci., vol.XXXIX, 1915, p.178.

tinuous increase in the proportion of olivine (the only mineral to sink appreciably) from top to bottom, while the corresponding rise in specific gravity is, if anything, still more striking (pp.44,47). These two features are brought out clearly in two graphs (figs. 1 and 2) where height above the visible base of the sill is measured along the abscissae, and specific gravity or percentage of olivine along the ordinates. The smoothness of the specific gravity curve is particularly noteworthy, any slight divergence of the points from it being more than accounted for by the probable error in estimating the heights*. The normative olivine of the three analyses shows a similar downward increase when plotted against the height (fig. 3). It has already been mentioned that there are no 'schlieren' or banding in the sill, the only discontinuous variation being the occurrence of the thin pegmatite veins by which residual magma was expelled at several stages during crystallisation.

That olivine was the only mineral to sink appreciably is shown by the comparative constancy of the ratio of the properties of the other two major constituents -- augite and plagioclase. The divergencies from the mean ratio show no regular tendency (fig. 4), and may be fully accounted for by the

*The crinanite of Eilean an Tighe also shows a slight downward increase in specific gravity (p.47).

Fig 1.

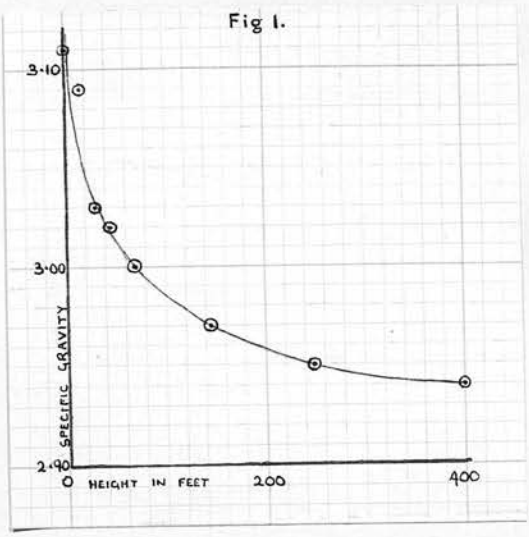


Fig 2.

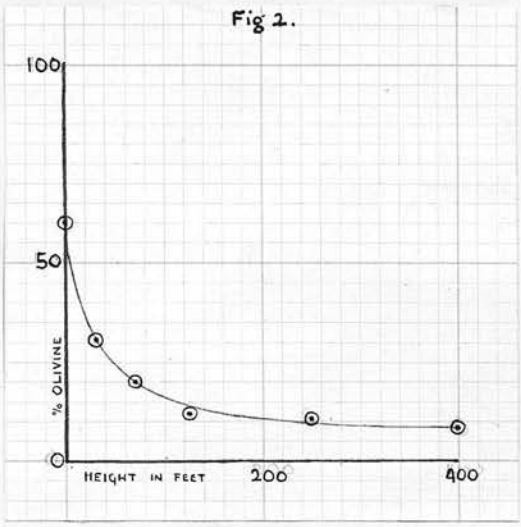


Fig 3.

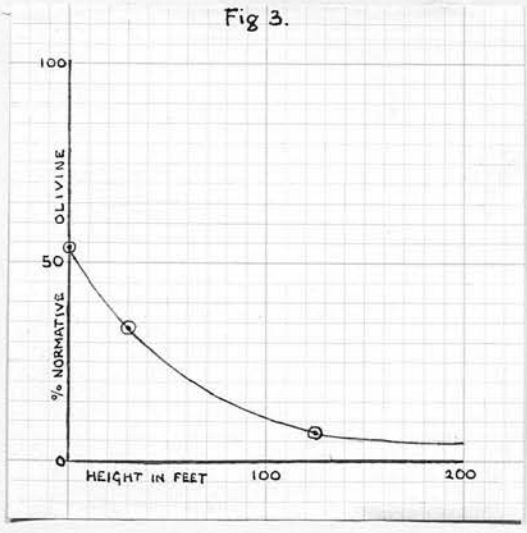
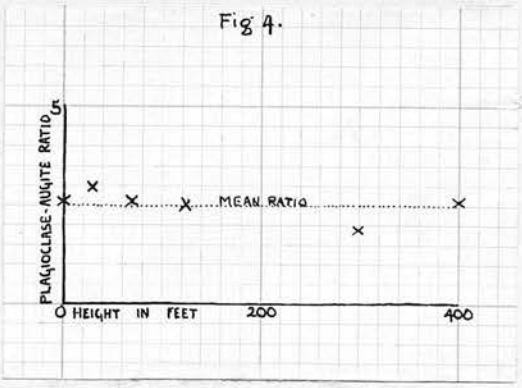


Fig 4.



errors of the micrometric method of estimating the mode. It is obviously a very difficult matter to obtain accurate figures when the whole of a large rock section may be occupied by a single augite-felspar cluster, even if several slices are measured. Had there been any sinking of pyroxene crystals, a concentration of that mineral would have occurred in and above the picrite zone, with a corresponding fall in the augite-plagioclase ratio. The texture of the rocks, too, indicates that pyroxene commenced to crystallise at a distinctly later period than the olivine.

The Cooling History of the Sill may now be considered. The first stage is the intrusion of a magma of normal crinanitic composition in an almost completely fluid condition, as the extreme rarity of phenocrysts testifies. As the temperature fell olivine began to crystallise, and by virtue of its high specific gravity was able to sink in the fluid magma. An accumulation of olivine crystals was thus formed near the bottom of the sill. There was probably a slight fall of magnetite crystals at the same time, but their small size militated against sinking. The variation in the size of the olivine crystals in the more basic types is considered to be due to growth during settling. A similar variety of size is seen in sinking fors-

terite crystals in one of Bowen's[1] artificial melts . The crystals of olivine in the picrite are distinctly smaller than the majority in the overlying olivine-dolerite, this being due to the smaller distance travelled before coming to rest and consequent limitation of the opportunities of growth[2].

While the olivine still continued to crystallise, basic plagioclase and augite made their appearance, but their mode of crystallisation was very different. In the picrite zone they certainly both formed large plates which enclosed poecilitically the closely packed mass of olivine crystals at a comparatively early stage, but above, where chemical (and probably physical) conditions were different, the plagioclase had a distinct tendency to crystallise out in small well-formed laths, while the pyroxene obstinately refused to show crystal boundaries, forming large clumps which enclosed numerous plagioclase crystals. These pyroxene-felspar clusters make up the bulk of the crinanite and much of the olivine-dolerite. Olivine, meanwhile, continued to crystallise, but its power to sink vanished as the magma became more viscous and full of crystals. It was then

[1] Amer. Jour. Sci., vol.XXXIX, 1915, p.179.

[2] N.L.Bowen, Loc. cit. p.177.

partly enclosed by the pyroxene-felspar clusters, or if it persisted in its crystallisation to a late stage as it did in the crinanite, ophitic olivine-felspar clusters were formed in the same manner as the pyroxene-felspar examples. The later olivine of the crinanite rivalled, indeed, the pyroxene in its obstinate refusal to form crystal boundaries, and in the upper portions of the crinanite the olivine-felspar clusters reach a diameter of over half an inch.

There does not appear to have been any perceptible change during crystallisation in the composition of the olivine, but while the first pyroxene was practically colourless, the outer zones, in places at least, are distinctly purple and probably titaniferous. The plagioclase, also, shows distinct zonary banding -- especially outside the pyroxene-felspar clusters -- varying from basic labradorite to oligoclase. In the olivine-dolerite and picrite the iron ore is magnetite of early crystallisation occurring in small grains, but in the crinanite it is ilmenite which assumes a characteristic skeletal habit. It is frequently enclosed in pyroxene-felspar clusters, however, and is probably, therefore, another mineral to crystallise out at an early stage.

The latest stages of crystallisation are seen between the ferromagnesian-felspar clusters in the shape of acid plagio-

clase round the margins of basic laths, and finally, in interstitial analcite and natrolite which represent the thoroughly aqueous and sodic residuum of the magma. During these last stages the augite ceased to crystallise as normal titanaugite, and the occurrence of a few scraps of aegirine-augite, due to reaction with the sodic liquid, show the end of its story. Crystallisation of olivine appears to have ceased a little earlier.

Had there been no pressure upon the crystal-mesh during solidification, the crinanite and olivine-dolerite would have been distinctly more alkaline. As it was, a considerable amount of alkaline magma was expelled through veins in the picrite (and probably through the chilled upper margin of the sill) at various periods during crystallisation. The first fraction seems to have been expelled soon after the complete solidification of the picrite, and successive fractions of increasing alkalinity were removed until the sill was rendered free from liquid. The later fractions were of zeolitic composition and had a marked corrosive effect upon the earlier.

In Garbh Eilean no examples of auto-intrusion, that is, intrusion of magmatic liquid into rifts in the crystal-mesh, are seen in the crinanite or olivine-dolerite. The Jurassic strata of Eilean an Tighe have, however, brought about this phenomenon

in the crinanite. These Jurassic beds end abruptly against the igneous rock at Sgeirean Mol na h-Athadh and were almost undoubtedly floated up from below. They reacted with the magma and gave off a stream of gas bubbles which ultimately became filled with zeolites, but also gave rise to lines of weakness in the crystal mesh into which pegmatite veins of teschenitic composition were intruded[1].

The cause of the pressure which gave rise to the intrusion of all the above pegmatite veins is doubtful, but may, as Dr. Tyrrell[2] suggests for certain sills of Central Scotland, be due simply to the weight of the cover. The matter will, however, be more fully discussed in connection with the lower sill of Eilean Mhuire.

Two well-marked continuous reaction-series may be traced in the various types of the sill:-

(1) Lime felspar → lime-soda felspar → soda-lime felspar → soda felspar.

(2) Titanaugite → aegirine-augite → aegirine.

Any member of the first series may take part in the discontinuous reaction series -- plagioclase → analcite → natrolite,

[1] c.f. E.B.Bailey, Q.J.G.S., 1928, p.568.

[2] Q.J.G.S., 1928, pp.565-6.

while the following reaction pairs have been noted:-
Ilmenite → biotite, olivine → biotite, olivine → barkevikite, ilmenite → arfvedsonite, aegirine → arfvedsonite.

No process other than gravitational settling of olivine seems able to account for the differentiation of the sill. Assimilation may be ruled out at once, for there is no indication of appreciable reaction between the crinanite and Jurassic beds of Eilean an Tighe, which show a sharp and well-defined junction, neither were any traces of xenoliths found. Density stratification while still liquid is the only other alternative, and this, too, may be dismissed with equal brevity in view of Bowen's[1] experimental work on the diffusion of silicate melts.

[2] THE LOWER SILL OF GARBH EILEAN.

The Jurassic beds of Garbh Eilean are divided and underlain by another crinanite sill. It is probable that only a small portion of the top of the sill is exposed and that the lower part is under water. Tracing its course above water from east to west, it is first seen forming the conspicuous promontory of Bidean a'Roimh at the extreme east of Garbh Eilean, and has here a maximum visible thickness of about 100 feet. It shows

[1] Jour. Geol., 1921, pp.295-317.

columnar structure at this point, but not to the same extent as the sill above. At the west of the promontory the sea has eroded out a very fine natural arch, known as Toll a'Roimh, along a major joint (PLATES IIIb,IVa), while immediately to the west of the arch the Jurassic beds make their appearance. From this point the top of the sill descends in a westerly direction until it forms the skerries Sgeirean a'Bhaigh (PLATE IIIa) where, still overlain by Jurassic beds, it may be followed off-shore for ¼-mile to the west. The upper contact of the sill is seen in the skerries and shows very little chilling. It is, however, sharply defined. At the east of Sgeirean a'Bhaigh the igneous rock divides the Jurassic strata into two portions, but is otherwise non-transgressive, conforming its dip to the sedimentary deposits.

The rock of the lower sill is fine-grained and dark grey with a tinge of green -- the olivine being more serpentinised than in the crinanite of the upper sill, and 'ophimottling' of the augite less conspicuous. Microscopic examination confirms these differences, which are, however, of degree only. The crinanites of the two sills are very similar indeed, containing the same minerals with almost the same texture in the same proportions. The augite in the lower sill is, perhaps, less strongly coloured, and tends to form smaller and more compact

groups with the felspar;;but much of the olivine has decidedly ophitic characters. Although it is extensively altered in places to dark green or brown serpentine, fresh crystals are by no means uncommon, and are quite colourless. The interstitial analcite of the rock shows in many cases very distinct anomalous double refraction ~~which is~~ probably due to the prolonged boiling in Canada balsam which many of the sections had to undergo before grinding.

[3] THE UPPER SILL OF EILEAN MHUIRE.*

Above the Jurassic strata of Eilean Mhuire there is a sill of crinanite, now almost entirely removed by denudation, but of which a fragment forms the highest part of the island. Exposures are poor and are limited to a few large blocks projecting from the grassy slopes at, and immediately below, the summit.

In the hand specimen the rock has a somewhat troctolitic appearance, the ferromagnesian minerals standing out as black spots in a matrix of greasy-looking felspathic minerals. Under the microscope the rock is seen to be a crinanite not unlike that of the lower sill of Garbh Eilean. The pale brown zonal augite has the same habit, forming ophitic clusters, seldom over 5mm across; but the colourless olivine, which is mostly

* Vide p. 18.

altered to green serpentine, occurs in distinctly smaller amount than in the Garbh Eilean example, the proportion not exceeding 4%. This paucity of olivine is, however, compensated for by the abundance of zeolites, analcite and natrolite, which make up over 5% of the rock and impart the greasy appearance to its matrix. Analcite is the more abundant, and both minerals frequently show alteration to turbid brown decomposition products. The iron ore is more compact in its mode of crystallisation than in the Garbh Eilean sill and does not often exhibit a truly skeletal habit. The specific gravity of this rock is 2.

[4] THE LOWER SILL OF EILEAN MHUIRE.

The lower sill of Eilean Mhuire, which occurs underneath the Jurassic strata of that island, is the most complex of the whole group. It is, moreover, excellently exposed though many of the sections are quite inaccessible, being on vertical cliffs. The visible thickness of the intrusion is about 200 feet, but a large part is doubtless below water.

Along the shoreline the sill is generally quite easy of access, by boat at least, but except at the eastern extremity of the island sheer cliffs tower above the rocky shore platform

Immediately to the east of Bid na Faing, however, grassy slopes are intermingled with the cliffs and provide relatively accessible exposures. At the eastern part of the island, which is joined to the main mass by a narrow and lofty neck of rock, the cliffs are much less steep and may be scaled with comparative ease, and it is a stroke of good fortune that the most interesting rocks appear to be concentrated here. Columnar jointing is not conspicuous, but the joint planes are usually quite well marked (PLATE IXa). The most striking feature of the sill is, perhaps, its stratiform appearance at the eastern end, due to the injection after solidification of horizontal basaltic sheets. The sill itself, indeed, seldom departs from a horizontal position. By far the greater part of the intrusion consists of crinanite, and it is only east of Bagh Chlann Neil that other types are seen. At several points on the N.E. and N.W. cliffs the upper contact appears to be exposed, but it is invariably quite inaccessible. Elsewhere the contact is grassed over.

While the crinanite is a medium grained dark rock, both on the weathered surfaces and on freshly fractured specimens showing typical 'ophimottling', some of the types to the east of Eilean Mhuire are of very different appearance. A coarse subophitic analcite dolerite or gabbro allied to teschenite and

comparatively rich in analcite forms the lowest visible part of the sill from the neck eastwards. In this rock the augite and felspar crystals give the rock a mottled black and white appearance. This modification becomes even richer in analcite in an upward direction, passing into true teschenite, and some 20 feet above sea level the teschenite gives place to a coarse-grained crumbling rock which is more leucocratic and obviously rich in alkali felspar and zeolites, being, in fact, a syenite. The syenite persists upwards until a height of about 90 feet above sea level is reached, and is then followed by a coarse decomposed dolerite which caps the eastern eminence of the island.

All the above modifications contain 'schlieren' -- especially the syenite, which is also drusy and riddled with felsic segregations of irregular shape and disposition. These latter may attain quite a considerable size, and as a rule are distinctly fresher than the crumbling syenite. It was probably either in the syenite or in its segregations that Heddle detected nepheline. The 'schlieren' have comparatively sharp junctions which are, however, unchilled, and in the teschenitic types a rude parallelism of the minerals may be observed.[1] The

[1] c.f. A.Geikie, "Ancient Volcanoes of Great Britain", 1897, vol.II, p.309.

junctions between the various types are also unchilled and inconspicuous.

The syenite and the teschenite are both cut by several horizontal sheets of basalt which may reach a thickness of 20 feet, and may be traced for two or three hundred yards along the cliffs. This basalt is a fine-grained, black, non-porphyritic rock which shows marked chilling against both teschenite and syenite, being obviously of considerably later date. Neither basalt nor syenite is seen much to the west of the rocky neck, and both probably die out near Bagh Chlann Neil. The sea-cave referred to by Heddle in his record of nepheline (vide supra) is doubtless one of the many rifts in the rock caused by wave-erosion along major joints.

(b) PETROGRAPHY.

Crinanite. The crinanite of the lower sill presents few striking features, being very similar to that of the lower sill of Garbh Eilean. The augite is the same pale-brown colour, while "ophimottling" and ophitic structure are much less in evidence than in the crinanite-picrite sill. The olivine, when fresh, is seen to have a distinctly granular habit, groups of colourless grains averaging .5mm in diameter being common. It

is, however, usually serpentinised, there being in some sections quite considerable amounts of migratory green serpentine associated mainly with the iron ore and zeolites. Zeolites occur in moderate abundance, natrolite playing a more conspicuous part than in any of the other crinanites; and the skeletal habit of the iron ore is a well-marked feature, some patches measuring 2.5mm across. The minerals of this rock occur in practically the same proportions as in the crinanite of the upper sill of Garbh Eilean.

Teschenite or analcite-dolerite. The teschenite or analcite-dolerite of the eastern end of the island is different in texture from any of the crinanites. Taking the less alkaline type first, the olivine is seen under the microscope to be much less abundant than in the crinanites, comprising only 4% of the rock. It occurs in well shaped crystals averaging .6mm across and, though generally altered to green or brown serpentine, is colourless when fresh. Occasionally it is penetrated by the ends of plagioclase laths.

The pyroxene is abundant and almost identical in its optical properties to that of the crinanite of the picrite-crinanite sill of Garbh Eilean. It is, however, subophitic in habit, forming stout prisms up to 3mm across, which are usually penetrated in every direction by plagioclase laths, though they

sometimes exhibit crystal boundaries. The 'ophimottling' of the crinanites is conspicuous by its absence, but zoning of the hourglass type is common.

The felspar is almost entirely zonal plagioclase varying from medium labradorite (Ab_2An_3) at the centre of the crystals, to oligoclase at the margin. It occurs in well-formed elongated laths up to 1.5mm in length, which penetrate both augite and olivine and make up nearly 60% of the rock. These laths are sometimes to a slight extent replaced by analcite along cracks and even in small patches. Analcite, besides occurring as a replacement product of plagioclase, is, as one might expect, quite abundant interstitially, the usual proportion being about 8%, and it is generally unaltered. Natrolite, however, was not recorded in this type.

The iron ore is mainly titaniferous magnetite or ilmenite, but pyrites occurs to a limited extent, the two minerals comprising 7% of the rock. Small needles of apatite form, as usual, an ubiquitous accessory. The specific gravity of the rock is 2.97, and the mode is given below.

A gradual upward transition is seen from analcite-dolerite into teschenite. This is due to a considerable increase in the proportions of analcite and acid plagioclase and a dwindling almost to vanishing point in the proportion of olivine, though

a good deal of migratory serpentine may be observed in the rock. The augite in the teschenite assumes an idiomorphic columnar habit, the crystals measuring up to 1cm in length and 2mm in breadth, some of them showing pronounced elongation in the direction of the c-axis. Although they usually show good crystal boundaries they may, on rare occasions, be penetrated by the ends of plagioclase laths. The pleochroism of this pyroxene is slightly different from that of the analcite-dolerite, agreeing well with that given by Harker for the augite of a gabbro from Eilean Mhuire[1], i.e. X lemon yellow, Y purplish-brown, Z lemon yellow. Zoning with stronger tints in the interior is very frequent in the augite, which may assume a faint greenish tinge at the margin through the presence of a small proportion of the aegirine molecule.

The felspar of the teschenite, like that of the analcite-dolerite, is almost entirely plagioclase, but though the centres of the crystals are still medium labradorite(Ab_2An_3) the proportion of oligoclase at the margin is decidedly greater. Much of the plagioclase is replaced in a patchy fashion by analcite, or altered to turbid brown decomposition products. The well-formed laths are larger than in the analcite-dolerite but do not

[1] "Ancient Volcanoes of Great Britain", 1897, vol.II, p.309.

show the same elongation. The analcite occupies large areas between the felspars, amounting to about 12% of the rock. It is perfectly clear and is sometimes penetrated by needles of apatite or flakes of biotite, which seems to indicate a primary origin for the zeolite.

The iron ore is mainly ilmenite in skeletal crystals, occasionally altered to leucoxene and frequently fringed by a reaction border of biotite, but pyrites has been observed. Apart from the olivine and analcite, the proportion in which the various minerals occur is the same as in the analcite-dolerite.

In some varieties of the teschenite there is distinct parallelism of the minerals, and it seems probable that the gabbros described by Dr. Harker[1] are simply varieties of teschenite poor in analcite.

Upper dolerite. The upper dolerite, which caps the eastern extremity of Eilean Mhuire, is somewhat different in texture and mineralogical composition from the analcitic types in the lower part of the sill. It is a coarse, crumbly, decomposed-looking rock in the hand specimen, but is seen under the microscope to be in fair preservation. Purplish-brown zonal augite, similar in its optical properties to the pyroxene of the tes-

[1] Loc. cit. supra.

chenite but with inclusions of magnetite dust, is by far the most abundant constituent of the rock, amounting to 50%. It occurs in large ophitic plates up to 1cm across, which do not, however, exhibit "ophimottling", and have often distinct crystal boundaries. A very few shapeless, serpentinous pseudomorphs probably indicate the former presence of olivine, but the proportion of this mineral cannot have exceeded 2%.

Elongated laths of zonal plagioclase, mainly (Ab_2An_3), make up nearly 40% of the rock and are often enclosed in augite. They are usually about 1mm in length, and in many cases are stained by migratory decomposition products. The interstices between the felspars are frequently occupied by a decomposed brownish mesostasis (4%) which contains clear analcite areas, and sometimes quartz, the latter mineral being probably of secondary origin. Large skeletal ilmenite (6%) and small apatite needles make up the remainder of the rock.

Dr.H.H.Thomas, having seen the writer's sections, commented to him on the resemblance of this dolerite to the Ben Hiant Type of quartz-dolerite so common in Ardnamurchan[1].

The junctions of both dolerite and teschenite with the central syenitic portion of the sill were not detected either in

[1] Geol. Survey, Summary of Progress for 1925, p.127.

the field or in thin section, and it is probable that they are both gradual, although the transition must be complete within a few feet in each case.

Syenite. A layer some 60 feet in thickness in the centre of the sill is formed by the syenite which, like the upper dolerite, is a coarse, brownish, crumbly rock apparently much altered. This decomposition is seen also in some thin sections, whereas others are surprisingly fresh.

The chief constituent of the rock is alkali felspar which is frequently unaltered. It consists partly of oligoclase ($Ab_1 An_4$) and partly of soda-orthoclase. The plagioclase either forms well-shaped elongated laths up to 1cm in length showing albite, carlsbad, and pericline twinning, or occurs as the core of a crystal surrounded by soda-orthoclase. It is usually zonal, the most basic variety being andesine, while the more acid parts approach albite in composition. Alteration to brown decomposition products is more prevalent than in the soda-orthoclase. The latter felspar, besides forming broad fringes round crystals of oligoclase, occurs as untwinned, or simply twinned, tables equal in size to the plagioclase laths towards which it is allotriomorphic. The mean refractive index was found by oils to be 1.529 ± .003, and the mineral is optically negative. It has an abnormally low optical axial angle which, from the

marked curvature of the isogyre, was estimated to be about 30°. The two felspars together make up 50% of the rock.

Pyroxene comes next in order of abundance, the commonest variety being a pale purple titanaugite which shows hour-glass zoning to a slight extent. This mineral is usually surrounded by a fringe of grass-green aegirine-augite or by deep green aegirine, and sometimes contains cracks bordered by these alkaline pyroxenes. It forms stout prisms up to 6mm in length, which show a certain amount of idiomorphism but which are sometimes penetrated by the extremities of plagioclase laths. The aegirine-augite and aegirine may also form separate prisms, idiomorphic towards all minerals except plagioclase, and seldom exceeding 1mm in length. Some of the aegirine prisms are associated with small crystals of blue arfvedsonite, which also occurs very sparingly in small allotriomorphic crystals. These metasilicates comprise about 20% of the rock.

Zeolites, of which the chief is analcite, are also very common, occupying large interstitial areas. In these patches the analcite is unaltered and was the first zeolite to crystallise, for it invariably presents idiomorphic boundaries towards the others. The nature of these other zeolites is a little uncertain, but refractive index tests with oils show that a variety with low double refraction and $\beta = 1.498 \pm .003$ occurring in

minute divergent fibres is probably scolecite: stilbite also occurs in spheroidal masses of radiating fibres. The zeolitic content of the rock approaches 20%.

The syenite also contains about 3% of dark brown pseudomorphs up to 2mm across, and with frequent rectangular or hexagonal outline, the shape being strongly suggestive of the former presence of nepheline. Skeletal ilmenite in large crystals is abundant and often shows reaction borders of biotite. Apatite is conspicuous, too, in needles up to 1.5mm in length, usually coloured bluish-grey by inclusions.

A large amount of serpentinous matter derived from the decay of ferromagnesian minerals is irregularly distributed in the syenite, and it is possible that olivine was originally present. This is particularly the case in an essexitic modification of the syenite which occurs at the top of the neck, and which contains a fair amount of plagioclase as basic as Ab_1An_1.

The mode of the rock is given below, but it was not considered fresh enough for analysis.

Greyish-white segregations are common in the syenite and are of irregular shape and size, the maximum breadth observed being about two feet, while the distribution is apparently haphazard. The rock is slightly finer in grain than the normal syenite and distinctly richer in felsic constituents. It is also visibly

porous and crumbly, containing numerous druses lined with analcite and spheroidal aggregates of radiating fibrous zeolites.

Under the microscope the rock is seen to consist of the same minerals with the same habit as the normal syenite, but in different proportions. The felspars, which amount to over 60% of the rock , have the same habit as in the normal syenite, but the plagioclase is nearly all albite with positive sign and very minute multiple twinning. The mean refractive index by oils was found to be 1.534 ± .003. Both the albite and soda-orthoclase are usually quite fresh, and their relative abundance is exceedingly variable.

Pyroxenes form only 10% of the rock, aegirine and aegirine-augite together being as abundant as titanaugite, while the optical properties of all three varieties are the same as in the normal syenite. Alkaline amphiboles comprise about 1%, and besides arfvedsonite with deep blue to lavender pleochroism, occasional crystals of riebeckite may be detected which vary in tint from dark blue to greenish-yellow, while barkevikite with brown - light yellow pleochroism is still more rare. All three minerals occur in intimate association, and frequently form crystal aggregates with aegirine. The habit of these alkaline pyroxenes and amphiboles is, indeed, very similar to those described by Dr.Thomas in the alkali-syenite of Gamhnach Mor in

Mull[1].

The zeolites of the segregation veins do not differ notably in occurrence, constitution , or abundance from those of the normal syenite. Nepheline, however, is distinctly more abundant, and occasional patches of the unaltered mineral may be detected in the dark brown pseudomorphs. The mineral is seen to have a slightly higher refractive index than the albite, straight extinction, negative optical character, and one good cleavage accentuated by decomposition products. It alters locally to a mineral with slightly higher refractive index, positive sign, and double refraction slightly above that of quartz, which resembles closely a mineral associated with nepheline, described by Dr.Tyrrell[2] and Mr.Bailey[3]. Theiron ore is distinctly less abundant than in the normal syenite , and is probably titaniferous magnetite, as the skeletal habit is rare; but apatite is again abundant.

Both the normal rock and its segregations considered by themselves are analcite-syenites, but the occurrence of nepheline renders them unique in British petrographic literature. Nepheline syenites with analcite from various localities have been

[1]Mull Memoir, pp.189-191. [2]Geol. Mag., 1915, p.309.

[3]Mem. Geol. Sur., E. Lothian, 1910, p.111.

described, principally by Lacroix[1], but these rocks tend to be richer in the felspathoid than in the zeolite, which is not usually primary. The habit of the zeolites in the Shiant rocks renders it extremely probable that they were the last products of solidification of a sodic magma, and they are therefore considered to be primary like the zeolites of the analcite-syenite of Howford Bridge. The segregation rock, being reasonably fresh, was chosen for analysis and the results are given on p.84 together with the mode and a discussion of the affinities of both syenitic types.

Olivine basalt. The sheets of this rock which cut the eastern end of the sill have been described microscopically by Dr. Harker[2] whose account is confirmed by the writer in almost every particular. The unchilled rock is a virtually non-porphyritic olivine-basalt containing as rare corroded phenocrysts only olivine and labradorite up to 4mm in length. Elongated laths of labradorite ($Ab_2 An_3$) up to .5mm in length comprise the bulk of the rock, greenish-brown patches of sub-ophitic augite, rounded grains of unaltered olivine averaging .2mm in diameter, a small quantity of mesostasis or analcite, and minute cubes of magnetite making up the remainder.

[1] e.g. "Min. de Madagascar", 1922, vol.II, p.614.

[2] Op. cit., p.310.

Towards the margin of the sheets the rock becomes much finer in grain and contains a good deal of devitrified glass. The specific gravity, the mode, and the analysis of the normal basalt are given below, while a microphotograph appears on PLATE XII, fig.(3).

(c) MODES.

	A	B	C	D
Olivine	4	-	-	13
Augite	23	15	6	15
Alkali pyroxene	-	6	5	-
Alkali amphibole	-	1	1	-
Plagioclase	58	-	-	61
Alkali felspar	-	50	62	-
Nepheline	-	3	4	-
Zeolites or glass	8	20	18	5
Iron ore	7	5	4	6

A. Analcite-dolerite, sea level, extreme east of Eilean Mhuire. PLATE XII, fig.2.

B. Analcite-syenite, 60 feet above sea level, on cliff at east end of Eilean Mhuire.

C. Acid segregation in syenite, 25 feet above sea level on cliff at east end of Eilean Mhuire. PLATE XII, fig.1

D. Basalt sheet, 20 feet above sea level on cliff at south-east end of Eilean Mhuire. PLATE XII, fig.3

The modes of A, B, and C represent the <u>average</u> type at each

locality, and it is possible in all three cases to find "schlieren" of distinctly more felsic or more mafic composition.

ANALYSES.

	I	a	b	II	c
SiO_2	58.36	58.81	56.44	46.48	45.8
TiO_2	.48	.76	1.16	2.00	2.4
Al_2O_3	15.82	14.81	15.54	15.59	15.0
Fe_2O_3	4.87	4.58	3.27	4.54	3.8
FeO	2.53	4.21	3.67	8.62	9.5
MnO	.27	.27	n.d.	.28	.3
(Co,Ni)O	.02	n.f.	n.d.	-	-
MgO	.59	.80	1.73	9.19	8.2
CaO	1.99	2.33	4.16	8.98	9.4
BaO	.01	.03	n.d.	-	-
Na_2O	7.47	5.60	5.81	2.79	2.5
K_2O	4.31	4.96	4.27	.71	.5
H_2O+	2.62	.82	2.06	.85	1.8
H_2O-	.72	2.00	.44	.81	.9
P_2O_5	.35	.20	.83	.11	.2
CO_2	n.f.	-	.97	n.f.	-
Cl	.01	-	-	-	-
S	-	-	-	.14	-
Totals	100.42	100.18	100.35	*100.24	100.3

*The total given has been subjected to a deduction of .04% O for sulphur, and .81% for moisture ~~calculated~~ estimated before analysis.

NORMS.

	I	II
Orthoclase	25.6	3.9
Albite	49.8	23.6
Anorthite	-	28.1
Nepheline	4.0	-
Acmite	5.1	-
Diopside	6.0	11.5
Hypersthene	.2	10.5
Olivine	-	11.0
Magnetite	4.6	6.5
Ilmenite	.9	3.8
Apatite	1.0	.3
Pyrites	-	.2

I. Acid segregation in syenite, same locality as C; analyst E.G.Radley. PLATE XII, fig.1.

a. Syenite, Gamhnach Mor, Carsaig Bay, Mull; analyst E.G.Radley. Quoted from Mull Memoir, p.27.

b. Analcite-syenite, Howford Bridge, Mauchline; analyst M. Dittrich. Quoted from Tyrrell, Q.J.G.S., 1928, p.559.

II. Olivine-basalt sheet, in cliff at extreme south-east of Eilean Mhuire, 20 feet above sea level; analyst N.Sahlbom. PLATE XII, fig.3.

c. Average Plateau Magma-Type. G.W.Tyrrell, loc. cit. supra.

The above analysis of the syenitic segregation material of Eilean Mhuire brings out clearly its very sodic nature. Reasonable agreement is seen between the Shiant analysis and one

of the Gamhnach Mor alkali-syenite in Mull, quoted alongside, but it will be observed that the Shiant rock is the more alkaline, probably owing to its high analcite content, the Mull rock containing neither nepheline nor analcite. Both these Tertiary syenites are distinctly more acid than the type analcite-syenite of Howford Bridge which is probably of Permian age and whose analysis is also quoted. An analcite-syenite from Emery, Utah, is, however, still more basic[1].

The analysis of the olivine-basalt which was made for the writer by Dr.N.Sahlbom shows very good agreement with the average composition of the Tertiary Plateau Magma-Type as calculated by Dr.Tyrrell. Moreover, no agreement is shown with any analysis of a British Tertiary rock not referred to this magma-type, e.g. any type of the tholeiites.

SPECIFIC GRAVITIES.

Analcite-dolerite, sea level 2.97

Olivine-basalt, same locality as D 2.81

The crumbly and porous nature of the syenites renders any determination of specific gravity untrustworthy, but 2.50 was the mean of several widely differing estimations.

[1] J.Gilluly ; Amer. Jour. Sci., 1927,vol.XIV, p.205.

(d) DIFFERENTIATION OF THE SILL.

The mode of differentiation of the lower sill of Eilean Mhuire must have been quite unlike that of the crinanite-picrite sill of Garbh Eilean whose cooling history is so clear. In the western, or main, portion of Eilean Mhuire there does not appear to be any trace of gravitational differentiation, the crinanite of the lower sill retaining practically the same mineralogical composition from top to bottom of the cliffs, while in the eastern portion there is actually a definite concentration of augite in the coarse, slowly-cooled top of the sill. (In the following discussion the later olivine-basalt sheets will be neglected). Thus, sinking by gravity of early formed crystals was not a cause of differentiation.

There remain three hypotheses open to account for this differentiation:-

(1) The intrusion of an already heterogeneous magma.

(2) The subsequent intrusion of the syenite into the partially cooled analcite-dolerite and teschenite.

(3) The injection of residual magma during crystallisation into rifts in the crystal mesh.

The first hypothesis has been applied by Harker[1] to account

[1] Skye Memoir, pp.75, 120.

for the banded gabbros and peridotites of Skye, and by Campbell and Stenhouse[1] to account for the various modifications in the picrite-teschenite sill of Inchcolm. The recent work of Greig[2] on immiscibility (or better, limited miscibility) in silicate melts shows that the occurrence of a natural unhomogeneous silicate liquid is most unlikely. There is, however, in the case of the Eilean Mhuire sill, the remote possibility of the simultaneous intrusion of two viscous magmas of widely differing composition which, on account of their increasing viscosity through cooling, had not time to mix perfectly. Crystallisation in such viscous magmas would, however, almost undoubtedly have been far advanced before intrusion, resulting in a much greater development of flow structure and hybridism than is actually seen in the sill. The first hypothesis is, then, improbable.

Turning to the second, we find that, while the junctions between syenite, dolerite, and teschenite do not altogether preclude this hypothesis, there is no veining of the basic rocks by the more acid, or vice versa, and this absence of a feature which might well be looked for if the sill was intruded in two stages is significant.

The third hypothesis was suggested by Bowen[3] to account for

[1] Trans. Edin. Geol. Soc. vol.IX, part 2, p.130.

[2] Amer. Jour. Sci., vol.XIII, pp.1-44, 133-54.

[3] Loc. cit. supra.

differentiation of banded sills and laccolites and has recently been developed by Bailey and by Tyrrell. Bowen considers that the "auto-intrusion", as he very appropriately terms it, is due to deformation of the masses by lateral thrust during crystallisation, but Tyrrell[1], applying the hypothesis to the crinanite analcite-syenite sill of Howford Bridge and other unhomogeneous sills in Central Scotland, attributes the auto-intrusion to the pressure exerted on the residual magma by the superincumbent rock-column, while Bailey[2] considers it to be due to the expansive force of volatile constituents prior to the final consolidation of the rock.

The resemblance, in the mode of occurrence of the various types, of the lower sill of Eilean Mhuire to the much thinner one of Howford Bridge is noteworthy, but Tyrrell's development of Bowen's hypothesis, although exceedingly simple and ingenious, presents difficulties of application in certain cases. Why, for instance, is there no sign of segregation veins in many of the dolerite sheets of Skye which are thick, of similar composition to the Shiant sills, and must have been subjected to very considerable pressure by the superincumbent rock in the case, at least, of the lower members? It is also obvious that some

[1] Loc. cit. supra.

[2] Loc. cit. supra.

other reason must be found for the occurrence of segregation veins in the plateau lavas of Mull[1], the pressure from the superincumbent rock being in this case extremely small.

The present writer is inclined to attribute the main differentiation of the Eilean Mhuire sill into alkaline dolerite and syenite to auto-intrusion due either to deformation during cooling or to the pressure exerted by the superincumbent rock-column -- the evidence for and against either ~~process~~ cause being inconclusive. In the case of the later segregations of syenitic composition, however, the drusy nature of the syenite seems to give good support to Bailey's suggestion, and the felsic segregations are then thought to be due to the development of cracks in the crystal framework in the manner outlined by him, and to the infilling of these by residual magma. This hypothesis is thought to account also for the pegmatite veins in the crinanite of Eilean an Tighe.

The reaction series to be observed in the lower Eilean Mhuire sill are practically the same as those made out in the picrite-teschenite sill of Garbh Eilean, but the continuous reaction series afforded by the plagioclase felspars is carried a stage further by the imperceptible passage of albite into soda-orthoclase.

[1] Mull Memoir, pp.138-140.

The basalt sheets are not in any way connected with the main differentiation of the sill, being clearly intruded after complete solidification had taken place.

[5] THE GALTACHEAN.

The line of rocks known as the Galtachean appears to be a remnant of a single great sill of crinanite, perhaps to be correlated with the crinanite-picrite sill of Garbh Eilean and Eilean an Tighe. The same well-marked columnar structure is to be seen in all eleven islets, but while the disposition of the columns indicates a constant southerly direction of dip, the angle is very variable, changing from 20° to almost 90° in places. These changes of dip are rapid and are accompanied in the eastern islands by marked curvature of the columns. All the islets present steep rocky faces towards the north, but the southern, or dip slopes,of the larger islands are more accessible, particularly in the case of Galta Mor. No trace of sedimentary strata is to be seen on any of them.

The group appears to be made up almost entirely of fresh crinanite, which in the hand specimen bears a close resemblance to types from the upper parts of Garbh Eilean and Eilean an Tighe. In Galta Mor, however, there is a considerable develop-

ment of pegmatite segregation material -- not merely in veins but in large bands reaching a thickness of at least ten feet. These bands are most conspicuous near sea level to the south west of the island and again near the summit. They consist of a coarse grey rock in which prisms of augite stand out clearly from a felspathic matrix.

(b) PETROGRAPHY.

Crinanite. Under the microscope the crinanite of the Galta chean is seen to be identical with that of Garbh Eilean and Eilean an Tighe. Specimens from all heights on Galta Mor show the markedly ophitic olivine typical of the upper parts of the crinanite-picrite sill, but the rock is fresher and has unaltered olivine which is absolutely colourless, thus confirming the hypothesis that the occasional brown colour of the mineral in Garbh Eilean is due to alteration. On Galta Beg a specimen collected slightly above high tide mark shows rounded grains of olivine rather than ophitic patches, together with relatively scanty augite, and resembles strongly the higher parts of the olivine-dolerite in the crinanite-picrite sill.

Pegmatite. Three different types of pegmatite were found on Galta Mor. The first is an essexitic or teschenitic type

which forms the summit of the island. Felspar is the most abundant constituent, consisting partly of analcitised zonal plagioclase laths up to 3mm in length, varying from acid labradorite to oligoclase, and partly of untwinned soda-orthoclase fringing the plagioclase or occurring as broad separate tables. The two felspars together make up about 60% of the rock, and the plagioclase occurs in ophitic relationship with large plates of zonal titanaugite sometimes fringed with green aegirine-augite and comprising about 20% of the rock. Small crystals of aegirine occur separately, and the remainder of the rock consists of clear interstitial analcite (10%), iron ore (6%), and serpentinised olivine (3%).

At a lower point, about 100 feet above sea level, another variety is encountered, forming small veins reminiscent of those of Eilean an Tighe. The resemblance is confirmed by microscopic examination, the two rocks being very similar indeed. There is, however, little or no brown mesostasis in the Galta Mor example.

The third variety of pegmatite forms thick bands in the lower part of the island and is syenitic in composition, having a strong resemblance to the syenitic segregations of Eilean Mhuire and also to the syenite of Gamhnach Mhor in Mull[1]. Analcite is

[1] Mull Memoir, pp.189-191.

scarcer than in the Eilean Mhuire rock, and felspar -- particularly soda-orthoclase -- more abundant. The soda-orthoclase has a distinctly larger axial angle than that from the Eilean Mhuire syenite. Nepheline is much scarcer and soda-amphiboles entirely absent in the Galta Mor rock which is, on the whole, the freshest syenitic type in the group. The mode is given below and a microphotograph (PLATE XI fig.4).

Mode of syenitic pegmatite from S.W. of Galta Mor:-

Augite	8
Alkali-pyroxene	4
Nepheline	1
Alkali-felspar	67
Zeolites	15
Iron ores	5

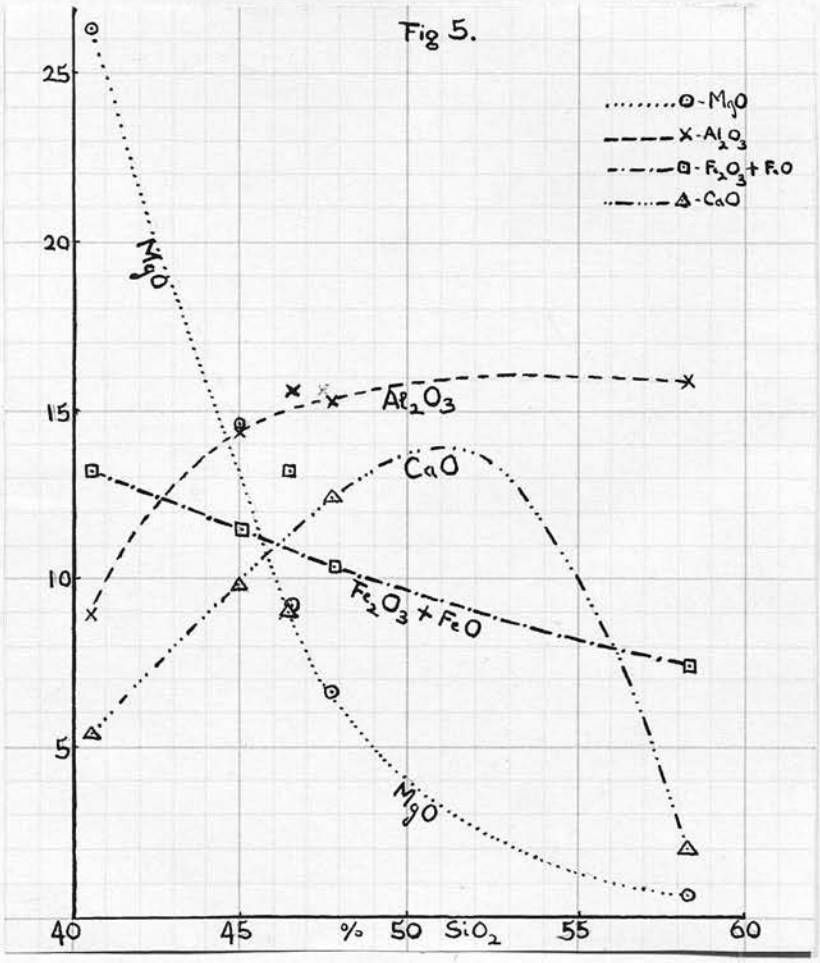
(c) DIFFERENTIATION.

The occurrence of the pegmatite bands on Galta Mor is considered to be due to auto-intrusion of residual magma into the crinanite in three distinct stages during crystallisation: first the thin teschenitic veins, second the essexitic bands of the summit, and finally the syenite bands of the lower south west part. The cause of this auto-intrusion must, as in the lower sill of Eilean Mhuire, remain doubtful, the same alternatives being offered.

[6] AGE and AFFINITIES of the SHIANT SILLS and GENERAL CONCLUSIONS.

There can be little question that all the igneous rocks of the Shiant isles are of Tertiary age, for in some cases they are seen to intrude strata of Jurassic age, while there is an exceedingly strong genetic connection between all types except the olivine-basalt sheets which are to be regarded as the latest manifestation of igneous activity, This genetic connectio may be well shown by plotting the major oxides against silica on a variation diagram.(fig.5).

Fig 5.



The points given by the analysis of the olivine-basalt are then seen to diverge greatly from the smooth curves or straight lines yielded by the other four analyses which are plainly all on a single line of descent from a common stock.

Although the Tertiary age of the Shiant sills does not admit of much argument, there is considerable doubt as to the stage of Tertiary igneous activity to which they belong. Dr.Harker[1] has suggested that the Shiants are close to the focus of activity which gave rise to the numberless dolerite sills of northern Skye. There is certainly, as far as our information goes, a resemblance in composition between the Shiant crinanites and the Skye sills, and it may indeed be the case that the Shiant group belongs to a deeper-seated phase of this activity, where slower cooling permitted differentiation of the sills to take place to a marked degree, but while the probability of this is admitted, a definite opinion must be witheld until our knowledge of the Trotternish sills is less scanty. It may, however, be mentioned that the description and microphotograph given by Professor Jehu and Mr.R.M.Craig[2] of the olivine-dolerite of the Maddy More sill which lies off the east coast of North Uist, agrees well with the crinanite of Garbh Eilean and Eilean an Tighe. An investigation of the islands of Trodday and Fladda-

[1] Skye Memoir, p.237.
[2] Trans. Roy. Soc. Edin., Vol. LIX, part 2, pp. 485-6.

chuan to be undertaken shortly by the writer may throw more light on this point.

There is also the possibility that the Shiant sills may belong to an earlier phase of activity than the North Skye sills, and that the latter were contemporaneous with the later olivine-basalt sheets of Eilean Mhuire, which apparently belong to the early and parent Plateau Magma-Type[1].

It seems clear, however, that, whatever the exact age of the Shiant sills may be, they belong to a fairly early stage of Tertiary igneous activity, and that they throw considerable light on the mode of origin of many of the ultrabasic and alkaline types of the Tertiary Province of the Inner Hebrides. It has been shown that both picrite (sometimes approaching dunite) and syenite like that of Gamhnach Mhor may be produced in thick sills from crinanite by crystallisation differentiation alone, without any assimilation of the country rock; the former through the sinking by gravity of early formed olivine crystals, and the latter by squeezing out or auto-intrusion of alkaline residual magma. The facts are, moreover, in marked agreement with Bowen's theories of magmatic differentiation which he has recently so ably and convincingly expounded[2].

[1] Vide Mull Memoir, p.30.

[2] 'Evolution of Igneous Rocks', 1928.

These modes of differentiation are in striking contrast to those lately described by Dr.O.Pačak[1] in his excellent account of the Moravian picrites and teschenites. Here the main differentiation into basic and ultrabasic types is considered to have been accomplished by gravity prior to intrusion, while extensive assimilation of limestone country rock and "pneumatolytic" differentiation after intrusion is postulated[2], giving rise to thoroughly alkaline teschenites, some of which resemble the teschenite of Eilean Mhuire. The picrites[3], too, except for distinctly lower magnesia, agree well in composition with the picrite of Garbh Eilean. It has, however, been seen already that assimilation played no part in the production of the Shiant types. Moreover, the country rock is either argillaceous or arenaceous.

VII. GLACIATION.

In his account of the glaciation of the Shiant Isles, Heddle considers that the glaciated appearance of the western shores of Garbh Eilean and Eilean an Tighe and the occurrence of erratics along the shores indicates a flow of the ice, which un-

(1) Bull.Internat. de L'Acad.des Sciences de Boheme, 1926, pp.1-98.
(2) OP.cit.,pp.71-74, 87-89. (3) Vide analyses, op.cit.,p.62.

doubtedly overrode the group during the Glacial Period, from west to east. He states also that the erratics are recognisable "Long Island" rocks and records the presence of hornblende-gneiss and Cambrian (Torridonian?) grit amongst them. No striae were found on any part of the bed-rock.

The present writer confirms the above ~~facts~~ observations, but gives them a very different interpretation based largely on recent work carried out by Professor Jehu and Mr.Craig on the Long Island. He considers that the unglaciated appearance of the eastern shores of Garbh Eilean and Eilean an Tighe is due to the westerly dip of the sill alone, that all traces of glaciation there must have been obscured long ago by the constant fall of columns from the scarp cliffs, and that the vast scree slopes of these shores have buried numerous erratics. He disagrees, too, with Heddle's statement that the blocks of gneiss and red Torridonian arkose found on the dip slopes of the two western islands and on the grassy top of Eilean Mhuire must necessarily have come from the Long Island, for identical types are to be found at many points on the mainland. The glaciated appearance of the dip slope of Garbh Eilean (PLATE IV b) seems to him to indicate a flow of ice from south to north rather than from east to west, and the formation of the very distinct N-S fault hollow is considered to be due mainly to the superior erosive action

of the ice working along this soft band. It is thought, in fact, that the "mer-de-glace" of the Minch flowed northward from the mainland and from Skye and completely covered the Shiant group. In confirmation of this hypothesis we have the record by Professor Jehu and Mr.Craig of N-S striae on the island of Harris to the west of the Shiants.[1]

VIII. QUATERNARY AND RECENT DEPOSITS.

Raised Beaches. There are no definite traces of raised beaches on any of the islands, but the comparatively level ground to the north-west of Eilean an Tighe on which stood the shepherd's house and potato patch may, perhaps, represent the 25 foot beach platform, for the bluff to the east of it has the appearance of a sea-cliff.

Peat. A large part of the dip slopes of Garbh Eilean and Eilean an Tighe is covered by a thin coat of peat, but in three places indicated on the map this covering thickens out considerably and fills up hollows with a swampy variety of peat.

IX. PLACE NAMES.

The Gaelic place names on the Geological map appended have

[1] Trans. Roy. Soc. Edin., vol.LV, Part 2, p.486.

been revised in accordance with information kindly supplied by Mr.Malcolm Macsween.

ACKNOWLEDGMENTS.

The investigation of the islands was greatly facilitated by the cordial co-operation of a great many gentlemen. Permission to survey the group was very kindly given by Mr.Compton Mackenzie, who also rendered the author assistance in many other ways, and the visits to the group were made easy by the never-failing help of Mr.Malcolm Macsween of Tarbert.

The working up of the results was made pleasurable by the constant encouragement and advice of the Director and Officers of the Geological Survey, and for this the author is particularly indebted to Sir John Flett, Mr.Murray Macgregor, Dr.H.H. Thomas, and Mr.E.B.Bailey, while Mr.Radley's four excellent analyses have proved of great value. Similar good offices were most kindly rendered by Professor T.J.Jehu and Dr.R.Campbell of the University of Edinburgh, and the work would not have been completed by this date had it not been for the great facilities for work on the group granted to the author by Mr. D.E.Innes of the University of St.Andrews during the Summer Term of the Academic Year 1927-28. In addition the author was

exceedingly fortunate in being able to draw upon the great knowledge of Jurassic ammonites of Mr.S.S.Buckman and Mr.J. W.Tutcher, a knowledge which was placed most generously at his disposal.

The author also desires to express his extreme indebtedness to Dr.A.Harker for his great kindness in permitting the author to undertake the work which he himself was prevented through illness from carrying out, and for his valuable advice and encouragement.

Grateful acknowledgment of the generous financial assistance rendered by the Carnegie Trust for the Universities of Scotland is finally expressed.

XI. EXPLANATION OF PLATES.

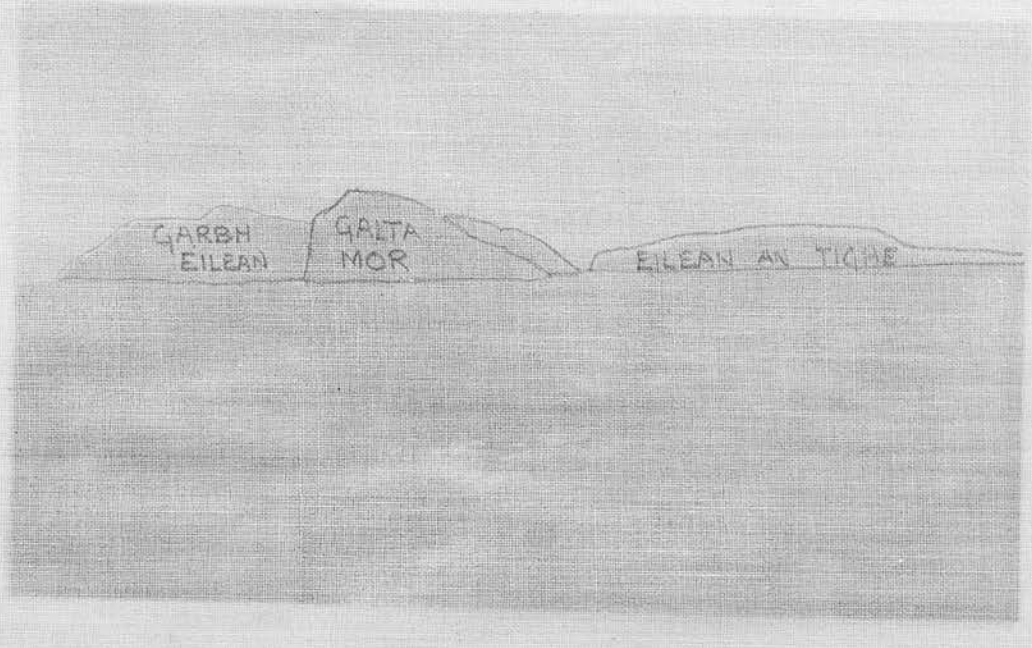
PLATE I.

(a) The Shiant Isles, showing Galta Mor, Garbh Eilean, and Eilean an Tighe. Seen from a point one mile west of Galta Mor.

(b) Eilean Mhuire seen from shingle beach joining Garbh Eilean and Eilean an Tighe.

PLATE I

(a)


GARBH EILEAN
GALTA MOR
EILEAN AN TIGHE

(b)

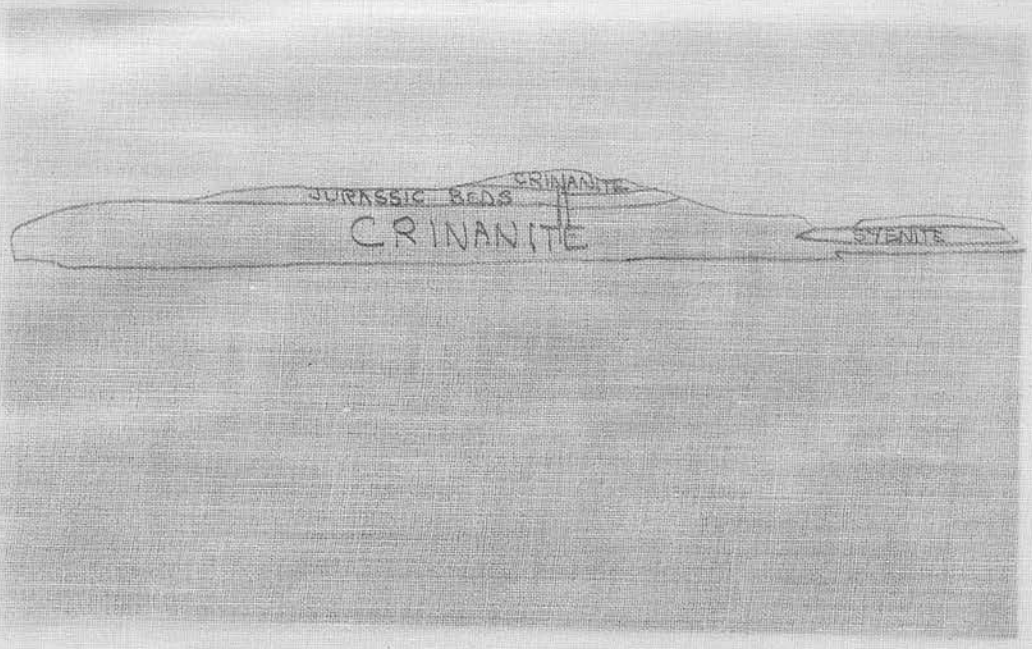

JURASSIC BEDS
CRINANITE
CRINANITE
SYENITE

PLATE I

(a)

(b)

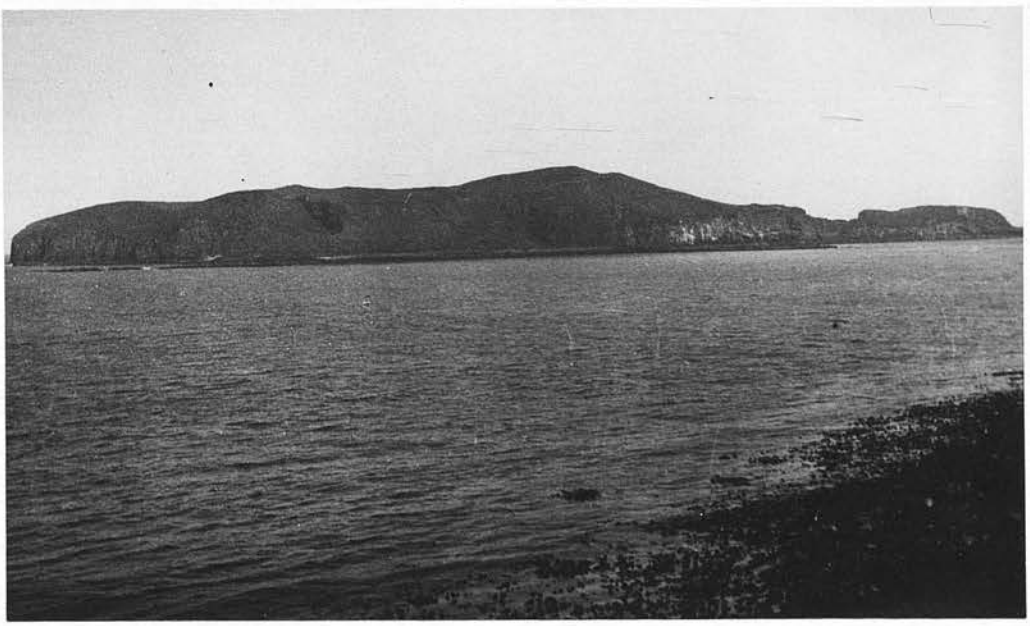


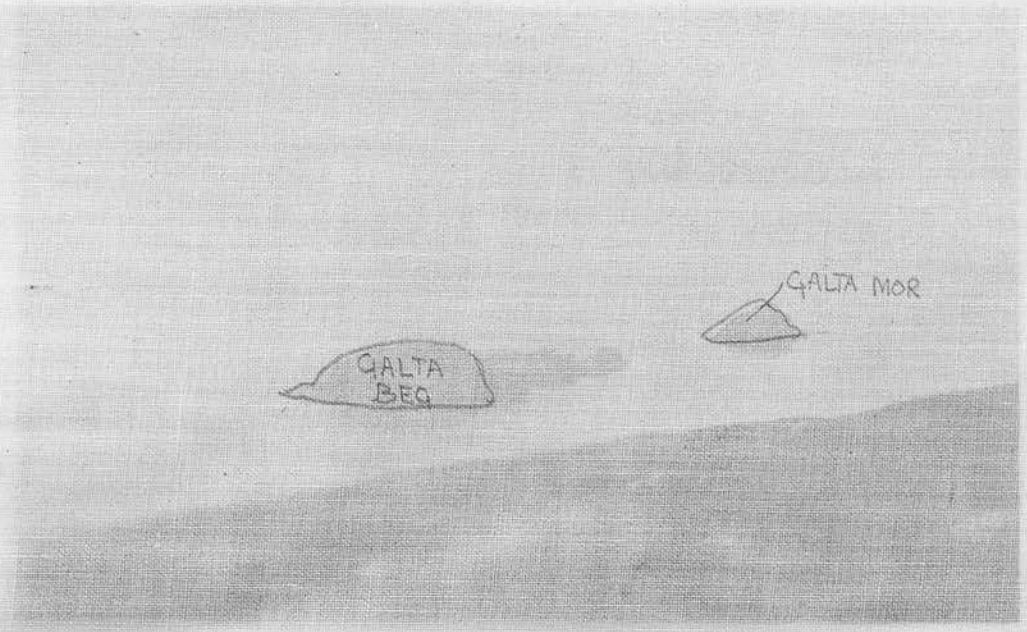
PLATE II.

(a) The Galtachean seen from Garbh Eilean.

(b) West side of Garbh and Eilean an Tighe with the Galtachean in the distance.

PLATE II

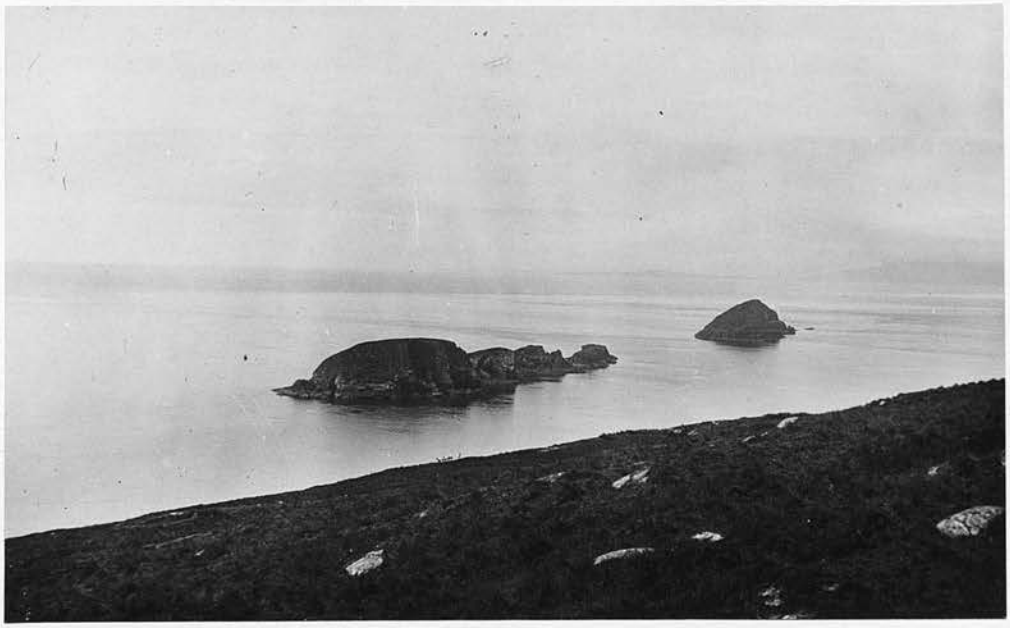
(a)


GALTA MOR
GALTA BEG


GALTACHEAN
PARK DISTRICT
GARBH EILEAN
EILEAN AN TIGHE
BOTHY

PLATE II.

(a)



(b)

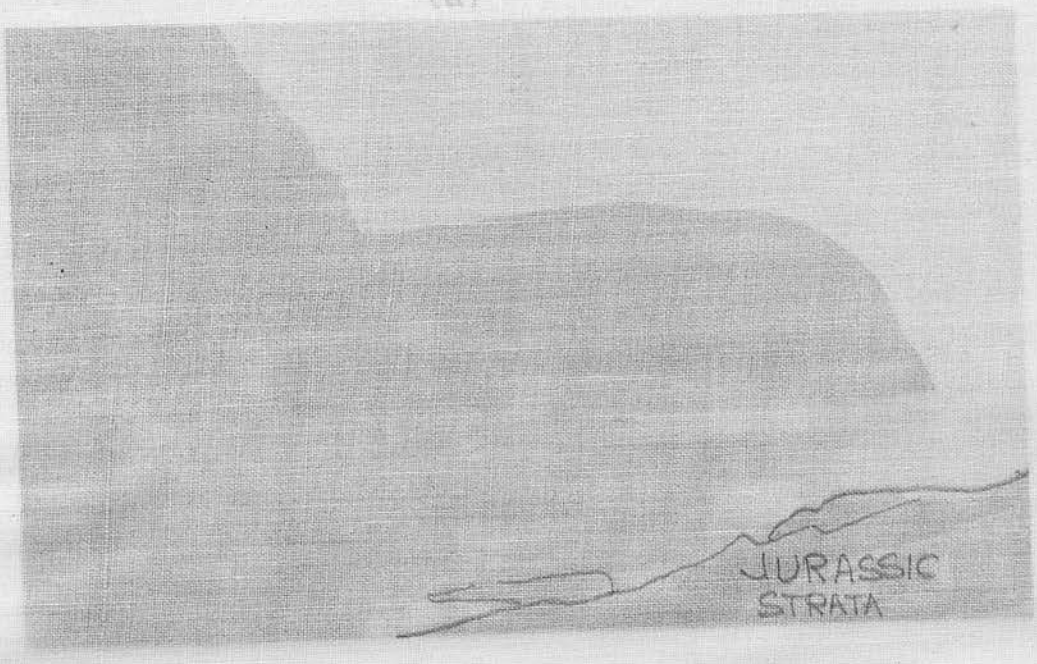
PLATE III.

(a) Northern precipice and scree slopes of Garbh Eilean with Jurassic beds in the foreground.

(b) North-east portion of Garbh Eilean showing scree slopes and natural arch (Toll a'Roimh).

PLATE III

(a)



(b)

PLATE III

(a)

(b)

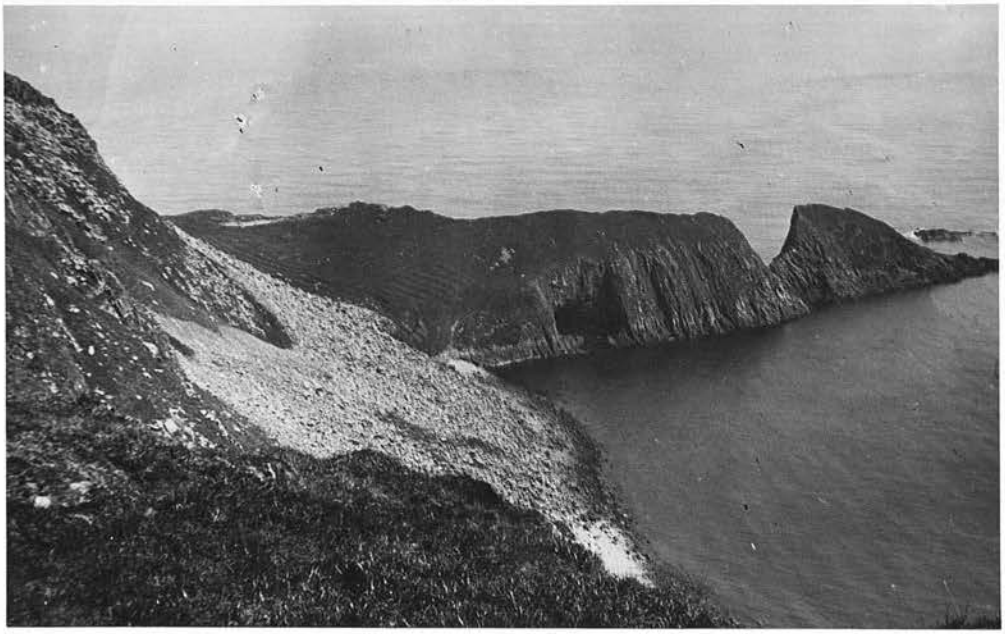


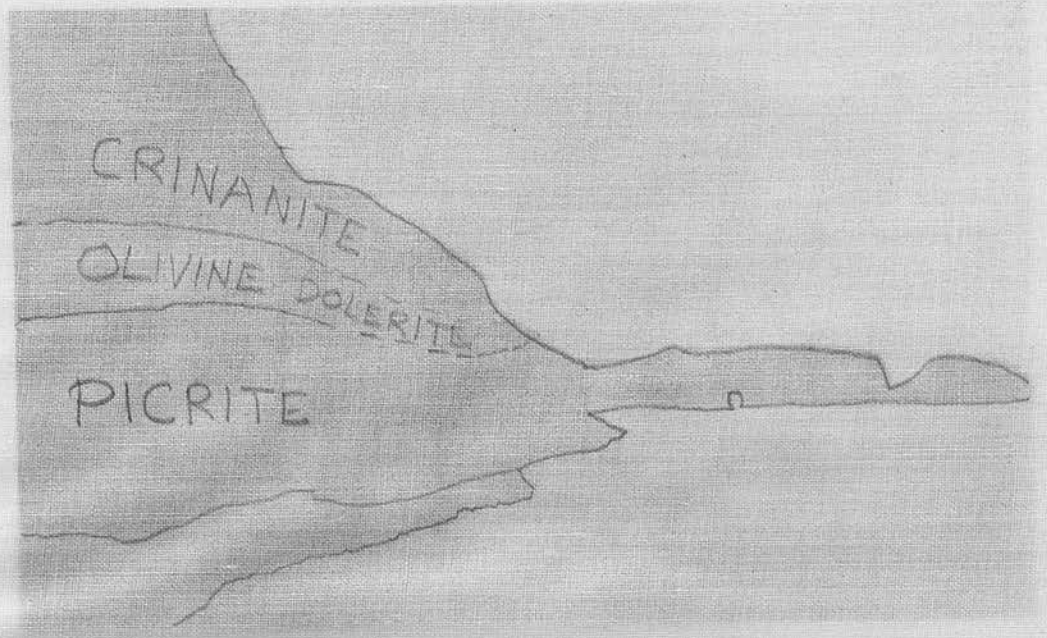
PLATE IV.

(a) East side of Garbh Eilean, showing picrite in foreground and natural arch in distance.

(b) Fault feature running N - S across Garbh Eilean.

PLATE IV

(a)



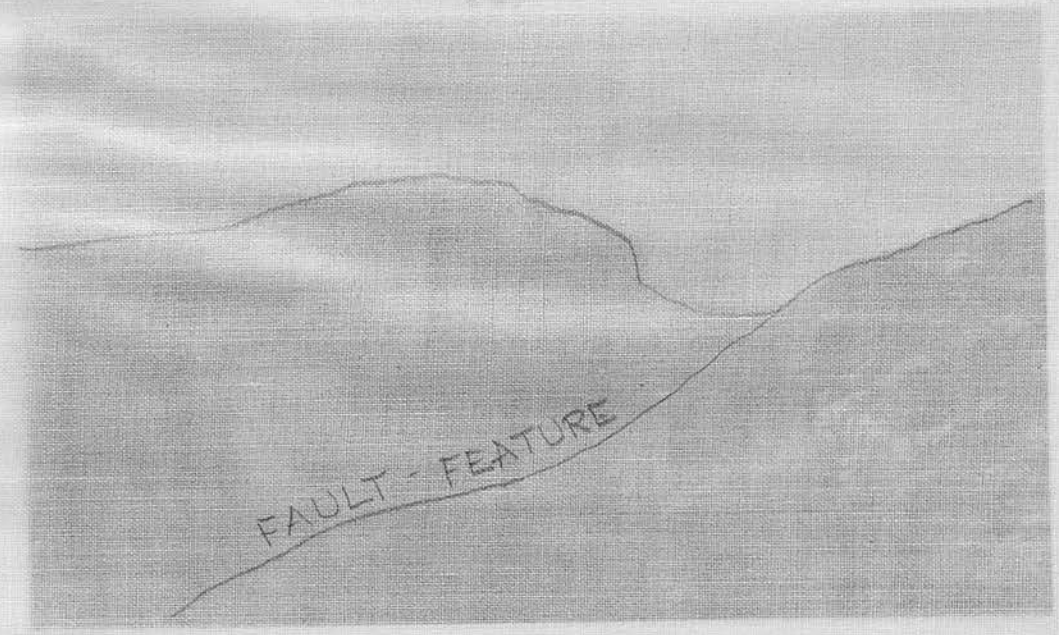


PLATE IV

(a)

(b)

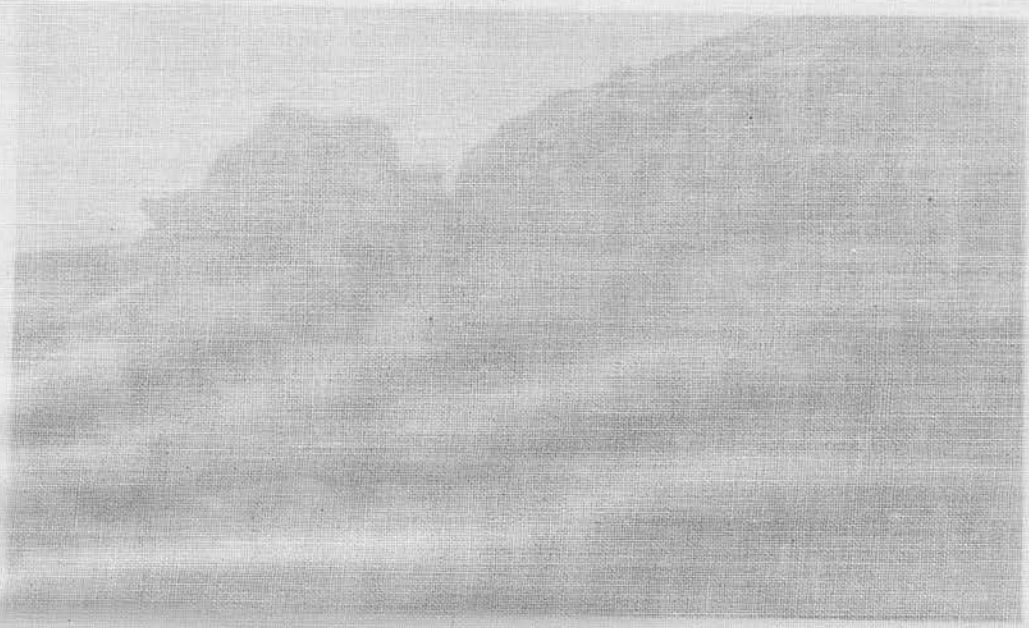
PLATE V.

(a) Fissure caused by opening of major joint. South-west of Garbh Eilean.

(b) Jurassic strata ending abruptly against crinanite. North-west of Eilean an Tighe.

PLATE V

(a)



(b)

PLATE V

(a)

(b)

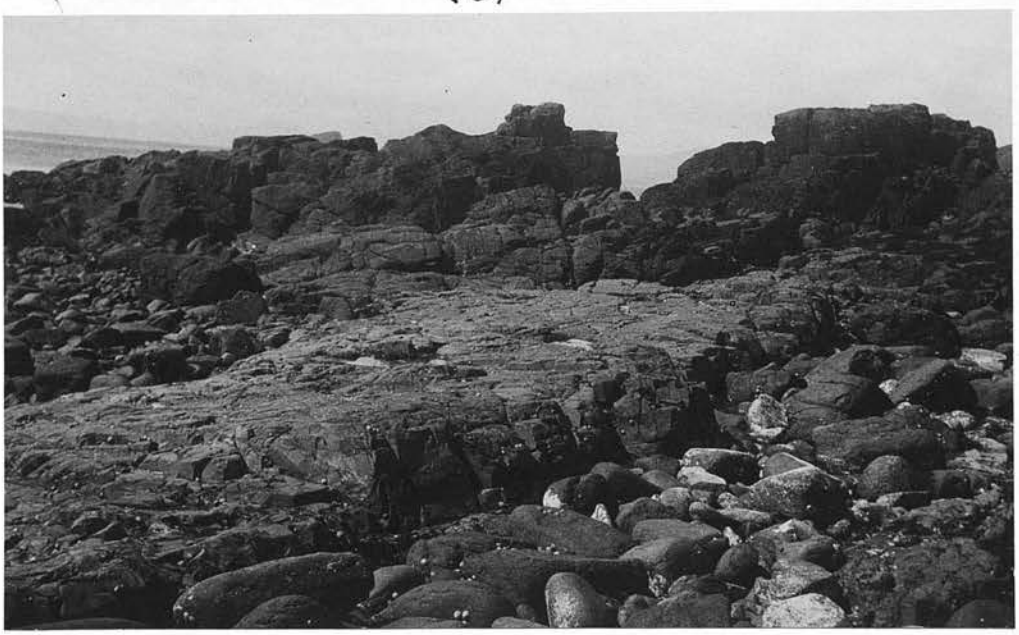


PLATE VI.

Northern precipice of Garbh Eilean seen from Glaic na Crotha.

PLATE VI

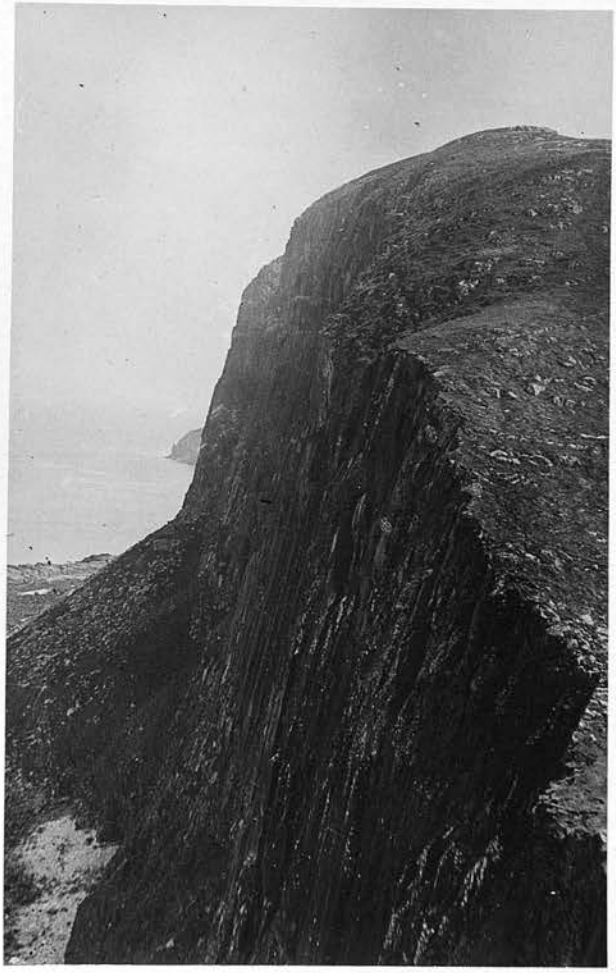


PLATE VII.

(a) North-east face of Garbh Eilean showing scree slope composed of broken columns.

(b) South face of Garbh Eilean, with shingle beach in foreground, showing most complete section through sill.

PLATE III

(a)

(b)

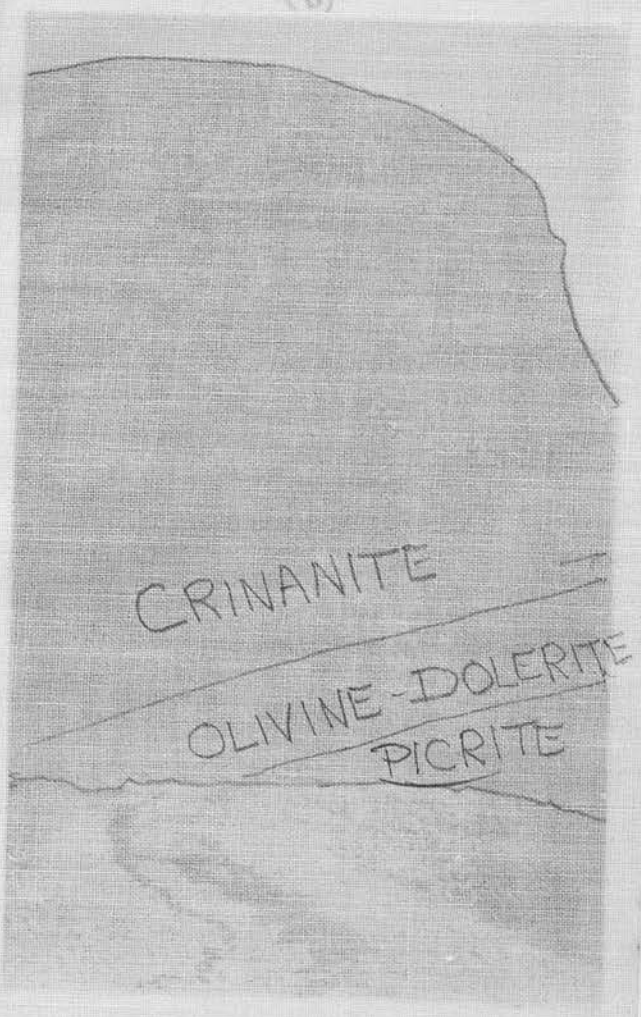
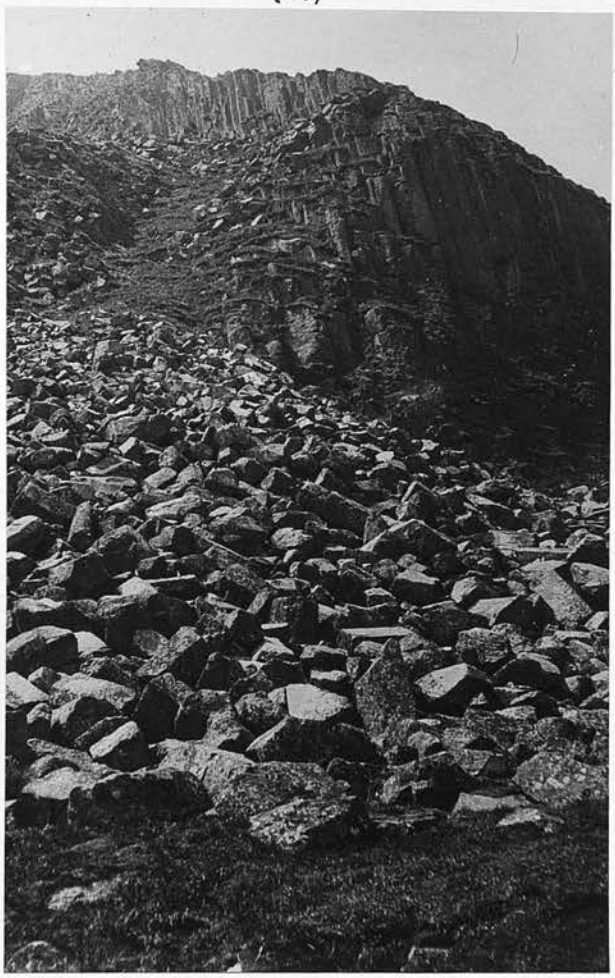


PLATE VII

(a)



(b)

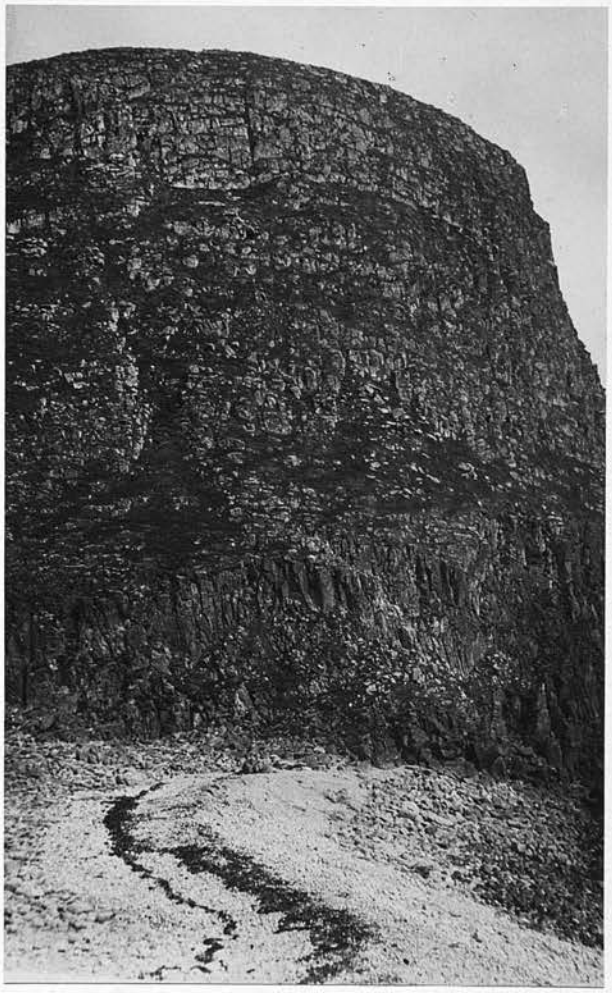
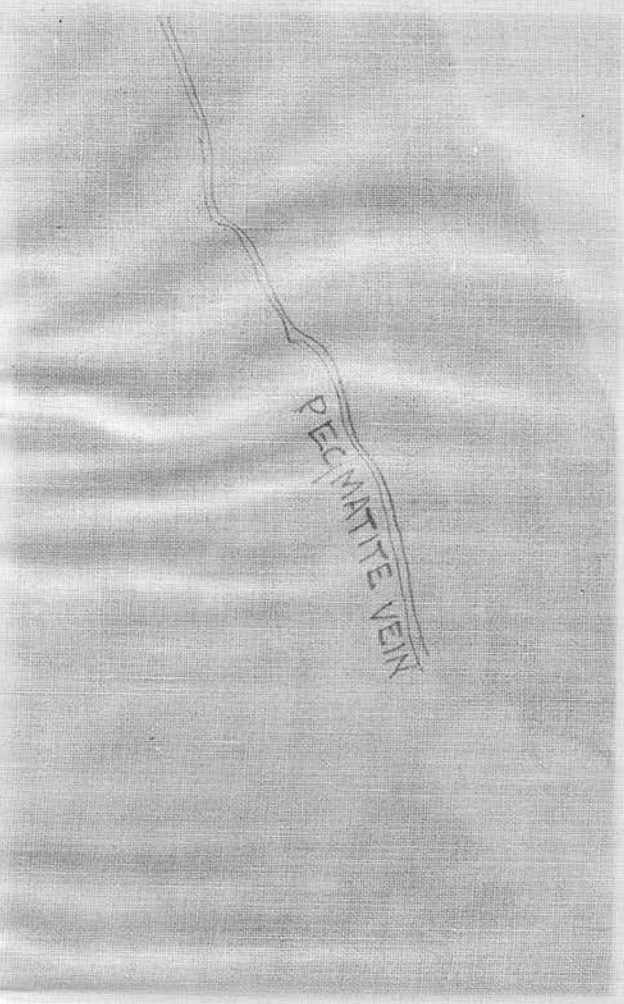


PLATE VIII.

(a) Columns of picrite on south-east shore of Garbh Eilean traversed by 4-inch pegmatite vein.

(b) 2-inch pegmatite vein traversing picrite with carious weathering. South-east shore of Garbh Eilean.



(b)

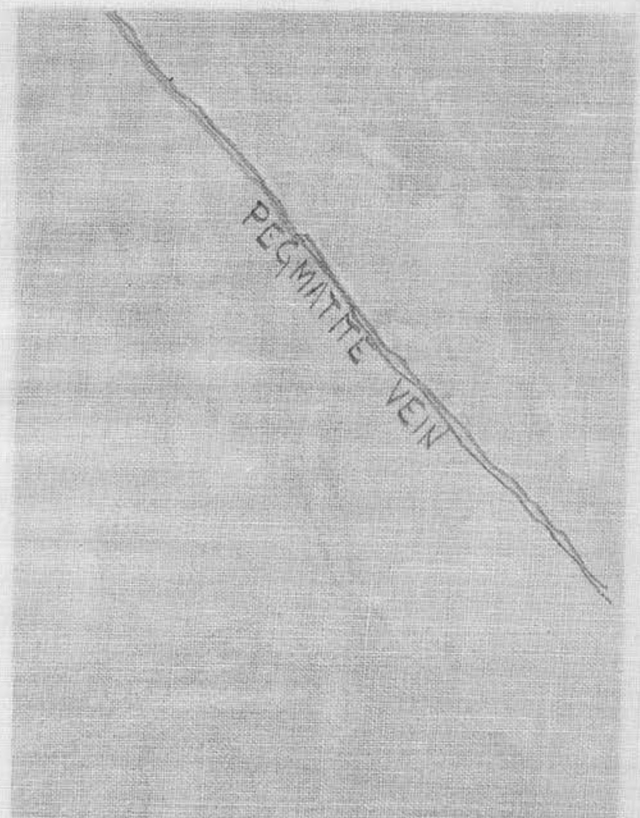
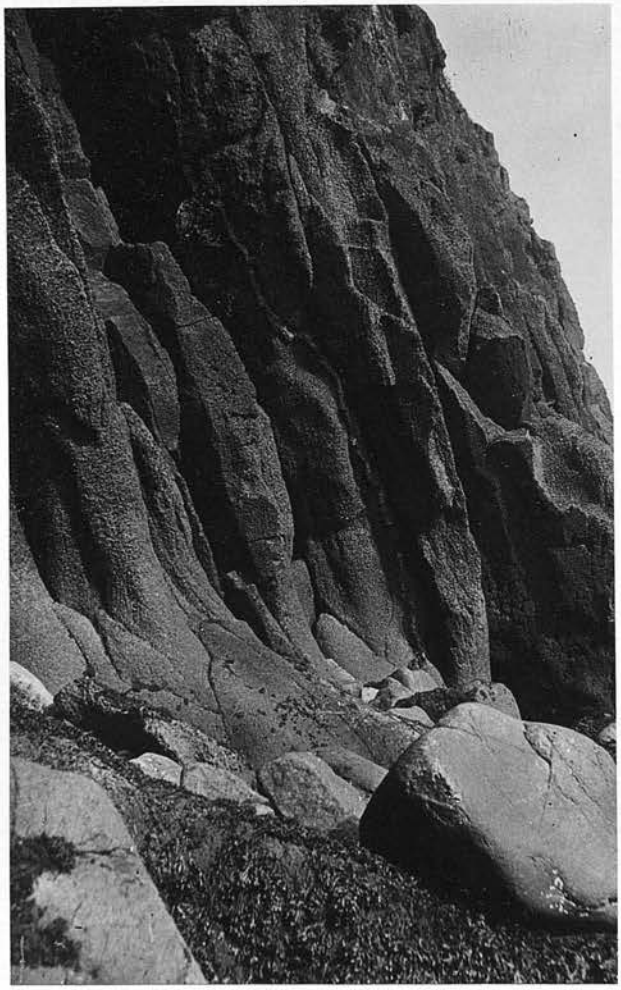


PLATE VIII

(a)



(b)

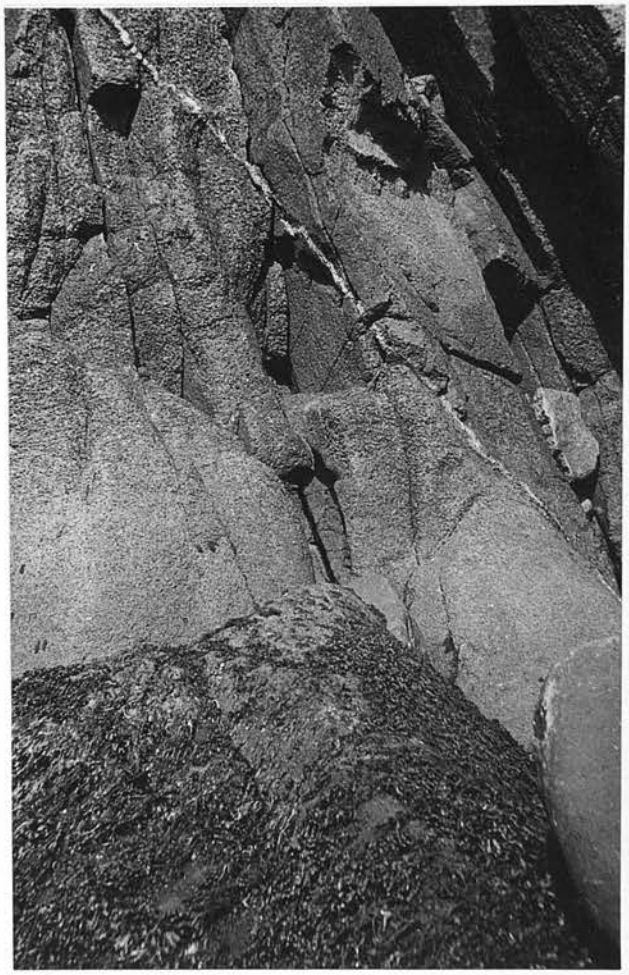
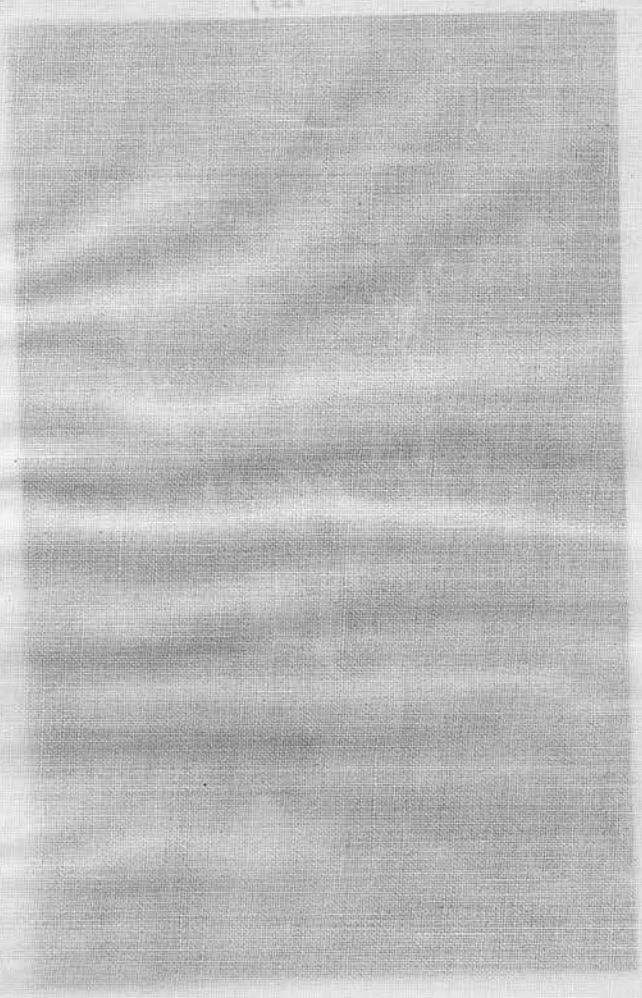


PLATE IX.

(a) Lower crinanite sill of Eilean Mhuire, showing sea-birds nesting on cliffs. North-west of Eilean Mhuire.

(b) Jurassic strata overlying crinanite sill. North-west cliff of Eilean Mhuire.

(a)



(b)

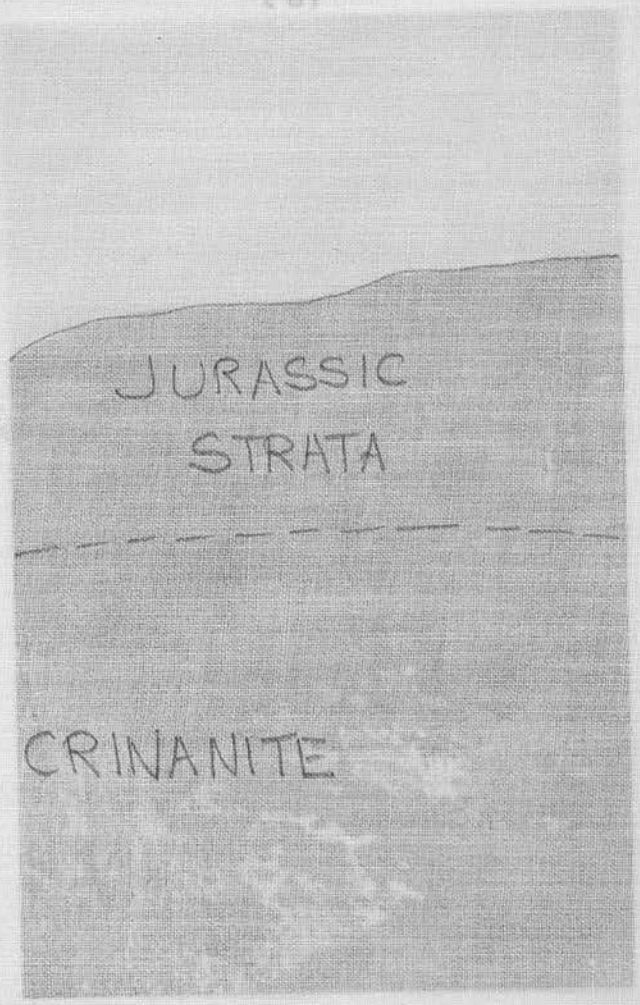
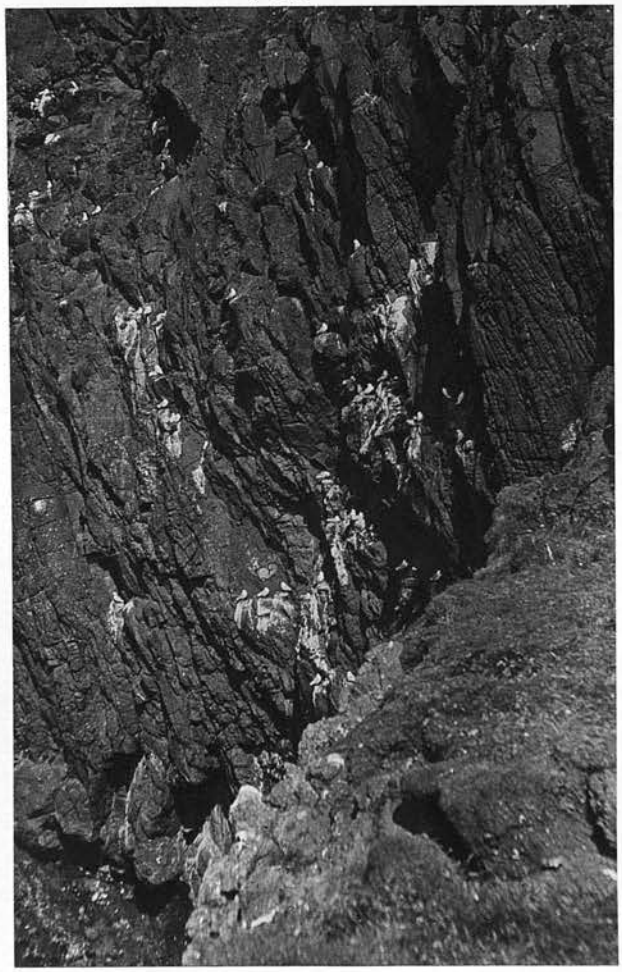


PLATE IX

(a)



(b)

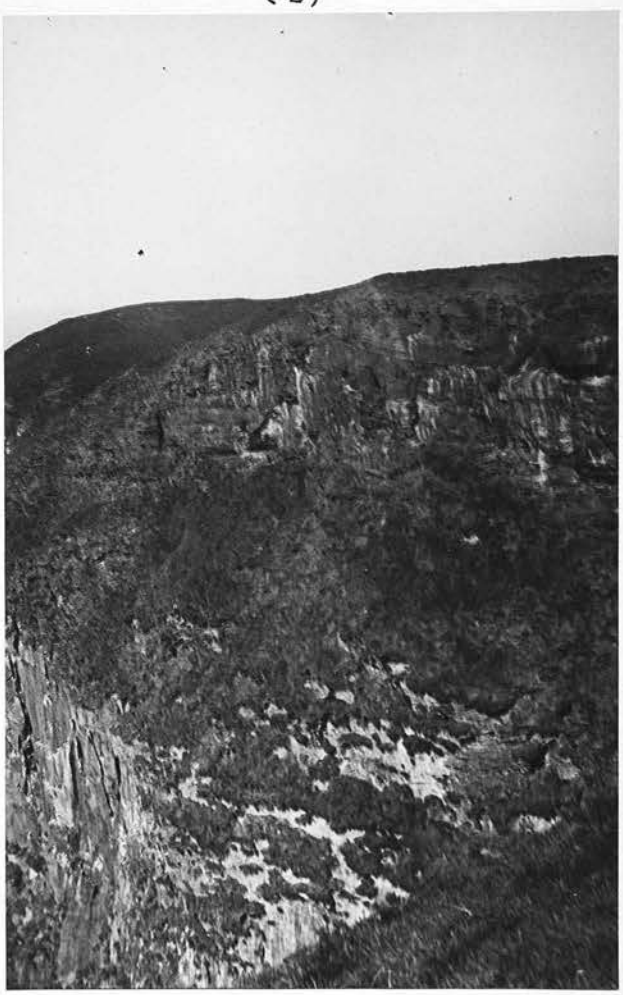


PLATE X.

Fig.1. Picrite from base of cliffs at extreme S.of Garbh Eilean
Rounded grains of fresh olivine are poecilitically enclosed on the right of the field by augite, and on the left by bytownite. Fluid inclusions and small grains of magnetite are enclosed by the olivine. The larger dark areas are serpentinous, and a vein of doubly refracting zeolites traverses the field from top to bottom. x 18.

Fig.2. Basic olivine-dolerite, 30 ft. higher in sill than Fig.1
Rounded grains of unaltered olivine are still abundant an tend to form composite groups. Felspar has increased in quantity but diminished in grain. Ophitic augite on the right of the field shows well marked zoning. x 18.

Fig.3. Crinanite, 70 ft. higher in sill than Fig.1.
The olivine is decidedly less abundant but still retains its granular habit. The augite, however, is more ophitic and also encloses olivine near the left of the field. The rock is more felsic than Fig.2. x 18.

Fig.4. Crinanite, 125 ft. higher in sill than Fig.1.
The mineralogical composition of the rock is similar to that of Fig.3., but the olivine at the bottom of the field is distinctly ophitic and deep coloured, probably owing to incipient alteration. x 18.

PLATE X

Fig. 1.

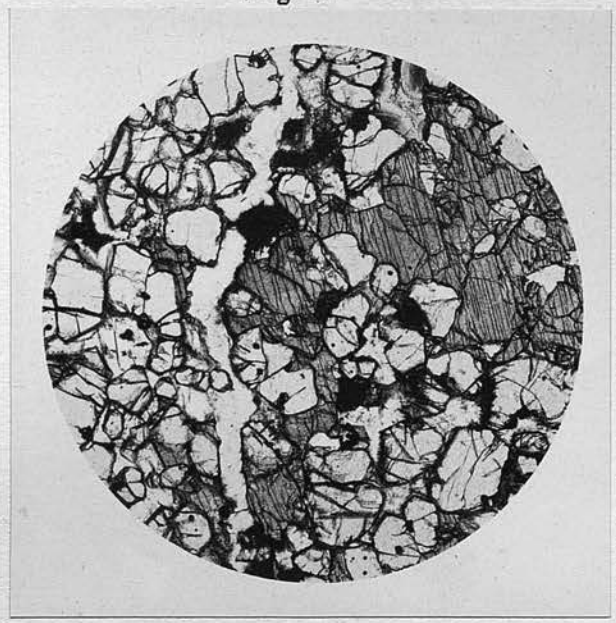


Fig. 2.

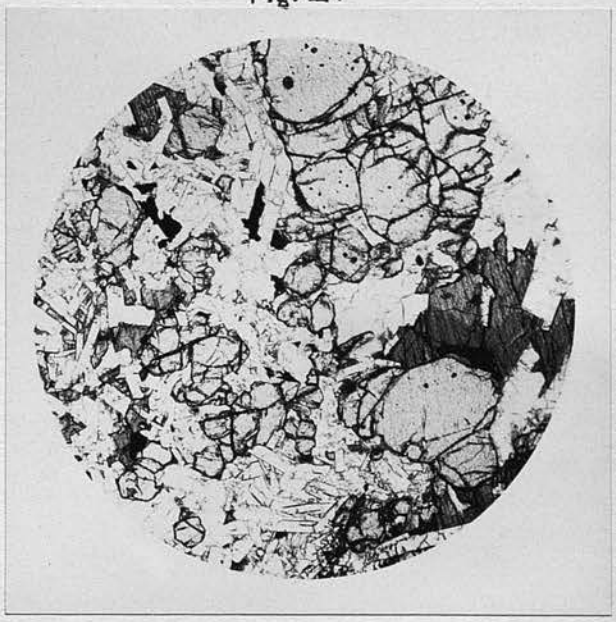


Fig. 4.

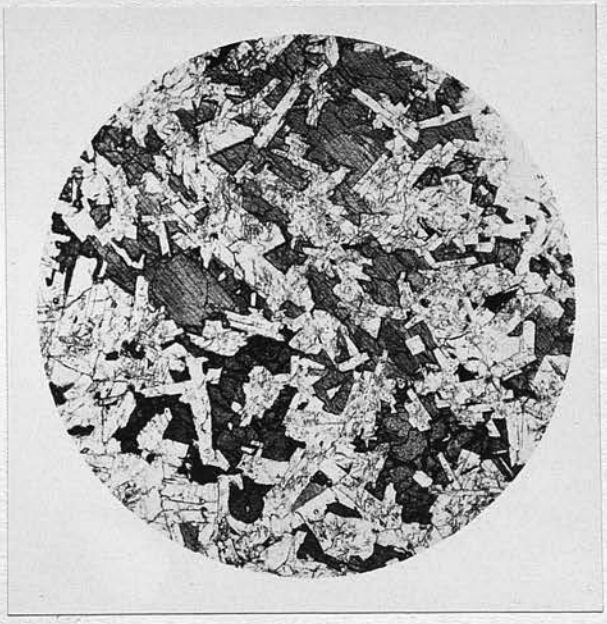


Fig. 3

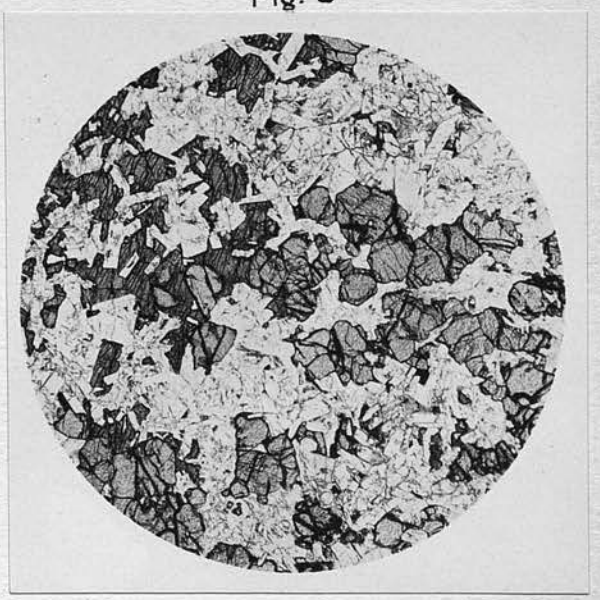


PLATE XI.

Fig.1. Crinanite, 250 ft. higher in sill than PLATE X Fig.1. The mineralogical composition remains the same as PLATE X Fig.4, but the olivine shows alteration to serpentine along cracks and is less strongly coloured. x 18.

Fig.2. Crinanite, 400 ft. higher in sill than PLATE X Fig.1. The mineralogical composition is unchanged except for the appearance of skeletal ilmenite crystals in the lower half of the field, but the olivine is less altered than in the previous Fig. x 18.

Fig.3. Pegmatite vein in dolerite, S. end of Sgeirean Mol na h-Athadh, Eilean an Tighe.
A large plate of zonal titanaugite at the right of the field encloses ophitically laths of acid labradorite which are turbid and partly analcitised. At the left of the field an area of dark mesostasis penetrated by apatite needles is seen, while several large crystals of iron ore appear at the bottom. x 18.

Fig.4. Syenitic segregation in dolerite, S.W. side of Galta Mor, 10 ft. above sea level.
The rock consists essentially of large plates of alkali felspar -- mainly soda-orthoclase. Dark serpentinous decomposition products are seen near the top of the field, and a hexagonal area of analcite (possibly after nepheline) may be detected at the bottom. x 18.

PLATE XI

Fig. 1

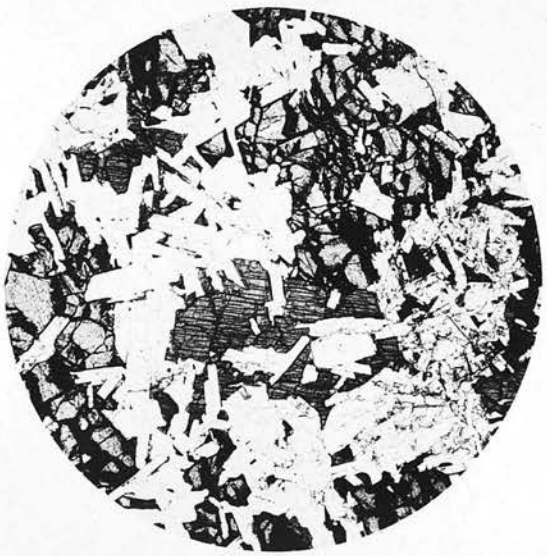


Fig. 2.

Fig. 3.

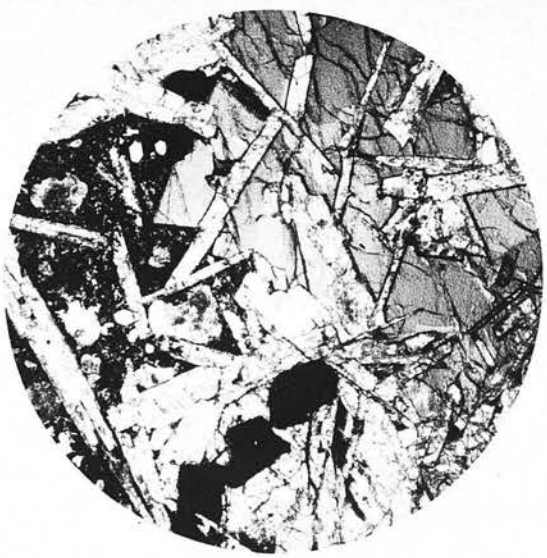


Fig. 4

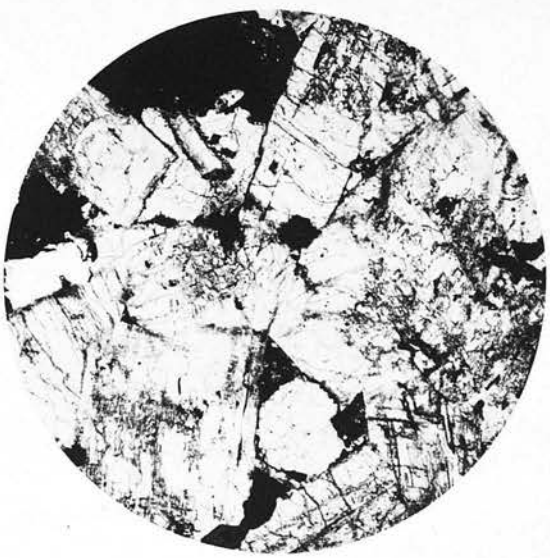


PLATE XII.

Fig.1. Syenitic segregation in composite sill, extreme E. of Eilean Mhuire, 25 ft. above sea level. X nicols.
The field is made up almost entirely of large plates of alkali-felspar -- soda-orthoclase and albite, the latter showing lamellar twinning. One or two small crystals of aegirine-augite are enclosed in the felspar. x 18.

Fig.2. Analcite-dolerite, extreme E. of Eilean Mhuire, sea level
A large crystal of titanaugite to the left of the field is penetrated subophitically by laths of partly analcitised plagioclase. Ilmenite is conspicuous near the top and bottom of the field, and a crescentic area of analcite is equally prominent to the right. x 18.

Fig.3. Olivine-basalt, sill cutting syenite, extreme S. of Eilean Mhuire, 30 ft. above sea level.
Small grains of olivine, augite and magnetite together with laths of labradorite make up the even textured rock. The pyroxene is dark, subophitic, and associated with decomposition products. x 35.

PLATE XII

Fig. 1

Fig. 2.

Fig. 3

Scale

0 1/4 1/2 3/4 1 Mile

Sgeirean a' Bhaigh

Tobhaichean Caola

Glaic na Crotha

Àiridhean a' Bhaigh

Natural Arch

Toll a' Roimh

Bidean a' Roimh

Rudha Stocanis

375

528

Mullach Buidhe

Carnach Mhor

Garbh Eilean

Rudha nan Sgàrhb

Airidhean nah-Annaid

Airidhean na Càrnaiche Mòire

470

Galta Beag

Sròn Lionta

Mol Mòr

Mol na h-Athadh

Sgeirean Mol na h-Athadh

Leòidean Mòra

Eilean an Tighe

High Water Mark of Ordinary Spring Tides

410

Leac Nighe

Pile

Càmpar

Mianuis

Sgeir Mhiannuis

Clach Uaine

Ciugh Rudha

Cadha na Gaoidhsich

Eilean Mhuire

Àiridh Mhuire

Bid na Faing

290

25

Bagh Chlann Neil

BASALT VEINS

Seann Chaisteal

140

Sgeir na Ruideag

BASALT VEINS

Continuation westward

Damhag

Galta Mor

Sgeir Mhic a' Ghobha

Staca L'àidir

Bodach

Galta Beag

Galtachean

Geological Map of the SHIANT ISLANDS

by

F. WALKER, M.A., Ph.D.

Peat

Syenite and Essexite.

Picrite.

Olivine-dolerite, Crinanite, Teschenite.

} INTRUSIVE INTO UPPER LIAS AND PRESUMABLY TERTIARY

g3 Shales etc. } UPPER LIAS (WHITBIAN)

—·⊥·— Faults, a crossmark on downthrow side.

\+ Horizontal strata.

25↙ Dip of strata, amount in degrees.

▽ 470 Heights shown thus, are by Aneroid and are only accurate to the nearest 10 feet.

G.G.T.