ABSTRACT.

The Cnoc nan Cuilean Area of the Ben Loyal Igneous Complex.
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The Ben Loyal igneous complex forms a group of mountains, situated about six miles to the south of Tongue in northern Sutherland.

The three plutonic masses of the complex are (a) The Ben Loyal range, (b) Cnoc nan Cuilean, and (c) Beinn Stumanadh.

Though all three are composed essentially of syenites, each presents distinct petrographic features, and the Cnoc nan Cuilean mass, unlike the other two, shows a development of basic contact and basic marginal igneous rocks.

The present paper is concerned primarily with the petrology of the Cnoc nan Cuilean mass, but the Ben Loyal intrusion is also considered in connexion with the form and structure of the complex.

The country rocks are dominantly highly siliceous granulites of the Moine Series, which, beyond the area affected by the intrusions, dip at 20° - 30° to the south-east. As the igneous areas are approached, the strike tends to become parallel to the intrusion margins and the dips become steeper. It is suggested that the Ben Loyal and Cnoc nan Cuilean intrusions are irregular cones in shape, with their apices pointing downwards and with marginal sheet-like apophyses.

The igneous rocks of the Cnoc nan Cuilean area are (a) the main syenite (pulaskite), composed essentially of anorthoclase and albite (largely intergrown as perthite) and aegirineaugite (b) variable marginal syenites, consisting of more melanocratic syenites, "basic patches" (composed of aegirineaugite) and evident xenoliths. These are traversed by complex sets of pegmatite and aplite veins and small dykes.

In the vicinity of the igneous mass the Moine granulites have been transformed metasomatically into rocks ranging from highly albitic granulites to aegirine-augite-schists and hornblende-schists. Chemical and mineralogical evidence shows that the alkalies (principally soda) and alumina were "fixed" first and also possessed the greatest mobility. Later, such additional constituents as lime, magnesia and iron oxides formed aegirine-augite and hornblende: these minerals attain their maximum development in the immediate vicinity of the contact.

The source of the metasomatizing agencies is difficult to ascertain, but it seems very improbable that they were supplied by a syenitic magma. It is therefore suggested that "primary" alkalumina emanations displaced cafemic constituents from deep-seated "rocks of Lewisian type" thereby providing the materials necessary for the development of the marginal metasomatic rocks. The rocks of Lewisian type, which consist of hornblende-gneisses and schists, occur interbanded with the Moine granulites and, although they are not exposed at the surface nearer than the north-western slopes of Ben Loyal, there is structural evidence for their existence below the Cnoc nan Cuilean mass.

The igneous contact itself is often characterized by transitions from basic schists to basic marginal syenites. A significant feature of these phenomena is the assumption of igneous characters by the more felspathic foliae of the schists and their injection into the basic bands.

The contact transitions are considered to be rheomorphic phenomena, representing the final stage in the process of metasomatism, whilst the variable marginal syenites are interpreted as due to the hybridization of modified basic-metasomatic rocks (as represented by the "basic patches") by felspathic syenite magma("migma") of rheomorphic origin.

THE CNOC NAN CUILEAN AREA OF THE BEN LOYAL IGNEOUS COMPLEX

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BY

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THE CNOC NAN CUILEAN AREA OF THE BEN LOYAL IGNEOUS COMPLEX

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[Plates III–VI]

Contents

I. Introduction

The Ben Loyal Igneous Complex forms an impressive group of mountains situated in northern Sutherland about six miles south of Tongue. The rock types include three distinct varieties of syenites, composing respectively the Ben Loyal range, Cnoc nan Cuilean and Ben Stumanadh, together with related syenites, aplites and pegmatites which constitute numbers of dykes, sheets and veins.

The only previous work on this area of which an account has been published was carried out by the officers of the Geological Survey during the mapping of sheets 108 and 114 (Scotland). In the Geological Survey memoir on Central Sutherland (1931, pp. 174–9), H. H. Read gives a brief description of the field occurrence and petrology of the syenites; the rocks are described as unfoliated syenites and nordmarkites and their general petrographic characters are noted. The evident similarity of the Ben Loyal rocks to those of the Loch Ailsh intrusion is demonstrated both mineralogically and with the aid of chemical analyses. For more general references see J. Phemister (1936, p. 57) and E. B. Bailey and O. Holtedahl (1938, p. 35).

During the investigation here recorded, a field study was made of the Cnoc nan Cuilean and the Ben Loyal intrusions, and, for purposes of comparison, several traverses were made over the Ben Stumanadh mass.

The primary purpose of this paper is to describe and interpret the petrography of the Cnoc nan Cuilean mass. This intrusion presents features not to be seen in the other two masses, namely, the development of basic contact and basic marginal igneous rocks. Since, however, the forms of all the intrusions show features in common, the field evidence afforded by the Ben Loyal mass is also considered.

Broadly the complex is of Caledonian age. The Moine granulites had already attained their present regionally metamorphic character when the syenites were emplaced, for they have been contact-metamorphosed by the intrusions. Furthermore, the main syenites are free from signs of foliation or shearing.

Cnoc Creagach (Craggie), immediately to the north of Ben Hiel, consists of breccias and conglomerates of Middle Old Red Sandstone age which contain boulders and pebbles of the Ben Loyal syenites.

From the close chemical and petrological similarities of the Ben Loyal rocks with the syenites of Loch Ailsh (Phemister 1936) and Cnoc na Sroine (Shand 1910), it is reasonable to suppose that all three complexes are coeval, if not also fundamentally comagmatic (cf. Read 1931, pp. 178–9). It is also interesting to observe that the Loch Ailsh mass has been involved in the post-Cambrian thrust-movements.

The Ben Loyal intrusions are therefore considered to be of " Newer Granite " age (that is, late Caledonian), probably ranging into Lower Old Red Sandstone times.

II. Field Relations

The plutonic rocks of the complex consist of (a) the Ben Loyal Range mass, occupying an area of about 7 square miles; (b) the Cnoc nan Cuilean mass, with an area of approximately 1½ square miles; and (c) the Ben Stumanadh masses, occupying about 3 square miles and presumed to consist of a series of irregular sheets.

(a) The form of the Cnoc nan Cuilean and Ben Loyal intrusions and their structural relationships to the country rocks

The country rocks are dominantly highly siliceous granulites of the Moine Series. Beyond the area affected by the intrusions, they maintain a remarkably constant strike and dip: the strike is approximately north-east and south-west, whilst the dip is 20°–30° to the south-east. Only one small band of pelitic schists has been found in the vicinity of the complex, in Allt Innis Ceann an Locha.

Interbanded with the Moines to the north-west and west and south of the Ben Loyal range is a series of belts of hornblende schists and gneisses (" rocks of Lewisian Type " of Read 1931). These are, however, not found in contact with the intrusive rocks.

As will be seen from the map (Pl. VI), there is a remarkable deflection in the strike of the country rocks as the igneous areas are approached. Towards the contact the strike-lines become parallel to the intrusion margins. Even at distances of two miles from the igneous masses, this re-orientation is often evident. With few exceptions, the dip of the granulites is towards the contact, and as the latter is approached the dip increases to about 45°–60°. Locally, the granulites are highly crumpled in the immediate vicinity of the intrusions, as on Creag na Speirig and to the north of Ben Hiel.

Although actual contacts are rarely visible, they can generally be located with a possible error of only a few yards. On the map, areas are left blank where there are no exposures and where, in consequence, there is little or no evidence as to the position of the contact.

Visible contacts are as follows :—

(a) Ben Loyal mass: (1) in Allt Chaonasaide; (2) at frequent intervals on the steep slopes to the north-west of the main peaks of Ben Loyal; (3) in Allt Fhionnaich; (4) in Allt Innis Ceann na Lochà; and (5) on Creag na Speireig.

(b) Cnoc nan Cuilean: (6) on the north-west and west slopes of Cnoc nan Cuilean; (7) on the slopes of Meall Eudainn; and (8) in the falls and rapids of Allt Torr an Tairbh.

In some localities (for example, 2, 3, 5, and 8 above) the granulites are seen to pass underneath the syenites at various angles (sometimes concordantly, elsewhere discordantly), whilst small subsidiary sheets of syenite or syenite-aplite are developed beyond or below the main contact. All visible junctions are on steep slopes and, without exception, syenite occurs at higher levels than the granulites, though the actual altitude varies greatly from place to place. The contact is seen to rise from 750 to 1250 feet as one proceeds from Allt Chaonasaide towards Allt Fhionnaich; whilst on Creag na Speireig and Cnoc nan Cuilean it is at 1500 or 1600 feet. Although no contact is visible along the shores of Loch Loyal (except at Allt Torr an Tairbh), it cannot there exceed 750 feet, and to the east of Ben Hiel it must be below 400 feet.

The precise form of the intrusion is difficult to ascertain, though it is clearly not laccolithic, as Phemister suggests (1936, p. 57). The country

TABLE I.—CLASSIFICATION OF THE ROCK GROUPS

Rock Groups		Chief Rock Types	References to Descriptions
	Country rocks	Siliceous granulites	F, p. 153; P, p. 164.
Metamorphic aureole	Zone A: Contact metamorphism	"Glazed" granulites.	F, p. 155; P, p. 165.
	Zone B: Metasomatism	Basic schists, banded rocks, etc.	F, p. 155; P, p. 165.
	Zone C: Transition rocks	Rheomorphic and mobilized rocks	F, p. 155; P, p. 165.
The igneous complex	Variable marginal syenites	Rocks of hybrid origin, basic syenite, basic patches, aplites, etc.	F, p. 150; P, p. 159.
	Main syenite	Homogeneous alkaline syenite (pulaskite)	F, p. 150; P, p. 157.
Minor intrusions	Aplites, pegmatites, etc.	—	F, p. 157.

Note: In the last column, F = field relations and P = petrography.

rocks at visible junctions pass underneath the marginal syenite, which suggests that the intrusions narrow in depth. Perhaps the intrusions are shaped like irregular cones with their apices pointing downwards and with marginal sheet-like apophyses, thereby resembling the funnel-shaped bodies to which Salomon (1903, p. 310) has given the name "ethmolith". Balk (1927, fig. 39, p. 299) suggests that the Cortlandt Complex (Peekskill, N.Y.) may have a similar structure. An account of other comparable examples from the south-western United States and northern Mexico has been given by H. Schmitt (1933, p. 12).

(b) The Rocks of the Cnoc nan Cuilean Area

(i) The Main Syenite

This is the rock type to which the brief descriptions on pp. 175–6 of the Survey memoir (Read 1931) largely apply. The bold dome of Cnoc nan Cuilean (1828 feet) and the elevated area extending to the crag-lines at the top of Meall Eudainn and Meall nan Cat are formed of this relatively homogeneous syenite. Excellent rock surfaces are exposed, largely in the form of *roches moutonnées.*

The rock is massive, moderately coarse-grained, and of a pink colour, speckled with small, dark green prisms and grains of pyroxene. Felspar, the dominant constituent, forms crystals, up to about 0·5 cm. in length, which frequently show simple twinning. Occasionally, vertical joints, usually trending approximately north-west and south-east, have been emphasized by weathering. Though the rock is mainly homogeneous, local variations in composition do occur, and these are significant in view of the characters of the marginal zone. Thus there are frequently found (a) patches, strings and winding channels of pyroxene aggregates; (b) undoubted xenoliths, generally of finer grain and always of more basic composition than the host, though composed of the same minerals as the latter; and (c) considerable areas with very sparse mafic minerals, but clearly grading into, and quite continuous with, the main syenite.

(ii) The Variable Marginal Syenites (the Basic Xenolith and Hybrid Zone)

Extending inwards from the contact, and often attaining a width of several hundred yards, is a zone of basic syenites characterized by extreme structural complexity. These rocks are particularly well exposed in the line of crags (at about 750 feet) which extends from the falls in Allt Torr an Tairbh, above Loch Loyal Lodge and around the upper slopes of Leitirmhòr and Meall Eudainn.

The rock types may be described as follows :—

(*a*) *The " Syenites "*.—The host rocks are a group of extremely variable syenites. Although all are composed of felspar and pyroxene, the relative proportions of these minerals vary between very wide limits and in a strikingly irregular manner.

A number of varieties may be recognized. Occasionally the transition between them is abrupt (though never sharp), but more commonly one grades imperceptibly into another.

(1) A moderately coarse-grained, somewhat leucocratic type with equigranular texture and pink colour, variegated by small specks of dark green pyroxene.

(2) A compact, finer-grained type of basic syenite.

(3) A type in which small grains of pyroxene occur in irregular winding aggregates (cf. variation (a) of the main syenite).

(4) A type characterized by a schistose texture, wherein both felspar and pyroxene are of about the same grain-size (up to 2 mm.) and show a common alinement of crystals. Somewhat leucocratic and melanocratic varieties occur : these may alternate and produce a distinctly banded or foliated rock.

It is noteworthy that by local increase in grain-size, small areas become pegmatitic in texture (see below).

(*b*) *The "Basic Patches"*.—The "syenites" are often crowded with basic patches (compare the "basic knots" of Phemister 1926) composed almost entirely of pyroxene (cf. Pl. III, fig. 2). These vary in size from 8 or 10 cm. across, down to a few millimetres, and in outline are rounded or smoothly angular; frequently they possess a schistose texture. Though often fine- or medium-grained (0·5 to 1·0 mm.), in exceptional cases large crystals of pyroxene, even attaining a size of 1 cm., have been noted. In these examples the host rock tends to be pegmatitic. As a rule, the margins of the basic patches are perfectly sharp, though sometimes they are obscured by impregnations of the surrounding felspathic material.

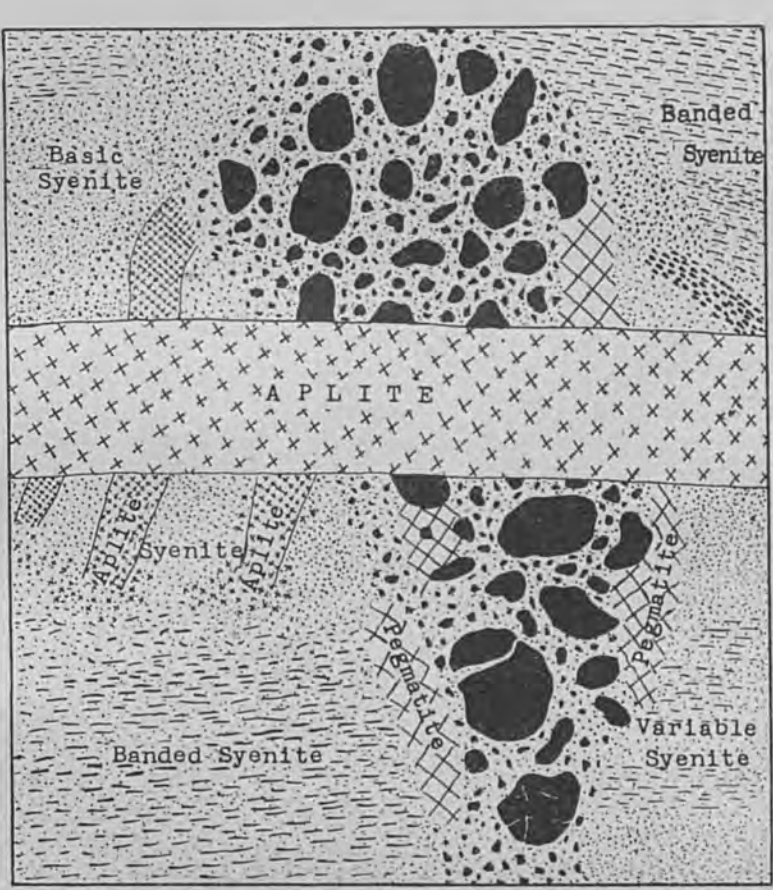

FIG. 1.—Diagrammatic illustration of variable syenite from crags above Leitirmhòr. The relations between basic patches, pegmatites and aplites are clearly shown. The largest aplite vein is about 2½ inches in width.

(*c*) *Dykes and Veins*.—The extreme abundance of the small dykes and veins in these rocks and the complexity of their relationships makes it evident that they represent an essential and significant part of the marginal zone.

Pegmatites form veins (0·5 to 3 cm. across) and irregular areas in the syenites. Frequently the basic patches are surrounded by pegmatitic material [see also (a) and (b) above]. Some of the pegmatites are formed only of felspar, or of quartz and felspar, but others contain, in addition, large crystals of pyroxene and actinolite, which commonly occur in bands parallel to the vein margins. Particularly in the case of the irregular areas of pegmatite, the junctions with the surrounding "syenites" are diffuse and gradational (Figs. 1 and 2). In many places the syenite appears to be impregnated with pegmatite material, rather than cut by it.

Pegmatites composed essentially of felspar and large crystals of magnetite (1 to 2 cm. long) are not uncommon. A qualitative analysis showed that the magnetite contains a small proportion of titania, but no appreciable amount of any other likely minor constituent.

Aplites are extremely abundant, varying in dimensions from the size of small dykes (6 inches to 1 foot) down to tiny veins which frequently form ramifying networks of extreme complexity (Figs. 1 and 2). In texture the aplites are of medium grain and are largely composed of felspars, with sparse mafic minerals and occasional quartz. Two phases

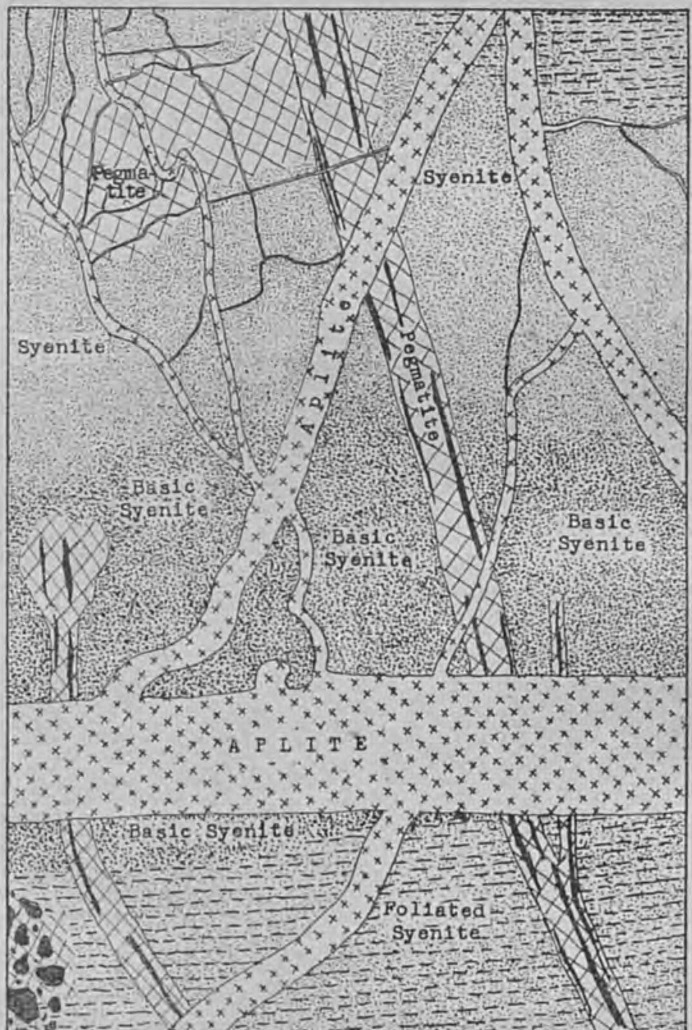

FIG. 2.—Diagrammatic illustration of variable syenite from crags above Leitirmhòr, showing the complexity of the networks of pegmatites and aplites. The largest aplite vein is 4 inches in width.

of aplitic injection can be distinguished. The earlier aplites occur as irregular veins which often grade into the surrounding basic syenites and impregnate them with felspathic material. They cut the pegmatite areas, but are, in turn, cut by the later aplites. The latter, considerably the more numerous group, form dykes and veins cutting sharply across "syenites", basic patches, pegmatites and earlier aplites. The later aplites in particular form intricate networks of bifurcating veins (Figs. 1 and 2).

Finally, there are found thin straight veins of clear quartz, which cut all the other rocks described. Locally such veins are occupied by flat blades of deep green actinolite.

These phenomena are developed on so small and intricate a scale that they are often clearly exhibited in hand-specimens (cf. Pl. IV, fig. 2).

No boundary of any kind exists between the basic syenites and the main syenite. The latter differs only in being less variable and more leucocratic. Further, there is no distinction between the main syenite and the more felspathic areas in the marginal zone.

(iii) The Country Rocks

The country rocks of the Cnoc nan Cuilean area consist almost exclusively of typical quartz-felspar granulites of the Moine Series (Read 1931, p. 36). Stream sections in the practically unmodified granulites are provided by Allt Innis Ceann an Locha, Allt na Dalach Rhiabhach and Allt Bealach na Beiste. In hand-specimens the rocks are usually massive and coloured grey, white or pink. They have a gritty appearance, with abundant grains of quartz. Occasionally they are flaggy, owing to the concordant orientation of flakes of muscovite along certain "bedding" planes. Types with a small proportion of biotite also occur.

No belts of hornblendic rocks of Lewisian type are found nearer than the west and north-west slopes of the Ben Loyal range (Pl. VI). Since, however, there is a possibility that they may occur in depth, beneath the intrusion, they must also be considered. They consist principally of hornblende schists, hornblende granulites and coarser-grained hornblende gneisses. Interbanding of all these types is common. The chief minerals are hornblende, felspar and quartz: with increase in the proportion of hornblende the rocks become dark green schists, whilst with dominant felspar they become light-coloured felspathic gneisses.

(iv) The Metamorphic Aureole

Proceeding towards the contact from the unaltered granulites, the following zones may be distinguished:—

(A) A zone of contact metamorphism without indications of appreciable addition of material.

(B) A zone of metasomatism in which the rocks have been chemically modified, but with retention of the original structures.

(C) A transition zone, characterized by change of composition and structure; the progressive change being towards the production of "igneous" rock types. In many cases no actual contact occurs, but locally there are signs that the material became mobile.

The first two divisions correspond to those recognized by Goldschmidt in the Kristiania region (Goldschmidt 1911, p. 108). The third illustrates the process referred to by Backlund as "rheomorphism" (Backlund 1937, p. 234).

It is noteworthy that the zones B and C are not disposed regularly around the intrusion. Those rocks which exhibit effects to be ascribed merely to the reheating and partial recrystallization of the normal granulites are, as would be anticipated, fairly uniform in their distribution and extend to distances of about a quarter of a mile from the contact. The zone of metasomatism, on the other hand, is variable both in width and in the composition of added material (Anderson 1937, p. 22). This complexity is seen particularly in Allt Torr an Tairbh, where, associated with the occurrence of numerous apophyses of syenite, there are correspondingly numerous zones of metasomatism (Fig. 3).

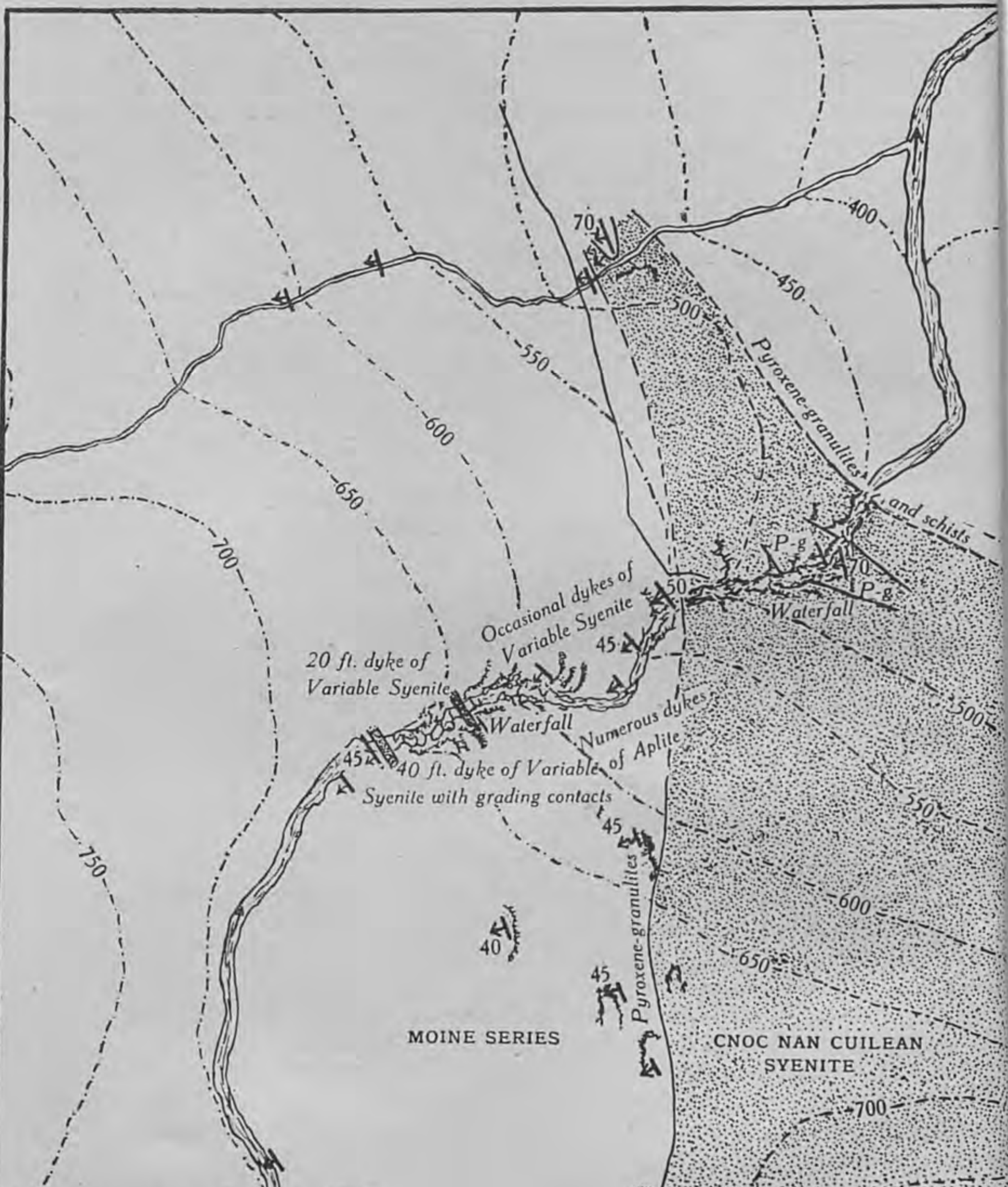

Fig. 3.—Sketch map of Allt Torr an Tairbh. Scale : 2·8 inches to 1 mile.
P.g. = pyroxene granulites and schists.

(A) *The Zone of Contact Metamorphism.*—Rocks of this zone may be seen to the east of Lochan na Beiste, in Bealach na Beiste and at intervals in Allt Torr an Tairbh. They are coarse-grained siliceous granulites of a white or pinkish colour; weathered surfaces show large blebs of quartz. Commonly, too, they show characteristically "glazed" surfaces. Where they are flaggy, large muscovite flakes occur on the foliation planes, while thin parallel, usually concordant, bands or veins of quartz are common.

(B) *and* (C) *Metasomatic and Transition Zones.*—Allt Torr an Tairbh provides an excellent section through a series of irregular sheets and dykes of syenite, which are apophyses of the main mass (Fig. 3). The stream descends in a series of rapids and falls from an elevated area (about 900 feet above sea-level) which is largely covered by peat, alluvium and drift. The last fall is a striking feature, about 40 feet in height, below which the stream meanders across a peaty plain to flow into Loch Loyal (392 feet above sea-level). The strike in the granulites is approximately north and south in the lower falls, but gradually swings towards north-west and south-east on the plateau. The dip varies from 20° to 70°, but is always in a westerly direction.

The first exposures encountered, on proceeding upstream, are in the entrance to a small gorge about 60 yards below the first fall. The rocks are pyroxene-bearing granulites, which grade into dark schists and banded rocks (454–458): all dip 20° to the west. Within a few yards variable basic syenite occurs. The actual junction is sometimes gradational, sometimes sharp, though irregular. Where a grading contact occurs, parts of the more leucocratic bands of the schists appear to assume a syenitic aspect and to impregnate or cut the more basic foliae. The leucocratic material has evidently been mobile. The foliation, from being regular, becomes crumpled, discontinuous and partly obliterated. The contact igneous rock often has a somewhat schistose texture also. Coarse-grained pegmatite areas are common and contain large blades of pyroxene (0·5 to 1 cm. in length). The pegmatites usually have indefinite outlines and merge into the host rock, which is in places pyroxene-schist, though more generally basic syenite.

The syenite extends underneath the schists, since the latter, for the next 30 yards, are found in the sides of the gorge, about 10 feet above the stream-level. Here transitions to basic syenite are well developed: considerable masses of crumpled schist occur, impregnated in places with felspathic material (see Pl. III, fig. 1). Two areas of basic schists, each about three yards in length, can be seen in the stream 40 yards below the fall. They show similar gradations towards variable syenites on their flanks. The syenite itself is characterized throughout by shadowy relics of schistose structures (Fig. 5).

Until the fall is reached, both sides of the gorge consist largely of schists and transitional rocks (mainly pyroxene-rich, but also containing hornblendic bands) which grade downwards into variable syenite. For the next 80 yards upstream, including the main fall, the rocks are all of variable syenite with many basic patches of dark schistose relics. Pink or orange-coloured veins and small dykes of aplite, with sharp contacts, are common in the syenite, which tends to become more leucocratic as it is traced upstream. At about 590 feet granulites appear again. Here they are largely glazed felspathic rocks (see p. 165); basic schists are found less abundantly. It is noteworthy that gradational boundaries are also less common.

In the higher falls of Allt Torr an Tairbh and up to about 680 feet the dominant rocks are glazed granulites. Large aplite dykes up to about three feet in width occur; they are often irregular and winding. In a fall at about 600 feet three aplite dykes cut the granulites, whilst two others are found above the fall.

Three large dykes or apophyses of variable syenite are exposed in this part of the stream. The largest is about 20 yards across and contains, along its centre, an aplite dyke three feet wide. The margins of the syenite are not exposed. Another, similar dyke shows gradational contacts, flanked by pyroxene schists. It is also cut by an aplite dyke.

Above the series of falls, the stream flows slowly and exposures are fewer and poorer. At about 715 feet, near a sharp bend in the course of the stream, another irregular intrusion of dark syenite occurs. The neighbouring rocks show rapid gradations from glazed siliceous granulites, through dark hornblende schists, to basic syenite. Banded schists are common, and, as the igneous rock is approached, the lighter bands are seen to become irregular and to cut across or impregnate the darker bands. By further loss of the original structures, accompanied by increased mobility, dark syenite is formed. Elsewhere, moderately basic schists grade rapidly into a basic syenite.

On the north-eastern slopes of Cnoc nan Cuilean are found rocks similar to those occurring in the upper reaches of Allt Torr an Tairbh. Again the sequence is through hornblende schists. Banded schists with alternating hornblende-rich and quartz-felspar-rich foliae, are the dominant rocks. In patches the leucocratic bands become igneous in texture and send off tortuous veins and tongues into the basic schist (354–365). It is important to observe that these bands and veins are not directly connected with syenite and aplite; to begin with, only small portions of the felspathic bands become igneous in texture and behaviour. The remainder of each band retains the character of a normal felspathic granulite. In more advanced stages the basic bands are seen to have been broken up, distorted and twisted by invasive mobilized felspathic material. With more random orientation of the basic areas, the rock becomes a syenite with enclosed xenoliths.

It is necessary here to state the field evidence for the contention that the rocks described among the metasomatic types as hornblende schists are not the same as the rocks of Lewisian type referred to on p. 169. First, the rocks of Lewisian type always occur interbanded with the Moine granulites and extend for considerable distances along the direction of strike. Secondly, the occurrences of hornblende schists in the metamorphic aureole are always obviously related to igneous contacts and pass laterally into granulites, along either the dip or strike. Thirdly, no rocks of Lewisian type are exposed in the normal granulites, nearer than the north-western slopes of Ben Loyal (Pl. VI).

It appears reasonable to conclude that the hornblende schists which occur near the contacts have been formed in situ by metasomatic processes. It is highly probable, however, that schists of Lewisian type underlie the intrusion, and that these may have provided some of the materials that have transformed the granulites. This suggestion will be discussed more fully later (p. 178). Meanwhile, it should be noted that the ubiquitous inward dip in the vicinity of the syenite mass precludes the possibility that hornblende schists from the country rocks can have been forced upwards at the margins of the intrusion.

(v) Related Minor Intrusions

In Allt Torr an Tairbh there occur several large sheets or dykes of variable basic syenite; some of these are seen to be directly connected with the main syenite mass (see pp. 150, 159).

Aplite dykes and veins are common in all localities; they are particularly numerous in the marginal syenite zone and in the contact rocks, but are also abundant in the main syenite as well as in the granulites as far away as Allt Innis Ceann an Locha.

The aplites are medium- or fine-grained rocks of pink or pale-orange colour, and are composed largely of felspar, together with some quartz and sparse mafic minerals.

III. The Petrography of the Cnoc nan Cuilean Mass and its Metamorphic Aureole

(a) The Main Syenite

Since about 90% of the rock is composed of felspars, these minerals determine the textural features of the syenite.

The felspars consist of :—

(1) A soda-rich potash felspar with the following characters: α and γ, 1·522 and 1·529 respectively; specific gravity 2·56; optic axial angle relatively small—about 45° to 50°; and a wavy or patchy extinction which is sometimes accentuated to a hazy cross-hatching. These characters indicate a notable content of soda felspar. Calculations based on an analysis of the syenite (see Table II, column I, p. 160) suggest that the albite content may be as high as 20 or 25%. It is significant that Alling (1921) shows that values of this order are usual for many "potash" felspars, including a large number that have been described as normal orthoclase or microcline. The nomenclature of such felspars is discussed by Alling (1921, pp. 230–5, and 1936, pp. 59–69). The term "anorthoclase" will be adopted here.

(2) Albite, which has the following characters: maximum extinction angle in the [100–001] zone—13° to 15°; α and γ, 1·530 and 1·541 respectively; and positive optic sign. These characters indicate a composition of about Ab_{94}.

The greater part of the felspars are intergrown into beautiful perthitic textures, of which the following types may be recognized :—

(1) A regular banded intergrowth, ranging from a perthite in which albite occurs as fine strings or rods, to an antiperthite with dominant albite. The banding is approximately at right angles to the c-axis.

(2) A regularly flecked variety.

(3) A coarse "patch" perthite, in which the intergrowth is irregular (see Pl. V, fig. 1).

(4) A "plumose" variety: here the margin of the crystal is dominantly albite, from which narrowing tongues extend towards the interior (Alling 1938, p. 147).

(5) An antiperthite composed of albite enclosing numerous alined, rather fuzzy patches of anorthoclase.

The albite of the perthites is only twinned here and there, fine twinning often alternating with untwinned areas. In the regularly banded varieties the twin planes are generally at right angles to the bands. Where anorthoclase is subordinate, as in (5), the discontinuity of the albite twinning produces an effect similar to that of "chequer-albite" (Goldschmidt 1911, pp. 301–5; Becke 1913, pp. 124–5; Read & others 1926, pp. 26–7).

While it is realized that to a limited extent perthitic intergrowths may have been features of original crystallization (particularly in the case of the banded types), it is thought that the bulk of the albite crystallized after the anorthoclase and partly replaced it (cf. Gillson 1928, and Gilluly 1933). In support of this view the following points are ranged :—

(1) Albite is always clear, whilst the anorthoclase is usually cloudy.

(2) Every gradation exists, even in the same slide, between perthite and antiperthite. If the felspars were originally in the form of a metastable anorthoclase of approximately constant composition, the resultant re-crystallized perthites would, presumably, be of uniform type. Consequently, some other process must have operated.

(3) In the "plumose" varieties of perthite, the margining albite has the appearance of penetrating the enclosed anorthoclase. Alling (1938) suggests a replacement origin for similar perthites.

(4) Perthites occur in which the cross-hatching is developed only where there are strings of albite. This suggests that the cross-hatching may have been induced by stresses incidental to replacement by albite.

Commonly perthite forms large plates (up to about 0·5 cm. in length), approximately rectangular, though with somewhat irregular edges. Simple Carlsbad twins are abundant; in some cases the perthite intergrowth is "reflected" by the twin-plane. Frequently the perthite crystals contain "schiller inclusions": these are tiny black rods, possibly largely of hæmatite, and are orientated approximately parallel to the cleavage traces.

The dovetailing or saw-toothed sutures which are described by Phemister (Read & others 1926, p. 26) as characterizing the margins of the perthites of the Loch Ailsh mass have not been observed in this area. Marginal albite is often continuous with the albite component of a perthitic individual, whilst albite also occurs in smaller, irregular, independent grains lying between the perthite plates. Less commonly, small discrete grains of anorthoclase, without albitic intergrowths, may be observed.

Two extreme textural types can be recognized in the syenite, between which there is every gradation: (i) that in which the felspar is almost exclusively formed of large crystals of antiperthite and the two components are regularly intergrown (e.g., 352, 345); (ii) that in which large crystals are few and are dominantly of irregularly intergrown perthite, whilst individual anhedral grains of albite are considerably more numerous (215, 218).

In general it appears that (i) is more characteristic of the interior of the mass and that (ii) occurs nearer to the zone of variable basic syenites. It is noteworthy, moreover, that the ratio between potash and soda felspars remains approximately the same, namely 3 : 2, in both types.

Aegirine-augite is the most abundant coloured mineral and occurs either as stout, subhedral prisms (up to about 1·5 mm. in length), or as irregular, somewhat rounded grains or aggregates. It is a deep green, aegirine-rich variety and usually shows zoning. In general the marginal zones are more deeply coloured and the centres paler, but frequently the zoning is irregular and patchy, with sharp junctions between the various shades. The extinction angle increases with the depth of colour, rising to about 65° or 70° for $Z_{\wedge}c$ in the deep green varieties. 2V is rather large (65° to 70°), and the distinct inclined dispersion ($Z_{v\wedge}c > Z_{\rho\wedge}c$) produces abnormal tints near the extinction positions. The extreme refractive indices of a moderately coloured variety are $\alpha = 1{\cdot}690$ and $\gamma = 1{\cdot}715$, which gives a birefringence of 0·025.

Two types of alteration have been noted as affecting the aegirine-augite of the syenite.

(a) The most widespread is the development of ragged needles, spongy prisms and irregular outgrowths of a pale green actinolite, around, and sometimes penetrating, the pyroxene. Grains of iron ore and tiny blebs of clear albite are closely associated with the actinolite. The original outlines of the pyroxene are never preserved.

(b) In specimens of syenite which contain carbonate veins (232, 437) aegirine-augite is partially or completely pseudomorphed by carbonates; actinolite and grains of ore are associated, but these probably belong to alteration (a), which appears to be earlier than (b).

The inference is that (a) is due to the formation of new, lower temperature minerals at the expense of pyroxene, during a later stage in the development of the rock, whilst (b) is clearly of hydrothermal origin.

Wedges and irregular grains of brown sphene are usually abundant, particularly in proximity to the pyroxene. Small zoned grains and irregular patches of orthite are common (see p. 163). Apatite generally forms anhedral crystals, which are sometimes large and commonly clouded with smudgy inclusions. Actinolite occurs also in ragged crystals which have no evident relation to the pyroxene. Scattered magnetite, ilmenite, reddish flakes of haematite, brown secondary limonite and occasional grains of zircon are invariable accessories. In some sections a few flakes of fawn-brown biotite have been observed. Other secondary minerals are sericite and epidote, both of which develop from the felspars.

Chemical Composition and Comparisons.—In column I of Table II an analysis of a syenite from the summit of Cnoc nan Cuilean is given. It compares closely with an analysis already published (Read 1931, p. 177) of a rock from the south slope of Cnoc nan Cuilean. For comparison, analyses of other similar rocks are included in the table. Both mineralogically and chemically, the rock is well designated " pulaskite ", as defined by Phemister (Read & others 1926, p. 46). Those varieties which are poor in mafic constituents may be regarded as " perthosites " (ibid., p. 47). There is a very striking similarity between these rocks and the pulaskites and perthosites of the Loch Ailsh mass. In the lower part of Table II the normative composition of the pulaskite (column I) is given, together with the approximate mineral composition as calculated from the analysis, with the aid of a micrometric measurement made on a rock slice.

(b) The Variable Marginal Syenites

In general, the basic syenites and their associated basic patches contain an identical mineral assemblage. The variations take place in the proportion of mafic minerals, the grain size, and the texture. As the amount of the mafic minerals increases so the rock grades from pulaskite to albite-shonkinite or even to pyroxenite. According to the definitions of Shand (1921) and Phemister, pulaskites contain no more than 30% of mafic constituents.

The principal minerals are anorthoclase, albite and aegirine-augite.

With some exceptions, anorthoclase is more abundant than albite in the basic syenites, whilst perthites are less common than in the pulaskites. The following textural types may be distinguished :—

(1) A variety in which the felspar is largely composed of slightly

TABLE II.—CHEMICAL ANALYSES OF SYENITES

	I	II	III	IV	V	VI
SiO_2	62·16	63·33	64·28	61·60	60·20	60·89
Al_2O_3	16·82	16·98	17·13	17·11	20·40	17·14
Fe_2O_3	1·53	1·41	1·84	3·09	1·74	3·32
FeO	1·54	1·14	0·66	0·54	1·88	0·95
MgO	1·43	1·17	0·59	1·04	1·04	1·16
CaO	3·79	2·58	2·09	3·25	2·00	3·58
Na_2O	5·09	6·06	7·50	5·35	6·30	4·54
K_2O	6·39	5·90	4·02	6·11	6·07	5·71
H_2O +	0·24	0·18	0·13	0·63	0·23	1·22
H_2O −	0·05	0·14	0·04	—	0·10	0·39
CO_2	nil	0·00 ?	0·60	n.d.	nil	n.d.
TiO_2	0·38	0·53	0·39	0·79	0·14	0·49
ZrO_2	0·03	n.d.	0·06	n.d.	trace	n.d.
P_2O_5	0·35	0·24	0·14	0·06	0·15	0·27
Cl	0·02	n.d.	0·00	n.d.	0·09	n.d.
F	0·04	0·00 ?	0·01	n.d.	n.d.	n.d.
FeS_2	n.d.	0·14	0·00	n.d.	nil	n.d.
SO_3	n.d.	n.d.	0·08	n.d.	0·13	n.d.
$(Y,Ce)_2O_3$	trace	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	0·09	0·10	0·23	n.d.	trace	0·09
BaO	0·44	0·34	0·00	n.d.	n.d.	n.d.
SrO	trace	n.d.	0·00	n.d.	n.d.	n.d.
	100·39	100·24	100·09	99·57	100·47	99·94

I. Pulaskite, summit of Cnoc nan Cuilean. Specimen No. 352. Analyst: B. C. King.

II. Pulaskite, south slope of Cnoc nan Cuilean, $1\frac{1}{8}$ miles N. 10° W. of Inchkinloch. Analyst: B. E. Dixon. Read 1931, p. 177, column I.

III. Pulaskite, Loch Ailsh mass. Analyst: E. G. Radley. Read & Phemister 1926, p. 44, column II.

IV. Arfvedsonite-syenite, Melfi, Chad Territory, French Congo. Analyst: Pisani. Washington 1917, p. 422–3.

V. Pulaskite, Fourche Mountain, near Little Rock, Arkansas. Analyst: H. S. Washington. Washington 1917, p. 286–7.

VI. Quartz-banakite, Stinkingwater River, Yellowstone Park. Analyst: W. H. Melville. Washington 1917, p. 286–7.

NORMATIVE COMPOSITION (A) AND MODAL COMPOSITION BY WEIGHT (B) OF CNOC NAN CUILEAN PULASKITE, SPECIMEN NO. 352, COLUMN I ABOVE.

A

Quartz		1·05	Q = 1·05
Orthoclase		37·81	F = 83·11
Albite		41·18	
Anorthite		4·12	
Corundum		0·36	C = 0·36
Acmite		1·62	P = 12·25
Diopside	$CaSiO_3$	5·51	
	$MgSiO_3$	3·57	
	$FeSiO_3$	1·55	
Magnetite		1·41	M = 2·14
Ilmenite		0·73	
Apatite		0·84	A = 0·84
Zircon		0·06	Z = 0·06
Water			0·29
			100·10

B

Orthoclase ($Or_{73}Ab_{25}An_2$)	52·3
Albite ($Ab_{90}An_4Or_6$)	27·6
Pyroxene ($Di_{57}He_{26}Ac_{17}$)	16·6
Ores, etc.	2·6
Apatite	0·9
	100·0

Note: The formulae of the minerals given in parentheses are those required to correlate the normative composition with the modal measurements. For the pyroxene, Di = diopside, He = hedenbergite, and Ac = acmite.

cloudy anorthoclase, with a characteristic hazy extinction, having a grain-size of 0·1 to 0·5 mm., and forming a simple granular mosaic. Little rod-shaped "schiller inclusions" are common. Small crystals of clear albite are wedged between the grains of potash-felspar and often overlap or penetrate them. Frequently the albite is untwinned. More complicated intergrowths of anorthoclase and albite are not uncommon, though large perthites are rare (207, 212, 462).

(2) A variety in which the felspar is chiefly formed of perthite with an equigranular texture (0·5 to 1·0 mm.). The perthite is mainly anorthoclase with very fine streaks of albite, which gives a silky appearance to the crystals. Irregular flakes of clear albite are again common, overlapping the intergranular margins (223). This texture is seen in some of the schistose syenites and in certain basic patches.

(3) A variety occurring in some of the more leucocratic bands of the schistose syenites, in which albite is dominant, though unevenly distributed. The albite forms fine granular areas (0·1 to 0·2 mm.) between, and encroaching on, larger crystals of anorthoclase and perthite.

Large crystals of felspar, sometimes 1 cm. or more in length, occur sporadically in rocks of the marginal zone, particularly where pegmatites are numerous. They range in composition from practically non-perthitic anorthoclase (464) to antiperthite or chequer-albite (212), but most of them are beautiful perthites like those of the pulaskites. Occasionally they show subhedral outlines, with minutely irregular edges.

The pyroxene, a green aegirine-augite, varies considerably in form and composition from section to section. Euhedral outlines are never seen, and even subhedral crystals, in which the faces of the prism zone are developed, are rare. Commonly the crystal edges are irregularly serrated, though an approximately prismatic habit prevails. Crystals are often poikilitic, due to inclusions of felspar or grains of iron ore, apatite or sphene. Where the rock is schistose, the pyroxene prismoids show an approximately parallel alinement, while in the more basic varieties they build an irregular ramifying network (223). Other sections show marked clotting of aegirine-augite into equigranular aggregates (202, 205). Elsewhere, the pyroxene occurs as independent, often slender, prisms (216, 464). In the basic patches a mosaic of equidimensional crystals is the most usual texture, but some sections show relics of a schistose orientation among the pyroxene prisms. Grain-size is also extremely variable and, not infrequently, bears no relation to the size of the felspar crystals. In some slices the aegirine-augite prisms are commonly 0·15 to 0·20 mm. in length (202, 212); in others, large plates 4 to 6 mm. across are encountered (328).

The pyroxene varies from a pale green or nearly colourless diopside-augite to a deep green, strongly pleochroic aegirine-rich augite: the absorption order is always $X > Y > Z$. More or less distinct zoning is the rule, though it is not always concentric. Some crystals (e.g., in slice 232) actually contain kernels of colourless pyroxene. Generally the pyroxene of the basic patches is strongly coloured.

Highly pleochroic hastingsite occurs in a number of sections, either as irregular patches in the aegirine-augite crystals (223), or independently, with or without cores of pyroxene (464). The felspars surrounding such crystals generally show considerable clouding and sericitization. The detailed optical characters of this amphibole will be found in Table III, column IV. The principal diagnostic features of the mineral are a small optic angle, relatively low birefringence, and deep coloration, with very

TABLE III.—AMPHIBOLES FROM THE BEN LOYAL AREA

	I Sodic hornblende	II Hornblende	III Hornblende	IV Hastingsite	V Actinolite	VI Actinolite-tremolite
Occurrence	Main Ben Loyal syenite	Metasomatic zones of Cnoc nan Cuilean mass	Hornblende rocks of Lewisian type	Hybrid and contact rocks of Cnoc nan Cuilean	Cnoc nan Cuilean —after pyroxene.	Hydrothermally altered rock from Meall Eudainn
Form	Subhedral prisms and tablets	Irregular grains and poikiloblasts	Sub-parallel blades	Small flakes and porphyroblasts	Ragged prisms and outgrowths	Radiating aggregates of prisms and grains
Colour and pleochroism X	Pale yellow-green	Pale yellow-brown	Pale yellow-brown	Brown-yellow	Very pale yellow-green	Colourless or Very pale yellow-green
Y	Green	Deep olive-green	Deep olive-green	Deep olive-green	Pale green	Pale green
Z	Blue-green	Deep green	Deep green	Very deep blue-green	Pale blue-green	Pale blue-green
	Z = Y > X	Z = Y > X	Z = Y > X	Z = Y > X	Z > Y > X	Z > Y > X
Refractive indices α	1·648	1·673	1·659	1·686	1·635	1·636
β	1·658	1·685	1·672	1·697	1·648	—
γ	1·662	1·694	1·682	1·700	1·658	1·658
Birefringence	0·014	0·021	0·023	0·014	0·023	0·022
Optic angle: (−2V approx.)	50°	55°–60°	Moderate	15°–20°	70°–80°	Large
$Z_{\wedge}c$:	25°	22°	23°	c. 30°	15°	16°–17°

strong pleochroism. These agree fairly well with the characters of hastingsite described by Quensel (1914, pp. 145–52) and even more closely with those of the variety described by Adams and Barlow (1910, pp. 243–7). The latter, like the Cnoc nan Cuilean hastingsite, has the optic plane in the normal position, namely, parallel to (010). Phemister (Read & others 1926, pp. 31–2) gives an account of a similar mineral. Closely comparable amphiboles are described by Mathur and Jhingran (1931).

TABLE IV

	I	II	III
SiO_2	56·20	51·13	48·66
Al_2O_3	10·54	12·79	12·36
Fe_2O_3	1·83	4·34	3·09
FeO	4·72	5·09	5·86
MgO	5·43	3·60	8·09
CaO	12·50	12·39	10·46
Na_2O	2·28	2·58	2·71
K_2O	4·19	5·12	5·15
H_2O +	0·25	0·74 }	1·46
H_2O −	0·35	n.d. }	
CO_2	nil	n.d.	n.d.
TiO_2	0·21	0·97	0·97
P_2O_5	0·84	1·26	1·07
MnO	0·45	0·21	0·13
	99·79	100·22	100·01

I. Basic or shonkinitic syenite from slopes above Ben Loyal Lodge. Analyst: W. H. Herdsman.
II. Shonkinite, Forcella, Canzacoli, near Predazzo, Tyrol. Washington 1917, p. 597. Analysts: Dittrich and Polet.
III. Average of six shonkinites: Daly 1933, p. 23, no. 98.

NORMATIVE COMPOSITION OF BASIC SYENITE (column I above)

Quartz		1·76	
Orthoclase		24·80	50·18
Albite		19·29	
Anorthite		6·09	
Diopside	$CaSiO_3$	21·03	42·25
	$MgSiO_3$	12·72	
	$FeSiO_3$	7·14	
Hypersthene	$MgSiO_3$	0·85	
	$FeSiO_3$	0·51	
Magnetite		2·76	3·15
Ilmenite		0·39	
Apatite		2·01	
Water		0·60	
		99·95	

Actinolite is a widespread secondary mineral associated with the pyroxene; it forms ragged outgrowths from the edges of the aegirine-augite crystals. Similar replacement also affects the hastingsite.

The accessories of the basic syenites are the same as those found in the pulaskites, though generally occurring in greater abundance. In the schistose rocks, thin bands of sphene are sometimes visible in the hand specimen (223). The sphene, which is commonly anhedral and granular, is a reddish brown pleochroic variety often with kernels of a paler colour. Orthite, also, though irregularly distributed, is in some sections very abundant and sometimes forms irregular networks which surround plates of aegirine-augite and apatite. Its deep brown colour, strong pleochroism, patchy zoning and peculiar alteration to an amorphous (metamict) substance serve to identify it. Small concentrically zoned grains are also found. Both apatite and zircon form larger and more abundant crystals than in the pulaskites. Black, formless grains of magnetite and ilmenite are always present. Biotite is rare, but in a small stream beside the fall in Allt Torr an Tairbh (see Fig. 3) a highly basic syenite occurs, containing numerous aggregates of large biotite flakes.

TABLE V

Country rocks	Highly siliceous quartz-felspar granulites.
(A) Zone of contact metamorphism	Glazed siliceous granulites with fine veinlets and blebs of quartz.
(B) Zone of metasomatism	Quartz-felspar granulites and quartz-felspar-aegirine-augite (or hornblende) granulites.
	Felspar-aegirine-augite (or hornblende) granulites.
	Aegirine-augite (or hornblende)-felspar schists.
	Banded rocks: aegirine-augite (or hornblende) schists with felspar granulites.
	Aegirine-augite (or hornblende) schists.
(C) Transition zone	"Composite" rocks: basic schists distorted and veined by leucocratic bands.
	Variable syenite with abundant xenoliths and numerous relict basic schist structures.
Marginal syenite	Variable syenites with basic patches.

Note: In some localities dominantly felspathic rocks persist right to the contact. In such cases gradational junctions are infrequent and the marginal syenites are rarely very basic.

Chemical Composition.—An analysis of a basic syenite has been made (Table IV, column I). Comparison with similar rocks shows that it may be termed a shonkinitic syenite. Other varieties containing more soda are albite-shonkinites. The basic syenites contain considerably less alumina than the basic metasomatic rocks (Table VI, columns E and F), a further contrast being that potash is more abundant than soda. The low content of alumina reflects the fact that practically all the lime of the rock is present in pyroxene.

(c) The Country Rocks and "Glazed" Granulites

The dominant mineral of the Moine granulites which surround the Cnoc nan Cuilean intrusion is quartz, which generally forms from 50 to 80% of the rock. The texture is granoblastic: the grain-size varies somewhat, but is commonly about 0·5 mm. The quartz grains, which occasionally exhibit patchy extinction, form a granular mosaic with smoothly sutured margins. Felspar commonly occurs interstitially, though it also makes sinuous penetrations into, or even encloses, grains of quartz. Usually the chief felspar is a faintly cross-hatched potash variety associated with a smaller proportion of albite or albite-oligoclase. The latter is often slightly zoned and both felspars show patchy clouding. Small flakes of a pale green-brown biotite are present in varying amount and chlorite and muscovite also occur in a similar habit. Iron ores, granules of colourless sphene, epidote, zircon and apatite are usual accessories.

The "glazed" granulites of the zone of contact metamorphism are composed of the same minerals, but are generally of coarser grain. The quartz grains usually exhibit strain shadows, whilst the proportion of quartz is often rather greater than in the unaltered rocks. It appears possible that some of this may have been introduced, having been driven forward from the metasomatic zone. Often there are veinlets and blebs composed entirely of quartz crystals.

(d) The Rocks of the Metasomatic and Transition Zones

These rocks may be conveniently described under three headings: (i) aegirine-augite types, (ii) hornblende types, and (iii) felspar types. All three frequently occur interbanded.

(i) *Aegirine-augite types.*—In general these rocks show progressive increase of both pyroxene and felspar, at the expense of quartz, as the igneous contact is approached.

Quartz-felspar-aegirine-augite granulites (200, 201, 209, etc.) represent an early stage of metasomatism. The grain-size is usually about 0·5 mm., though coarser-grained varieties are not uncommon. The dominant quartz, which commonly shows a wavy extinction, forms an interlocking mosaic with winding intergranular sutures. Irregular grains and small plates of felspar occupy the interstices of the quartz mosaic, but they also penetrate and overlap the quartz grains. In most rocks the chief felspar is anorthoclase (e.g., 200), which often shows hazy cross-hatching and is generally cloudy, while the albite is usually quite clear and untwinned.

Many of these rocks are characterized by sieved porphyroblasts of aegirine-augite, which are always anhedral and range from crystals with numerous inclusions to elaborate networks of optically continuous pyroxene (Fig. 4). Frequently they are penetrated or fringed by ragged pale green actinolite; elsewhere a further alteration to aggregates of yellowish green flakes of a micaceous or chloritic substance may be observed in all its stages. Both actinolite and chlorite occur also as independent prisms and flakes, without any evident relationship to the pyroxene. Occasionally small ragged flakes of a pale biotite are found. Irregular grains of ilmenite and magnetite are abundant and are commonly rimmed with colourless or pale brown granular sphene. Zircon, apatite and orthite are other usual accessory minerals.

Other rocks of this type show a schistosity due to the occurrence of parallel strings of granular aegirine-augite.

Certain specimens (e.g., 558) show sieved porphyroblasts of hastingsite, some of which contain cores of the pyroxene. In others, felspar is seen cutting across quartz crystals and isolating optically continuous areas or irregular meshworks, wherein even the details of the wavy extinction can be traced on either side of the felspar crystals. These are evidence of the replacement of quartz by felspar (see p. 171).

Felspar-aegirine-augite granulites contain little or no quartz. Potash felspar is usually rare, whilst albite is abundant. The texture is granular with an average grain-size of about 0·5 mm. Straight or smoothly rounded crystal edges are usual. The albite is often untwinned or only partially twinned, whilst the potash-felspar occurs only as small shreds or irregular tiny plates within or between the albite grains. Some of the felspars contain cloudy altered patches, largely composed of relatively coarse flakes of sericitic mica associated with grains and small meshworks of a pale yellow-green epidote (Pl. V, fig. 5).

Irregular grains and anhedral prisms of a rather pale aegirine-augite are abundant. Often associated with the pyroxene are granular pale brown sphene and grains of magnetite and ilmenite, whilst apatite, zircon and orthite occur as small accessory crystals. The dark minerals are frequently aggregated in strings or bands, giving a schistose texture to the rock. Flakes and irregular porphyroblasts of hastingsite, often

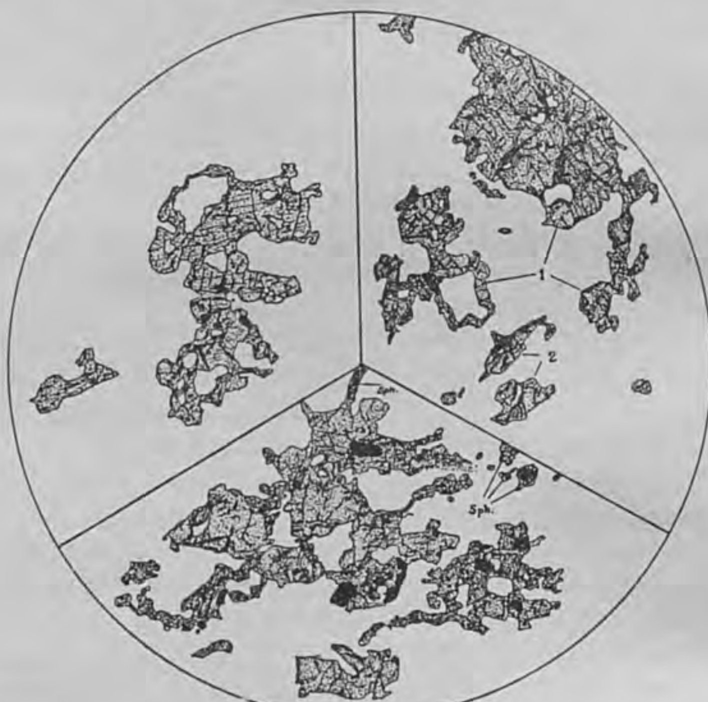

FIG. 4.—Poikiloblastic crystals of aegirine-augite in siliceous granulite (slice 200, from Allt Torr an Tairbh). The pyroxene areas in each sector of the diagram are optically continuous (except where the contrary is indicated), even where no direct connexion occurs. The background consists of a granular mosaic of quartz, together with some potash felspar.

containing cores of pyroxene, are abundant in some specimens (206, 455, 700, 701), as well as occasional " clumps " of ragged biotite.

Aegirine-augite schists and banded rocks.—Though consistently basic schists do occur (456, 457), it is more usual to find rocks formed of an alternation of bands containing practically only aegirine-augite with other bands of a more felspathic nature (208, 454) (Pl. V, fig. 2). In the very basic rocks the microscope reveals a granular mass of pyroxene making up nearly the entire area, with sparse interstitial felspars and many irregular grains of cloudy apatite. The pyroxene is nearly always of the deep green, strongly pleochroic variety (for analysis see Table VII).

Transitional types.—Generally these rocks may be resolved into two parts : (a) distorted schistose bands, with granular felspars and biotite, hastingsite and aegirine-augite in sub-parallel arrangement. These merge into (b) patches and irregular streaks of rather basic syenite,

TABLE VI.—CHEMICAL ANALYSES OF METASOMATIC ROCKS

	A	B	C	D	E	F
SiO_2	82·79	80·36	79·22	71·22	56·66	53·60
Al_2O_3	6·90	10·34	8·43	15·70	17·24	16·38
Fe_2O_3	1·41	0·81	2·26	0·66	2·01	2·27
FeO	0·64	0·95	1·48	1·65	4·85	5·66
MgO	0·44	0·60	0·69	0·92	3·92	5·81
CaO	1·44	0·66	1·47	2·41	6·83	7·58
Na_2O	1·75	1·75	3·30	5·56	5·36	4·66
K_2O	3·63	4·23	1·43	0·97	1·18	1·52
H_2O +	0·45	0·21	0·44	0·35	0·60	1·09
H_2O −	0·06	0·06	0·21	0·18	0·45	0·17
CO_2	0·07	nil	nil	nil	nil	nil
TiO_2	0·42	0·12	0·94	0·18	0·53	0·71
P_2O_5	0·06	0·07	0·06	0·11	0·08	0·26
MnO	0·17	nil	nil	trace	0·14	0·18
	100·31	100·16	99·93	99·91	99·85	99·89

A. Typical siliceous granulite. (*Note:* 0·08 of BaO is included in the total.) Analyst: E. G. Radley. Read & Phemister 1926, p. 134.
B. Siliceous granulite (with aegirine-augite), from Allt Torr an Tairbh (585 feet). Specimen No. 473. Analyst: W. H. Herdsman.
C. Aegirine-augite-bearing quartz-felspar granulite, from Allt Torr an Tairbh (450 feet). Specimen No. 201. Analyst: W. H. Herdsman.
D. Quartz-bearing felspar-hornblende granulite, from Allt Torr an Tairbh (710 feet). Specimen No. 570. Analyst: W. H. Herdsman.
E. Aegirine-augite-felspar schist (with hastingsite and biotite), from Allt Torr an Tairbh (460 feet). Specimen No. 457. Analyst: W. H. Herdsman.
F. Hornblende-felspar schist (with aegirine-augite and biotite), from Allt Torr an Tairbh (710 feet). Specimen No. 578. Analyst: W. H. Herdsman.

composed of plates of aegirine-augite and much perthitic felspar; the felspars have a typical inequigranular "igneous" texture.

It must be emphasized that the gradation between these two is complete: intermediate stages occur in which aegirine-augite plates are set among granular, non-perthitic felspars. Often the schist bands are almost "spongy" as a result of the abundance of irregular patches with syenitic textures (700, 701) (see Pl. III, fig. 1). Where the rock is dominantly igneous in character, there persist abundant areas of "ghost-like" basic schist (see Fig. 5).

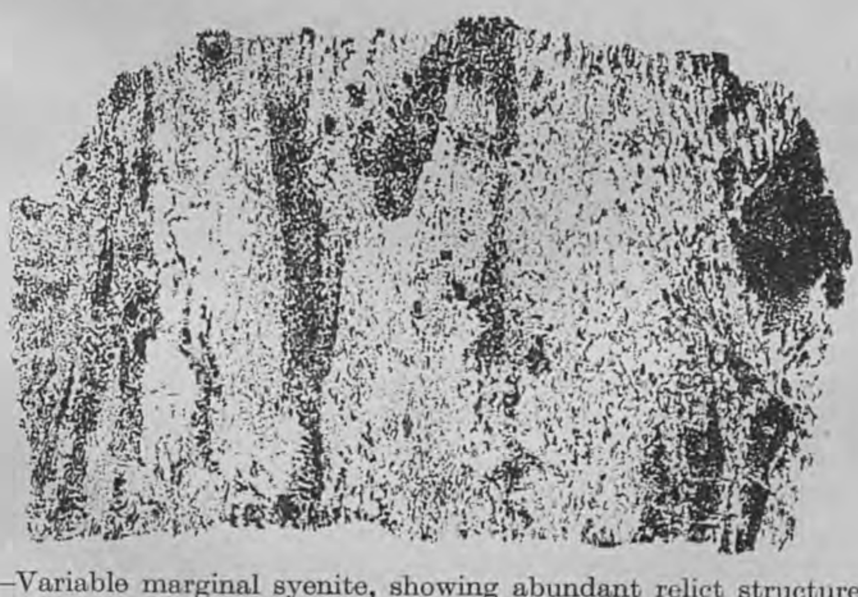

FIG. 5.—Variable marginal syenite, showing abundant relict structures of basic schist: specimen 470 from the lowest fall in Allt Torr an Tairbh. The general parallelism of all the schistose areas is noteworthy.

(ii) *Hornblende types.*—Among these rocks a similar progressive series can be recognized. An early stage in metasomatism is represented by certain " spotted " granulites, largely composed of quartz and potash felspar, but also containing large (0·5 cm.) beautifully poikiloblastic crystals of hornblende (Pl. V, fig. 4), which are sometimes altered to aggregates of actinolite and chlorite.

Felspar-quartz-hornblende granulites (570, 572).—In the varieties rich in quartz, potash felspar is generally dominant over oligoclase or albite. In such cases the potash felspar forms a typical mosaic with the quartz (Pl. V, fig. 6). With decrease of quartz, oligoclase gradually becomes the chief felspar. It frequently shows slight zoning to a more albitic margin. When dominant, the oligoclase forms an equigranular mosaic, having a grain-size of 0·5 to 0·8 mm., but commonly with smooth intergranular sutures. Irregular inclusions or tiny blebs of quartz are often seen in the

TABLE VII.—ANALYSIS OF PYROXENE FROM METASOMATIC ROCK (No. 202)

	A	B (Metal atoms)		C	
SiO_2	51·40	1·935	} 1·935 + 0·065: 2·000 = Z	$CaMgSi_2O_6$	57·28
Al_2O_3	1·67	0·074 {0·065, 0·009		$CaFeSi_2O_6$	27·93
				$NaFeSi_2O_6$	10·13
TiO_2	0·01	0·001	} 0·009 to MgO: 0·994 = Y	Balance :	
Fe_2O_3	4·32	0·122		$CaSiO_3$	1·69
FeO	8·10	0·254		Al_2O_3	1·67
MnO	0·27	0·009		Fe_2O_3	0·97
MgO	10·60	0·599			
CaO	21·98	0·886	} CaO to Na_2O: 0·994 = X		99·67
K_2O	trace	—			
Na_2O	1·47	0·108			
H_2O	0·29	—			
	100·11				

A. Chemical composition of aegirine-augite. Analyst : B. C. King.
B. Calculation from analysis according to crystal-lattice formula : $Y_mX_{2-m}(Si,Al)_2(O,OH,F)_6$ where X = (Na, K, Ca); Y = (Fe, Mg, Ti, Al); and Z = (Si, Al).
C. Normative composition in terms of the " minals " : diopside, hedenbergite, and acmite.

oligoclase. When subordinate in amount, as is usually the case, the potash felspar occurs only as tiny shreds or irregular patches in or between the oligoclase crystals (cf. p. 171). When in contact with the quartz, however, it presents sutured margins as in the unaltered granulites. The oligoclase is frequently clouded by a patchy mass of coarse sericite flakes. This is quite distinct in appearance from the clouding described as affecting the potash felspar (pp. 165–6). Commonly the flaky aggregates develop between the oligoclase crystals and proceed irregularly towards their centres.

Anhedral grains of a pale aegirine-augite are found; sometimes they include felspar and quartz poikiloblastically. Inclusions of iron ore, grains of zircon and minute rods and wedges of sphene are also associated with the pyroxene. An olive-green hornblende, often with kernels of aegirine-augite (see Table III, column II) is the chief mafic mineral. It usually possesses irregular skeletal outlines and is often riddled with included areas of quartz and felspar. The mafic minerals show a schistose alinement. Spongy prisms and needles of actinolite replace hornblende and aegirine-augite. Where associated with hornblende the actinolite often exhibits merging junctions. The usual accessories and secondary minerals are found (cf. pp. 165–6). An analysis of a granulite of this type appears in Table VI, column D.

Hornblende schists (e.g., 577, 578) contain hornblende as the dominant constituent; oligoclase is the only other important mineral. Elaborately sieved porphyroblasts of hornblende, containing scattered kernels of aegirine-augite, are particularly well developed. The analysis (Table VI, column F) illustrates clearly the basic character of these rocks.

Transitional rocks (e.g., 573, 575, 576).—In the hand-specimen these rocks show bands of hornblende schist partly distorted and penetrated by irregular, discontinuous streaks of more felspathic material, which, however, still contains a high proportion of mafic minerals. Aegirine-augite is rather more abundant than hornblende in these types: the two minerals not uncommonly occur in separate foliae. The pyroxene, for the most part, has a granular habit (Pl. V, fig. 5); the hornblende is usually poikiloblastic. In the schistose portions much of the oligoclase forms a granular mosaic of polygonal grains (0·1 to 0·2 mm. average diameter).

Bands and patches are often found in which all the felspar has been converted to sericite and abundant granules of epidote. Numerous small grains of hornblende (often with cores of aegirine-augite) and aegirine-augite occur together with a sprinkling of tiny grains of magnetite, ilmenite and sphene. Such finely granular bands and patches appear to be characteristic of these transitional rocks; but the reasons for their development remain obscure.

Slide 576 contains a band with numerous aggregates of quartz crystals (Pl. V, fig. 4), side by side with other bands exhibiting transitional features. Individual quartz crystals exceed 2·5 mm. in diameter: sprinkling with tiny black inclusions is common. Albite-oligoclase occurs between the quartz crytals and penetrates them irregularly. Single optical units of quartz across which every detail of the wavy extinction can be traced are dissected by the felspar into numerous irregular areas.

Gradation into variable syenite takes place by (a) disappearance of hornblende (and quartz), (b) reappearance of potash felspar (anorthoclase), (c) development of crystals of felspar showing irregular perthitic intergrowths, and (d) gradual modification of the granular habit of the felspars.

Petrographic examination supports the field evidence (see p. 156) in demonstrating that the contact hornblende schists are not the same as the " hornblende rocks of Lewisian type ". The contact rocks may be distinguished by the optical character and poikiloblastic habit of the hornblende, by the fact that the latter is evidently formed at the expense of the aegirine-augite, and by the occurrence of local gradations along the strike into siliceous granulites. It should be observed that hornblende schists are often interbanded with aegirine-augite types. Not merely are rocks like the latter not to be found in the rocks of Lewisian type, but they are apparently unique in the North-West Highlands.

(iii) *Felspar types.*—The petrology of these rocks has been largely covered in connexion with the other two groups, since they rarely occur independently. In general, as the contact is approached, potash felspar increases somewhat at first, but nearer the contact albite takes the place both of potash felspar and of the remaining quartz. Bands composed mainly of albite, with sparse mafic minerals, are occasionally present even up to the contact; they tend, however, to assume an igneous appearance and to penetrate the darker foliae (see pp. 155–6).

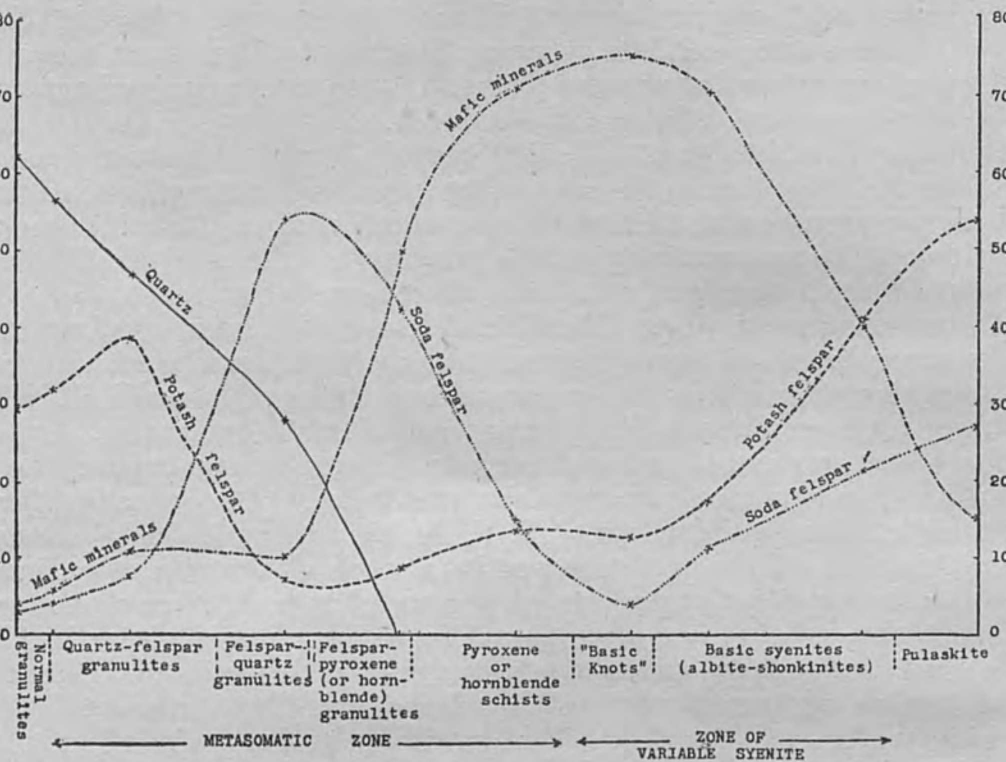

FIG. 6.—Composite mineral variation diagram of the rocks of the Cnoc nan Cuilean area. No single rock series has been employed, but the curves represent summations from all the available evidence.

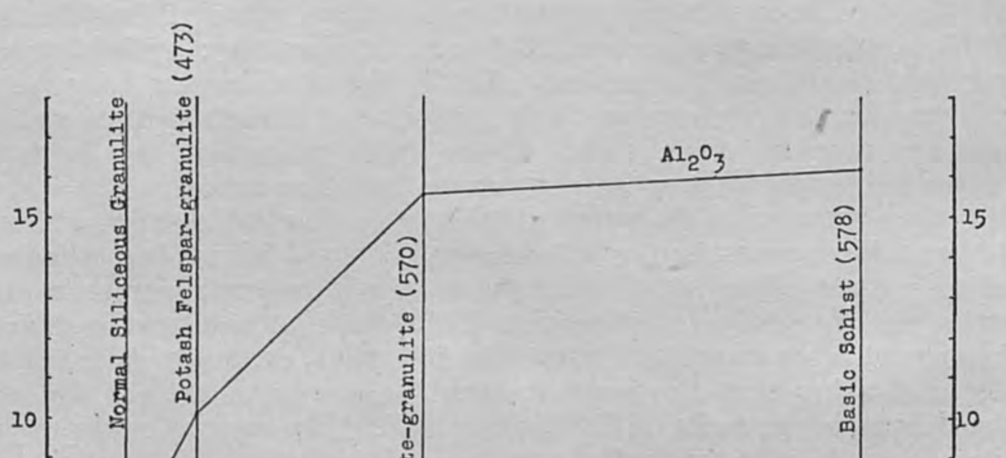

FIG. 7.—Chemical variation diagram. Only a selected number of typical analyses have been used. The values for the normal siliceous granulite have been taken from column A of Table VI.

IV. Metasomatism in the Cnoc nan Cuilean Area

(a) The Chemical and Mineralogical Changes during Metasomatism

Analyses of a number of the metasomatic rocks are recorded in Table VI, together with an analysis of a typical siliceous granulite. The modal composition of several of these rocks has been measured, and has been employed in constructing Fig. 6. The important features to be observed in the diagram are (1) the sharp decrease in the proportion of quartz towards the contact, (2) the initial rise in potash felspar, which then falls off sharply, (3) the considerable rise in soda felspar, as the quantity of potash felspar diminishes, and (4) the steady rise and " culminating " peak in the curve of the mafic minerals, which succeeds the maximum of soda felspar.

These features are reflected in the chemical variation diagram (Fig. 7).

(b) The Order of Replacement of Minerals in the Metasomatic Zone

The order of replacement is as follows :—

(1) Quartz shows replacement both by felspars and by mafic minerals.

(2) In all cases albite (or oligoclase) replaces potash felspar. Albite-rich rocks contain potash felspar only as minute shreds or irregular patches with a relict appearance (see p. 168).

(3) Pyroxene appears to have been, at least in part, developed before albite, since it exhibits poikiloblastic textures only in highly siliceous rocks (p. 165).

(4) Hornblende was probably contemporaneous with, or later than, albite, since it often forms poikiloblastic crystals, which enclose areas of albite (or oligoclase) (see p. 168).

(5) Hornblende is always later than pyroxene (cf. pp. 165, 169).

(c) Porphyroblastic, Crystalloblastic and Poikiloblastic Textures

These three terms (Becke 1903) are used to describe the forms of minerals which have grown in a solid or highly viscous medium as a result of metamorphic recrystallization or metasomatism. Poikiloblastic textures are characteristic of many of the contact schists and granulites of the Cnoc nan Cuilean area. Typically they exhibit numerous included or partly enclosed areas of earlier minerals, the textures of which are similar to those in the unaltered rock types. Reynolds (1934, p. 613 *et seq.* and 1936A, pp. 345–8) gives critical accounts of these textures in connexion with their development in the hybrids which surround the Newry Complex. Gillson and Kania (1930, p. 511 *et seq.*) adduce convincing evidence in favour of a replacement origin for poikiloblastic hornblende in the Cortlandt Complex. A similar origin is postulated for the porphyroblastic minerals of the Cnoc nan Cuilean area.

(d) Relations between Metasomatism and the Structure of the Country Rocks

A feature of many of the metasomatic rocks is their banded character (pp. 155–6). It is evident from their petrology that the felspathic bands are similar to the more homogeneous felspathic granulites which occur nearer to the unaltered country rocks. The darker bands, on the other hand, are pyroxene or hornblende schists, which are typically developed close to the contact. Apparently, therefore, to some extent the basic foliae represent a higher grade of metasomatism than the felspathic layers with which they are interbanded. The determinative factors in this variation are naturally obscure. As a possible explanation it may be suggested that the more micaceous layers and "partings" in the original granulites have facilitated the fixation of the mafic metasomatic materials. These layers would therefore be more profoundly affected. It is significant that the orientation of the foliae of these banded rocks, where not severely crumpled, is the same as that of the neighbouring unaltered granulites. The effects of metasomatism are well known to exhibit considerable local variations. Thus, a similar banding is seen in tourmalinized grits. Ore deposits of metasomatic origin are frequently restricted to certain bands (Lindgren 1933, pp. 696, 700).

(e) Comparison with other Areas

Siliceous sediments, which have been metasomatized to quartz-glaucophane schists, were recorded by Washington (1901, pp. 35–9), whilst an account of similar rocks was given by Ransome (1894) from California. Aegirine-augite-bearing contact rocks have been described by Lacroix (1903) in the neighbourhood of alkaline igneous rocks in Madagascar. He clearly demonstrates their metasomatic origin. Goldschmidt (1911, p. 108) cites an aegirine nordmarkite containing an inclusion of biotite-bearing plagioclase-diopside hornfels, wherein the plagioclase has been partially replaced by aegirine. An example of aegirine-augite-bearing schist from Switzerland is provided by Cornelius (1913, p. 375), whilst Suzuki (1933) described an aegirine-augite-bearing riebeckite-quartz schist from the Kamuikotan system of Japan. He considers it to be of metasomatic origin. Kalb, in a series of papers (1934, 1936, 1937), has given excellent examples of quartz-biotite hornfelses, which, where in contact with sanidinite of the Laacher See area, have been transformed into aegirine-sanidine rocks.

The introduction of soda (represented by albite) into the country rocks is a phenomenon which is widely attested, particularly in the case of adinoles (Clements 1899, Fox 1895). Lacroix (1895) recorded the development of albite in Jurassic limestones margining an intrusion in the Pyrenees.

D. L. Reynolds (1934) has shown that the hornfelsed Lower Palaeozoic rocks at the eastern end of the Newry Complex have been progressively enriched in alkalis and alumina, with the eventual production of "mobilized sediments". Kennedy and Read (1936, p. 123) show that enrichment in potash has taken place in the hornfelsed greywacke which margins the Newmains dyke, Dumfriesshire. They ascribe the process to the agency "of a fluid or gas with great penetrative powers". Barth (1936) demonstrated that the metasomatism of sediments by potash has eventually led to the formation of gneisses. M. Macgregor (1937, p. 470) found potash enrichment in the hornfelses surrounding the Criffel–Dalbeattie granodiorite complex.

Fenner (1936) gives an account of the formation of rhyolites from dacites in Yellowstone Park, a process which is taking place at the present time through the action of high-pressure superheated steam and other agents of which geysers are a surface expression. Billings (1938) describes the transformation of the original sillimanite in regionally metamorphosed argillaceous sediments into muscovite, as a result of later introduction of potash.

G. H. Anderson (1937) shows that the Cambrian sediments in the Northern Inyo Range of California, which have been intensely metamorphosed by intrusive granites, are enriched in albite and to a lesser extent in potash felspar. Further, he shows that potash enrichment predominates on the margin of the granites, whilst soda has been introduced in the roof rocks.

Similar evidence has been obtained from the examination of xenoliths. Thus Daly (1928) gives an account of partially felspathized quartzite masses in the norites of the Bushveld Igneous Complex, and Wells and Wooldridge (1931), Nockolds (1932) and Iwao (1936) describe xenoliths in which felspar porphyroblasts have developed as a result of the introduction of alkalis from the surrounding granites. That xenoliths can be made over to resemble igneous rocks, without destruction of their xenolithic habit, has been established by Grout (1933).

A clear case of enrichment in both soda and potash has occurred in quartz xenoliths enclosed in hornblendite at Port Easdale in Colonsay (Reynolds 1936B); and quartz inclusions in alkaline basic and ultrabasic lavas from South-West Uganda have been partially "transfused" to a glass resembling obsidian (Holmes 1936). More recently (1938) Reynolds has also described metasomatized quartz xenoliths in the lamprophyre dykes of the Ards Peninsula and of Newmains, Dumfriesshire.

An account of these processes, together with a comprehensive survey of evidence from many areas, is given by Holmes in a memoir published by the Geological Survey of Uganda on the petrology of the volcanic area of Bufumbira (Holmes & Harwood 1937, pp. 243–77).

Examples of the introduction of magnesia, lime and iron oxides, in which pryoxene and amphiboles have been developed as a result of the metasomatic introduction of cafemic constituents, have already been quoted (p. 172). In some of the examples mentioned above (those described by Reynolds, Holmes and Anderson) enrichment in cafemic constituents, as well as alkalis and alumina, has been demonstrated. The classic examples are the "skarn rocks" of Norway (Goldschmidt 1911), wherein such minerals as andradite and hedenbergite have been introduced. Similar minerals were recorded by Barrow and Thomas (1908) from the contacts of the Dartmoor granite. An example of magnesia metasomatism was described in 1935 by Sundius (see also Taylor 1938).

(f) The Mechanism of Metasomatism

The variation diagrams indicate that a process of selective diffusion over a wide range of constituents into siliceous granulite has been responsible for the mineral transformations. There is no evidence in this area that the metasomatism took place during late magmatic stages, or as a result of the agency of large quantities of volatiles, such as H_2O, CO_2, B_2O_3, Cl, F and S. Both these features have been stressed in the case of pyrometasomatic replacements (cf. Brauns 1911, 1912, and Lindgren 1933, pp. 695–712) and of hydrothermal activity. The following observations are consistent with the hypothesis that metasomatic replacement occurred as a result of high temperature emanations.

(a) The "mineral facies" (Eskola 1925) in the higher grades of metasomatism is identical with that of the marginal syenites.

(b) The diffusion order of the magmatic introductions is incompatible with what would be expected if it were dependent upon transference as volatile compounds of Cl, F, SO_3 etc., which are commonly considered to become concentrated in late residual melts.

(c) Accessory minerals of kinds which are usually associated with high concentrations of such volatiles do not occur; thus even carbonates are exceptional.

(d) In the transition zone and the marginal syenites there is clear evidence that rocks, which had already been metasomatized, were partially incorporated in still liquid material.

A closely similar diffusion order has recently been established by a number of petrologists. Quirke and Collins (1930) find that magnesia, lime and iron oxides are less diffusible than alumina and alkalis. From an investigation of " transfused " quartz xenoliths in katungite, Holmes (1936, p. 417) demonstrated a similar sequence. Collins (1936) has shown that not only does the diffusion range vary for different constituents, but that it also varies from place to place. Reynolds (1938, p. 37) in the dykes of the Ards Peninsula, has observed the following sequence for the major constituents: K_2O, Na_2O, Al_2O_3, CaO, FeO, MgO (least diffusible).

In the metasomatized rocks of the Cnoc nan Cuilean area, replacements in most cases commenced along intergranular boundaries and, thereafter, proceeded more or less evenly towards the centres of the grains (cf. Pl. V, fig. 3, and Fig. 4). No veins or channels occur which might indicate the transference of metasomatizing materials in the liquid state. The granulites appear to have been readily permeable, perhaps preferentially so along planes of foliation (p. 155), by incoming material, in whatever state it was introduced.

The evidence leads to the conclusion that the material responsible for the mineral transformations migrated as a sequence or flux of emanations. Recently it has been suggested that such emanations are due to ionic migration from a source in depth (see Reynolds 1936B, p. 403, and 1938, p. 57; and Holmes 1936, p. 417). Evidence is accumulating from X-ray investigations of mineral structures that ionic transfer through crystal lattices is a genuine process (Desch 1934, p. 115).

V. Rheomorphism in the Cnoc nan Cuilean Area

The rocks which belong to the transition zone are considered to be of rheomorphic origin. They are thought to represent the extreme stages of metasomatism, in which the energy associated with the introduced constituents was so great as to have rendered the rocks at least plastic and certain bands actually fluid (cf. Sederholm 1907, p. 49, and 1926, p. 135). Backlund has given the name " rheomorphism " to this process (1937, p. 234).

The reasons for believing the process to have taken place in situ are as follows. First, it is impossible to decide either in the hand-specimen or under the microscope at what point the rock is igneous or metasomatic in character. Secondly, the igneous streaks and patches are often completely isolated from each other and from the larger masses of nearby syenite.

Where the contact rocks are banded, it is the leucocratic bands which first assume igneous characters, whereupon the mobilized material sends tongues into, or impregnates, the darker schist bands. Where banding is less pronounced, streaks of moderately basic syenite occur in a schistose host of similar composition.

In view of the close similarity between the igneous and non-igneous components, the criteria on which a distinction is possible are here summarized.

(1) Non-igneous types are characterized by the granular texture of the felspars (usually very even-grained), without perthitic inter-

growths. The mafic minerals have a more or less schistose orientation and consist of pale aegirine-augite, hornblende and brown biotite, or green aegirine-augite, associated with hastingsite and green-brown biotite. Poikiloblastic textures are common.

(2) Igneous types have an inequigranular texture with much of the felspar as perthite, whilst green aegirine-augite, which forms stumpy prisms, is the only dark mineral.

The formation in situ of rocks with igneous characters has been described by G. H. Anderson (1937, pp. 22–6), who shows that metasomatism and recrystallization of the Palaeozoic sediments surrounding granites have produced rocks which resemble " injection gneisses ". Waters (1938) gives an account of xenoliths which have been transformed into rocks of " diorite aspect " whilst the " mobilized sediments " which surround the Newry granodiorite are considered by D. L. Reynolds to be of rheomorphic origin (1934 and 1936). Another recent contribution relating to the same problem is by Cannon (1937) in the Piseco Lake area. Backlund (1938) considers that metasomatism and rheomorphism (including magma-formation) on a large scale have been responsible for the Rapakivi granites and their related effusive rocks.

VI. Hybridism in the Cnoc nan Cuilean Area and the Source of the " Basic Patches "

It is, I think, evident that neither crystal sinking nor crystal segregation could have been responsible for those features which are characteristic of the marginal syenites, namely: the occurrence of basic patches with xenolithic habit, and the rapid and complex variations in the host syenites.

The variable marginal syenites are thought to be due to the hybridization of rock material, now seen only as " basic patches ", by highly felspathic magma that may have had the same origin as the leucocratic rheomorphic veins. The following facts support this suggestion :—

(1) Leucocratic veins often disrupt basic patches, by reaction with which they become partially converted into variable syenite.

(2) Although some of the basic patches have sharp junctions, there are many that are impregnated to such a degree that they grade completely into variable syenite of one kind or another.

(3) The small-scale gradational features (1) and (2) seen in the marginal zone are reproduced on a large scale in the transition from the basic syenites (of the marginal zone) to the pulaskites of the interior of the mass.

The original nature and source of the basic patches are not easily determined. Two extreme types of basic patches may be distinguished : (a) those in which the dominant aegirine-augite occurs in large plates without parallel orientation, whilst the felspars are largely perthitic, and (b) those in which the aegirine-augite shows a schistose arrangement and the felspars are often granular and non-perthitic.

The basic patches might therefore represent fragments either of an earlier marginal ultrabasic phase of the intrusion or of basic metasomatic rocks which occur around the exposed contact and possibly also in depth.

Since no trace of an outcrop of pyroxenite occurs in the area, there is no evidence in favour of the former alternative. For the latter, however, there is considerable support : the features of the transition zone show that at least some of the basic patches were derived from the highly metasomatized country rocks. The suggestion is that patches of type (a) above are those in which the original schistose textures, still retained in (b), have been effectively obliterated.

VII. Further Petrogenetic Considerations

(a) The Relations between Metasomatism, Rheomorphism and Hybridism

The field and petrological features of the Cnoc nan Cuilean area bear direct witness to the operation of three essential processes :—

(1) Intense metasomatism of siliceous granulites by a flux of emanations. In general this has led to simultaneous development of two final products : (i) aegirine-augite and hornblende schists, and (ii) highly felspathic (quartz-free) granulites or fine-grained gneisses.

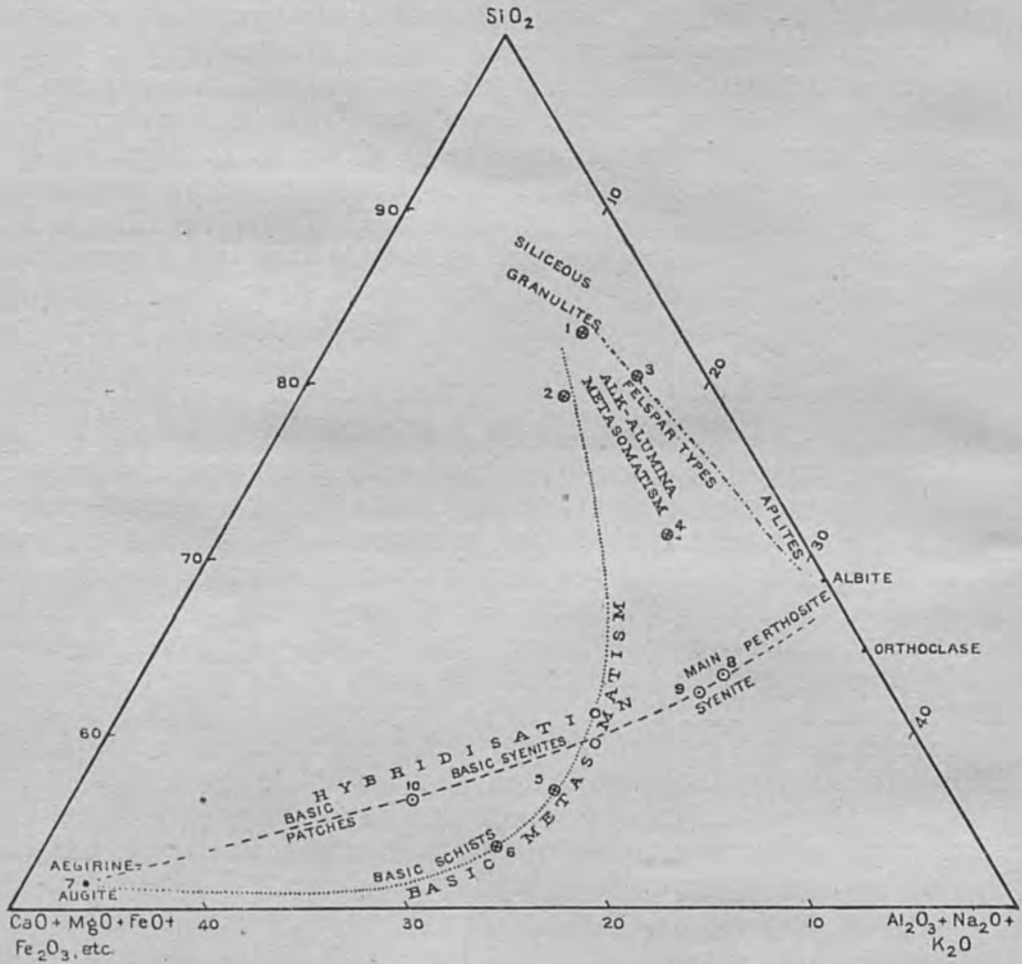

Fig. 8.—Triangular diagram summarizing the chemical relationships among the rocks of the Cnoc nan Cuilean area.

Note.—In the above diagram the numbers refer to analysis as follows :—

No. 1.	Table VI,	column	A.		No. 6.	Table VI,	column	F.
No. 2.	,, ,,	,,	C.		No. 7.	,, VII,	,,	A.
No. 3.	,, ,,	,,	B.		No. 8.	,, II,	,,	II.
No. 4.	,, ,,	,,	D.		No. 9.	,, ,,	,,	I.
No. 5.	,, ,,	,,	E.		No. 10.	,, IV,	,,	I.

The same numbers are employed in Fig. 9.

(2) Rheomorphism as a culminating stage of metasomatism. Corresponding with the two divisions of (1), it is found that the basic metasomatic rocks retain their schistose character to a considerable degree, whilst they become enveloped and impregnated by felspathic material, which has a dominantly " igneous " aspect, both texturally and by reason of its evident mobility. It has acted magmatically towards the basic schists.

(3) Hybridization of highly basic material consisting of aegirine-augite and often possessing a schistose texture, by mobile material of felspathic (perthositic) composition.

With the aid of the triangular diagrams (Figs. 8 and 9) it is possible to follow these processes in terms of their chemistry. It is seen that :—

(1) Alk-alumina metasomatism, as evidenced by the felspathized granulites, generates rocks (e.g., 3 in diagram) the compositions of which lie between those of siliceous granulite and perthosite.

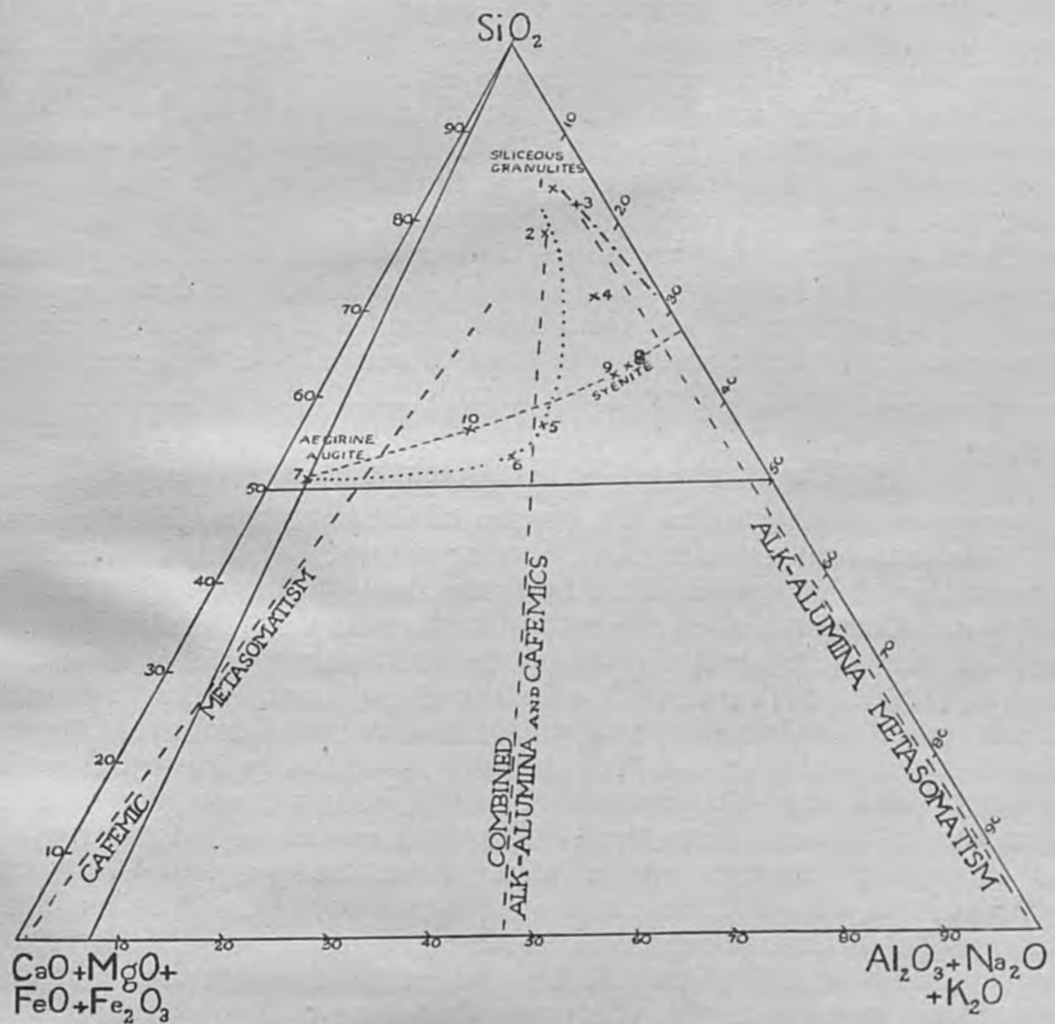

FIG. 9.

(2) The course of basic metasomatism is represented by a curve, which links dominantly felspathic rocks with basic schists (5 and 6) and continues thence towards aegirine-augite or hornblende. That the introduction and fixation of material have been selective is clear from the fact that the line is curved (see especially Fig. 8).

(3) The process of hybridization is represented by a nearly straight line between pyroxene and perthosite (or syenite) : it is therefore essentially due, keeping in mind the field evidence, to a simple admixture between the respective end members.

It must be observed that between the line of "felspathic types" and the initial portion of the curve for "basic metasomatism" is an area in which many rock types would find a place, such as some of the "banded rocks". The initial portions of the two metasomatic lines are characterized predominantly by the same process, felspathization.

(b) The Petrogenetic Significance of the Rheomorphic Rocks

The transition or rheomorphic rocks represent the local transformation, in situ, of certain bands of highly metasomatized granulites into igneous rocks. They are the extreme product of metasomatism, in which the introduction of highly energized material was sufficient to raise the temperature to a point at which the material of the felspathic foliae passed through a liquid phase. It is the writer's opinion that the rheomorphic zone may be interpreted as a manifestation of a dynamic petrogenetic process in an arrested state. Another such "frozen" stage of the process is the partial hybridization of basic patches by leucocratic syenite, as exhibited by the marginal rocks of the intrusion. It would indeed be a remarkable coincidence if, with so many features in common, the process of hybridization were not a further stage in the development of rheomorphism. This conjecture naturally leads to the broader petrogenetic interpretation of the main syenite as the rheomorphic-magmatic product in depth of the action of a succession of alk-alumina emanations on a dominantly sedimentary series, namely, the Moine granulites.

(c) The Source of the Metasomatizing Agencies

Any hypothesis regarding the source of the metasomatizing agencies must take into consideration the following points: (a) the absence of any evidence that there was an earlier basic magma; (b) the association in the Cnoc nan Cuilean area of a basic metasomatic zone with an intrusive mass, of which the only certainly magmatic component was a leucocratic syenite; (c) the absence of both a basic marginal zone and a basic metasomatic zone from the other two syenite masses of the Ben Loyal Complex.

On chemical and comparative grounds it is highly improbable that a magma with the composition of the pulaskite could have effected the metasomatic transformations. The field evidence, indeed, suggests that the syenite magma was to some extent independent of the disposition of the cafemic metasomatic rocks (see pp. 147, 153). Since it is highly probable that the syenites in all three masses of the Ben Loyal Complex had a similar origin, the association of basic marginal and basic metasomatic zones with the Cnoc nan Cuilean syenite suggests that an additional factor was operative in the petrogenesis of the latter mass.

The source of the "primary" emanations thought to be responsible for the genesis of the syenite lies outside the present field of investigation. It may be suggested, however, that the additional factor required to account for the special features of the Cnoc nan Cuilean mass may have been a localized process akin to "metamorphic diffusion", whereby potash displaced by the "primary" emanations from the Moine granulites, and cafemic constituents similarly displaced from deep-seated rocks of Lewisian type, may have been driven forward and concentrated in advance of the syenite. Although, as already indicated (pp. 156, 159), rocks of Lewisian type are not exposed at the surface in this area, it is nevertheless highly probable that they occur in depth. An examination of the structure of the surrounding country rocks (see map, Pl. VI) provides evidence for this inference.

Differential fixation of the metasomatizing emanations (as illustrated by the banded rocks described on pp. 166, 169) can be ascribed to variations in the cafemic/alk-alumina ratio of the ascending emanations, from place to place and from time to time, and to initial mineral variations in the invaded granulites, as described on pp. 171–2, 177.

VIII. Summary

Structural evidence suggests that the Cnoc nan Cuilean and Ben Loyal igneous masses have the form of cones with their apices pointing downwards. The Cnoc nan Cuilean intrusion consists of a main syenite (pulaskite) area and a marginal zone of variable syenites, with numerous "basic patches" and felspathic veins.

The country rocks are siliceous granulites of the Moine Series. Against the Cnoc nan Cuilean mass these have been metasomatically altered to a series of rocks ranging from albite granulites to aegirine-augite and hornblende schists.

The contacts are frequently of a transitional nature and are interpreted as representing the final stage in a process of metasomatism.

The variable marginal syenites are considered to be the result of hybridization of highly modified basic metasomatic rocks by a felspathic syenite of rheomorphic origin.

The primary metasomatizing agencies are thought to have been alk-alumina emanations which displaced potash from the invaded Moine granulites and cafemic constituents from more deep-seated rocks of Lewisian type, thereby providing the materials necessary for development of the marginal zone.

Grateful acknowledgment is due to Professor Arthur Holmes and Dr. Doris Reynolds, under whose guidance this study was begun, for their generous assistance and advice in the preparation of the paper; to Dr. L. Hawkes, for his constant encouragement and helpful criticism during the course of this work; to Dr. J. Phemister for the opportunity of examining numerous thin sections from the collections of the Geological Survey and for several instructive conversations; and to my wife for much welcome assistance with references and other bibliographical details during my absence in Uganda.

The photographs in this paper are the work of Mr. S. H. Morris of the Geological Department of Bedford College, to whom also my thanks are due. Finally I am indebted to the Royal Society for a grant, out of which the cost of seven chemical analyses has been defrayed.

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EXPLANATION OF PLATES III–VI.

PLATE III

FIG. 1.—Crumpled aegirine-augite-hastingsite-biotite-albite schist from below the lowest fall in Allt Torr an Tairbh. Bands, streaks and patches (often transgressive in habit) having a syenitic texture are clearly visible. The actual specimen is 8 inches long.

2.—Variable basic syenite, from crags above Leitirmhòr, containing dark xenoliths and "ghost-like" relict schist areas. The actual specimen is 7½ inches long.

PLATE IV

FIG. 1.—Variable syenite from the crags above Leitirmhòr, showing basic patches and associated aplites and pegmatites. The actual specimen is 6½ inches across.

2.—Transition type of rock from the north-western slopes of Cnoc nan Cuilean, showing a mass of basic schist isolated to form a xenolith. The actual specimen is 4½ inches across.

PLATE V

FIG. 1.—Patch perthite, main pulaskite (No. 352). Summit of Cnoc nan Cuilean. × 15.

2.—Banded aegirine-augite granulite (No. 208). Allt Torr an Tairbh. × 15.

3.—Partially replaced quartz area in transition rock. The quartz is optically continuous and penetrated and enlarged by felspar (No. 576). Allt Torr an Tairbh. × 35.

4.—Poikiloblastic hastingsite in spotted granulite: the light minerals are quartz and felspar. Note the way in which replacement has largely followed intergranular boundaries. The hand-specimen has a characteristic spotted appearance. (See p. 168.) (No. 559.) Allt Tor an Tairbh. × 11.

5.—Transition rock. Aegirine-augite-felspar granulite; abundant iron ore; felspar heavily sericitized. (No. 576.) Allt Torr an Tairbh, above falls. × 15.

6.—Hornblende-felspar granulite (No. 362a). North-western slopes on Cnoc nan Cuilean. × 15.

PLATE VI

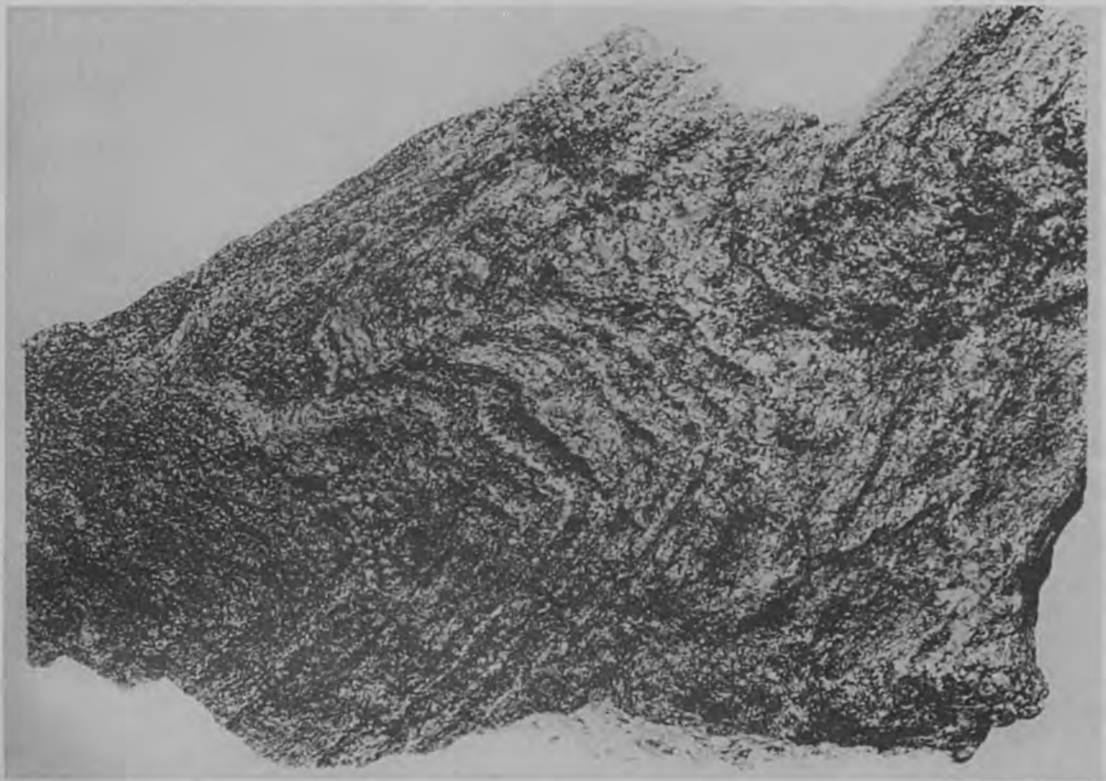
Geological map of the Ben Loyal complex. Scale: 2 inches = 1 mile. (*Note:* The metamorphic and metasomatic rocks are indicated only at localities where actual exposures are known.)

DISCUSSION

Prof. H. H. READ explained the conditions under which the account of the Ben Loyal mass was prepared for the central Sutherland Survey memoir. The mass was mapped long ago by John Horne, whose maps, with a dozen hand-specimens, provided the material on which the account was based. It was pointed out in the memoir that, though Horne had connected the Cnoc nan Cuilean area with the main Ben Loyal mass through the covered ground of the Allt Torr an Tairbh, it was very probable that the Cnoc nan Cuilean stock was completely separated from the main mass. This suggestion had been confirmed by the present author's detailed mapping.

The speaker welcomed this paper as a first-class demonstration of metasomatism on a considerable scale. The paper was clearly the result of detailed field and petrographical work and indicated that the long-neglected Ben Loyal mass would amply repay further studies of this kind. In the speaker's opinion, the position of the young worker in petrological geology was an enviable one, since the whole concept of magmatic and igneous activity was under scrutiny—a scrutiny likely to yield results of surpassing interest. At the present stage of this inquiry, the question of the primary origin of emanations and the like was not of great importance. After all, it was only fair to state that the orthodox magmatists had a somewhat hazy notion of the genesis and nature of magma itself.

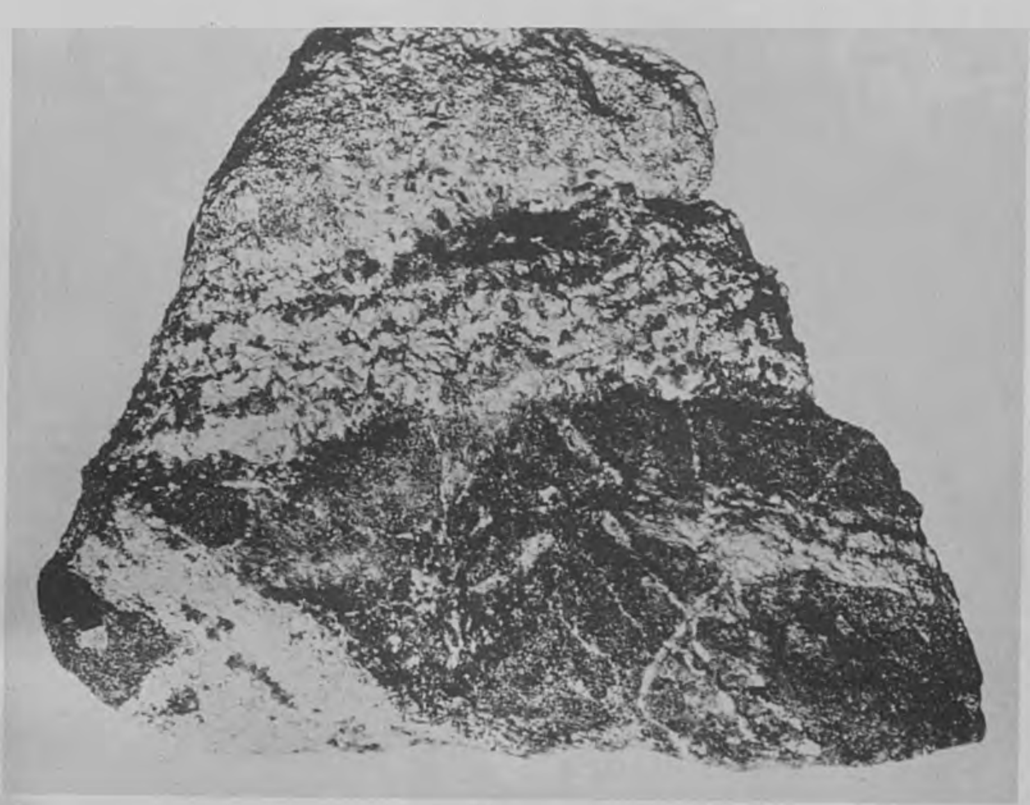
Dr. J. PHEMISTER said that the paper represented a great advance in our knowledge of the intrusions of northern Scotland. He agreed with the author that it was probable that the Cnoc nan Cuilean mass was not connected with the main intrusion of Ben Loyal at the surface. The author's view that the shapes of the intrusions were inverted cones did not seem to be well-founded. The intrusions appeared in an area of complicated structure, and the inward marginal dips, which occurred only on



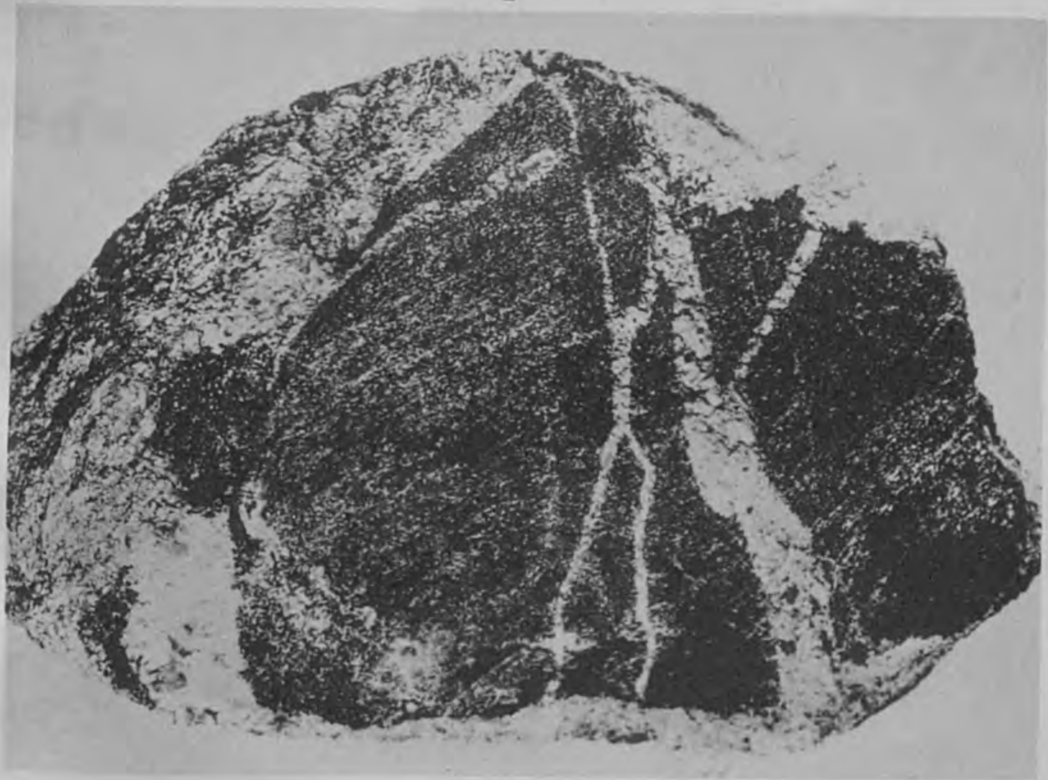
1

2

1. CRUMPLED AEGIRINE—AUGITE—HASTINGSITE—BIOTITE—ALBITE SCHIST, ALLT TORR AN TAIRBH.
2. VARIABLE BASIC SYENITE, LEITIRMHÒR.

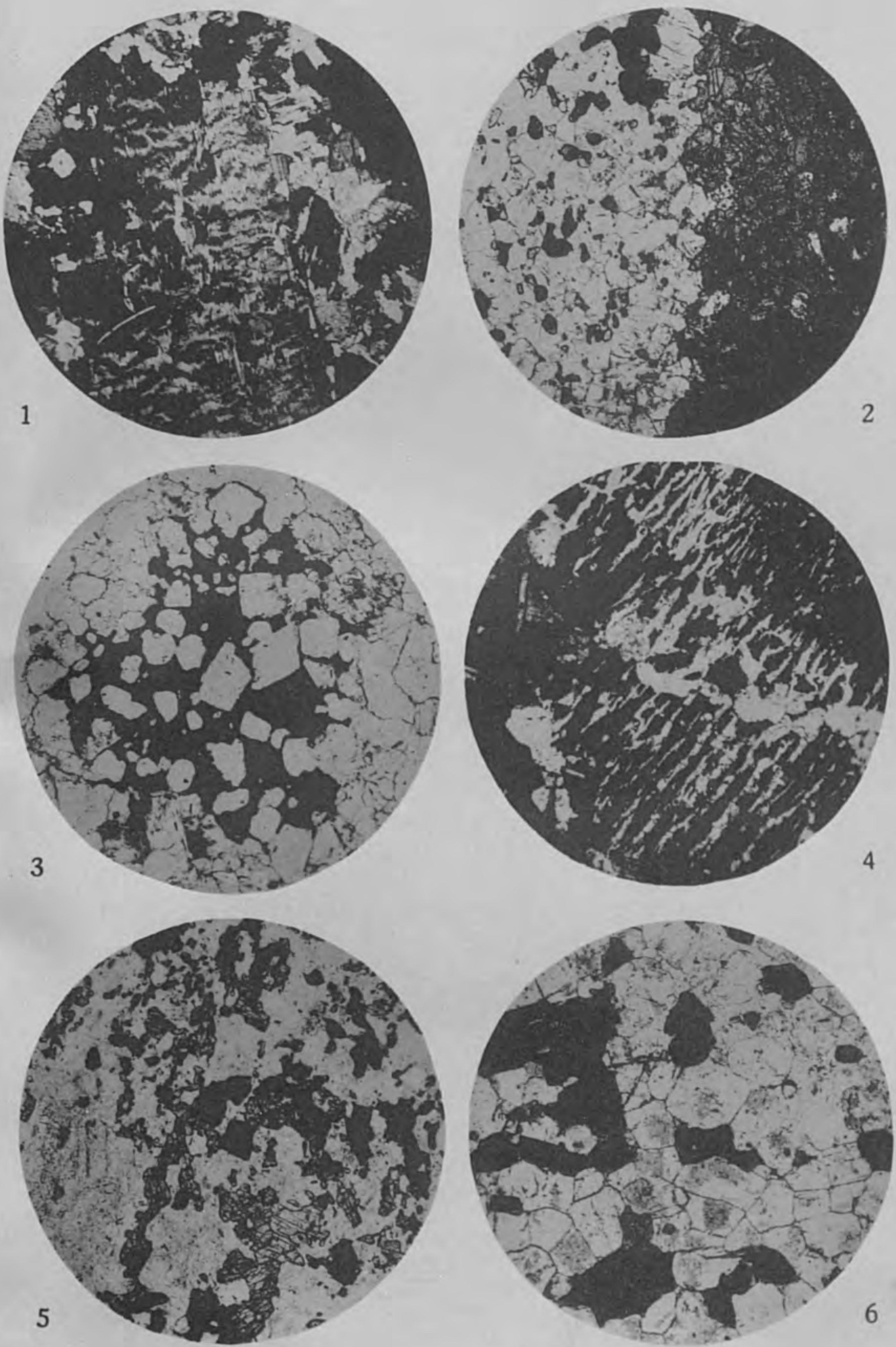


1



2

1. Variable syenite. Leitirmhòr.
2. Transition rock. Cnoc nan Cuilean.



ROCKS OF THE CNOC NAN CUILEAN MASS.


GEOLOGICAL MAP OF THE
BEN LOYAL IGNEOUS COMPLEX
LEGEND
Ben Stumanadh Syenite
Variable basic syenite
Mica schist
Moine Series
(Rocks of Lewisian type)
ONE MILE
LOCH LOYAL
BEN LOYAL
Ben Hiel
LOCH AN DITHREIBH
LOCH HALUIM
Creag Dhubh
Lettermore
Lettermore Stream
(Unexposed)
Càrn an Tionail
An Caisteal
Inchkinloch

the north and west of the main (Ben Loyal) intrusion, were perhaps controlled more by local structure than by the essential form of the intrusion. The Cnoc nan Cuilean mass seemed to be an ordinary stock with basic material at margins and roof. The author's demonstration of marginal metasomatism with development of aegirine-augite and hornblende in the schists was of great interest and importance.

The speaker, however, thought it a matter for regret that the author should have been led to mar his excellent study by advocating the hypothesis that the syenites and mesocratic rocks were derived from the schists by the metasomatic action of emanations, a hypothesis much advertised at the moment, but in this case opposed to material evidence. The syenites were of the same type as those of Loch Ailsh and Loch Borrolan, where the country rocks were different. The mesocratic rocks of Cnoc nan Cuilean, which had their counterpart in the Loch Ailsh and Loch Borrolan intrusions, were regarded by the author as metasomatic transformations of the schists by addition of cafemic constituents derived by the action of "primary" emanations of unknown composition from an unknown source on hornblende schists at an unknown depth in an area of problematical structure and constitution. These mesocratic rocks seemed more likely to be an early basic phase of the syenite intrusions, as at Loch Ailsh and Loch Borrolan.

Prof. H. H. Read then spoke again. He stressed that it was important to realize that the author did not propose that the material which formed the syenite body originated in the place where it was now exposed; on the other hand, it had developed from Moine rocks by metasomatism at depth similar to that observed on a small scale and at a higher level at Cnoc nan Cuilean. Objections to the author's views based upon dissimilarities of the country rocks surrounding the various alkaline masses of North Scotland were therefore completely groundless.

The author had suggested that there was evidence for the existence of rocks of "Lewisian" type below the Cnoc nan Cuilean body. The present speaker supported that opinion, as, from unpublished data, it was known that the Moines became increasingly of "Lewisian" type as they were followed from central Sutherland to the north coast.

Prof. C. E. Tilley said that it was difficult to gather from the abstract and the account now given the relative proportions of speculation and factual evidence presented for the origin of the basic masses fringing the Cnoc nan Cuilean mass. Had other interpretations been fully tested? For example, did the evidence preclude the possibility that these basic rocks represented an early intrusion disrupted, metamorphosed and metasomatically changed by the dominant alkali syenite? Such an interpretation could not be dismissed solely on the evidence of schistosity in some of the basic masses and it would not be out of place to recall in this connexion the classical work of Brøgger on the basic igneous schists associated with the intrusion of the alkali syenites of the Langesundsfjord area of southern Norway. He hoped that a discussion of the problem was to be found in the body of the paper.

The following written communication was received from Dr. D. L. Reynolds :—

"It would be difficult to find a clearer and more convincing example of metasomatism than the contact enrichment of the Moine granulites in aegirine-augite and hornblende that Mr. King has discovered. Of particular interest is his suggestion that the cafemic constituents necessary for the development of these minerals may have been derived from rocks that underlie—or underlay—the area, and not from syenite magma. On this interpretation, the zone of enrichment in aegirine-augite and hornblende corresponds with Wegmann's ' magnesium front ' that is characteristically developed in areas undergoing granitization. One sees this ' magnesium front ' in another and more usual form in the aureoles of biotite and cordierite enrichment that surround many of the Caledonian intrusions of Scotland and Northern Ireland.

" It is of interest in this connexion to recall some of the small-scale evidence of the process of expulsion of cafemic constituents from regions undergoing granitization. In particular, Goodspeed has described small granodiorite blocks, occurring at Cornucopia in north-eastern Oregon, which have been formed metasomatically from the quartz-biotite-hornblende-hornfels in which they are enclosed. The hornfels in contact with some of the granodiorite blocks shows an increase in biotite, chlorite and magnetite. As Goodspeed points out, the felspathization that has taken place at certain loci, leading to the production of the granodiorite blocks, was accompanied by a complementary outward migration of calcium, iron and magnesium. Similar blocks and replacement dykes of granodiorite occur in the hornfelsed Silurian rocks at Goragh Wood, County Armagh. These also have narrow biotite-rich selvedges, due to the outward migration of iron, magnesium and potassium. Other small-scale examples that probably have a similar explanation are the irregular veins and lenses of pegmatite with bordering zones enriched in biotite described by Sederholm from the migmatized meta-andesites of Finland, and the plane-sided and noded aplitic veins, with their biotite selvedges, described by Read from the injection gneisses of Sutherland.

" Professor Read has recently emphasized the importance of migratory material and metasomatism in regional metamorphism. Probably these processes will eventually be established as playing an equally important role in the emplacement and development of plutonic masses."

The following reply was subsequently received from the AUTHOR :—

" I welcome Prof. Read's concluding remarks regarding the present position of petrogenetic theory. The importance of the present study is as a demonstration of metasomatism and hybridization and any conclusions as to the ultimate source of the metasomatizing agencies must be regarded as speculative.

" Dr. Phemister's contention that the study is marred by the final hypothesis can be only a matter of opinion. On similar grounds it might well be contended that any hypothesis which claims that certain igneous rocks have been derived by a process of a ' flux of emanations ', migmatization, or ' ultra-metasomatism ' is opposed to material evidence. This attitude largely resolves into an instinctive feeling that the simpler or more strongly evidenced hypothesis is that which commends itself on the grounds of being readily visualized in ' ordinary ' mechanical terms.

" The Loch Borrolan mass has been regarded as a classic example both of crystal sinking and limestone assimilation. The only apparently direct evidence in favour of the latter was disproved by Dr. Phemister himself.

" Dr. Phemister, by analogy with the Loch Ailsh mass, and Prof. Tilley both ask whether the basic masses at Cnoc nan Cuilean do not represent an early basic intrusion disrupted by the dominant alkali syenite. This hypothesis was fully considered by the author, but rejected as not being the simplest conclusion and as being opposed by direct evidence. Basic masses occur only as xenoliths, and the change from a basic schistose patch to a non-schistose patch or streak is visibly associated with the incoming of syenitic material. On the other hand, basic schists do occur as metasomatically altered granulites and consequently the only material evidence for the original existence of a rock of this composition is to be found in the metasomatic zone. Why, then, should an earlier basic intrusion be postulated? This would require that the basic magma should first metasomatize the granulites to basic schists and then be itself disrupted and partially digested by a syenite magma.

"According to the hypothesis postulated by the author, one continuous process alone is invoked, which is closely supported by the continuity in the phenomena observed. Further, the theory of an earlier basic intrusion encounters an even greater difficulty, namely: the observed development of both felspathic and basic metasomatism in the same place. Bands or foliae of both types occur in the metasomatic rocks, which on being traced towards the main syenite mass become progressively less schistose, until the 'hybrid' types are produced. The basic material is the last to lose its schistose character, whilst the most felspathic bands become readily mobilized (rheomorphism). If one were to substitute the idea of an earlier wave or front of basic metasomatizing agencies for an earlier basic intrusion and a succeeding, but continuous and partly overlapping, wave of alkali-alumina metasomatism, in place of syenite injection, the two apparently conflicting hypotheses would have much in common. It should be stressed that it is only on the margins of the mass that these phenomena of rhemorphism and magma formation are actually evidenced in situ.

"Finally, I would like to thank Dr. Reynolds for her communication, which adds valuable supporting evidence for the existence of a front of basic emanations in widely separated areas."