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No. 1

**Demonstrations in petrogenesis from
Kiloran Bay, Colonsay.**

I. The transfusion of quartzite.

(With Plates XI and XII.)

BY

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With analyses by

AGNES GIBBS

and others.

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*Demonstrations in petrogenesis from Kiloran Bay,
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[Read November 5, 1936.]

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1. INTRODUCTION.

IN 1911 Dr. W. B. Wright¹ briefly described the feldspathized quartzite blocks in the hornblendite of Port Easdale, Kiloran Bay, Colonsay, Hebrides. He showed that the exposures provide a conclusive demonstration that the action of hornblendite magma on quartzite xenoliths was to convert them to alkali-felspar and quartz, so that

¹ W. B. Wright and E. B. Bailey, The geology of Colonsay. Mem. Geol. Surv. Scotland, 1911, p. 29.

in the final stage 'one can recognize in numerous angular and rounded patches of felspathic material, without visible xenolithic core, the ghosts of former masses of quartzite'.

Twenty-five years have elapsed since the publication of Dr. Wright's account, yet the importance of the record appears to have passed unnoticed. The purpose of this paper is, therefore, to recall the occurrence; to amplify Dr. Wright's description with additional observations and petrological and chemical detail; and to emphasize the petrological significance.

Stimulated by Dr. Wright's description, Dr. Holmes and I paid a preliminary visit to Colonsay in 1934. Finding much of interest we returned in 1936 and, in order that no detail should be overlooked, remapped the small intrusions of Port Easdale on the scale of 54 inches to the mile. For this purpose the coastline, with its disconnected rocky outcrops, had to be remapped. As a result of our visits much additional evidence of first-class petrological importance has been obtained. We propose to deal with this evidence in a series of papers of which the present communication, restricted to the phenomena attending the transfusion of quartzite, forms the first.

2. GEOLOGICAL SETTING.

The sedimentary rocks, which constitute the major part of the island of Colonsay, consist of a folded, crumpled, and cleaved series of phyllites, limestone, mudstones, grits, and conglomerates, regarded by Wright and Bailey as of Torridonian age. Kiloran Bay breaches and occupies the centre of a structural basin in this series, the shores of the bay being margined by the Staosnaig phyllites, the youngest beds of the succession. The latter are in turn margined by the Colonsay limestone and successively older members of the sedimentary sequence.

On the northern shore of Kiloran Bay the Staosnaig phyllites are pierced by three small composite intrusions consisting of hornblendite, appinite, and syenite. Two of these form the northern and southern shores of Port Easdale, whilst the third outcrops in the higher ground directly to the north. Each of the three intrusions comprises an elongated mass of syenite, trending in a W.-E. or NW.-SE. direction, together with marginal phases of hornblendite and appinite (hornblende and alkali-felspar). Further, the marginal phases of each intrusion contain abundant angular and rounded blocks of

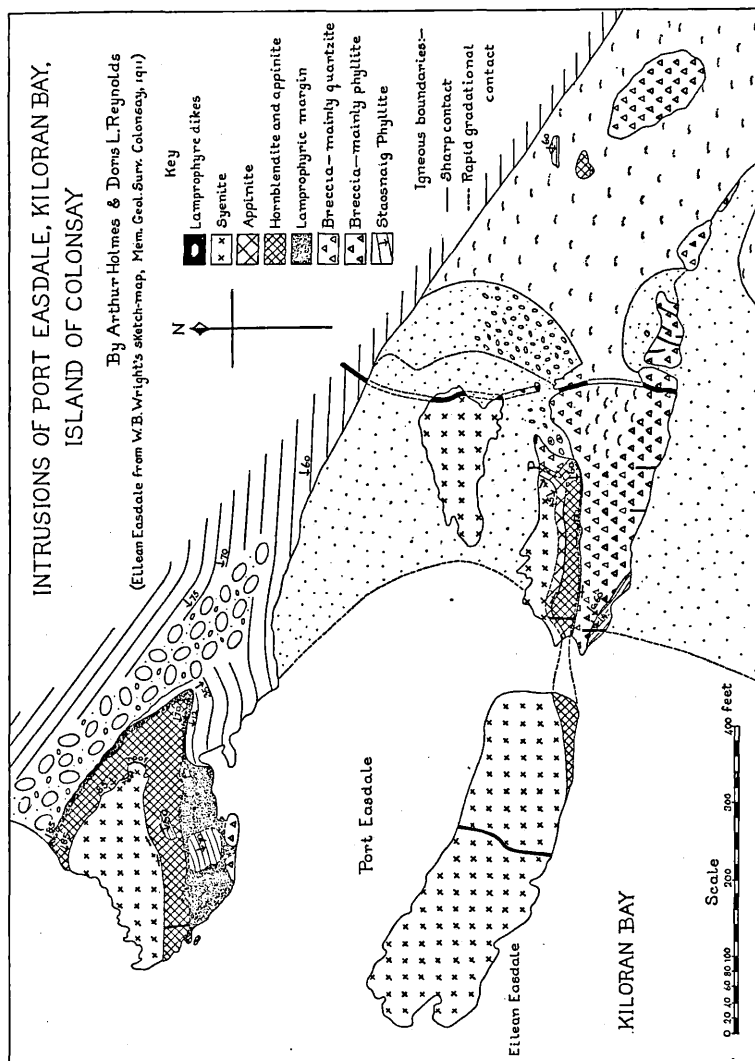


FIG. 1. Geological map of the intrusions of Port Easdale. The strike lines of the Staosnaig phyllites are diagrammatic, except where observations of dip are recorded. The arrows on the igneous types and on the breccia refer to the dip of the contact planes. P indicates the locality of the syntectonic pegmatite veins (pl. XI, fig. 4).

quartzite which are to be seen in all stages of conversion to both syenite and appinite.

The most southerly of the three intrusions throws light on the origin of the xenolithic quartzite blocks. Only the southern limb of this intrusion is exposed, its northern margin being concealed beneath the sand of the bay. The intrusion is elongated from west to east and the exposed portion consists of successive zones, from north to south, of syenite, appinite, hornblendite (showing gradations to appinite throughout its mass), lamprophyre, and sedimentary breccia (developed by magma pressure). The distribution and ascertained relations of these various types are shown on text-fig. 1.

In the present connexion the breccia is of importance. It shows a sharp contact against the Staosnaig phyllites and is as much an intrusion as are the igneous types. At its outer margin, where it adjoins the phyllites, it is formed almost completely of closely interlocking angular blocks of similar phyllite. A few feet in from the margin, however, angular and occasional rounded blocks of white quartzite, sometimes two feet or more across, are also present, together with rarer blocks of limestone. The latter, as Wright suggested, is probably the Colonsay limestone which margins and dips under the phyllites of Kiloran Bay. Away from the margin the proportion of quartzite blocks increases until the igneous contact is reached. There the breccia is composed almost completely of rounded and angular blocks, together with much larger masses, of white quartzite. The latter, measurable in yards, are obviously representatives of a massive quartzite horizon. The blocks vary from a few inches up to two or three feet across, and the proportion of rounded relative to angular members increases greatly towards the igneous contact.

No quartzite formation outcrops in the island, although it was noted by Wright that similar quartzite occurs as small pebbles in conglomerate beds at two horizons in the local Torridonian and also as xenoliths in some of the lamprophyre dikes. The facts indicate that the quartzite represents a formation older than the exposed country-rocks.

That the breccia results from magma pressure is evidenced by its restriction to the igneous margin. That it represents upheaval is evidenced (*a*) by the dip of the contact plane against the phyllite (text-fig. 1), and (*b*) by the disposition of the rock types within the breccia, the oldest variety occurring in contact with the igneous rocks.

It remains to account for the rounding of some of the quartzite blocks in the breccia. So striking is this rounding that Wright was led to regard the blocks as water-worn boulders, derived from a loose surface formation, which had fallen into a fissure or pipe. Dr. Holmes and I discovered, however, that many of the boulder-like forms in the breccia have pink felspathic rims, sometimes two or three inches broad, similar to those of the xenolithic quartzite blocks in the hornblendite and appinite of the intrusion. The inference is that the rounded blocks in the breccia have undergone a form of magmatic attack similar to that experienced by the xenoliths in the basic magma. It will be shown later in the paper that felspathic material developed from the quartzite may become paligenetic magma. If this occurred in the breccia, under conditions of high stress, mobile material formed around the periphery of the blocks would readily squeeze away, and rounded forms would result. It seems probable that the quartzite blocks thus attacked were once directly in contact with the hornblendite magma. Indeed, the hornblendite is still roofed, at one point along the contact, by a slab of quartzite, about one foot thick, which is margined against the hornblendite by a felspathic layer two or three inches thick. The fact that a few rounded forms occur towards the outer margin of the breccia may be accounted for by the greater ease with which such bodies, possibly lubricated by magmatic material, could slip through the heaving mass.

The massive quartzite adjoining the igneous intrusion at its eastern extremity has the appearance of being turned up on edge, as though punched upward by the rising intrusion. This, together with the intrusive contact exhibited between the breccia and the Staosnaig phyllites, is indicative of the enormous upward pressure exerted by the rising magma.

Further evidence of magma pressure is obtainable from the intrusion which margins the northern shore of Port Easdale. Here the invaded phyllites have been forced outwards, as is evidenced by the curve of the strike lines round the intrusion (text-fig. 1). Both the northern and southern limbs of the intrusion are exposed in this case, and breccia is seen to be developed only on the southern margin. The breccia, moreover, consists of fragments of phyllite only.

3. FIELD DESCRIPTION.

(a) Metasomatized Quartzite Xenoliths.

In all three intrusions the major part of the hornblendite and appinite is thickly sprinkled with blocks of white quartzite similar to that in the breccia which margins the southern intrusion. The largest blocks, which are up to two and a half feet long, are frequently of roughly rectangular form, whilst the smaller examples are usually rounded.

In the southern intrusion the quartzite xenoliths are fairly evenly distributed through the exposed portions of the hornblendite and appinite. In the hornblendite cliffs to the north of Port Easdale, however, there is some evidence that they are concentrated in the upper part of the intrusion, since a level charged with quartzite blocks passes downwards to one which is almost free from such inclusions. The distribution is, however, by no means uniform, for patches of hornblendite free from such inclusions, sometimes six feet or more across, are surrounded by zones heavily charged with xenoliths.

Whereas a few of the quartzite xenoliths in the upper part of the intrusion are unaltered, the great majority are in some degree changed to syenite or appinite (pl. XI, fig. 1). The varied appearances which they present are as follows:

1. In the apparently less altered xenoliths a core of white quartzite is sharply margined by a narrow feldspathic rim, up to 1 cm. in width. The latter, which is usually pink, but locally white, may be quite free from ferromagnesian minerals or may contain sparse small crystals of hornblende. Where it adjoins the quartzite, the feldspathic rim commonly becomes rich in mafic minerals. This melanocratic zone is extremely narrow, generally being 1 or 2 mm. across but occasionally swelling out to 5 mm. Blebs of quartz are sometimes visible in the feldspathic rim.

2. More completely replaced xenoliths sometimes exhibit a core of quartzite surrounded by a narrow inner feldspathic zone, like that just described, and a broad outer zone of appinite or syenite. There is a sharp boundary between the quartzite core and the feldspathic rim, and between the latter and the appinite or syenite. In the outer zone the hornblende is frequently blade-like and occasionally, in zones of appinite, it reaches a length of 6 cm., thus contrasting strongly with the stumpy prismatic hornblende of the hornblendite (text-fig. 2).

3. In other examples, a quartzite core is directly surrounded and sharply bounded by a rim of appinite or syenite without the intervening felspathic zone. In such cases the hornblende is evenly distributed throughout the felspathized region. The percentage of hornblende varies, however, from one example to another, and in the more leucocratic varieties of syenite it is absent, chlorite being the characteristic mafic mineral.

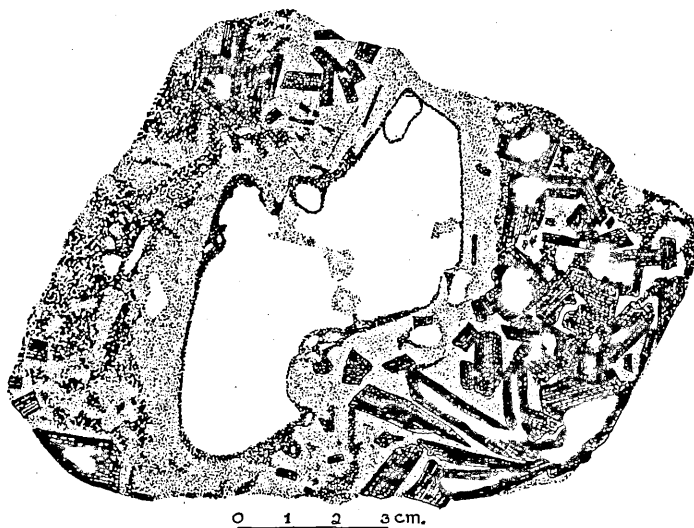


FIG. 2. Metasomatized quartzite xenolith, described in the text under type 2. A narrow mafic zone, which adjoins the residual quartzite, is followed successively outwards by a pink felspathic zone and an appinitic zone.

4. Many of the xenoliths have been completely replaced by appinite or syenite. Leading up to this type there are examples in which small isolated relics of quartzite still remain; the latter are surrounded by elongated hornblendes with a stellate arrangement.

Whatever form the replacement may take, one of the most striking phenomena in the metasomatized quartzite xenoliths is the invariable sharpness of the contact between the residual quartzite and its metasomatized portion. Moreover, where the quartzite core is surrounded by two successive zones (type 2 above) the boundary between these is also sharp. If seen on a large scale in the field such boundaries would inevitably be interpreted as intrusive contacts. From the well-defined replacement rim lobe-like forms composed of felspar frequently

penetrate the quartzite. Again, sharp contacts are seen, although the blunt endings of the vein-like projections testify to the replacement origin of the latter.

Such sharp boundaries are at first surprising. Reference to experimental work on replacement structures in metals, however, shows that actually they are to be expected when replacement results from compound formation dependent on diffusion through a solid. According to Desch,¹ in the study of diffusion in metals it has been found that: 'When an intermetallic compound is formed by diffusion, the boundary of the new phase is perfectly sharp, and such sharpness may be taken as an indication of compound formation.' In the present case the development of the compound feldspar results from the introduction of potassium, sodium, and aluminium into quartzite.

Although the metasomatized xenoliths present so many different appearances, yet the following facts, relating to the diffusion of feldspar-forming and mafic materials into the quartzite, stand out clearly.

(a) Feldspar-forming materials only have in some cases been introduced into the xenoliths, as evidenced by type 1 above.

(b) Feldspar-forming materials have in some cases advanced a short distance farther into the xenoliths than the mafic materials, as evidenced by types 1 and 2 above.

(c) Feldspar-forming and mafic materials have in some cases advanced the same distance into the xenoliths, as evidenced by types 3 and 4 above.

(d) Ferromagnesian minerals, within a feldspathic zone, sometimes form a narrow green rim against quartzite, but are separated from the main hornblende-bearing region by a feldspathic rim. This is exemplified in some of the cases described as types 1 and 2 above.

(e) Ferromagnesian minerals have in no case been introduced into the xenoliths beyond the limit of feldspathization.

These facts appear to indicate that the process of metasomatism takes place in two successive, but overlapping, stages: (1) introduction of feldspar-forming materials, (2) introduction of mafic materials for forming ferromagnesian minerals. Case (c) suggests that a certain amount of ferromagnesian material may travel with the vanguard of potassium, sodium, and aluminium, the main introduction of mafic material following slightly later.

Against the enclosing rock the boundaries of the metasomatized

¹ C. H. Desch, *The chemistry of solids*. 1934, p. 112.

xenoliths may be sharp (as is invariably the case in type 1), ill-defined, or merging. In the last case the original quartzite xenoliths are now represented by felspathic patches or schlieren. Where the hornblendite is free from xenoliths it is also free from felspar, but in the neighbourhood of felspathized quartzite blocks it becomes felspathic and is then better termed appinite. Similarly, where appinite is the enclosing rock it becomes more felspathic around felspathized quartzite xenoliths and approaches syenite.

(b) *Syntectic Veins.*

Some of the felspathized quartzite xenoliths have meteor-like tails of felspathic material which pass out from the metasomatized blocks in various directions through the hornblendite. In some cases these 'tails' are broad and short, whilst in others they are vein-like in their proportions, being many yards long, although they may be less than an inch wide (pl. XI, fig. 2). The appearance indicates that the felspathic material, resulting from the metasomatism of quartzite, has in these cases become magmatic. At one point, near the seaward end of the southern limb of the intrusion margining the northern shore of Port Easdale, such felspathic material is locally so abundant that it cuts the hornblendite in a roughly rectangular network of veins (pl. XI, fig. 3). Indeed, the hornblendite now appears as rounded inclusions in a pink felspathic matrix. Without the evidence of the complete exposure, this small portion would hardly fail to be interpreted as resulting from the invasion of solid hornblendite by felspathic magma. The appearance is reminiscent of the Arran gabbro-granite complexes; the dolerites veined with granophyre in Ardnarmurchan; the hornblendite veined with leucocratic material on Garabal hill; and the peridotite veined with felspathic material at Crocknafoyle, in the Newry complex. Yet here, in Colonsay, there is conclusive evidence that the hornblendite magma itself generated such vein material from sediment. The vein material was in fact syntectic magma.

The roughly rectangular character of the vein network suggests that the felspathic material migrated along the contraction joints in the hornblendite, indicating that the felsic syntectic magma had a lower crystallization temperature than the hornblendite magma.

At the extreme eastern end of the intrusion to the south of Port Easdale, the hornblendite is seen for two or three feet in vertical contact with quartzite. Along the contact the quartzite is felspathized

in an irregular zone which has a maximum width of about two inches. From this felspathic margin several veins of pink pegmatite extend into the hornblendite and beyond it into the appinite (pl. XI, fig. 4). The veins, which are about 6 or 8 inches wide, have, in places, irregular margins against the hornblendite. The irregularities are seen to result from a certain amount of mixing of the two types. One vein in particular has a highly irregular upper margin above which the hornblendite, for a distance of several inches, contains small patches or blebs of pink felspar. The heterogeneous appearance is reminiscent of an emulsion in which the felspar forms the disperse phase. The facts indicate that the syntectic pegmatite veins were injected into the hornblendite whilst the latter was still fluid, and that blebs of the felspathic magma began to rise up through the hornblendite magma. Lack of complete mixing, evidenced by the emulsion-like structure, is suggestive of high viscosity. Around the felspathic patches there are blade-like crystals of hornblende sometimes several centimetres long.

4. PETROLOGY.

(a) *Hornblendite.*

Where free from inclusions of quartzite, the hornblendite is a medium-grained dark-green rock consisting essentially of stumpy euhedral to subhedral crystals of amphibole which average about 4 to 5 mm. in length. In thin section the amphibole crystals are found to be composite, in that they consist of several varieties which are associated both in zonal fashion and as replacements one of the other. The optical characters of the varieties are set out in table I.

TABLE I. Optical data of amphiboles in the hornblendite.

	γ' .	$\gamma-a$.	$\gamma:c$.	2V.
Brownish-green hornblende	... 1.657	0.019	20°	} Negative and close to 90° through out.
↓ Green hornblende	... 1.643	0.020	18°	
Actinolite	... 1.638	0.025	18°	
↓ Tremolite	... 1.634	0.027	15°	

The limit of error of γ' , measured on cleavage flakes, is ± 0.002 , except in the case of tremolite for which γ' is correct to the third place. $\gamma-a$ was determined with a Berek compensator.

The central part of the crystals, which is brownish-green hornblende with γ green $> \beta$ brownish-green $> a$ pale brownish-green, merges outwards in a very irregular but gradual manner to a green variety.

The latter may closely resemble the brownish hornblende in its optical characters, but where zoning is most conspicuous $\gamma:c$ decreases outwards to 18° at the margin of the crystal, there being a concomitant increase in birefringence and decrease in refractive indices. The optical characters appear to indicate gradation to an actinolitic hornblende. The irregular form of the zones, which are not always bounded by crystallographic planes, possibly indicates that each zone is in part a replacement of earlier amphibole.

These crystals are usually terminated by outgrowths of tremolite, or of pale actinolite followed outwards by tremolite. In some examples there is a complete outer zone of tremolite which is very narrow in the prism zone, often barely visible, and of considerable extent on the terminal faces. The outgrowths of tremolite, or of actinolite and tremolite, are sharply separated along crystallographic planes from the rest of the crystal. Where both varieties are present, they, in turn, may be sharply bounded one against the other, or they may show rapid gradation.

Commonly there has been replacement of the zoned hornblende by tremolite. The latter, in such cases, embays the margins of the amphibole and also occurs in irregular areas within it (pl. XII, fig. 1). Tremolite also replaces the hornblende either along its cleavages or as fine veinlets in the green marginal zone. In both cases it commonly spreads out into rounded lobe-like areas on entering the central brownish hornblende, the latter evidently being the most unstable variety. In regions of replacement small relics of the earlier amphiboles, in optical continuity with the original crystal, often remain. Occasionally a pale-coloured actinolite, similar to that of the marginal outgrowths, also replaces the hornblende in a vein-like manner.

The zonal and replacement textures of the amphibole show that the crystallization sequence was brownish hornblende \rightarrow actinolitic hornblende \rightarrow actinolite \rightarrow tremolite, indicating a progressive decrease in alumina, soda, and iron.

Associated with the tremolite is a pale-coloured optically positive pennine, with $\alpha = \beta$ very pale green $> \gamma$ very pale yellowish-green; β between 1.587 and 1.588; $\gamma - \alpha$ 0.004; and 'ultrablue' or weak grey interference tints. It sometimes occupies the central portion of tremolite replacement-veinlets in the hornblende. Moreover, where brownish hornblende is replaced by lobes of tremolite the latter is commonly associated with pennine and calcite. In such cases pennine

appears to have replaced tremolite to some extent, since disconnected relics of the latter, optically continuous with the main tremolite, remain embedded in the pennine.

Large crystals of an almost colourless pennine sometimes contain central cores or isolated relics of biotite. In this case the pennine ($\beta < 1.588$) evidently replaces biotite, and it contains strings of a dense whitish material, resembling leucoxene, which follow the cleavage traces. Pennine with relics of biotite is sometimes enclosed within the hornblende.

Locally the hornblende is rich in biotite, which is partly enclosed by and partly encloses hornblende. It is of a dull brown to greenish-brown colour, commonly becoming greener towards the margin of the flakes. The flakes average about 1.5 mm. across, but in patches they reach a size of 2 or 3 cm. They are particularly characterized by sharp crumpling.

Interstices between the amphibole and biotite or pennine crystals are occupied by large anhedral crystals and finely-granular aggregates of calcite; radiating tufts of pennine; and fibres of tremolite. The latter penetrate both pennine and calcite. In many instances calcite is also interlaminated with tremolite.

Finally, there has been replacement of the earlier minerals by calcite, which cuts across all the other constituents in veinlets, and sometimes occupies considerable areas in which small isolated residuals of optically continuous amphibole remain.

Accessories consist of apatite, as large stumpy prisms, and sparse pyrite and iron ore.

The crystallization sequence of the hornblende, as indicated by zoning and replacement textures, was as follows: hornblende and biotite; amphiboles successively less aluminous than the original hornblende; actinolite; tremolite; pennine; calcite. The crystallization periods of the last three minerals appear to have been in part simultaneous; the final mineral deposited, however, is always calcite. The sequence indicates crystallization from a magma which became progressively less rich in alkalis and alumina, and in which magnesia and lime became concentrated.

(b) *Appinite.*

The appinite of the marginal intrusions differs from the hornblende in containing varying amounts of albite, perthite, and quartz, the quartz commonly being intergrown with the feldspars as micropegma-

tite. In addition apatite is more abundant than in the hornblendite. As in the hornblendite, biotite is locally abundant, and the hornblende shows outgrowths of, and replacement by, tremolite and actinolite. There are patches in which the hornblende is largely or wholly replaced by chlorite. The characteristics of the minerals are similar to those—described in the following pages—of corresponding minerals in the metasomatized quartzite xenoliths. As in the metasomatic rims, patches of quartz which appear isolated in thin section are sometimes optically continuous. The felsic constituents, including apatite, are partially replaced by calcite, being much dissected by veinlets of this mineral.

(c) *Quartzite Xenoliths.*

The quartzite xenoliths consist almost entirely of a fine-grained mosaic of quartz grains in which a few larger individuals of quartz are embedded. The quartz is characterized by strain shadows. Felspar is present in very small amount, and it is impossible to tell whether it is an original constituent or the result of introductions. Both albite and perthite are represented; they have characteristically crystalloblastic outlines with curved re-entrants around quartz grains, and are usually clouded with an exceedingly fine brown substance. Perthite sometimes encloses optically continuous blebs of quartz, thus simulating a rude micrographic intergrowth. Calcite, chlorite, and pyrite are present in small amount, and sparse rounded detrital grains of zircon are characteristic.

The quartzite cores, in partially replaced blocks, are crossed by streams of minute bubbles which extend into the quartzite from the metasomatized rim. Sometimes such streams of bubbles, which pass from one quartz individual to another, cut through felspar, their passage being marked by a clear band in the latter. This band is optically continuous with the remainder of the felspar, but is completely cleared of inclusions, so that it contrasts sharply with the clouded neighbouring portions.

Here and there along the course of bubble-streams short veinlets of calcite replace quartz. The veinlets may cut across the centre of quartz grains or extend along their boundaries. In the latter case calcite projects, in minute antennae-like structures, from the sides of the veinlet along the boundaries of neighbouring quartz grains—a typical replacement texture. Such calcite veinlets begin and end abruptly in thin section, being continued at either extremity by a

stream of bubbles. Similar streams of bubbles, which locally pass into veinlets of calcite, or rarely quartz, are also present in the metasomatized rims, and from the latter they are sometimes traceable into the quartzite.

Veinlets of feldspar (perthite and albite) with which chlorite is occasionally associated, extend into the quartzite from the metasomatized rims. They usually take a highly sinuous course, since they are generally developed along the boundaries of quartz grains. Like the calcite, the feldspar fingers out from the sides of the veinlets along the boundaries of neighbouring quartz grains (pl. XII, fig. 6), indicating that it replaces quartz. Occasionally feldspar veinlets cut across large individuals of quartz. Here again the feldspar fingers out on either side of the veinlet, but in this case it extends into a quartz crystal instead of along intergranular boundaries. As a consequence of this invasion, the quartz shows lines of stress radiating from each feldspathic finger.

(d) *Metasomatized Quartzite.*

As already described in the field section (p. 372), most of the quartzite xenoliths are partially or wholly altered to varieties of syenite and appinite, the syntectonic rock types occurring either separately or in concentric zones in individual xenoliths. In the latter case syenite adjoins the centrally placed residual core of quartzite.

(i) *Minerals and Textures.*

In the syntectonic rocks, perthite, albite, hornblende, actinolite, tremolite, chlorite, epidote, allanite, apatite, pyrite, sphene, and calcite have developed as a result of metasomatic introductions. In addition, quartz and zircon are present, having persisted from the original quartzite. The quartz has usually recrystallized, whilst the zircon generally retains its detrital form.

The syntectonic rocks form a series, ranging from micropegmatite and quartz-rich syenite to melanocratic appinite, the various members of which differ in the relative proportions of mafic to felsic constituents. Moreover, whereas hornblende is characteristic throughout the greater part of the series, chlorite is the common mafic mineral, usually to the exclusion of hornblende, in the more leucocratic varieties. A wide range of textures are developed, and much variation is sometimes shown within a single rim. It should, however, be stressed at the outset that the rocks constituting the rims have

an igneous aspect, and that in no case, without the complete evidence, would they be suspected of having originated as replacements of pre-existing rock.

Felspars. Perthite occurs both as subhedral to anhedral crystals and in micropegmatitic intergrowths with quartz. The potash-felspar of the perthite shows simple twinning of Carlsbad type only. Albite is present in the potash-felspar in irregular areas at the margin, and in minute discontinuous veinlets and patches, optically continuous with the marginal albite, within the crystal. In some instances the veinlets are directly continuous with the marginal albite, and have the appearance of being outgrowths from the latter. Dependent on the orientation of the section, the albite veinlets either extend parallel to the vibration-direction of the slow ray in the potash-felspar or make an acute angle with that direction, the maximum angle measured being 30° . The data indicate that the veinlets extend parallel to the intersection of the basal plane and one of the primary prism faces. In some sections the albite appears as small patches which tend to have straight margins parallel to the *c*-axis, but are otherwise of irregular outline. The albite is usually untwinned, but it may show an occasional patchy development of albite lamellae. More rarely, albite is present in the potash-felspar as larger and less frequent patches in which albite lamellae are easily visible and are often of 'chess-board' type.

The ratio of albite to potash-felspar in the perthite varies within wide limits. From the examples described above there are gradations, through varieties in which potash-felspar is almost completely margined by albite, to a type in which potash-felspar is present only as disconnected patches in albite. Finally, there are examples in which potash-felspar appears as very small and sparse patches within euhedral or subhedral albite. The albite in these cases does not develop albite lamellae, except in rare small patches, but, like the potash-felspar, it exhibits twinning of Carlsbad type.

The relations exhibited between albite and potash-felspar in the perthitic intergrowths suggest that the former replaces the latter (cf. the 'patch perthite' of Andersen¹). Further, the fact that in the rare instances where albite lamellae are present their development is of 'chess-board' type is significant, since this texture commonly results from replacement. It cannot, however, be overlooked that

¹ Olaf Andersen, The genesis of some types of feldspar from granite-pegmatites. Norsk Geol. Tidsskrift, 1928, vol. 10, p. 170, pl. 3, figs. 2 and 3.

the feldspars are here known to replace quartz, and it is therefore possible that the textural features displayed by the perthitic intergrowths may result from the simultaneous growth of potash-feldspar and albite in a solid medium, being in fact a crystalloblastic development. Albite is also present, however, as euhedral to subhedral crystals in which no trace of potash-feldspar has been observed. Such crystals stand in strong contrast to the albite of the perthite, since in them albite lamellae are well developed; the lamellae are commonly persistent across the crystals, but are occasionally of 'chess-board' type. In the forefront of the replacement rim the polysynthetically twinned albite is sometimes seen to be directly replacing quartz. It is therefore possible that the twinned albite results from replacement of quartz, whereas the untwinned variety replaces potash-feldspar.

The ratio of albite (well-twinned variety) to perthite varies from one specimen to another. Usually albite is considerably less abundant than perthite. In some instances, however, it is as abundant as perthite, and occasionally it is the more abundant feldspar. It is often micropegmatitically intergrown with quartz and two types of such intergrowth have been recognized. In one, quartz, and in the other, albite appears to form the host mineral. Similar micropegmatitic relationships between albite and quartz, in reconstituted xenoliths from the Dartmoor granite, have been recorded and figured by Brammall.¹

Both the untwinned albite of the perthite and the twinned crystals exhibit a faint brown clouding due to the presence of minute opaque inclusions, some of the larger of which can be seen to be ragged flakes of haematite. In the well-twinned albite the clouding is sometimes arranged in bands parallel to the albite lamellae. The potash-feldspar of the perthitic intergrowths, although it contains sparse inclusions of a similar kind, is relatively clear.

Occasionally both perthite and twinned albite are crowded with sericite² flakes. This development of sericite is quite sporadic and cannot be correlated with any particular position in the replaced xenoliths. Aggregates of sericite, in which no feldspar is visible, are locally developed. Both perthite and twinned albite are sometimes rendered opaque by the presence of a grey substance, associated with

¹ A. Brammall and H. F. Harwood, The Dartmoor granites: their genetic relationships. *Quart. Journ. Geol. Soc. London*, 1932, vol. 88, pp. 205, 207.

² The term sericite is used throughout this paper without implication as to the potassic or sodic character of the mica.

sericite. In such instances the felspar is visible only in small clear areas near the margin, the actual margin being clouded with a fine brown substance.

Where a core of quartzite remains in the metasomatized xenoliths the limit of general feldspathization can be seen, in thin section, to be sharp. The felspar of the replaced portion, however, extends into the quartzite in minute antennae-like processes which are frequently developed along the margins of adjacent quartz grains (pl. XII, fig. 6; see also pl. XIII, fig. 4 of the following paper¹). This fact indicates that the felspar-forming materials penetrated the quartzite most readily along intergranular boundaries. In places feldspathization has spread in this way along the boundaries of neighbouring quartz grains for a short distance in advance of the limit of general replacement. In such examples the quartz grains may have the appearance of being embedded in a sparse feldspathic matrix, or, with a greater development of felspar at the expense of quartz, they may appear as rounded poikilitic inclusions in a felspar crystal. Narrow vein-like forms of felspar sometimes extend from the metasomatic rim into the quartzite. They, like the rim itself, are margined against the quartzite by antennae-like processes of felspar which extend between adjacent quartz grains (pl. XII, fig. 6).

The antennae-like outgrowths of felspar are not, however, restricted to the intergranular boundaries. Where a large quartz grain margins the replaced portion, it is penetrated by such feldspathic outgrowths which terminate bluntly within the grain (text-fig. 3). Sometimes large quartz grains are in this way much dissected. Not infrequently large quartz grains lie across the metasomatic boundary, one part being in the quartzite and the other in the feldspathized zone. In such cases the feldspathization can often be seen to take place along definite crystallographic directions, the quartz becoming cut up into rhomb-shaped portions, of roughly similar size, which exhibit straight extinction with the diagonals of the rhombs (text-fig. 4). This suggests that the felspar-forming materials penetrate quartz most readily along rhombohedral planes, and is possibly an indication that quartz has a coarse rhombohedral mosaic structure.

Quartz. The percentage of quartz in the metasomatized quartzite xenoliths is very variable. In some cases quartz is absent, whereas in others it is present in amount comparable to that of granitic

¹ A. Holmes, Transfusion of quartz xenoliths in alkali basic and ultrabasic lavas, south-west Uganda. *Min. Mag.*, 1936, vol. 24, p. 421.

rocks. For the most part the quartz has recrystallized so that the grain-size has become considerably coarser than that of the quartzite cores. In many examples it forms micropegmatitic intergrowths with the feldspars; in others it is associated with the feldspars in granitic fashion; and in others again it is interstitial. Where it exhibits granitic texture or occurs interstitially, neighbouring isolated portions are often optically continuous.

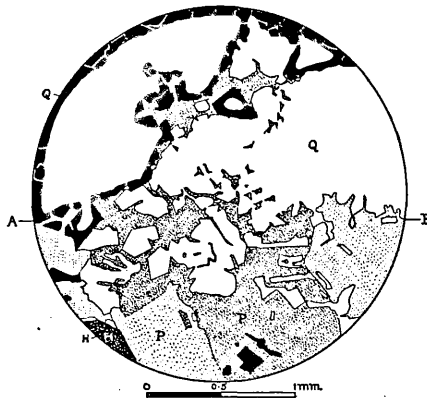


FIG. 3.

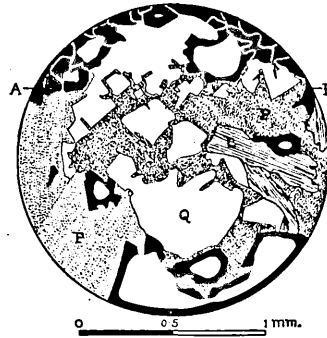


FIG. 4.

FIG. 3. Contact between the residual quartzite and the replaced portion of a xenolith. A-B marks the limit of general feldspathization, Q = quartz, P = perthite, and H = hornblende. The quartz shown white is all part of one individual, which has been partially feldspathized. A replacement veinlet of feldspar extends, from the zone of general feldspathization (below A-B), along the margin of this large grain, penetrating the latter and spreading into the adjacent smaller grains via their intergranular boundaries.

FIG. 4. Contact between the residual quartzite and the replaced portion of a xenolith. A-B marks the limit of general feldspathization. Q = quartz, P = perthite, and C = chlorite. The quartz shown white is all part of one individual, which has been partially feldspathized, the feldspar mainly following rhombohedral planes.

The anhedral quartz almost always shows strain shadows, the shadows, in every observed case, extending parallel to the vibration-direction of the slow ray. This appears to indicate that the strain is developed in planes parallel to the *c*-axis. Occasionally the strain gives an appearance of lamellar twinning parallel to the *c*-axis, alternate lamellae extinguishing simultaneously at a small angle with *c*. The strained quartz is distinctly biaxial.

In the micropegmatite the quartz sometimes, but not always, shows strain. Where intergrown with albite the direction of the strain lamellae makes a high angle with the albite lamellae in all observed cases.

The quartz is crossed by lines of dot-like inclusions which include both gas bubbles and minute irregular specks of an opaque material.

Hornblende of the same type as that which characterizes the hornblende is present in the metasomatic rocks. It shows similar, though less conspicuous, zoning in which the brownish-green variety ($\gamma:c = 20^\circ$, $\gamma' 1.657 \pm 0.002$, $\gamma - \alpha 0.019$, negative, $2V$ close to 90°) occurs centrally, and merges outwards to green hornblende ($\gamma:c = 18^\circ$, $\gamma' 1.643 \pm 0.002$, $\gamma - \alpha 0.020$, negative, $2V$ close to 90°). The latter also builds independent but relatively small crystals which particularly characterize the forefront of replacement rims. Outgrowths of tremolite and actinolite are less common than in the hornblende, but replacement of the early hornblende by these two amphiboles has often taken place. Felted aggregates of actinolite are sometimes present, and appear to replace leucocratic constituents as well as earlier hornblende.

The hornblende occurs both as isolated crystals and in aggregates. It often builds euhedral crystals which vary in habit from stumpy to elongated prismatic. Subhedral forms are also evident in which prism and clinopinacoid faces are usually well developed, while the terminations are irregular, and not infrequently have a frayed appearance. More rarely the faces of the prism zone show an irregular development. Simple twinning parallel to (100) is not uncommon.

The hornblende exhibits a variety of textures. In cross-section it sometimes has the appearance of being only half developed. Such an appearance is usually taken to indicate that the crystal is broken. In the present instances, however, where the hornblende results from metasomatic introductions into solid rock, such an interpretation is untenable, and the appearance probably results from irregular growth of hornblende in the vertical zone. Curved crystals are common. In addition to the frayed terminations, already mentioned, embayed margins and sieve-like inclusions of quartz, felspar, and micropegmatite are occasionally exhibited (text-fig. 5). Crystal zones often have the appearance of being abruptly truncated against the leucocratic constituents. In some examples the crystals have the appearance of being split apart, along cleavage planes, by lamellae of quartz or felspar which are optically continuous with neighbouring

crystals (text-fig. 6). Portions of hornblende, which may be exceedingly small, are in places isolated from, although optically continuous with, the main crystal. These textures, several of which are commonly regarded as evidence of corrosion, can here only be interpreted as crystalloblastic developments, dependent on the fact that crystallization has taken place in an essentially solid medium.

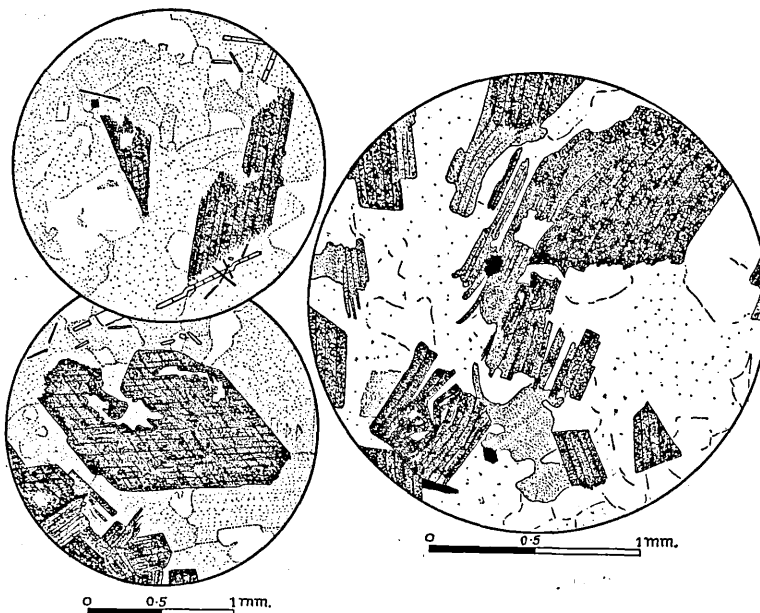


FIG. 5.

FIG. 6.

FIG. 5. Crystalloblastic developments of hornblende in the replacement rim of a quartzite xenolith, illustrating textures commonly attributed to corrosion.

FIG. 6. Hornblende from the metasomatized rim of a quartzite xenolith, showing replacement textures which simulate mechanical distortion and 'splitting apart' along cleavage planes.

It must not be supposed, however, that such crystalloblastic textures are always the most characteristic. Just as commonly—even in the same slides—the hornblende exhibits euhedral or subhedral form. Where this is the case the rock would not, without the excellent field evidence, be suspected of having originated in any way other than by crystallization of magma. It should be stressed that hornblende, even when it is euhedral, may be either entirely

enclosed within feldspar, quartz, or micropegmatite, or it may cut across the boundaries of these minerals.

Chlorite is present both as a replacement of hornblende, which is sometimes completely pseudomorphed, and as a direct replacement of quartz and feldspar. It has $\alpha = \beta$ bluish-green $> \gamma$ very pale green, and is optically positive with $2V$ very small. In measured examples from a rim of appinitic composition β is about 1.589 and $\gamma - \alpha = 0.0045$. The data indicate that it is clinocllore not far from pennine in composition.

Where it replaces hornblende, the chlorite is commonly fibrous, in which case it extends along the cleavage planes; in some examples, however, it builds aggregates of small spherulites. Where chlorite replaces quartz and feldspar it often builds aggregates of small spherulites which exhibit bulbous boundaries towards the replaced minerals. From the spherulites, vermicular chlorite commonly fingers out into both quartz and feldspar. In some examples, more noticeably in syenitic types of replacement and in the forefront of the replacement rims, chlorite which replaces felsic constituents develops crystal form and exhibits lamellar twinning parallel to (001).

In rare instances, chlorite encloses feldspar and euhedral crystals of hornblende, the latter sometimes terminated in toothed outgrowths of tremolite.

Chlorite is also present in little veinlets which are situated along the boundaries of quartz and feldspar. Such veinlets are in places traceable into calcite veinlets.

Allanite is common in the syntectic syenite and rare in the syntectic appinite. It builds small euhedral crystals (usually about 0.13 mm. across, and rarely reaching a size of 0.3 mm.) in which (100), $(10\bar{1})$, and (001) are developed. It is strongly zoned, the darker zones occurring in the centre of the crystal, and has γ dark brown $> \alpha$ pale brown; $a:c = 36^\circ$, and the birefringence is low. The allanite is sometimes intergrown with or surrounded by epidote. The latter mineral also occurs separately, in which case it is sometimes, but not always, associated with chlorite.

Calcite is common both as large anhedral crystals, intergrown with the other minerals, and in veins which cut through the other minerals. The large crystals are in some cases seen to antedate the aggregates of chlorite spherulites. This is inferred from the fact that the chlorite fingers into the calcite, and occurs within it as vermicules, just as it does in the quartz and feldspar.

From the large crystals of calcite, antennae-like structures extend along the boundaries of neighbouring individuals of quartz and feldspar, or actually penetrate these minerals. In some instances veins of calcite extend from the crystals, and from the sides of the veins calcite fingers into the felsic constituents. Some of these veins terminate as single or bifurcating veinlets of quartz. The large individuals of calcite exhibit lamellar twinning, and the lamellae are in many cases curved.

Apatite has been introduced both as abundant needles, sometimes of minute dimensions, and as crystals which may be much elongated in habit or short prismatic. The crystals either occur enclosed within quartz, feldspar, and hornblende, or they cut across the boundaries of these minerals. They are frequently clouded with swarms of minute rod- and dot-like forms of an opaque mineral. The needle-like apatite is often highly concentrated in quartz and feldspar.

Apatite reaches its maximum development in the appinitic type of replacement. It is sometimes sporadic in its occurrence, tending to segregate at certain points. Although commonly perfectly formed, it occasionally has finely crenulate margins and fingering terminations. In many instances the crystals are curved, and elongated crystals are not infrequently disconnected parallel to the base, the isolated portions being either in line or in echelon.

Pyrite is common, and reaches its maximum development in the appinitic type of replacement. It occurs within both felsic and mafic minerals and, although it often develops cubic form, it sometimes exhibits typical replacement textures, antennae-like processes of pyrite extending from an anhedral central mass, along the intergranular boundaries of neighbouring quartz and feldspar. In some instances compact crystals of pyrite poikilitically enclose apatite and hornblende.

Sphene is one of the less common minerals. It usually builds euhedral crystals, most of which are small, though occasional large examples, up to 0.5 mm. across, are present.

Zircon, with a rounded detrital form, as in the quartzite, persists in the metasomatized portions. It occurs as inclusions in quartz and feldspar, some of which lie across the mineral boundaries. Very rarely it is crystalloblastic in its development, when it exhibits curious sigmoid forms.

(ii) *Rock Types.*

The various products of replacement, regarded as rock types, may now be briefly described:

Micropegmatite, which may be devoid of mafic minerals or may contain hornblende and/or chlorite, is common in the forefront of the replacement rims around residual cores of quartzite (pl. XII, figs. 4 and 6). The felspathic rims described on p. 372 of the field description under types 1 and 2 usually consist of micropegmatite. In some of these felspathic rims, however, only the innermost margin consists of micropegmatite; away from the quartzite this passes into leucocratic syenite or quartz-syenite.

Syenite. Under this term is included a series of rocks which ranges between micropegmatite and appinite. There are leucocratic quartz-free syenites which fall within Phemister's¹ delimitation of perthosite, and closely allied to these are varieties gradational towards leucocratic micropegmatite. The latter varieties of syenite differ from perthosite only in the presence of a little quartz; they may be termed quartz-perthosite. The mafic minerals of the perthosites and quartz-perthosites, chlorite, allanite, and epidote, are present only in accessory amount. By the incoming of hornblende the perthosites grade through hornblende-syenite, which is usually quartz-bearing, to appinite. The various types of syenite respectively characterize different xenoliths; they also occur, in some instances, in association within a single xenolith.

The analysed syenite (table II, no. 3), collected from a large xenolith that is almost completely replaced by pink syenite, is a quartz-perthosite characterized by albite, perthite, and quartz, with accessory chlorite, allanite, epidote, calcite, sphene, zircon, apatite, and pyrite. Texturally it varies from roughly equi-granular to seriate-granular (pl. XII, fig. 3). The feldspars tend to develop form, whilst the quartz occurs interstitially or intergrown in granitic fashion with the feldspars. In many instances portions of quartz, though completely isolated in thin section, are optically continuous. Chlorite is subhedral to anhedral in form, and sometimes shows crystalloblastic development. In the latter case, it has outlying optically-continuous portions and, rarely, is sieved with inclusions of the leucocratic constituents. In the sections examined, the

¹ J. Phemister, The geology of Strath Oykeil and Lower Loch Shin. Mem. Geol. Surv. Scotland, 1926, p. 47.

chlorite does not appear to replace an earlier ferromagnesian mineral. Sericite is sparsely dispersed through the feldspars, and calcite replaces the feldspars in small veinlets and irregular patches.

In perthosite, which is free or almost free from quartz, the feldspars, although they are mutually intergrown, show an approximation to rectangular outline in thin section. Crystalloblastic textures are sometimes developed; in some instances, for example, twinned albite, with crenulate margins, has optically-continuous outlying portions.

In the syenites which are rich in quartz, micropegmatite is developed. These rocks grade from a variety which contains mafic minerals in accessory amount only to quartz-bearing hornblende-syenites. Both the quartz-rich syenites and the micropegmatites exhibit textures which characterize micropegmatite-bearing rocks in general. The micropegmatite may be coarse in texture or of a finer feathery variety. Euhedral crystals of feldspar are sometimes optically continuous with the feldspar of the surrounding micropegmatite. Anhedral quartz is similarly sometimes optically continuous with the quartz of neighbouring micropegmatite. In some instances a single quartz crystal is intergrown with two or more differently orientated crystals of feldspar. In short, there is no textural clue from which it could have been suspected that the metasomatic micropegmatite did not arise as a result of the crystallization of magma.

A point of special interest in the syenitic type of replacement is the relation between quartz and feldspar. In the forefront of the replacement rim, feldspar develops along the margins of quartz grains, the latter sometimes remaining as inclusions in feldspar crystals. Farther into the replacement rim the quartz has generally recrystallized. If it is present in only small amount it is interstitial, whereas when present in greater amount it is either micropegmatitically intergrown with the feldspars or, less commonly, is associated with them in granitic fashion. The relationship between quartz and feldspar is thus dependent in part on position in the replacement rim and in part on the proportion of quartz present.

As noted in the field section under type 1, p. 372, there is commonly a narrow green zone, generally 1 or 2 mm. wide, situated at the contact between leucocratic feldspathic rims and residual quartzite cores. In thin section this is found to differ from the main leucocratic zone in the abundance of ferromagnesian material. Chlorite

is the most common mafic mineral, but green hornblende is sometimes present. A block of quartzite with a felspathic rim from the marginal breccia appears to throw light on the origin of this narrow green frontal zone. The quartzite of the block contains fairly abundant biotite, yet the marginal felspathic rim is of leucocratic micropegmatite rich in 'chess-board' albite. Immediately at the contact with the quartzite, the micropegmatite contains chlorite together with a few flakes of biotite which have persisted from the quartzite. Away from the margin, however, chlorite is rare in the micropegmatite, and biotite, partly chloritized, is very rare, whilst rutile needles are common (pl. XII, fig. 5). The evidence suggests that the constituents of the biotite from the quartzite became mobilized during the felspathization process, the Mg and Fe being carried forward to the forefront of the zone of replacement.

Appinite. The appinites, which are all quartz-bearing, range from hornblende-syenite to varieties which differ from the hornblendite only in the presence of a little felspar and quartz. They contain hornblende of the brownish and green varieties which characterize the hornblendite; actinolite and tremolite, which are present both as replacements of and outgrowths from hornblende, the actinolite sometimes being present also as irregular aggregates; perthite; albite; quartz; chlorite; calcite; apatite; pyrite; and rare allanite and epidote. The characteristics of these minerals have already been described.

Quartz is often micropegmatitically intergrown with the felspars, but it also occurs interstitially and associated in granitic fashion with the felspars. As in the syenites, isolated portions of quartz are in many instances optically continuous.

The appinites vary in grain from medium to coarse, and are practically always coarser in grain than the associated syenites. The analysed appinite (table II, no. 2) contains blade-like crystals of hornblende up to 6 cm. long, which are embedded in a pink quartzofelspathic matrix. In common with many examples of the apinitic type of replacement, small druses, margined by calcite crystals which exhibit form towards the cavity, are present.

(e) *Syntectic Veins.*

The pegmatite veins, which arise from the narrow felspathic zone developed at the margin of the quartzite against the hornblendite (p. 376 and pl. XI, fig. 4) and penetrate the latter rock, show rapid

variation from point to point. One such vein about six inches wide, from which the analysed specimen (table II, no. 5) was collected, varies, in a single hand-specimen, from quartz-perthosite of equigranular texture to leucoeratic micropegmatite-bearing syenite. There are, moreover, patches in the vein which are rich in chlorite (prochlorite with β about 1.61) and epidote. The chlorite usually replaces and often retains cores of biotite, the latter with crumpled cleavage traces. The epidote, which is associated with the chlorite, is more strongly coloured than that in the replacement rims. Iron ore is a common associate of chlorite.

The feldspars are albite and perthite, the latter with a patchy development, as in replacement rims. In chlorite-rich regions the feldspars are commonly crowded with flakes of sericite, amongst which apatite is often segregated. The apatite characteristically develops acicular crystals up to 3 mm. long. These are sometimes curved or arranged in echelon. The rock contains large patches of calcite, up to a centimetre across, and where it adjoins the hornblendite it contains hornblende similar to that in the latter rock but of bladed habit and up to several centimetres in length. So far as could be judged, the analysed specimen was free from hornblende, but it contained some chlorite and epidote.

Texturally the pegmatite is closely similar to the corresponding rocks of the replacement rims and, except that epidote is considerably more abundant and the chlorite is prochlorite instead of clinocllore or pennine, there are no obvious criteria by which it could be distinguished from these.

The syntectic veins which form a network in the hornblendite (p. 375) are of the composition of appinite or mafic syenite. They are composed of hornblende, a little tremolite, and actinolite, chlorite, perthite, albite, and quartz, together with accessory apatite, epidote, sphene, pyrite, and calcite. The characteristics of these minerals are similar to those of the corresponding minerals in the replacement rims. The hornblende is for the most part euhedral, but it occasionally has frayed margins, re-entrants, and sieve-like inclusions of the felsic minerals. It sometimes has outgrowths of tremolite and actinolite and may be partially replaced by chlorite. The quartz is in part interstitial, in part intergrown with the feldspars in granitic fashion, and in part a constituent of micropegmatite. In the two former cases neighbouring patches of quartz are sometimes optically continuous. This latter texture, together with those suggestive

of crystalloblastic development exhibited by the hornblende, probably indicates crystallization in a highly viscous medium. Indeed, as in the case of the pegmatite, there is, in thin section, no obvious criterion which distinguishes these veins from the replacement rims. As in the latter, calcite replaces the other minerals to some extent.

In the 'tails' which extend from metasomatized quartzite xenoliths (p. 375, pl. XI, fig. 2 and pl. XII, fig. 2) the minerals and textures are again essentially similar to those which characterize the replacement rims; allanite is occasionally present.

(f) *Syenite.*

No systematic petrological investigation of the syenite of the main intrusions has yet been made, but the following notes, made from a study of a few thin sections, indicate their similarity to the rocks of the replacement rims.

The syenite of the two intrusions of Port Easdale consists of perthite, albite, quartz, abundant chlorite (prochlorite with $\beta 1.612 \pm 0.002$), and epidote, together with accessory apatite, pyrite, allanite, and calcite. The chlorite and epidote, in the thin sections examined, have no appearance of having replaced earlier ferromagnesian minerals. The texture is seriate-granular with the constituents ranging from subhedral to anhedral. Neighbouring patches of quartz, which are isolated in thin section, are in many instances optically continuous. The syenite of the intrusion on the hill to the north of Port Easdale contains hornblende, which is partially altered to chlorite.

Mineralogically and texturally, the syenite of the main intrusions is very similar to parts of the pegmatite veins. Moreover, the presence of allanite indicates consanguinity with the rocks of the replacement rims and the syntectic veins derived from them.

5. CHEMISTRY.

In tables II and III the chemical analyses and norms of the rock types are listed. The hornblendite (1) was collected from a zone free from quartzite xenoliths in the intrusion which margins the northern shore of Port Easdale. It is typical of the felspar-free hornblendite which characterizes both the Port Easdale intrusions. It differs from analysed hornblendites of other areas in being richer in magnesia and poor in alkalis.

The quartzite (4) is the residual part of a typical quartzite xenolith from the southern intrusion.

The appinite (2) and the syenite (3) were collected from relatively large metasomatized quartzite xenoliths, which retain residual cores

TABLE II. Chemical analyses.

	1.	2.	3.	4.	5.	6.
SiO ₂	42.54	52.30	66.04	95.17	68.38	57.66
Al ₂ O ₃	9.00	15.23	17.68	3.45	14.00	12.86
Fe ₂ O ₃	1.84	2.29	0.33	0.12	1.10	5.60
FeO	7.80	5.30	0.94	0.09	0.54	3.38
MgO	19.41	5.77	0.20	0.04	0.51	2.90
CaO	10.82	7.85	1.81	0.38	4.00	5.08
Na ₂ O	0.53	2.16	4.95	0.01	5.49	3.57
K ₂ O	0.33	3.00	5.16	0.37	3.78	4.64
H ₂ O+	4.61	1.76	0.80	0.08	0.48	1.76
H ₂ O-	0.17	0.09	0.11	0.07	0.06	0.06
CO ₂	1.81	0.90	0.97	nil	0.86	0.71
ZrO ₂	nil	nil	0.15	0.14	0.02	0.007
TiO ₂	0.74	0.72	0.11	0.09	0.09	0.38
P ₂ O ₅	0.08	1.11	0.18	0.06	0.26	0.70
Cl	0.01	n.d.	n.d.	n.d.	n.d.	n.d.
S	0.15	1.37	0.06	0.06	0.06	0.33
Cr ₂ O ₃	0.08	trace	nil	n.d.	n.d.	n.d.
V ₂ O ₃	0.05	0.04	0.02	n.d.	n.d.	n.d.
NiO	0.10	0.17	nil	n.d.	n.d.	n.d.
MnO	0.18	0.14	0.02	trace	0.03	0.08
SrO	nil	0.02	nil	trace	0.08	0.05
BaO	nil	0.09	0.15	nil	0.09	0.07
Li ₂ O	trace	n.d.	n.d.	n.d.	n.d.	n.d.
	<u>100.25</u>	<u>100.31</u>	<u>99.68</u>	<u>100.13</u>	<u>99.83</u>	<u>99.83</u>
Less O	0.06	0.51	0.02	0.02	0.02	0.12
	<u>100.19</u>	<u>99.80</u>	<u>99.66</u>	<u>100.11</u>	<u>99.81</u>	<u>99.71</u>

1. Hornblendite. Northern shore of Port Easdale. Analyst, L. S. Theobald.
2. Appinite. Rim of quartzite xenolith. Southern shore of Port Easdale. Analyst, Agnes Gibbs.
3. Syenite. Rim of quartzite xenolith. Southern shore of Port Easdale. Analyst, Agnes Gibbs. A second analysis made on another sample of material from the same specimen gave SiO₂ 65.85, Al₂O₃ 18.30.
4. Quartzite xenolith. Southern shore of Port Easdale. Analyst, Agnes Gibbs.
5. Pegmatite. Syntectic vein in hornblendite. Southern shore of Port Easdale. Analysis by Messrs. Imperial Chemical Industries Ltd., Research Dept., Billingham, Co. Durham.
6. Syenite. Intrusion south of Port Easdale. Analysis by Messrs. Imperial Chemical Industries Ltd., Research Dept., Billingham, Co. Durham.

of quartzite; both are from the southern intrusion. The appinite is a somewhat leucocratic variety transitional to hornblende-syenite. The syenite falls within Phemister's (loc. cit.) delimitation of perthosite, except that it is quartz-bearing. The latter fact accounts

for its lower alkalis and alumina, relative to silica, as compared with the perthosite of Loch Ailsh.

The appinite and syenite which result from the transfusion of quartzite xenoliths are chemically, as well as mineralogically and

TABLE III. Norms of analyses in table II.

		1.	2.	3.	4.	5.	6.
Q ...	...	—	7.16	15.71	92.96	17.85	9.88
C ...	...	—	—	3.20	2.56	—	—
Z ...	...	—	—	0.22	0.20	0.04	0.02
or	...	1.89	17.75	30.50	2.13	22.32	27.44
ab	...	4.51	18.25	41.89	0.11	46.45	30.20
an	...	21.20	23.01	2.03	1.26	2.39	5.37
di	CaSiO ₃ ...	8.59	1.65	—	—	1.47	4.82
	MgSiO ₃ ...	6.26	1.18	—	—	1.23	3.97
	FeSiO ₃ ...	1.48	0.33	—	—	—	0.26
wo	...	—	—	—	—	3.07	—
hy	MgSiO ₃ ...	15.13	13.19	0.50	0.10	—	3.25
	FeSiO ₃ ...	3.59	3.79	1.19	—	—	—
ol	Mg ₂ SiO ₄ ...	18.87	—	—	—	—	—
	Fe ₂ SiO ₄ ...	4.90	—	—	—	—	—
cm	...	0.11	—	—	—	—	—
mt	...	2.66	3.31	0.48	—	1.37	8.12
h ...	...	—	—	—	0.13	0.16	—
il ...	...	1.76	1.72	0.21	0.06	0.17	0.91
tn	...	—	—	—	0.20	—	—
ap	...	0.20	2.62	0.37	0.14	0.60	1.65
pr	...	0.25	2.56	0.11	0.11	0.11	0.62
cc	...	4.11	2.05	2.21	—	1.96	1.61
water	...	4.78	1.85	0.91	0.15	0.54	1.82
		100.29	100.42	99.53	100.11	99.78	99.94

texturally, normal igneous rocks. In text-fig. 7 their constituents are plotted on a variation diagram together with those of the hornblendite and quartzite. The diagram turns out to be of a common type, such as is frequently interpreted as evidencing crystal differentiation, yet here the process was one of migration of various constituents from hornblendite magma into quartzite.

Comparison of the chemical analyses, or their diagrammatic representation on text-fig. 7, reveals the following important facts with regard to the syntectic appinite and syenite.

- (1) They do not represent admixtures of hornblendite and quartzite.
- (2) All the constituents, with the exception of SiO₂ and ZrO₂, appear to have been provided almost entirely by the hornblendite magma. The concentration of ZrO₂ in the quartzite and syenite

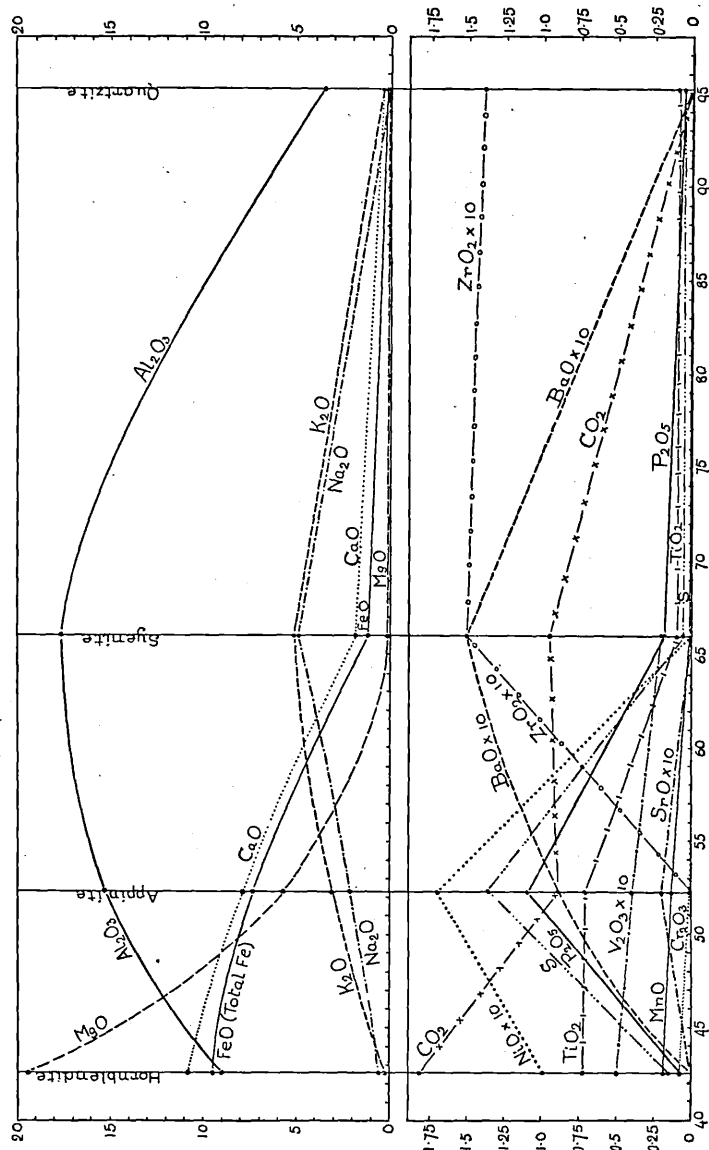


FIG. 7. Variation diagram for the series hornblende-rim-appinite-rim-syenite-xenolithic quartzite.

tallies with the observation that practically all the zircon in the syenite exhibits a detrital form.

(3) Certain constituents, i.e. Al_2O_3 , K_2O , Na_2O , P_2O_5 , S, NiO, BaO, and SrO, have actually become concentrated in the appinite and syenite, Al_2O_3 , K_2O , Na_2O , and BaO reaching a maximum in the syenite, and P_2O_5 , S, NiO, and SrO in the appinite. BaO is of particular interest since, although it is absent from both the hornblendite and the quartzite, it is present in both the syenite and appinite.

(4) Soda is more abundant than potash in the hornblendite, yet in the appinite and syenite potash is more abundant than soda.

It is evident, from the concave and convex curves of the variation diagram, that the constituents of the hornblendite magma were introduced differentially into the quartzite xenoliths. It is, however, not at present apparent how the migration was effected; even to discuss the migratory units in terms of oxides is to make an assumption. Remarks will therefore be restricted to the behaviour of individual elements. It is particularly noteworthy that, although Mg is by far the most abundant metallic element in the hornblendite, it was the least diffusible, as shown by the downward slope and concave form of the curve representing MgO in text-fig. 7. Potassium, on the other hand, which is now poorly represented in the hornblendite, was amongst the most diffusible elements, as shown by the upward slope and convex form (as far as the syenite) of the curve representing K_2O in text-fig. 7. Similarly, barium, which is now actually absent from the hornblendite, was one of the most diffusible elements from its magma.

The migratory elements can be classified, for this area, as follows:

<i>Most diffusible.</i>	<i>Less diffusible.</i>	<i>Least diffusible.</i>
Al	Fe	Mg
K	Ca	
Na	C	
P	Ti	
S	Cr	
Ni	V	
Ba	Mn	
Sr		

It will be recalled that the order of mineral formation in the hornblendite indicates crystallization from a magma which became impoverished in alumina and alkalis. The loss of the magma is thus balanced by the major gains of the quartzite.

The circumstances which contributed towards the present distribution and relative concentration of the elements in the transfused xenoliths probably include: (a) sequence of introduction into the xenoliths; (b) relative rate or power of diffusion through the xenoliths; (c) sequence (in both space and time) of fixation by the xenoliths. The various zonal arrangements of rock types in the transfused xenoliths (see pp. 372-3) suggest that (a) was an important factor, potassium, sodium, and aluminium having been introduced before the calcic-forming constituents entered in force.

The analysed pegmatite (5) was collected from one of the 6-inch syntectic veins described on p. 392 and figured on pl. xi, fig. 4. Chemically it is a somewhat soda-rich quartz-syenite. Although it had a similar origin to the syenites of the replacement rims, it is chemically remarkable in that it differs from the analysed rim-syenite in containing more soda than potash.

The analysed syenite (6) was collected from the intrusion to the south of Port Easdale. Chemically it is related to plauenite; alumina is low, however, and iron high. Except for the low alumina and high iron it very nearly fits the curves for the metasomatic rocks on the variation diagram text-fig. 7.

6. COMPARABLE EXAMPLES.

Ontario.—Quartzite xenoliths which have been similarly feldspathized and changed by a process of transfusion into rocks of igneous composition have been described by Collins from diabase sills. In 1913 he recorded the presence of light-coloured red patches, of coarser grain than the normal diabase, in the sills of the Gowganda district.¹ The patches vary in size from about an eighth of an inch in diameter up to several hundreds of feet in length. No evidence as to their origin, however, was found in this district. Later, in a study of the gabbro sills of the north shore of Lake Huron, the origin of similar leucocratic patches was discovered.² At Blind River, for example, the gabbro contains many patches which are more leucocratic and coarser in grain than the normal gabbro of the sill. Some of these contain cores of quartzite which are obviously remains of xenoliths

¹ W. H. Collins, The geology of the Gowganda mining division. Mem. Geol. Surv. Canada, 1913, no. 33, p. 63.

² W. H. Collins, North shore of Lake Huron. Mem. Geol. Surv. Canada, 1925, no. 143, p. 80. See also T. T. Quirke, Espanola district, Ontario. Mem. Geol. Surv. Canada, 1917, no. 102, p. 51.

derived from the neighbouring Mississagi quartzite. All stages of alteration have been found in the sills from blocks of quartzite which are only marginally corroded to others which are represented by patches of gabbro conspicuously lighter in colour and coarser in grain than the normal sill rock. In some cases the inclusions are bordered against the sill rock by a dark rim, varying from less than an inch up to more than a foot in width, composed mainly of hornblende. In other examples, the altered inclusions merge insensibly into the normal gabbro. They are composed of an intimate intergrowth of hornblende, intermediate plagioclase, which is commonly graphically intergrown with quartz, and some epidote.

The inclusions in one of the sills near Sudbury have been investigated by Jones.¹ In this intrusion there are lens-shaped and irregular bodies of white rock, with dimensions varying from a few feet up to 100 by 40 feet, some of which have a central core of quartz. One such patch, about 42 feet in diameter, was studied in detail with chemical analyses. It has a marginal zone consisting of hornblende and bytownite and an inner zone, adjoining central quartz, of andesine and quartz. In the outer zone the hornblende and bytownite exhibit textural relationships similar to those of the normal sill rock. The hornblende crystals attain their greatest size towards the middle of the outer zone, where they reach a length of 10 inches. From this region towards the centre of the mass they become smaller and sparser, finally dying out. With the disappearance of hornblende the plagioclase changes from bytownite to andesine.

Jones concludes that the change in the xenolith took place in an essentially solid state by diffusion into it of various constituents from the gabbro magma. From the zonal character of the transfused inclusions he deduces that the various constituents had different penetrative abilities. Alumina, soda, and lime penetrated farther into the xenolith than magnesia and iron.

Felspathized xenoliths of quartzose sediment have been recorded by Fenner² from the gabbro of the Sudbury lopolith. In places the xenoliths are surrounded by a zone of rock which is similar to the granophyre of the upper part of the intrusion, whilst in other cases they are so digested as to have almost disappeared. In explanation

¹ W. A. Jones, A study of certain xenoliths occurring in gabbro at Sudbury, Ontario. Toronto Univ. Studies, Geol. Ser., 1930, no. 29, pp. 61-73.

² C. N. Fenner, Journ. Geol. Chicago, 1926, vol. 34, pp. 735-736.

of phenomena of this type Fenner suggests 'that before and during assimilation of the quartzose body it was soaked with volatile material emanating from the magma, and that a modification of the composition of the magma and the sediment was thus effected, much of the material lost by the magma being retained by the sediment.'

Bushveld, Transvaal.—Daly¹ has described, with chemical analyses, successive stages in the alteration of quartzite xenoliths in the mafic quartz-syenite and granite of the Bushveld complex. The chemically unaltered quartzite is grey or white in colour and generally contains little else besides quartz, the average silica percentage of four analysed varieties being 95.5. Descriptions of three xenoliths, as follows, illustrate the various stages in the alteration.

(a) A slightly altered xenolith from the mafic quartz-syenite is pink in colour and contains 17 per cent. by weight of cloudy felspar, consisting of soda-rich orthoclase and oligoclase-albite (Ab_{92}) in about equal proportions. Subordinate constituents are rare granules of diopsidic augite and magnetite and a few blades of green hornblende.

(b) A more altered xenolith, from the same rock, is redder in colour, about half of the rock being composed of felspar. The feldspars are similar to those in the last example, but the orthoclase, which is less rich in soda, is more abundant than plagioclase. The rock contains a few shreds of biotite and a little magnetite. Texturally it differs from the last example in that it contains some feathery micropegmatite. In spite of the intense feldspathization, the rock retains its cross-bedding, indicating that the alteration took place while the xenolith remained essentially in the solid state. Chemical analyses show that alumina, potash, and soda were introduced into the quartzite; the process was, therefore, one of metasomatism.

(c) An even more altered xenolith, enclosed in coarse red granite, shows no trace of original bedding. It contains about 40 per cent. of quartz arranged in clumps; 50 to 55 per cent. of felspar; small proportions of biotite and of hornblende with occasional cores of diopsidic augite; a few needles of apatite and very rare specks of iron ore. The feldspars are perthite, in which orthoclase and practically pure albite are intergrown, and subordinate plagioclase. The analysis shows the rock to be a normal acid granite. Daly remarks that 'In the field all of the five geologists, including Dr. Hall, were impressed

¹ R. A. Daly, Bushveld igneous complex of the Transvaal. *Bull. Geol. Soc. America*, 1928, vol. 39, pp. 746-750.

with the igneous look of the xenolith. To explain it one of the working hypotheses used is that the present state of the xenolith may be the result of ultra-metamorphism. The secondary magma may, however, never have been quite homogeneous, but may have held in it, undissolved, many grains of quartz, such as now appear in thin section as rounded individuals, separate and in clusters.'

Illimausak, Greenland.—Inclusions of sandstone, surrounded by a zone of soda-granite, have been described by Ussing¹ from the augite-syenite of the Illimausak region, Greenland. From the descriptions of the evidence, this appears to provide an example of transfusion closely analogous to that in Colonsay. The augite-syenite contains numerous inclusions of sandstone; the largest is over 100 metres long and 50 metres broad. All the fragments, large as well as small, are surrounded by and separated from the augite-syenite by a zone, from a half to two metres wide, of soda-granite, which frequently contains a large number of very small rounded fragments of sandstone. From the soda-granite rim small apophyses extend into the sandstone, and the syenite, in the neighbourhood of the sandstone inclusions, is cut by veins of soda-granite.

Ussing's description of the rim is as follows: 'Directly surrounding the sandstone there is always a black zone, not more than $\frac{1}{2}$ a centimeter broad and containing exclusively black-green pyroxene or black hornblende in short prisms which lie at right angles to the surface of contact; then comes a slightly broader, white zone, which consists of large anhedral feldspar and quartz with a relatively small amount of black minerals, and outwardly the white zone passes into the more uniform soda-granite. The size of grain of the latter is sometimes variable, so that coarse grained portions may alternate with fine-grained in the most irregular manner, even within one and the same hand-specimen. . . . As a rule the junction between the soda-granite and the surrounding augite-syenite presents a sharp line; the augite-syenite retains its normal character right in to the contact.' It is perhaps a point of petrological significance that chemically the soda-granite of the rims is very similar to the large granite body of Illimausak.

Microscopically, at the contact between soda-granite and sandstone, the region of feldspathization is seen to be advancing into the sandstone along the margins of the quartz grains.

¹ N. V. Ussing, Geology of the country around Julianehaab, Greenland. Medd. om Grønland, 1912, vol. 38, pp. 51-54 and 116-118.

A point of special interest in the Illimausak occurrence, which is paralleled in Colonsay, is the evidence that the syntectic soda-granite became magmatic and remained fluid longer than the augite-syenite which generated it, since, in the vicinity of sandstone fragments, the augite-syenite is cut by veins of soda-granite.

Glen Coe, Scotland.—An example of feldspathization of quartzite xenoliths has been recorded by Bailey¹ from the porphyrite fault-intrusion of Glen Coe. The porphyrite is described as often being 'not only richly charged with xenoliths of baked mica-schist and quartzite, but also loaded with quartz grains separated from the quartzite'. Moreover 'the quartzite, where it retains its individuality, is frequently saturated with pink feldspar from the porphyrite'.

In his petrological description of these metasomatized xenoliths Bailey records that the feldspars developed in the quartzite are orthoclase and albite or albite-oligoclase. I am indebted to the Director of the Geological Survey for allowing me to examine the thin sections of the altered quartzite xenoliths. It is a point of special interest that here, as in Colonsay and the Illimausak region, the feldspathization of the quartz takes place most readily along intergranular boundaries.

That the quartzite xenoliths served to fix migratory alkalis is clear from Bailey's observation that the 'portion of the Fault-Intrusion which develops the permeation phenomena . . . differs from the more coherent portions of the same intrusion in being much richer in alkali'. At the time of writing, Bailey himself clearly realized the importance of this observation for he adds, 'There is a tempting field here for further careful work, and one which is likely to yield pregnant suggestions in regard to magmatic differentiation.'

General comments.—This section cannot be concluded without reference to a recent paper by Collins² in which he reviews various examples, including those discussed in the previous pages, of alteration of xenoliths by diffusion into them of material from magma in which they were enclosed. He finds (*a*) that in specific examples diffusion is not uniform for all constituents, some penetrating farther than others and being concentrated differently, as indicated by zonal arrangements; and (*b*) that the penetrative power of various consti-

¹ E. B. Bailey, *The geology of Ben Nevis and Glen Coe*. Mem. Geol. Surv. Scotland, 1916, pp. 112, 164.

² W. H. Collins, *Derivations of granitic rocks*. Report XVI Internat. Geol. Congress, Washington, 1933, 1936, vol. 1, pp. 271-282.

tuents varies from one locality to another. With regard to the alkalis, for example, in one of the cited instances, potash penetrated farthest and in greatest abundance, and in another soda. He concludes that the process involved molecular transfer of highly mobile material and chemical reaction, rather than a mechanical soaking into the solid rock of the adjoining magma or a fluid portion of it. The present investigation confirms these conclusions, but I can see no reason for believing that the transfer was molecular rather than atomic or ionic. In Colonsay not only has there been differential introduction of various constituents into the xenoliths, but the latter have actually been converted to felspar-rich types although immersed in a magma which, on crystallization, gave rise to an ultrabasic felspar-free rock. Although the felspar-forming material penetrated most readily along the boundary of quartz grains, it appears to have been capable of passing through the crystal mesh of quartz (see p. 383), a fact which suggests ionic introductions. It is a point of interest that sodium ions have been experimentally passed through quartz parallel to the *c*-axis.¹

7. SUMMARY AND PETROLOGICAL CONCLUSIONS.

At Port Easdale, Colonsay, micropegmatite, syenite, and appinite have been developed by replacement of quartzite xenoliths engulfed in hornblendite magma. The syntectic rock types occur either separately or in concentric zones in individual xenoliths. In the latter case micropegmatite or syenite adjoins the centrally placed residual core of quartzite. The syntectic rocks also occur in the hornblendite as leucocratic patches and rarer schlieren without visible residual cores of quartzite. The process involved the differential diffusion of the various magmatic constituents into the quartzite; of the major constituents, aluminium, potassium, and sodium appear to have been introduced first. Chemically, the rocks thus developed do not represent a mixture of hornblendite and quartzite; Al_2O_3 , K_2O , Na_2O , P_2O_5 , S, NiO, BaO, and SrO have actually become concentrated in the metasomatic varieties. Moreover, there is more potash than soda in the metasomatic rocks, whereas the hornblendite contains more soda than potash.

The rocks which result from the transfusion of quartzite present an igneous appearance, and without the field evidence it would not be possible to deduce that they are not 'igneous' in the common sense of the term.

¹ C. H. Desch, *The chemistry of solids*. 1934, p. 115.

Finally, the process of transfusion gave rise to syntectic magma of syenitic and appinitic composition. This is represented by pegmatite veins developed from feldspathized quartzite along the contact of the intrusion; by veins of syenite and appinite which emerge from transfused quartzite xenoliths; and locally by an intricate network of such veins in the hornblendite, so that the latter appears as mafic xenoliths in a relatively leucocratic matrix.

Arising out of the Colonsay evidence, the following points of outstanding petrogenetic significance may perhaps be emphasized.

(1) A field association of melanocratic and leucocratic rocks does not in itself constitute evidence of crystal differentiation as the mode of origin of the types concerned. Nor does such an association, even though all gradations between the extreme types be represented, constitute evidence that the whole of the rock materials once formed part of a homogeneous magma.

The necessity for stressing this latter point is made apparent in several recent discussions of which one, by Kennedy and Read,¹ may be taken as an example. A dike of markfieldite, which they describe, is characterized on the one hand by patches, schlieren, and veins of a leucocratic variety, and on the other by irregular patches and schlieren of a more mafic variety, the three rock types concerned being linked by a complete series of transitional types. The statement, based on these field relations (*loc. cit.*, p. 118), that 'there is no escape from the conclusion that the heterogeneous nature of the intrusion results from splitting or differentiation of an originally homogeneous magma' goes far beyond the evidence. The data presented in the present communication provide one means of escape.

(2) Sharp contacts do not necessarily indicate intrusive contacts, they may equally well represent diffusion limits.

(3) The facts that a rock exhibits an 'igneous' appearance, both in hand-specimen and microscope section, and is of igneous composition do not constitute evidence that it crystallized from a magma. It should be specially emphasized that rocks which many petrologists have tacitly assumed to be of igneous origin may be metasomatic replacements.

(4) The enclosure of crystals, even though they are euhedral, in other minerals does not constitute evidence that the enclosed mineral

¹ W. Q. Kennedy and H. H. Read, The differentiated dyke of Newmains, Dumfriesshire, and its contact and contamination phenomena. *Quart. Journ. Geol. Soc. London*, 1936, vol. 92, pp. 116-145.

was the first to crystallize; its constituents may have been introduced at a later stage.

(5) Micropegmatite does not necessarily result from the crystallization of magma of eutectic or other composition. This point has already been emphasized by many writers.

(6) The presence of abundant apatite is frequently taken as evidencing a concentration of volatile constituents and, in consequence, of indicating that the rock in which it occurs crystallized from a highly fluid magma. In the appinite of metasomatic origin described in the present communication, apatite is highly concentrated, particularly in the felsic constituents, occurring both as fine needles and prismatic crystals. Yet the rock has never existed in a state other than essentially solid.

(7) Curvature of crystals or their twin-lamellae does not necessarily indicate external stress; it is a characteristic replacement texture.

(8) Strain shadows in quartz do not necessarily result from external stress; they may also result from strain dependent on metasomatic introductions. This point and those referred to under 2, 3, 4, 7, 9, and 13 are the more necessary of emphasis in that such structural, textural, and chemical features of certain of the rocks of the Killarney area, Ontario, have been presented by Jones¹ as if they were evidence unfavourable to Quirke's² conclusions that the rocks result from the transfusion of quartzite. Actually, however, not one of the facts cited by Jones is inconsistent with such a metasomatic origin.

(9) The fact that a mineral has the appearance, in thin section, of being only half developed is not necessarily an indication that it is a broken crystal. In Colonsay, hornblende which results from introductions into rock which was essentially solid sometimes has this appearance.

(10) Crenulated and frayed margins, sieve-like inclusions, and 'splitting apart' of minerals along their cleavages are not necessarily indicative of corrosion. Nor are sieve textures necessarily indicative of contact alteration. Minerals which develop as the result of metasomatic introductions may exhibit such textures, e.g. hornblende in the rocks described in this paper.

(11) Ability to construct a normal variation diagram for a rock

¹ W. A. Jones, The petrography of the rocks in the vicinity of Killarney, Ontario. Toronto Univ. Studies, Geol. Ser., 1930, no. 29, pp. 39-60.

² T. T. Quirke, Killarney gneisses and migmatites. Bull. Geol. Soc. America, 1927, vol. 38, pp. 753-770.

series does not constitute evidence of crystal differentiation. A perfectly normal variation diagram can be constructed for the hornblendite and the rocks resulting from the transfusion of quartzite.

(12) The fact that in an association of rock types one variety is chemically the equivalent of a mixture of two or more other varieties does not constitute evidence that the former represents the parent magma from which the other rocks arose as a result of differentiation. Such evidence is adduced by Kennedy and Read (*loc. cit.*, p. 131), to quote a recent paper, as confirmative of crystal differentiation. In the case described in the present communication, the syntectic appinite, which results from the transfusion of quartzite, is chemically equivalent to a mixture of the syntectic rim-syenite and hornblendite.

(13) Finally, the fact that a rock exhibits intrusive contacts and shows signs of having flowed and at one time existed in what is normally regarded as a magmatic state, does not constitute evidence that its magma originated in the hidden depths. Syntectic magma, developed at observed levels, may give rise to rocks with just such appearances, as witnessed by the pegmatite veins in the Colonsay hornblendite, and by the network of veins with which the latter is locally dissected.

In conclusion I should like to express my great indebtedness to Lady Gibbs and to thank her for her generous collaboration on the chemical side.

DESCRIPTION OF PLATES XI AND XII.

Micro-sections of rocks from Port Easdale, Colonsay, Argyllshire.
(Photomicrographs, Plate XII, by G. W. O'Neill.)

PLATE XI, FIG. 1. Quartzite xenoliths with metasomatized rims in the hornblendite of Port Easdale. Reproduced from Plate IV of the *Geology of Colonsay*, Mem Geol. Surv. Scotland, 1911, by permission of the Controller of H.M. Stationery Office.

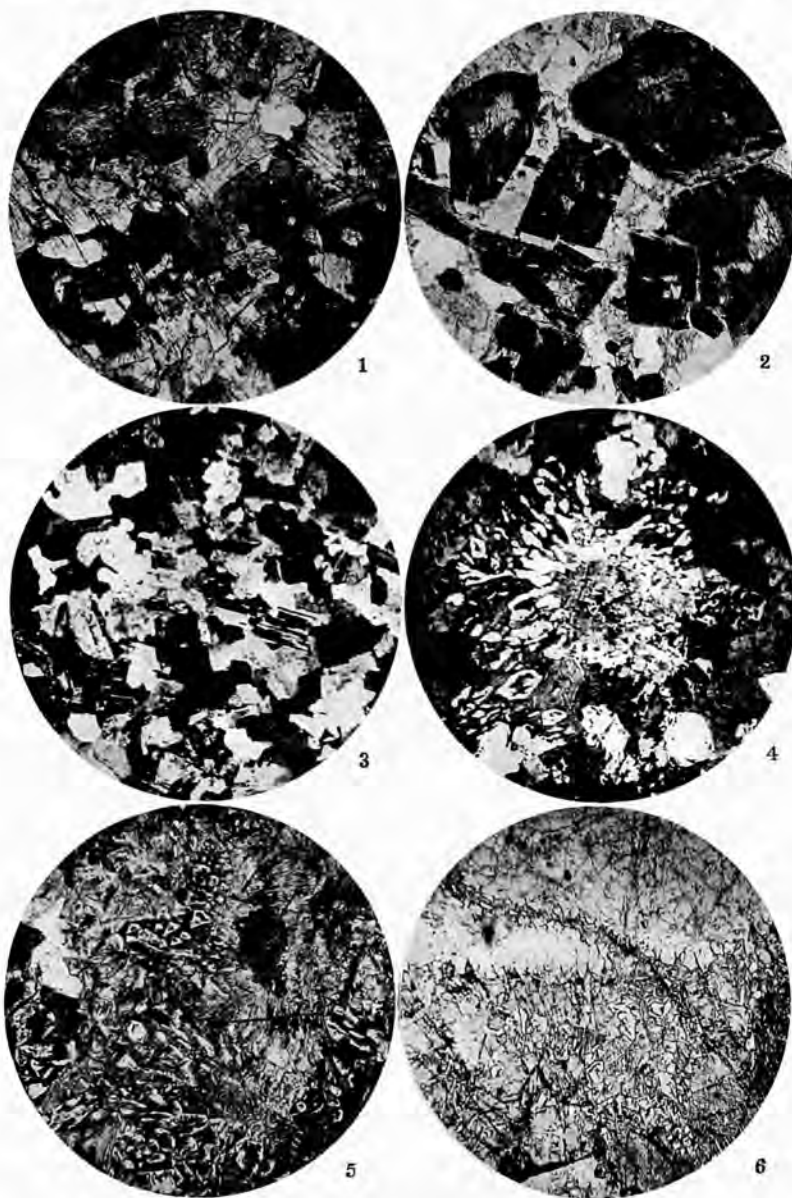
FIG. 2. A feldspathic tail-like vein extending from the metasomatized rim of a quartzite xenolith. The vein is slightly touched up, in order to ensure reproduction.

FIG. 3. Hornblendite cut by a network of leucocratic veins of syntectic origin. Western end of the intrusion margining the northern shore of Port Easdale.

FIG. 4. Syntectic pegmatite veins developed from the feldspathized margin of the quartzite (back) and penetrating the hornblendite (front). Southern shore of Port Easdale, locality marked P on text-fig. 1.



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PLATE XII, FIG. 1. Hornblendite, showing replacement of hornblende by tremolite. Ordinary light, $\times 11$. (See p. 377.)

FIG. 2. Syntectic appinite from a vein projecting from the metasomatized rim of a quartzite xenolith. As in the hornblendite, the hornblende is partially replaced by tremolite. Ordinary light, $\times 26$.

FIG. 3. Syntectic syenite, metasomatized rim of a quartzite xenolith. Nicols crossed, $\times 15$. Analysed specimen.

FIG. 4. Micropegmatite from the metasomatized rim of a quartzite xenolith. Nicols crossed, $\times 13$.

FIG. 5. Micropegmatite, metasomatized rim of a quartzite block in the breccia which margins the intrusion to the south of Port Easdale. The needle-like mineral is rutile. Ordinary light, $\times 13$.

FIG. 6. Contact between a residual core of quartzite and its metasomatized rim. The region of feldspathization is seen to be advancing into the quartzite in minute antennae-like processes which extend along the intergranular boundaries. A feldspathic vein has developed, along intergranular boundaries, in advance of the limit of general feldspathization. Ordinary light, $\times 13$.

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WITH THE AUTHOR'S COMPLIMENTS.

To _____

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**The Two Monzonitic Series of the
Newry Complex.**

BY

DORIS L. REYNOLDS,
The University, Durham.

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August, 1936, pp. 337-364.]

The Two Monzonitic Series of the Newry Complex

By DORIS L. REYNOLDS, The University, Durham.

(PLATE V.)

- I. INTRODUCTION.
 - II. OLIVINE-MONZONITE.
 - III. SYENITE.
 - IV. CRYSTALLOBLASTIC TEXTURES.
 - V. THE TWO MONZONITIC SERIES AND THEIR RELATIONSHIPS.
 - VI. COMPARISON WITH OTHER AREAS.
 - VII. INTERPRETATIONS :—
 - (a) Mobilized Sediment.
 - (b) The Two Monzonitic Series.
- APPENDIX : REPLY TO PROFESSOR E. B. BAILEY.

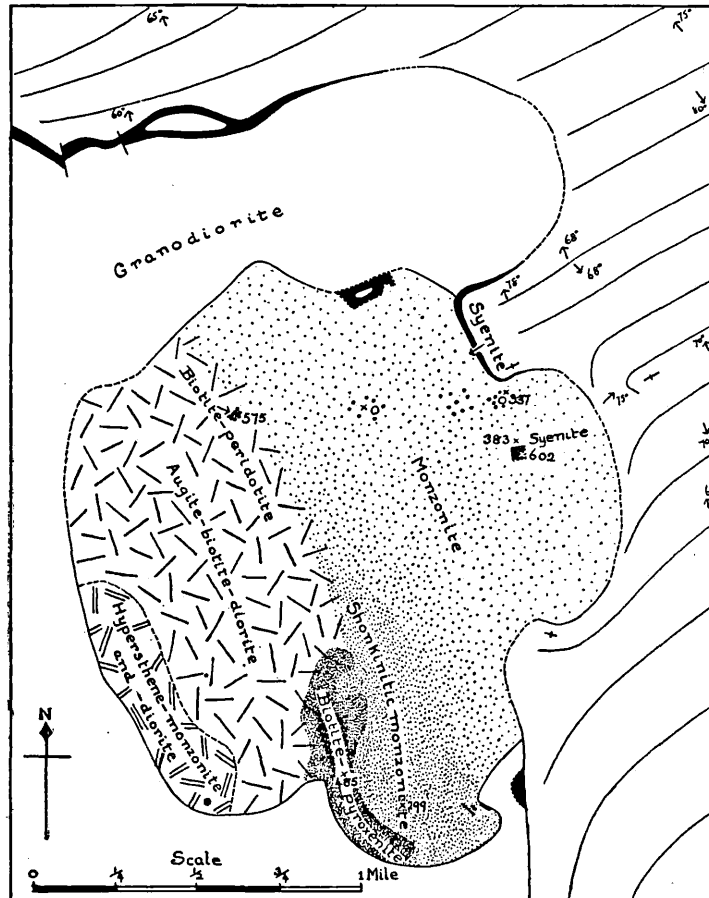
I. INTRODUCTION.

IN a study of the rocks of the eastern end of the Newry Complex,¹ the writer distinguished two contrasted groups of hybrid rocks—(i) the *Slievegarron* type, and (ii) the *Seeconnell* type—both of which are intimately associated with biotite-pyroxenite and biotite-peridotite. The *Slievegarron* hybrids comprise an augite-biotite-diorite series. The typical augite-biotite-diorite (1934, p. 611) is a highly undersaturated rock heteromorphous with certain varieties of orthoclase-basalt and leucite-basanite; it might equally well be described as biotite-essexite-gabbro. No further discussion of these rocks will be undertaken in this paper, but it seems desirable to point out that they should not be confused—as unfortunately they have been—with gabbro-diorite.

The present contribution is mainly devoted to the *Seeconnell* hybrids, which are dominantly monzonitic. Over most of the area characterized by *Seeconnell* types the rocks are related to the

¹ D. L. Reynolds, "The Eastern End of the Newry Igneous Complex," *Quart. Journ. Geol. Soc.*, 1934, **90**, 585-636. Further references to this paper are made by year and pages only.

biotite-pyroxenite. This relationship is evidenced (a) in the field, in that there is gradation from biotite-pyroxenite, through shon-



TEXT-FIG. 1.—NORTH-EASTERN CORNER OF THE NEWRY IGNEOUS COMPLEX. Outcrops of mobilized sediment are shown in black. The structure of the Silurian sediments is indicated by strike lines and dips. The heavy dots to the east of the biotite-peridotite indicate occurrences of monzonite found in thin section to be mineralogically related to the biotite-peridotite. The two localities where olivine is present in such types are marked 0. The numbers refer to the analysed rock specimens.

kinetic monzonite, to monzonite and syenite (see Fig. 1); and (b) mineralogically, in that diopside, similar to that in the biotite-pyroxenite, occurs throughout the Seeconnell suite, whilst large

flakes of biotite of biotite-pyroxenite type are present in the more melanocratic Seeconnell rocks.

Due east of the small exposure of biotite-peridotite, however, the Seeconnell hybrids are characterized by a pinkish augite and a biotite of amber to foxy-brown colour, both of which resemble the corresponding minerals in the biotite-peridotite. At two localities such rocks were found to contain olivine (see Fig. 1). On mineralogical grounds, therefore, they were regarded as being related to the biotite-peridotite rather than to the biotite-pyroxenite (1934, p. 618).

The combined evidence of mineralogy and field distribution thus points to the existence, in the hybrids of Seeconnell type, of two analogous rock-series which converge towards syenite :—

Biotite-pyroxenite — shonkinitic monzonite — monzonite —> syenite
 Biotite-peridotite ————— olivine-monzonite —> syenite

When the 1934 paper was published only three members of the two series had been analysed. Since then, two other types, olivine-monzonite and syenite, have also been analysed. The main purpose of the present paper is to record these new analyses; to describe the analysed specimens; and to establish the two converging monzonitic series and their relationships, on a chemical basis. For brevity the two series may be referred to as the biotite-pyroxenite and biotite-peridotite series.

II. OLIVINE-MONZONITE.

The chemical composition, norm, and mode of the analysed olivine-monzonite, No. 337, from Slievenisky (for exact locality see Fig. 1) are listed under D in Tables I and II.

The texture of the olivine-monzonite is characteristically crystalloblastic, as will be apparent from the descriptions of the individual minerals given below.

Augite, the most abundant ferromagnesian constituent, forms large crystals which reach a size of about 3 by 2 mm. It is pinkish in colour and resembles the augite in the biotite-peridotite (1934, p. 604). $Z \wedge c = 45^\circ$. Although showing a tendency to develop faces in the prism zone, the crystals have characteristically irregular outlines, with curved re-entrants and slender outgrowths. Outlying portions of augite, though completely isolated in the leucocratic matrix, are commonly found to be optically continuous with a neighbouring crystal. Such outlying portions vary in size down to forms of such extreme delicacy that they are visible only under high magnification. In the *camera lucida* drawing, Fig. 2, an augite is shown which has outlying portions not only in the leucocratic matrix, but also in a neighbouring augite. Such textures constitute indubitable evidence of crystalloblastic development. Moreover, the augite frequently exhibits sieve texture, the sieves being filled with felspathic material similar to that of the matrix.

Biotite, frequently developed around iron ore, the outline of which it follows, builds flakes up to 2.5 mm. across. It is amber to foxy brown in colour, similar to the mica in the biotite-peridotite, but in contrast with the duller brown variety which characterizes the melanocratic rocks of the biotite-pyroxenite series. Like the augite, it is crystalloblastic in its development: irregular neighbouring portions, isolated in the leucocratic matrix, being optically continuous. Moreover, the biotite frequently shows fringe-like dactylitic outgrowths which cut across the boundaries of the felspathic elements of the matrix. In these outgrowths the biotite sometimes passes to a green variety.

Olivine occurs in relatively large crystals or glomeroporphyritic groups (up to 3 by 2 mm.) which are widely dispersed so that, as shown in the mode, it makes up but 3 per cent of the rock. It resembles the olivine of the biotite-peridotite (1934, p. 604) in being optically negative and showing an almost straight isogyre in β sections. It is surrounded by a narrow corona structure composed of an inner zone of rhombic pyroxene and an outer zone of fibrous biotite, the latter varying in colour from brown to green. Colourless needles which show oblique extinction, and are probably pyroxene, traverse the biotite and extend beyond it. The fibres and needles of biotite and pyroxene alike penetrate the leucocratic matrix, cutting clean through from one felspar crystal to another. The corona structure is, therefore, crystalloblastic and has developed later than the matrix felspar. The olivine exhibits various stages of alteration to serpentine. Some examples are completely pseudomorphed, and in these cases also the corona structure is present.

Felsic Constituents.—The leucocratic portion of the rock consists of andesine (about Ab_{67}), which is sometimes zoned, together with an optically negative soda-potash felspar. The latter is usually untwinned, but occasionally exhibits exceedingly fine twin lamination, with nearly straight extinction. The plagioclase occurs as relatively large crystals and groups of crystals. Although there is some approximation towards roughly rectangular outlines, the crystals have exceedingly crenulate margins, with delicate protuberances and isolated, but optically continuous, outlying portions. The latter are enclosed by alkali felspar and plagioclase alike. Indeed, the plagioclase closely resembles the augite in the peculiarities of its development and, like it, is typically crystalloblastic.

The alkali felspar, which forms a matrix to the other minerals, is extremely irregular in outline: neighbouring individuals being intergrown in an intricate manner, reminiscent of a highly complex jig-saw puzzle. Again, isolated portions are optically continuous. The alkali felspar is riddled with exceedingly fine vermicular quartz. From the presence of round blebs, representing cross-sections, the form of the quartz vermicules is inferred to be tubular; the terminations are generally blunt or bulbous. The vermicules average about .005 mm. across and are too fine to interrupt the interference

colours or extinction of the felspar (see Plate V). Their identification as quartz rests in the refractive index, which is slightly higher than that of Canada balsam, and in the fact that they are not attacked by hydrochloric acid. By altering the focus of the microscope, the quartz vermicules can be observed at various levels in the alkali felspar. They sometimes cross the boundaries between adjacent felspars. Neighbouring vermicules may be arranged in sub-parallel or fan-like groups; branched forms occur here and there. The vermicular quartz has not been observed traversing the plagioclase, but not infrequently it penetrates the marginal zone of the augite and enters the biotite. In the latter it sometimes reaches the interior, where it spreads out like a malignant growth. The symplectite of vermicular quartz with felspar is clearly a myrmekite-like structure.¹ It is characteristic of much of the rock on the eastern side of Slievenisky and was briefly mentioned in the 1934 paper (p. 616).

Taking into account the actual amounts of biotite and olivine in the mode of the olivine-monzonite, and comparing these with the normative composition, it can easily be calculated that the quantity of free quartz in the rock is of the order 2.2 per cent.

Professor E. B. Bailey, who has examined sections of some of the monzonites, including a slide of the olivine-monzonite here described, writes² as follows: "Many of the augite-monzonite suite, even where they contain fresh olivine, also contain abundant micropegmatite. This has been called myrmekite by Miss Reynolds, though I do not quite like the name, as the material does not resemble closely the myrmekite with which I am familiar in Scotland. One olivine-rich slice may be taken as a type. The olivine is mostly fresh, though encased in reaction products. The micropegmatite is so abundant that it is inconceivable that its material was present when the olivine crystallized. One finds therefore conclusive evidence of migration of early crystals relative to melt (presumably residual melt)."

In connection with these remarks it should be noted that the "olivine-rich slice" is that under description No. 337. Whether or not it is preferable to describe the symplectite (see Plate V) as myrmekite or micropegmatite, the fact remains that the rock contains about 2.2 per cent of quartz, which hardly corresponds to "abundant micropegmatite". Moreover, a slice with only 3 per cent of olivine cannot properly be described as "olivine-rich". Reference to the norm (D in Table II) shows the rock to be undersaturated, the quantity of normative olivine being of a similar order to that actually present in the rock. Obviously the association of olivine and quartz in the amounts present is in no way abnormal, whether the olivine crystallized from a melt having the composition of the actual rock or whether it represents a result of metasomatic introductions. An interpretation on the latter lines is offered towards the end of this paper (see page 358 et seq.).

The plagioclase is clouded with fine dust-like inclusions, amongst which fine rods of an opaque mineral, possibly iron ore, can be distinguished. It also contains blebs of biotite. The clouding is patchy in distribution and follows the direction of the twin lamellae, parallel to which the minute rods are also orientated. The microlites

¹ J. J. Sederholm, *Bull. Géol. Comm. Finlande*, 48, 1916.

² E. B. Bailey, "Memorandum" *re* Newry Igneous Complex, *GEOL. MAG.*, LXXIII, 1936, 270.

resemble those which characterize many basic igneous rocks, as noted by Gillson.¹ The symplectite of alkali feldspar and quartz exhibits a similar clouding, but here the material is much coarser and amongst the dust-like inclusions there are fine rods and hair-like growths which penetrate quartz and feldspar alike (see Plate V). The rods sometimes maintain their direction on passing from plagioclase into the quartz-feldspar symplectite where, however, they become coarser. Blebs of biotite also attain a larger size in the alkali feldspar than in the plagioclase. The opaque rods with which the symplectite is clouded can also be seen, though rarely, to continue into the biotite. The facts—(a) that the swarms of minute rods occur in plagioclase and alkali feldspar alike, and sometimes maintain their direction in passing from one to another; (b) that individual rods in the alkali feldspar cut across successive quartz vermicules; and (c) that the rods can also be found, though rarely, in the biotite—indicate that the clouding is due to migration of material after the feldspars, quartz-feldspar symplectite, and biotite had completed their growth.

The clouding of the plagioclase is regarded by Professor Bailey (1936, p. 270) as evidence that the monzonitic rocks have suffered contact metamorphism (i.e. baking). The only later intrusion to which such metamorphism could be referred is the granodiorite of the area.² It is, however, impossible to correlate clouding with contact metamorphism by the granodiorite, for the following reasons:—

(a) Clouding in the monzonitic rocks does not become more conspicuous as the granodiorite is approached, but is equally well developed towards the sedimentary contact, i.e. away from the granodiorite.

(b) In the augite-biotite-diorite, which is also cut by the granodiorite, clouding of the plagioclase is not characteristically developed.

In his discussion of clouding phenomena in plagioclase, MacGregor³ has not overlooked the hypothesis that clouding may sometimes be due to autopenmatolysis. Presumably, therefore, it may equally well be considered as due to pneumatolysis without the theoretical limitation implied by the prefix *auto*. Such pneumatolysis in the Seeconnell hybrids is only a minor detail of the whole complex process whereby the hybrids themselves are believed to have been formed—a process of the nature of pyrometasomatism, which is further discussed on page 359.

Accessories.—Iron ore occurs in irregular masses, many of which are surrounded by biotite. Large crystals of apatite occur in both the felsic and the mafic portions of the rock. Minute needle-like crystals of apatite penetrate the leucocratic constituents.

III. SYENITE.

The chemical composition, norm, and mode of the analysed syenite, No. 383, from Slievenisky (for exact locality see Text-fig. 1) are listed under E in Tables I and II.

¹ J. L. Gillson, *U.S.G.S. Prof. Paper* 158 D, 1929, 80.

² In case the implication of this statement is not clear, it should be emphasized that the augite-biotite-diorite is not a later intrusion, but is gradational to the biotite-pyroxenite—monzonite and biotite-peridotite—monzonite series.

³ A. G. MacGregor, *Min. Mag.*, 22, 1931, 524–538.

Though variable in texture, the syenite is always crystalloblastic. The analysed specimen, which is described below, is a fair average of the hornblendic variety. The latter grades to a variety in which augite is of more frequent occurrence.

TABLE I.

	A.	B.	C.	D.	E.	F.	G.
SiO ₂	45.91	41.71	53.10	55.20	56.52	66.65	68.80
Al ₂ O ₃	3.51	8.55	14.52	15.30	18.30	14.33	14.15
Fe ₂ O ₃	2.11	2.51	0.86	0.68	1.50	0.55	0.50
FeO	9.73	9.79	6.40	5.76	4.29	5.62	5.03
MgO	19.42	14.65	6.71	5.20	2.23	3.00	2.39
CaO	14.28	11.74	6.78	6.50	3.62	1.47	1.20
Na ₂ O	0.31	0.60	2.99	3.02	4.47	2.49	1.62
K ₂ O	0.58	3.65	4.82	4.80	5.79	2.99	1.97
H ₂ O +	1.42	1.41	1.00	0.50	0.71	1.82	2.95
H ₂ O -	0.11	0.16	0.06	0.30	0.08	0.13	0.23
CO ₂	0.45	0.16	0.02	none	none	none	none
TiO ₂	0.72	2.15	1.09	1.66	1.11	0.92	0.87
P ₂ O ₅	1.00	1.62	0.83	0.72	0.80	0.17	0.18
Cl	0.02	0.01	0.04	n.d.	0.03	0.02	n.d.
F	n.d.	0.16	0.07	n.d.	n.d.	n.d.	n.d.
S	tr.	0.03	none	n.d.	none	tr.	tr.
Cr ₂ O ₃	0.10	0.04	0.03	n.d.	none	0.01	0.01
V ₂ O ₅	0.03	0.06	0.03	n.d.	0.02	0.02	sm. tr.
NiO	0.06	0.04	0.02	n.d.	none	0.01	n.d.
MnO	0.26	0.24	0.15	0.22	0.11	0.08	sm. tr.
SrO	none	0.04	0.08	n.d.	0.08	tr.	none
BaO	0.08	0.50	0.29	n.d.	0.17	0.04	sm. tr.
Li ₂ O	none	tr.	tr.	n.d.	tr.	tr.	n.d.
Less O	100.10	99.82	99.89	99.86	99.83	100.32	99.90
		0.08	0.04				
		99.74	99.85				

- A. Biotite-peridotite, No. 575, Crocknafoyle (1934, p. 605). Analyst, L. S. Theobald.
 - B. Biotite-pyroxenite, No. 485, Seeconnell (1934, p. 608). Analyst, L. S. Theobald.
 - C. Shonkinitic monzonite, No. 299, Seeconnell (1934, p. 617). Analyst, H. F. Harwood.
 - D. Olivine-monzonite, No. 337, Slievenisky. New analysis by W. H. Herdman.
 - E. Syenite (Plauenite), No. 383, Slievenisky. New analysis by L. S. Theobald.
 - F. Mobilized sediment, No. 602, Slievenisky (1934, p. 603, No. 1). Analyst, L. S. Theobald.
 - G. Sediment. Weighted average, 2 parts greywacke, No. 712 and 1 part shale, No. 713 (1934, p. 603, Nos. 3 and 4).
- Note.—The exact localities of the analysed specimens are marked on the map, Fig. 1.

The mafic minerals, common hornblende and biotite, are of approximately the same grain size as the leucocratic constituents of the major part of the rock. They are poikiloblastic; isolated

TABLE II.

Norms.

	A.	B.	C.	D.	E.	F.
q	—	—	—	—	—	29.46
or	3.34	4.45	28.36	28.38	34.47	17.79
ab	2.62	—	20.96	25.53	37.47	20.96
an	6.39	9.73	11.95	13.26	12.23	6.67
lc	—	13.52	—	—	—	—
ne	—	2.84	2.27	—	.43	—
c	—	—	—	—	—	4.49
di { CaSiO ₃	23.08	15.66	9.28	5.95	.23	—
MgSiO ₃	16.00	10.70	5.70	3.54	.10	—
FeSiO ₃	5.15	3.70	3.04	2.10	.13	—
hy { MgSiO ₃	8.50	—	—	7.62	—	7.50
FeSiO ₃	2.77	—	—	4.52	—	8.58
ol { Mg ₂ SiO ₄	16.80	18.20	7.70	1.24	3.85	—
Fe ₂ SiO ₄	5.92	6.73	4.69	.82	3.77	—
mt	3.02	3.71	1.39	1.00	2.09	.70
il	1.37	4.26	2.13	3.16	2.13	1.67
ap	2.35	3.70	2.02	1.72	2.02	.34
cc	1.10	.50	—	—	—	—
water, etc.	1.72	1.79	1.26	.80	.84	2.06
	100.13	99.49	100.75	99.64	99.76	100.22

Modes (percentages by volume.)

Olivine	22.4	—	—	3.0	—	—
Augite	63.3	27.4	21.9	20.4	tr.	—
Hornblende	4.7	21.2	—	—	5.3	—
Biotite	5.4	45.3	24.3	6.8	8.9	29
Quartz	—	—	tr	ca.2.2	tr	47
Felspar	—	—	53.5	63.7	82.8	22
Cordierite	—	—	—	—	—	—
Apatite	2.3	2.9	.9*	.6*	.6*	—
Iron ore	2.7	3.2	tr.	1.3	1.8	—
	100.8	100.0	100.6	98.0	99.4	98

A. Biotite-peridotite, No. 575. Modal augite includes a little hypersthene.

B. Biotite-pyroxenite, No. 485. Modal hornblende includes 1.8 per cent. actinolite.

C. Shonkinitic monzonite, No. 299. Modal augite includes a little hornblende.

D. Olivine-monzonite, No. 337. Modal olivine includes .5 per cent. serpentine. The figure for quartz is calculated, as indicated in the text, and subtracted from the amount of felspar actually measured, i.e. 65.9.

E. Syenite, No. 383. The rock contains a little sphene.

F. Mobilized sediment, No. 602. Staining method used to distinguish felspar + cordierite from quartz.

* These figures refer only to the larger crystals of apatite. The fact that they are low compared with the corresponding normative figures is due to the impossibility of measuring the apatite which occurs as fine needles in the felspar.

sinuous portions, which enclose and wrap round anhedral feldspar, being in optical continuity. In one section a crystal of hornblende, of somewhat larger size than usual, contains a central core of augite. The augite itself encloses blebs and channels of hornblende, which exhibit intricate boundaries and are optically continuous with the hornblende rim. On the other hand, the hornblende rim contains outlying ragged blebs of augite which, in turn, are optically continuous with the central core. The appearance between crossed nicols is one of extreme intricacy. Moreover, the hornblende has an exceedingly irregular margin, with protuberant growths extending into and wrapping round neighbouring feldspar. Such an association of hornblende and augite is not uncommon in specimens of syenite from Slievenisky.

The leucocratic portion of the rock contains oligoclase-andesine and soda-potash feldspar, with here and there a trace of quartz. For the most part the feldspars form an almost equigranular intergrowth. The texture, however, is very variable, and there are patches with a considerably coarser grain. In these, large crystals of oligoclase-andesine, which exhibit a patchy twinning, are intergrown with one another in a highly intricate fashion. They sometimes exhibit zoning in which the zones are highly irregular in outline. Associated with this plagioclase, and frequently enclosed within it, there are small very irregular scraps of soda-potash feldspar, riddled (as in the olivine-monzonite) with exceedingly fine vermicular quartz. Neighbouring scraps of alkali feldspar, though isolated, are optically continuous.

The felsic constituents not uncommonly contain inclusions of opaque material which may be dust-like in its dimensions, or appear as small dots, hairs, or rods; blebs of biotite are also present. Iron ore occurs as an accessory in small irregular masses. It is crystalloblastic and since it wraps round and sometimes completely encloses feldspar, it seems likely that it was of late development. Sphene is present in small amount and is also crystalloblastic. Apatite needles, sometimes hair-like in their dimensions, are common in the feldspars; larger crystals of apatite, which are bluish in colour, are of rare occurrence.

IV. CRYSTALLOBLASTIC TEXTURES.

It will be convenient here to sum up the evidence relating to the occurrence and mode of origin of the crystalloblastic textures in rocks from this area. Such textures are characteristic not only of the olivine-monzonite and syenite just described, but also of all the rocks of Seeconnell type (1934, p. 613 et seq.).

The petrological significance of crystalloblastic texture lies in the evidence it provides that crystal growth took place in a solid or highly viscous medium. It is known to be developed (*a*) as a result of recrystallization induced by the action of a neighbouring

intrusion, and (b) as a result of reconstitution dependent on pneumatolytic or hydrothermal introductions, as, for example, when tourmaline develops in tourmalinized grits and other rocks. Moreover, it is now known that replacements due to artificially induced metasomatism¹ sometimes give rise to similar textures.

If the textures in the Seeconnell examples resulted from contact alteration attributable to the intrusion of a younger magma, then their occurrence and distribution should be in some way related to the granodiorite. However, there is no such relationship. The augite-biotite-diorite, to which the Seeconnell types grade westwards, lies nearer to the main granodiorite, yet in it sieve textures are rare and crystalloblastic developments in general are considerably less common. Such would not be the case if the crystalloblastic development of the Seeconnell rocks were a consequence of contact metamorphism. Moreover, on the northern margin of the Complex (see 1934, Plate xxii) two isolated exposures of hybrid types occur. One of these, on Legananny Mountain, is of monzonite (Seeconnell type) whereas the other, on Rough Hill, is of augite-biotite-diorite (Slievegarron type). The monzonite exhibits conspicuous crystalloblastic textures, whilst in the augite-biotite-diorite, which must have been equally influenced by the granodiorite, such textures are much less characteristically developed, except away from the granodiorite and towards the sediments, where the latter are migmatized by the augite-biotite-diorite.

It can only be concluded that the crystalloblastic textures are definitely not referable to the action of the granodiorite. Since there is no other younger intrusion which could have caused contact metamorphism, I have adopted the alternative explanation that the textures result from recrystallization during reconstitution due to the effects on the invaded rocks of pyrometasomatic introductions from biotite-pyroxenite and biotite-peridotite magmas.

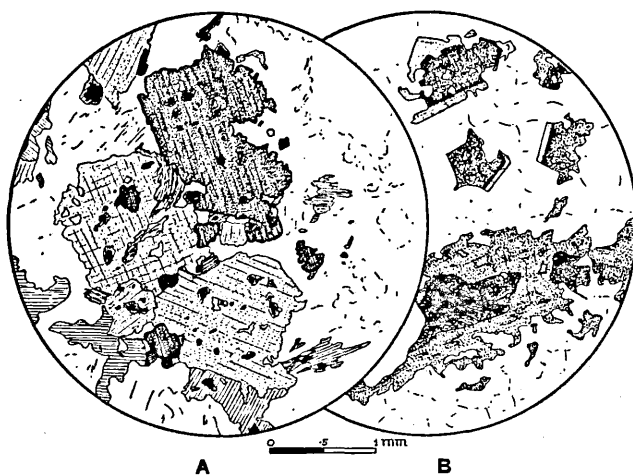
A similar problem relating to the genesis of poikilitic minerals was encountered by Gillson and Kania² in the course of an investigation of the mela-norite of the Cortlandt series. Poikilitic hornblende, with a rambling shape and sieved with feldspar and pyroxene, is regarded as partly or entirely due to replacement. The form of the magnetite indicates that it, too, must have been formed partly or wholly by replacement during a late stage in the crystallization history of the rock. As indicated in the diagrams illustrating Gillson and Kania's paper, the minerals closely resemble the Seeconnell crystalloblasts in form, even as regards the detail of the development of "porcupine" biotite in the cleavages of the hornblende. Biotite of similar habit is not uncommon in the augites of the Seeconnell hybrids. For a detailed discussion of replacement and resultant textures, with an unusually full bibliography of the

¹ C. Shouten, *Econ. Geol.*, **29**, 1934, 611-658.

² J. L. Gillson and J. E. A. Kania. *Econ. Geol.*, **25**, 1930, 511 et seq.

subject, reference should be made to Gilluly¹ on the replacement origin of albite-granite.

As a result of his examination of some of the Seeconnell monzonites, Professor Bailey has suggested that the ragged augites, which I regard as porphyro-poikiloblasts, are phenocrysts, representing some of the earliest products of crystallization, corroded by an alleged residual melt. Of one example he writes (Memo., p. 269), "the crenulate borders abruptly cross zoning marked by iron ore, and corrosion seems certain." It must, therefore, be pointed out



TEXT-FIG. 2.—EXAMPLES OF CRYSTALLOBLASTIC TEXTURE.

- A.—Olivine-monzonite (No. 337) from Slievenisky, showing augite, biotite, iron ore, and felsic constituents. The heavily shaded portions of augite are optically continuous with the main crystal, which is similarly shaded.
 B.—Tourmaline in tourmalinized grit from the aureole of the Dartmoor granite; near Ivy Tor, Belstone, Devon.

that such an appearance is far from being inconsistent with a porphyroblastic development. In particular, I would refer to the development of tourmaline in a grit near Ivy Tor, Belstone, on the northern margin of the Dartmoor granite. In thin section the tourmaline commonly exhibits conspicuous zoning in tints of brown and blue. It is sieved with quartz inclusions and against the crenulate margins the quartz matrix frequently transgresses the outer zones. Some sections show a complete development of zones parallel to only one of the crystal faces. On the other faces the zones appear to be sharply truncated by the matrix (see Text-fig. 2).

If the sieve texture of the Seeconnell augites be attributed to corrosion, it becomes necessary to explain the absence of pyroxene

¹ J. Gilluly, *U.S.G.S. Prof. Paper* 175 C, 1933. See also C. S. Ross, *ibid.*, 179, 1935.

or amphibole from the infillings of the sieves. If the sieves were due to solution, it seems impossible that the mafic material could in every case have been removed completely from such confined spaces. It is further to be noted that the tourmaline in tourmalinized grits exhibits isolated portions in optical continuity with a larger neighbour, exactly reproducing the structural details characteristic of the Seeconnell augites. Tourmaline is probably the best example that could be cited to illustrate the features which originate from the operation of pyrometasomatic processes. Independently of this comparison, however, it is inconceivable that small portions of augite, sometimes hair-like in delicacy, should be isolated from their parent crystal by corrosion due to a migrating residual melt, and yet remain in perfect optical continuity.

V. THE TWO MONZONITIC SERIES AND THEIR RELATIONSHIPS.

As already noted, field and petrographic evidence shows that biotite-pyroxenite, shonkinitic monzonite, and syenite form a gradational series. The chemical evidence now available further emphasizes this serial gradation (see analyses B, C, and E in Table I and the variation diagram, Text-fig. 3).

On Slievenisky, at the locality marked by No. 602 on the map, Text-fig. 1, the syenite in turn can be seen to grade to mobilized sediment. In describing the rocks of the Newry Complex the mobilized sediment was termed "fused sediment" (1934, p. 602). This name is unsuitable, however, since it introduces a thermal hypothesis into the description of a mechanical fact. This rock-type will in future, therefore, be designated *mobilized sediment*.

Although the mobilized sediment falls into subrang *Toscanose* (I.4.2.3.) in the C.I.P.W. classification, comparison with the numerous analyses that fall into the same division (e.g. the 381 analyses in Washington's Tables, 1917, pp. 201, et seq.) discloses the fact that this rock differs chemically from normal igneous rock-types in several important respects—notably by the abnormal combination in the mobilized sediment of low alkalis and high iron and magnesia, relative to silica. When the mobilized sediment is classified according to Johannsen's modal system (cf. mode under F in Table II), it is found to fall into the group of quartz-tonalites, 224P, in which quartz forms over 50 per cent of the leucocrates. Johannsen¹ observes that descriptions of only two rocks of this family are to be found in the literature. One is a paragneiss, described by von Eckermann² from Mansjö Mountain, Loos, Middle Sweden. The other, described by Eskola,³ is a rock from the contact aureole of the Orijarvi area. Though Eskola believes this rock to be a metasomatized eruptive rock, he remarks that it has the composition of a sediment. The

¹ A. Johannsen, *A Descriptive Petrography of the Igneous Rocks*, ii, 1932, 43.

² H. von Eckermann, *Geol. Förel. Förh., Stockholm*, 44, 1922, 309.

³ P. Eskola, *Bull. Géol. Comm. Finlande*, 40, 1914, 219.

mobilized sediment is thus chemically, as well as mineralogically, more nearly of sedimentary than of igneous composition. Its chemical composition is plotted on the variation diagram, Text-fig. 3, and a weighted average of the local graywacke and shale (Table I, under G) is plotted for comparison. The latter, based on analyses of the two dominant types, is a sufficiently close approximation to the average sediment to demonstrate the fact that the mobilized sediment is chemically more closely comparable with the local sedimentary rocks than with the syenite to which it grades.

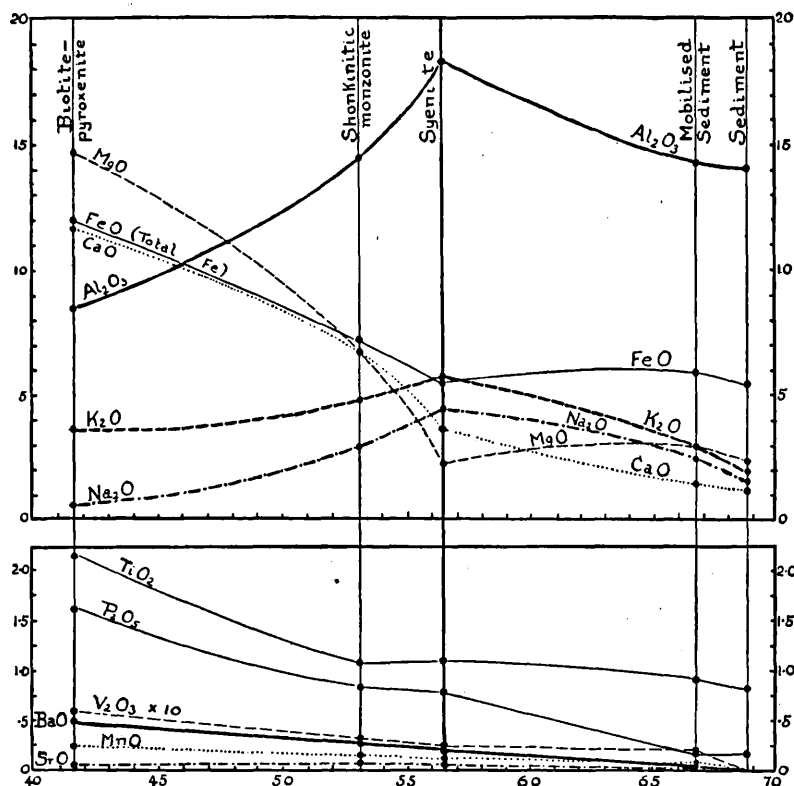
On the basis of field relations and mineralogical and chemical composition I regard the mobilized sediment as resulting from the enrichment of the country rocks in alkalis, alumina and, to a less extent, in lime. The variation diagram, Text-fig. 3, shows that in these constituents the mobilized sediment is intermediate in composition between the country rocks and the syenite, and that it is more closely related to the former. The curves for iron and magnesia may appear to present an anomaly, since the mobilized sediment is richer in these constituents than either the syenite or the unaltered country rock. The rocks of the contact aureole, however, exhibit a marked increase in biotite, as compared with the normal sediment. Indeed, in certain lustrous black schistose rocks from the aureole, biotite may form as much as 50 per cent of the rock. This enrichment in biotite, which the mobilized sediment shares in common with the sediments of the aureole, is reflected by the convex form of the curves for iron and magnesia.

On the variation diagram, Text-fig. 3, the curves for the minor constituents are shown. They are of particular interest, since several of them fall smoothly from biotite-pyroxenite, through the hybrid types and the mobilized sediment, to unaltered sediment. This strongly suggests that these constituents were derived from the biotite-pyroxenite magma. The same conclusion applies to part of the TiO_2 and P_2O_5 .

As already noted, the field distribution and mineralogy of certain monzonitic types, which in two localities contain olivine, indicate that they are related to biotite-peridotite rather than to biotite-pyroxenite. On the variation diagram, Text-fig. 4, olivine-monzonite is plotted together with biotite-peridotite and syenite. The serial relationship between these types is evident.

Comparison of the two variation diagrams, Text-figs. 3 and 4, indicates that there is a marked chemical relation between the biotite-pyroxenite series and the biotite-peridotite series. The main differences are expressed by the greater steepness of the various curves in the latter. For corresponding silica percentages, alkalis and alumina are lower, while magnesia and lime are higher, in the biotite-peridotite series. The mineralogical expression of this difference is that the biotite-peridotite and olivine-monzonite contain olivine and a relatively low percentage of biotite, whereas the biotite-pyroxenite and the shonkinitic monzonite contain no olivine,

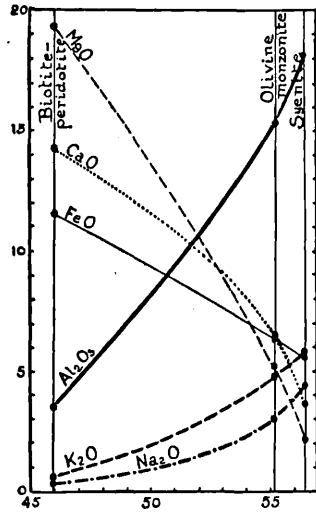
but have a high percentage of biotite. In other words, high alkalis (mainly potash) and alumina in the biotite-pyroxenite series led to the development of biotite rather than olivine. Normatively the members of both series are undersaturated. The chemical difference is, however, expressed by the fact that the biotite-pyroxenite series contains normative nephelite in addition to olivine, whereas in the



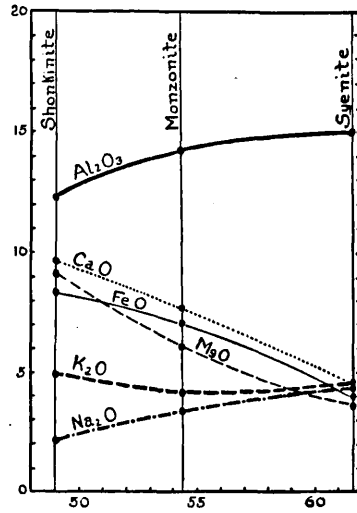
TEXT-FIG. 3.—Newry Complex. Variation diagram of the series ranging from biotite-pyroxenite to country rock.

biotite-peridotite and olivine-monzonite normative nephelite does not appear.

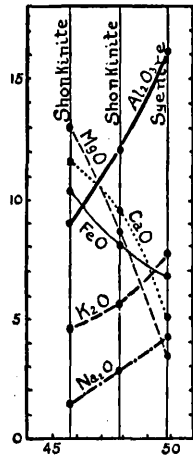
The relation between the two series is clearly displayed on the triangular diagram, Text-fig. 8. The line P—BP, directed towards the pole representing alumina plus alkalis, indicates the differentiation trend of the ultrabasic types. The variation-line of the biotite-peridotite series meets the variation-line of the biotite-pyroxenite series at syenite. Chemical gradation, therefore, corresponds in both



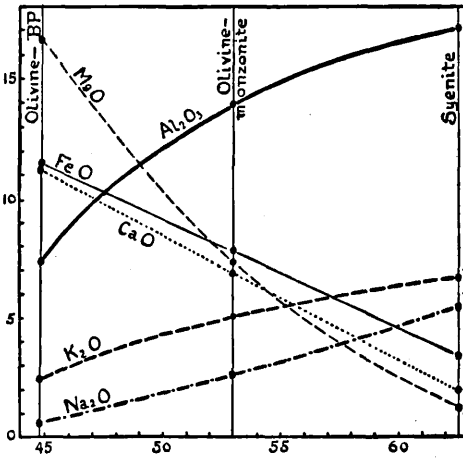
TEXT-FIG. 4.—Newry Complex. Variation diagram of the biotite-peridotite series.



TEXT-FIG. 5.—Yogo Peak, Montana.



TEXT-FIG. 6.—Shonkin Sag, Montana.



TEXT-FIG. 7.—Rossland area, B.C.

cases to field gradation. The diagram also emphasizes the greater richness of the biotite-pyroxenite series in alkalis and alumina, as compared with the biotite-peridotite series.

The mobilized sediment and the unaltered country rocks (graywacke and shale) are also plotted on the triangular diagram and, as in Text-fig. 3, the resemblance of the mobilized sediment to the sedimentary types is made evident. It is a point of great significance that the line drawn on Text-fig. 8 from average sediment through mobilized sediment continues through the calculated composition of the alkali-enriched sediment (1934, p. 629), towards the pole representing alumina plus alkalis. This indicates that the addition of a small amount (only 3 per cent.) of emanations rich in alkalis and alumina would be chemically adequate to convert the average sediment into mobilized sediment. The differentiation products of the ultrabasic magma can readily be ascribed to the effects of ascending emanations of essentially the same composition. It is therefore a reasonable inference that the emanations responsible for the alkali metasomatism of the sediments had their immediate source in the ultrabasic magma, that is, in the earliest known magma of the area.

It is further evident from the triangular diagram that the chemical composition of the various rock-types is consistent with the interpretation I have already given of their field and petrological characters (1934, p. 628). Chemically, the monzonitic and syenitic rocks are precisely what would be expected from syntaxis of biotite-pyroxenite and biotite-peridotite magmas with alkali-enriched (syenitized) sediment.

VI. COMPARISON WITH OTHER AREAS.

The Newry Complex provides the first recorded occurrence of the potassic series shonkinitic monzonite—syenite from rocks of Caledonian age in the British Isles. The suite is characterized by high alkalis, with considerably more potash than soda, and by high magnesia. In contrast with this, the Scottish Caledonian rock suites are, in general, marked by lower total alkalis, commonly with less potash than soda, and by higher lime than magnesia. Many of them are closely related to the appinites.

The most closely comparable suite—probably of Caledonian age—in the British Isles occurs in Sutherlandshire; its members have been described by Read¹ as the hybrids of Ach'uaine. They resemble the Newry rocks in their high potash, but differ in having higher lime and carbon dioxide, and lower magnesia and iron. Mineralogically, they differ from a typical shonkinitic series in their abundant hornblende. The hybrids of Ach'uaine represent transitional types between the shonkinitic—syenite series and the appinite series.

¹ H. H. Read, *Mem. Geol. Surv. Scotland* (Strath Oyckell and Lower Loch Shin), 1926, pp. 154-166.

In the Loch Ailsh mass, which is probably also referable to the Caledonian igneous cycle, the rocks parallel the shonkinite—syenite series of Newry, but are sodic in character.¹

Biotite-pyroxenite is associated both with the hybrids of Ach'uaine and with the rocks of the Loch Ailsh mass. It thus forms a link with the biotite-pyroxenite series of Newry. It is a point of geochemical interest that the biotite-pyroxenite of Loch Ailsh, in accord with the sodic character of the associated rocks, is itself relatively rich in soda as compared with the biotite-pyroxenites of the other two areas.

The Seeconnell, Ach'uaine and Loch Ailsh rocks differ, in their high alkalis, from the other British Caledonian rock suites so far described. In this connection the alkali-lime index applied by Peacock² to the classification of igneous rock series provides a useful means of discrimination. Whereas all three of the suites mentioned above are alkali-calcic in character, the others so far described are calc-alkali, and, with the exception of that of Garabal Hill, contain more soda than potash.

TABLE III.

Alkali-Lime Indices.

Alkali Series.	Alkali-calcic Series.	Calc-alkali Series.
Shonkin Sag,	Loch Ailsh . . . 51.3	Ben Nevis . . . 56.6
Montana . . . 48.2	Rossland . . . 51.9	Cairnsmore of
	Ach'uaine Hybrids . . . 52.2	Carsphairn . . . 57.0
	Newry (B. Pyr. Series) 52.2	Loch Doon . . . 57.4
	Newry (B. Per. Series) 54.7	Haddo House,
	Yogo Peak, Montana 54.75	Aberdeenshire 58.2
		Garabal Hill . . . 59.6

The indices for the typical shonkinitic series of Shonkin Sag,³ Yogo Peak,⁴ and Rossland,⁵ are given for comparison with those of the Newry series. As regards individual rocks, the shonkinite of Yogo Peak and the olivine-monzonite of Rossland very nearly fit the variation diagram, Text-fig. 3, for the biotite-pyroxenite series of Newry. As regards the suites, the variation diagrams for Newry, Text-figs. 3 and 4, show marked resemblance to those for the Western American areas, Text-figs. 5, 6, and 7. The curves for the Rossland area, representing the biotite-pyroxenite and olivine-monzonite of Christina Lake, with the syenite of the Traill batholith as the end member, are most similar in their interrelations to those for Newry. The Shonkin Sag rocks fall within a small silica range and, as might therefore be expected, they are correspondingly rich in alkalis. The

¹ J. Phemister, *Mem. Geol. Surv. Scotland* (Strath Oykell and Lower Loch Shin), 1926, pp. 22-111.

² M. A. Peacock, *Journ. Geol.*, **39**, 1931, 54-67.

³ L. V. Pirsson, *U.S.G.S. Bull.*, **237**, 1905.

⁴ L. V. Pirsson, *U.S.G.S. 12th Ann. Rep.*, 1898-9, Part iii.

⁵ R. A. Daly, *Geol. Surv. Canada Mem.* **38**, 1912, Part i. For the analysis of the biotite-pyroxenite see D. L. Reynolds, *Min. Pet. Mitt.*, **46**, 1935, p. 450, Analysis No. 5.

Yogo Peak series has higher lime relative to magnesia and is less rich in alkalis at the felsic end.

Of the three American shonkinitic series with which comparison is here made, only that of the Rosslund area is known to have biotite-pyroxenite as its most basic member. It is, however, a point of interest that Pirsson in 1898, from a study of the rocks of Yogo Peak, actually anticipated the discovery of biotite-pyroxenite many years before the first example of this rock was described. Commenting on his variation diagram for the Yogo Peak series, he writes (*op. cit.*, p. 575):—

“It shows that if differentiation had gone on as far beyond the shonkinite as the latter is from the monzonite there would have been formed, not a pyroxenite, but a missourite, and it shows the intimate relation between the latter and shonkinite. This relation is confirmed in fact, for the stock which furnishes the original missourite has shonkinitic phases.

“We may thus deduce that in regions where monzonite occurs as a main stock type both shonkinite and missourite facies and dependencies are to be expected and should be carefully looked for.

“It is also quite true that this deduced magma might express itself as a pyroxene-biotite rock (biotite instead of olivine and leucite), and especially if the magma crystallized under such conditions that water vapour and fluorine, necessary for the formation of biotite, could not readily escape.

“The more basic type of shonkinite, described in the original paper and mentioned in this work under shonkinite, with its large and abundant poikilitic biotites, would thus in part be accounted for.

“Such a rock, though of pyroxenic habit, is very different from the pyroxenites which represent the differentiation end products of the gabbro-peridotite group, as shown by its abundant potash, and is not to be confounded with them.”

If it is clear from the data assembled in this paper that the Seeconnell hybrids constitute two monzonitic series ranging between potassic ultrabasic and syenitic types, then it becomes equally obvious that these hybrids cannot be referred to reaction between granitic magma and either gabbro, pyroxenite, or peridotite. Yet this suggestion has been offered and it is therefore desirable to refute it in detail.

(a) Reference to the variation diagrams (Text-figs. 3 and 4) makes it amply evident that the two monzonitic series are chemically, as well as mineralogically, essentially different from any known gabbro—granite or even gabbro—syenite suite. Potash is everywhere dominant over soda. Alumina varies sympathetically with the alkalis throughout the silica range. Magnesia lies above lime for all silica percentages below 52. The alkali-lime indices are 52.2 and 54.7 against an average of about 59 for gabbro—granite suites.

(b) There are no gabbros or granites associated with the Seeconnell rocks.

(c) In areas where gabbro and granite do react to produce hybrid types, the latter are not like those of Seeconnell.

(d) If granitic magma had reacted on pyroxenite to produce biotite-pyroxenite in the Newry Complex, the residual magma would have been greatly enriched in silica and impoverished in potash. No such abnormally siliceous sodic residuum can be traced, the most acid rock of the area being much less siliceous than normal granite.

(e) Similar objections apply to the case of peridotite.

VII. INTERPRETATIONS.

(a) Mobilized Sediment.

It has been thought possible by some petrologists that the zone of mobilized sediment resulted from the invasion and brecciation of sediment by igneous material, the latter not having been produced *in situ*. My own view, on the contrary, is that such igneous material as may be inferred from the structure of the zone is *igneous* only in the sense that its material temporarily attained mobility as a local result of ultra-metamorphism stimulated by the introduction of highly energized emanations. Indeed, I can see no satisfactory alternative to the conclusion that the mobilized sediment consists of transfused (biotitized and feldspathized) sediment, which contains inclusions of less altered sediment.

The transfusion process which endowed the material with the ability to move was, I believe, essentially one of metasomatism due to emanations, rich in alkalis and alumina, derived from the ultra-basic magma. To such a process Sederholm's term *anatexis* can well be applied, since Sederholm¹ attributed *anatexis* mainly to "the influence of emanations from the abyssal magma, whatever may have been its composition". The actual movement, or *palingenesis*, of the transfused sedimentary material is possibly to be attributed to either internal expansion, dependent on metasomatic additions (including energy), or to externally applied stresses.

This interpretation is based on (a) the mineralogical similarity of the mobilized sediment to the sediments of the contact aureole; (b) the gradation between mobilized sediment and contact-altered sediment; (c) the lack of chemical correlation between the mobilized sediment and igneous rocks (see p. 348); and (d) the evidence of the outer portion of a zone of migmatites on Rough Hill.

The latter zone, which margins the augite-biotite-diorite, retains a bedded appearance in the field. Close examination, however, reveals the fact that it consists of dark, closely packed, lens-like portions up to a few inches in length, embedded in a coarser material. The dark lenses, rich in biotite, maintain a linear and planar orientation parallel to the adjacent sedimentary bedding, and are obviously

¹ J. J. Sederholm, *Bull. Géol. Comm. Finlande*, **77**, 1926, 135.

relics of altered sediments of the same type as the biotite-rich schist-like rocks of the aureole. The coarser material which surrounds the lenses is identical, both in hand specimen and thin section, with the mobilized sediment. It is mechanically inconceivable that the coarser material could represent an injection of magma, modified or otherwise. The conclusion seems inescapable that the coarser material has resulted from the action of metasomatic introductions (possibly both ionic and molecular) into the sediments.

After an examination in the field of the Rough Hill occurrences, Professor Bailey stated (1936, p. 267): "I accept the contention that much igneous material has marginally entered the contact zone of the sediments; also that it is probable that this penetration has occurred to some extent molecularly without disruption of bedding". In the light of this admission I can see no reason why the mobilized sediment should be regarded as an independent intrusive igneous type, since it is mineralogically and texturally identical with the coarser material of the Rough Hill outer zone. Nevertheless, referring to the mobilized sediment, Professor Bailey writes: "Where shown marginal breccia I usually felt that one could see modified igneous material invading modified sediment." That the mobilized sediment is igneous in habit, in that it contains inclusions of less altered sediment and exhibits signs of flow, I not only recognize, but actively maintain. But recognition that the material has at one stage been capable of internal mobility does not seem to me to compel the assumption that most of it was derived from an external source. I would here recall a pertinent remark of Quirke's with regard to an analogous occurrence. Writing of the Killarney area, Ontario, he says¹: "we seem to find quartzites outside the borders of granitic invasions so completely altered into granitic material that they have partaken even of its physical activity, resulting in intrusive movements and actual invasion of other and less siliceous formations. *This is a critical point in any argument, that sedimentary rocks have been altered into igneous rocks.*" The italicized emphasis is my own, the object being to direct attention to a point which is persistently disregarded by many petrologists.

The mobilized sediment is not unique. Similar zones occur around many of the Scottish Caledonian intrusions. Moreover, it is instructive to compare them with an example figured by Sederholm² of a "Bedded leptite changed by palingenesis into an eruptive rock where some portions have flowed, while others have remained as fragments." Of the photograph illustrating this occurrence—which might well pass for one of the Newry mobilized sediment—Sederholm remarks:—

"The rock of the southern shore of Lingonsörn is a bedded leptite which retains in many places its character of a highly metamorphic schist showing an alternation of salic and femic beds. But the greater

¹ T. T. Quirke, *Bull. Geol. Soc. Amer.*, **38**, 1927, 762.

² J. J. Sederholm, *Bull. Géol. Comm. Finlande*, **77**, 1926, 28.

part of it has been changed, by a process surpassing metamorphism and even 'ultrametamorphism', into a rock which now behaves like an eruptive, but in which we still observe so much of the bedded structure of the leptite that it is obvious that at least a great part of the rock is simply a leptitic schist which has been 'ultra-metasomatically', if such an expression is allowed, changed to such a degree as to reach the stage of refusion."

Elsewhere, Sederholm¹ states that the opponents of the idea assert that anatexis "can be proven only if we are able to show gradations from unmelted to melted rocks in which the original chemical character has been retained". Though the latter assertion cannot be justified, Sederholm records a close approach to such an example in his description of a conglomerate, on the north-west shore of Viasholm in Pernå, which is composed of waterworn pebbles of basic rocks, mainly meta-andesites. Amongst these rocks there are some "which behave like eruptives, penetrating the neighbouring conglomerate, but are obviously only portions of the same rock which have undergone fusion" (loc. cit., p. 130). Moreover, a "part of the conglomerate has simply been 'refused' without any addition of granitic material" (p. 130). In this occurrence Sederholm finds that both mineralogically and texturally the paligenetic conglomerate is a cross between a metamorphic and an eruptive rock. From the closely similar chemical analyses of the conglomerate and the paligenetic conglomerate (op. cit., pp. 134 and 136), it appears that the process of anatexis involved, not addition of magma as such, but an introduction of alkalis, principally soda, into the conglomerate.

The Newry mobilized sediment is just such an example. It retains the chemical character of the local sediments with but small additions, the necessary additions amounting to no more than 3 per cent of the resulting rock.

Further reference may now be made to the high biotite content of both the mobilized sediment and the contact hornfels (p. 349). The biotite enrichment results from metasomatism and appears to be dependent (a) on introduction of alkalis, and possibly of alumina and iron, from the emanations, and (b) on introduction of magnesia as a result of a forward migration of magnesia from an interior zone of sediments already overcome by the transfusion process. Wegmann has recently noted such an origin for migrating magnesium in discussing the advance of frontal zones developing about growing regions of migmatization.²

As already noted Professor Bailey regards the mobilized sediment as contaminated igneous material. Since the mobilized sediment grades in the field to syenite, the latter should, on this hypothesis, represent the invading igneous material. Reference to Text-fig. 3 shows that if such were the case then the mobilized sediment would be equivalent to four parts syenite and twenty parts sediment. That

¹ J. J. Sederholm, *Bull. Géol. Comm. Finlande*, **58**, 1923, 128.

² C. E. Wegmann, *Geol. Rundschau*, **26**, 1935, 327 and 328.

is, the syenite would have "assimilated" five times its own bulk of sediment. Even if it be assumed that the sediment had the extreme composition of the analysed graywacke (which possibility is the most favourable to the hypothesis) the mobilized sediment would be equivalent to eighteen parts syenite and twenty parts sediment, and the syenite would have "assimilated" one and a ninth times its own bulk of sediment. Thus, when considered quantitatively, even Professor Bailey's interpretation leads to a conception of "soak", rather than of assimilation. It has, moreover, the disadvantage that the proportion of introduced material (17 to 47 per cent) is too great for the application of the same hypothesis to cases where the sedimentary bedding is retained, as on Rough Hill. On my own interpretation this difficulty does not arise, since only 3 per cent of material need be introduced.

The petrogenetic significance of the mobilized sediment is that it provides evidence of an arrested stage in the generation of magma. The idea which needs to be stressed is that the mobility implies, above all, a concentrated influx and liberation of energy. The resultant behaviour of the energized material does not, in itself, imply that the whole, or even the greater part, of the material came from the same magmatic source as the energy. There is no warrant for the generalization that magma necessarily originates only in the hidden depths.

(b) *The Two Monzonitic Series.*

Criteria which must be taken into account in considering interpretations of the two monzonitic series include:—

(a) The parallel development of the respective rock sequences, as seen in the field (see Text-fig. 1), within the biotite-pyroxenite and biotite-peridotite series.

(b) The internal gradational characteristics of the two series (involving field relations and both mineralogical and chemical composition), and the extension of the gradation at the felsic end through mobilized sediment to hornfelsed sediment.

(c) The conspicuous crystalloblastic character of the two series.

(d) The similarity of the textures to those exhibited by migmatites, on Rough Hill, which have arisen through the soaking of augite-biotite-diorite "magma" into hornfelsed sediments (1934, p. 612).

Judged by these criteria, the two following interpretations (suggested by two of the petrologists who visited the area last year), to which more detailed references have already been made under appropriate headings, appear to be untenable:—

(1) Crystallization differentiation of basic magma, coupled with reactions due to migrating residual melt on early-formed crystals, and followed by contact metamorphism (see Bailey, 1936, p. 270). Crystallization differentiation is incompatible with the existence and distribution of the two monzonitic series, to say nothing of the

existence and distribution of the associated augite-biotite-diorites. It fails also to account for the variation of the minor constituents (see p. 349 and Text-fig. 3) and for the crystalloblastic textures. In turn, the latter cannot be explained either by corrosion due to migrating residual melt (p. 347) or by baking due to contact metamorphism (p. 346).

(2) Hybridization of peridotite, pyroxenite, and gabbro by later acid magma. The chemical and other objections to this hypothesis have been reviewed on p. 354.

The interpretation which I adopt is essentially one of cumulative pyrometasomatism of the invaded sedimentary rocks by the ultrabasic magmas, with accompanying introduction of energy, possibly in sufficient quantity to lead locally to the generation of magma (*magma* of Reinhard). The rising of successive gaseous phases from biotite-pyroxenite and biotite-peridotite magmas into the country rocks would readily account for the distribution of rock-types in the area of Seeconnell hybrids. The rising, at an early stage, of emanations rich in alkalis and alumina, both through and beyond the ultrabasic magma, would account both for (a) the differentiation of the ultrabasic magma with development of biotite-peridotite and biotite-pyroxenite in its upper parts, and (b) the feldspathization (syenitization) of the country rocks (see Text-fig. 8). If this process were followed by the passage into the country rocks of magmatic material rich in calcic constituents, in the one case from biotite-pyroxenite magma and in the other from biotite-peridotite magma, then two parallel monzonitic series with differences such as those actually observed, would necessarily result. To quote Fenner¹ :—

“According to a simple principle of thermodynamics, in a system consisting of solid, liquid, and gas, if the solid and liquid are in equilibrium, also the liquid and gas, then the solid and gas must be in equilibrium. . . .

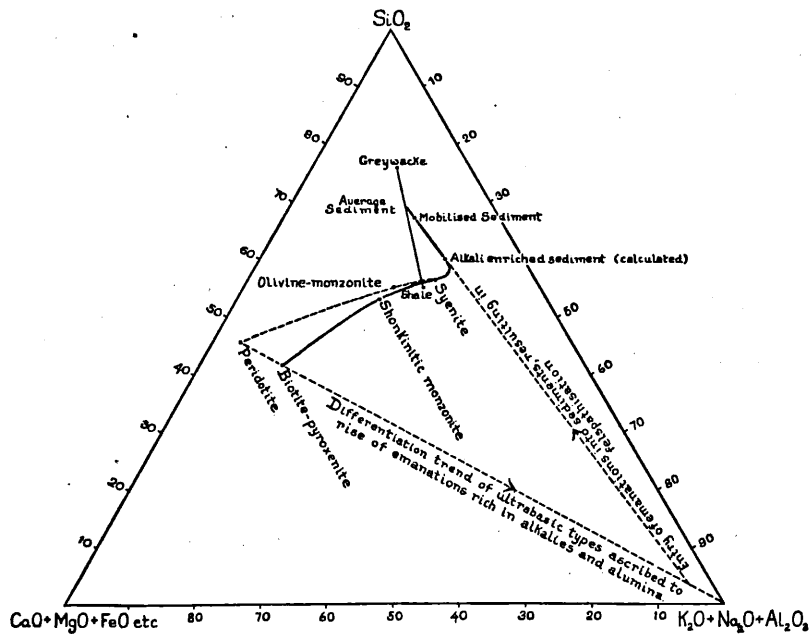
“With reference to actual magmas and the minerals formed by gases escaping from them, these principles have important applications. It is apparent that modifications of the ideal system are required, but there should be a strong tendency to reproduce in the contact rocks the same minerals that are crystallizing in the magma.”

In Text-fig. 8 the two successive, but possibly overlapping stages (a) introduction of alkalis and alumina, and (b) introduction of calcic constituents, are diagrammatically illustrated for the biotite-pyroxenite series by the sharp bend in the line connecting *sediment—mobilized sediment—syenite—shonkinitic monzonite*. Two similar stages can also be recognized on the diagram for the biotite-peridotite series. It should perhaps be emphasized that no member of either series is regarded as a simple mixture of biotite-pyroxenite or biotite-peridotite and sediment. Indeed, comparison of the chemical

¹ C. N. Fenner, “Pneumatolytic Processes in the Formation of Minerals and Ores,” in *Ore Deposits of the Western States*, Lindgren Volume, 1933, 80–81.

analyses suggests that the mafic constituents were themselves introduced differentially. The two successive stages referred to are comparable to those recognized by Quirke and Collins¹ in the Killarney area. There it is shown that the process of conversion of sediment to granite was one of feldspathization, followed up and accompanied by the introduction of ferromagnesian-forming substances, in the later stages.

As already indicated (page 359), it is believed that the process of transfusion culminates in the development of magma. This



TEXT-FIG. 8.—Triangular diagram to illustrate the chemical relationships of the two monzonitic series of the Newry Complex.

belief is based (a) on the igneous habit of the mobilized sediment, which represents only an early and arrested stage in the process, and (b) on evidence of the development of syenite magma resulting from the process of feldspathization of quartzite in Colonsay.² At the time when crystallization began, or was already in progress, any magma so formed might be homogeneous or inhomogeneous, according to the temperature and time factors. If, at the requisite temperatures, there was insufficient time for complete mixing of

¹ T. T. Quirke and W. H. Collins, *Geol. Surv. Canada Mem.*, **160**, 1930, 54-5.

² D. L. Reynolds, *Min. Pet. Mitt.*, **46**, 1935, 460.

the mafic and felsic portions to be accomplished, an inhomogeneous magma of the nature of a temporary emulsion would result. Evidence of such inhibited mixing, an account of which is in preparation, has been found in Colonsay. The tendency to establish equilibrium might, in such cases, persist into the period of crystallization, and early-formed mafic minerals might then be attacked by the felspathic or quartzo-felspathic magma, which, having a lower range of crystallization temperatures, could originate even while mafic minerals were crystallizing, and, if formed, would certainly remain fluid for a longer time.

In conclusion, I gratefully acknowledge a grant from the Government Grant Committee of the Royal Society out of which the cost of chemical analyses has been defrayed. I wish also to place on record that the conclusions outlined in this paper have been reached in co-operation with Professor Arthur Holmes. We feel some confidence in maintaining them because they are closely interlinked with the results of other investigations on which we are engaged.

APPENDIX: REPLY TO PROFESSOR E. B. BAILEY.

After this paper had been submitted to the GEOLOGICAL MAGAZINE, Professor Bailey's *Memorandum*, which had previously been circulated, was published (GEOL. MAG., 1936, pp. 267-70). The more important points raised in the *Memorandum* had already been reviewed in the paper. By the courtesy of the Editors I am permitted to add the following systematic reply to Professor Bailey's remarks, in order to deal with those which find no place in the discussions of the preceding pages. The numbering of the paragraphs that follow correspond to those of the *Memorandum*. References to the original Newry paper (*Quart. Journ. Geol. Soc.*, 1934) are made by year and page; references to the present paper are made by page only.

1. For a discussion of the evidence and interpretation of the "contact zone" and "marginal breccia", to which I refer under the term *mobilized sediment*, see pp. 348 and 355 et seq.

Professor Bailey's reference to the Rough Hill area is to migmatites which contain hornblende porphyroblasts. I agree that the rocks in question are essentially igneous in composition, but I infer from their retention of bedding that they were developed from sediment, and therefore consider that they resulted from intimate soak.

2. (a) As pointed out on p. 356 et seq., examples are already known which prove that metasomatic introductions may so thoroughly mobilize the invaded material as to allow the latter to simulate the appearance of normal igneous intrusion. The fact that the party were not agreed as to whether the material in question was an "igneous vein" or a metasomatized portion of the graywacke (i.e. of the sedimentary raft), itself emphasizes that transitions from sedimentary to igneous rocks occur.

(b) What Professor Bailey regards as pseudomorphs after olivine are aggregates of small granules of diopsidic augite and rhombic

pyroxene, associated with biotite, iron ore, and apatite (1934, p. 615). I know of no evidence that would suggest the possibility that these aggregates might be pseudomorphs after olivine. Professor Bailey was repeatedly asked if there was any such evidence; from the vague replies, and the absence of any reference to such evidence in the *Memorandum*, it appears that his interpretation is based on a purely personal impression. See under paragraph 6 for further remarks on alleged pseudomorphs after olivine.

3. None of the rocks in the area under discussion are gabbro-diorites. The rock to which Professor Bailey specifically refers is the analysed augite-biotite-diorite (1934, p. 611). As pointed out on p. 337, it is an undersaturated essexitic gabbro of petrological affinities very different from those of the gabbro-diorites. The other rocks belong to shonkinitic and monzonitic types, as already shown in the preceding pages. Professor Bailey was referred last autumn to Tröger's *Kompendium*, 1935, p. 146, for a survey of gabbro-diorites. Nevertheless, nine months later he still repeats the original error.

I do not understand what Professor Bailey means by his statement that biotite-pyroxenite is "not fully represented in Argyll". It will, however, suffice to point out that the type is already known from Colonsay, Glen Orchy, Kentallen (recently found by Mr. R. M. Laurie), and just over the boundary beyond Loch Shiel; everywhere with associates similar to those of the Newry Complex, though generally less conspicuously potassic.

4. The felspathic types referred to occur only in the biotite-pyroxenite and augite-biotite-diorite, and so far as field observation is concerned there is no disagreement.

5. My interpretation of the augite-biotite-diorite was based on the evidence of intricate and nebulous veining of the biotite-pyroxenite by plagioclase (essentially). The pegmatite vein to which Professor Bailey refers towards the end of paragraph 5 has no bearing on this question. It is obviously of later introduction and as such received separate description in the Newry paper (1934, pp. 592 and 625).

Professor Bailey's positive statements *re* slowly crystallizing magmas relate to an unproven hypothesis and not to proven fact. It is obviously impossible to know—as Professor Bailey claims to—that the Newry exposures are "exactly analogous to those shown by many slowly crystallizing magmas" which have behaved in the hypothetical manner he imagines. His references to Mull and the veins in quartz-dolerites are, in fact, references to his own opinions and not to relevant evidence. This has already been clearly demonstrated by Professor Holmes (*GEOL. MAG.*, 1936, p. 228), who shows that Professor Bailey's opinions are inconsistent with (a) mechanical fact; (b) the physico-chemical principles of crystallization differentiation established by the work of Bowen and his colleagues; and (c) field associations.

Such evidence as directly bears on the origin of the quartz-dolerite leucocratic veins is indeed in favour of what Professor Bailey states to be in his opinion impossible. Falconer (to whom Professor Bailey refers me) in describing such micropegmatite veins and interstitial portions in the Linlithgow quartz-dolerite sills notes (a) that "in places peculiar ragged portions of quartz occur in the midst of linear micropegmatite and simulate very closely corrosion effects" and (b) that "The amount of quartz increases, as a rule, towards the centres of the interstitial spaces, and angular fragments or irregular portions of the same mineral are frequently found embedded in the linear micropegmatite". In the gabbro sills of the north shore of Lake Huron, leucocratic patches, which are richer in felspar than the normal rock, have been shown by Collins to result from diffusion of various constituents from the gabbro-magma into xenoliths of quartzite (W. H. Collins, *Geol. Surv. Canada, Mem.* **143**, 1925, p. 80; and *Rep. XVI Int. Geol. Cong.*, Washington (1933), 1935). Recently Mountain (*Trans. Geol. Soc. South Africa*, **38**, 1936, pp. 93-112) has described the transformation of Table Mountain Sandstone into granophyre occurring as veins in an olivine-dolerite sill of Karroo age; the evidence is conclusive. Professor Holmes and I have found equally conclusive evidence of the transformation of quartzite into leucocratic veins occurring in "epidiorite" sills near Malin Head.

6. The question of the origin of the "ragged augites" is fully discussed on p. 347.

Professor Bailey claims to have "found that pseudomorphs after olivine (some may be after hypersthene) are common, though not interpreted as such". He regards as pseudomorphs after olivine not only the pyroxene granules mentioned under paragraph 2 (b) of this appendix, but also "aggregates of a pale actinolitic hornblende" and "aggregates of actinolite associated with iron-ore". I do not know why he should think that these actinolitic aggregates represent olivine; he produced no evidence. Presumably the argument is that since Becke found olivine inside pilitite, therefore every aggregate of acicular amphibole, even though it is not observed to be associated with olivine or to have the form of olivine, must nevertheless be pseudomorphous after olivine. It may, however, be pointed out that actinolite aggregates similar to those in the Newry rocks occur in the Ducktown area as metasomatic replacements of quartz (C. S. Ross, *U.S.G.S., Prof. Paper*, **179**, Plate 10 C). The only evidence in the Newry area which relates to the origin of actinolite aggregates is that the latter are sometimes seen to be replacing diopside (1934, p. 615).

In the olivine-monzonite every stage of replacement of olivine by serpentine is represented from 100 per cent olivine to 100 per cent serpentine; the correlation between olivine and serpentine pseudomorphs is therefore complete. There is, however, no correlation whatsoever between olivine (or its form) and either the clusters

of pyroxene granules or the actinolitic aggregates. Incidentally, it may be pointed out that if there were evidence that the minerals under discussion replace olivine, this would in no way vitiate my interpretation of the rocks. I cannot agree with Professor Bailey that there is any necessity to "assume" that olivine has crystallized from a melt. Both forsterite and fayalite are well known in contact zones and, so far as I know, nobody believes that forsterite-marble, for example, crystallized from a melt. It is necessary to judge each rock on its own merits. Relevant evidence relating to the Newry olivine-monzonite is discussed in the preceding pages.

7. For a detailed discussion of the points raised under paragraph 7 see the description of quartz vermicules in felspar, to which Professor Bailey refers as "abundant micropegmatite", on p. 340. See also Plate V, and the analysis, norm, and mode of the olivine-monzonite listed under D in Tables I and II.

8. There is no evidence whatsoever in the area of the conversion of amphibole into granules of enstatite or of any other pyroxene.

For a description and discussion of cloudiness in felspars of the Newry rocks, see p. 341, where it is shown that the cloudiness is not referable to contact alteration.

9. Professor Bailey states, "I am of opinion that the basic rocks at the east end of the Newry complex are full of illustrations of differentiation by crystallization coupled with the necessary concomitant reactions." The facts with which this opinion is inconsistent are summarized on p. 358. Here, perhaps, it may be emphasized that the adverse comments made by Professor Bailey do not amount to scientific criticism since they are only expressions of his opinions, feelings, and expectations.

I do not need to be reminded of Dr. Bowen's work, for which I have a great admiration and to the stimulus of which I should like to pay tribute. I am, however, aware that many phenomena have been recorded which are incompatible with crystallization differentiation; that there is a growing literature on the metasomatic origin of rocks of igneous composition; and that we are still a long way from being able to formulate any general principles of igneous rock genesis.

EXPLANATION OF PLATE V.

FIG. 1.—Olivine-monzonite, No. 337, from Slievenisky, north-east corner of the Newry Complex. $\times 43$. The mineral on the left of the field is olivine, fringed with a corona structure in which there is an inner zone of rhombic pyroxene and an outer zone of biotite. Crystals of apatite are associated with the corona. The right of the field shows soda-potash felspar riddled with vermicular quartz. The black patch at the top of the field is biotite and iron ore.

FIG. 2.—Part of Fig. 1 more highly magnified. $\times 210$. The crystal to the upper left of the field is the apatite just above the centre of Fig. 1. The detail of the symplektite shows (a) the minute size of the quartz vermicules; (b) the presence of acicular iron ore cutting through both quartz and felspar; and (c) the crystalloblastic character of the corona, the biotite fibres of which (seen below the apatite) penetrate the symplektite.



FIG. 1.

× 43

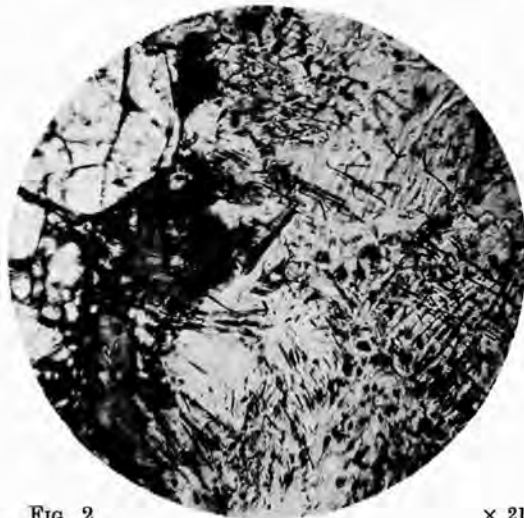


FIG. 2.

× 210

G. W. O'Neill Photo.

QUARTZ-FELSPAR SYMPLEKTITE IN OLIVINE-MONZONITE

[Extracted from the GEOLOGICAL MAGAZINE, Vol. LXXIII,
December, 1936, pp. 560-562.]



No 3.

THE AUGITE-BIOTITE-DIORITE OF THE NEWRY COMPLEX

SIR,—In the October number of the GEOLOGICAL MAGAZINE Professor Shand takes exception to certain statements of mine about the rocks of Slievegarron, which I have called augite-biotite-diorite. Before proceeding to discuss the main point at issue, I frankly confess to an error of omission. My statement that the analysed rock is “undersaturated”, to which Professor Shand rightly objects, should, of course, have read “normatively undersaturated”. That the rock really is undersaturated in this chemical sense is shown by the appearance in the norm of 6.25 per cent. of nephelite and 15.73 per cent. of olivine. I cannot, however, resist the temptation to point out that in the very act of protesting Professor Shand commits a precisely similar offence. He refers to augite-biotite-diorite as “diorite”, which it certainly is not. Fortunately the matter is less serious than if a chemist referred to nitro-glycerine as glycerine.

The real question is that of the name which should be given to the rock under discussion. The rock is the predominant member of a series which ranges from biotite-pyroxenite to andesine-rich types. Mineralogically, it is accurately described as *augite-biotite-diorite*, since in addition to augite and biotite the essential minerals are andesine and hornblende.

Although one-quarter of the rock is made up of biotite and the plagioclase is An_{35} , the rock becomes a soda gabbro in Professor Shand's classification. Perhaps the incongruousness of a *potash* soda gabbro leads Professor Shand to desert the facts and agree with Professor Bailey “that gabbro-diorite is the most appropriate name for the rock”. It is very easy to show that the

rock is not a gabbro-diorite. In Tröger's *Kompendium*, p. 146, we learn that the term gabbro-diorite was introduced by Törnebohm for normal gabbro with uralitic hornblende, and that by later authors it has been adopted both for plagioclase-rich gabbro (= ossipite) and for rocks which chemically and mineralogically stand midway between diorite and gabbro. The augite-biotite-diorite of Slievegarron is demonstrably none of these things. It is not a normal gabbro for its plagioclase is An_{35} ; it is not plagioclase-rich, for it actually contains less plagioclase than typical gabbro; and far from standing between diorite and gabbro it stands, both chemically and mineralogically, between plagioclasite and biotite-pyroxenite. Obviously the rock is not a gabbro-diorite, and the very modes cited by Professor Shand show that it is not, though by failing to quote the figures for biotite he hides the real contrast. Yet Professors Bailey and Shand, both members of the B.A. Committee on Petrographic Classification and Nomenclature, not only pronounce the rock to be a gabbro-diorite, but go out of their way to proclaim their opinion to the world.

The Slievegarron rocks under discussion do not differ from gabbro in the direction of diorite, but in the direction of alkali-rich gabbro. The suggestion that they might be described as biotite-essexite-gabbro was intended to emphasize this alkaline character of the rocks, with a view to drawing attention to a significant difference from gabbro-diorite. The suggestion arose from the observation that texturally, as well as mineralogically and chemically, the rocks bear a remarkable resemblance to others which have been described as essexite or essexite-gabbro. It may be noted in passing that the term essexite does not exclude andesine, and that a rock is none the less alkaline because a considerable proportion of its alkali is potash. Chemically, the rock falls comfortably into Niggli's essexite-gabbro magma group, as the following figures show:—

	<i>si</i>	<i>al</i>	<i>fm</i>	<i>c</i>	<i>alk</i>	<i>k</i>	<i>mg</i>
Augite-biotite-diorite .	114.5	23	43	21.5	12.5	.30	.61
Essexite-gabbro magma	105	23	43	24	10	.25	.45

Niggli himself points out that in the gabbro-diorite magma group the *si* values are higher (average 135) and the *alk* values (for corresponding values of *si*) lower than in the essexite-gabbro magma group. Here is further proof that the augite-biotite-diorite is not a gabbro-diorite.

A biotite-augite-diorite from Predazzo is precedent for the term augite-biotite-diorite, and it may be noted that although the Predazzo rock is considerably less rich in alkalis (Slievegarron, 6.31; Predazzo, 4.36 per cent.), yet it also falls into Niggli's essexite-gabbro magma group. Professor Shand does not give any reason for objecting to my use of the name augite-biotite-diorite. The only one I can think of which he may have had in mind is that the rock contains more than 30 per cent. of coloured minerals, and so lies

outside the group of rocks which he calls "soda diorite". As to this it is only necessary to remark that the rock has not been called "soda diorite", and that the artificial limitation which applies to "soda diorite" does not by any means apply to diorite or to augite-biotite-diorite.

As to the meaning which I attach to the term augite-biotite-diorite, I think I have explained this as clearly as even Professor Shand could wish by providing a detailed description of the rock, accompanied by a mode, a chemical analysis, a norm, and a figure. If Professor Shand or any other "student of rock names" objects to the term because of the relatively high proportion of mafic minerals, and to the alternative "biotite-essexite-gabbro" because the alkali mineral is biotite instead of nepheline or aegirine, then there will be an obvious case for coining a new name.

DORIS L. REYNOLDS.

THE UNIVERSITY,
DURHAM.
10th October, 1936.

Überreicht vom Verfasser

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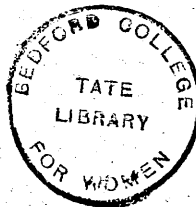
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The Genetic Significance of Biotite-Pyroxenite
and Hornblendite.

By DORIS L. REYNOLDS (Durham, England).

With 1 figure.



LEIPZIG 1935

AKADEMISCHE VERLAGSGESELLSCHAFT M. B. H.

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PART I.

I. Introduction.

A recent investigation of the eastern end of the Newry Igneous Complex, Co. Down, Ireland [51], has revealed field and petrological evidence that the parent magmas were ultrabasic, being now represented by biotite-pyroxenite and biotite-peridotite. The ultrabasic magma rose by soaking into the sediments and at the same time gave off emanations rich in alkalis. As a result it was preceded by a zone in which the sediments were felspathised. The hybrids, developed by the felspathisation of the sediments and their subsequent soaking with biotite-pyroxenite magma, form a graduated series shonkinitic monzonite — monzonite — syenite. Closely related types occurring in the area are hypersthene-monzonite, augite-biotite-diorite, hypersthene-diorite, and granodiorite.

In view of this discovery and the fact that during the last few years biotite-pyroxenite and allied ultrabasic types (including hornblendite) have been described from several widely spread localities, in which the associated rocks are also similar, it seems desirable to set on record the collective information now available for this group and to indicate its genetic significance. Biotite-pyroxenites and biotite-peridotites from most of these localities are well represented by specimens in the collection of the Geology Department of the Durham Colleges, England, and the writer is indebted to Professor ARTHUR HOLMES for putting these at her disposal and for allowing her to use a number of analyses, hitherto unpublished.

II. The Biotite-pyroxenite Series.

The biotite-pyroxenites form part of a series which ranges from potash-peridotites having only a slight excess of potash over soda, through peridotites which contain variable amounts of biotite to biotite-pyroxenite itself. Even in the latter there is variation, in that the percentage of biotite may increase to such an extent that the rock becomes a pure biotite (glimmerite), or decrease until it is almost negligible so that the resulting rock is a pyroxenite, with only a slight excess of potash over soda. In order to save a tiresome repetition of names, this series will be referred to in later sections of this paper by the letters B. P.

Members of the B. P. series are now known as intrusive rocks in eleven localities, the details being as follows:

Scotland.	Ross-shire [21] and Caithness [34]	Scyelite.
	Loch Ailsh, Sutherlandshire [45]	Biotite-pyroxenite.
	Central and Southern Sutherland (Hybrids of Ach'uaire) [48, 49, 50]	Scyelite and biotite-pyroxenite.
	Argyllshire (including Colonsay) [15, 17, 36, 52]	Olivine-biotite-pyroxenite.
Ireland.	Newry complex, Co. Down [51]	Biotite-pyroxenite and biotite-peridotite.
England.	Malverns ¹⁾	Biotite-pyroxenite.
Canada.	Rosland area, British Columbia [18].	Olivine-biotite-pyroxenite.
United States	Libby stock, Montana [38]	Pyroxenite, Biotite-pyroxenite and biotite.
	Cortlandt series, near Peekskill, New York [55].	Biotite-peridotite and biotite-pyroxenite.
Italy.	Predazzo and Monzoni [9].	Biotite-pyroxenite and olivine-biotite-pyroxenite.
India.	Raniganj coalfield [22].	Mica-peridotite (olivine biotite-pyroxenite).
Ceylon.	Central, Uva and Sabaragamuwa Provinces [14].	Biotite-pyroxenite

In addition, biotite-pyroxenite is known as ejected blocks at the following localities.

Italy.	Mte. Somma [37]. Soccavo, Vallone, Phlegrian Fields [41]. Villa Senni, Alban district [60]. Mte. Vulture [41], Scarrupata, Ischia [53].
Uganda.	Many of the explosion craters and volcanoes of the Toro-Ankole and Bufumbira ²⁾ districts [31].
Upper Burma.	Wunbo, Lower Chindwin District [12].

Petrologically the various members of the series show striking similarities and only biotite-pyroxenite itself requires description in detail. The biotite-pyroxenites all contain monoclinic pyroxene and biotite, with apatite (not observed in the Burma occurrence) and iron-ores as accessories, whilst many are olivine-bearing. At the Villa Senni there is sometimes a little interstitial leucite, whilst melanite is recorded from Uganda and the Libby stock. A brownish hornblende is frequently present: e. g. in the biotite-pyroxenites of Loch Ailsh and Newry. Sphene is recorded from the Loch Ailsh and Uganda occurrences.

¹⁾ Privately communicated by Prof. A. BRAMMALL.

²⁾ Privately communicated by Prof. A. HOLMES.

Analyses of Biotite-pyroxenites.

	1	2	2	4	5	6	7
SiO ₂ . .	41.71	45.94	40.73	37.78	44.81	44.68	47.41
Al ₂ O ₃ . .	8.55	10.42	6.29	11.83	7.42	4.82	6.39
Fe ₂ O ₃ . .	2.51	1.72	10.29	2.46	2.94	5.91	7.06
FeO . . .	9.79	6.05	8.89	4.34	8.89	2.78	4.80
MgO . . .	14.65	15.88	12.17	11.22	16.81	15.52	15.34
CaO . . .	11.74	11.89	14.82	15.31	11.16	15.23	14.32
Na ₂ O . . .	0.6	0.74	0.87	0.62	0.65	0.45	0.69
K ₂ O . . .	3.65	3.80	2.25	4.29	2.50	2.63	1.40
H ₂ O ⁺ . .	1.41	2.38	0.43	1.24	1.26	1.50	2.10
H ₂ O ⁻ . .	0.16	0.40	0.04	0.15	0.19	1.94	—
CO ₂ . . .	0.16	0.41	0.17	7.8	0.10	0.07	—
TiO ₂ . . .	2.15	0.41	2.86	1.93	2.26	1.62	—
ZrO ₂ . . .	—	—	—	—	—	—	—
P ₂ O ₅ . . .	1.62	0.12	0.19	0.53	0.80	2.01	—
Cl	0.01	—	trace	—	0.07	0.11	—
F	0.16	0.08	0.00	—	0.12	0.14	—
S	0.03	0.03	0.00	—	0.17	0.03	0.49
Cr ₂ O ₃ . .	0.04	0.03	0.00	0.19	0.10	0.04	—
V ₂ O ₃ . . .	0.06	0.08	0.00	0.02	0.06	0.06	—
NiO	0.04	0.01	0.00	—	0.01	0.07	—
MnO	0.24	0.13	0.41	0.41	0.18	0.11	—
SrO	0.04	none	—	—	0.15	0.10	—
BaO	0.5	0.22	0.01	0.00	0.12	0.07	—
Li ₂ O . . .	trace	trace	0.00	—	—	—	—
Total . . .	99.82	100.83 ¹⁾	100.42	100.22 ²⁾	100.77	99.89	100.00

1. Biotite-pyroxenite. Newry Complex, Seeconnell, Co. Down, Ireland. Analyst L. S. THEOBALD [51, p. 608].
2. Biotite-pyroxenite. Upper Wych, Malvern Hills, England. Analyst A. W. GROVES. (The writer is indebted to Prof. A. BRAMMALL for permission to use this analysis.)
3. Biotite-pyroxenite. Loch Ailsh Mass. Near Benmore Lodge, Sutherlandshire, Scotland. Analyst E. G. RADLEY [45, p. 66, analysis 1].
4. Biotite-pyroxenite. 'Basic hybrid of Ach'uaine type'. Near Ach'uaine, Sutherland, Scotland. Analyst E. G. RADLEY [49, p. 163, analysis 1].
5. Olivine-biotite-pyroxenite. Near Christina Lake, 2 miles N. of Fife Railway Station, Rossland District, British Columbia. New analysis by Messrs. I. C. I. Ltd., Research Dept., Billingham, Co. Durham, England.
6. Biotite-pyroxenite. Libby Stock, Montana. New analysis by Messrs I. C. I. Ltd. Research Dept., Billingham, Co. Durham, England.
7. Augite-peridotite. Montrose Point, Cortlandt Area, New York. Analyst W. H. EMERSON. (G. H. WILLIAMS, Am. J. Sci. **3**, 32, 40.)

¹⁾ incl. CuO = 0.09.

²⁾ incl. FeS₂ = 0.1.

Analyses of Biotite-pyroxenites.

	8	9	10	11	12	13	14
SiO ₂ . .	41.30	45.11	48.34	44.49	43.35	44.83	38.9
Al ₂ O ₃ . .	5.19	9.86	5.68	8.72	9.67	8.82	6.83
Fe ₂ O ₃ . .	14.39	6.65	2.30	4.54	5.26	2.56	4.53
FeO . .	9.07	1.57	3.45	4.55	2.65	3.14	4.73
MgO . .	10.16	15.51	17.33	12.38	15.74	18.00	16.92
CaO . .	14.73	12.06	19.90	17.81	12.20	13.81	10.95
Na ₂ O . .	0.54	1.43	0.61	0.80	0.44	2.15	0.36
K ₂ O . .	1.33	5.14	1.39	2.42	4.74	3.72	4.42
H ₂ O ⁺ . .	0.84	1.03	0.27	0.68	0.59	1.34	2.35
H ₂ O ⁻ . .	—	0.06	0.07	0.03	0.07	0.02	0.89
CO ₂ . .	0.18	—	—	—	0.04	0.43	1.55
TiO ₂ . .	2.01	1.52	0.66	2.26	4.38	1.06	4.78
ZrO ₂ . .	—	—	—	—	none	—	—
P ₂ O ₅ . .	trace	0.08	0.09	0.77	trace	0.12	1.42
Cl . . .	—	—	trace	—	trace	—	0.07
F . . .	—	—	—	—	0.11	—	0.05
S . . .	—	—	—	—	trace	—	0.04
Cr ₂ O ₃ . .	—	0.11	—	—	0.05	—	0.06
V ₂ O ₃ . .	—	—	—	—	0.04	—	0.03
NiO . .	—	—	—	—	0.04	—	0.07
MnO . .	0.20	0.15	—	0.10	0.09	0.07	0.11
SrO . .	—	trace	—	—	none	—	0.33
BaO . .	—	0.08	—	—	0.30	—	0.35
Li ₂ O . .	—	—	—	—	trace	—	—
Total . .	99.94	100.36	100.09	99.55	99.79 ¹⁾	100.07	99.82 ²⁾

8. Biotite-pyroxenite. Malgola, Predazzo, Tyrol. Analysts DITTRICH and POHL. (J. ROMBERG, *Anh. Abh. Preuß. Akad. Wiss.*, p. 67. 1904.)
9. Biotite-pyroxenite. Ejected block. Mte. Somma, Italy. Analyst E. NARICI [41, p. 233].
10. Biotite-pyroxenite. Ejected block in tuffs. Soccavo, Vallone, Phlegrian Fields, Italy. Analyst E. NARICI [41, p. 227].
11. Biotite-pyroxenite. Villa Senni, Alban district, Italy. Analyst MARY G. KEYES [60, p. 187].
12. Biotite-pyroxenite. Ejected block. Lutale Crater, Bufumbira Volcanoes, Uganda. Analyst H. F. HARWOOD. (New analysis by courtesy of Prof. A. HOLMES and Prof. H. F. HARWOOD.)
13. Biotite-pyroxenite. Wunbo, Lower Chindwin, Upper Burma. Analyst S. PARKER [12, p. 329, analysis 5].
14. Biotite-pyroxenite. Aldihi Colliery, Raniganj Coalfield, India. New analysis by Messrs I. C. I. Ltd. Research Dept., Billingham, Co. Durham, England.

1) incl. CuO = 0.03.

2) incl. CuO = 0.08.

Analyses of Biotite-peridotites.

	15	16	17	18
SiO ₂	43.56	46.0	45.91	47.33
Al ₂ O ₃	3.06	6.8	3.51	6.84
Fe ₂ O ₃	3.59	3.0	2.11	0.02
FeO	3.80	7.5	9.73	5.62
MgO	31.32	23.9	19.42	19.31
CaO	3.57	8.1	14.28	16.99
Na ₂ O	0.29	0.8	0.31	0.41
K ₂ O	1.31	0.9	0.58	0.88
H ₂ O ⁺	7.04	} 2.4	1.42	0.55
H ₂ O ⁻	0.14		0.11	0.21
CO ₂	1.31	—	0.45	0.02
TiO ₂	0.37	—	0.72	1.26
ZrO ₂	—	—	—	none
P ₂ O ₅	0.02	—	1.00	0.21
Cl.	—	—	0.02	trace
F	none	—	—	0.01
S	—	—	trace	trace
Cr ₂ O ₃	0.25	0.2	0.10	0.32
V ₂ O ₃	—	—	0.03	0.04
NiO	0.02	—	0.06	0.04
MnO	0.19	—	0.26	0.12
SrO	—	—	none	none
BaO	none	—	0.08	0.03
Li ₂ O	none	—	none	trace
Total	100.16 ¹⁾	99.6	100.10	100.22

15. Scyelite. Boss in Moine Series. Shore of Loch Shin, near Overscaig Hotel, Sutherland, Scotland. Analyst B. E. DIXON [50, p. 168].
16. Enstatite-diallage-hornblende-biotite-olivine rock. Garabal Hill Complex. Analyst PLAYER [17, p. 115].
17. Biotite-peridotite. Newry Complex, Crocknafoyle, Co. Down, Ireland. Analyst L. S. THEOBALD [51, p. 605].
18. Biotite-bearing Peridotite. Ejected block. Mabungo Crater, Bufumbira Volcanoes, Uganda. Analyst H. F. HARWOOD. (New analysis by courtesy of Prof. A. HOLMES and Prof. H. F. HARWOOD.)

The pyroxene is always a member of the diopside-hedenbergite series and varies in the different localities from pale to deep green. It not infrequently contains minute rod-like inclusions of titaniferous iron-ore, with a zonal distribution. The biotite is deeply coloured, dark-brown or foxy-red, and is strongly pleochroic. The ratio of

¹⁾ incl. FeS₂ = 0.32.

pyroxene to biotite varies, so that there is every gradation from a nearly pure pyroxenite to biotite (glimmerite), the latter occurring in the agglomerate at the Villa Senni, in Uganda, and in the Libby stock. The wide range in the relative proportions of pyroxene and biotite not only becomes evident in a survey of biotite-pyroxenites from different localities but is sometimes equally exhibited in individual occurrences, e. g. in the Libby stock, where there is a variation from a nearly pure pyroxene-rock to a nearly pure biotite-rock, although the prevalent type is pyroxene-rich, with 10 to 20 per cent of biotite, 10 per cent of apatite, and a little magnetite.

Apatite is the most notable accessory and frequently builds large prisms. At the Libby stock it sometimes forms as much as 15 per cent of the rock. The occurrence of apatite is rather sporadic in the rocks as a whole. Phemister remarks, in his description of the biotite-pyroxenite from Loch Ailsh, that "The distribution of apatite in the ultrabasic rock does not follow any apparent law. It may disappear entirely in one specimen and be extremely abundant in a section from a quite similar rock", and this seems to be generally true.

By the incoming of olivine, biotite-pyroxenite grades to biotite-peridotite, with which it is associated in the Newry area. There is also an association of biotite-pyroxenite and biotite-peridotite in the region of Predazzo-Monzoni and in the Cortlandt series. When present, olivine is always of early crystallisation and may be enclosed in either augite or biotite. From its optical characters it can usually be inferred that it contains about 10 per cent of FeO.

Texturally the rocks are all alike, consisting of a coarse intergrowth of pyroxene and biotite, in which the pyroxene has invariably completed its crystallisation first, being wrapped round by biotite. Biotite is also frequently present as small inclusions in the augite, arranged parallel to its cleavage. Where hornblende is present it wraps round the augite and, as already mentioned, in the olivine-bearing varieties the olivine is of early crystallisation.

That the rocks of the series show certain chemical similarities is evident from the table of analyses. Low SiO_2 and Al_2O_3 are combined with high MgO, CaO, and iron, whilst K_2O is high relative to Na_2O . Of the rarer constituents TiO_2 , P_2O_5 , and BaO are of first importance and notably high. SrO fluctuates greatly but is usually low; F is high and Cl and Li_2O are negligible; NiO fluctuates and Cr_2O_3 is lower and V_2O_3 higher than the average for igneous rocks.

III. The Origin of Biotite-pyroxenite.

The various members of the biotite-pyroxenite series represent rock magmas and cannot in any instance be regarded as accumulates of sunken crystals. That the mica-peridotites have existed as magmas is generally realised, but in the case of the less well known biotite-pyroxenites this statement perhaps requires exemplification.

In the Rossland area DALY [18, p. 337] records the olivine-biotite-pyroxenite as an irregular intrusion cutting the Baker gabbro, whilst in the case of the Libby stock, LARSEN and PARDEE [37, p. 98] describe the pyroxenites as the earliest of the intrusive bodies.

Judging from the textural features, PHEMISTER [45, p. 86], LACROIX [37, p. 210] and WASHINGTON [60, p. 193] all regard the biotite-pyroxenites they describe, from Loch Ailsh, Monte Somma and Villa Senni respectively, as representing rock magmas and in each case the author concludes that the biotite-pyroxenite is a deep-seated differentiate from an alkali-rich magma. The mode of differentiation is not discussed, however (except by BURRI and HUBER [12, p. 331]) and presumably all have in mind a deep-seated crystal differentiation followed by refusion.

The ejected blocks of biotite-pyroxenite from the Katwe Crater, Uganda are regarded by HOLMES [31, p. 408] as derivatives of mica-peridotite, in the liquid line of descent from a primary peridotite magma.

It is only in the Newry area [51] that there is, so far, any direct field-evidence bearing upon the origin of biotite-pyroxenite. The Newry Complex is situated directly north of the Mourne Mountains and biotite-pyroxenite is exposed at its eastern end in Co. Down, where it forms a sheet-like mass with a steep easterly dip. It outcrops over an area of approximately one-tenth of a square mile, but this is merely a relic of the earliest intrusion in the complex, the original horizontal extent of which was at least ten square miles, as judged from the distribution of isolated occurrences of derivative types and the distribution of the frequent xenoliths of derivative types in the later granodiorite. It is obviously only the result of a happy accident that any biotite-pyroxenite remains.

The temperature of the biotite-pyroxenite at the time of intrusion was sufficiently high to partially fuse the contact graywackes and shales, the more calcareous bands alone escaping. The biotite-pyroxenite-

nite magma rose partly by soaking into the zone of fusion, giving rise to shonkinitic monzonite, monzonite, and syenite with crystalloblastic textures, and partly by shouldering stress. The latter is evidenced by the way in which the strike lines of the invaded Silurian sediments leave the Caledonian trend and swing out round the margin of the complex, being cut only by the younger granodiorite. The biotite-pyroxenite was obviously intruded as a highly fluid magma at a high temperature and cannot, therefore, be regarded as due to the refusion of a depth accumulation of crystals. Its high degree of fluidity at the time of intrusion would be inexplicable on such a hypothesis. The ease with which it saturated the partly fused graywackes and shales is probably to be attributed to a high content of volatiles. Attention has already been drawn to the importance of TiO_2 and P_2O_5 in biotite-pyroxenite, a feature which can be interpreted as indicating that it is a liquid end-product of differentiation, standing in the same relation to potash-peridotite as pegmatite does to granite.

It will be shown in the following pages that migration of the alkalis plays a leading part in the genesis of rock types. The demonstrable ease with which the alkalis migrate suggests that the B. P. series as a whole represents a differentiate from primary peridotite, due to an enrichment in potash and alumina of the upper part of the intruding ultrabasic magma. Such an enrichment would result in the crystallisation of biotite in place of olivine. Missouriite, which is associated with the B. P. series in the agglomerate at the Villa Senni [60, p. 179], and occurs associated with hybrids of B. P. origin in the Highwood Mountains [46], probably represents an even more advanced stage of potash enrichment. The leucite-bearing biotite-pyroxenite in the agglomerate at the Villa Senni forms a connecting link between B. P. and missourite.

IV. Rocks Associated with Members of the B. P. Series.

From the accumulated data of various regions, it is evident that members of the B. P. series are frequently associated with other ultrabasic types. Hornblendite is a common rock associate, and all gradations can be found, by the incoming of hornblende, from B. P. to hornblendite. Cortlandtite may accompany the hornblendite. As already shown, pyroxenites are closely associated with biotite-pyroxenite. Some of them show their close connection in that they

contain a slight excess of potash over soda, whilst others are of the more normal type, in which there is a slight excess of soda over potash. By the incoming of olivine the pyroxenites grade to peridotites and even to pure dunite.

From an examination of a variety of areas, it becomes evident that whereas some rock types are closely connected with B. P. others are more closely connected with hornblendite. Varieties which frequently accompany B. P. include shonkinite, monzonite, hypersthene-monzonite, and syenite (Plauen type), whilst types more closely connected with hornblendite in their distribution include kentallenite, members of the appinite series (BAILEY [4, p. 167, 168]) hornblende-diorite, hornblende-gabbro, syenite rich in soda, and plagioclases consisting almost entirely of oligoclase, andesine, or labradorite. Rocks which are associated with both B. P. and hornblendite are biotite-gabbro, augite-biotite-diorite, hypersthene-biotite-diorite (sometimes termed norite), granite, adamellite, tonalite and granodiorite, with the lamprophyres as noteworthy hypabyssal representatives.

These rock suites are particularly characteristic of orogenic regions and the earlier and more basic varieties usually occur marginally in the 'granite' batholiths and as frequent inclusions in the acid rocks.

In the following pages it is hoped to show that the ultrabasic types represent the parent magmas and that the other rock varieties are due to syntexis of B. P. or hornblendite with sediments (including metamorphic varieties) which they have already feldspathised by their own advance emanations.

V. Hybrids due to Syntexis of Ultrabasic magma and Sediments.

Throughout the following discussion the term sediments is frequently used in a broad sense. It is intended to convey a rock type of sedimentary origin, although it may have suffered subsequent metamorphism. The sedimentary material, unless particularly specified, is a mixture of siliceous and muddy material, that is, an average sediment. Limestones are not considered. In the Newry area the evidence goes to show that the highly calcareous types are the least prone to attack. Relics of such bands remain as xenoliths of diopside-hornfels in hybrid types which have been developed almost in situ from a mixture of biotite-pyroxenite and more average sediment.

In the case of the B. P. and related magmas, high temperature combines with high vapour-content to make them a particularly sensitive and receptive type, so that by reaction with the invaded country rocks on the one hand and differentiation, due to migration of the alkalis, on the other, they are capable of giving rise to a great variety of different rocks. Indeed it is to the extreme sensitiveness of these magmas that the very rarity of B. P. and hornblendite themselves is to be attributed.

a) The Shonkinite—Monzonite—Syenite Series.

Shonkinite, monzonite and syenite form a series which is due essentially to the feldspathisation of sediment and its subsequent soaking by B. P. magma. The various members of the series may be formed in three different ways.

1. By the direct soaking of B. P. magma into sediments, an advance-guard of alkali emanations from the magma causing preliminary feldspathisation of the sediments. The latter process is due to the combination of alkalis of B. P. origin and alumina, of magmatic or sedimentary origin, with the quartz of the sediments, there being a resulting development of soda-orthoclase. This case is exemplified in the Newry area, where there is gradation from the intruding B. P. through shonkinitic monzonite and monzonite to syenite, which is developed in contact with the sediments.
2. By the invasion of B. P. by feldspathic magma as in the case of the 'basic knots' of Loch Ailsh [45, p. 89]. The feldspathic magma is essentially syenite and is itself to be attributed to reaction between ultrabasic magma and sediments.
3. By magmas developed in depth by processes similar to those stated in cases 1 and 2.

A discrimination between these three cases can be made by a study of the textures of the hybrid.

In case 1, when the rocks are the result of the soaking of B. P. magma into sediments, the textures are crystalloblastic. Augite, frequently accompanied by biotite, and sometimes by olivine, has grown in the interstices of the sediment from the invading magma in the manner of porphyroblasts. It forms large crystals in a matrix of sedimentary origin which is considerably finer in grain and consists of feldspar (mainly soda-orthoclase), a little quartz and frequently biotite.

The augite, owing to the fact that it has grown in a highly viscous or almost solid medium, has incorporated a certain amount of the latter and has, in consequence, developed a sieve texture and in general a highly crenulate margin [51, Fig. 9]. Some of the larger individuals, however, show perfect form, having acquired sufficient strength on growth to clear themselves of inclusions in an outer zone [51, Fig. 10]. The augite is usually well zoned and sometimes encloses small flakes of biotite arranged parallel to the cleavage traces. Biotite of magmatic origin also forms porphyroblasts and encloses the matrix to such an extent as to appear poikilitic. When olivine is present it is also porphyroblastic; it may be somewhat rounded but more frequently develops good form and does not exhibit the sieve texture so characteristic of the augite. The fine-grained matrix is gray in colour, with a hornfelsic aspect, and on a microscopic scale it retains textures characteristic of metamorphosed sediment. It differs from the sediments mainly in the substitution of soda-orthoclase for quartz. The rocks which exhibit these textures in the Newry area were termed Hybrids of Seeconnell type and this term will now be used in describing similar textures from other localities.

In case 1, as exhibited in the Newry area, there has been, in addition to the actual soaking of the sediments by B. P. magma, an advance migration of the alkalis from the B. P. into the sediments. Evidence of this alkali migration in the development of the series shonkinite—monzonite—syenite is found both analytically and in the field. A graphical subtraction of the analysis of the biotite-pyroxenite from that of the shonkinitic monzonite gives a result that corresponds well with an average of the analyses of the local graywacke and shale, except that the alkalis are high. There is also a greater relative increase in soda than in potash, although the percentage of potash present is higher than that of soda. In the field the rocks in question form a marginal zone between biotite-pyroxenite and sediments, and there is a gradation from biotite-pyroxenite through shonkinitic monzonite and monzonite to syenite, the latter being found in contact with the sediments [51, p. 613]. In the shonkinitic monzonite the ratio of B. P. to sediments is high. Here the potash from the invading magma was in excess of the amount necessary to form orthoclase in combination with the silica of the sediments and, as a result, porphyroblasts of biotite of B. P. origin

are present, in addition to sedimentary biotite. In the syenite very little of the B. P. magma is present and the development of soda-orthoclase is largely due to an enrichment of the sediments in alkalies by the vanguard of alkali emanations. In this case the biotite is entirely of sedimentary origin. The monzonites include all transitions between these two cases.

That a zone of enrichment in alkalies preceded the advancing magma, is evidenced by the noticeable rise in the percentage of biotite in the hornfels near the contact, and in the fact that the sediments margining the intrusion, which have been actually fused, show a considerable increase in the alkalies as compared with the normal graywacke and shale of the area, the increase being greater for soda than potash.

The conversion of sedimentary quartz to feldspar, by the addition of alkalies and alumina of magmatic origin, is not only characteristic of the Seeconnell type of hybrids in the Newry area, but is a change of widespread occurrence. Other notable instances are found in the feldspathisation of quartzite in Colonsay [15] and in the Glen Coe fault intrusion [4], and in the development of Killarney granite from Huronian quartzite [47] and of the marginal granite of the Cassia batholith from a similar pre-Cambrian quartzite [3]. In the Seeconnell hybrids the original hornfels textures are retained, the further change being merely a conversion of quartz to feldspar. The physical explanation of the change is probably to be found in the fact that the ratio of silicon (including the aluminium, which replaces it to some extent) to oxygen in feldspar is 1 : 2 as in quartz. The linkage of silicon-oxygen tetrahedra in the feldspars is also similar to that in quartz. Highly significant is the statement of TAYLOR, DARBYSHIRE and STRUNZ [56, p. 495] that "Quartz is built up by linking together puckered rings of six tetrahedra to form a continuous framework, and rather similar six-rings can be distinguished in the feldspar framework".

In the Newry area it is very noticeable that in biotite-pyroxenite which is only slightly contaminated with sediments, the feldspar is coarse in grain, whereas in the rock types which may be regarded rather as sediments soaked with B. P. magma the feldspar always forms a fine matrix. Where only a small amount of sediment was incorporated in the B. P. magma the heat was evidently sufficient to fuse it and this accounts for the coarse grain of the feldspar, whereas,

in those rock varieties in which sediments form a high percentage, fusion has been only partial and the original grain size of the sediments is retained by the feldspar.

Rocks which exhibit Seeconnell textures may show intrusive contacts, as is found in the case of quartz-diorite on Rough Hill in the Newry Complex [51, p. 612]. A small percentage of magma in the interspaces of a sediment is evidently sufficient lubricant to allow the whole mass to rise to a higher level. It should be remembered, however, that movement of a few feet or even a few inches is adequate to account for an intrusive contact.

Descriptions of Seeconnell textures are readily found in the literature, outstanding examples occurring in the following regions to which reference is made in Part II: Predazzo and Monzoni; Oslo region; Rosslund area, British Columbia; and Argyllshire, Scotland.

In case 2, the hybrids are due to the invasion of B. P. by a feldspathic magma and there is a characteristic clot-like grouping of the ferromagnesian minerals. The feldspathic or quartz-feldspar magma (syenite and quartz-syenite respectively) may originate as in case 1, or as discussed later (see p. 461).

In case 3, where magmas are produced in depth by processes similar to those which operated in cases 1 and 2, the resulting rocks will exhibit normal igneous textures.

b) The Origin of Soda-syenite. (Colonsay).

At the northern end of Kiloran Bay, in Colonsay, an island of the Inner Hebrides, hornblendite has invaded a series of schists and quartzites, which have been shattered by magma pressure, so that the intrusion is margined by a coarse breccia. As in the Newry area, the ultrabasic magma, unable to rise by stoping, exerted shouldering stress and at the same time incorporated the country rocks. The area has been briefly described by WRIGHT [15] and will be dealt with fully in a separate paper by the writer. A concise statement of the main facts, however, is given here.

The hornblendite is thickly crowded with blocks of quartz and quartzite, each of which is surrounded by a halo of pink alkali-feldspar, formed by the addition of alkalis and alumina from the ultrabasic magma to the silica of the quartzite. The quartzite blocks can be seen in all stages of reaction, grading from those which are rimmed

by feldspar to others which have been completely replaced by feldspar. Round the feldspathised quartzite inclusions the hornblende frequently forms blade-like crystals which may reach a length of 5 or 6 cms. Indeed the presence of small quartz inclusions, which might easily be overlooked, can frequently be located in the centre of radial aggregates of blade-like hornblende.

Where the hornblendite is in contact with quartzite at the margin of the intrusion a feldspathic reaction rim is developed, and from this contact rim pink pegmatite veins run laterally into the hornblendite. In contact with the pegmatite veins the hornblende again becomes coarse in grain, forming blade-like crystals several cms. in length, with a tendency to a radial arrangement round feldspathic patches.

In thin section the pegmatite and feldspathic rims from the quartzite inclusions are seen to consist of micro- and cryptoperthite with a little albite and hornblende. Chemically the pegmatite shows a considerable excess of soda over potash ($\text{Na}_2\text{O} = 5.49$; $\text{K}_2\text{O} = 3.78$), so that the rock is actually a soda-syenite. It falls within PHEMISTER'S delimitation of perthosite¹) [45, p. 47].

Where the hornblendite magma assimilated a little quartz, alkali feldspar is present in small amount and the resulting rock is a member of the appinite²) series (BAILEY [4, p. 167, 168]).

Outcropping in the centre of the hornblendite intrusion, and showing intrusive contact, is a pink hornblende-syenite. This closely resembles the feldspathised quartzites and the pegmatite veins just described, both in hand specimen and in thin section under the microscope.

c) The Appinite—Diorite—Plagioclase Series.

By soaking into aluminous sediments, while giving off emanations rich in alkalis, hornblendite magma is believed to give rise to a series which parallels the shonkinite—monzonite—syenite series, and which grades from hornblendite itself, through hornblende-diorite to plagioclase. The more basic members of the series, which may be regarded as basic diorites are members of the appinite series (BAILEY [4, p. 167, 168]).

¹) Perthosite is an alkali feldspar rock with orthoclase and albite each between 30 and 70 per cent.

²) Appinites include melanocratic varieties of hornblende-syenite and -diorite.

There is indubitable evidence in Colonsay of the reality of migration into sediments of soda and to a less extent of potash from hornblende magma, with consequent development of soda-syenite and appinite. Moreover RITTMANN [54] has recorded good evidence in Kellang, an island west of Ceram in the Mollucas, Dutch East Indies, for the development of plagioplite by reaction between hornblende-gabbro and quartz-diorite on the one hand and sediments on the other. In Kellang peridotites and pyroxenites which have suffered widespread serpentinisation, are intrusive into a series of schists and gneisses which are overlain unconformably by Mesozoic sediments. The schists and gneisses are mainly composed of quartz, cordierite and feldspars, with a local development of sillimanite and biotite. The ultrabasic rocks enclose or are cut by streak-like schlieren and dyke-like masses of uralitised gabbro and quartz-diorite. These contain inclusions of sediments and schists in all stages of resorption and also streaks, veins and dykes of plagioplite. The plagioplite comprises quartz-bearing varieties and types that range towards chloritised diorite in composition.

RITTMANN shows that there is complete transition between the plagioplite and hornblende-gabbro on the one hand and between plagioplite and the xenoliths of schists and sediments on the other. At times the feldspathised xenoliths are so abundant that the 'dykes' are described as gangbreccien. Some of these xenoliths resemble the plagioplite so closely that their true nature is revealed only by the microscopic detection of such minerals as cordierite and sillimanite. Similar veins of plagioplite occur in the ultrabasic rocks and are also of widespread occurrence in the country rocks. The country rocks themselves have been so thoroughly feldspathised that there is every gradation to the plagioplite.

The combined evidence from Colonsay and Kellang is very suggestive, and it becomes more strikingly significant when taken in conjunction with the facts that:—

- a) There is a similar association of rock types in many regions, the series hornblende—appinite—diorite—plagioclase sometimes being completely represented e. g. in the Vermilion batholith of Minnesota [27], the Saganaga [28] and Rest Island [16] 'granites' of Minnesota and Ontario and in the Orijärvi region [20].
- b) There is a frequent association of the hornblende series with the hybrid series developed from B. P.

d) The Origin of Kentallenite.

For the origin of the kentallenites there is evidence in Argyllshire, Scotland. As already stated, there is a serial gradation from B. P. with a preponderance of potash over soda to hornblendite with a preponderance of soda over potash. If members of this series which approach hornblendite in composition (that is varieties with a higher percentage of soda than potash, or varieties in which the alkalis approximate to equality) soak into aluminous sediments, kentallenites are developed. This is well exemplified at Balnahard in Colonsay, where olivine-biotite-pyroxenite grades to hornblendite. Marginally the hornblendite magma has soaked into the country rocks, to which the hornblendite now grades through a hybrid variety with textures that resemble those of Seeconnell type from the Newry Complex. In the hand specimen the hybrid exhibits phenocrysts, or rather porphyroblasts, of olivine and augite in a fine-grained gray matrix with a sedimentary aspect. Passage towards the sediments takes place by the disappearance of the porphyroblasts. In thin section the rock is found to be a kentallenite, with characteristic iron-rich olivine, and augite which is frequently zoned. These are set in a very fine-grained matrix which consists in the main of zoned plagioclase, with some potash feldspar and biotite. The potash feldspar occurs interstitially or encloses the plagioclase in a poikilitic fashion. The soaking of sediments by hornblendite magma has evidently resulted in the crystallisation of porphyroblasts of olivine and augite from the magma, the residual part of which, in combination with the sedimentary material, has given rise to the feldspar and biotite of the matrix. Associated with the biotite-pyroxenite and hornblendite at the same locality is kentallenite of a normal type [15, p. 31], readily recognisable in a hand specimen and with a comparatively coarse-grained matrix. This can be assumed to have originated through the soaking of the country rocks at greater depth by a magma of similar hornblendite composition, the syntectic magma having been intruded to a higher level. The hornblendites as a class are rich in iron, and the olivine to which the corresponding magmas give rise on invading sediments is necessarily an iron-rich variety. Here then is probably the explanation of the curious appearance of the olivines in kentallenite, which are crowded with inclusions of minute rods and grains of iron-ore. Possibly at a high temperature the olivine is capable of holding the iron in solution, but as the tem-

perature falls the iron crystallises out. The Balnahard occurrence is not the only example of an association of kentallenite with hornblendite in Colonsay. The same two rock varieties outcrop at no great distance apart on the east coast, where they are associated with the monzonite intrusion near Scalasaig. Again the kentallenite exhibits the Seeconnell type of textures. It then becomes a point of interest to examine the associates of the other kentallenites of Argyllshire. At Glen Orchy [36] the kentallenite forms a sill-like intrusion the lower part of which is a hornblende-rich biotite-pyroxenite containing a little potash-felspar. This grades upwards to kentallenite which, at the upper contact, assumes the appearance of the Seeconnell type, with augite showing a sieve texture. This rock is without doubt the result of the invasion of the country rocks by the hornblendic B. P. The upward gradation from hornblendic B. P. to kentallenite is probably to be attributed to the concentration of the volatiles in the upper part of the sill, where attack of the sediments would in consequence take place. From the description of the kentallenites of Brannie Burn [36], it is apparent that the intrusion at An-Sithein resembles that at Glen Orchy, since a variety of B. P. forms the lower part of the intrusion. The kentallenites of Kentallen and nearby intrusions [4] are associated with appinite and monzonite.

As pointed out by HILL and KYNASTON [30], the kentallenites show a gradation from a type in which plagioclase is the more abundant felspar, to one in which orthoclase predominates. The latter variety differs from the shonkinites only in that olivine is an essential and important constituent. This variation in the relative abundance of soda-lime-felspar and potash-felspar is to be correlated in the main with the variation in the composition of the invading magma. If the magma approaches the composition of hornblendite the resulting kentallenite will have plagioclase as its predominant felspar, whereas increase in the percentage of potash relative to soda in the invading magma will result in a corresponding increase in the percentage of orthoclase in the kentallenite. Possibly the amount of quartz in the sediments plays an important part in this connection, in so far as it is the agent which fixes the potash.

In summary then, the kentallenites are due to the soaking of aluminous sediments by members of the B. P.—hornblendite series which approach the hornblendite end in composition. This explains

a) the characteristic texture, i. e. the occurrence of olivine and augite as large crystals in a fine-grained matrix; b) the iron-rich character of the olivine; c) the mineralogical variations found in the group; and d) the fact that kentallenite grades to shonkinite as potash increases.

e) Connecting links between the Series a) and c).

Corresponding with the fact that every gradation occurs between hornblendite and B. P. (e. g. Colonsay and Loch Ailsh) through biotite-bearing hornblendite and hornblendic B. P., there is every gradation to be found between the two hybrid series to which they give rise. Kentallenite forms a link between the two series at the basic end in that it shows a range in composition from varieties with higher soda than potash to others with higher potash than soda. This variation is reflected by the composition of the felspar. In some examples plagioclase is the dominant felspar, whilst in others orthoclase predominates and the shonkinites are approached in composition. Just as the kentallenites bridge the gap between the two series at the basic end, so there is every gradation between diorite and monzonite, whilst syenites range in composition from plauenite through perthosite to plagioclase. These relationships are expressed diagrammatically in Fig. 1.

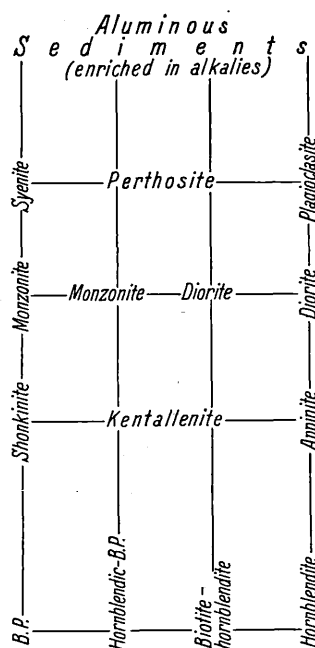


Fig. 1.

f) Augite-biotite-diorite, Biotite-gabbro and Hypersthene-bearing Rocks.

In the Newry area [51] augite-biotite-diorite is associated with biotite-pyroxenite and is due to the invasion of the latter by a magma that had the composition of plagioclase (oligoclase-andesine) with a small percentage of mafic constituents. This type is similar to the plagioclase end of the hybrid series due to syntexis of hornblendite and sediments. It is represented by the andesinite of the Orijarvi

region [20], the plagioclase of the Monzoni area [9], and the syenite (plagioclase) which occurs in the marginal zones of the Vermilion and neighbouring batholiths [26, 27, 28, 16]. Augite-biotite-diorites thus appear to be due to a mixing of members of the two series B. P. — syenite and hornblendite — plagioclase. If the mixing takes place at a high temperature in depth a magma results which is capable of intrusion to higher levels [51, p. 626].

The biotite-gabbros probably have an origin which is similar in all essentials to that just described, except that the plagioclase end is richer in lime and of the composition of labradorite. The variation in the ratio of lime to soda in the plagioclase end is a problem which remains for solution.

Hypersthene-bearing monzonites and diorites and biotite-norites form members of the hybrid series under discussion. The hypersthene in all these types is of the highly pleochroic variety characteristic of hornfels and unlike that in the associated pyroxenites. It may sometimes be due to the breakdown of the diopside molecule in the presence of sedimentary alumina, when B. P. invades aluminous sediments, and at other times, when accompanied by orthoclase, it may possibly be a direct effect of high temperature metamorphism of the biotite of sedimentary origin.

g) The Origin of Granitic rocks in Orogenic Regions.

There is now evidence from several areas to show that granitic rocks can be produced from sediments as a result either of invasion by an intruding magma or of feldspathisation by emanations from an intruding magma.

A spectacular example of the development of granite from sediments has been demonstrated by QUIRKE and COLLINS [47] from the Huronian area north of Georgian Bay. They show how Huronian sediments, comprising quartzites, conglomerates and graywackes, have been converted to Killarney granite by magmatic emanations rich in soda and potash. Not only is it shown that the fold structures characteristic of the Huronian formations are continued in the region of granite and gneiss, but the details of conversion of sediments to granite are traced texturally, mineralogically and chemically.

Quartzite, porphyry, gneiss and Killarney granite are shown to constitute a gradational and closely related series. Quartzites grade into porphyry by the appearance of phenocrysts of orthoclase

or microcline. The felspar phenocrysts, although sometimes exhibiting form, are more frequently irregular in outline, showing uneven boundaries towards the matrix like the porphyroblasts in the Seeconnell types. By increase in the amount of felspar, the porphyry grades to gneiss and granite.

Of special interest is the fact that granite, the development of which from quartzite by a process of transfusion is demonstrated, is elsewhere intrusive. The authors believe that the intrusive relationship is to be explained by the fact that granite magma was developed from quartzite at greater depth and under more intense metamorphic conditions, being then forced upward for some thousands of feet.

Chemical analyses of quartzite, porphyry, gneiss and granite indicate that a considerable percentage of alkalis must have been introduced into the quartzite to convert it into porphyry. Smaller amounts of iron-oxides, lime and magnesia were also introduced. Most of the soda and potash is shown to have come in during the first stage, in which quartzite was converted into porphyry, and there was a continued but much slower increase in these constituents in the later stages. Iron oxides, lime and magnesia, for making biotite and magnetite show very little increase until the stage of transition from porphyry to gneiss. As QUIRKE and COLLINS observe "Felspar-forming substances evidently penetrated farther and more rapidly than the ferromagnesian introductions".

As to the source of the alkalis and the lesser amounts of iron, lime and magnesia, QUIRKE and COLLINS believe that they were derived by some process of differentiation from a deep-seated zone of diabasic composition. They show that sills and dykes of diabase were intruded into the Huronian sediments prior to the formation of the granite. In the area of granite and gneiss the so called 'diabase' consists of hornblende, or hornblende and biotite, sometimes with abundant garnet. In one specimen fragmentary quartz and felspar are also present. QUIRKE and COLLINS regard these rocks as diabase metamorphosed beyond recognition. It is evident, however, that they are identical with the hornblendites and biotite-bearing hornblendites which are described in the present paper and shown to give off a vanguard of alkali emanations on intrusion.

ANDERSON [3] has recently described a clear case of the development of granite from quartzite in the marginal zone of the Cassia batholith of Idaho. The country rocks are quartzites which have

been impregnated by magmatic emanations with consequent development of albite and microcline, the latter appearing as large porphyritic crystals. Both varieties of felspar are regarded by ANDERSON as replacing the quartzite, of which they enclose relics. As can be seen from the photomicrographs the quartzite inclusions give the phenocrysts a sieved appearance. The phenocrysts also exhibit minutely crenulate outlines against the matrix. In the outer part of the granitised zone the bedding of the quartzite is retained, whilst, throughout the zone, microscopic examination reveals the presence of mosaics of interlocking quartz grains, which are relics of the invaded quartzite.

OSBORNE [43] has described an excellent example of a granite-schist transition zone in Ontario.

In the Newry area [51, p. 612, 622, 630] quartz-rich diorite and granodiorite, with Seeconnell textures, have arisen due to the migmatitisation of sediments by augite-biotite-diorite. In another part of the Newry area porphyritic granodiorite occurs marginally against sediments. Microscopically it is found to be in the main hornfelsed sediments in which porphyroblasts of zoned plagioclase, about 1 cm. in length, have grown from invading material. The porphyroblasts frequently enclose quartz mosaics of sedimentary origin, and whereas the porphyroblasts appear to be idiomorphic in the hand specimen, under the microscope they frequently show crenulate margins against the sedimentary matrix.

The granodiorites of the Newry area are not of an unusual type, since relics of sediments are frequently to be seen in the finer types from other areas. Usually, however, the mosaic textures of such sedimentary relics have been interpreted as protoclastic and cataclastic textures. The term glomero-granular has been applied by HAWKES [29, p. 167] to a similar texture which he found to be characteristic of the coarser grained varieties of granite.

From the salient facts of the few cases cited above, it is evident that 'granite' in orogenic regions is developed from sediments in several different ways.

1. By enrichment of siliceous sediments (including metamorphic derivatives) in alkalis, and possibly alumina, of ultrabasic origin.
2. By the soaking of one of the felspathic magmas, plagioclase, syenite or perthosite, into sediments or their metamorphic derivatives.

3. By the soaking of one of the hybrid types of intermediate composition into siliceous sedimentary or metamorphic rocks, with an accompanying enrichment of the invaded rocks in alkalis.

The 'granites' which are the result of the operation of processes 1 and 2 tend to be leucocratic, whilst those which are the result of process 3 are characterised by hornblende or hornblende and biotite. Augite is a less common constituent and sometimes occurs as residual cores in the hornblende. These three processes may take place in situ, in which case the 'granite' is usually porphyritic, or in depth with the production of magma.

PART II.

VI. Suggested Interpretations of Various Areas.

Owing to exigencies of space it is here possible to make brief reference only to a few described examples where it is evident from the literature that syntexis of ultrabasic magmas and sediments has taken place.

a) The Region of Predazzo and Monzoni.

In the Predazzo and Monzoni area pyroxenite, olivine-pyroxenite and biotite-pyroxenite are associated with monzonite, shonkinitic monzonite, augite-biotite-diorite and plagioclasite. According to BRÖGGER [9] the pyroxenites occur only as a border facies at the roof contact, above monzonite. He considers that the invading magma was differentiated into monzonite and pyroxenite, due to the early crystallisation of the most basic portion at the cooling surface. In the light of other regions, however, his diagram [9, p. 71, Fig. 7] can be interpreted as showing the relics of an early intrusion of pyroxenite, which now forms the roof to a later monzonite.

Of particular interest is BRÖGGER's description of a border facies, which is developed where pyroxenite comes in contact with schist. It has a dominant porphyritic texture, with pyroxene, biotite and plagioclase as phenocrysts in a dense fine-grained groundmass of plagioclase, orthoclase and quartz, with pyroxene and much biotite. Without doubt this is a description of the Seeconnell type of textures. Moreover BRÖGGER points out that the border facies types are connected through all gradations with the usual monzonite. It is evident therefore, that pyroxenites were first intruded and by soaking into

the schists gave rise to monzonites of Seeconnell type. This early intrusion was followed by a later intrusion of monzonite which represents a depth mixture of pyroxenite and schist previously enriched in alkalis.

With regard to the augite-biotite-diorite, its analysis falls so exactly between the analyses of plagioclase and biotite-pyroxenite as to leave little doubt that it represents a mixture of the two.

b) The Oslo Region.

Some, at least, of the rocks of the Oslo district must belong to the series of hybrids here discussed, for in his description of the contact facies (Seeconnell type) of the pyroxenites in the Predazzo area, BRÖGGER remarks that in the Christiania (Oslo) district a similar porphyritic border facies to the abyssal rocks is a usual phenomenon [9, p. 77]. In addition, the clot-like grouping of the ferromagnesian minerals in the well known laurvikite, in which the clots exhibit the characteristic B. P. assemblage, is suggestive.

The geochemistry of the Oslo rocks [10] is in conformity with such a hybrid origin, since as a whole they are rich in BaO, TiO₂, and P₂O₅. The BaO content of the pulaskites and nordmarkites is particularly suggestive in this connection, being exactly what would be expected if they had an origin similar to that of the sodasyenite of Colonsay.

c) The Rossland area, British Columbia.

In the Rossland area a number of associated stocks and bosses are intrusive into schists of Palaeozoic age. The area has been mapped and described by Daly [18], who has shown the rock types to include peridotite, olivine-biotite-pyroxenite, hornblendite, biotite-gabbro, shonkinite, shonkinitic monzonite, monzonite, syenite and granodiorite.

The Baker gabbro, which outcrops near Christina Lake, is cut by an irregular intrusion of olivine-biotite-pyroxenite, of which an analysis is given on p. 450 (No. 5). The gabbro is rich in biotite and differs from normal gabbro in its high content of potash and in the fact that the ferromagnesian minerals are collected into clots. This rock presents the same problem as the augite-biotite-diorite of the Newry area, from which it differs only in the greater lime content of the plagioclase.

On the northern contact of the Baker gabbro is a shonkinitic monzonite, intruded into the Sutherland schists. This rock resembles the shonkinitic monzonite of the Newry area both chemically and texturally. It is of the Seeconnell type, the mafic minerals (augite, olivine and biotite) being associated with a finer grained felspathic matrix. Biotite occurs both as phenocrysts with a poikilitic texture and also as minute flakes in the groundmass, and furthermore the optic axial angle is different in the two varieties. A similar rock outcrops in Fifteen Mile Creek, and Daly draws attention to the fact that in this occurrence, whereas the mica phenocrysts are double the size of those in the rock from Christina Lake, yet the feldspars are even finer grained than in that rock. In view of the texture of the shonkinitic monzonite and its association with biotite-pyroxenite, it is evident that, as in the Newry complex, it is the result of the soaking of B. P. into the country rocks (here schists), which were previously enriched in alkalis by an advance-guard of emanations from the invading magma. This interpretation explains the difference in grain size between the mafic and felsic constituents, and the difference in optic axial angle exhibited by the two varieties of biotite, the fine grained variety of which is a residual from the schists.

The Rossland monzonite, intrusive into Carboniferous sediments, represents a further stage in the soaking of B. P. into the country rocks, in which the resulting rock contains a higher percentage of sediments than the shonkinitic varieties. Evidence for this is found in G. A. YOUNG's description of the monzonite, quoted by DALY, from which it appears that a) the monzonite includes a number of related rock types, the coarsest of which grades to B. P. consisting of hornblende, pyroxene and biotite; and b) the fine grained monzonites exhibit Seeconnell textures. That the field occurrence of the monzonite is in keeping with such an origin is evident from the fact that it represents the upper portion of an igneous intrusion, being in places still capped by its roof.

Another monzonite, intrusive in schists at the confluence of Bear Creek and Columbia river, appears to have had a similar origin, since it merges to biotite-hornblendite, from which it differs in the additional presence of orthoclase, andesine and quartz.

The series is completed with syenite in the Coryll batholith and granodiorite and tonalite in the Trail batholith.

In the Rossland area, as in the case of some of the Caledonian intrusions of the British Isles, magma pressure is evidenced by the presence of shatter zones round the Trail and Coryll batholiths.

d) The Cortlandt Series.

The Cortlandt series, situated about 35 miles north of New York City and intruded in the Manhattan schists, forms a small but very complete igneous complex in which ultrabasic rocks and norites were first intruded (ROGERS [55, p. 60]). Peridotites are rare, but pyroxenite constitutes nearly one-fourth of the whole series. ROGERS, who has described the various members of the series in detail [55] has summarised the relations of the more important types in a most enlightening diagram. This shows a passage from peridotite through biotite-olivine-pyroxenite to biotite-pyroxenite, the latter being associated with the norites. On the other hand it shows gradation from peridotite through hornblende-olivine-pyroxenite and hornblende-pyroxenite to hornblendite and hornblende-norite, the two latter types showing further gradation to biotite-hornblende-norite and the diorites.

ROGERS regards many members of the Cortlandt series as hybrids due to reaction of magma with sediments. In the present connection the following points are of significance:

1. On Montrose Point a raft of wernerite-schist is enclosed in the pyroxenites and "Lying between this rock and the pyroxenites, in several places at least, a typical diorite is found". Further, the diorites, where best developed, are associated with pyroxenite and outcrop between biotite-augite-norite and schists. Apart from this occurrence diorites occur in isolated patches only, three of which are situated along the southern border of the complex.
2. Quartz-norite was found at one locality only, in the extreme south of the complex, where it lies between biotite-norite and mica-schist and is believed by ROGERS to be due to reaction.
3. Syenite is recorded from three small outcrops only, of which two occur on the borders of the complex, one in the south and one in the north. Mineralogically the latter is a monzonite rather than a syenite. These rocks ROGERS regards as due to reaction between the norite magma and the mica-schists.
4. Sodalite-syenite outcrops in the main diorite zone where it margins an inclusion of quartz-schist. This occurrence provides an

example par excellence of the potency of the alkali-migration (in this case principally soda) to which reference has so repeatedly been made.

BOWEN [7, p. 208-210] has claimed the Cortlandt series as an example of reaction between basaltic magma and aluminous sediments. The fact that no rocks of indubitable basaltic composition have been recorded from the area, however, leaves this view as unsubstantiated theory. The term gabbro has been applied by ROGERS in three cases. In one, however, it is evident from his description that the rock is mineralogically an augite-biotite-monzonite; its position on the northern contact between biotite-augite-norite and mica-schist being significant in connection with its origin. In the second case the rock is chemically a monzonite [55, p. 61]. In the third case the types termed gabbro occur in two localities adjoining schist inclusions and from ROGER'S description appear to be a variety of hornfels.

e) Hybrids of Ach'uaire Type, Scotland.

In the Moine series and in the granite and injection complexes of Central and Southern Sutherland, innumerable small elongated bosses of rocks of intermediate composition occur, with many of which biotite-pyroxenite, scyelite and sometimes hornblendite are associated. Both ultrabasic and intermediate varieties are described by READ [48, 49, 50] as hybrids of Ach'uaire type, and attributed to the mixing of granitic magma with either an ultrabasic magma or with solid ultrabasic rock. In view, however, of the similarity of the B. P. to that of Loch Ailsh and indeed to the biotite-pyroxenites as a class, it is evident that it is not a hybrid as READ believes, but actually the immediate ultrabasic parent.

The 'granitic end' is a felspathic type, akin to perthosite [45] and trondhjemite. Its composition can be obtained approximately by constructing a variation diagram from the analyses of the B. P. and the hybrid types. Choosing a silica percentage so that the ratio of soda to lime is that in the observed plagioclase Ab_{85} , a composition is found which falls between the analyses of a typical Moine granulite and that of a pelitic type from the area, except that the calculated alkalis are somewhat higher, there being a greater relative increase in soda than potash. The 'granitic end' may well represent the rocks of the Moine series enriched in alkalis from the ultrabasic magmas.

The intermediate hybrids are of two main types a) homogeneous varieties in which there is a fairly complete mixing of the melanocratic and leucocratic constituents, b) true inclusion-complexes of granitic magma with fragments of both intermediate and ultrabasic rocks, or of intermediate hybrid magma with fragments of ultrabasic rocks.

The evidence may be interpreted as follows. B. P. and hornblendite were intruded into the schists and granulites of the Moine series. They would rise mainly by soaking. Where the country rocks were of a pelitic or semi-pelitic type hybrids of the homogeneous variety would be produced. In this case alkalis from the invading magma, in combination with quartz and alumina from the country rocks, would give rise to the feldspars, whilst augite, hornblende and biotite would crystallise from the magma. Where the country rocks were pure or almost pure quartzites, as in Colonsay, syenite, quartz-syenite or granite would be developed. The syenite might be either a plautenite or a perthosite, dependent on the composition of the parent magma, the granite showing a similar variation. Magma of such syenite or granite, or indeed of any of the hybrid varieties, might, under suitable circumstances, rise and cut the other types, so that true intrusion-complexes would be formed.

f) The Loch Ailsh Mass, Sutherlandshire, Scotland.

In the Loch Ailsh mass, described by PHEMISTER [45] and regarded as a laccolith, there is an upward passage from B. P. (grading to hornblendite) through shonkinite to pulaskite and nordmarkite. These layers are cut and overlain by perthosite, which hybridised the basic shonkinite giving rise to 'basic knots'.

PHEMISTER regards the association of rock types as due to the differentiation, in depth, of a fairly basic alkaline magma, but he stresses the fact that the B. P. was intruded as a magma. The series parallels that of the Newry area but is richer in soda and from PHEMISTER's descriptions it is evident that there are many textural similarities. Sieve textures are described from shonkinites at two localities, whilst the intricate suturing of the margins of the feldspars in the syenites resembles those from Slievenisky in the Newry area.

PHEMISTER describes the laccolith as intrusive in Cambrian sediments, with its floor resting on the Pipe Rock and its roof in the

Durness limestone. From this it would appear that the Fucoïd Beds and Serpulite Grit have as a whole vanished, remnants of them only remaining as xenoliths in the intrusive mass. This is of particular interest in that the Fucoïd Beds are largely argillaceous and capable of producing rocks of the shonkinite—syenite series when soaked by B. P. magma. The greater richness in soda of the series when compared with that of the Newry area is consistent with the fact that the parent B. P. is itself considerably richer in soda relative to potash (see p. 450 Nos 1 and 3). The perthosite probably represents the reaction of the ultrabasic magmas with the Basal Quartzite and Pipe Rock.

g) Argyllshire, Scotland.

In the Caledonian intrusions of Argyllshire [4, 15, 17, 36, 40, 52, 62] the suite of rocks under discussion is well developed. The parent magmas are represented by ultrabasic types, which include B. P. and hornblendite, and increasing acidity in the associated rocks corresponds with increase in the proportion of added alkali-enriched sediments. Brief reference only will here be made to important textural evidence.

At Garabal Hill [62] the ultrabasic types are associated with diorite, tonalite and granodiorite. At Glen Orchy and An-Sithein sills of hornblendic B. P. grade upwards to kentallenite which exhibits Seeconnell textures at the upper contact. In Colonsay hornblendite is associated with appinite and syenite, the two latter types having been developed by reaction of hornblendite magma and quartzite.

Many of the 'granites' are margined by earlier intrusions of augite-diorite and monzonite, which exhibit, according to BAILEY'S description, textures of Seeconnell type. He says "These rocks have often a rather distinctive appearance in hand specimens, for the augite crystals, set in a pale felspathic ground show as dark spots about an eighth of an inch across. Specimens from one and the same boss vary much in regard to the development of their biotite, which may occur either as rather irregular small crystals or as large poikilitic plates" [4, p. 167, 170]. The augite phenocrysts and poikilitic biotite represent the invading B. P. whilst the felspathic ground and irregular small crystals of biotite represent the country rocks which were enriched in alkalies by advance emanations from the invading B. P.

Light is thrown on the origin of the aplogranites, which occur as marginal facies of less leucocratic granite, in WALKER's [59] description of the White granite (aplogranite) which occurs as a marginal facies between the Ballachulish granite and the Appin quartzite. The White granite grades to the normal granite (a basic hornblende-biotite-granodiorite with a little pyroxene) and shows intrusive contact against the quartzite. It is poor in mafic minerals and towards its contact with the Appin quartzite becomes porphyritic with phenocrysts of oligoclase, hornblende and biotite in a groundmass of quartz and orthoclase. The hornblende and biotite are said to have a 'worm-eaten' appearance due to the fact that they enclose many small grains of quartz. This is a Seeconnell type of texture and is due to the growth of these crystals from invading magma as poikiloblasts in the quartzite. In view of BAILEY's observations on the feldspathisation of quartzite xenoliths in the Glen Coe fault intrusion [4, p. 112] it is evident that the White granite represents first an enrichment of the quartzite in alkalies, and secondly its permeation by basic granodiorite or diorite. A small movement only of this hybrid zone would account for its intrusive contact against the quartzite. A similar sharp contact has recently been noted by ANDERSON [3] between the marginal zone of the Cassia batholith, which is feldspathised quartzite, and the quartzite itself.

The tonalites, granodiorites and adamellites are not infrequently porphyritic in an outer zone, as exemplified by the Starav Granite and the Outer Granite of Ben Nevis. The felspar phenocrysts resemble the porphyroblasts in the Seeconnell types in that they exhibit allotriomorphic boundaries. One specimen from the Outer Granite of Ben Nevis described by BAILEY [4, p. 166] exhibits phenocrysts of hornblende, biotite, plagioclase, orthoclase and quartz in a definite groundmass of granular quartz and felspar. The allotriomorphism of the phenocrysts of potash felspar suggest that they grew from an invading magma in a highly viscous or nearly solid medium. In the case just noted from the Outer Granite of Ben Nevis, it appears that the invading magma was of the nature of adamellite, the invaded medium consisting of a granular aggregate of quartz and orthoclase, resembling the aplogranites of the area, and being essentially quartzite enriched in alkalies.

h) The Hybrids of the Trégastel-Ploumanac'h Area.
Côtes du Nord, France.

A hybrid series has been described from Trégastel-Ploumanac'h by THOMAS and CAMPBELL SMITH [58]. The hybrids include hypersthene-gabbro, augite-biotite-diorite, hornblende-biotite-diorite, quartz-biotite-diorite and monzonite, all of which are believed by the authors to have resulted from the attack of granite magma on olivine-norite. They draw attention to the similarity of the whole series to the hybrids of Ach'uaine type described by READ; to the similarity of the lustre-mottled biotite-hypersthene-gabbro to the kentallenites of Argyllshire; and to the similarity between the dioritic stages and certain rocks associated with the Ballachulish granite. They also compare the xenoliths of the hybrids in the Newry granodiorite from Ballymagreechan quarry, near Castlewellan, to the mica-diorite stage of hybridisation at Trégastel-Ploumanac'h.

The writer has been able to examine about twenty thin sections of the various types from Trégastel-Ploumanac'h and finds them to correspond exactly with the hybrids of the Newry Complex, and has no hesitation in suggesting that they are of similar origin.

THOMAS and CAMPBELL SMITH have drawn attention to the occurrence, in the rocks of Trégastel-Ploumanac'h, of ovoid patches of quartz and perthitic orthoclase, rimmed with pyroxene or hornblende, which they refer to as 'ocelli'. These 'ocelli' occur not only in the rocks described as hybrids, but also in the most basic rock found in the area, which is olivine-biotite-norite. After examining the feldspathisation of the quartzite inclusions in the hornblendite of Colonsay, which are rimmed by hornblende, there can remain no doubt as to the similar origin of the ocellar structure of the rocks of Trégastel-Ploumanac'h. They are relics of quartz from the invaded country rocks (schists and gneiss), now seen in all stages of conversion to feldspar. The orthoclase and quartz are sometimes graphically intergrown, or arranged concentrically, as in Colonsay.

The interpretation of the hybrid series then becomes evident. The hybrids have resulted from the invasion of the country rocks by olivine-biotite-pyroxenite, possibly accompanied by a hornblendic type. The ultrabasic magma has risen by soaking, with an accompanying migration of the alkalis into the country rocks, in which there has been in consequence a development of feldspar.

i) The Highwood Mountains (Shonkin Sag), Montana.

The rocks of the stocks and laccoliths of the Highwood mountains [46] include syenite, sodalite-syenite, leucite-syenite, monzonite, shonkinite, and missourite.

In the laccoliths of Shonkin Sag, Square Butte, and Palisade Butte, there is an association of syenite and shonkinite. Since the processes which operated to produce this association must in each case have been similar, the discussion will here be confined to the Shonkin Sag laccolith. This is intrusive into almost horizontal sandstone of Cretaceous age. The following tabulation of the median section of the laccolith is that given by PIRSSON [46], who estimates that the syenite forms only 5 per cent of the whole mass.

Pseudoleucite-basalt-porphry	5 ft.
Dense shonkinite	5 ft.
Shonkinite	5- 6 ft.
Transition rock	3 ft.
Syenite	25-30 ft.
Transition rock	15 ft.
Shonkinite	60-75 ft.
Pseudoleucite-basalt-porphry	15 ft.
	<hr/>
	140 ft.

Various interpretations of the association of rock types in the Shonkin Sag laccolith have been suggested by PIRSSON [46], DALY [18, p. 251], and OSBORNE and ROBERTS [44], yet so far no one has adequately explained the curious textures of the transition zone. The photograph of the Shonkin Sag transition rock given by OSBORNE and ROBERTS [44, Fig. 2, p. 336], might well be a photograph of the transition zones round the almost completely feldspathised quartzite inclusions in the hornblendite of Colonsay. The stellate groups of slender augites, in which the individuals may be as much as 6 cms. long, embedded in feldspathic material, are exactly analogous to the Colonsay transition zones in which there are similar stellate groups of slender hornblendes in a feldspathic matrix.

With a recognition of the true nature of the transition zone the origin of the syenite is evident. It represents a giant inclusion of Cretaceous sandstone, which was incorporated and transfused in the shonkinite or more basic parent magma. Judging from the photograph which illustrates PIRSSON's original description of the Shonkin Sag laccolith, there appears to be field evidence for this,

since the bedding of the sandstone between the fringing sheets ends abruptly against the main body of the laccolith, although the roof sandstone is continuous above the highest fringing sheet and the main intrusion. It is thus evident that the continuation of the sediments between the fringing sheets must have been incorporated in the main part of the laccolith.

j) Idaho.

ANDERSON [2] has recently described a giant hornblendite from Idaho. He regards it as a member of the group of related igneous rocks, characterised by hornblende, which outcrop in north-central Idaho. Nearby there are bodies of hornblende quartz-diorite, 'outliers' of the Idaho batholith, one of which is only half a mile away. A few miles to the east and south is the Idaho batholith itself, with a wide border zone of gneissic to non-gneissic quartz-diorite (hornblende for the most part), and a central somewhat younger core of quartz-monzonite and granite. In the same region there are also dykes of dunite and harzburgite, largely altered to anthophyllite.

The hornblendite, which ANDERSON regards as a product of a pegmatitic magma, is exceedingly coarse in grain, hornblende crystals sometimes reaching a length of 14 inches. It encloses blocks of country rocks and is cut by irregular light-coloured feldspathic veins and lenses. Microscopic examination shows that the feldspathic seams are composed wholly of calcic oligoclase.

The rock is intrusive in a series of banded, highly feldspathic gneisses of sedimentary origin, of which ANDERSON states: "Before metamorphism the sediments were probably pure to impure quartzites, but, as the metamorphism has resulted mainly from igneous intrusion, the quartzites have been rendered highly feldspathic from magmatic contributions. The gneisses 50 feet and more from the hornblendite contact contain very little hornblende, but become increasingly hornblende near the contact, locally changing to hornblende gneiss or to amphibolite". Further he adds, "The magmatic solutions composed largely of the hornblende materials and rendered highly fluid by the dissolved mineralisers have invaded the feldspathic country rock and have, in part, impregnated and replaced the rock by hornblende". This seems to be a clear case of the development of appinite in situ.

With regard to the felspathic veins which traverse the hornblendite, ANDERSON points out that the oligoclase may either have been an original constituent of the hornblendite magma, or that it may represent reaction between any residual solutions and the felspathic wall rock. The writer would suggest that the emanations which felspathised the quartzose country rocks had their origin in the hornblendite magma and that the felspathic veins are due partly to felspathisation of inclusions of country rock, and partly to similar marginal reaction between hornblendite magma and country rock, veinlets of material formed at the contact having intruded the hornblendite. The case is similar to that of the felspathisation of quartzite in Colonsay, where a narrow felspathic zone has been produced marginally where the hornblendite is in contact with quartzite. From these felspathic reaction rims, pegmatite veins can be seen to run laterally into the hornblendite.

ANDERSON and KIRKHAM [1] have also described an association of shonkinite, monzonite, syenite, nordmarkite, granite and aplite from south-western Idaho. The shonkinite—syenite series shows striking resemblance to that of the Highwood and Little Belt mountains.

j) The Vermilion and Saganaga Batholiths of Minnesota and Ontario.

The early border phases of the Vermilion and Saganaga batholiths described by GROUT [26, 27, 28] range from hornblendite (associated with pyroxenite and even magnetite-rock in the Vermilion batholith) through appinite (termed shonkinite of Basswood type by GROUT) to plagioclase with 16 percent of hornblende (syenite of GROUT). The felspars, even in the most basic types, are oligoclase, albite and orthoclase. The border phases are banded, and in the Vermilion batholith the bands are shown to strike parallel to the boundary of the batholith, which in turn is parallel to the strike of the country rocks (Knife Lake slates). In the Saganaga batholith, which is intrusive in the Older Gneiss, the order of consolidation is established as a) hornblendite, b) appinite, c) plagioclase and granodiorite.

GROUT attributes the banded border phases to the crystallisation of basaltic magma along the walls of the batholith under the influence of a gentle convective circulation. The writer suggests that the marginal phases are to be attributed to the lit-par-lit injection of

hornblendite magma into the country rocks, the soaking of the latter by hornblendite magma and their enrichment in alkalis, and possibly in lime, from magmatic emanations having given rise to the appinites and plagioclasites.

Textural evidence of such a hybrid origin for the border phases is found in the spotted character of the appinites, there being white spots in a dark ground. The light areas are oligoclase, which enclose euhedral hornblende in poikilitic fashion. There is here a distinct resemblance to the hybrids of Ach'uaine, as is evident from a comparison of the two types [compare 27, Fig. 12, p. 583 and 47, Fig. 5, p. 158].

A feature of great interest in the Saganaga batholith is that the hornblende-granite (granodiorite) of the main mass contains what appear, in the hand specimen, to be large quartz phenocrysts from an eighth to half an inch across. Under the microscope, however, the quartz 'phenocrysts' are found to be aggregates of grains in various optical positions, the grains having sutured contacts. In fact WINCHELL previously described these quartz-aggregates as being due to crushing. According to GROUT, there is little to indicate dynamic action. In these quartzose areas are oligoclase crystals which GROUT says 'seem to be remnants of good crystals, now much corroded'. He further continues 'The quartz aggregates are therefore attributed to late growth and magmatic replacement rather than to early phenocrysts and later breaking up'. The writer would suggest as a more probable interpretation of these patches, that they are actually relics of country rock, apparently part of the Older Gneiss, which escaped complete feldspathisation. The corroded appearance of the plagioclase resembles the irregular outline of the porphyroblastic feldspars which have grown in feldspathised quartzite etc., as is clearly shown by comparison of the illustration given by GROUT [28, Fig. 9, p. 574] with the photomicrographs of the feldspathised quartzite from the marginal zone of the Cassia batholith, described by ANDERSON [3, Figs. 6 and 7, p. 387-388]. Further, on some islands north of Saganaga Falls, in the midst of an area of typical granite, the rock has, according to GROUT, only a few quartz 'phenocrysts', and these are in ill-defined bands or schlieren, as if developed along zones or planes by some movement of the late magma. The account reads like a description of relics of quartzite bands.

Similar border phases are associated with the granites of Giant's Range, Kekequabic Lake, Snowbank Lake and Rest Island [16], whilst in Finland ESKOLA [20] has recorded corresponding border phases of early consolidation in the oligoclase-granite batholith of the Orijärvi region.

1) Other Comparable Rock Suites.

The areas chosen for illustration, in the previous pages, form but a small proportion of described areas to which reference might be made. Similar rock assemblages are characteristic of orogenic regions of all ages. A few additional examples of individual interest will be briefly mentioned.

The members of the Opdalite-Trondhemite series of Caledonian age, described by GOLDSCHMIDT [23, 25] from southern Norway, are associated with ultrabasic types. In the photomicrographs which illustrate GOLDSCHMIDT's description, the opdalite [23, Plate IV, Fig. 6] shows textural, as well as mineralogical, resemblance to the sediments which have been migmatized by augite-biotite-diorite in the Newry area, interstitial orthoclase representing the sedimentary matrix enriched in alkalis. The trondhemite from Dombass [23, Plate V, Fig. 3] also contains interstitial relics of the country rocks with a mosaic and somewhat schistose texture.

The Bergen-Jotun series parallels the Opdalite-Trondhemite series.

NIGGLI [42] has shown that two rock series characterise the late Alpine igneous activity of the Peri-Adriatic province, namely, diorite—tonalite—quartz-diorite—granite and shonkinite—syenite—quartz-syenite. The identity of these two series with the hybrid suites of hornblendite and B. P. parentage respectively, will be evident. In his study of the igneous rocks of Traversella, north of Turin in the west of the peri-Adriatic province, KENNEDY [35] points out that the region recapitulates, both chemically and mineralogically, the magmatic province as a whole. Of particular interest, therefore, is the following description of the "so-called porphyrite from Arissa": "This chilled variety exhibits a peculiar texture. There is a pseudo-protoclastic groundmass of albite and quartz which fills the inter-spaces between larger crystals of quartz, plagioclase, and biotite, while hornblende is relatively scarce". This description could well be applied to textures of Seeconnell type and is probably evidence

of felspathisation of the schists by emanations from a soda-rich magma, followed by an actual seeping in of magma.

The gneissic rocks of Lewisian age in Scotland [57] include varieties which resemble the hybrids of both B. P. and hornblendite parentage. The most striking feature of the complex is the association of rocks rich in ferromagnesian minerals with others rich in feldspar and quartz. Within the area mapped as Lewisian gneiss, especially in the neighbourhood of Gairloch and Loch Maree, there are metamorphosed sediments which include mica-schists, quartz-schists, limestone and graphite-schist. It is, therefore, possible that the Fundamental Complex as a whole represents a lit-par-lit injection and soaking of such sedimentary material by ultrabasic magma. This would readily account for the banded structure, which includes all variations from the actual ultrabasic types themselves to sediments which were merely enriched in alkalis and which are now represented by quartzo-feldspathic portions.

DALY [18] has shown the layering in the Purcell and Moyie sills of British Columbia to be due to assimilation of quartzite, followed by subsequent differentiation, partly due to migration of alkalis from the magma to the quartzite. At the upper contact of one of the thickest sills the quartzite, although showing bedding, has "field habit and microscopic character markedly like those of the sill granite" [19]. The parent magma is believed to be gabbro. In thin sections which the writer has examined, the anomalous hornblende-gabbro closely resembles the appinites of Argyllshire, and its abnormality, when considered as a gabbro, is readily understandable if the invading magma was approximately of the composition of hornblendite.

Other complexes which probably owe their origin to processes such as those described in previous pages include the Yogo Peak stock, Montana [61]; the monzonitic stocks in Colorado, e. g. those near Caribou, Boulder County [7]; the monzonitic complex of the Mount Dromedary District, New South Wales [11]; and the syenite of Plauenscher Grund, near Dresden.

VII. Albite-schists.

Intimately connected with the subject matter of this study of comparative petrology is the origin of the albite-schists which occur

in the South-Western Highlands of Scotland, Co. Antrim in Ireland, and in the Stavanger district in Norway.

GOLDSCHMIDT [24] has shown that the porphyroblastic albite-schists of the Stavanger district were originally phyllites, and that they were converted to albite-schists by the addition of SiO_2 , Na_2O , and possibly CaO . He believes that the added material had its source in the neighbouring intrusion of trondhjemite. This explanation is of particular interest in the present connection, in that it is in conformity with the writer's interpretation of trondhjemite itself, towards the formation of which the albite-schists represent a preliminary stage. As the trondhjemite contact in the Stavanger district is approached, micropertthite appears in the schists in addition to albite until, in the innermost contact zone, there is actual "injection-gneiss". This clearly illustrates the usual rule that soda migrates further than potash. It is likely, in view of the evidence presented in the earlier pages of this paper, that the soda-emanations which effected these changes had their origin in hornblendite magma at greater depth.

The albite-schists of the Scottish Highlands and Co. Antrim are characterised by the presence of abundant porphyroblasts of albite. In 1923 BAILEY [5] stated his view that the albite in these schists in the Scottish Highlands owed its development to the sodic character of the original sediments. More recently BAILEY and MCCALLIEN [6, 39] have examined the albite-schists of Co. Antrim, with the result that the same view is still expressed. They discard the idea of soda enrichment, which was earlier advanced by CLOUGH [13], apparently on the grounds that there is no increase in albitisation on approaching granite contacts.

The interpretation of the high soda content of the albite-schists as an original chemical feature of the mud from which the albite-schists have developed, however, is not in accordance with the following observations which were made by CLOUGH with reference to the albite-schists of the Cowal area. These observations, are, however, consistent with CLOUGH's idea of soda enrichment:—

1. Albites are sometimes absent from one part of a micaceous band, yet are abundant in another part of the same band at no great distance away [13, p. 41, 42].
2. Albites frequently occur in strings which may cross the bedding and early foliation [13, p. 41].

3. In the field, albites occur in greatest abundance in the more micaceous layers which have been developed in strain slips, and they may occur in these layers even when the rock traversed by them is a quartzose grit, and shows no albites [13, p. 40].
4. The albites were developed after the movement which caused the foliation of the schists, since the puckered foliation planes of the rock are tracable through the albites by the aid of frequent inclusions of magnetite and quartz [13, p. 40].
5. In beds which at the time of formation of the Cowal 'anticline' must tectonically have been amongst the lowest beds of the district, whatever their original stratigraphical position, albites are more abundant and larger than in the higher-lying beds [13, p. 42].

In Ireland the Cushendun porphyry intrudes and is clearly related to the albite-schists. The writer does not suggest that the Cushendun porphyry was the source of the emanations, but rather that it is the result of a more advanced stage of the same process i. e. enrichment of the schists in alkalies of magmatic origin. The magma concerned probably approached hornblendite in composition. It is not to be expected that it should be visibly associated with the albite-schists. The rocks in direct contact with the hornblendite will have been converted to members of the series appinite—diorite—plagioclase—granodiorite. It is only diffused migration of sodic emanations from a magma which lay some distance away, in this case in depth, that could possibly cause albitisation without at the same time giving rise to more marked changes. It has already been mentioned that the sediments margining the Newry Complex, which were partially fused by the invading biotite-pyroxenite, were enriched in alkalies and particularly in soda. They lay at a sufficient distance from the ultrabasic magma to be free from actual injection. At the western end of the Newry Complex porphyroblasts of potash felspar 1 cm. in length are developed in the contact shales.

With regard to the albite-schists of the south-western Highlands of Scotland, the Garabal Hill Complex, in which hornblendite represents a parental magma, lies within the albite zone. Although the actual contact-effects of the complex are confined to an aureole about a mile in width, this is no disproof of the widespread existence, laterally and in depth, of hornblendite, from the magma of which soda emanations could have risen. Indeed, the existence of the albite-

schists could itself reasonably be regarded as evidence of otherwise hidden magmatic activity. The rocks of the Garabal Hill complex, probably represent more advanced stages of the feldspathisation and injection process, from the site of which they have risen up and actually intruded the albite zone.

VIII. Hypabyssal Representatives (Lamprophyres).

The hypabyssal representatives of the hybrid series due to syntexis of ultrabasic magmas and sediments include the lamprophyres and associated porphyries and porphyrites, in addition to the aplites. The lamprophyres, with which the writer hopes to deal more fully in a separate paper, characterise the hypabyssal phase in the majority of the areas discussed in this paper and in the descriptions of almost every area the authors have drawn attention to the chemical similarity which exists between the lamprophyres and certain members of the plutonic series. In particular the high barium content of the potash-rich lamprophyres may be regarded as a symptom of B. P. parentage.

It is hardly necessary to stress the mineralogical resemblances which exist between the lamprophyres and the plutonic rocks discussed in the previous pages. Soda-orthoclase or sodic plagioclase (albite to andesine), associated with augite and biotite in highly melanocratic minettes and kersantites is a feature shared in common with the shonkinites, kentallenites and augite-biotite-diorites. The hornblendic lamprophyres, vogesite and spessartite, characterised by potash feldspar and plagioclase respectively, are the equivalents of the appinites.

The lamprophyres commonly exhibit an ocellar texture, the ocelli characteristically showing an association of quartz and feldspar and being not infrequently rimmed by crystals of a mafic mineral. A probable interpretation of these ocelli is that they are relics of sialic quartz in various stages of conversion to feldspar: small-scale equivalents of the quartzite inclusions in the Colonsay hornblendite.

The lamprophyres as a group, are the result of syntexis of ultrabasic magma, approaching B. P. or hornblendite in composition, with material of primarily sedimentary origin. Not infrequently they are associated with highly feldspathic dyke rocks, such as feldspar-porphry. These parallel the feldspathic types pulaskite, perthosite and plagioclasite, so frequently found in the plutonic complexes, types which are in the main sediments enriched in alkalis from ultra-

basic magma. Aplites, in veins and dykes are also commonly associated with the lamprophyres. They are the hypabyssal equivalents of the aplogranites (see p. 476), and texturally they stand in strong contrast to the pegmatites. They represent quartz-rich sediments only partially converted to felspar by alkali enrichment, and only partially fused, so that a hornfels texture is retained.

IX. Conclusions.

It will have become apparent in Part II of this paper, that there is a great similarity in the rock types which characterise orogenic regions of all ages. It will also have been noticed how many and varied have been the previous explanations of their origin. By some writers they are attributed to differentiation from a basaltic parent magma with the early crystallisation of hornblende; by others to a similar differentiation with the early separation of biotite. Similar rocks in other regions are referred to the differentiation of a monzonitic parent magma, or to the differentiation of a fairly basic alkaline magma. In other cases similar types are explained as products of hybridisation of ultrabasic magma or rock by a granite magma or as products of some other form of assimilation. Even biotite-pyroxenite has had an uncertain status for, although it has repeatedly been shown to have crystallised from a magma, others have persisted in regarding it as a hybrid.

It is now established that B. P. and hornblendite represent highly fluid rock magmas, rich in volatiles. It is demonstrable that these magmas have not only soaked into the rocks of sedimentary origin, but have given off emanations rich in alkalies which have caused widespread feldspathisation of sediments and schists. It is hardly conceivable that B. P. and hornblendite represent pegmatitic magmas, unless peridotite itself, with which they are so frequently associated, represents a primary magma. This conclusion has far-reaching petrological and geophysical consequences. In particular it can no longer be held that basaltic magma is the common parent of the majority of igneous rocks. It is noteworthy that DALY has recently listed nearly a hundred examples of assimilation [19, p. 298 to 311], yet in not a single case is the parent magma regarded as peridotite. Since 1915 HOLMES has been almost alone in advocating the importance of peridotite as a primary magma and the main source of magmatic heat [32]. He has recently shown, in the case

of Uganda [31], that the potash-rich volcanic rocks provide strong evidence of a peridotitic parentage.

Amongst the hybrid series, biotite-gabbro and hornblende-gabbro are found in several instances and for this reason should be carefully distinguished from normal gabbro. In only a few cases can normal gabbro be found associated with the types here discussed, and in no instance is there any evidence that it has acted as a parent magma.

The scheme of petrogenesis given in the present paper, provides a common explanation for rocks in orogenic regions of all ages; explains the frequent association of rocks of Atlantic and Pacific type; and accounts for the vanished sediments in batholithic regions.

In concluding, the writer would like to express her thanks to Professor ARTHUR HOLMES, not only for the advantage of constructive discussion, but also for the encouragement and inspiration which led to the writing of the paper.

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THE EASTERN END OF THE NEWRY
IGNEOUS COMPLEX

N^o 5.

BY
D. L. REYNOLDS



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XVIII

THE EASTERN END OF THE NEWRY IGNEOUS
COMPLEX

BY DORIS LIVESEY REYNOLDS, M.SC. F.G.S.

Read February 7th, 1934

[PLATE XXII]

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I. INTRODUCTION

THE Newry Igneous Complex, generally known as the Newry granite, extends from Slieve Croob in County Down, where it attains its greatest height, south-westward past Newry into County Armagh. A general account of the "granite" was given by J. E. Richey and H. H. Thomas in their recent description of the Tertiary Ring Complex of Slieve Gullion.¹ As pointed out by Richey, it has an elongate outcrop with dimensions of roughly 26 by 6 miles, extending in a direction E. 35° N. to W. 35° S. parallel to the prevalent strike of the Silurian rocks, and can be assigned to the Old Red Sandstone period of activity.

The eastern end of the mass is now definitely dated by the fact that on Seeconnell it is cut by hornblende-lamprophyres (spessartites), similar to the uncrushed hornblende types in the Ards Peninsula and there found to belong to the Caledonian

¹ J. E. Richey, with petrological notes by H. H. Thomas, "The Tertiary Ring Complex of Slieve Gullion (Ireland)." *Q.J.G.S.* vol. lxxxviii, 1932, pp. 787-93.

period of activity, but to be post-Caledonian folding in age.¹
This evidence, in conjunction with the absence of signs of

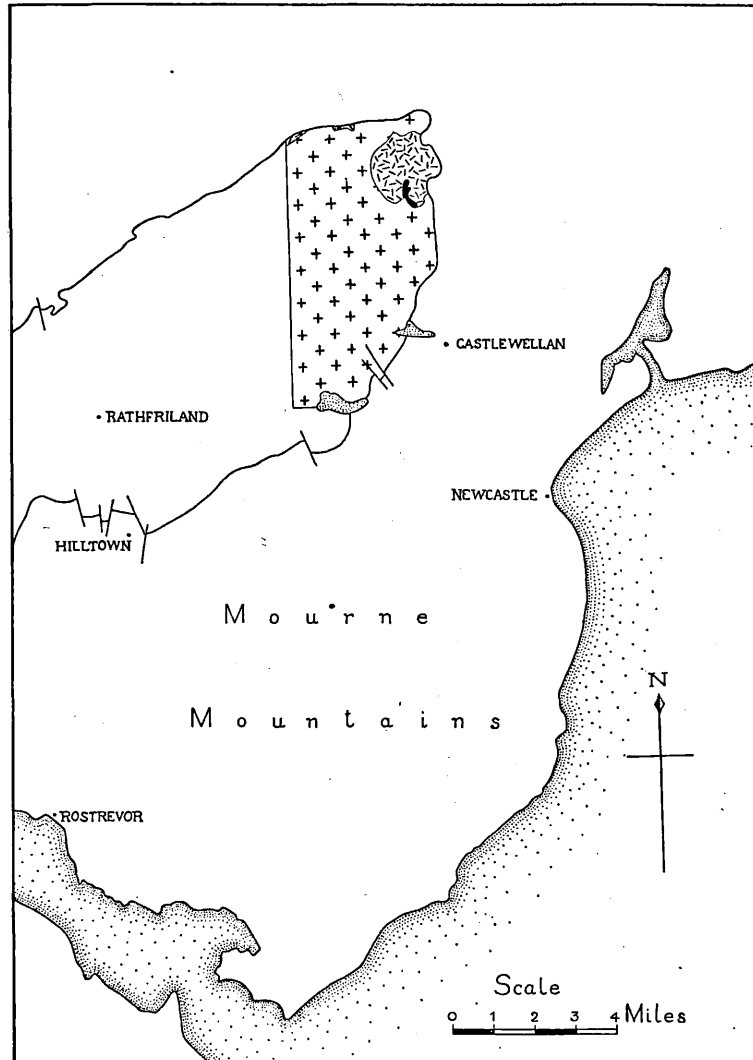


FIG. 1.—Sketch-map showing the area described in the paper.

crushing in the eastern end of the mass, fixes the age within narrow limits.

¹ D. L. Reynolds, "The Dykes of the Ards Peninsula, Co. Down." *Geol. Mag.* vol. lxxviii, 1931, p. 97.

The present paper forms part of a detailed investigation of the area, and deals with the eastern end of the complex as far westward as Slievenaboley and southward to Lough Island Reavy, the region described being about 21 square miles. This small area is so crowded with interest in regard both to variety of rock-types and evidence of hybridization and ultrametamorphism, that it is considered to merit separate description.

Previous work in the area was done by Egan of the Geological Survey in 1872, when it was mapped on the 1-inch scale.¹ From the descriptive memoir it is clear that Egan recognized a variety of rock-types, but of these no detailed descriptions are given, nor are they differentiated on the 1-inch map.

In the present investigation the area has been mapped on the 6-inch scale. It has not been found necessary to make alterations in the boundary of the complex, but within it the separate rock-types have been traced and delimited.

II. FIELD DESCRIPTION

(a) Topography

The eastern end of the Newry Complex forms the highest part of the mass, and is characterized by a succession of rugged hills which have an approximate parallelism, trending in directions that vary from north-west to north-north-west. They probably attained their present form in Glacial times, and slight variation in their trend is explained by corresponding variation in the foliation of the "granite" which controls the direction of ease of weathering. Hill country continues for a few miles beyond the eastern boundary, being coincident with the hardened metamorphosed sediments. The eastern contact-plane runs indiscriminately across hill and valley, the summits of the hills crossed being formed for the most part by the relatively resistant hornfels.

Along the northern contact, with the exception of Slieve Croob, the "granite" country forms the highest peaks; consistent with the fact, to be shown later, that the plane of contact here dips steeply southward, so that to some extent the hornfels is overlain by the "granite". The exception at Slieve Croob, the highest point in the area, where hornfels forms the summit (1755 feet), is explained by the fact that this is a portion of the roof.

Boulder-clay is absent from all the higher ground and exposures are good on the hill slopes, except for occasional concealment by bogland, as on parts of Slievenisky and Rough Hill. The lower ground is under cultivation, but as this forms only a small portion of the area, the rocks are on the whole well exposed.

¹ F. W. Egan, "Explanatory Memoir to Sheet 48." *Geol. Surv. Ireland*, 1872.

(b) Rock-types and Internal Contacts

Four distinct rock-types are exposed in the area: namely, peridotite, biotite-pyroxenite, hybrids (here used as a field term to include rocks corresponding in mineral composition to monzonites and diorites), and granodiorite, the position and extent of each being shown on the map, Pl. XXII.

Peridotite is exposed in a small area not larger than 3000 square yards, along the turf-path east of Crocknafoyle. Its contacts are not visible, though it appears to grade to picrite and augite-diorite, and possibly to merge through these into the surrounding hybrid. The peridotite is a dull black, coarsely crystalline rock which weathers with a curious nobbly appearance. Gradation to picrite and augite-diorite is due to hybridization, and is evidenced by the appearance of felspar in small blebs.

The ultrabasic rock has in part been invaded by a plagioclase magma, good evidence of which is to be found to the east of the turf-path. Here a slab of rock about four feet square exhibits xenoliths of the peridotite in a dioritic matrix. The xenoliths are rounded and show reaction with the felspathic magma, so that they can be seen in all stages of gradation from unaltered peridotite to almost imperceptible ghost-xenoliths. The ultrabasic rock appears to have been shattered in situ, and the invading magma has introduced a sedimentary xenolith about 12 by 4 inches in size.

Biotite-pyroxenite outcrops along the western side of Seeconnell, below the summit, and from the crescentic fashion in which it curves round the hill it may be concluded to be sheet-like in form, with a steep easterly dip. At its northern end it is a handsome coarse-grained rock, with lustrous black micas. Southwards it grades into a finer grained variety with marked foliation striking 54° W. of N. and dipping steeply eastward. Except to the south-west, the biotite-pyroxenite is surrounded by a zone of hybrid rocks into which it grades by the incoming of leucocratic minerals. This is obviously a case of reaction and not an intrusive contact, and it becomes an arbitrary matter as to where to place the boundary of the ultrabasic type. I have used colour as a criterion, and those rocks which are sufficiently deficient in felsic minerals to appear black are mapped as biotite-pyroxenite, although uncontaminated biotite-pyroxenite actually occurs only in the centre of the zone, where the outcrop attains its greatest width.

The mode of hybridization on the western side is clearly exhibited on the western side of the Backaderry Road, near the farmhouse at the foot of Slievegarron and at the northern end of the main outcrop. The biotite-pyroxenite is here intricately

veined with a white plagioclase rock. In places, the latter occurs as distinct veins and small dykes which contain xenoliths of biotite-pyroxenite, and at others it grades, through types like the typical black hybrids of Slievegarron, into a coarse variety of biotite-pyroxenite containing bleb-like inclusions of felspar. From this evidence it is clear that the hybrids to the west of the main outcrop of biotite-pyroxenite have resulted from the permeation of the ultrabasic rock, at least after partial crystallization, by a plagioclase magma and consequent reaction.

Not infrequently the biotite-pyroxenite includes rafts and small xenoliths of altered sediments. Such a raft of augite-hornfels, 10 feet in width and striking north-north-west parallel to the strike of the neighbouring country-rocks, appears on the western slope of Seeconnell. In the banks of the stream which follows the eastern foot of Seeconnell, just south of the bridge where the stream passes under the road, to the north of the hill, all stages of reaction between biotite-pyroxenite and sedimentary rafts are exposed. The biotite-pyroxenite shows spheroidal weathering and is margined by rafts of sediments. The latter have become highly crystalline with porphyroblasts of felspar, whilst the biotite-pyroxenite passes to a fine-grained highly micaceous type, rather resembling a biotite-hornfels in appearance, but with phenocrysts of augite. The significance of this reaction will be dealt with in the petrological section (p. 618).

The biotite-pyroxenite also appears in two isolated areas in the hybrid zone. One, at the southern end of Slievegarron, at a height of 1000 feet, near the contact of hybrid and granodiorite, has an elongate outcrop striking 81° W. of N. and is about 50 yards long by five wide. It grades into the surrounding hybrid by the incoming of leucocratic minerals. The other isolated outcrop occurs to the south-east of Seeconnell at the margin of the hybrid zone. It is exposed in a cultivated field near the point where the stream crosses the road. Its western contact with the hybrid is obscured by cultivation. On the eastern side, however, a small cutting has been opened in which the biotite-pyroxenite, exhibiting spheroidal weathering, is cut by a small granodioritic intrusion about four feet wide. The latter has found its way along the contact between pyroxenite and sediments, in addition to penetrating the pyroxenite in ramifying veins. The altered sediments are rich in biotite and are characterized by abundant porphyroblasts of felspar.

The hybrids occur in the zone surrounding the biotite-pyroxenite and in two isolated areas on the northern boundary, one extending from White Rocks across the north of Legananny Mountain, and the other on Rough Hill, which is the hill west

of Legananny Mountain. The rocks of these areas vary from monzonites to diorites in composition, though they often differ significantly from these types in texture.

To the east of the main outcrop of biotite-pyroxenite, the hybrids are usually fine grained, grey in colour on a freshly fractured surface, and characterized by augite phenocrysts that reach a size of 4 by 5 mm. Biotite and leucocratic minerals can also be distinguished macroscopically. For convenience of reference these will be termed hybrids of the Seeconnell type.

To the west of the main outcrop, the hybrids more closely resemble the biotite-pyroxenite, but with the addition of leucocratic minerals. They are often blacker in colour than the type just described, augite is discernible macroscopically but does not appear as phenocrysts, and lustrous biotite is usually the most obvious mineral. The percentage of dark minerals is very variable and there is frequent gradation to biotite-pyroxenite. This group of hybrids will be distinguished as the Slievegarron type.

The distribution of both Seeconnell and Slievegarron types is indicated on the map, Pl. XXII. It should be understood, however, that this distinction is a broad one only, and it is not everywhere possible, in the field, to distinguish between the two types. In addition, examples of the Slievegarron type occur in the area characterized by the Seeconnell type and vice versa.

Evidence of the origin of the Slievegarron type has already been discussed in the description of the biotite-pyroxenite. Evidence of the origin of the Seeconnell type, however, rests mainly on microscopic examination, and is deferred to a later section.

Xenoliths of hornfelsed sediments, which frequently merge into the surrounding igneous rocks, are common in all the hybrids.

On Slievegarron, along the western margin of the main hybrid zone, a belt of rocks characterized by hypersthene occurs. In the field, these rocks show some resemblance to the granodiorite, but are darker in colour. Although they are marked by large poikilitic plates of biotite, they are distinctly less rich in this mineral than the hybrids of Slievegarron type with which they are in contact. Their boundary has been plotted on the map mainly as the result of an examination of a large number of thin sections, since the hypersthene is not recognizable macroscopically.

The main part of the area is occupied by granodiorite, rich in biotite, which shows intrusive contacts against the hybrids. Such contacts are readily found on Rough Hill and Legananny Mountain. The contact to the west of the main

hybrid zone can usually be found only within two or three feet, the marginal rocks having been badly rotted. To the southwest of the hybrid zone the granodiorite comes directly in contact with the biotite-pyroxenite. It veins the hybrids and penetrates the biotite-pyroxenite in the two dyke-like masses that are indicated on the map, and possibly in others that are less well defined.

The granodiorite is coarse in grain right up to its contact with the rocks of the main hybrid zone, but a fine-grained variety occurs in contact with the hybrids on Rough Hill. It is best developed on the eastern side of Rough Hill and its outcrop dies out on the western side. It is evidently an earlier intrusion than the normal granodiorite, since it occurs as inclusions in the latter.

Throughout its mass the granodiorite is characterized by xenoliths which conform in elongation and arrangement to the direction of foliation. Examples are to be seen to perfection in the quarry at Ballymagreehan. In addition to inclusions of hornfels, rounded and elongated xenoliths of the hybrid types, sometimes many feet across, are common, and small residual patches of the latter, rich in biotite, are always present. The presence of these enclaves suggests that the area now occupied by granodiorite was formerly occupied by the hybrids, a view which is supported by the occurrence of the latter not only in the zone surrounding the biotite-pyroxenite but also at two localities on the northern margin. The granodiorite ichor thus appears to have risen up through and incorporated the hybrids. That there was no great lapse of time between the two intrusions and that the hybrids in the centre of the area were, although crystalline, still in a heated condition is indicated by the absence of a chilled margin to the granodiorite where it is in contact with the main hybrid zone.

Aplite and narrow pegmatite veins cut all the rocks of the district. They vary from less than an inch to about six inches in thickness and usually occur as gently dipping sheets.

Felspathic veins are also common. In the quarry at Ballymagreehan they traverse the granodiorite, against which some of them have sharp boundaries whilst others merge imperceptibly into the adjacent rock by the incoming of ferromagnesian minerals that have obviously been derived from it. The transitional type thus produced is whiter and coarser grained than the normal granodiorite, and is similar to certain local varieties of the granodiorite, the origin of which may probably be explained by reference to this comparison.

Similar felspathic veins cut the hybrids, and more especially those of the Slievegarron type, into which they frequently merge by a process of suffusion. This phenomenon is well exhibited on Rough Hill, where rapid variations from melanocratic to highly felspathic varieties are found.

An interesting pegmatite vein, about three inches in width, cuts the biotite-pyroxenite at the foot of Slievegarron near its contact with the granodiorite. It consists solely of biotite and plagioclase and is the only one of its kind that has been seen in the area.

(c) Structures of the Complex and its Relation to the Sediments

The igneous complex is intruded into rocks of Silurian age which consist of alternating beds of greywacke and shale varying in thickness from a few inches to 14 feet or more, greywacke on the whole predominating.

From Lough Island Reavy northwards as far as Seeconnell the contact can be mapped with ease. It is steep, extending in general straight across hill and valley. Wherever any inclination can be detected it is directed outwards, away from the complex, a dip of 64° E. being visible on Clanvaraghan Mountain, where it conforms to the dip of the sediments.

For about a mile northward from Seeconnell, the contact crosses low ground which is under cultivation and it can be studied only in isolated exposures. On the eastern slopes of Slievenisky, however, it is again well exposed and, as shown on the map (Pl. XXII), a promontory of sedimentary rocks extends into the hybrids and granodiorite. This is a portion of the domed roof, dipping gently east-north-east at 14° . The strike of the roof sediments varies from north-eastward to 16° S. of E., the dip being almost vertical, so that the roof-contact is seen to be transgressive.

The contact is not again well exposed until it reaches the eastern slopes of Slieve Croob, where it curves round to the northern margin of the granodiorite and dips steeply northward. The summit of Slieve Croob forms part of the roof of the intrusion, the junction following the contours of the hill, and here again the granodiorite cuts across the dip of the roof-sediments at a high angle. About 2000 feet south-west of the summit, south of the bench-mark 1648 feet, there appears to be a small fault striking 14° W. of N. and having a westerly throw. This repeats the roof on its western side for a distance of roughly 500 feet, where the roof can be seen to pass to wall with a steep southerly dip. Another small parallel fault downthrowing to the west then again repeats the roof, the slope of which, as it approaches wall, is well exposed on the lower western slopes of Slieve Croob, where a dip of approximately 4° to a point about 12° W. of N. can be ascertained. Westward from Slieve Croob, the mapping along the northern slopes of Legananny Mountain and over the summit of the hill to the west shows that the wall of the intrusion here dips southward towards the complex at an angle of 50° to 60° .

The eastern wall conforms to the bedding of the sediments, whilst the northern wall conforms to the strike of the sediments and dips in the opposite direction, cutting the bedding at a low angle, possibly from 20° to 40°. Everywhere the roof transgresses the dip of the sediments at nearly a right angle. Fig. 2 illustrates the form of the complex.

On the map, Fig. 3, the eastern boundary is depicted, and from the numerous dips determined by the Geological Survey (Sheets 48 and 60) and a few additional measurements which I have made strike-lines have been drawn for the sediments. From this map it is evident that intrusion followed the Caledonian folding, the trend of which is transgressed, almost at right angles, by the north-eastern end of the granodiorite. Magma pressure must be responsible for the manner in which the strike-lines elsewhere swing round in conformity with the margin of the complex. A similar effect of magmatic pressure has been recognized in the case of the Strontian granite.¹ In the present instance, it is likely that the biotite-pyroxenite, unable to rise by stoping, exerted this shouldering stress. The later granodiorite, characterized as it is by xenoliths of the hybrids and transgressing the strike of the sediments at right angles on its north-eastern margin, was probably emplaced by stoping.

The granodiorite is well foliated with a planar foliation

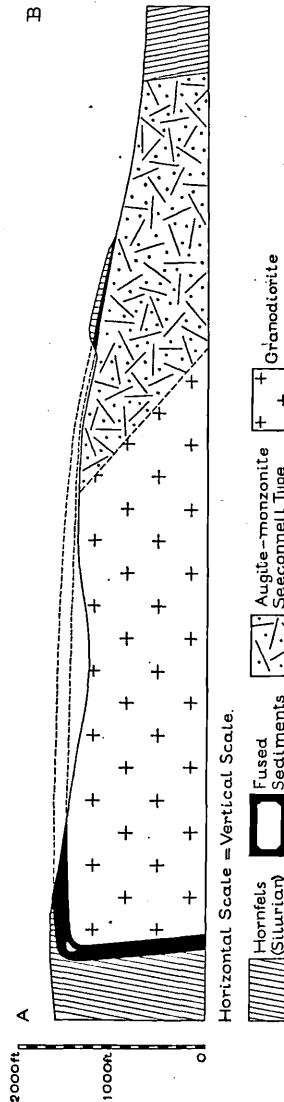


FIG. 2.—Section along A-B, Plate XXII, showing the form of the intrusion. The shading of the hornfels indicates the angle of dip.

¹ A. G. MacGregor & W. Q. Kennedy, "The Morvern-Strontian 'Granite'," *Summ. Progr. Geol. Surv. for 1931, Part II, 1932, p. 115.*

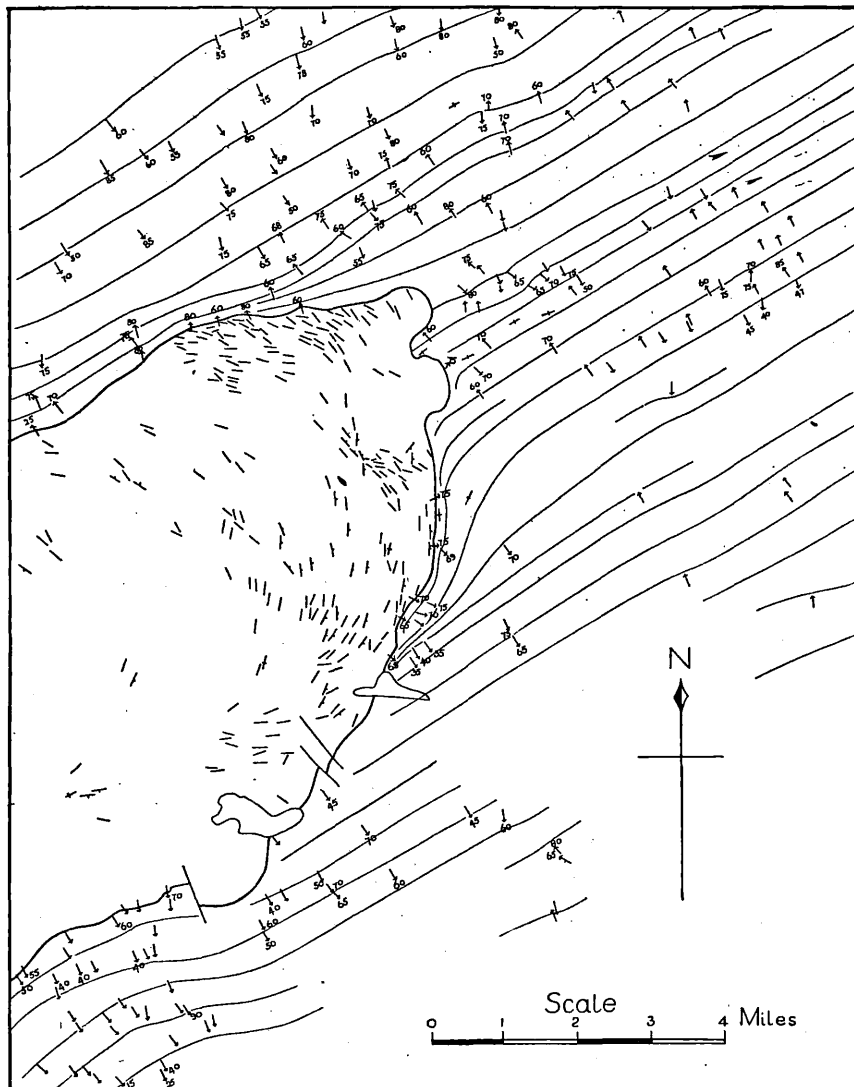


FIG. 3.—Map showing fluxion foliation in the granodiorite and the strike lines of the invaded Silurian sediments. The curving of the strike lines round the complex is indicative of magma pressure, and is probably to be attributed to the ultrabasic intrusions, since the later granodiorite transgresses the strike at its north-eastern end.

which tends to parallelism with the walls of the complex. The strike and, where possible, the dip of the foliation have been mapped for a slightly larger area than that described in the present paper, and are indicated on the map, Fig. 3. The foliation appears to be due to magmatic fluxion, the counter-clockwise motion of which was impeded by the southerly slope of the northern contact-plane. This idea is consistent with the way in which the foliation swings out round the southern contact with the biotite-pyroxenite and the main hybrid zone, crossing their trend almost at right angles. The hybrids show no sign of foliation.

The various igneous rocks, and more particularly the granodiorite, exhibit rectangular jointing, the three directions of which are apparently dependent on the external form of the complex. One joint-plane always shows parallelism to the nearest wall, a second stands vertically and normal to the wall, whilst a third, so far as can be tested, conforms to the roof.

(d) Metamorphism and Fusion

The sediments are converted to biotite-hornfels for a distance of at least a mile from the contact. At the eastern contact they are lustrous and schistose, due to the great development of biotite, whilst at greater distances, although biotite becomes much less conspicuous, the greywackes and shales continue to be noticeably baked and hardened.

Of greater interest is the evidence for fusion of sediments to be found in the district. This phenomenon is best exhibited on Slieve Croob, west of the summit. There, in a broad band with a maximum width of 500 yards, is a fine-grained rock which weathers in an irregular manner, giving rise to a furrowed surface. The rock is massive in appearance, with no sign of foliation, and of very uneven texture, there being variation, in specimens only a few inches square, from a type which closely resembles a fine-grained biotite-granite to one that is essentially a hornfels particularly rich in biotite. Occasionally, these two varieties appear as roughly parallel bands, probably indicating the original bedding; more frequently, however, their distribution is quite irregular. In places there are disconnected quartzose lenticles, sometimes branched, and only a few inches in length and about an eighth of an inch in width; these are obviously due to segregation within the mass. On Slieve Croob the fused rock is jointed with the granodiorite, of which, at first glance, it appears to be a fine-grained marginal modification.

That this material once existed in a molten condition is evidenced by the occurrence of lenticles of augite-hornfels scattered through its mass with an irregular orientation, and by the obvious signs of movement shown by the matrix, which

curves and twists round the fragments of augite-hornfels so as to suggest that it was stirred whilst in a highly viscous condition. This phenomenon is seen at its best to the south-east of Slievenisky, where an isolated patch of fused sediment, probably a relic of roof or of roof-pendant, is present in the hybrid zone. In it, rectangular fragments of augite-hornfels, still showing signs of bedding, are found crowded together with every possible orientation, as indicated in the diagram, Fig. 4.

Evidence of the origin of the fused sediment is to be found in the wall of the intrusion on the eastern slopes of Slieve Croob. There, on approaching the granodiorite, the change from hornfels to obviously fused sediment occurs at about 20 feet

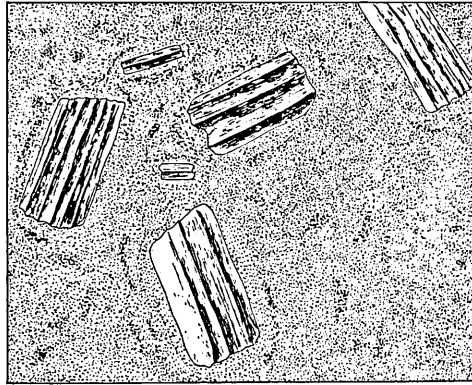


FIG. 4.—Sketch showing rectangular fragments of diopside-hornfels in a matrix of fused sediment, as seen to the south-east of Slievenisky. The illustrated part of the exposure is about two feet wide.

from the margin. Although the rock is finely crystalline and almost granitic in appearance, the original bedding is preserved and dips at a high angle towards the granodiorite contact. Traced from this point towards the granodiorite, the rock becomes more massive and only isolated portions continue to show relics of bedding. Frequently it can be seen that the bedded parts have been transgressed along joint-planes by the surrounding fused material, which evidently became sufficiently mobile to flow. In places the liberated blocks have been carried forward and swung round at high angles to their original position. Some still retain their rectangular outline, whilst others have become rounded and lenticular in form. At the actual contact, the original sediment forms the massive rock previously described as being

jointed with the granodiorite; it contains occasional unfused lenticles of augite-hornfels.

Just within the margin of the zone of fusion, north of Legananny Mountain, a band of augite-hornfels about three feet wide outcrops. A similar band, which may be a continuation of it, can be traced across the valley between Legananny Mountain and Rough Hill. In the valley, the fused sediment is absent, while the augite-hornfels occurs as a band in the hornfelsed sediments and is seen to represent a definite lithological type, such as a highly calcareous shale. On the eastern slope of Rough Hill this band again enters the zone of fusion and at one point it can be observed in process of destruction, the fused material having repeatedly broken through the band, so that it is now cut up into isolated lenticles orientated

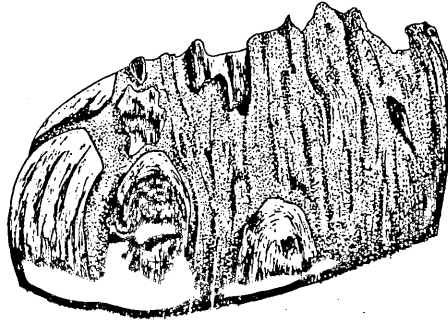


FIG. 5.—Band of augite-hornfels in process of destruction by the invasion of fused sediment along bedding- and joint-planes. Eastern side of Rough Hill. The exposure is about four feet wide.

in the direction of strike (see Fig. 5). In a small stream to the west of Rough Hill, fused sediment and augite-hornfels are finely interbedded, the latter forming strings of lenticles not more than an inch thick which still mark the original bedding.

Sometimes the residual lenticles of augite-hornfels are zoned parallel to their margin.

The distribution of the fused sediment is of interest in connexion with its origin. When traced away from the contact it passes into a hornfels zone which includes biotite- and cordierite-hornfels. In the nature of the case there is no sharp mappable line between the zone of fusion and that of normal contact alteration. On approaching the hornfels, signs of movement in the fused and recrystallized mass disappear and then the textures gradually change. In mapping the limit of fusion, the outer line has been drawn to indicate the limit within which actual flow took place.

Along the eastern side of the granodiorite, fused sediment

is absent on Clanvaraghan Mountain, but occurs in a small area just to the south of the contact between the granodiorite and the hybrid zone. Its boundaries and extent, however, cannot be mapped, since the ground in this area is under cultivation. Similarly, it is not possible to say whether the fused sediment is present along the eastern margin of the hybrid zone. In the roof, however, to the east of Slievenisky, typical fused sediment containing lenticles of augite-hornfels can be mapped, beneath the zone of biotite-hornfels, along the northern and western boundaries. The actual contact on the southern side is masked by a line of bog. The fused sediment, which here forms the roof of the hybrid intrusion, dies out to the north-east at the passage from roof to granodiorite wall. Isolated portions of fused roof-sediment outcrop in the hybrid zone on the ridge north-east of the summit of Slievenisky and on the south-eastern slopes of the same hill. It is also present along the northern boundary, where its outcrop commences on the eastern slope of Slieve Croob at a height of a little over 1000 feet and widens westward; its greatest thickness is attained below the summit of the hill, where it forms the roof of the complex. On the lower eastern slopes of Slieve Croob, the granodiorite contains xenoliths of fused sediment, indicating the presence of the latter, eastward of its present termination, prior to the intrusion of the granodiorite. Fused sediments rim the granodiorite wall across the west of Slieve Croob, and edge the wall of the hybrids to the north of Legananny Mountain. Here they terminate, together with the hybrids, both reappearing on Rough Hill.

The evidence given above shows plainly that the fusion of the sediments antedated the intrusion of the granodiorite; moreover, the manner in which the outcrop of the zone of fusion follows the roof and wall of the hybrid intrusion demonstrates that fusion was caused either by the hybrids or, more probably, by their parent magma, which can be shown to be the biotite-pyroxenite. It was evidently selective, as can be seen even more clearly in thin section, residual patches of hornfels being everywhere present, whilst the more calcareous parts of the shales escaped fusion entirely.

The breaking up of the bands of augite-hornfels and their random distribution as lenticles in the fused material were probably due to movement initiated by the intruding hybrids. The textures of the latter, as will be shown in the petrological section, often indicate high viscosity, and the drag of this rising viscous mass on its still more viscous walls could well account for the destruction of the bands of augite-hornfels, and for the contortions in the fused material where it was dragged round residual rotated lenticles.

The fused sediment serves as a means for comparing the outlines of the area originally occupied by the hybrid rocks

with that of the later granodiorite. Since on Slieve Croob it forms the roof of the granodiorite, it is evident that the latter there rose to approximately the same level as the hybrid intrusion. It also appears that the walls of the two intrusions practically coincide, the granodiorite transgressing slightly beyond the limits of the earlier intrusion in places—for example, in the valley between Rough Hill and Legananny Mountain, to the east of Slieve Croob, and along the eastern wall.

Two parallel wall-like inclusions of fused sediment outcrop in the hybrid zone on the lower eastern slopes of Seeconnell and are separated by a depression occupied by hybrids. They strike in a north-north-westerly direction parallel to the margin of the hybrid and the strike of the contact sediments. In them, relics of the original bedding are preserved as a series of narrow bands and strings of lenticles of augite-hornfels, the strike being parallel to the margin of the rafts and the dip being eastward at an angle of 45° or more. They are of interest since they suggest that the hybrid or its parent magma rose along the bedding-planes of the sediments.

(e) Contact of Granodiorite and Hybrids with Sediments

The contact between granodiorite and sediments is everywhere sharp but intricate. Veins of granodiorite penetrate the hornfelsed and fused Silurian rocks, patches of which have been detached and appear to be floating off into the igneous rock, whilst the granodiorite is visibly contaminated for a distance of several feet from the contact. On Slieve Croob, veins of granodiorite and quartz penetrate the fused sediment for a distance of many yards from the contact, while marginally all stages of reaction between the granodiorite and fused sediment is exhibited.

The contact between hybrids and sediments is not easily studied. Along the eastern side, with the exception of the roof-contact on Slievenisky, it occurs in low ground which is under cultivation, whilst on Slievenisky it is masked by a line of bog many yards in width. Along the northern contact, peat masks the line of junction on White Rocks and Legananny Mountain, so that in the whole area it can be studied only on Rough Hill. Here the contact is sharp, in that it is easily seen, the dip and strike of the altered sediments still being evident. The contact sediments have been fused. At the foot of the hill, on the western side, the fused rock is banded with unfused layers of augite-hornfels which can be seen in process of breaking up into lenticular patches. Higher up the hill-slopes, the fused sediment forms a massive rock, rich in residual lenticular patches of augite-hornfels with a random

arrangement. Here the fused sediment has been largely "granitized" (migmatized) by the hybrid augite-biotite-diorite, which has risen up the bedding-planes and soaked through the sediments, probably while they were still in a state of partial fusion. The sediments, even while retaining their original bedding, have an igneous aspect for a distance of 20 yards or more from the contact, as though pseudomorphed by the neighbouring igneous rock. Fractured surfaces show that they contain large phenocrysts, resembling the augite in the augite-biotite-diorite, whilst small residual patches of fused sediment and augite-hornfels are of frequent occurrence.

North of the summit of the hill, and on the western side of the wire fence, which runs roughly in a north-east and south-west direction, the intrusive hybrid itself exactly resembles the altered sediments just described, even to the occurrence of the characteristic patches of augite-hornfels. It differs only in the fact that it is here massive and exhibits rectangular jointing.

The contact phenomena here described provide important evidence bearing on the mode of intrusion of the hybrids. The augite-biotite-diorite on Rough Hill evidently rose by soaking into the zone of fused sediments and gradually incorporating them, the whole, while sufficiently mobile, moving on to a higher level.

III. PETROLOGY

(a) Metamorphic Rocks

(i) Varieties of Hornfels.—The sediments on the eastern margin and beyond the zone of fusion on the northern margin have been converted to biotite- and cordierite-hornfels. As the contact is approached, biotite is developed to such an extent as to suggest that there has been an enrichment in potash. This increase in the percentage of biotite towards the contact is well illustrated in a traverse across Clanvaraghan Mountain and Slievehanny.

Near the contact on Clanvaraghan Mountain, the biotite-hornfels is medium grained with a granulitic texture. It is exceedingly rich in reddish brown biotite, which is crowded with pleochroic haloes and is wrapped round the quartz; a little white mica is also present. In addition to abundant quartz, there are small amounts of orthoclase and andesine, the latter frequently being zoned. Six-sided and rectangular aggregates of pinitic represent cordierite. Zircon and faintly bluish apatite are present as accessories, the latter having aggregates of dust-like inclusions in a central zone.

Farther from the contact on Clanvaraghan Mountain, the biotite-hornfels is finer grained, the quartz has crenulate

margins, and the biotite, which is less abundant, occurs in small flakes orientated parallel to the original bedding. A little orthoclase and plagioclase are present, with apatite and zircon as accessories. The change from granulitic to mosaic texture on passing away from the contact or the zone of fusion is general throughout the area.

Three-quarters of a mile from the contact, on Slievehanny, the sediments are compacted and hardened, but in thin section the only change from the original greywacke is seen to be the development of small biotite flakes from the muddy matrix. A little pleochroic blue apatite is present.

It is of importance that throughout the hornfels zone small pleochroic blue apatites occur sparsely as an accessory.

The augite-hornfels, which occurs as bands in the contact aureole, as residual lenticles in the zone of fusion, and as xenoliths in the biotite-pyroxenite and hybrids, is always grey, compact, and porcellanous in appearance. In section it is seen to be fine grained and to consist of quartz, diopsidic augite, and a little plagioclase, which varies from andesine about Ab_{58} to andesine-labradorite Ab_{50} . Small granules of a strongly coloured sphene and iron ore are not uncommon. A reddish brown biotite, which poikilitically encloses the augite and quartz, is present in the bands in the contact aureole. As a rule, quartz, with a mosaic texture, forms rather more than 50 per cent of the rock. The augite granules are anhedral and often rounded in outline; their faintly green colour, extinction angle, and optic axial angle suggest diopside. They are at times aggregated into small clusters which may be strung out in the direction of bedding. Idocrase is sometimes present and small pleochroic blue apatites form a rare accessory.

The augite-hornfels lenticles in the zone of fusion sometimes exhibit concentric banding parallel to their margin. A section from such a banded rock, collected from the course of a small stream at the western foot of Rough Hill, shows gradations from a central zone of fine augite-hornfels, through biotite-augite-hornfels with poikilitic biotite, to a similar type with poikilitic hornblende in addition, the latter growing at the expense of the augite where it is in contact with the fused sediments.

A banded lenticle of augite-hornfels from one of the rafts of fused sediment in the hybrid zone, on the eastern side of Seeconnell shows a change from a fine-grained idocrase-augite-hornfels in the centre, in which idocrase forms most of the matrix of the rock, through augite-hornfels and biotite-augite-hornfels, to a coarser equigranular rock in contact with the fused sediment. The coarser outer zone consists of quartz, zoned andesine, biotite, and augite, the latter being in part converted to hornblende. The banding in these residual augite-hornfels lenticles is probably to be attributed to the

outward migration of the more mobile alkali-rich constituents of the rock.

These varieties of augite-hornfels are evidently due to the alteration of highly calcareous bands.

(ii) Fused Sediments.—The rocks due to recrystallization in the zone of fusion show rapid changes from small residual patches of coarsely crystalline biotite- and cordierite-hornfels to types with a fine granitic texture, due to more complete fusion and recrystallization.

The more completely fused portion (Fig. 6) is equigranular and notably coarser in grain than the normal hornfels of the

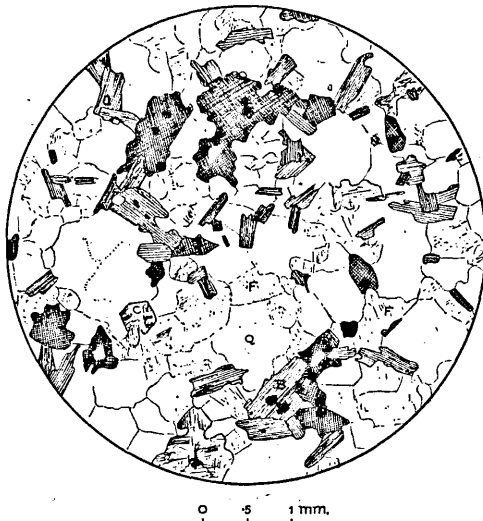


FIG. 6.—Fused sediment, No. 602, from Slievenisky, showing biotite (B), quartz (Q), cordierite (C), and orthoclase and plagioclase (F).

area. Quartz, the most abundant mineral, often is almost square in outline, extinguishing with the diagonals, so that it has evidently developed bipyramidal form. At other times it is intercrystallized with the other constituents, or more rarely forms a poikilitic matrix. Reddish brown biotite, with pleochroic haloes, is abundant and shows considerably better form than that in the normal hornfels, (001) faces being frequently developed. It commonly penetrates quartz or orthoclase, and more rarely is wrapped round the quartz. It has no tendency to a parallel orientation, such as is common in biotite-hornfels. A little plagioclase, oligoclase-andesine, or andesine, is always present as euhedral or subhedral crystals which are usually zoned. In a section of the fused rock from

the roof on Slievenisky, andesine Ab_{65} is very abundant, almost equalling quartz in amount. Orthoclase is of rare occurrence. Pinite aggregates, after cordierite, are common, and fresh cordierite, with pleochroic haloes, not infrequent. The cordierite is euhedral or subhedral, in the former case being prismatic parallel to the c axis or tabular parallel to (001). Apatite is present as an accessory and is rarely blue and pleochroic. The leucocratic constituents are outlined and stained by a yellowish substance, due to the diffusion of the limonite wrapping originally present round the grains.

Segregation lenticles are present in places. They consist principally of quartz, which is slightly coarser in grain than in the surrounding rock, and a little anhedral plagioclase. Biotite is absent from these lenticles and only a little cordierite is present marginally.

The residual patches of biotite-hornfels consist of biotite, quartz, and a little cordierite. The biotite, which resembles that in the fused portion, sometimes forms 50 per cent of the rock and is very coarsely crystalline. The quartz varies considerably in grain-size and frequently forms a poikilitic matrix.

Below are analyses of the more completely fused portion of the rock and its residual biotite-rich patches, together with analyses of an unaltered greywacke and shale from the district:—

	1.	2.	3.	4.
SiO ₂	66.65	58.50	75.70	55.00
Al ₂ O ₃	14.33	14.15	10.30	21.84
Fe ₂ O ₃	0.55	1.22	0.34	0.82
FeO	5.62	10.92	4.18	6.73
MgO	3.00	5.75	1.69	3.78
CaO	1.47	0.55	1.55	0.50
Na ₂ O	2.49	1.23	1.59	1.67
K ₂ O	2.99	4.15	0.98	3.94
H ₂ O +	1.82	1.20	2.25	4.35
H ₂ O -	0.13	0.20	0.20	0.30
CO ₂	none	none	none	none
TiO ₂	0.92	1.80	0.95	0.70
P ₂ O ₅	0.17	0.08	0.18	0.18
Cl	0.02	n.d.	n.d.	n.d.
F	n.d.	n.d.	n.d.	n.d.
S	tr.	tr.	tr.	tr.
Cr ₂ O ₃	0.01	n.d.	0.02	none
V ₂ O ₃	0.02	n.d.	none	sm. tr.
NiO	0.01	n.d.	n.d.	n.d.
MnO	0.08	0.15	none	tr.
SrO	tr.	n.d.	none	none
BaO	0.04	n.d.	none	tr.
Li ₂ O	tr.	n.d.	n.d.	n.d.
	<hr/>	<hr/>	<hr/>	<hr/>
	100.32	99.90	99.93	99.81

1. Fused sediment (602), Slievenisky. Analyst, L. S. Theobald.
2. Biotite-rich patches in fused sediment (602), Slievenisky. Analyst, W. H. Herdsman.
3. Greywacke (712), Edendarriff Mountain. Analyst, W. H. Herdsman.
4. Shale (713), Edendarriff Mountain. Analyst, W. H. Herdsman.

The analysis of the more completely fused part of the sediment supports the field evidence that it results from the differential fusion of greywacke and shale, the biotite-rich patches representing residual portions of shale.

From an examination of the analyses, it is evident that the mixture of fused sediment and biotite-rich residual patches, with a predominance of the former as found in the zone of fusion, is enriched in alkalis as compared with the average of the analysed greywacke and shale. This is in keeping with the visual demonstration of potash enrichment in the hornfels zone, on approaching the contact.

(b) Peridotite

This is a coarse-grained rock richer in augite than olivine, and with subordinate biotite, brown hornblende, and hypersthene, the minerals all being anhedral.

The augite has a faint pinkish tint with $Z \wedge c = 45^\circ$, and is probably a titaniferous variety. Occasional crystals show sparse, black, rod-like inclusions, arranged parallel to the cleavage traces and the basal plane. The augite encloses irregular patches of brown hornblende, both minerals having a parallel crystallographic orientation. The hornblende is probably hastingsite, since $Z \wedge c = 31^\circ$ and it is strongly pleochroic, with $Z = \text{dark brown} > Y = \text{dark brown} > X = \text{yellow}$. It sometimes shows simple twinning parallel to (100).

Olivine occurs in large anhedral crystals. It is optically —ve with an optic axial angle of almost 90° and probably contains about 10 per cent of FeO. A yellowish brown non-pleochroic serpentine is developed along the cracks of the olivine. It is optically —ve with X normal to (001) and $2V$ practically zero; there is much associated magnetite. The biotite is a foxy brown variety and intensely pleochroic, with $X = \text{yellow} < Y = Z = \text{foxy brown}$. It shows no pleochroic haloes and is frequently associated with iron ore.

Hypersthene, which is colourless or only faintly pleochroic, with $Z = \text{colourless}$, $X = \text{pale pink}$, is present in small amount and partly converted to green serpentine.

Accessory minerals are apatite and iron ore, of which the former is abundant and enclosed in all the other constituents.

The analysis, norm, and mode of specimen No. 575 are tabulated on p. 605.

As already described (p. 588), the peridotite has been permeated and hybridized by a felspathic magma, so that all gradations between peridotite and contaminated invading ichor can be found.

In the commonest type, which is only slightly altered, the peridotite is flecked with white felspathic patches. Microscopically it resembles the unaltered peridotite, except for the appearance of pools of andesine-labradorite, and the rock may

be classed as picrite. The plagioclase is definitely finer in grain than the ferromagnesian constituents.

PERIDOTITE, Crocknafoyle

	ANALYSIS	MOL. PROP.	NORM	
SiO ₂	45.91	0.765	or	3.34
Al ₂ O ₃	3.51	0.034	ab	2.62
Fe ₂ O ₃	2.11	0.013	an	6.39
FeO	9.73	0.139		
MgO	19.42	0.486	di	23.08
CaO	14.28	0.256		16.00
Na ₂ O	0.31	0.005		5.15
K ₂ O	0.58	0.006	hy	8.50
H ₂ O +	1.42	—		2.77
H ₂ O -	0.11	—	ol	16.80
CO ₂	0.45	0.011		5.92
TiO ₂	0.72	0.009	mt	3.02
P ₂ O ₅	1.00	0.007	il	1.37
Cl	0.02	—	ap	2.35
F	n.d.	—	cc	1.10
S	tr.	—	water, etc.	1.72
Cr ₂ O ₃	0.10	0.001		100.13
V ₂ O ₅	0.03	—		
NiO	0.06	0.001		
MnO	0.26	0.004		
SrO	none	—	MODE	
BaO	0.08	0.001	olivine	22.4
Li ₂ O	none	—	pyroxene	63.3
			hornblende	4.7
			biotite	5.4
			apatite	2.3
			iron ore	2.7
	100.10			100.8

Analyst, L. S. Theobald.

In a more advanced stage of hybridization, the ultrabasic rock has been converted to diorite. Macroscopically it is distinctly felspathic and is characterized by large poikilitic plates of biotite. In thin section, the felspathic constituents are seen to form the main part of the rock and are not differentiated from the mafic portion in grain-size. Plagioclase predominates, but orthoclase is also well represented. The biotite is less rich in colour than that in the unaltered peridotite, but is still of a distinctly reddish tone. It is also distinguished from that in the peridotite by the occasional presence of pleochroic haloes. The augite of the peridotite has been mainly converted to hornblende, which occurs as large anhedral crystals, in reaction relation to augite, the latter merely forming residual cores. Hornblende is also present as aggregates of acicular crystals. The olivine and hypersthene of the peridotite have entirely vanished. Of the accessories, apatite is the most abundant, iron ore occurs associated with biotite in irregular patches, whilst sphene has been introduced by the invading ichor and forms large anhedral crystals. The

peridotite has been entirely reconstructed and converted to diorite, whilst still retaining normal igneous textures.

The contaminated invading magma forms the matrix-rock in the exposure. Like the diorite just described, the matrix has large poikilitic plates of biotite, though as a whole it is much lighter in colour. Microscopically it can hardly be distinguished from the final stage of hybridization of the peridotite, being a slightly more felspathic diorite. Its ferromagnesian constituents are hornblende and biotite, the former with residual augite cores, giving evidence that augite was incorporated from the peridotite. The biotite may also have its origin in the peridotite, as is suggested by its reddish tint, but its spongy texture indicates crystallization *in situ*. The invading ichor was evidently a plagioclase magma practically devoid of ferromagnesian constituents, sphene being the most important accessory in its contaminated representative.

(c) Biotite-pyroxenite

The biotite-pyroxenite is typically coarse grained and consists almost entirely of biotite and augite with a little brown hornblende, apatite and iron ore forming accessories. Felspar is absent from the uncontaminated biotite-pyroxenite, but by the incoming of plagioclase and a little orthoclase it shows gradations to the augite-diorite of the hybrid zone.

The augite is anhedral, being intimately intergrown with biotite, by which it is usually completely surrounded. It is a practically colourless or faintly greenish diopsidic augite with $Z \wedge c = 42^\circ$. A zone of black rod-like inclusions is frequently present and occurs either centrally or a little within the margin. The rods are arranged in two crystallographic directions, one parallel to the cleavage traces and the other parallel to the basal plane. From the fact that these inclusions give rise to leucoxene on decomposition, it is inferred that they are a titaniferous variety of iron ore. The augite is also characterized by inclusions of small biotite flakes, arranged parallel to the cleavage traces.

The biotite is a dark reddish brown, strongly pleochroic variety, being distinctly darker and less red in colour than that in the peridotite. The crystals have well developed basal planes and are usually outlined by strings of ilmenite, whether in contact with one another or with the other minerals of the rock. Similar strings of ilmenite sometimes extend along the cleavage planes, and in their neighbourhood the biotite is often bleached. Pleochroic haloes are absent.

Brown hornblende, probably hastingsite, is present in anhedral crystals which are intimately intergrown with the augite. It is pleochroic with $Z = \text{deep greenish brown} > Y = \text{pale brownish} > X = \text{pale yellow}$, and resembles that in

the peridotite. In addition, there are aggregates of actinolite associated with iron ore.

Apatite is abundant and enclosed by all the ferromagnesian minerals. It frequently builds large crystals which sometimes have dust-like inclusions in their interior. Iron ore is abundant and pieces of biotite-pyroxenite a cubic inch in size can be lifted to the electromagnet through a considerable distance.

The analysis, norm, and mode of the uncontaminated biotite-pyroxenite, No. 485, are tabulated below. The predominance of biotite—clearly brought out by the mode—suggests that the rock might more strictly be called an augite-

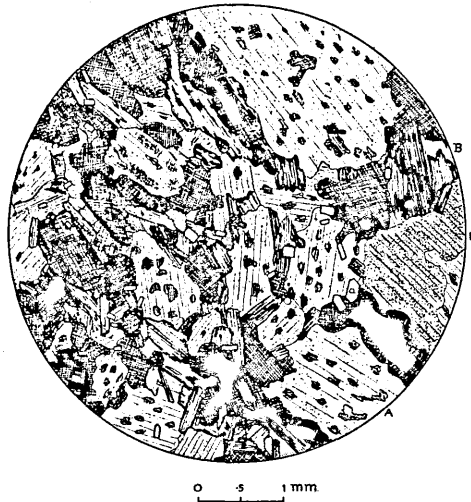


FIG. 7.—Biotite-pyroxenite (No. 485) from Seeconnell, showing biotite (B) with rims of titaniferous iron-ore, augite (A) with inclusions of biotite and in one case showing the development of ilmenite rods, brown hornblende (H), and accessory apatite (a).

biotite, but petrologists have fought shy of using the cacophonous term "biotite" except for monomineralic biotite-rocks. The adoption of the term "biotite-pyroxenite" is justified by usage, if not by text-book definitions, petrologists such as Lacroix and Rittmann (Mte. Somma), Plemister (Loch Ailsh), Larsen (Libby Stock, Montana), Holmes (Uganda volcanoes), and Burri (Upper Burma) having already used it for rocks essentially similar to that of Seeconnell.

In the types that grade to the rocks of the hybrid zone, felspar first makes its appearance in isolated pools. Plagioclase predominates and approximates to andesine, Ab_{64} orthoclase being present in only small amount. Where it is in contact with plagioclase, the augite has a reaction rim of

green hornblende, grown in optical continuity with the augite core, and the rim of titaniferous iron ore is absent from the biotite.

BIOTITE-PYROXENITE, Seeconnell

ANALYSIS		MOL. PROP.	NORM	
SiO ₂	41.71	0.695	or	4.45
Al ₂ O ₃	8.55	0.084	an	9.73
Fe ₂ O ₃	2.51	0.016	lc	13.52
FeO	9.79	0.136	ne	2.84
MgO	14.65	0.366	(CaSiO ₃	15.66
CaO	11.74	0.209	di- MgSiO ₃	10.70
Na ₂ O	0.60	0.010	FeSiO ₃	3.70
K ₂ O	3.65	0.039	ol- Mg ₂ SiO ₄	18.20
H ₂ O +	1.41	—	Fe ₂ SiO ₄	6.73
H ₂ O -	0.16	—	mt	3.71
CO ₂	0.16	0.005	il	4.26
TiO ₂	2.15	0.028	ap	3.70
P ₂ O ₅	1.62	0.011	cc	0.50
Cl	0.01	—	water, etc.	1.79
F	0.16	0.005		
S	0.03	—		99.49
Cr ₂ O ₃	0.04	—		
V ₂ O ₃	0.06	—		
NiO	0.04	—	MODE	
MnO	0.24	0.003	biotite	45.3
SrO	0.04	—	augite	27.4
BaO	0.50	0.003	hornblende	19.4
Li ₂ O	tr.	—	actinolite	1.8
			iron ore	3.2
			apatite	2.9
Less 0	0.08			100.0
	99.82			
	99.74			

Analyst, L. S. Theobald.

In addition to the accessories mentioned above, a little sphene and zircon are present in the hybridized biotite-pyroxenite.

The hybridized biotite-pyroxenite shows some resemblance to the rocks of the Ach'uaine type described by H. H. Read,¹ from Sutherland, and there ascribed to the hybridization of an ultrabasic biotite-free rock, composed of olivine, pyroxene, and probably hornblende, by an acid felspathic magma equivalent in composition to a mixture of oligoclase and orthoclase, the hybridization leading to the abundant formation of hornblende, biotite, and alkali feldspars. In the case of the hybridized biotite-pyroxenite from Seeconnell, the biotite is known to be a primary mineral from the unaltered biotite-pyroxenite, but the development of green hornblende

¹ H. H. Read, "The Geology of the Country around Golspie, Sutherland." *Mem. Geol. Surv. Scotland*, 1925, pp. 45-51. "The Geology of Strath Oykeil and Lower Loch Shin." *Mem. Geol. Surv. Scotland*, 1926, pp. 154-66. "The Geology of Central Sutherland." *Mem. Geol. Surv. Scotland*, 1931, pp. 165-73.

rims round the augite and of pools of felspar resembles the changes described in the hybrids of Ach'uaire type.

(d) Hybrids

The description of these rocks will be facilitated by stating at the outset that they have two modes of origin. In part (Seeconnell type) they have arisen through the reaction of biotite-pyroxenite, and more rarely of peridotite, with the sediments, and in part (Slievegarron type) they are due to the hybridization of biotite-pyroxenite and peridotite by a plagioclase magma. As already stated, it is sometimes possible to distinguish between these two types in the field. The distinction is not simple, however, and some rocks are the result of both processes and cannot be determined macroscopically. The separation of the types, fortunately, can be satisfactorily accomplished by microscopic examination. One of the types of hybrid in which both processes operated forms the belt already described as the hypersthene zone. Here, hybrids of the Slievegarron type appear to have permeated aluminous sediments.

(i) Hybrids of Slievegarron Type (Augite-biotite-diorite).—On Slievegarron the hybrids of this type show every transition to the biotite-pyroxenite, and throughout the area they occupy they frequently grade to melanocratic varieties, closely approaching the biotite-pyroxenite. In thin section, they are found to be augite-diorites consisting of augite, hornblende, biotite, and plagioclase with occasional orthoclase and rare quartz. Accessory minerals are apatite and iron ore. Of rare occurrence only are olivine and hypersthene. The textures are typically igneous and glomerular, the ferromagnesian minerals showing a distinct segregation into clots which are separated by felspathic areas. In some cases, plagioclase appears to have grown as porphyroblasts which have swept the ferromagnesian minerals to their margins.

The mafic minerals exactly resemble those in the biotite-pyroxenite. The augite is faintly green in colour, with the same optical properties, inclusions of biotite, and zones of titaniferous iron ore as in the biotite-pyroxenite; it occasionally has a slight sieve texture enclosing small areas of felspar and quartz, but this is not very pronounced. Green hornblende is present in reaction relation to the augite, the latter having become unstable in the plagioclase magma. The biotite resembles that in the biotite-pyroxenite not only in colour, the development of basal planes, and the absence of pleochroic haloes, but also in the fact that the crystals are outlined by rims of titaniferous iron ore where they are in contact with one another, with other ferromagnesian minerals,

and with enclosed apatite. These rims are absent, however, where the biotite is in contact with the felspathic matrix, thus supporting the field evidence that the felspar was introduced by the invading magma. In this magma, titaniferous iron oxide was evidently soluble. Sphene in occasional strings and fringes is developed in and around the biotite, where it appears to be a reaction product between the titaniferous rim and the felspathic magma.

Olivine was found in a specimen collected north of Slievegarron (south of the road to Backaderry), where it occurs



FIG. 8.—Augite-biotite-diorite (hybrid of Slievegarron type) (No. 332) from Slievegarron, showing characteristic aggregates of augite and biotite and the absence of the rim of titaniferous iron ore from the biotite, where this is in contact with andesine.

enclosed in augite, and as separate crystals, rarely with a hypersthene rim. The rock is igneous in texture, with andesine, Ab_{62} , as the predominant felspar. Where the olivine comes in contact with orthoclase, it is surrounded by a finger-like dactylitic outgrowth of augite. Augite similarly shows dactylitic outgrowths where in contact with orthoclase, whilst the biotite sometimes has dactylitic outgrowths extending parallel to its cleavage and tipped with augite. The olivine is mainly fresh, but some of the smaller crystals are serpentinized to a pleochroic antigorite (—ve) with $X = Y =$ yellowish, $Z =$ bluish green.

The andesine in the hybrids of Slievegarron type is near Ab_{65} . It approximates in grain-size to that of the augites,

giving the rock an equigranular texture. Orthoclase is sometimes present in subordinate amount and quartz is rare. Iron ore and colourless prisms of apatite are associated with the ferromagnesian areas.

There is every gradation from the biotite-pyroxenite, through biotite-pyroxenite containing small pools of andesine, to the hybrid augite-biotite-diorites. The petrological evidence thus supports the field evidence in showing that the augite-biotite-diorites owe their origin to the hybridization of the biotite-pyroxenite by a felspathic magma composed almost entirely of andesine. Hybridization appears to have occurred after the crystallization or partial crystallization of the biotite-pyroxenite, as is shown not only by the field evidence, but by the aggregation of the ferromagnesian minerals, the absence of the ilmenite rim round the biotite where in contact with feldspar, and the fact that the plagioclase sometimes has the appearance of porphyroblasts.

The analysis, norm, and mode of a specimen of augite-biotite-diorite, No. 322, from Slievegarron is tabulated below.

AUGITE-BIOTITE-DIORITE, Slievegarron					
ANALYSIS		MOL. PROP.		NORM	
SiO ₂	49.10	0.818	or	15.01	
Al ₂ O ₃	16.56	0.163	ab	21.48	
Fe ₂ O ₃	1.37	0.009	ne	6.25	
FeO	6.99	0.097	an	20.29	
MgO	7.50	0.188	di	CaSiO ₃	6.96
CaO	8.40	0.150		MgSiO ₃	4.30
Na ₂ O	3.85	0.063		FeSiO ₃	2.24
K ₂ O	2.46	0.027	ol	Mg ₂ SiO ₄	10.22
H ₂ O +	0.85	—		Fe ₂ SiO ₄	5.51
H ₂ O -	0.20	—	mt	2.09	
CO ₂	none	—	il	2.74	
TiO ₂	1.35	0.018	ap	2.02	
P ₂ O ₅	0.90	0.006	water	1.05	
Cl	n.d.	—			
F	n.d.	—			100.16
S	tr.	—			
Cr ₂ O ₃	0.03	—			
V ₂ O ₃	sm. tr.	—			
NiO	n.d.	—			
MnO	0.30	0.004	augite and hornblende	24.1	
SrO	0.06	0.001	biotite	24.9	
BaO	0.26	0.002	andesine ¹	45.0	
Li ₂ O	n.d.	—	apatite	1.6	
			iron ore	3.1	
	100.18				98.7

Analyst, W. H. Herdsman.

¹ Including a trace of orthoclase and quartz.

Rocks which differ somewhat from the typical augite-biotite-diorites described above, outcrop along the turf-path

east of Crocknafoyle and, as previously described (p. 588), are due to hybridization of peridotite by a plagioclase magma. They differ from the more usual augite-biotite-diorites in the pinkish colour of the augites, which are probably titaniferous, in the red-brown colour of the biotites, the more usual presence of olivine, and also in the grain-size of the plagioclase, which is distinctly smaller than that of the ferromagnesian minerals, so that it appears to form a matrix.

On Rough Hill, augite-biotite-diorites of Slievegarron type come into contact with sediments which they have permeated (see p. 599) and made over to quartz-diorite. At a distance of 50 yards from the contact, the augite-biotite-diorite resembles that of Slievegarron, except for greater richness in quartz, which sometimes forms a poikilitic matrix for the other constituents, the presence of pleochroic haloes in the biotite, the fact that some of the apatite is blue and pleochroic, and the frequent occurrence of sphene.

Nearer the contact, contamination by sediments is evidenced by numerous residual patches of hornfels and by certain mineralogical and textural changes. The augite has been converted to hornblende, in which it is occasionally present as small residual cores. Close to the contact, the hornblende has a sieve texture and crenulate margins, evidence of growth in a highly viscous or solid medium. The biotite shows a corresponding change to a lighter and redder variety, becoming less regular in outline and developing a distinct tendency to grow round the leucocratic minerals. Both the biotite and the hornblende exhibit pleochroic haloes. Orthoclase increases in amount and the percentage of quartz is higher than in the hybrids on Slievegarron, so that the rocks may here be termed quartz-monzonites and quartz-diorites. Accessories at the contact are blue pleochroic apatite, sphene, and zircon.

The sediments migmatized by the augite-biotite-diorite form fine-grained, grey quartz-diorite which contains residual lentils of hornfels and fused sediment. In thin section, the quartz-diorite is seen to be a mixture of sedimentary and igneous materials and to show similarities to the contact monzonite and diorite. From the invading magma, andesine and hornblende have grown as porphyroblasts. The hornblendes have occasional augite cores and exhibit sieve texture to some extent. The plagioclase is a strongly zoned andesine. The biotite, which is reddish brown in colour and exhibits pleochroic haloes, forms ragged interstitial flakes in the matrix, which consists, in addition, of much fine-grained quartz, plagioclase, and a little orthoclase. Small blue apatites, zircon, and sphene are accessories.

The intrusive rock north of the summit of Rough Hill, the resemblance of which to the migmatized sediments just described was mentioned in the field description (p. 600), is

indistinguishable from these sediments in thin section. Plagioclase and hornblende have grown as porphyroblasts in a matrix of sedimentary origin, which is composed of much quartz, andesine, a little orthoclase, and numerous ragged reddish brown biotite flakes which wrap round the other constituents. The accessories are small pleochroic blue apatites, zircon, and sphene. The rock is evidently due to the soaking of sediments by augite-biotite-diorite, the mass having been sufficiently mobile to rise to a higher level, so that it now shows intrusive contacts against the hornfels. In a thin section from a coarser variety of the same rock, the hornblende has marked sieve texture and highly crenulate margins, like those found in the contact specimens. The larger hornblendes have sometimes developed crystal faces and an outer zone free from sieve-like inclusions, a fact which is probably to be ascribed to the greater power of crystallization and capacity to expel inclusions acquired by the crystals as they increased in size.

Xenoliths with a greenish colour, sometimes several inches across, are present in the contaminated hybrids just described (augite-biotite-diorite and sediments) and are found to be residual patches of augite-hornfels.

(ii) *Hybrids of Seeconnell Type (Augite-monzonite)*.—These rocks, which are due to the reaction of the biotite-pyroxenite and peridotite magmas with the Silurian greywackes and shales, are much more variable than the augite-biotite-diorites. Classified on a mineralogical basis alone, they may be termed shonkinitic monzonite, monzonite, and syenite, the greater part of the series being of the nature of augite-monzonite, but it must be emphasized that the members exhibit textures which are more characteristic of hornfels than of igneous rocks. The series shonkinitic monzonite—monzonite—syenite is gradational from the biotite-pyroxenite and peridotite, which are locally already hybridized by plagioclase magma, to the sedimentary contact.

The Seeconnell type of hybrid is characterized by diopsidic augite, hornblende, biotite, soda-orthoclase, plagioclase, quartz, and rarely olivine and hypersthene, accessories being iron ore, apatite, sphene, and zircon.

The augite resembles that in the biotite-pyroxenite and augite-biotite-diorite in its faintly green colour, optical properties, and the frequent presence of numerous minute flakes of biotite arranged parallel to the cleavage traces. It differs, however, in several respects. The black rod-like inclusions, arranged parallel to the *c* axis and the basal plane, are more abundant. In the smaller crystals they are sometimes evenly disseminated, and when present in the larger crystals are concentrated in a zone within the margin or, more

rarely, centrally. The augites, unlike those in the augite-diorites, occur in isolated crystals, which near the biotite-pyroxenite average 4 by 3 mm. and decrease in size towards the sedimentary contact. Everywhere they exhibit highly crenulate margins and a pronounced sieve texture, enclosing small biotite flakes and abundant irregular patches of felspar (mainly orthoclase) and quartz. This sieve texture is sometimes restricted to an inner zone, within the region of black inclusions, and at other times has a constant distribution throughout the crystal. In their crenulate margins and sieve texture, the augites resemble the porphyroblasts which have

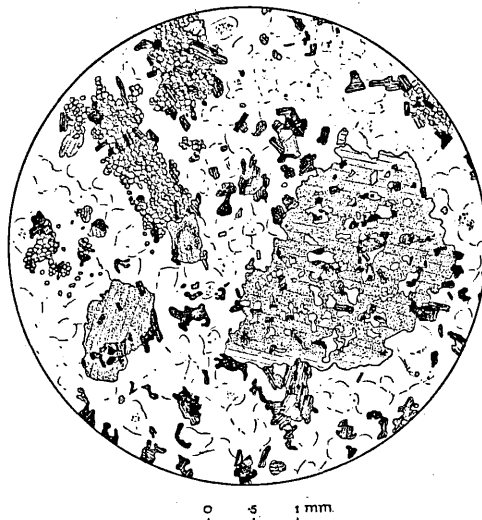


FIG. 9.—Augite-monzonite (hybrid of Seeconell type) (No. 294) from southern side of Seeconell, showing porphyroblasts of augite, clusters of augite granules (relics of augite-hornfels), and a matrix of biotite, orthoclase, and quartz.

developed in the migmatized sediments and contact hybrids on Rough Hill, and this resemblance suggests that they grew in a highly viscous, if not solid, medium. At first their power of growth was too small to sweep away neighbouring quartz and felspar crystals, but later they acquired a greater force of crystallization, so that their outer zones are often free from inclusions, and it is a noticeable fact that the larger the crystals the more nearly they develop crystal faces (see Fig. 10). These crystals are frequently zoned, and twinned on (100). The numerous small biotite flakes arranged parallel to the cleavage traces of the augite often extend beyond the extremities of the crystal and resemble the "porcupinitic" biotite

figured by Sederholm¹ from an ophitic diabase from north-western Finland.

In addition to the large augites, aggregates of small diopside-augite granules, associated with biotite, iron ore, and apatite, occur in some specimens. They are clearer than the phenocrysts and more nearly colourless. Occasionally, these granular aggregates have a definite alinement in parallel bands, the granules being strung out in the direction of banding. This arrangement is not shared by the augite phenocrysts, which, indeed, frequently cross the bands and enclose or partly enclose the aggregates. The augite granules resemble those in the augite-hornfels, and their linear arrangement suggests that they are relics of such bands. They were certainly in existence before the growth of the augite phenocrysts.

Green hornblende is present in reaction relation to augite,

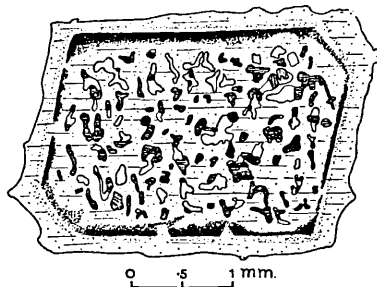


FIG. 10.—Porphyroblast of augite from augite-monzonite (No. 299), Seeconnell, showing sieve texture in an inner zone, the zonal distribution of rods of titaniferous iron ore, and an outer zone which is free from inclusions.

and the extent to which this reaction has proceeded varies from place to place. Even on Seeconnell, types free from hornblende grade in a few yards to types in which a considerable proportion of augite has been made over to hornblende. Here, increase in hornblende is synchronous with increase in plagioclase; in those rocks in which plagioclase is practically absent the augite has no hornblende rim. As the sedimentary contact on Slievenisky is approached, hornblende becomes more abundant relative to augite, and ferromagnesian minerals as a whole diminish.

Aggregates of a pale actinolitic hornblende, in acicular crystals, are sometimes present, and their origin can at times be traced to the aggregates of augite granules.

Biotite is always present as small and irregular flakes,

¹ J. J. Sederholm, "On Synantectic Minerals and Related Phenomena." *Bull. Comm. géol. Finlande*, no. 48, 1916, pp. 5, 41, and pl. i, fig. 2.

scattered through the matrix, which enclose and are wrapped round the feldspar and quartz. Pleochroic haloes round small zircons and apatite are common and become more abundant as the contact with sediments is approached on Slievenisky. These biotites appear to be identical with those in the hornfels zone. In addition, large flakes of biotite, of the same type as that which characterizes the biotite-pyroxenite, become evident as the latter is approached.

The feldspars, quartz, and associated biotite form a matrix for the augite phenocrysts, which is always of much smaller grain-size than the augites. On Seeconnell the matrix is finely equigranular and resembles the fused sediments, whilst on Slievenisky the matrix is of very irregular grain-size and the crystals have highly crenulate margins, giving the appearance of a very complicated jig-saw puzzle.

Soda-orthoclase is the most abundant feldspar, and frequently, as over the greater part of Seeconnell, it is present almost to the exclusion of plagioclase. The plagioclase is an andesine and usually resembles the soda-orthoclase in grain-size. Occasionally, however, and most noticeably on Slievenisky, it forms in addition large crystals with the appearance of porphyroblasts, which have crenulate margins and are often zoned. Such plagioclases are frequently crowded with dust-like inclusions in their inner zones.

As the hybrids are traced away from the biotite-pyroxenite towards the sedimentary contact, myrmekite becomes common. Occasionally, leaf-like growths of myrmekite consisting of an intergrowth of plagioclase and quartz extend into the orthoclase from points where the latter is in contact with plagioclase, but more frequently the myrmekite takes another form and consists of an association of orthoclase and quartz; whole orthoclase crystals, with finely crenulate margins, are then riddled with vermicular quartz. The myrmekite is sometimes intergrown with, and sometimes encloses or is enclosed by, andesine. Myrmekite is particularly characteristic of most of the material collected from Slievenisky, and is so abundant in specimens from south of the roof-contact as to form the main part of the rock.

Near the biotite-pyroxenite, quartz occurs as small anhedral crystals in the matrix with the feldspars, but as the sedimentary contact on Slievenisky is approached, it increases in amount and forms a poikilitic matrix to the feldspars. The same phenomenon is well exhibited on approaching the isolated roof portion on the south-eastern slopes of Slievenisky, where quartz is optically continuous over wide areas in the sections and wraps round and encloses the feldspars and biotite.

Apatite is abundant and is the most interesting of the accessories. It occurs as prisms which may be enclosed in any of the minerals, and as minute needles in the quartzo-feldspathic

matrix. In addition to the normal colourless apatite, a blue or violet pleochroic variety is also present. The colour is frequently restricted to a central zone which is crowded with dust-like inclusions. That the colour is not due to these inclusions is obvious from its presence in crystals free from them. Distinct pleochroism, sometimes strong, is shown. X = blue or violet > Z = pale brownish. These apatites sometimes exhibit strong zoning and colour striations parallel to the basal plane.

Iron ore is most abundant in the area near the biotite-pyroxenite and decreases towards the sedimentary contact.

Zircon and sphene are rarer constituents, only becoming evident on approaching the sedimentary contact. They form anhedral crystals of fair size, the zircons having a tendency to be rounded, and sometimes to be wrapped round orthoclase in the matrix.

The following analysis, norm, and mode are of a specimen of shonkinitic monzonite, No. 299, from Seeconnell, collected near the ultrabasic rock. It represents the most basic variety of the augite-monzonite.

SHONKINITIC MONZONITE, Seeconnell

ANALYSIS		MOL. PROP.	NORM	
SiO ₂	53.10	0.885	or	28.36
Al ₂ O ₃	14.52	0.142	ab	20.96
Fe ₂ O ₃	0.86	0.006	an	11.95
FeO	6.40	0.089	ne	2.27
MgO	6.71	0.168	di	CaSiO ₃ . . . 9.28
CaO	6.78	0.121		MgSiO ₃ . . . 5.70
Na ₂ O	2.99	0.048	ol	FeSiO ₃ . . . 3.04
K ₂ O	4.82	0.051		Mg ₂ SiO ₄ . . . 7.70
H ₂ O +	1.00	—	il	Fe ₂ SiO ₄ . . . 4.69
H ₂ O -	0.06	—		mt . . . 1.39
CO ₂	0.02	—	il . . . 2.13	
TiO ₂	1.09	0.014	ap . . . 2.02	
P ₂ O ₅	0.83	0.006	water, etc.	1.26
Cl	0.04	—		
F	0.07	0.003		100.75
S	none	—		
Cr ₂ O ₃	0.03	—		
V ₂ O ₃	0.03	—		
NiO	0.02	—	MODE	
MnO	0.15	0.002	augite ¹	21.9
SrO	0.08	0.001	biotite	24.3
BaO	0.29	0.002	leucoeratic	
Li ₂ O	tr.	—	minerals ²	53.5
			apatite	0.9
	99.89			100.6
Less 0	0.04			
	99.85			

Analyst, H. F. Harwood.

¹ Including a little hornblende.

² Mainly soda-orthoclase with a little plagioclase and quartz.

On Slievenisky, south of the roof-contact, the augite-monzonite differs from the more usual type in the presence of olivine (optically —ve, with $2V$ almost 90°) and in the pinkish tint of the augite, which resembles that in the peridotite. The rock appears to be the result of the reaction of peridotite with sediments.

On the western slopes of Slievenisky, occasional crystals of strongly pleochroic hypersthene, similar to that in the hypersthene zone, occur in the augite-monzonite, thus forming a link between the augite-monzonites and the hypersthene-monzonites.

In connexion with the origin of the hybrids of Seeconnell type, a study of the contacts between biotite-pyroxenite and enclosed sedimentary rafts is important. Reaction, producing a type similar to these hybrids, was found in a stream-bed south of the point where it passes under the road directly north of Seeconnell, the field description of which has already been given (p. 589). The biotite-pyroxenite of this exposure exhibits small felspathic areas in which the predominant feldspar is plagioclase, its only abnormality being the presence of a little blue apatite in addition to the usual colourless type. The contact sediments are highly micaceous and exhibit pink porphyroblasts of feldspar, sometimes as much as 4 mm. in length. In thin section, they are found to consist of biotite, feldspar, and a little quartz, with pleochroic blue apatite and zircon as accessories. The texture is typically porphyroblastic, both orthoclase and plagioclase (oligoclase-andesine), of which the former predominates, having grown as porphyroblasts, concentrating the biotite around their margins. The feldspar includes minute rounded flakes of biotite and needles of apatite. The biotite is a strongly pleochroic variety occurring mainly as ragged flakes wrapped round the feldspars and quartz. It exhibits pleochroic haloes and resembles that in the normal hornfels.

Another type, which occurs as a streaky inclusion in the biotite-pyroxenite, macroscopically resembles hornfels in its high percentage of biotite with a parallel arrangement. It contains augite porphyroblasts, however, sometimes 4 mm. in length, and appears to represent a more advanced stage in the alteration of the sediments, due to permeation by the biotite-pyroxenite magma. Microscopically, it is found to be rich in porphyroblasts of augite resembling those in the biotite-pyroxenite and in granular aggregates of a more colourless variety of diopsidic augite. The matrix consists of feldspars, predominantly orthoclase with a little plagioclase (oligoclase-andesine) and abundant biotite. It is finer grained than the rock just described. The leucocratic minerals are outlined by, and enclose flakes of, biotite and are riddled with needles of apatite. Apatite occurs occasionally as large colourless

prisms with pyramidal terminations. The matrix shows a tendency to foliation, to the direction of which some of the augite porphyroblasts conform. In thin section, this rock resembles the hybrids from Seeconnell, except that it is considerably richer in biotite.

In the isolated outcrop of biotite-pyroxenite to the south-east of Seeconnell, the biotite-pyroxenite was at one time in contact with sediments from which it has since been separated by the intrusion of a narrow dyke of granodiorite. In the hand-specimen, the sediments from the contact resemble those just described in their development of porphyroblasts of feldspar. Microscopically, the leucocratic minerals are finer grained, and small anhedral and subhedral crystals of feldspar are enclosed by poikilitic quartz. Of the feldspars, plagioclase (oligoclase-andesine) probably predominates. The biotite builds larger flakes than in the sediments of the other exposure and shows a distinct parallelism, probably marking the original bedding.

The biotite-pyroxenite of this exposure is hybridized with plagioclase and orthoclase. The most noticeable thing about it, however, is its richness in a strongly coloured apatite which is intensely pleochroic with X = deep blue or purple, Z = pale brown. It exhibits strong zoning and is frequently colourless in a narrow outer zone. In addition, it sometimes shows strong colour striations parallel to the basal plane. It is a fact of significant genetic importance that the biotite-pyroxenite contains this coloured apatite only where it is in contact with sediments.

The evidence proves conclusively that the hybrids of Seeconnell type owe their existence to the permeation of the country-rocks by (a) biotite-pyroxenite-magma; (b) the same magma locally more or less contaminated by plagioclase magma; and (c) peridotite magma, also locally contaminated (examples rare).

(iii) The Hypersthene Zone (Hypersthene-monzonite and Diorite).—Rocks rich in hypersthene are restricted to the area mapped on the western slopes of Slievegarron, and are monzonites and diorites characterized by hypersthene, augite, biotite, plagioclase, and orthoclase, with iron ore, apatite, and zircon as accessories.

The hypersthene is either anhedral (with rounded or coarsely crenulate outlines) or has a tendency to develop faces in the prism zone. It differs from the hypersthene in the peridotite in possessing strong pleochroism X = pinkish brown > Z = very pale green; schiller texture is often well developed. The hypersthene is sometimes surrounded by a narrow reaction rim of green hornblende. It may occur as isolated individuals, but is frequently aggregated into groups associated with much

iron ore. The latter has crystallized at the same time as the hypersthene and felspathic matrix, with both of which it is intergrown, occasionally enclosing the feldspars with an intermediate fringe of biotite.

The biotite forms large poikilitic plates, sometimes a centimetre across, which enclose feldspar and quartz. In places it has dactylitic outgrowths parallel to its cleavage planes.

Augite is usually present in small amount. It forms anhedral crystals, characterized by rounded or crenulate margins and sieve texture, the latter being less well developed than in the hybrids of Seeconnell type.

Plagioclase (oligoclase-andesine) is the predominant feldspar. It tends to be euhedral, and when it is most abundant the texture of the rock is igneous in aspect. With increase in orthoclase, the texture becomes less igneous in appearance and approaches that of hornfels. The feldspars have then highly crenulate outlines, fitting together like the pieces of a jig-saw puzzle. The orthoclase may be poikilitic, when it encloses small well-formed and rounded crystals of plagioclase. Myrmekite, of the type in which orthoclase is riddled with vermicular quartz, is not uncommon.

HYPERSTHENE-MONZONITE, Slievegarron

ANALYSIS		MOL. PROP.	NORM	
SiO ₂	56.24	0.937	qz	0.42
Al ₂ O ₃	16.54	0.162	or	26.69
Fe ₂ O ₃	2.07	0.013	ab	29.34
FeO	3.96	0.056	an	16.12
MgO	5.04	0.126	di	CaSiO ₃ . . . 3.36
CaO	5.67	0.102		MgSiO ₃ . . . 2.30
Na ₂ O	3.48	0.056		FeSiO ₃ . . . 0.79
K ₂ O	4.53	0.048	hy	MgSiO ₃ . . . 10.30
H ₂ O +	0.61	—		FeSiO ₃ . . . 3.83
H ₂ O -	0.11	—	mt	3.02
CO ₂	0.21	0.005	il	1.37
TiO ₂	0.74	0.009	ap	1.34
P ₂ O ₅	0.59	0.004	cc	0.50
Cl	0.04	0.001	water, etc.	0.81
S	0.01	—		
Cr ₂ O ₃	0.01	—		100.19
V ₂ O ₃	0.02	—		
NiO	0.01	—		
MnO	0.11	0.001	MODE	
SrO	0.08	0.001	hypersthene	13.4
BaO	0.26	0.002	augite	10.4
Li ₂ O	tr.	—	biotite	1.8
			leucocratic	
			minerals ¹	70.4
			apatite	1.0
			iron ore	2.6
	100.33			99.6

Analyst, L. S. Theobald.

¹ Oligoclase-andesine, soda-orthoclase, and traces of quartz.

Quartz is present in small amount, either inter-crystallized with the other constituents, or as a poikilitic matrix for the whole. In the latter case it has a curious appearance, for, although in optical continuity over wide areas, it appears only as narrow ribbons fitting between the parallel outlines of adjacent minerals.

Accessories, in addition to iron ore, are apatite, which is common and of the normal colourless variety, and, more rarely, zircon in very irregular grains. Occasionally, zircon encloses rounded grains of orthoclase and grows out along the contact of neighbouring orthoclase crystals, either having completed its growth after the feldspars, or more probably having developed in a highly viscous medium.

The analysis, norm, and mode of a typical hypersthene-monzonite, No. 349, from Slievegarron is tabulated on p. 620.

(e) Granodiorite

The granodiorite is typically medium grained and non-porphyrific. It is characterized by plagioclase, alkali feldspar, quartz, hornblende, biotite, and occasionally augite, with apatite (sometimes blue or purple), sphene, zircon, and iron ore as accessories.

The plagioclase is usually oligoclase, andesine being rare. Zoning from Ab_{74} in the centre to Ab_{76} at the margin is common; sometimes a central zone of similar composition to that of the outer zone is present, the two zones being separated by a more calcic region. Not infrequently, there is an outer rim of myrmekite, formed by the intergrowth of plagioclase and vermicular quartz. The plagioclase is generally euhedral in contrast to the anhedral potash feldspar and quartz.

Alkali feldspar is usually distinctly less abundant than plagioclase and is represented by orthoclase, perthite and, less commonly, microcline. By increase in the alkali feldspars the granodiorite grades in places to adamellite.

Small petaloid areas of myrmekite, which consists of oligoclase and vermicular quartz, sometimes extend into the potash feldspar, whilst the microcline is occasionally margined by myrmekite, which consists of microcline and vermicular quartz. The type of myrmekite due to the intergrowth of orthoclase and vermicular quartz is uncommon.

Quartz is never abundant and sometimes is present in small amount only, so that locally the rock might well be termed a tonalite. Quartz increases in amount where the granodiorite is obviously contaminated by sediments, and most notably so at the contact on Slieve Croob.

The ferromagnesian minerals are very variable and they characteristically occur segregated in small clots. The biotite is a strongly pleochroic variety with X = pale yellow, Y =

Z = vandyke brown. It occasionally develops basal planes, but is not infrequently quite ragged in outline, wrapping round the feldspars and quartz. Pleochroic haloes are not uncommon. As the augite-biotite-diorite is approached, the biotite often becomes richer in colour, with a marked tendency to develop basal planes and ilmenite rims where adjacent crystals come in contact.

The hornblende is of a normal green variety, with crystal faces developed in the prism zone; twinning is common on (100). Much, if not all, of the hornblende is probably derived from the hybrids through which the granodiorite has risen. The evidence for this is the fact that throughout the mass hornblende crystals occasionally have a central core of augite which resembles that of the hybrids. Such cores become common where the granodiorite is in contact with the hybrids, both to the west of the main hybrid zone on Slievegarron and to the south of the hybrids on Rough Hill, Legananny Mountain, and White Rocks. The ferromagnesian minerals also increase in amount and size on approaching the hybrids.

The relative proportion of hornblende to biotite is very variable. These minerals may be roughly equal in amount or biotite may be present almost to the exclusion of hornblende, as to the east of Slieve Croob and on Benraw Mountain, where hornblende is practically absent and biotite abundant in clots associated with magnetite, the latter frequently exhibiting form.

The analysis, norm, and mode of a typical granodiorite, No. 311, from Carrivmoragh Hill is tabulated on p. 623.

The earlier fine-grained granodiorite, exposed on Rough Hill and occurring as xenoliths in the more common coarse-grained type, is of interest in that it throws light on the origin of the granodiorite as a whole. It is richer in ferromagnesian minerals than the coarser variety. The hornblende, with occasional augite cores, occurs in clots. The biotite is highly irregular in outline and poikilitically encloses quartz. It is a dark brown strongly pleochroic variety rich in pleochroic haloes round apatite and zircon.

Plagioclase, the predominant feldspar, has grown as porphyroblasts; while the larger crystals tend to be euhedral, the smaller ones have crenulate margins. It is a zoned andesine, and characteristically has zonal inclusions of minute blebs of biotite.

Occurring interstitially and enclosed in a grid-like manner in the plagioclase are small mosaics of quartz, obviously of sedimentary origin. A yellowish substance outlines many of the quartz grains and forms a general staining on the others. It appears to have resulted, as in the fused sediments, from the diffusion of the original wrapping of limonite round the sedimentary grains, and is a useful index in identifying patches of sedimentary origin.

GRANODIORITE, Carrivmoragh

	ANALYSIS	MOL. PROP.	NORM	
SiO ₂	65.05	1.084	qz	21.48
Al ₂ O ₃	17.08	0.168	or	14.46
Fe ₂ O ₃	0.81	0.005	ab	30.39
FeO	3.06	0.043	an	18.07
MgO	2.53	0.063	c	1.94
CaO	3.80	0.068	hy	6.30
Na ₂ O	3.60	0.058	{ MgSiO ₃	3.83
K ₂ O	2.35	0.026	{ FeSiO ₃	1.16
H ₂ O +	0.50	—	mt	1.37
H ₂ O -	0.05	—	il	0.34
CO ₂	none	—	ap	0.57
TiO ₂	0.70	0.009	water, etc.	—
P ₂ O ₅	0.18	0.001		99.91
Cl	n.d.	—		—
S	tr.	—		—
Cr ₂ O ₃	none	—		—
V ₂ O ₅	sm. tr.	—	MODE	—
NiO	n.d.	—	quartz	26.7
MnO	tr.	—	oligoclase	41.2
SrO	0.02	—	orthoclase	16.2
BaO	0.07	0.001	hornblende	5.3
Li ₂ O	n.d.	—	biotite	10.6
	99.80			100.0

Analyst, W. H. Herdsman.

Sparse iron ores and zircon and more abundant apatite form accessories. Most of the apatite is of the blue or purple pleochroic variety. It occurs as inclusions in all the other constituents. Minute needles of apatite are characteristically enclosed in the plagioclase and in the minerals of the sedimentary matrix.

The evidence indicates that three types of material have contributed to the formation of the fine-grained granodiorite: (a) biotite-pyroxenite, which has given rise to much of the ferromagnesian material; (b) the plagioclase magma, which forms one of the parents of the augite-diorite; and (c) sediments, which form about 30 per cent of the rock.

The normal granodiorite of the area, although showing intrusive contact against the fine variety on Rough Hill, obviously resembles the latter as the contact is approached. In it the sedimentary component has been more completely recrystallized and is, in consequence, coarser in grain. The ferromagnesian minerals still occur in clots; the plagioclase is porphyroblastic with crenulate margins and is crowded with minute blebs of biotite, fine needles of apatite, and dust-like inclusions, all of which have a tendency to orientate themselves parallel to the albite lamellæ. Some coloured apatite is present. From this marginal variety there is every gradation to the ordinary granodiorite with a normal igneous texture.

(f) Xenoliths in the Granodiorite

An exhaustive study has not yet been made of the xenoliths in the various igneous types, and it will suffice here to give a brief statement only of some of the varieties found in the granodiorite.

(i) Xenoliths of the Hybrids.—These are of widespread occurrence, but so far only those from the granodiorite exposed in the quarry at Ballymagreehan have been examined in any detail. Many of the xenoliths resemble the augite-monzonites of Seeconnell. Except for the occurrence of residual cores, the augites have been converted to hornblende. Biotite with pleochroic haloes is present in ragged flakes, and the matrix consists essentially of orthoclase and quartz, both with crenulate margins. Some plagioclase is present and appears to have grown as porphyroblasts. As accessories, sphene is present in large anhedral grains, zircon in small well-formed crystals, and the matrix is riddled with needles of apatite.

Another common variety is medium grained and equigranular and has oligoclase-andesine as the predominant feldspar. Where the latter is in contact with orthoclase, myrmekite is sometimes present and consists of an intergrowth of the plagioclase and vermicular quartz. Quartz occurs interstitially and as a poikilitic matrix. Ferromagnesian minerals are sparse; a little hypersthene is present but it has mainly been converted to hornblende, in which it is occasionally found as a central core. Augite is present in granules and as cores in the hornblende, and biotite forms poikilitic plates. This variety of xenolith resembles the hypersthene rocks in the zone to the west of Slievegarron.

Xenoliths of a fine-grained granodiorite are also present. They have phenocrysts of zoned andesine in a fine-grained matrix of andesine, orthoclase, quartz, and some myrmekite. Quartz is more abundant than in the normal granodiorite. Biotite is the only ferromagnesian mineral and is present in small amount only; zircon is an accessory. This type of xenolith possibly represents an early fine-grained variety of granodiorite, such as is seen on the northern boundary on Rough Hill; comparison reveals only a slight difference in texture.

(ii) Xenoliths of Sedimentary Origin.—Xenoliths of biotite-hornfels are common in all the varieties of igneous rocks and hybrids, but so far very few have been studied in thin section. As a general rule, these xenoliths closely resemble the contact hornfels from near the zone of fusion or the margin of the complex. They are equigranular, and consist mainly of quartz, biotite, a little andesine, and microcline; the small biotite flakes being wrapped round the other constituents.

An inclusion of hornfels occurring in the granodiorite on the western slopes of Slievegarron has a coarse-grained matrix of orthoclase and perthite which poikilitically enclose biotite, green spinel, and a little andesine. The spinel is associated with and often enclosed by the biotite. The latter has a decussate arrangement, frequently develops basal planes, and is rich in pleochroic haloes.

A similar variety, which differs only in the absence of spinel, the presence of a little quartz, and the finer grain of the felspathic matrix was collected as an inclusion in the granodiorite on Slieve Croob.

Reference to inclusions of fused sediment in the granodiorite has already been made on p. 598.

(g) Pegmatite, Aplite, and Felspathic Veins

The pegmatite veins consist of quartz, perthite, and plagioclase in fairly equal amounts, and large biotites, often decomposed to chlorite and epidote, with large anhedral crystals of sphene and a little zircon as accessories.

An unusual variety of pegmatite, described in the field section as cutting the biotite-pyroxenite at the eastern foot of Slievegarron, consists entirely of large well-formed biotite flakes and andesine.

The aplite veins are fine-grained and of very uneven grain-size, all the constituents being anhedral. Quartz, microcline, and orthoclase are the predominant minerals; plagioclase is rare. Biotite, in small amount, is the only ferromagnesian mineral.

Felspathic veins are common in the area and differ from the pegmatites and aplites in the paucity or absence of quartz. They cut the hybrids on Slievegarron and Seeconnell in narrow veins which merge marginally into the diorites and monzonites. On Rough Hill they are more abundant and merge by suffusion into the hybrids. They consist of andesine and orthoclase or perthite, the relative proportions of which are widely variable. The potash feldspar frequently encloses the plagioclase poikilitically, and much sphene and, rarely, zircon form accessories.

It is possible that these late felspathic injections represent the last "squeeze-outs" from the plagioclase magma. Their richness in sphene is probably to be correlated with the fact that ilmenite was soluble in the first injections of plagioclase magma (see p. 610). Titanium gained in this way by a lime-rich magma might be expected to contribute to the formation of sphene at a lower temperature.

IV. PETROGENESIS

Peridotite and biotite-pyroxenite form the earliest intrusions in the area. These two types are not seen in contact in the

field. From the fact that they each contribute to the formation of the hybrids of Seeconnell type, however, it seems likely that they were intruded at approximately the same time. A variation diagram makes it evident that the biotite-pyroxenite may be a differentiate from the peridotite due to the sinking of olivine and pyroxene.¹

Field and petrological evidence show that the augite-biotite-diorites are hybrids due to the invasion of biotite-pyroxenite and, to a lesser extent, peridotite by a plagioclase magma. In part, the augite-biotite-diorites were formed in situ, as in contact with the biotite-pyroxenite on Slievegarron, and in part they were formed at greater depth, since they sometimes show intrusive relationships. Figure 11 was constructed in order to ascertain the composition of the plagioclase magma which contributed to their formation, by subtracting biotite-pyroxenite from augite-diorite. When a silica percentage is chosen, such that the ratio of lime to soda corresponds to that of the plagioclase determined in the microscopic examination of the augite-diorite (that is, Ab₆₅), the added material is found to be 80 per cent andesine, with probably a little biotite and iron ore, as follows:—

CALCULATED COMPOSITION OF THE PLAGIOCLASE MAGMA		NORM	
SiO ₂	54.40	ab	49.78
Al ₂ O ₃	22.30	an	28.91
Fe ₂ O ₃	0.60	lc	7.41
FeO	5.00	ne	0.85
MgO	2.30	ol	4.06
CaO	6.00	ol	5.51
Na ₂ O	6.14	mt	0.93
K ₂ O	1.64	il	1.52
TiO ₂	0.75		
	99.13		98.97

This plagioclase magma existed in considerable volume, and its origin becomes a point of interest. To Professor Holmes I owe the suggestion that it may be the result of the high-pressure metamorphism of the plateau-basalt layer to eclogite, brought about during mountain folding. By a graphical construction it is easy to verify the fact that plateau-basalt magma minus the plagioclase magma equals eclogite low in alumina. In short, therefore, the plagioclase magma may well represent the difference in composition between eclogite and plateau-basalt. The high-pressure metamorphism of 100 parts of plateau-basalt to eclogite is capable of giving rise to anything from 27 to 36 parts of plagioclase magma, by

¹ Further work on the biotite-pyroxenites has indicated that the differentiation of the peridotite magma is more likely to be due to an upward concentration of potash and alumina. (Added September, 1934.)

weight, and the thickness of the basaltic layer is an ample source of supply. It is of importance in this connexion that Eskola¹ has recorded the frequent association of dunite,

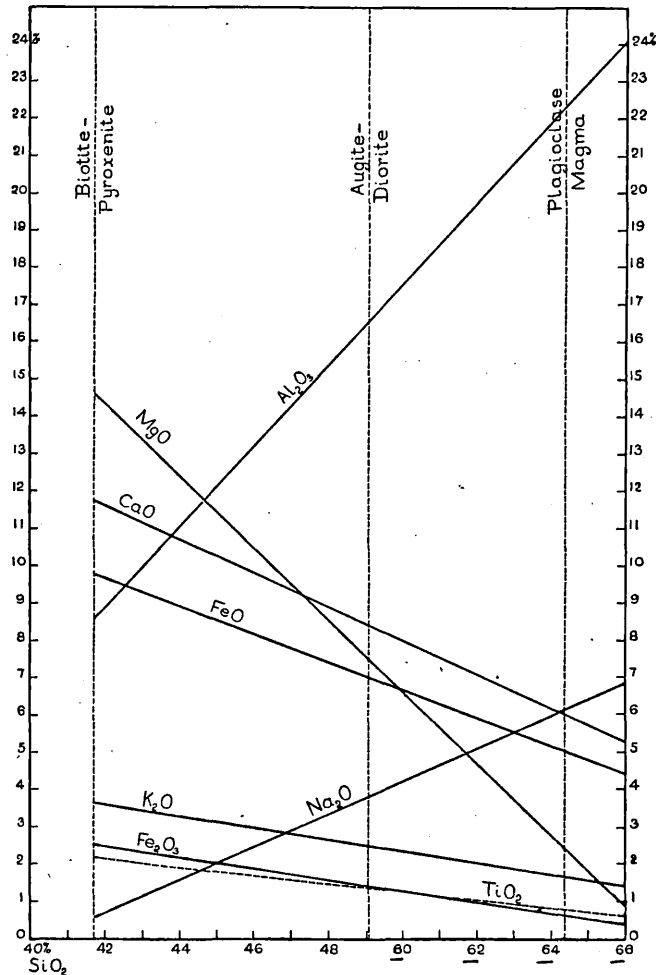


FIG. 11.—Graph showing the composition of the plagioclase magma by subtraction of biotite-pyroxenite from augite-biotite-diorite.

eclogite, and labradorite rock in Norway. The labradorite rocks are aplitic in texture, and although the plagioclase is

¹ P. Eskola, "On the Eclogites of Norway." *Vidensk. Skrift. I. Mat.-nat. Kl.* 1921, No. 8.

commonly between Ab_{45} and Ab_{60} in composition, yet it varies in different occurrences from Ab_{75} to Ab_{32} . Orthoclase is sometimes represented and a little biotite or hornblende or both may be present. The labradorite rock, therefore, although usually more calcic, resembles that described in the present paper. Near Stensvik at Dalsfjord, labradorite rock covers a large area on the mountain slope and is underlain by eclogite, in its turn underlain by dunite and saxonite, the labradorite rock being the younger and passing into the eclogite via an eruptive breccia. This evidence supports the view that the plagioclase magma described in the present paper may be genetically connected with eclogite.

The hybrids of Seeconnell type have been shown to be due to the soaking and incorporation of sediments by biotite-pyroxenite and, more rarely, peridotite, with an occasional small addition of plagioclase magma. The evidence on which this conclusion is based is as follows :—

1. The hybrids of Seeconnell type occur only in contact with sediments.
2. The augite has grown as porphyroblasts with sieve texture and crenulate margins.
3. The biotite resembles that in the hornfels zone and, unlike that in the biotite-pyroxenite, exhibits pleochroic haloes the number of which increase as sediments are approached.
4. Biotite, soda-orthoclase, plagioclase, and quartz form a matrix which resembles the fused sediment in texture.
5. Augite decreases and leucocratic minerals, especially quartz, increase as sediments are approached, giving rise to the series shonkinitic monzonite—monzonite—syenite—quartz-syenite.
6. A blue or purple pleochroic apatite, found to a lesser extent in the sediments, is always present in the hybrids of Seeconnell type, this variety of apatite also occurring in the other rocks of the area where they are in contact with, and obviously contaminated by, sediments.
7. The accessories, zircon and sphene, increase in amount as sediments are approached.
8. Where the augite-diorite of Slievegarron type is contaminated with sediments on Rough Hill, a variety results similar to the augite-monzonite, except for the greater abundance of plagioclase.
9. The occasional presence of porphyroblasts of andesine in the augite-monzonite shows that there has been a slight addition of plagioclase magma in places.

It is possible that the biotite-pyroxenite was able to rise only by soaking through the sediments, since its high specific gravity would make stopping impossible. The incorporated

sediments were probably in a state of fusion, for the hybrids of Seeconnell type are margined by fused sediments. A rough idea of the composition of the invaded sediments can be obtained by subtracting biotite-pyroxenite from augite-monzonite by a graphical method. Assuming that they contained 60 per cent of silica, then the analysed shonkinitic monzonite is 38 per cent biotite-pyroxenite and 62 per cent sediments, the composition of the sediments being as follows:—

SiO ₂	. . . . .	60.00
Al ₂ O ₃	. . . . .	18.20
FeO	. . . . .	4.25
MgO	. . . . .	2.00
CaO	. . . . .	3.86
Na ₂ O	. . . . .	4.45
K ₂ O	. . . . .	5.55
		<hr/>
		98.31

This corresponds to a mixture of greywacke and shale, except that lime, soda, and potash are high. The soda and lime may be partly accounted for by the presence of a small amount of the plagioclase rock, but the subtraction of this raises the potash even higher, while still leaving the soda and lime somewhat high as compared with the analysed greywacke and shale. The lime is easily accounted for if a small quantity of calcareous shale was present. Such would most probably be the case, since metamorphosed calcareous shales occur in the hornfels zone and relics of augite-hornfels are found in the augite-monzonite. Potash and soda, however, present an anomaly which can only be explained by assuming that the sediments were enriched in alkalis. Various assumptions have been made in establishing this result, the silica percentage of the added material and the percentage of plagioclase rock present being unknown. Whatever reasonable assumptions are made, however, the same result is reached.

The hypersthene-monzonites and diorites appear to be due to the soaking of argillaceous sediments by augite-biotite-diorite, their situation in the augite-biotite-diorite zone with a strike parallel to that of the marginal sediments being of importance in this connexion. The invaded sediments show changes characteristic of high-temperature metamorphism, a strongly pleochroic hypersthene, orthoclase, and quartz having resulted. By subtracting augite-biotite-diorite from hypersthene-monzonite, on a straight-line diagram, the composition of the invaded sedimentary material can be found. The sediments were evidently mainly of an aluminous variety, so that a low silica percentage should be assumed. If they contained 58 per cent of silica, the analysed hypersthene-monzonite, which is probably the most potash-rich of the hypersthene rocks, and consequently the richest in sediments,

consists of 80 per cent sediments and 20 per cent of augite-biotite-diorite, the sediments having the following composition:—

SiO ₂	. . . . .	58.00
Al ₂ O ₃	. . . . .	16.50
Fe ₂ O ₃	. . . . .	2.25
FeO	. . . . .	3.23
MgO	. . . . .	4.40
CaO	. . . . .	5.00
Na ₂ O	. . . . .	3.40
K ₂ O	. . . . .	5.00
		<hr/>
		97.78

Again high potash, soda, and lime are evident. Soda and lime may in part be accounted for by the fact that the invading augite-biotite-diorite was richer in plagioclase than the analysed specimen, and high lime by the presence of a little calcareous shale. As in the case of the sediments that contributed to the augite-monzonite, however, there has been considerable enrichment in potash and soda. If the sediments are assumed to have been more siliceous, then the potash enrichment appears even greater.

In two separate instances, therefore, it is evident that the sediments invaded by the biotite-pyroxenite and augite-biotite-diorite were abnormally rich in alkalis, a conclusion which is not surprising in view of the fact that potash and soda enrichment are known to have occurred in the inner metamorphic aureole, the enrichment there being connected with the intrusion of the biotite-pyroxenite.

As stated in the petrological section, it is quite evident that biotite-pyroxenite, sediments, and plagioclase magma contributed to the formation of the earlier fine-grained granodiorite. The evidence shows that the augite-biotite-diorite permeated through and crystallized in solid or almost solid rocks, and it is probable that the fine-grained granodiorite was formed practically in situ by the invasion of the sediments by the augite-biotite-diorite. The widespread coarse-grained granodiorite is intrusive and, except marginally, its textures are normally igneous. Experience gained by an examination of the fine variety, however, leads one to suspect that the coarser type is also effectually a mixture of biotite-pyroxenite, sediments, and plagioclase magma, the first two probably having been incorporated, at least in part, in the form of the augite- and hypersthene-bearing hybrids. So complete is the mixture this time that it must have taken place in depth at a high temperature, the granodiorite having stopped its way to its present level (see p. 593).

It might be supposed that the granodiorite is a straightforward differentiate from the augite-biotite-diorite, due to the

sinking of ferromagnesian clots, but the construction of a variation diagram at once makes it clear that such cannot possibly be the case. It is possible to demonstrate by a graphical construction, however, that the chemical composition of the granodiorite is consistent with the origin postulated above.

All the rocks of the area, therefore, can be explained in terms of biotite-pyroxenite, plagioclase magma, and sediments, the place of the biotite-pyroxenite being taken rarely

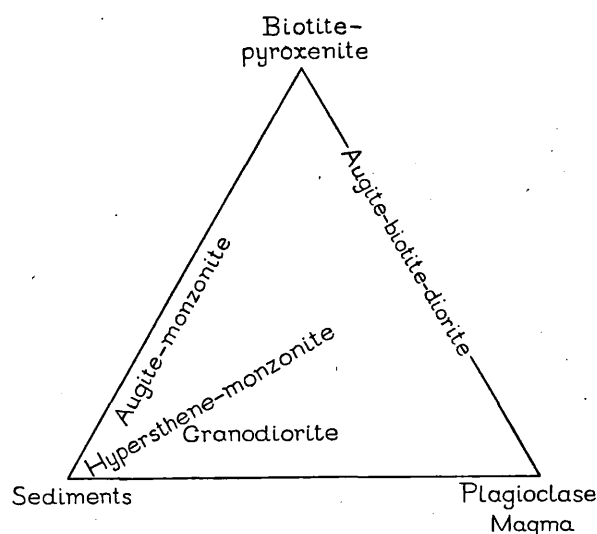


FIG. 12.—Diagrammatic representation of the various rock types in terms of biotite-pyroxenite, plagioclase magma, and sediments.

by peridotite. This relationship is illustrated diagrammatically in Fig. 12.

The history of the area may be summarized as follows :—

1. Peridotite and its differentiate biotite-pyroxenite were intruded into Silurian greywacke and shale, which they fused differentially.
2. The ultrabasic magmas rose partly by shouldering stress and partly by soaking into the fused sediments, thus giving rise to augite-monzonite with crystalloblastic textures.
3. Simultaneous with and also subsequent to the intrusion of the ultrabasic types, a plagioclase magma rose up into and hybridized them, resulting in the development of augite-biotite-diorite.

4. The augite-biotite-diorite, where intruded into the zone of fusion in the centre of the area, gave rise to hypersthene-monzonite and diorite, whilst marginally it migmatized the fused sediments, quartz-diorite being formed as a result.
5. Fine-grained granodiorite was formed practically in situ by the intrusion of augite-biotite-diorite into sediments.
6. The common coarse-grained granodiorite, possibly due to mixing in depth of biotite-pyroxenite, plagioclase magma, and sediments, rose by stopping through the earlier members of the complex.

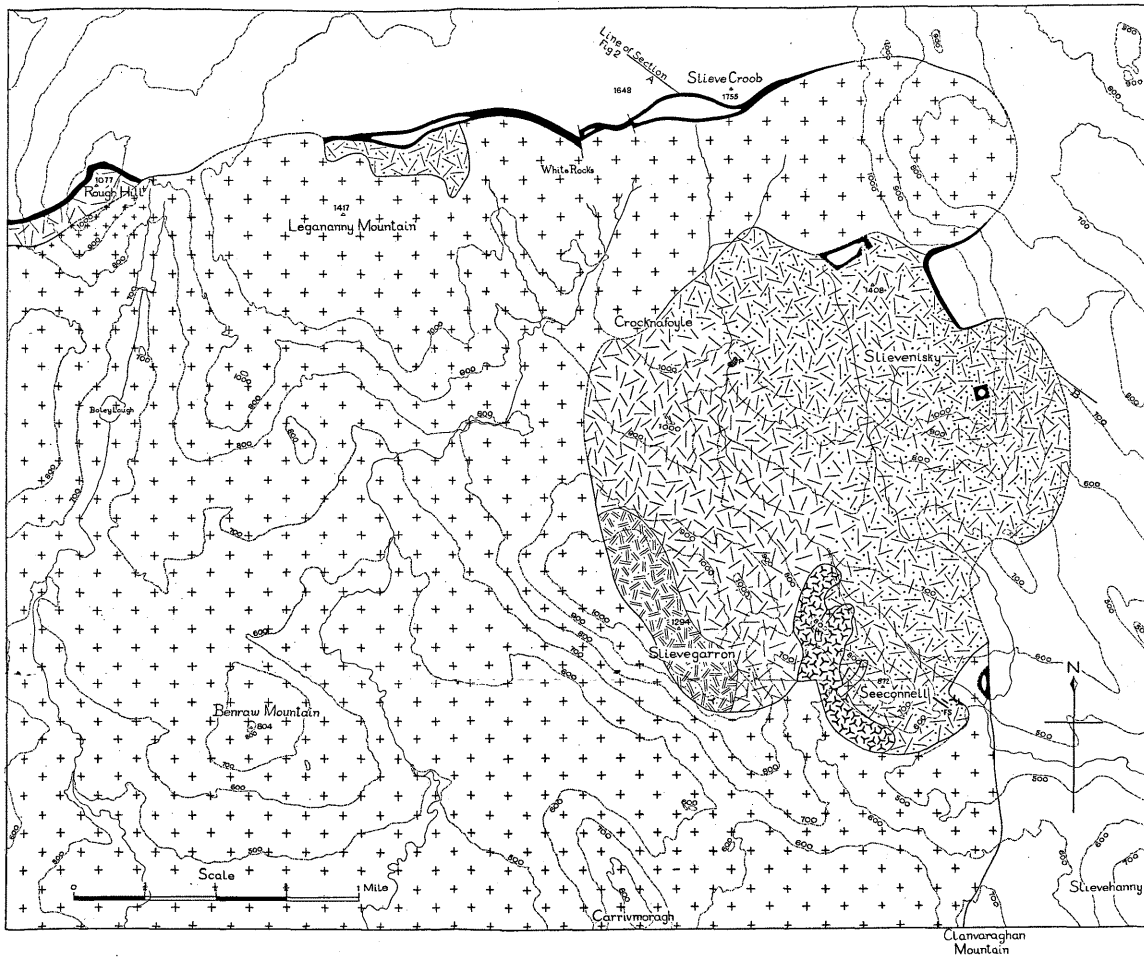
In conclusion, I wish to express my thanks to the Royal Society for a grant in aid of chemical analyses and thin sections; to Mr. L. S. Theobald for undertaking four of the analyses; to Dr. H. F. Harwood for one analysis; to Mr. Johnson of the Geology Department, University College, London, for substantial help in making thin sections; and finally to Professor Arthur Holmes for discussion and criticism which have helped materially in the construction of the paper.

EXPLANATION OF PLATE XXII

Geological map of the north-eastern end of the Newry Igneous Complex.
Scale: 3 inches to 1 mile, or 1 : 21,120.

DISCUSSION

Prof. HOLMES stated that, hitherto, the attempts to account for hybrid types having the composition of monzonites and diorites had been largely in terms of acid and basic materials, such as granite and gabbro, as the reacting units. In the area studied by the author, however, neither granite nor gabbro was present. In place of gabbro, peridotite and biotite-pyroxenite occurred, together with an independent plagioclase magma; and, in place of granite, sediments demonstrably fused by the earlier and hotter ultrabasic intrusions. This was the first case in which such an association had been recorded. In Daly's recent book on igneous rocks, one looked in vain for any example of syntexis between peridotite magma and sialic rocks, and the only suggestion that peridotite might itself be a primary magma arose from the speaker's work with Dr. Harwood on the biotite-pyroxenites and related leucitic rocks of the Ruwenzori district. Work now in progress on the petrology of the Bufumbira volcanic field had led to the recognition of potash-rich limburgite as the volcanic equivalent of biotite-pyroxenite. Magma of this composition differentiated directly to leucite-basalt and leucitite. By the incoming of plagioclase, leucite-basanites developed, and by the further addition of acid materials, latites and trachy-



Part of the
**NEWRY IGNEOUS
 COMPLEX**
 (North-eastern end)

- Granodiorite
- Fine grained Granodiorite
- Hypersthene-monzonite
- Augite-biotite-diorite Slievegarran Type
- Augite-monzonite
- Biotite-pyroxenite
- Peridotite (P)
- Fused Sediments (F.S.)
- Hornfels (Silurian)

andesites were generated. Unfortunately, from the nature of the case, the evidence from volcanic rocks was meagre, and decidedly inferior to that displayed in the Newry Complex, where the author had found a wealth of confirmatory evidence so clear and consistent as to leave no possibility of doubt as to the correctness of her interpretations. The conclusions established by her had become available at a particularly appropriate moment, just when they were likely to throw much-needed light on the more obscure problems offered by the Bufumbira volcanoes.

One geochemical aspect appeared worthy of comment. In the Ruwenzori paper the speaker had pointed out that many "intermediate" rocks—diorites, monzonites, syenites, etc.—contained far more BaO than either granite or gabbro, and that no magmatic source for this remarkable excess could be traced. If, however, biotite-pyroxenite and related rocks represented parental magmas, then, as the author had pointed out to him, this problem was adequately solved, for, in all its known occurrences, biotite-pyroxenite was extraordinarily rich in BaO.

The plagioclase magma, which had been traced over a wide area by the author, might seem to be an unorthodox innovation. The speaker thought that it might be related to anorthosite magma. There was now ample evidence that anorthosites had been magmas; that they were, of their nature, very hot; and that, by syntexis with sialic materials, they graded into magmas having the composition of quartz-syenite. Questions of their origin were purely speculative, but it should be clearly realized that there was nothing speculative about the plagioclase magma recognized by the author. Its products and behaviour were demonstrated facts of observation.

Dr. W. Q. KENNEDY said that the similarity between the marginal phenomena described by the author and the structures developed around the Morvern-Strontian granite complex in Argyll, also of Caledonian age, was very striking. In both areas the attitude of the wall rocks had been forced into conformity with the strike and dip of the igneous contact and the marginal foliation of the intrusion, while "eruptive breccias" were produced from the hard bands in the country rocks. At Strontian no melting had occurred, and the phenomena were due solely to rock-flowage. Even contact-metamorphism was absent.

Referring to the postulated "plagioclase magma", he thought that this presented certain difficulties. The direct evidence was not convincing, for the development of plagioclase porphyroblasts in enclaves was the normal effect of a granitic or granodioritic magma. Plagioclase was common as veins in most ultra-basic masses, and was known only in this form in

ultra-basic rocks. The veins had no separate existence and had been shown to result from desilication of a granitic magma.

Finally, in view of the postulated syntectonic origin of the granodiorite, it was well to remember that, not only was it strikingly similar to the widespread granodiorite magma of the Scottish Caledonian province, but that the numerous granite complexes of the latter area were intruded into country-rocks of widely different nature, and the component rocks invariably showed the same order of intrusion.

Dr. HERBERT H. THOMAS said that some years ago, when examining a few rocks from the Newry "granite", he felt that they were far from normal igneous rocks and was convinced that the complex deserved the closest study. All would agree that the complex had now received the detailed attention it merited and that the author had unfolded a most interesting history. By careful mapping and study of the intrusive contacts she had been able to establish an indisputable time-sequence for the various members of the complex. This is a necessary preliminary to any petrogenetic survey of the rock types involved. She had proved the production of several of the component masses by hybridization and assimilation at depth. The speaker was not happy about that somewhat hypothetical plagioclase magma, for there seemed to him very little evidence of, or necessity for, its existence in bulk. Further, he felt that some of the monzonitic types were too potassic to be produced without the intervention of a granitic magma.

Mr. W. CAMPBELL SMITH suggested that the biotite-pyroxenite might itself be derived from the peridotite as a reaction product of the latter with more acid magma, and not as a result of gravitative differentiation. He asked why it was necessary to assume the intrusion of a plagioclase magma, and whether a granitic magma was not competent to produce the effects observed.

Dr. A. BRAMMALL referred specially to the author's conclusion that, for the hybrid diorites, etc., the hybridizing medium was not granitic but a "plagioclase magma" acting on biotite-pyroxenite in particular. He considered that, while the new evidence revealed a mode of origin not hitherto suspected, it did not weaken the case for granitization of gabbros, diabase, greywacke, etc. He stated that, in the core of the Malverns, many examples of the latter process were associated with more restricted occurrences involving biotite-pyroxenite, and that some of the more homogeneous "mixed" types evolved were superficially similar to the hornblende-rich intrusive mass quarried at Hollybush. Although the origin of the Hollybush mass by granitization of basic material might be considered a possibility, neither field evidence nor analytical work sustained the case; whereas critical geochemical detail,

mineralogy, and microstructures suggested a connexion with biotite-pyroxenite. Granting this connexion, the Hollybush type could be regarded as a mixture of the Malvern pyroxenite with an iron-rich fluid containing about 60 per cent of normative andesine with only negligible orthoclase, and somewhat similar in composition to some "macedonites" occurring in South Victoria. The difficulties in this case had been considerably reduced after an exchange of views and specimens with the author.

Mr. A. B. EDWARDS said that the macedonites of Central Victoria, referred to by Dr. Brammall as chemically equivalent to the "plagioclase magma" of the author, had close affinity with the mugearites of the British Tertiary suite, but were considerably richer in potash than the latter. They formed a group within a suite of lavas which appeared to have evolved, mainly by crystal differentiation, from a single basaltic parent magma. The most basic members of the province were limburgites. Accepting the analogy of the limburgites with the biotite-pyroxenites of the Newry Complex, and of the macedonites with the plagioclase magma, a possible origin could be conjectured for the latter. The difficulty arose, however, of comprehending the mechanism by which the more abyssal, partially crystalline pyroxenite magma could rise above, and then be invaded by, the lighter and more fluid plagioclase-rich derivative. Any movement initiating an uprising of the pyroxenite magma would be expected to cause movement in the plagioclase magma above.

The AUTHOR, in reply to Dr. Kennedy, said that she was interested in his remarks on the similarity of intrusions of Caledonian age in Scotland to those of the Newry area. She saw no difficulty in the occurrence of monzonite in sills, since hybridization, which was known to have occurred at shallow depths, must have been even more effective at lower levels, where actual magmas would result from the mixing.

Several of the speakers had appeared to regard the plagioclase magma with suspicion. The author agreed that an adequate explanation of its origin was a difficulty, but pointed out that this was a question of theory and did not affect the evidence for its existence. This evidence was based upon field and petrological observation. The biotite-pyroxenite was seen to grade to a type which was veined with plagioclase, and a further intimate mixing of the two types had given rise to augite-biotite-diorite, in which the originally fluid state of the plagioclase was indicated in that it had dissolved all the iron ores with which it came in contact. Similar felspathic rocks had already been recorded as intrusive masses from other areas, and perthosite, described by Dr. Phemister from Loch Ailsh (where it was also associated with biotite-

pyroxenite) and the trondhjemites of Norway were cited as examples, the latter being enriched in silica.

She owed to Professor Holmes the suggestion that the origin of the plagioclase magma was bound up with its association with regions of compression. In such areas the basaltic layer might be differentially converted to crystalline eclogite and a residual plagioclase magma. Graphical constructions showed that plateau-basalt was chemically equivalent to eclogite low in alumina plus plagioclase, and this was discussed in the paper. If plagioclase magma arose thus it would, of necessity, be very hot and unable to avoid contamination on rising, and this would explain the absence, pointed out by Dr. Thomas, of unadulterated plagioclase rock in the area. The author hoped to show later that hybrids formed from biotite-pyroxenite were associated with regions of compression in many other areas, and that in such regions true gabbro was characteristically absent, as might be expected if the explanation of the plagioclase magma were correct. As examples, the igneous provinces of Monzoni and Predazzo were cited and the trondhjemite-opdalite series of Norway; in America, the western folded region was rich in examples, whilst the Cortlandt series was an excellent example in the Appalachian fold region.

In reply to Dr. Thomas, the author said that the monzonites were due to admixture of the ultrabasic types and sediments, both strongly potassic, and the plagioclase magma had taken very little part in their formation.

To Mr. Campbell Smith's question she replied that the biotite-pyroxenite provided no evidence of being a hybrid. It lay in the liquid line of descent from potash peridotite, and its high concentration of TiO_2 and P_2O_5 suggested that it stood in the same relation to potash peridotite that pegmatite did to granite. Granite was not competent to produce the observed results, since the augite-biotite-diorite was not only almost free from quartz but was normatively undersaturated. The results of a graphical subtraction of biotite-pyroxenite from augite-biotite-diorite, choosing a silica percentage such that the ratio of Na_2O to CaO was that of the actual plagioclase Ab_{65} , corresponded to a magma composed of about 80 per cent plagioclase, the remaining 20 per cent representing iron ores and biotite.

The author was interested to hear from Dr. Brammall of biotite-pyroxenite and hybrid diorites in the Malvern area, and particularly so since that was also a region of compression.

In reply to Mr. A. B. Edwards, the author said that no difficulty in explaining the order of intrusion arose in the Newry area if the origin of the biotite-pyroxenite and plagioclase magma were such as she had suggested.

WITH THE AUTHOR'S COMPLIMENTS.

To _____

106.

The Dykes of the Ards Peninsula,
Co. Down.

BY

D. L. REYNOLDS, M.Sc.

Extracted from the GEOLOGICAL MAGAZINE, Vol. LXVIII, Nos. 801 and 802,
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pp. 97-111 and 145-65, March and April, 1931.]

The Dykes of the Ards Peninsula, Co. Down.

By D. L. REYNOLDS, M.Sc.

(PLATE VI.)

1. INTRODUCTION.
2. GENERAL FIELD RELATIONS.
3. THE OLDER OR CRUSHED DYKES.
 - (a) Field description.
 - (b) Petrology.
4. THE YOUNGER OR UNCRUSHED DYKES.
 - (a) Field description—
 - (i) Distribution.
 - (ii) Types of rock and their order of intrusion.
 - (iii) Xenoliths.
 - (b) Petrology.
5. PETROGENESIS.
6. SUMMARY OF CONCLUSIONS.

1. INTRODUCTION.

THE Ards peninsula, which forms the eastern part of Co. Down, is about 20 miles long and varies from 3 to 5 miles in breadth. On the west it is separated from the mainland by Strangford Lough, the east coast facing the Irish Sea.

The country rocks are slates and grits of Silurian age, with a prevalent S.W.-N.E. strike and a high angle of dip, the direction of which varies due to a succession of folds which date from Caledonian times. Into this series numerous dykes are intruded, the great majority of which have their strike coincident with that of the country rocks, the remainder taking a direction at right angles, or rarely at 30° to this. These intrusions form a part of a great series of dykes which occur throughout the north of Ireland, cutting the Caledonian folds, but nowhere penetrating the Carboniferous strata.

Previous knowledge of the Ards dykes is due to the Geological Survey,¹ who mapped them, recorded their main exposures and

¹ Expl. Sheets 49, 50, and part of 61, *Geol. Surv. Ireland*, 1871, 36-45; Expl. Sheets 37, 38, and part of 29, 1871, 25-29, 32-33.

first classified them as intrusive felstones, minettes and diorites, together with ashes of Silurian age. Later McHenry and Watts,¹ in a brief account of the intrusions, described them as lamprophyres belonging to the groups of minettes and kersantites. In 1899 Seymour and Egan² revised the igneous geology of the Ards, and, after a study of thin sections, Seymour found all the rocks to be lamprophyres, the varieties of which differ from one another in the fact that the predominating ferro-magnesian mineral is sometimes biotite, sometimes hornblende, and more rarely augite. Believing plagioclase to be the most abundant felspar, he classified them as kersantites and camptonites.

Nothing is known of the relation of the various types of rock and practically nothing of their petrology. The present study was undertaken to correct the early classification, to determine the distribution of rock types and their order of intrusion and, if possible, to gain some insight into their origin. The investigation was restricted to coast exposures, the greater part of the interior being under cultivation. The Strangford and Irish Sea coastlines of the Ards, however, provide a double traverse across the strike of the country rocks and 260 dykes were examined.

2. GENERAL FIELD RELATIONS.

The distribution of the dykes round the shore is indicated on the sketch map, Fig. 1. In the field they can be separated into two series, according to age. Those which occur in the south, whilst penetrating and truncating folds in the Silurians, are themselves cleaved and crushed, frequently having the appearance of schists. The majority follow the strike of the Silurian slates and grits, and the foliation is parallel to their sides. They were evidently intruded during a pause in the Caledonian folding, continuation of pressure in approximately the same direction afterwards reducing them to a schistose state.

The younger series is practically confined to the north of the area, and the majority of the dykes again have a prevalent S.W.-N.E. strike. They are not seen in contact with the older series, but are noticeably different, being fresher, more massive, and showing no signs of crush.

Similar relations between lamprophyre dykes and earth-movements occur in Colonsay, where the varied age of the intrusions as related to cleavage has been described by Wright³ and in the *Geological Survey Memoir* of the district.⁴ The early lamprophyres

¹ *Guide to the Collections of Rocks and Fossils belonging to the Geological Survey of Ireland*, 1898, 74-5.

² *Summ. Progr. Geol. Survey*, 1899, 180-1.

³ W. B. Wright, "The Two Earth-Movements of Colonsay": *Quart. Jour. Geol. Soc.*, lxiv, 1908, 297-311.

⁴ "The Geology of Colonsay and Oronsay": *Memoir Geol. Survey Scotland*, 1911, 38 and 39.

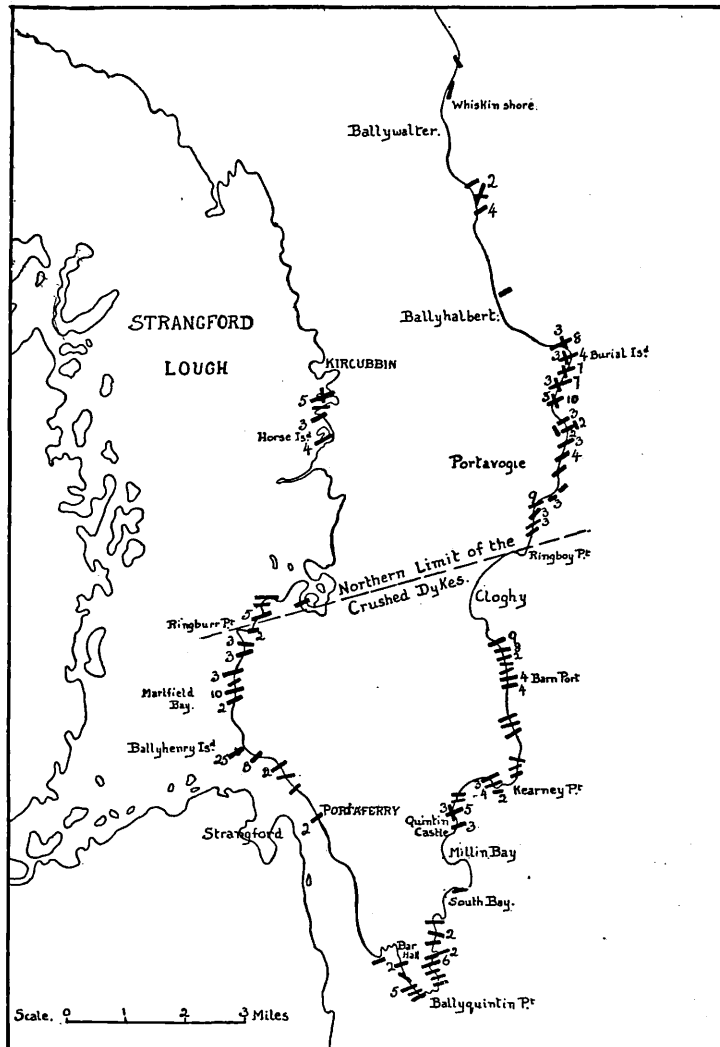


FIG. 1.—Map showing the general distribution of the dykes around the coast of the Ards Peninsula. Owing to the small scale of the map it has been found necessary in many instances to group the dykes and in these cases the numerals indicate the number of them represented by each line. For the same reason groups of dykes are shown as intersecting on the map, whereas in reality a few members only are in contact.

of the Ards, however, although greatly crushed, have not been folded by the later movements. Normal and sheared lamprophyres, together with lamproschists, are also recorded from the Ben Wyvis¹ area and crushed lamprophyres from the Isle of Man.²

In addition to numerous dykes with a strike parallel to that of the Caledonian folds, both the older and newer series include a smaller number of members which cut these and have a strike at right angles to the axis of folding. The evidence of regional tension which such conjugate intrusions afford has been discussed by Evans.³ Applying his conclusions in the case of the Ards dykes, it appears that both the crushed and uncrushed series were intruded during periods of tension which occurred as a reaction after Caledonian compression. In each case there was stretching in all directions, varying from a maximum perpendicular to the axis of folding to a minimum parallel to it. Consequently, at both periods, splitting, accompanied by dyke intrusion, took place first parallel to the folds and released all the components of tensional force perpendicular to that direction. The only forces remaining then being parallel to what was the direction of minimum tension, there was subsequent splitting and dyke intrusion on a smaller scale at right angles to the folds.

The crushed series of dykes thus afford evidence of a distinct pause in the Caledonian compression, during which pressure was relaxed and tensional forces came into play. It is worthy of note that after the final period of stress the site of igneous activity had moved northward.

The total thickness of the crushed dykes intruded parallel to the strike of the country rocks, as measured on the east coast, is 102 feet. There was thus a stretching of the earth's crust by this amount in a north-westerly direction, in a distance of 5·6 miles, as a result of the first period of tension. That is, the earth's crust was lengthened in the direction of maximum tension by ·3 per cent. This estimate must be regarded as a minimum, since it is likely that dykes are concealed both in the sandy bays and in seaweed-covered areas.

The combined thickness of the younger dykes, intruded parallel to the bedding, and exposed on the east coast is 488 feet. These dykes occur within 9·6 miles of country, measured at right angles to the strike. In this case, therefore, the earth's crust was lengthened by 1 per cent.

In addition to the two definite series of intrusions described, there are a few dykes of pyroxene-minette exposed between Ringburr Point and Old Man's Head, including the dyke at the latter locality, which cannot be definitely assigned to either series. In the field they

¹ "Geology of Ben Wyvis, etc.": *Mem. Geol. Surv. Scotland*, 1912, 116-26.

² "Geology of the Isle of Man": *Mem. Geol. Surv.*, 1903.

³ J. W. Evans, *Pres. Add. Geol. Soc., Quart. Jour. Geol. Soc.*, lxxxii, 1925, xxxvi.

are seen to be cleaved, but are not foliated like the older dykes. Petrologically they resemble the younger type. A dyke of vogesite, outcropping on the northern shore of South Bay is also cleaved, but has not been rendered schistose and petrologically resembles some of the vogesites of the newer series. It is possible that these dykes may be intermediate in age, and it is striking that on the west coast they are intermediate in position between the older and younger series.

3. THE OLDER OR CRUSHED DYKES.

(a) FIELD DESCRIPTION.

Intrusions belonging to the older series are not found north of Ringburr Point on the west coast, or north of Slanes Point on the east, but in the absence of exposures in the sandy Cloghy Bay the northern limit for the crushed dykes has been drawn on the map from Ringburr to Ringboy Points, thus following the strike of the country rocks.

The members of this series are all narrow, as is apparent from the following summary of the thickness of 101 dykes which were measured :—

<i>Thickness.</i>	<i>Number.</i>
1 ft. and under . . .	35
1 ft. to 2 ft.	37
2 ft. to 3 ft.	17
3 ft. to 4 ft.	5
4 ft. to 5 ft.	2
5 ft. to 6 ft.	5

Thus of the measured dykes 88 per cent have a thickness of only 3 feet or less.

With the exception of two or three pinkish rocks, the dykes are grey, or greenish grey, in colour and are not easily recognized in the field, for they closely resemble the almost vertical slates and grits into which they are intruded and are frequently buried in seaweed. The cleavage of the slates is often seen to continue through them, and they show a marked foliation, sometimes appearing schistose.

At first sight the majority resemble sills, since they follow the strike of the sedimentary beds, but closer inspection reveals the fact that while some wind across the strike of the Silurians in places, or truncate crumples, others transgress in the vertical sense, either piercing their way through the crests of small folds or exhibiting an angle of dip which differs from that of the sediments. Very rarely, almost vertical dykes cut across the strike of the country rocks at approximately 3°. Examples occur at the southern end of Ballyhenry Island and to the north of Lower Ballyspurge.

Dykes which cut the strike of the Palaeozoic rocks at right angles

are not common. These are usually sheet-like in character, and rarely have a dip of more than 30° , the direction being variable. Wherever they are seen in contact with the sill-like dykes, they cut through them. This relationship is well exhibited in a small bay just to the north of Quintin Castle, where several dykes with a strike parallel to that of the slates occur, and three others with a N.N.W. strike cut the slates at right angles. Two of the latter cut across the former, the more easterly of the two also truncating small folds in the slates.

An interesting dyke occurs at Kearney Point, where it appears in detached horizontal portions extending in an E.N.E. direction. It varies from 10 to 14 inches in thickness, and rests on the upturned edges of a series of small folds in the Silurians. Traced eastward, it develops a dip of about 22° to the S.E., and passes into the sedimentary rocks.

There are no composite dykes, but one multiple intrusion was noted at the southern end of Ballyhenry Island. The members, intruded side by side and occasionally separated by an inch or two of slate, measure respectively 8 and 5 inches across. They cut the bedding and cleavage of the slates at 30° , striking 8° N. of E.

(b) PETROLOGY.

Members of the crushed series are all lamprophyres, and are usually in an advanced stage of decomposition and highly charged with carbonates, largely due to infiltration along the planes of schistosity and replacement of the feldspars. Qualitative chemical tests indicate the presence of lime, iron, and magnesium carbonates. Minerals which were originally characteristic of these rocks are potash-feldspar, plagioclase, biotite, monoclinic pyroxenes, olivine, and quartz, with apatite, magnetite and iron pyrites as accessories. Hornblende was present in rare instance only.

The rocks are minettes and rarely vogesites, since in every case in which the feldspars are still recognizable potash-feldspar predominates. From its patchy extinction this feldspar is probably anorthoclase. Plagioclase is always present, and occasionally almost equals anorthoclase in amount. It gives a maximum extinction of 16° in the zone normal to (010), is optically positive with $\gamma < 1.54 > 1.536$, $\alpha < 1.532 > 1.528$, and consequently can be assigned to albite.

Biotite is the only ferromagnesian mineral which ever appears fresh; even here, however, freshness is the exception and decomposition to a chloritic substance with sagenite nets is usual, lenticles of calcite being frequently intruded between the cleavage planes. Well formed crystals are often observed, in addition to ragged flakes, and zoning is common.

A monoclinic pyroxene is represented in many of the rocks by pseudomorphs of carbonates and quartz, whilst lozenge-shaped pseudomorphs, also of carbonates and quartz and rimmed tangen-

tially by biotite, indicate the former presence of olivine in some specimens.

There is usually a little interstitial quartz and frequently a small amount of a pale green glass, which will receive further description in connection with the newer intrusions, where it also occurs and is more easily examined. Muscovite is sometimes present as a decomposition product.

Vogesites are uncommon, rare dykes only containing pseudomorphs after hornblende, in which case pyroxene and mica seem to have been absent.

Speaking generally, the proportion of felspar to ferro-magnesian minerals is higher in these rocks than in the younger series.

The texture is variable and does not depend altogether on the size of the intrusions. In some, the felspars are elongated and irregular in shape, averaging 0.6 mm. by 0.4 mm., whilst in others they form plumose aggregates and the structure approaches the spherulitic. The latter texture is sometimes found in dykes which are 2 feet or more in thickness, whilst the former, although characteristic of the larger intrusions, may appear in those which are only 10 inches in width. In some dykes the felspars have a lath-like form, the minute laths being separated by interstitial quartz and green glass. Two narrow dykes, one 10 inches thick at Kearney Point and another 6 inches thick at Barn Port, are distinctly spherulitic towards the centre, the crowded spherulites being embedded in a green glass which is crowded with secondary sericite. These rocks contain pseudomorphs after biotite with a linear arrangement due to flow; the pseudomorphs are present both in the spherulites and in the glassy matrix, indicating the intratelluric origin of the biotite. The specific gravity of the central spherulitic portion of the dyke at Barn Port is 2.767 at 4° C.

Rounded xenocrysts of quartz are common, and are bordered by a narrow reaction-rim now composed of carbonates. Xenoliths of quartzite are also frequently seen in thin section. Both xenoliths and xenocrysts have evidently been derived from the country rocks.

The ocellar structure, so often described in lamprophyres, is developed in some members of the crushed series. Bodies which are circular or oval in section are scattered through the rock, and contain anorthoclase, plagioclase, calcite, and a little quartz. The plagioclase is usually euhedral, whilst anorthoclase may be euhedral or anhedral. Quartz and calcite are always interstitial. The felspars are sometimes noticeably more coarsely crystalline than those of the matrix. These structures are rimmed tangentially by flakes of biotite. They show no definite internal arrangement, the enclosed minerals being disposed quite irregularly, or extending from side to side. Sometimes a felspar inside the structure extends beyond the biotite rim.

Signs of crush can be seen in thin section, although they are more evident in hand-specimens. Biotite flakes are sometimes

bent and in a few of the dykes the felspar matrix has undergone granulitization, a mosaic structure resulting. The minerals frequently show a parallelism which is probably partly due to an original flow structure and partly to crushing, and the foliation has been accentuated by the infiltration of carbonates along the lines of schistosity. Most of the quartzite xenoliths show a lenticular form, with their long axes parallel to the schistosity of the matrix.

4. THE YOUNGER OR UNCRUSHED DYKES.

(a) FIELD DESCRIPTION.

(i) DISTRIBUTION.

The younger dykes have their greatest development north of the limit of the crushed series, a few isolated examples only outcropping in the south; notable occurrences being:—

1. At the point north of Barhall, where just above low-water-mark a dyke of pyroxene-minette, about 4 feet thick, cuts the bedding of the country rocks and shows a variable dip which at its maximum is 38° to the west of north.

2. In Marfield Bay, where a vogesite dyke, approximately 7 feet wide, strikes 12° east of north-east parallel to the bedding of the country rocks.

3. Opposite Templecowey, a dyke of pyroxene-minette 10 feet wide, strikes 3° north of east parallel to the country rocks.

4. South of Slanes Bay a red felspar-porphry 2 ft. 6 in. wide strikes 3° north of east.

(ii) TYPES OF ROCK AND THEIR ORDER OF INTRUSION.

Dykes belonging to the younger series are of two main types: one characterized by hornblende and the other by biotite and monoclinic pyroxene. The former is predominantly red, whilst the latter is usually brown, with lustrous flakes of dark mica. It is not always possible, however, to distinguish between the two varieties in the field. Dykes containing hornblende form the most massive intrusions in the district and with one exception, on the headland south of Kircubbin, always follow the strike of the country rocks, whilst dykes bearing biotite and pyroxene occur both parallel to the strike of the country rocks and cutting it and the hornblende dykes at right angles. In no case does a hornblende dyke cut one containing biotite or pyroxene. Consequently it can be inferred that the hornblendic type was the first to be intruded. This relation between the two varieties is best exposed along the shore between Portavogie and Burial Island.

Intrusions characterized by hornblende belong to the four following types:—

- Hornblende-porphryrite.
- Vogesite.
- Spessartite.
- Felspar-porphry.

Hornblende-porphyrite, which forms the largest intrusions, is red in colour, with phenocrysts of green hornblende and felspar, the former being the more abundant. One dyke, 25 feet wide, is exposed in the sand on the shore south of Portavogie;

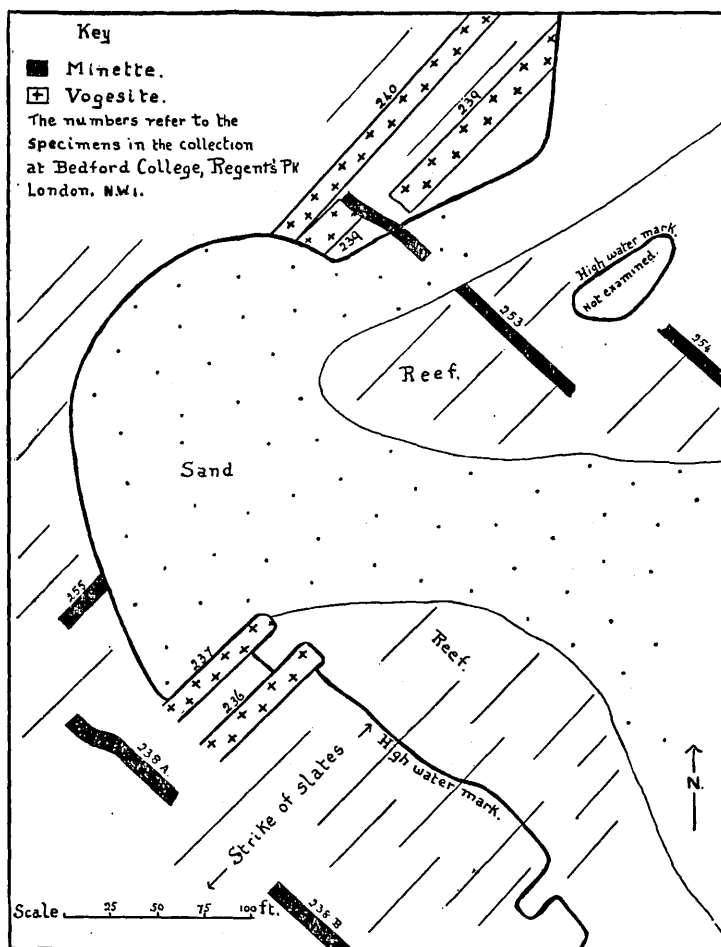


FIG. 2.—Map of part of the coast at the headland north of Portavogie illustrating the relation of hornblende- and biotite-diopside-bearing dykes.

another, 45 feet wide, outcrops slightly farther north, where it forms a low cliff and extends under the road opposite some cottages. A hornblende-porphyrite dyke 40 feet wide also outcrops at the quay, Portavogie.

Vogesite.—There are two varieties of vogesite, of which one is termed type A and the type B. The vogesite dykes of type A are red in colour and crowded with well-formed crystals of green hornblende, resembling the hornblende-porphyrites in appearance. Excellent examples are found on the shore to the north of Portavogie. They are more numerous, though narrower, than the porphyrite dykes.

Dykes of vogesite type B are green or brown in colour, and can be distinguished from type A in the field. The largest dyke is about 20 feet wide and outcrops on the headland south of Kircubbin.

Spessartites are brown or green in colour, and form intrusions of smaller size than the vogesites. They contain elongated crystals of brownish-green hornblende. A good example 3½ feet wide is found near the Butterlump Stone, south of Ballyhalbert, another typical dyke 7½ feet wide outcropping at the harbour at Ballyhalbert.

Felspar-porphry forms red dykes which are evidently mainly felspathic. Glomeroporphyritic groups of felspar and a subordinate green mineral can be identified in the hand specimen, the ferromagnesian mineral being much less abundant than in the vogesites. Only two dykes of felspar-porphry were found; one 2½ feet wide occurs south of Cloghy, whilst the other, which is 16 feet wide, outcrops near the harbour wall at Ballyhalbert.

No statement can be made as to the relative age of dykes of these four types of rock since they are all parallel. Table 1 shows their size.

Dykes containing biotite and monoclinic pyroxene are of the following varieties:—

- Pyroxene-minette and kersantite.
- Hornblende-minette.
- Pyroxene-vogesite.

Of these, pyroxene-vogesite and hornblende-minette dykes are always intruded parallel to the strike of the country rocks. In one instance, however, a dyke of the former intersects one of minette, and, consequently, the pyroxene-vogesite dykes cannot be regarded as distinctly older than those of minette. The minettes are of two varieties, which will be distinguished as type A and type B. Dykes of type A follow the strike of the sedimentary beds or take a course at right angles, whilst those of type B always cut the bedding of the country rocks at right angles and were probably the last to be intruded.

With the exception of minette type B, the varieties are indistinguishable in the field, all being dark brown or dark green in colour and characterized by a lustrous dark mica, crystals of which may measure as much as 1 cm. across. The mica flakes have a distinct parallelism due to flow. Pyroxene cannot be seen in the hand specimen.

Only three dykes of minette type B were found, but they differ greatly from the other mica types, from which they can be separated with ease in the field. Of the three dykes examined, one 2 feet and one 1 foot thick occur at Ballyhalbert harbour, whilst the third, which is 5 or 6 feet wide, outcrops south of the Coast Guard Station, Ballyhalbert. They exhibit abundant porphyritic crystals of a dark green monoclinic pyroxene, with a maximum length of 5 mm., which are embedded in a red felspathic matrix. Biotite can be detected in the hand specimens only by the glistening of its minute flakes. For the relative size and abundance of the dykes formed by these rocks see Table I.

TABLE I.—TABULAR SUMMARY OF THE THICKNESS OF DYKES OF VARIOUS TYPES OF ROCK.

Thickness.	Number of dykes of various types.								
	Hornblende Porphyrite.	Vogesite Type A.	Vogesite Type B.	Spessartite.	Felspar Porphyry.	Hornblende Minette.	Pyroxene Vogesite.	Pyroxene Minette Type A.	Pyroxene Minette Type B.
3 ft. & under	-	1	1	3	1	1	-	33	2
3 ft. to 6 ft.	-	1	3	1	-	1	-	17	-
6 ft. to 9 ft.	-	2	2	1	-	-	-	8	-
9 ft. to 12 ft.	-	4	1	-	-	-	1	2	-
12 ft. to 15 ft.	-	2	-	-	-	1	-	2	-
15 ft. to 18 ft.	-	1	-	-	1	-	-	-	-
18 ft. to 21 ft.	-	-	-	-	-	-	-	-	-
21 ft. to 24 ft.	2	-	1	-	-	-	-	-	-
24 ft. to 27 ft.	-	-	-	-	-	-	-	-	-
36 ft.	-	-	-	-	-	-	1	-	-
40 ft. to 45 ft.	2	-	-	-	-	-	-	-	-
Average size	34 ft.	9 ft.	7 ft.	4 ft.	9 ft.	7 ft.	24 ft.	4 ft.	3 ft.
Aggregate thickness	135 ft.	104 ft.	60 ft.	18 ft.	19 ft.	22 ft.	48 ft.	261 ft.	9 ft.

One multiple dyke only was found. It outcrops near the Butterlump Stone, south of Ballyhalbert and is of pyroxene-vogesite. It forms an intrusion of the symmetrical type, the centre portion measuring 8 to 9 inches and the outer portions 4 to 5 inches in thickness. This dyke is interesting as being the only example of a dyke which is parallel to the bedding of the country rocks cutting dykes which strike at right angles, the reverse in other cases always occurring. The two narrow dykes intersected by it are minette.

(iii) XENOLITHS.

Accidental xenoliths are common and usually consist of sub-angular slate and grit fragments. In a dyke at the foot of the

dunes, north of Portavogie quay, a rounded red gneissic inclusion was observed which measured about 5 inches across.

A cognate xenolith was found in the pyroxene-vogesite dyke outcropping at the Whiskin shore. It measured 24 by 22 inches and was roughly heart-shaped, with the apex pointing upwards. In the field it could be seen to contain coarsely crystalline biotite and felspar.

(b) PETROLOGY.

A study of the dykes in the field indicates the importance of the ferro-magnesian constituents, an importance which is even more apparent when the rocks are examined in thin section. Unfortunately the nomenclature of the lamprophyres is dependent on the determination of the felspars, which play the less important rôle, and it is particularly unsatisfactory in the case of the finer grained rocks where the felspars have a plumose texture and the presence of minute portions of green glass make a refractive index determination almost, if not quite, impossible.

In practically every case in which the plagioclase has been determined in the Ards lamprophyres, it has been found to be albite, whilst the patchy extinction of the potash-felspar suggests that it is anorthoclase. Thus, whichever felspar may predominate, the magma from which it crystallized was characterized by richness in soda.

For descriptive purposes the usual names have been employed, but the rocks are grouped into two classes according to the predominance of hornblende, or biotite and pyroxene, the felspars being regarded as of secondary importance.

(i) HORNBLENDE TYPE.

Hornblende-Porphyrite.

The porphyrites differ from the vogesites mainly in structure. They are porphyritic, with phenocrysts of felspar and hornblende which have a tendency to parallelism due to flow. The matrix consists of minute felspar prisms and a small amount of interstitial green glass and quartz. Magnetite in irregular grains and rather broad prisms of apatite form accessories. Pseudomorphs of a chloritic, or serpentinous substance associated with magnetite and haematite, are sometimes present. They are of indefinite shape and are always surrounded by small prisms of hornblende, which have evidently been formed by reaction between the original ferro-magnesian mineral and the still fluid magma.

The felspar phenocrysts show some alteration to sericite. Plagioclase probably predominates, but orthoclase or anorthoclase is also present in considerable amount. In the matrix potash-felspar is more abundant than plagioclase. The potash-felspar usually shows the patchy extinction suggestive of anorthoclase.

Hornblende occurs in elongated prisms with the forms {110} and {010} developed in the prism zone. Simple or lamellar twinning

is frequent parallel to (100). Pleochroism is well marked: X = pale yellowish green, Y = Z = deep green, and zoning is sometimes exhibited, in which the crystals usually have a paler margin with a slightly higher extinction angle. The maximum extinction measured in the prism zone is 22° and $\gamma - \alpha = .023$ approximately.

Although the rocks appear porphyritic, close examination reveals the fact that there are all gradations in the size of the hornblende and felspar crystals down to that characteristic of the groundmass. This structure has been shown by Beger¹ to characterize the lamprophyres from Lausitz, Saxony.

With regard to the order of crystallization, hornblende is occasionally enclosed in the felspar phenocrysts, whilst the larger crystals of hornblende are frequently riddled with inclusions of the matrix. When the hornblende is viewed in cross section, these inclusions sometimes appear in a definite zone, so that the crystal has an isolated outer shell. Some of the hornblende prisms have felspar crystals clinging to them in the prism zone, whilst hornblende is at times arranged around the largest felspars in a manner indicative of flow. Thus crystallization of the component minerals appears to have gone on simultaneously.

A specimen (No. 213)² from the dyke exposed in the sand on the shore south of Portavogie was selected for analysis, the analysis, norm and mode being as follows:—

Analysis. ³		Norm.		Mode (percentage volume).	
SiO ₂	55.40	quartz	6.78	hornblende	29.2
Al ₂ O ₃	16.22	orthoclase	12.79	felspar phenocrysts	12.6
Fe ₂ O ₃	1.71	albite	35.63	matrix, mainly felspar	
FeO	3.72	anorthite	13.34	with a little quartz	
MgO	5.45	corundum	2.04	and green glass	58.2
CaO	5.40	hypersthene	17.82		
Na ₂ O	4.20	magnetite	2.55		
K ₂ O	2.15	ilmenite	.76		
H ₂ O +	2.4	iron pyrites	.36		
H ₂ O -	.30	apatite	.34		
CO ₂	2.00	calcite	4.5		
TiO ₂	.42				
P ₂ O ₅	.24				
S	.22				
MnO	Traces				
	99.83				

Symbol II.(4)5.2".4.

Specific gravity = 2.768 ± .001 at 4° C.

Although the modal and normative minerals are different, yet some idea can be gained as to the nature of the potash-felspar pre-

¹ P. J. Beger, "Beiträge zur Kenntnis der Kalkalkalreihe der Lamprophyre im Gebiete des Lausitzer Granit-lakkolithen": *Neues Jahrb.*, B-B, xl, 1916, 583.

² These numbers refer to the specimens and thin sections in the collection at Bedford College, Regent's Park, London, N.W. 1.

³ The chemical analyses were made by Mr. W. H. Herdsman.

sent in the rock. Hornblende forms 29 per cent of the porphyrite by volume and is estimated to constitute 35 per cent by weight, any error being in the nature of an over-estimate. As a basis for calculation, the hornblende is assumed to be similar in composition to that from Edenville,¹ the analysis of which has been recast as a norm as follows:—

Analysis.		Norm.	
SiO ₂	41.99	orthoclase	6.12
Al ₂ O ₃	11.62	albite	3.14
Fe ₂ O ₃	2.67	nepheline	9.66
FeO	14.32	anorthite.	17.51
MgO	11.17	diopside	27.58
CaO	11.52	olivine	26.32
Na ₂ O	2.49	magnetite	3.94
K ₂ O	.98	ilmenite	2.89
H ₂ O	.61	fluorite	1.64
TiO ₂	1.46		
F ₂	.80		
MnO	.25		
Loss at 110°	.08		
	99.96		
O = F ₂	.33		
	99.63		

The norm indicates the amount in grams of normative minerals present in 100 grams of hornblende, so that 35 grams of hornblende would contain:—

orthoclase	2.14	grams
albite	1.1	"
nepheline	3.38	"

Recalculating the albite in the norm of the porphyrite so as to include 3.38 parts of nepheline, the partial norm of the rock becomes:—

orthoclase	12.79	grams
albite	29.34	"
nepheline	3.38	"

Then subtracting the normative potash- and soda-bearing minerals present in 35 parts of hornblende from the norm of the porphyrite, the total feldspar of the rock is found to contain albite and orthoclase in the ratio 28:11. If one-third of the feldspar by weight is albite, which is a distinct over-estimate, then the ratio of albite to orthoclase in the potash-feldspar is approximately 15:11 and it has the composition of anorthoclase. Making up the 35 parts of hornblende with hypersthene, magnetite, ilmenite and anorthite from the norm of the rock, together with the proportions of orthoclase, albite and nepheline shown above, the composition of the anorthoclase is found to approach Ab₁₃Or₁₁An₆. It is not

¹ W. E. Ford, "Optical Study of the Amphiboles": *Amer. Jour. Sci.*, xxxvii, 1914, 181.



Fig 1.



Fig 2.

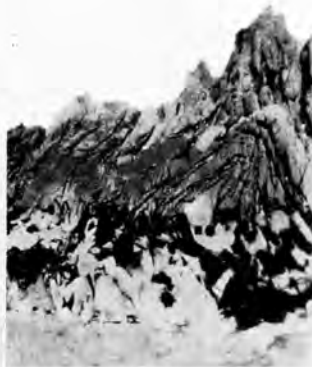


Fig 3.



Fig 4.

CRUSHED LAMPROPHYRE DYKES, ARDS PENINSULA.

To face p. 111.]

suggested that this represents the composition of the potash-felspar; it rather indicates the lowest ratio of albite to orthoclase and the highest ratio of anorthite to orthoclase it is likely to contain.

Anorthoclase, as defined by Alling,¹ may contain as little as 30 per cent albite, so that, if the potash-felspar included 4.7 parts of albite only to 11 of orthoclase, it would still be anorthoclase. In that case, calculating one-third of the felspar as albite as before, the total felspar in the porphyrite would contain albite and orthoclase in the ratio of 12.6 : 11. If the felspar includes only 12.6 per cent of albite, then the hornblende must contain 7.7 per cent of soda. That is, the potash-felspar must have the composition of anorthoclase, provided the hornblende does not contain a higher proportion of soda to potash than 7.7 : .98, which ratio is only exceeded in the soda amphiboles, normal hornblende rarely containing more than 3 per cent soda.

Actually the ratio of albite to orthoclase in the total felspar could not be so low as 12.6 : 11, since the quantity of normative anorthite present in the porphyrite is not sufficient to make up, with 12.6 grams of albite and 11 grams of orthoclase, the total weight of modal felspar.

This then constitutes proof that the potash-felspar in the porphyrites has the composition of anorthoclase.

EXPLANATION OF PLATE VI.

CRUSHED LAMPROPHYRE DYKES, ARDS PENINSULA.

FIG.

- 1.—A schistose minette dyke (No. 109) at Kearney Point intruded parallel to the bedding of the country rocks.
- 2.—A minette dyke (No. 115) at Kearney Point truncating folds in the Silurian slates and grits.
- 3.—A minette dyke (No. 144) in the bay north of Quintin Castle. The dyke, which is partly covered with seaweed, truncates a fold in the slates.
- 4.—A minette dyke (No. 36) at Old Man's Head which is cleaved but not foliated. The position of the dyke, which is intruded parallel to the bedding of the country rocks, is marked by the hammer.

¹ H. L. Alling, "The Mineralogy of the Feldspars": *Jour. Geol.*, xxix, 1921, 233.

(PLATES VIII-X.)

Vogesite.

THE vogesites are of two distinct types, one of which will be designated type A and the other type B.

Type A.

The vogesites of type A show resemblances to the hornblende-porphyrates, towards which they grade by the occasional presence of felspar phenocrysts. They possess a typical panidiomorphic structure. Hornblende, which is similar to that of the porphyrites, builds elongated crystals which may be seven or eight times as long as broad and vary in length from about 2 or 3 mm. to 0·08 mm. or less. The matrix is formed of small lath-like crystals of felspar, amongst which potash-felspar (orthoclase or anorthoclase) predominates, plagioclase also being present. The felspars are stained with haematite, particularly round their margins, so that they stand out in relief. Quartz and green glass occur interstitially. Magnetite and apatite are again present as accessories, but this time the magnetite appears as small octahedral crystals, whilst the apatite prisms are long and needle-like. The structural characteristic of the rock is the tendency of all the minerals to show form and, with the exception of quartz and magnetite, to be elongated. The larger hornblende crystals have a parallel arrangement due to flow. The serpentinous or chloritic pseudomorphs, seen in the porphyrites, are here even more evident and give definite lozenge-shaped and elongated sections exhibiting the meshwork structure characteristic of olivine. They are again surrounded by reaction rims of hornblende prisms, in which the hornblende is exactly similar to that in the main part of the rock.

These vogesites are on the whole fresh, but the hornblende has sometimes undergone a certain amount of alteration to chlorite and in some of the rocks has entirely decomposed. The feldspars have usually partly altered to sericite, particularly in the interior, a clear margin remaining. This probably indicates zoning.

Some of the rocks are characterized by what appear to have been small irregular cavities of the nature of druses. Feldspar crystals project into them and they are filled with quartz and calcite. They do not resemble the ocelli of the crushed series, with their characteristic rim of biotite flakes.

A curious rock (No. 288), in some ways allied to these vogesites, outcrops at the point north of the Butterlump Stone and strikes towards Burial Island. It is red in colour and forms a wall-like dyke. It is composed essentially of feldspar and green glass, with some calcite. The feldspars appear as small laths, with an average size of 0.4 mm. by 0.08 mm., amongst which orthoclase or anorthoclase predominates. The feldspar laths are arranged quite irregularly and frequently cross one another at right angles, the interstices between them being occupied by green glass. Apatite and magnetite are present as accessories. The rock is similar to the vogesites, type A, with the omission of hornblende and considerably more glassy base. It was analysed in order to gain some idea as to the composition of the glass, which has a refractive index of approximately 1.62, roughly that of a basaltic glass. The fine grain of the rock makes it impossible to determine the mode with any degree of accuracy; the glass, however, forms approximately 36 per cent of the rock by volume. The analysis and norm are as follows:—

Analysis.		Norm.		Partial Mode (percentage volume).	
SiO ₂	50.40	quartz	4.92	glass	36
Al ₂ O ₃	17.05	orthoclase	10.56	feldspar, calcite, and	
Fe ₂ O ₃	1.32	albite	33.01	iron-ore	64
FeO	6.15	anorthite	9.73		
MgO	5.30	corundum	5.2		
CaO	5.65	hypersthene	21.62		
Na ₂ O	3.94	magnetite	1.86		
K ₂ O	1.80	ilmenite	2.28		
H ₂ O +	3.60	apatite	.34		
H ₂ O -	.50	calcite	6.4		
CO ₂	2.80				
TiO ₂	1.24				
P ₂ O ₅	.18				
S	trace				
MnO	trace				

Symbol II".5.2.4.

99.93

Specific gravity = 2.726 ± .003 at 4° C.

From an examination of the norm it is apparent that the glass includes normative hypersthene, corundum, a small amount of feldspar and possibly quartz, corundum being present in surprisingly

large amount. It is evidently quite abnormal in composition. The ratio of albite to orthoclase in the norm strongly suggests that the potash-felspar present in the rock is anorthoclase.

Type B.

The vogesites of type B, although characterized by the same minerals as those of type A, differ from them in structure; the felspar matrix is more coarsely crystalline and they are not panidiomorphic. Plagioclase (albite and oligoclase) is euhedral, whilst the potash-felspar, which gives the patchy extinction suggestive of anorthoclase, is elongated in section and anhedral.

Hornblende, when most abundant, forms crystals which are almost as broad as long. In other cases it is elongated and needle-like, in which case it is considerably less coarsely crystalline than the felspar matrix, several small acicular crystals then being enclosed in a single felspar. The hornblende is usually zoned, the central part being browner in colour. Pleochroism in the centre zone is, X = pale yellowish green, Y = Z = brownish green; and in the outer zone, X = pale yellowish green, Y = Z = olive green. The outer zone exhibits the highest extinction angle in the prism zone, 22° being the maximum measured. Colourless and bluish-green outgrowths of amphibole, in optical continuity with the hornblende, are common. They are best developed on the terminal faces, but can sometimes be seen as additions to the clinopinacoid or filling cracks. These outgrowths have serrated boundaries and are often zoned, being bluish-green in colour where in contact with the central hornblende and colourless at their outer edges. The zones are well-defined, the change from one to another being abrupt. They have a lower refraction than the central hornblende, there being the most noticeable difference in the maximum refractive indices. The outgrowths are probably actinolite and tremolite and resemble those of tremolite described by Flett¹ from the lamprophyres of the Carn Dearg type.

Porphyritic and glomeroporphyritic groups of diopside or leucaugite occur sporadically in rocks of this type. The crystals are usually considerably larger in size than those of hornblende and are frequently altered to carbonates. At times the pyroxene is more abundant and then appears as small grains, which have been largely resorbed. Chloritic or serpentinous pseudomorphs, rimmed by hornblende, are again present and sometimes common. They are usually quite irregular in shape. Accessories are pyrite, apatite with a needle-like form, and rarely magnetite.

Some of the rocks are vesicular, the vesicles being filled with epidote, calcite, quartz, and felspar. Quartz, felspar and epidote frequently exhibit form, crystals of the latter having a radial arrange

¹ "The Geology of the country round Blair Atholl, Pitlochry, and Aberfeldy"; *Mem. Geol. Surv. Scotland*, 1905, 127.

ment; calcite is interstitial. These amygdales in no way resemble ocelli.

Vogesites of type B are characteristically fresh, but carbonates may be present in small amount, replacing the feldspars, and some epidote and chlorite are usually present.

Specimen No. 86, from a dyke on the headland south of Kircubbin, was selected for analysis as being the coarsest in grain and one of the least variable in mineral composition. It should be noted, however, that it is richer in hornblende than the average rock of this type and some of the hornblende has undergone a curious type of alteration, having been partly replaced by tremolite with similar optical orientation. The alteration extends along the cleavage planes, and magnetite, haematite and quartz have crystallized out as a result. Outgrowths of tremolite from the terminal faces of the hornblende are here very small. Quartz and potash-feldspar appear in fine micrographic intergrowth in places in the matrix. The analysis, norm and mode of this rock are as follows:—

Analysis.	Norm.	Mode (percentage volume).
SiO ₂ 49.40	orthoclase 8.34	feldspar 32.7
Al ₂ O ₃ 12.85	albite 23.06	hornblende 48.4
Fe ₂ O ₃ 1.98	anorthite 18.63	quartz 2.7
FeO 6.31	diopside 8.64	chlorite and
MgO 12.04	hypersthene 19.66	some epidote 18.3
CaO 7.40	olivine 10.77	
Na ₂ O 2.65	magnetite 2.78	
K ₂ O 1.35	ilmenite 2.13	
H ₂ O + 3.10	apatite 3.4	
H ₂ O - .20	calcite 2.3	
CO ₂ 1.00		
TiO ₂ 1.10		
P ₂ O ₅ .24		
S traces		
MnO .31		

Symbol III.5.3.4.
1(2).2.(1)2.2.

99.93

Specific gravity = 2.834 ± .002 at 4° C.

By computing an average composition for the hornblende calculated as a norm and subtracting it from the norm of the rock, it can be shown, as before, that the potash-feldspar is rich in soda, having the composition of anorthoclase. For this purpose one quarter of the feldspar is reckoned as plagioclase, this being an over-estimate.

The vogesite from South Bay, the age of which is doubtful, may be mentioned here. Petrologically it resembles type B, but has some tendency to the panidiomorphic structure, and is highly charged with carbonates. Its chief interest lies in the fact that there are outgrowths of a blue amphibole from the original hornblende. Similar outgrowths have been described by Seymour¹

¹ H. J. Seymour, "On the occurrence of a blue amphibole in a hornblende-kersantite from co. Down": *GEOL. MAG.*, 1900, 257.

in a rock from the same locality and assigned by him to the group of soda-amphiboles, of which riebeckite and arfvedsonite form typical examples. The rock (No. 196) examined by the writer differs from that described by Seymour in that biotite is absent and the predominant feldspar is orthoclase or anorthoclase. It is of medium grain and the hornblende crystals are elongated, the largest being 0.2 mm. broad, and varying from two to five times this in length. Outgrowths of blue amphibole are here only seen as additions to the terminal faces (Seymour records additions to the clino-pinacoid) and are always small, only occasionally reaching 0.1 mm. in length. They are in crystallographic continuity with the original hornblende, the cleavage in the two being parallel, but more sharply defined in

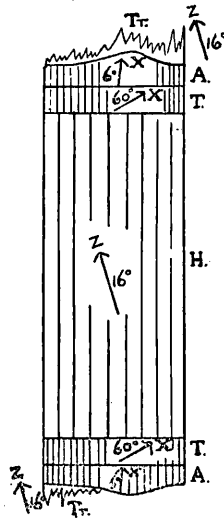


FIG. 3.—A crystal of hornblende with outgrowths of blue amphibole and tremolite. H = hornblende; T = zone which resembles torendrikite; A = arfvedsonite; Tr = tremolite.

the blue amphibole. The outgrowths are zoned, being paler in colour where in contact with the hornblende. At the outer edges they are strongly pleochroic, as follows: X = violet blue, Y = greenish blue, Z = straw colour, with the absorption $X > Y > Z$. They extinguish in the opposite direction to the hornblende, maximum extinction of 11° having been measured in the prism zone; this extinction direction being that of the fast ray X (see Fig. 3). The birefringence is weak and there is incomplete extinction in white light, indicating strong dispersion of the bisectrices.

In the paler zone the extinction is greater and the angle $X \wedge c$ approximates to 60° . It is also noticeable in this inner zone that the pleochroic axes do not coincide with X, Y, Z, the maximum

absorption being parallel to the crystallographic axis *c*. Pleochroism is bluish-green parallel to *c* and violet-gray at right angles. The refractive indices are lower than those for hornblende and the birefringence, though weak, is greater than that in the outer zone.

It is not possible to make exact optical determinations, owing to the small size of the outgrowths, but it seems likely that the more deeply coloured zone is arfvedsonite; whilst the inner paler one shows some resemblances to torendrikite.

On many of the crystals there is an additional exceedingly narrow outer margin of tremolite, in optical continuity with the original hornblende. It has a lower refractive index than that of the neighbouring blue amphibole.

Spessartite.

These rocks, which are typically trachytic in texture, are classified as spessartites since, in every case in which the matrix is not too fine grained for a discrimination to be made between the feldspars, plagioclase appears to predominate. Potash-feldspar, possibly anorthoclase, is always present in considerable amount, however, and some diffidence is felt in using the name "spessartite". It is not impossible that these rocks differ from those described as vogesites rather in the variety of hornblende they contain and their trachytic matrix than in the composition of the predominant feldspar, in which case they may themselves include both spessartites and vogesites.

Hornblende forms elongated porphyritic crystals which are two or three times as long as they are broad and have a maximum length of 2 or 3 mm. It is pale brown in colour and pleochroic, with *X* = pale yellowish brown, *Y* = *Z* = light brown. Zoning is sometimes exhibited. Though distinctly browner than the central brownish zone of the hornblende in the vogesites, it has a similar extinction angle, 20° being the maximum extinction measured in the prism zone. These hornblende phenocrysts are well formed, and have a parallel arrangement due to flow. They are often partly decomposed and are sometimes represented by pseudomorphs of chlorite, calcite, and quartz.

The matrix is mainly feldspathic with some needle-like brown hornblende, interstitial quartz and a minute quantity of green glass. Both the lath-like feldspar and the hornblende of the matrix show distinct signs of flow around the hornblende phenocrysts. The plagioclase is albite, being optically positive with $\gamma < 1.54 > 1.537$, $\alpha < 1.537 > 1.536$ and having a maximum extinction of 17° in the zone perpendicular to (010).

The texture of these rocks suggests that the porphyritic hornblende is of intratelluric origin.

Specimen No. 268 from a dyke near the Butterlump Stone, south of Ballyhalbert, was selected, to represent the group, for analysis.

In it the hornblende is mainly fresh and the matrix exceedingly fine grained. It is impossible to estimate the proportion of felspar, quartz, and hornblende in the groundmass, but felspar greatly predominates. The analysis, norm and partial mode are as follows:—

Analysis.		Norm.	Partial Mode (percentage volume).
SiO ₂	54.30	quartz	3.18
Al ₂ O ₃	15.46	orthoclase	11.12
Fe ₂ O ₃	1.86	albite	36.15
FeO	5.20	anorthite	17.51
MgO	5.61	hypersthene	20.86
CaO	5.50	magnetite	2.78
Na ₂ O	4.30	ilmenite	1.67
K ₂ O	1.94	apatite	.34
H ₂ O +	2.80	calcite	3.2
H ₂ O -	.44		
CO ₂	1.35		
TiO ₂	.90		
P ₂ O ₅	.22		
S	trace		
MnO	.22		

Symbol II.5".3.4.

100.10

Specific gravity 2.761 ± .003 at 4° C.

The proportion of normative albite to orthoclase is greater here than in the analysed vogesite and porphyrite and the percentage of modal hornblende distinctly smaller than in the porphyrite. Consequently it can be inferred that the felspar in the spessartite includes a higher percentage of albite, either as plagioclase or included in anorthoclase. The difference, however, is very small when regarded as a basis for classification.

Felspar-Porphyry.

The felspar-porphyries are composed almost entirely of felspar, with a preponderance of anorthoclase. They are characterized by phenocrysts and glomeroporphyritic groups of anorthoclase and albite, the individual crystals of which vary from 1 to 2 mm. in length. Anorthoclase is almost square in section, whilst the albite crystals are approximately twice as long as they are broad.

The matrix consists of euhedrons of anorthoclase and albite, together with a certain amount of finely crystalline interstitial material composed of felspar and quartz. The felspars are mostly fresh and the matrix includes only a small amount of calcite. No fresh ferro-magnesian mineral is present. Rare elongated pseudomorphs of chlorite and carbonates, however, probably represent hornblende phenocrysts, whilst small flakes of chlorite possibly indicate the former presence of acicular hornblende in the groundmass. The rocks are in this way allied to the hornblende types previously described.

Apatite and pyrite are accessory minerals; the latter is quite irregular in shape, whilst the former occurs in small but rather

broad prisms and, rarely, needles. Apatite is present both in the matrix and in the felspar phenocrysts, which are sometimes crowded with such inclusions.

(ii) BIOTITE-PYROXENE TYPE.

Pyroxene-minette (Type A) and Kersantite.

Minette is much more common than kersantite and the coarser-grained rocks are usually of this type. Characteristic minerals in both varieties are monoclinic pyroxene, biotite, anorthoclase, plagioclase, and quartz, with apatite, magnetite, and pyrite as accessories. Pseudomorphs after olivine are common in some of the rocks. The mafic components form phenocrysts, whilst the felspars and quartz occur in the matrix only, the latter being interstitial. The plagioclase is usually albite, but is sometimes an acid oligoclase. Many of these rocks are highly charged with carbonates, which are present as pseudomorphs after pyroxene and olivine and in the matrix.

Coarseness of grain does not altogether depend on the size of the intrusion, dykes of similar thickness differing greatly in this respect. The felspars in the coarser type are anhedral and may measure as much as 1 mm. across, whilst in the finer-grained rocks they have a sheaf-like grouping or occur as minute laths, the interstices being filled with green glass and quartz. They are frequently zoned, there being a central zone of albite and an outer zone of anorthoclase.

The pyroxene is of the variety characteristic of lamprophyres, being colourless or pale green in thin section and having an almost equal development of prism and pinacoid faces, so that it gives almost regular octagonal cross sections. It is probably in some cases diopside and in others an augite which differs but slightly from diopside in composition. In the former case $\gamma - \alpha = \cdot 029$ and in the latter $\gamma - \alpha = \cdot 024$ or $\cdot 026$. Both are optically positive with $2V = 58^\circ$ approximately. Owing to the difficulty of distinguishing between two varieties which are so similar, the pyroxene will be termed diopside indiscriminately.

Zoning is common and in the colourless pyroxene $Z \wedge c = 43^\circ$ in the central zone and increases by one or two degrees in the outer zones. Occasionally crystals have the same extinction angle in an inner and outer zone, with a slightly higher extinction in intermediate zones.

The pale green variety is pleochroic with X = pale green, Y = Z = pale yellowish green, the colour frequently being restricted to a central area. The refractive indices are higher than in the colourless diopside and $Z \wedge c = 56^\circ$. The colour, pleochroism, and extinction angle indicate the presence of soda.

Diopside forms crystals which vary in length from 2 mm., or exceptionally more, down to 1 mm. or less and are characteristically

about twice as long as they are broad. In some rocks, however, they are more elongated, the length being from five to eight times the breadth. They have their most perfect development in rocks with the finest felspar matrix. Where the groundmass is coarser in grain, although often more abundant, they have undergone resorption and frequently only small grains remain.

Crystals of diopside are sometimes replaced by biotite along their cleavage planes, so that the cleavage of the biotite is parallel to the *c* axis of the diopside and the biotite presents a brick-like appearance. This replacement may have proceeded to such an extent that only minute grains, in optical continuity, remain to suggest the former presence of diopside. (See Pl. IX, Fig. 3.) Rectangular groups of biotite crystals with this block-like arrangement are the result of complete replacement of the pyroxene. (See Pl. IX, Fig. 4.) Basal sections of biotite sometimes enclose optically-continuous grains of diopside.

This replacement suggests there was reaction between the diopside and a magma rich in alkalis, and probably much of the biotite originated in this way. The blocky appearance of the biotite resembles that figured by Bowen¹ as due to a similar replacement.

In the rock (No. 178) from the point north of Bar Hall, phenocrysts of diopside are surrounded by acicular crystals of anthophyllite. They measure 0.06 mm. in greatest length and are arranged radially around the diopside, having their best development on faces in the prism zone.

Biotite in thin flake-like crystals, the largest of which measure 1 cm. and the smallest 0.05 mm. across, exhibits a combination of the forms {110} {010} {001}, the basal flakes being elongated parallel to the edge (010) (001). It is pale in colour and characteristically zoned, having a dark margin and sometimes a dark interior in addition, in which case the interior is usually of a redder colour than the margin. Flakes frequently show re-entrants due to resorption, in which case the dark marginal biotite follows the embayed outline of the crystals rather than the hexagonal form of the central zones and thus appears to have been added after resorption ceased. The darker zones have a higher refractive index and are probably richer in iron than the pale biotite. Pleochroism is strong: X = pale yellow, Y = Z = brown. The refractive indices of the central reddish-brown zone, measured on a basal flake, are $\beta = 1.598$, $\gamma = 1.6$.

Lozenge-shaped and rounded pseudomorphs of serpentine, calcite, and quartz represent olivine. They are always rimmed tangentially by biotite flakes, an outer layer of which sometimes has the appearance of floating away from the central pseudomorph. The rounding of many of the pseudomorphs and their curved re-entrants indicates resorption of the original mineral. Where

¹ N. L. Bowen, "Genetic Features of Alnoitic Rocks at Isle Cadieux, Quebec," *Amer. Jour. Sci.*, iii, 1922, pl. 1, e. 1.

several pseudomorphs occur in contact, representing a glomeroporphyritic group of olivine, the biotite rim appears around the group but not between adjacent crystals. This biotite rim, so frequently described as characteristic in lamprophyres, is here quite evidently formed by reaction between the olivine and a magma rich in alkalis.

Flow-structure is well exhibited by the parallelism of the larger biotite flakes, the brick-like groups of biotite and the diopside



FIG. 4.—Drusy cavity in a kersantite (No. 233) showing the replacement of quartz and felspar by calcite. C = calcite; F = felspar; Q = quartz; B = biotite. Dots within the margin of the felspar represent speckling with calcite.

phenocrysts. This, together with the fact that both diopside and mica are well crystallized in rocks in which felspar is almost spherulitic in its development indicates that the diopside and biotite were in existence before intrusion.

Small druses, with a maximum width of 2 mm. are present in some of the rocks of this type. Euhedral crystals of felspar and

quartz extend into these structures, which are filled centrally with calcite. The quartz partly surrounds the felspar and often exhibits curiously crenulated and embayed margins where in contact with calcite, which encloses small isolated fragments of optically continuous quartz also with strikingly irregular boundaries. There can be little doubt that the calcite has partly replaced quartz (See Fig. 4.) The residual quartz fragments are sometimes exceedingly small, and in parts there has been complete replacement, so that perfect felspar crystals are surrounded by calcite. At times this replacement has proceeded to the felspars, which then have slightly serrated borders and a marginal speckling of minute calcite grains.

Although the felspars in the minettes and kersantites are often remarkably fresh, yet there is usually a sprinkling of carbonates, whilst diopside and olivine may be represented by calcite pseudomorphs. The calcite in the matrix is due to replacement similar to that noted in the druses. Here again quartz is first replaced, so that calcite now frequently occupies small wedge-shaped areas between the felspar laths and at first sight appears to be the final product of consolidation from the magma. Close inspection, however, often reveals some residual quartz and the fact that the edge of the felspar in contact with calcite is minutely fingered and speckled with calcite. Quartz xenocrysts have sometimes been similarly attacked. It seems, therefore, that in the uncrushed dykes carbonates are present in the matrix owing to replacement first of quartz and then of felspar. Many of the rocks have no appearance of weathering and this replacement may be attributed to the action of residual solutions, charged with carbonates, immediately after intrusion.

The rounded structures rimmed by biotite and usually described as ocelli (the views as to the origin of which have been summarized by Read¹) are present in many of the diopside-minettes and kersantites, sometimes in addition to the druses described above. They vary from 0.4 mm. to 1.2 mm. across. Although frequently oval in section, they sometimes have an elongated six- or eight-sided form which suggests crystal outline and occasionally two such structures occur in contact. They contain quartz, felspar, and calcite which in general have no definite arrangement. At times, however, the felspars tend to project from the biotite rim towards the centre. There is no real evidence in these rocks as to the origin of these forms, although in their persistent biotite rim they differ from the structures regarded as druses. This rim resembles that round the olivines, where it is due to reaction between the mineral and magma. If, in the case of the "ocelli", it is of the same nature, then these structures are evidence of the existence of a mineral

¹ H. H. Read, "The Mica-Lamprophyres of Wigtownshire": *GEOL. MAG.*, LXIII, 1926, 428.

which became unstable in the magma at an early stage, its form being at times preserved by the development of biotite.

A minette from Horse Island (No. 47) with a coarse-grained matrix was selected for analysis. It exhibits well the replacement of diopside by biotite, and the residual diopside has been largely resorbed. The analysis, norm, and mode are as follows:—

Analysis.	Norm.	Mode (percentage volume).
SiO ₂ 48.80	orthoclase 16.12	quartz 2.0
Al ₂ O ₃ 12.80	albite 23.06	felspar 44.5
Fe ₂ O ₃ 1.64	anorthite 14.46	diopside 17.4
FeO 5.98	diopside 7.53	biotite 23.9
MgO 10.35	hypersthene 12.74	magnetite 1.3
CaO 7.65	olivine 12.64	calcite with a
Na ₂ O 2.73	magnetite 2.32	little chlorite 9.9
K ₂ O 2.74	ilmenite 2.13	
H ₂ O + 3.00	pyrite .24	
H ₂ O - .50	apatite 1.34	
CO ₂ 1.70	calcite 3.9	
TiO ₂ 1.10		
P ₂ O ₅ .49		
S .12		
MnO .28		

Symbol III.5.3.3 (4).
1(2).(2)3.2.2.

99.88

Specific gravity = 2.819 ± .003 at 4° C.

The rock contains very little plagioclase and the fact that the norm shows a higher proportion of albite than orthoclase, in spite of the fact that there is 24 per cent of modal biotite, indicates that the potash-felspar has the composition of anorthoclase.

A rock from near the Butterlump Stone (No. 276) was selected for analysis to represent the type with a sheaf-like felspar matrix. The analysis, norm and mode are as follows:—

Analysis.	Norm.	Mode (percentage volume).
SiO ₂ 48.25	orthoclase 21.68	felspar 56
Al ₂ O ₃ 13.84	albite 19.39	diopside 17
Fe ₂ O ₃ 1.94	anorthite 16.40	biotite 20
FeO 4.86	diopside 3.56	calcite 6
MgO 8.08	olivine 4.10	
CaO 8.00	hypersthene 17.96	
Na ₂ O 2.26	magnetite 2.78	
K ₂ O 3.68	ilmenite 3.19	
H ₂ O + 2.72	pyrite 1.1	
H ₂ O - .20	apatite .67	
CO ₂ 2.70	calcite 6.1	
TiO ₂ 1.70		
P ₂ O ₅ .34		
FeS ₂ 1.10		
MnO .25		

Symbol III.5.3.3.
2.2.2.2.

99.92

Specific gravity = 2.807 ± .001 at 4° C.

Although the percentage of modal biotite is here slightly lower than in the minette (No. 47) previously quoted, yet the proportion of normative orthoclase to albite is higher. This rock must therefore be regarded as a minette. It thus seems likely that anorthoclase is capable of a plumose development.

Hornblende-Minette.

By the substitution of hornblende for diopside, the diopside-minettes grade to hornblende-minettes, which, in their turn, grade to hornblende-vegesites by decrease in the amount of biotite.

When hornblende is present in smaller amount than diopside, the latter shows signs of resorption, and the hornblende forms euhedral crystals, seldom longer than 0.4 mm., which sometimes have cores of diopside.

One rock (No. 46 from Horse Island) exhibits large phenocrysts of diopside with biotite developed along the cleavages and, in addition, a little fine hornblende, sometimes with enclosures of diopside, in the matrix. The reaction between diopside and magma which produces hornblende takes place at a later stage than the conversion of diopside to biotite.

As diopside decreases in amount, hornblende increases, until the rocks pass to hornblende-minettes, in which hornblende preponderates over diopside. In these rocks (No. 42 from south of Lady's Port and No. 43 from Ballywaddan are typical) the biotite sometimes has an addition of a bright bluish-green mica on the basal planes, or includes laminae of the same parallel to (001). The green mica is pleochroic with X = yellowish-green, Y = Z = bright bluish-green. Biotite is often enclosed by hornblende. In No. 42, pseudomorphs, possibly after olivine, are rimmed by both biotite and hornblende.

Diopside-Vegesite.

By decrease in the amount of biotite and increase in the amount of diopside, the diopside-minettes grade to diopside-vegesites. This type is rare and the best examples occur on the east coast, north of the Whiskin shore and in the multiple dyke near the Butterlump Stone.

The rock from north of the Whiskin shore (No. 327) is fairly coarse-grained and contains abundant euhedral crystals of diopside, which grade from 1 mm. in length down to 0.06 mm. or less. Anorthoclase, in very irregular grains, averaging about 0.8 mm. in length, is the predominant feldspar. Pseudomorphs of chlorite and epidote, which represent biotite, are subsidiary in amount to diopside, and there are rare small euhedral crystals of hornblende. The dyke (No. 325) which outcrops on the shore opposite Black Rock, north of Ballywalter, is of a somewhat similar variety, only it contains diopside and hornblende in equal amounts and the former shows signs of resorption.

The diopside-voesite (No. 271) near the Butterlump Stone forms a multiple dyke of the symmetrical type. The central intrusion is the coarser in grain and contains abundant euhedral crystals of diopside. The felspar matrix is plumose, and biotite is again replaced by chlorite and epidote. The marginal part has a finer grained plumose felspar matrix, and less abundant, though equally well developed, crystals of diopside, which have a linear arrangement due to flow and sometimes occur in glomeroporphyritic groups.

Pyroxene-Minette Type B.

Pyroxene-minette Type B is distinctly different from that previously described as Type A. In it the monoclinic pyroxene, which differs in character from that in Type A, is more abundant and is the most obvious mineral in a hand specimen. It forms crystals which vary in length from a maximum of 5 mm. down to 0.25 mm., many attaining the larger size. It exhibits a combination of the forms {100} {010} {110} {111}, the pinacoids and prism being equally developed, so that transverse sections are almost regular octagons. In thin section it has a scarcely discernible brownish or greenish tint and zoning is apparent, the outer zone sometimes having a slightly stronger colour. The largest crystals have a curious grid structure due to inclusions of the matrix, with which there appears to have been simultaneous crystallization. The inclusions are mainly of felspar together with small pseudomorphs after olivine, small flakes of biotite, stout prisms of apatite, and octahedra of magnetite. There is frequently an inner and outer zone which are free from such inclusions. Simple and polysynthetic twinning parallel to (100) are sometimes shown, and in the latter case the twin laths frequently wedge out in short lengths.

The optical data for the pyroxene are: $Z \wedge c = 46^\circ$, $\alpha = 1.686$, $\gamma = 1.707$, $\gamma - \alpha = .021$ (measured with a graduated quartz wedge), $2V$, positive = 58° approximately. The brownish colour, the extinction angle, the refractive indices, and the low double refraction probably indicate that the pyroxene approaches hedenbergite in composition.

Pseudomorphs after olivine are more plentiful than in the minettes of Type A and reach a length of 2 mm. The olivine is replaced sometimes by a single crystal and sometimes by several crystals of what appears to be a ferriferous variety of antigorite. It has a well-marked cleavage and is pleochroic: X = pale yellowish green, Y = Z = pale green. The acute bisectrix X is normal to the cleavage, $2V$ positive is small and $\gamma - \alpha = .015$. The pseudomorphs usually show good form. Occasionally, however, a curved outline is indicative of resorption of the original mineral. They are always surrounded tangentially by biotite flakes. Iron

oxide, although sometimes found as strings within the pseudomorphs, is more often restricted to the margin.

Biotite occurs as small ragged flakes which average only 0.2 mm. in length and do not show the characteristic zoning. It is reddish brown in colour and corresponds with the darker zone of the zoned biotite. Pleochroism is strong: X = pale yellowish, Y = Z = dark reddish brown. This biotite, although plentiful in small flakes, appears to belong to the matrix and is insignificant when compared with the pyroxene phenocrysts or pseudomorphs after olivine.

The accessories are also characteristic of the rock. Apatite forms comparatively broad prisms, reaching a size of 0.3 mm. by 0.25 mm., whilst magnetite is abundant in irregular grains, often measuring 0.3 mm. across.

In the rock from south of the Coast Guard Station and the thicker of the two dykes at Ballyhalbert harbour, the felspar matrix is medium in grain, the average grain size being 0.3 to 0.4 mm., but in the thinner dyke from the harbour the felspar is plumose and the biotite correspondingly finer. In both types the pyroxene and olivine pseudomorphs are equally large and are probably of intratelluric origin.

(iii) XENOLITHS AND XENOCRYSTS.

Accidental xenoliths and xenocrysts, derived from the country rocks, are not uncommonly seen in thin section. The former are usually fragments of grit and slate, whilst the latter are always of quartz.

The xenolith of red gneiss, found in a hornblende-minette at the foot of the dunes north of Portavogie Quay, shows distinct gneissic banding of quartz and felspar, and contains garnets, which are often altered to chlorite.

The cognate xenolith from the pyroxene-ogivesite at the Whiskin shore is a coarse-grained pyroxene-minette which contains a little hornblende. The hornblende sometimes encloses rounded grains of diopside, and where in contact with such resembles the outgrowths of tremolite and actinolite from the hornblende in ogivesite Type B. A small cognate xenolith of a different type was found in a section of the same rock. It measures about 3 mm. across and consists almost entirely of small calcite pseudomorphs after pyroxene and needles of apatite. The pseudomorphs measure less than 0.1 mm. in length. The matrix, which forms only a very small proportion of the xenolith, is feldspathic.

5. PETROGENESIS.

The lamprophyre dyke suite of the Ards peninsula is probably genetically related to the Newry igneous complex, and it is worthy of note that the ferro-magnesian minerals present in the dykes



Fig 1.



Fig 2.



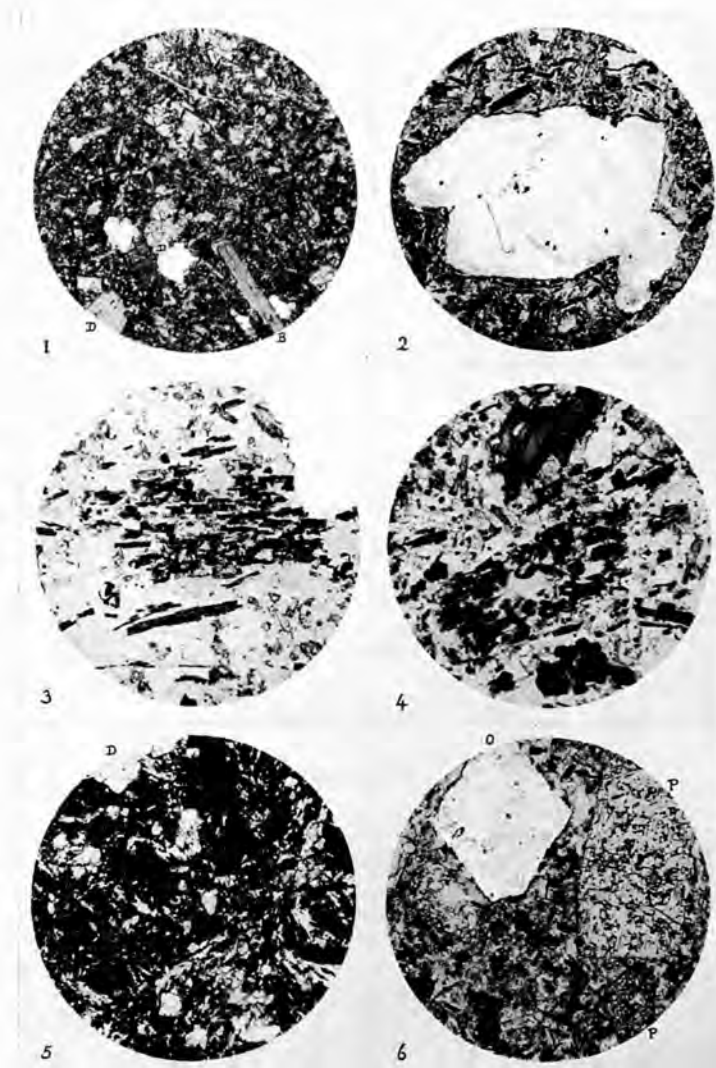
Fig 3.



Fig 4.

MEMBERS OF THE YOUNGER SERIES OF LAMPROPHYRE DYKES,
ARDS PENINSULA.

[To face p. 160.]



PHOTOMICROGRAPHS OF LAMPROPHYRES CHARACTERIZED BY BIOTITE
AND PYROXENE, ARDS PENINSULA.

can all be matched in the granite and associated rocks. The unravelling of the exact relationship awaits the more detailed investigation of the Newry complex.

The evolution of all the varieties of rock found in the dykes is not evident. Some attempt can be made, however, to account for the association of hornblende- and pyroxene-biotite-bearing types, on the assumption that the Newry granite was underlain by a basaltic substratum, differentiation being due to crystal sinking.

The differentiation which produced the granite would bring about an accumulation of olivine and pyroxene in the lower part of the basaltic substratum, and as crystallization proceeded it is not unlikely that hornblende would, in its turn, sink. It has been shown by Bowen¹ that hornblende which enters a basaltic liquid participates in reactions which precipitate, as crystals, earlier members of the reaction series, i.e. olivine, pyroxene, and possibly calcic plagioclase, the constituents of hornblende, other than those precipitated, entering into the liquid. From a study of the norms of ten hornblendites from Washington's *Tables*, he ascertained that the liquid would be enriched in albite and orthoclase. Since nepheline and diopside are capable of forming together a liquid of quite low melting point, he suggests that the nepheline and a nearly equivalent weight of diopside could also enter the liquid, excess of pyroxene being precipitated with the olivine.

In the present case, therefore, the sinking of hornblende crystals and consequent reactions would cause an increase in the amount of olivine and pyroxene present in the basalt, the magma at the same time becoming enriched in alkalies. With continued sinking of hornblende it is to be expected that the crystals of olivine and pyroxene would eventually be attacked by the alkalic magma, and, as already shown, evidence of such a reaction is to be found in the diopside-minettes of the newer series. Olivine is unfailingly rimmed by tangential flakes of biotite, whilst diopside sometimes has biotite developed along its cleavages, aggregates of biotite flakes, with a block-like structure, indicating the former presence of diopside where replacement is complete.

Probably biotite did not always grow in contact with the minerals at whose expense it was formed. The reaction may frequently have consisted of the resorption of diopside and olivine and the deposition of biotite elsewhere. In the rocks which give direct evidence of the development of biotite from diopside and olivine, the remaining diopside is sometimes much resorbed, whilst the olivine-pseudomorphs often have an embayed outline, due to resorption before the biotite rim was formed.

The reason for the conversion of early formed crystals to biotite, in preference to hornblende, is possibly to be found in the proportion of alumina present in the magma. Whatever the cause may be,

¹ N. L. Bowen, *The Evolution of the Igneous Rocks*, p. 270.

hornblende was formed as a result of such reaction only at a late stage, as is apparent in some of the hornblende-bearing minettes.

The crystallization of pyroxene, or its sinking from higher levels, appears to have continued after the growth of biotite commenced, for in some rocks, in which biotite encloses resorbed grains of diopside, well-formed crystals of the latter also occur, and sometimes partly enclose mica.

If the alkalic magma was the result of the fractional resorption of hornblende by basalt, then the magma was enriched in nepheline. The fact that this feldspathoid is not represented in the rocks of the district must be attributed to the liberation of silica due to the early crystallization of olivine and the later large-scale development of biotite.

To explain the association of the two types of rock, one rich in hornblende and the other in biotite and pyroxene, it must be assumed that the basaltic substratum itself became differentiated. There would then result an accumulation of olivine, pyroxene, and, in consequence, of biotite at low levels, the higher levels at the same time becoming saturated with hornblende. With the crystallization of hornblende, any diopside or olivine which still remained at these high levels would be resorbed and hornblende formed in their stead. As evidence of such a reaction the rounded grains of diopside present in some of the hornblende rocks may be cited, in addition to the fact that hornblende sometimes has a core of diopside, whilst the serpentinous pseudomorphs, which possibly represent olivine, are surrounded by small prisms of hornblende. Hornblende sinking from still higher horizons would no longer undergo fractional resorption on entering the upper part of the substratum.

At a later stage, it is likely that alkali-felspars would crystallize in the highest levels of the substratum and undergo a certain amount of gravity-sorting, together with hornblende. At the same time, the base of the level of saturation with hornblende would travel downwards, so that eventually hornblende would crystallize from the higher horizons characterized by biotite and pyroxene.

The variation at different levels, in what was originally a basaltic magma, may at this stage be supposed to be as follows :—

- (5) Level characterized by alkali-felspar with a little hornblende.
- (4) Level rich in hornblende with some alkali-felspar.
- (3) Level rich in hornblende.
- (2) Level containing pyroxene, olivine, biotite and hornblende.
- (1) Level rich in pyroxene, olivine and biotite.

The residual magma would be rich in alkalies and capable of crystallizing, mainly as anorthoclase and albite, on intrusion.

These suggested levels can be matched by the dyke-rocks in the Ards peninsula, which are listed below in comparable order.

The specific gravity, corrected to 4° C, is given opposite each type, and is consistent with the layering. When the specific gravity has been found for more than one rock of a type all determinations are given and, in addition, their average.

	Specific Gravity at 4° C.	Average Specific Gravity.
5. Felspar-porphry . . .	2.679 ± .001, 2.661 ± .001 . . .	2.67
4. Hornblende-porphryrite . . .	2.768 ± .001, 2.73 . . .	2.749
3. { Vogesite type A . . .	2.779 ± .001, 2.785 ± .002 . . .	2.782
{ Vogesite type B . . .	2.835 ± .001, 2.764 ± .001, 2.80 . . .	2.800
2. Hornblende-minette . . .	2.807, 2.837 . . .	2.822
1. { Pyroxene-minette type A . . .	2.819 ± .003, 2.807 ± .001 . . .	2.813
{ Pyroxene-minette type B . . .	2.86 . . .	2.86

The specific gravity for vogesite type B is very variable. Some of the rocks are rich in large crystals of hornblende, whilst others have fewer and smaller crystals. Possibly this type has been affected by a certain amount of crystal-segregation, during intrusion, owing to obstruction of the dyke-fissure, and perhaps caused by the crystals themselves.

Spessartite *s.g.* = 2.761 ± .003 has been omitted, since its relation to the other types is not known.

Intrusion was due to rise of the magma, with its crystal load, up the fractures produced by tensional forces. Thus, if the layering indicated is correct, the first dykes to be intruded would contain hornblende and the later ones biotite and pyroxene. This agrees with the order of intrusion found to have taken place in the younger or uncrushed dykes, where pyroxene-minette type B was the last to be intruded.

In the older crushed series hornblende types are very rare and the proportion of ferro-magnesian minerals to felspar is smaller than in the younger series. This is comprehensible when it is considered that the sinking of hornblende into the basaltic substratum and the differentiation of the basalt itself would probably not have gone on to so great an extent, prior to the intrusion of the crushed dykes, as indicated in the case of the younger series. It explains the smaller content of diopside and biotite, the quantity of which is dependent on the fractional resorption of hornblende. The scarcity of hornblende types can be accounted for on the grounds that the upper layers had not yet become saturated with this mineral.

The green glass, which is present in small amounts in the inter-spaces of the rocks and more particularly in those characterized by hornblende, is of an abnormal type. It contains a large proportion of alumina, which appears in the norms of the rocks as corundum, whilst rocks which contain no glass, or in which glass is present in minute quantities only, have no normative corundum. The glass can therefore be regarded as evidence that an excess of

alumina remained in the residual magma. This is strange considering that the rock analyses show a low percentage of this oxide. Perhaps it may be explained by the fact that the basaltic substratum would have been characterized by a lime-soda felspar, possibly labradorite, if it had crystallized as basalt, whereas the lamprophyres actually contain anorthoclase and albite, felspars less rich in alumina than labradorite. As far as the felspar matrix is concerned, therefore, an excess of alumina is to be expected. Whether it appears or not in residual glass may be dependent on the amount of biotite formed, since biotite is the only ferro-magnesian mineral which contains an excess of alumina over that provided by the partial resorption of hornblende.

Calcite, which replaces quartz and felspar, is characteristic of the younger dykes and more particularly of the pyroxene-biotite type. Since many of these rocks are otherwise fresh, it seems likely that this replacement was a juvenile reaction due to residual solutions charged with carbonates. The existence of such residual solutions may perhaps be connected with the reaction which has been shown to have taken place between diopside and magma, with the consequent production of biotite. Such a reaction must result in an accumulation of lime in the magma, probably greatly in excess of the amount which was able to enter into the composition of the felspar matrix. Any such lime would remain in the residual liquor, together with the volatile constituents, and be likely to be deposited as calcite, as a final stage.

6. SUMMARY OF CONCLUSIONS.

The lamprophyre and allied dykes of the Ards peninsula can be separated into two series in the field. The older dykes, which are crushed and foliated, are confined to the area south of a line from Ringburr to Ringboy Point, whilst the younger series has its greatest development north of this line. In each case the majority of the dykes have an approximate S.W.-N.E. strike parallel to that of the country rocks, and there is a smaller number of dykes which cut these and strike at right angles.

Both series were intruded during periods of tension, which occurred as a reaction to compression. The older series was intruded during a pause in the Caledonian folding, and was subsequently crushed and rendered schistose by continuation of pressure in the original direction. The younger series was intruded at the close of the Caledonian folding.

Members of the crushed series are all lamprophyres and mainly pyroxene-minettes. They are very much decomposed and heavily charged with calcite, largely due to infiltration along the planes of schistosity.

The younger dykes are of two types, one characterized by hornblende and the other by biotite and pyroxene as follows:—

1. HORNBLLENDE TYPE.

Hornblende-porphyrity.
Vogesite.

Type A.—Panidiomorphic texture.

Type B.—Euhedral hornblende in a matrix of anhedral felspar.

Spessartite.

Felspar-porphyrity.

2. BIOTITE-PYROXENE TYPE.

Pyroxene-minette.

Type A.—Phenocrysts of diopside and biotite and occasional pseudomorphs after olivine in a matrix of anhedral felspar.

Type B.—Phenocrysts of a pyroxene, which possibly approaches hedenbergite in composition, small ragged flakes of biotite and pseudomorphs after olivine in a matrix of anhedral felspar.

Pyroxene-kersantite.

Hornblende-minette.

Diopside-vogesite.

The potash-felspar in both hornblende and biotite-pyroxene types is anorthoclase.

The hornblende dykes, which always strike approximately from south-west to north-east, were the first to be intruded, and are cut by dykes bearing biotite and pyroxene. Dykes of pyroxene-minette type B were the last to be intruded.

The intrusions are probably connected genetically with the Newry igneous complex. The hornblende and biotite-pyroxene types are explained on the assumption that the Newry granite was underlain by a basaltic substratum enriched by olivine, diopside and hornblende from higher levels. The hornblende would undergo partial resorption, resulting in the precipitation of olivine and diopside, the magma at the same time becoming enriched in alkalis. Reactions between the early-formed crystals of olivine and diopside and the alkalic magma caused the development of biotite.

It is suggested that, as a result of differentiation in the basaltic substratum itself, olivine, diopside and, in consequence, biotite accumulated at lower levels in the substratum, whilst the higher levels gradually became saturated with hornblende, much of which, in addition to some alkali-felspar, crystallized prior to intrusion. The specific gravity of the various types of rock and the order of intrusion is in accordance with such a layering. The residual magma, on intrusion, crystallized mainly as anorthoclase and albite.

As a result of the development of biotite at the expense of diopside, the magma was enriched in lime in excess of the amount capable of entering into the composition of the felspar matrix. Such excess

remained in the residual liquor, together with the volatile constituents, and was finally deposited as calcite, which has been shown to replace quartz and felspar.

The writer was enabled to undertake this work by the award of the Anonymous Research Studentship at Bedford College in 1928-9.

EXPLANATION OF PLATES VIII-X.

PLATE VIII. MEMBERS OF THE YOUNGER SERIES OF LAMPROPHYRE DYKES, ARDS PENINSULA.

FIG.

- 1.—Two dykes of vogesite type A (Nos. 236 and 237) at the headland north of Portavogie.
- 2.—Dykes of vogesite and minette outcropping in the sand north of Portavogie quay.
- 3.—Coast near the Butterlump Stone, south of Ballyhalbert, showing a diopside-minette (No. 265) intersecting dykes of minette (No. 266) and spessartite (No. 268).
- 4.—A dyke of diopside-minette (No. 317) intruded parallel to the bedding of the slates at Wallace's Rocks, between Ballyhalbert and Ballywalter.

PLATE IX. PHOTOMICROGRAPHS OF LAMPROPHYRES CHARACTERIZED BY BIOTITE AND PYROXENE, ARDS PENINSULA.

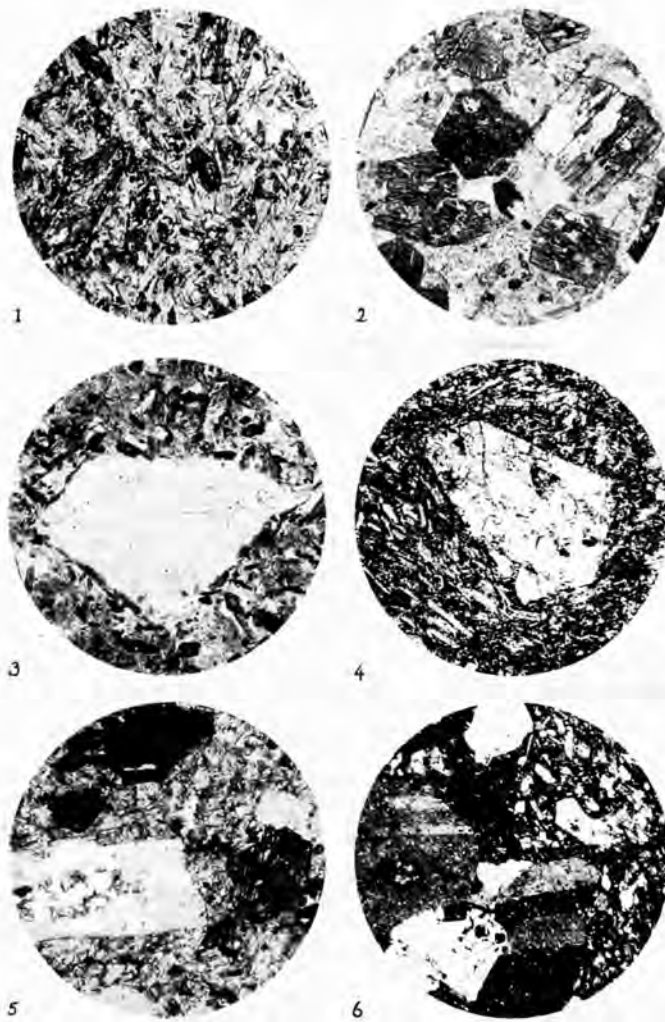
FIG.

- 1.—Ordinary light, $\times 14$. Diopside-minette type A (No. 276), with a plumose felspar matrix. From near the Butterlump Stone. B = biotite, D = diopside.
- 2.—Ordinary light, $\times 14$. Diopside-minette (No. 178) from the point north of Bar Hall, showing a group of pseudomorphs after olivine. The group is rimmed tangentially by biotite.
- 3.—Ordinary light, $\times 28$. Diopside-minette (No. 47), from Horse Island, showing the replacement of a crystal of diopside by biotite. The biotite flakes have been developed along the cleavage in the diopside.
- 4.—Ordinary light, $\times 28$. Kersantite (No. 233) from the bay south of Portavogie, showing a block-like group of biotite crystals due to complete replacement of diopside.
- 5.—Crossed nicols, $\times 28$. Diopside-vogesite (No. 271) from near the Butterlump Stone, showing a plumose felspar matrix. D = diopside.
- 6.—Ordinary light, $\times 14$. Pyroxene-minette type B showing large crystals of pyroxene (P) which probably approaches hedenbergite in composition and a pseudomorph after olivine (O) with a biotite rim. The matrix is of anorthoclase and biotite.

PLATE X. PHOTOMICROGRAPHS OF LAMPROPHYRES CHARACTERIZED BY HORNBLLENDE, ARDS PENINSULA.

FIG.

- 1.—Ordinary light, $\times 28$. Vogesite type A (No. 236) with a panidiomorphic texture. The dark crystals are of hornblende and the interstices between the small felspar laths are occupied by green glass.
- 2.—Ordinary light, $\times 28$. Vogesite type B (No. 86), showing hornblende crystals in a coarse-grained matrix of anorthoclase and plagioclase.
- 3.—Ordinary light, $\times 28$. Vogesite type B (No. 269) showing small elongated crystals of hornblende in a coarse-grained matrix of anorthoclase and plagioclase. The pseudomorph is of serpentine probably after olivine and is rimmed by hornblende.
- 4.—Crossed nicols, $\times 33$. Spessartite (No. 268) showing the trachytic type of matrix. The plagioclase shows flow round the hornblende phenocrysts.
- 5.—Ordinary light, $\times 28$. Hornblende-porphyrity (No. 213) showing phenocrysts of felspar and hornblende in a matrix of felspar.
- 6.—Crossed nicols, $\times 23$. Felspar-porphyrity (No. 314) showing a glomeroporphyrity group of anorthoclase and plagioclase in a matrix of felspar.



PHOTOMICROGRAPHS OF LAMPROPHYRES CHARACTERIZED BY
HORNBLLENDE, ARDS PENINSULA.

[To face p. 165.]

WITH THE AUTHOR'S COMPLIMENTS.

To _____

Some New Occurrences of Authigenic
Potash Felspar.

N^o 7.

BY

DORIS L. REYNOLDS, M.Sc.

*Extracted from the GEOLOGICAL MAGAZINE, Vol. LXVI, No. 783,
September, 1929.*



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[Extracted from the GEOLOGICAL MAGAZINE, Vol. LXVI,
pp. 390-9, September, 1929.]

Some New Occurrences of Authigenic Potash Felspar.

By DORIS L. REYNOLDS, M.Sc.

(PLATE XII.)

1. INTRODUCTION.
2. AUTHIGENIC FELSPAR IN—
 - (A) Triassic Sandstone.
 - (a) Crystal form and optical characters.
 - (b) Chemical composition.
 - (c) Specific Gravity.
 - (d) Comparison with Felspars in Igneous Rocks.
 - (B) Keuper Marl.
 - (C) Dolomitic Conglomerate.
 - (D) Magnesian Limestone.
3. COMPARISON WITH OTHER OCCURRENCES.
4. ORIGIN.

I. INTRODUCTION.

WHILST examining the Triassic sandstone of north-east Ireland, microscopic crystals of an authigenic mineral were found, in considerable quantities, in the sandstone from Benbradagh Hill, near Dungiven (Co. Londonderry). Mention has been made of this occurrence¹ and the mineral was provisionally assigned to orthoclase.

Subsequent examination, however, has shown it to be allied to anorthoclase and microcline, whilst further investigations have revealed the presence of similar authigenic felspar in other rocks.

2. AUTHIGENIC FELSPAR IN TRIASSIC SANDSTONE.

The mineral is most easily separated from the sandstone by pounding the rock to a sand, boiling it in HCl to free it from iron staining, washing, and collecting the fine silt which remains in suspension. This consists of chips of quartz and orthoclase, the latter sometimes kaolinized, together with well formed, perfectly fresh, authigenic felspar. A further separation can be made, after drying, by sliding the silt over a sheet of glass to which the authigenic felspar clings.

(a) *Crystal Form and Optical Characters.*

The crystals, thus obtained, average .03 mm. by .02 mm. by .01 mm. They are of two types, the majority closely resemble rhombohedra, whilst the remainder are lath shaped. The rhomb-shape results from a combination of the forms {110} {001}, the faces of which are sometimes equally developed, although the crystals are often tabular parallel to (001). The averages of thirty measurements show the plane angles on the faces to be 67° and 113° on (001) and 76° and 104° on (110). These angles agree with the plane angles, on similar faces, for orthoclase. Occasionally {010} is

¹ D. L. Reynolds, "The Petrography of the Triassic Sandstone of North-east Ireland," *GEOL. MAG.*, 1928, pp. 454-5.

developed, in which case the basal plane is bounded by six edges and elongated parallel to the edge (010)(001). The larger crystals flattened parallel to (001), measure .044 mm. by .032 mm. along the diameters on (001) and average .018 in thickness. Crystals only half this size are not uncommon.

The refractive indices are so near to that of Canada balsam that it is advisable to mount the crystals in water. The majority come to rest on (001), but by gently tapping the coverslip they can be adjusted to lie on any face or edge desired. With such rotation, and examination between crossed nicols, it has been found that the maximum birefringence is exhibited, when the crystals rest on (001), and consequently it may be inferred that the optic axial plane approximates to parallelism with this face. The optical orientation on (001) is illustrated in Fig. 2, and $\alpha = 1.518$, $\gamma = 1.524$, $\gamma - \alpha = .006$ (determined with a graduated wedge).

Crystals resting on a prism face have the fast ray vibrating at an angle of 2° or 3° to the (001) edge, whilst the slow ray vibrates in a direction inclined at approximately 12° to the prism edge. (See Fig. 3.)

A convergent light picture can usually be obtained, both on (001) and (110). On (001) the optic normal section, the isogyres come in from the sides very rapidly, darken the field, and immediately disappear in the direction of the acute bisectrix, which is the fast ray vibration direction, the mineral being optically negative. The prism faces are inclined to the obtuse bisectrix and give an optically positive convergent light picture.

Between crossed nicols, in direct sunlight, zoning is indicated by the extinction. The shadow swings in with a convex front from opposite edges and retreats with a concave front to the other two edges. In addition, many of the crystals show in patches an exceedingly fine lamellar twinning, in some cases giving a cross hatched appearance. The albite lamellae are the more easily distinguished, both on (001) and (110). On (001) the extinction angle between the albite twin lamellae measures 8° or 10° .

All these characters clearly indicate that the mineral is a feldspar, resembling orthoclase in form, and closely allied to it in optical orientation. The fine patchy lamellar twinning resembles that of anorthoclase or microcline, the extinction angle between the albite lamellae on (001) suggesting the former rather than the latter. This idea is borne out by the fact that on (110) the fast ray vibrates nearly parallel to the edge (001)(110), showing that an optic axis emerges in the angle between the direction of X and the normal to the prism face, or in other words, the optic axial angle is less than the prism angle, which is by calculation approximately 61° , a case which obtains in anorthoclase, but not in microcline or orthoclase.

The lath-like forms, which have an average size of .06 mm. by .02 mm. show a development of faces similar to the crystals already described, but are elongated parallel to the c axis. There is fine

lamellar twinning parallel to the prism edge, similar to that shown by the rhombs. In addition, the great majority exhibit penetration Carlsbad twinning, the composition plane being (010). Sometimes the two individuals are quite distinct, whilst at others they are almost completely intergrown, so that only the V-shaped termination and centre groove remain to indicate the character of the twin. When

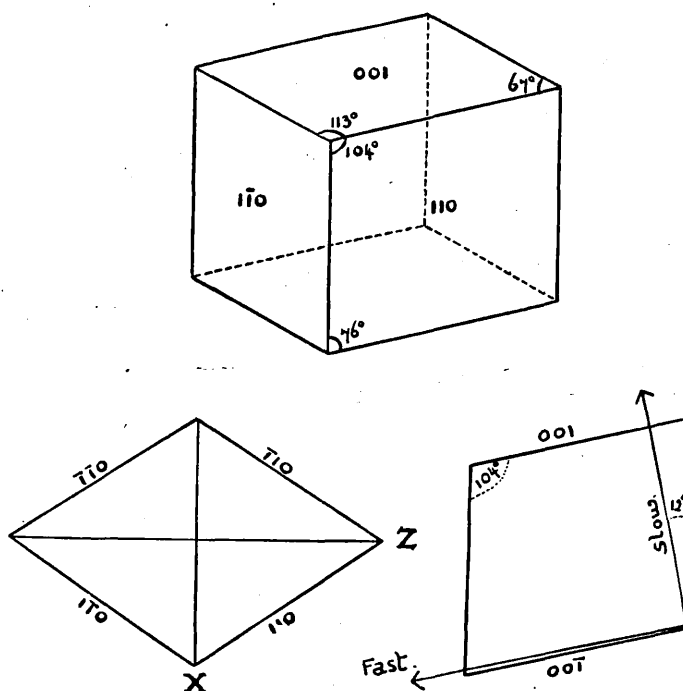


FIG. 1.—A rhomb-shaped crystal.
 FIG. 2.—Optical orientation on (001).
 FIG. 3.—Optical orientation on (110).

mounted in Canada balsam, the Carlsbad twins rest on a prism face, and the extinction angle measured between the two halves of the twin is 25°.

In the smallest forms of the type the birefringence is so feeble that it is impossible to distinguish between the twin halves, and the crystals give the impression of showing straight extinction, with the slow and fast rays vibrating parallel to the length and breadth respectively.

(b) *Chemical Composition.*

Only microchemical tests could be made, since it is not possible to obtain sufficient pure material for a chemical analysis. The

crystals were dissolved in hydrofluoric acid (the only acid in which they are soluble) and left to evaporate. After recrystallization in water, crystals of potassium hydrofluosilicate and sodium hydrofluosilicate were easily distinguished, the former being by far the more abundant. Sulphuric acid was then added, allowed to evaporate, and the residue dissolved in water. A grain of caesium chloride was placed in the drop, and after evaporation colourless octahedra of caesium alum crystallized out, indicating the presence of aluminium. These tests therefore strengthen the view that the mineral is a potash soda felspar, although soda is not present in so great an amount as one would expect in anorthoclase.

(c) *Specific Gravity.*

An attempt was made to determine the specific gravity of the mineral by flotation in potassium mercuric iodide. All crystals floated at 2.58 and sank at 2.50, an equal separation being attained at 2.54.

(d) *Comparison with Felspars in Igneous Rocks.*

It should be noted that although this authigenic mineral is undoubtedly a felspar, it does not exactly resemble any species recorded from igneous rocks. Its optical characters are those of anorthoclase, but in the excess of potash over soda it is more nearly allied to microcline, whilst its S.G. is lower than that recorded for any felspar. It exhibits the characteristic freshness of authigenic felspar.

B. AUTHIGENIC FELSPAR IN THE KEUPER MARL.

An unknown argillaceous mineral, which occurs as minute laths and aggregates, has been recorded by Bosworth,¹ from the Keuper marl around Charnwood. His description of the mineral suggests a similarity to the lath-shaped authigenic felspar described above, and in consequence specimens of Leicestershire marl have been examined, and the writer is indebted to Mr. H. H. Gregory for samples of marl from Croft quarry and Bardon Hill.

These samples were powdered, boiled in HCl, and graded by water settling. Minute laths and, more rarely, rhomb-like forms, similar to those described from the sandstone, are present in the finer sediment. The laths in these samples, however, do not form so large a proportion of the rock as found by Bosworth. The larger laths measure .004 mm. in length and show the V-shaped terminations of Carlsbad twins, whilst a shadow-like extinction can occasionally be discerned. Normally, however, the extinction appears straight, as in the smallest lath-like forms from the Benbradagh sandstone. The average refractive index is 1.52 and the double refraction low (not very high as recorded by Bosworth). The fast and slow rays vibrate parallel to the width and length of the laths respectively.

¹ T. O. Bosworth, "The Keuper Marls around Charnwood," *Leicester Lit. and Phil. Soc.*, 1911, pp. 82-9.

Most of the "rhombs" rest on a prism face and they are usually too small for the vibration directions to be determined, an average "rhomb" measuring only .002 mm. in diameter. When large enough to exhibit birefringence, however, the vibration directions agree with those of the similar forms in the sandstone.

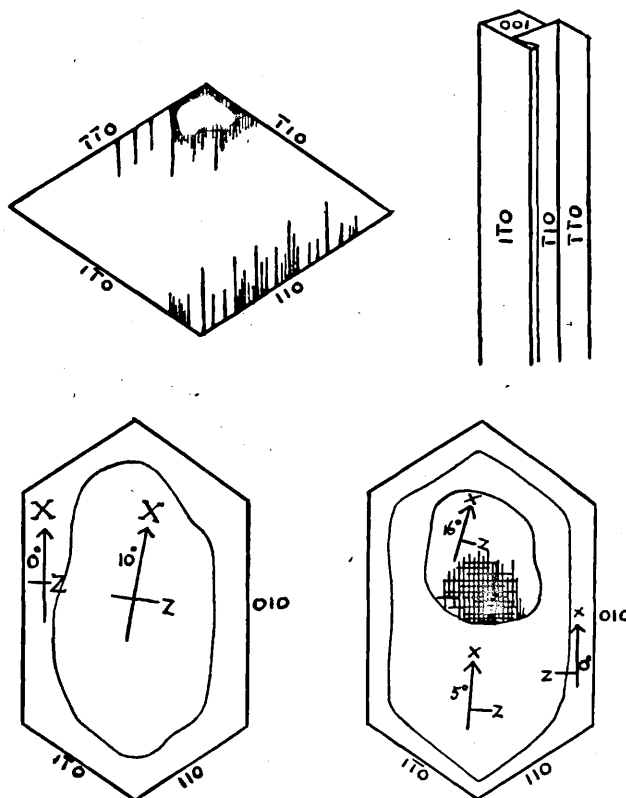


FIG. 4.—Lamellar twinning shown on (001).
 FIG. 5.—Carlsbad twin showing V-shaped termination and centre groove.
 FIG. 6.—Zoning and optical orientation on (001).
 FIG. 7.—Zoning, optical orientation and lamellar twinning on (001), shown by a crystal from the Magnesian limestone.

Bosworth¹ gives an analysis of the fine powder from the marl which remained more than 10 minutes in suspension in water, and which he believed to consist almost entirely of the "argillaceous mineral". The analysis, however, is undoubtedly of impure material.

¹ T. O. Bosworth, op. cit., pp. 87, 88.

Similar minute lath and rhomb-shaped crystals occur sparsely in the Keuper marl of the Belfast district. The rhombs rest on (110) as in the Leicestershire marl.

C. AUTHIGENIC FELSPAR FROM THE DOLOMITIC CONGLOMERATE.

Lath and rhomb-shaped feldspars also occur in the matrix of the Dolomitic Conglomerate from near Wells. The laths average .008 mm. by .003 mm., whilst the rarer "rhombs" are sometimes .004 mm. in diameter, though usually smaller.

D. AUTHIGENIC FELSPAR FROM THE MAGNESIAN LIMESTONE.

Samples of Magnesian limestone from Roker (Sunderland), treated with HCl, give a residue consisting of detrital quartz, feldspar, and rarer heavy minerals, such as tourmaline and zircon, occasional glauconite grains, a small amount of fine argillaceous material, and, in addition, rare but perfectly formed crystals of authigenic feldspar. These crystals average .052 mm. by .032 mm., and occasionally enclose minute grains of calcite. They differ from those previously described in greater variety of form and the type of zoning they exhibit.

The following forms, recorded in order of frequency, are present:—

1. {001} {010} {110} tabular parallel to (001) and elongated parallel to *a*.
2. {110} {001} tabular parallel to (001).
3. {110} {001} elongated parallel to *c*.
4. {001} {010} {110} {101} tabular parallel to (010).

When the crystals rest on (001) a centre zone, exhibiting oblique extinction at an angle of 10° to 12° with the edge (001) (010), can be distinguished, and an outer zone showing approximately straight extinction. The boundary between the zones is usually irregular, but approaches oval (see Fig. 6). The two zones are further distinguished by the fact that the outer zone shows both a lower refraction and birefringence than the inner one. Frequently both inner and outer zones show a patchy type of extinction, such as would result from submicroscopic microcline twinning. Occasionally cross-hatching is apparent in small areas, whilst in other crystals albite lamellae only are distinguishable. In either case the twinning is too fine to determine the extinction angle between the twin laths. One crystal resting on (001) distinctly shows three zones with extinction angles as given in Fig. 7. Microcline twinning appears in the centre zone.

When the crystals rest on (010) they usually extinguish as a single individual, the extinction then being 5° to 7° from the edge (010) (001). More rarely, zoning of a similar type to that observed on (001) is present.

The optical orientation agrees with that of the rhomb-shaped feldspars from the Benbradagh sandstone.

These crystals, like those already described, are related to the anorthoclase-microcline series. On (001) the extinction angle in the centre zone is high for anorthoclase and rather suggests a soda microcline, whilst the extinction in the outer zone suggests orthoclase or anorthoclase. As before, the optic angle is less than the prism angle (inferred from the fact that the fast ray vibrates across the prism face, making a low angle with the edge (110) (001), i.e. less than 61° as is found in anorthoclase in igneous rocks.

3. COMPARISON WITH OTHER OCCURRENCES.

Authigenic felspar, both albite and orthoclase, has long been known to occur in non-metamorphosed limestones and dolomites on the Continent, and characterizes various horizons of Carboniferous, Triassic, Jurassic, Cretaceous, and Eocene age. In addition, orthoclase, which Daly¹ believes to be authigenic, occurs in the Waterton formation, Alberta, and Spencer² has shown albite crystals, found in limestone from Bengal, to be authigenic. A summary of the literature on the subject is given by Spencer² and Daly³ and need not be repeated here. So far as the writer is aware, this is the first record of such felspars from arenaceous and argillaceous rocks.

Of the forms recorded in the present paper, the rhomb-like forms from the Triassic sandstone, Keuper Marl and Dolomitic Conglomerate resemble those described by de Lapparent⁴ from the Muschelkalk of Alsace and Lorraine. The lath-like Carlsbad twins, however, do not appear to have been seen elsewhere. Grandjean⁵ noted the presence of Carlsbad and Baveno twins in the Carboniferous limestone from Miatschkows, near Moscow, and Carlsbad twins in the Calcaire rose of Hallstadt, but the Carlsbad twins in both cases exhibit the usual form of two individuals flattened parallel to (010) and showing slight penetration.

The forms from the Magnesian Limestone can be matched by those recorded by Grandjean from various French limestones.

In optical characters, the presence of fine microcline twinning and zoning, the authigenic felspars here described, and more particularly those from the Magnesian Limestone, resemble those studied by Grandjean from the Chalk of the Paris basin,⁶ and various

¹ R. A. Daly, "Low-temperature Formation of Alkaline Felspars in Limestones," *Proc. Nat. Acad. Sci.*, iii, pp. 659-65, 1917.

² E. Spencer, "Albite and other Authigenic Minerals in Limestone from Bengal," *Min. Mag.*, vol. xx, pp. 365-80, 1925.

³ R. A. Daly, *op. cit.*

⁴ J. de Lapparent, "Cristaux de feldspath et de quartz dans les calcaires du Trias moyen d'Alsace et de Lorraine," *C.R. Acad. Sci., Paris*, clxxi, pp. 862-5, 1920.

⁵ F. Grandjean, "Deuxième note sur le feldspath néogène des terrains sédimentaires non métamorphiques," *Bull. Soc. Franc. Min.*, 1910, vol. xxxiii, pp. 92-7.

⁶ F. Grandjean, "Propriétés optiques et g n se du feldspath n og ne des s diments du Bassin du Paris," *C.R. Acad. Sci. Paris*, cxlviii, pp. 723-5, 1909.

horizons of Cretaceous and Jurassic limestones in France.^{1,2} These were referred to the microcline-anorthoclase series, and regarded as resembling microcline rather than anorthoclase, both optically and chemically, although it was noted that the optic axial angle is that of anorthoclase, being 44°.

4. ORIGIN.

Although a few writers have advocated a hydrothermal origin for authigenic feldspar in limestone, or believed it to be formed in connection with local dislocation of the beds in which it occurs, the majority are agreed that it grew in the calcareous mud on the sea floor, the growth taking place during the deposition of the limestone. Grandjean believes that the crystals ceased to grow after they were buried, and considers it probable that similar feldspars are crystallizing to-day on the sea bottom. De Lapparent³ suggests that certain algae of the *Girvanella* group have been the primary cause in the production of albite crystals in the Flysch limestone of the Pyrenees, the action of these algae having been partly responsible for the formation of the limestone. He repeats this suggestion in connection with the orthoclase and microcline crystals from the Muschelkalk of Alsace and Lorraine,⁴ and in the case of the Flysch limestone concludes that the feldspars were formed at the time the rock crystallized. Lory⁵ discovered secondary orthoclase crystals actually inside an ammonite shell.

The Benbradagh sandstone is calcareous, friable, and very much iron-stained. The detrital grains are angular and show no evidence of wind action and the material was probably accumulated by the action of small streams and deposited in water. After special treatment, a thin section of the rock was produced, in which the groundmass was retained, and the authigenic crystals can be seen in places round the thinned edge of the section.

The sandstone was pounded, boiled in HCl and after a prolonged search several kaolinized grains were found, from which crystals of authigenic feldspar projected in a manner recalling the growth of anatase crystals from leucoxene. On one grain as many as

¹ F. Grandjean, "Le feldspath neogene des terrains sedimentaires non-metamorphiques," *Bull. Soc. franc. Min.*, xxxii, pp. 103-33, 1909.

² F. Grandjean, "Deuxieme note sur les feldspaths neogene des terrains sedimentaires non-metamorphiques," *Bull. Soc. franc. Min.*, xxxiii, pp. 92-7, 1910.

³ J. de Lapparent, "Sur les cristaux du feldspaths developpés dans les calcaires du Crétacé supérieur pyrénéen," *Compt. Rend. Acad. Sci. Paris*, 1918, vol. clxvii, pp. 784-6.

⁴ J. de Lapparent, "Cristaux de feldspath et de quartz dans les calcaires du Trias moyen d'Alsace et de Lorraine," *Compt. Rend. Acad. Sci. Paris*, 1920, vol. clxxi, pp. 862-5.

⁵ C. Lory, "Sur la présence de cristaux microscopiques de minéraux du groupe des feldspaths, dans certains calcaires jurassiques des Alpes," *Compt. Rend. Acad. Sci. Paris*, 1886, vol. ciii, pp. 309-11.

six rhomb-shaped feldspars appear. This strongly suggests that the feldspar has grown from kaolin, directly or indirectly, by addition of potash.

It is well known that clays (hydrated aluminium silicates) exert a selective absorption on salt solutions, the alkali being absorbed whilst the acid is set free or combines with other bases. Potash is absorbed more readily than lime, magnesia or soda, and colloids are probably the most active absorbents. This absorption, which is sometimes of a chemical nature, might give rise to new minerals, e.g. Clarke¹ regards the absorption of potash and silica by colloidal ferric hydroxide as the final reaction in the formation of glauconite, the process being equivalent to that in which potassium compounds are taken up by clays.

Harris,² in investigating absorption phenomena, shown by soils and kaolin, found that kaolin in its natural condition does not affect a salt solution. If, however, it is first treated with an acid, and then washed, it has the power of liberating an acid from a salt solution. He suggested that the effect of the acid was to transform, by chemical reaction, some of the silicates into compounds which have the power of selective absorption.

This power to absorb potash and other alkalis possessed by aluminium silicates, in conjunction with the fact that feldspar appears to have grown from kaolin in the Benbradagh sandstone, is suggestive as to the origin of authigenic potash feldspar. All authigenic feldspars so far recorded occur in calcareous rocks, i.e. in limestone, dolomite, chalk, marl, and calcareous sandstone, so that possibly calcium carbonate is concerned in their formation. Warington³ found that hydroxides of iron and aluminium are most active as absorbents in the presence of calcium carbonate, which converts other alkaline salts into more easily absorbed carbonates.

Kaolin, or its amorphous equivalent, is probably present in small amounts in many limestones, it is certainly present in marl and to a small extent in sandstone. Acids, possibly from decaying organisms, may in some manner convert it to a state in which it has the power of selective absorption. Then, in the presence of calcium carbonate, potash is absorbed, either from the sea at the time of deposition of the ground rock, or at a later date from percolating water. How long the crystals take to grow it is impossible to say, but in the case of the sandstone it is unlikely that they can have formed before being covered, and possibly in all cases growth would continue during the consolidation of the rock. It does not seem impossible that such feldspars might sometimes be of recent origin, having

¹ F. W. Clarke, *Bull.* 695 *U.S. Geol. Surv.*, 1920, p. 514.

² J. E. Harris, "Some Absorption Phenomena in Soils and Kaolin," *Journ. Physical Chem.*, vol. xviii, 1914, p. 355.

³ R. Warington, "On the Part taken by Oxide of Iron and Alumina in the Absorptive Action of Soils," *Journ. Chem. Soc.*, vol. xxi, 1868, p. 1.

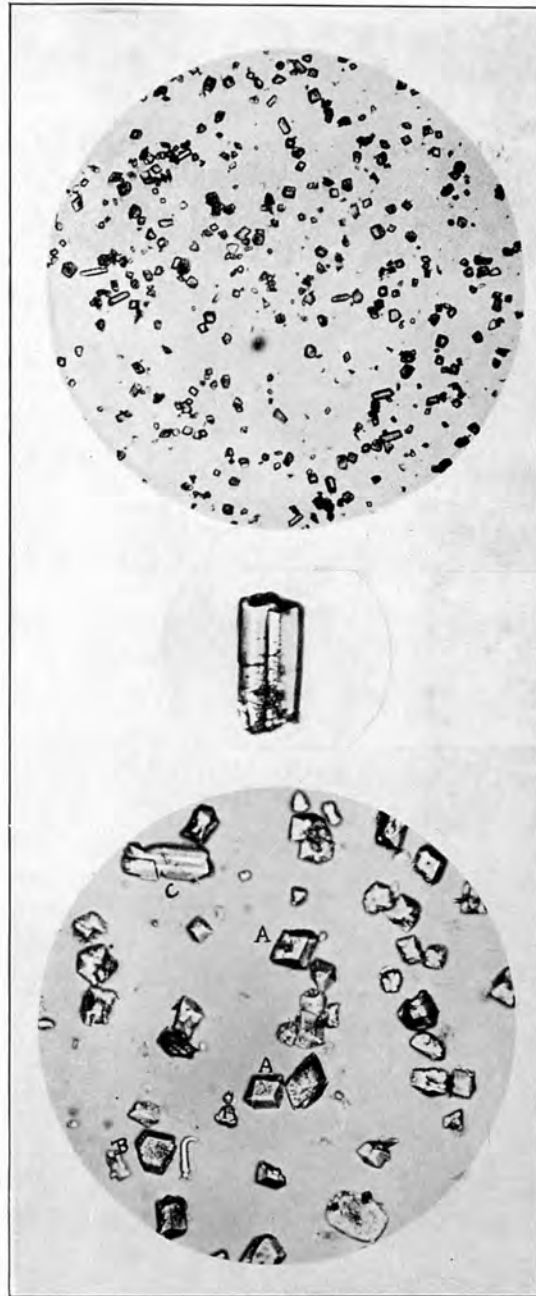
been formed by absorption from the ground water long after the rock has consolidated.

The writer wishes to thank Dr. Hawkes for the interest he has taken in the work, and for the suggestions he has made from time to time.

EXPLANATION OF PLATE XII.

Microphotographs of authigenic felspar from the Triassic sandstone at Benbradagh Hill, Co. Londonderry, mounted in water.

- 1.—Rhomb-shaped crystals and lath-like Carlsbad twins. $\times 67$.
- 2.—A Carlsbad twin in which each individual shows the form $\{110\} \{001\}$, and is elongated parallel to c . $\times 300$.
- 3.—Crystals. $\times 200$.
 - A. Showing development of $\{110\} \{001\}$ and tabular parallel to (001).
 - B. Similar to A, but with $\{010\}$ developed.
 - C. Carlsbad twin, elongated parallel to c .



AUTHIGENIC POTASH FELSPAR FROM THE TRIASSIC SANDSTONE AT
BENBRADAGH HILL, CO. LONDONDERRY

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OCTOBER, 1928.



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ORIGINAL ARTICLES.

The Alston Block.

By F. M. TROTTER, M.Sc., and S. E. HOLLINGWORTH, M.A., B.Sc.

INTRODUCTION.

THE area covered by this paper embraces the northern end of the Pennines—the uplands of Lower Carboniferous rocks centred about Alston, together with the low ground of the Tyne-Irthing gap to the north. It is bounded on the west by the Vale of Eden. The Pennine portion is separated structurally from the regions to the north and west by the Stublick and Pennine Faults respectively. The former trends E.N.E., it has a downthrow to the north and has resulted in the preservation of the string of Coal Measures outliers which form a connecting link between the Cumberland and Northumberland coalfields. The Pennine Fault, trending S.S.E., with a throw of several thousand feet to the west, brings the New Red rocks of the Vale of Eden against the Lower Carboniferous beds of the Pennine Escarpment. These two faults meet at right angles near Castle Carrock. To the south the Pennine Fault dies out near Stainmore, and another dislocation, the Dent Fault, trending S.S.W., develops, and eventually links up with the Craven Faults which have an E.S.E. trend. These four faults, as pointed out by Professor Kendall,¹ have the form of a reversed 3, and the region within this figure has become known generally as the Northumbrian Fault Block. Professor Marr has aptly termed the southern half of this area the "Rigid Block". The northern half of the Northumbrian Fault Block, which will be shown to possess many characters in common with the southern half, is here called the "Alston Block". Its limits are defined on three sides—by the Stublick Fault on the north, the Pennine Fault on the west, and by the Stainmore depression on the south. The last thus divides the

¹ Kendall, Professor P. F., and H. E. Wroot, *The Geology of Yorkshire* (printed for authors), 1924, p. 234.

Northumbrian Fault Block into two, physiographically and structurally. The eastern boundary of the Alston Block is concealed beneath the Mesozoic rocks.

The present paper deals with the post-Carboniferous earth-movements of the Alston Block and the adjoining areas to the west and north, and with the relation of these to the intrusion of the Whin Sill. The Alston Block is recognized as an independent morphological unit in the tectonic evolution of the North of England. There is evidence that it existed in Devonian times, and it is shown here that it acted as a block during the deposition of the Carboniferous rocks, with a relatively unstable geosynclinal trough to the north. During the Hercynian compression it was depressed relatively to a geanticline, then formed on the site of the trough to the north. The strata outside the north-western margins of the Block were compressed into a group of crescentic folds, and on its margins a series of small scale folds were developed. The Whin Sill was then intruded, and, later, the compression found relief in the formation of a series of tear-faults. Still later, the Block as now defined was uplifted by post-New Red faults.

These conclusions, based on new evidence obtained during the re-survey of the Brampton Sheet, are at variance with some of those reached by Mr. Versey¹ in a recent paper. He has concluded that the Northumbrian Fault Block was uplifted during the Hercynian earth movements and that some of the faulting which accompanied this elevation antedated the intrusion of the Whin Sill.

The age of the faulting and its relation to the Whin Sill are of considerable importance to mining engineers in this district, where limestone coals are being exploited in faulted ground, and where the value of the coals has been destroyed locally by the proximity of sheets of the Sill.

THE DEPOSITION OF THE CARBONIFEROUS ROCKS.

The tectonics of the area are intimately connected with the deposition of the Carboniferous rocks which will be considered briefly. Two major geosynclinal troughs in which exceptionally thick Carboniferous sediments were formed, can be recognized in the North of England. The northern² lies between the southern Uplands and a line extending from the Isle of Man through the Lake District and the Alston Block to Durham. Deposition commenced in this trough with the Cementstones (C₁)³ and this group together

¹ Versey, H. C., "Post-Carboniferous Movements in the Northumbrian Fault Block," *Proc. York. Geol. Soc.*, New Series, vol. xxi, 1927, pt. i, pp. 1-23.

² Trotter, F. M., and S. E. Hollingworth, "On the Upper Limestone Group and 'Millstone Grit' of North-East Cumberland," "Sum. of Prog." for 1926 (*Mem. Geol. Surv.*), 1927, pp. 103-5.

³ Trotter, F. M., in "Sum. of Prog." for 1926 (*Mem. Geol. Surv.*), 1927, p. 51.

with the Fell Sandstones (C_2-S_1), a group of sandstones and thin limestones (S_1),¹ and a thick marine series (S_2) were deposited while much of the area south of the trough was land. With the possible exception of the highest beds of S_2 age none of these groups are represented in the north end of the Isle of Man,² around the northern end of the Lake District,³ on the Pennine Escarpment near Croglin,⁴ or at Roddymoor⁵ in Durham.

The Southern, Pendle or Bowland geosynclinal trough corresponds roughly with the so-called "Central Basin" of deposition, which includes the area south of the Craven Faults and extends to the Loughshinny district of Ireland. Thick sediments were formed in this trough commencing with the (?) *Zaphrentis* zone, continuing throughout Lower Carboniferous and Millstone Grit times and to some extent during the Coal Measure period. These troughs are separated by a belt of ground containing the Northumbrian Fault Block in the east, and the Lake District-Isle of Man area in the west. Several thousand feet of shallow water sediments were deposited in the subsiding troughs before the intervening areas were submerged in S_2-D_1 times. After the submergence of the Lake District-Isle of Man and the Alston Block regions the sediments formed on them differed from the corresponding beds in the troughs in being much thinner.

A third geosynclinal area lies between the Lake District and the Alston Block. Professor Garwood⁶ has shown that in Ravenstone-dale, and northwards as far as the River Eamont, thick sediments were accumulated from C_1 times onward. North of the Eamont the Lower Carboniferous is largely buried beneath New Red deposits but in the Brampton district where the Lower Carboniferous re-appears all the zones from C_1 onwards,⁷ of Professor Garwood's type area have now been recognized. It is suggested, therefore, that these two areas were connected very early in the Lower Carboniferous period by a narrow gulf between the Lake District and the Alston Block. Thus a belt of thick sediments is probably continuous around the western and northern margins of the Alston Block.

¹ The S_1 group has been called the Craighill Sandstones and the S_2 group the Birdoswald Limestone Group on the new geological maps.

² Smith, Dr. B., "On the Carboniferous Limestone Series of the Northern part of the Isle of Man," "Sum. of Prog." for 1926 (*Mem. Geol. Surv.*), 1927, p. 114.

³ Earle, K. W., "The Lower Carboniferous Rocks of Cumberland," *Geol. Mag.*, 1922, p. 525.

⁴ Hollingworth, S. E., in "Sum. of Prog." for 1925, (*Mem. Geol. Surv.*), 1926, p. 81, fig. 6 (Croglin Section).

⁵ Lee, Dr. G. W., "On the Faunal Sequence of the Carboniferous Rocks met in the Roddymoor Boring, Co. Durham," "Sum. of Prog." for 1923 (*Mem. Geol. Surv.*), 1924, p. 146.

⁶ Garwood, Professor E. J., "The Lower Carboniferous Succession in the North-West of England," *Quart. Journ. Geol. Soc.*, vol. lxxviii, 1912, p. 484.

⁷ Trotter, F. M., in "Sum. of Prog." for 1926 (*Mem. Geol. Surv.*), 1927, p. 51.

Indications of the earlier existence of this Block may be mentioned here. Professor O. T. Jones¹ has suggested that the Lower Palaeozoic sediments beneath the Carboniferous area east of the Pennine Fault (i.e. the Alston Block of this paper) are comparatively thin and that they are underlain at no great depth by an Archean core. The pre-Carboniferous Middle Pennine Fault, with a downthrow to the west of 20,000 ft.² may be regarded as an expression of the western margin of the Alston Block in Devonian times.

It is therefore suggested that this Block acted as a structural unit from earliest Palaeozoic times to the end of the Carboniferous period. The reactions of the Block and the adjoining areas to later earth movements will be considered next.

HERCYNIAN EARTH MOVEMENTS.—FOLDS.

The Carboniferous sedimentation was terminated by uplift due to the oncoming of the Hercynian earth pressure from the south.

In the southern trough thick sediments were compressed into a well-known series of folds—the Bowland, Slaidburn, Clitheroe, and Lothersdale Anticlines, together with the Pennine Anticline farther south.

The resurvey of the Brampton Sheet has shown that the great northern trough also reacted to the Hercynian compression. Several anticlines have been recognized, the most important being the east-west Bewcastle Anticline, which is continuous at its western end with an anticline trending south-west. The southern limb of this curving anticline occupies the northern half of the Brampton area. As the St. Bees Shales unconformably transgress successive subdivisions in the denuded core³ of this anticline its age is definitely pre-New Red. The denudation removed 7,000 feet of Lower Carboniferous rocks, as estimated in the resurvey of the Brampton Sheet, in addition to the whole of the Upper Carboniferous, estimated to be 3,000 feet thick by Peach and Horne⁴ in the Canonbie Coalfield some 10 miles to the north-west.

A belt of highly dipping strata emerges from beneath the Trias $1\frac{3}{4}$ miles north of Farlam and can be traced in a curved line (see Fig. 1) for 3 miles to the north-east. This may be interpreted as a monoclinical fold on the southern limb of the Bewcastle anticline. A similar curved monoclinical fold has been observed on Denton Fell from Roachburn to Reaygarth. The major Bewcastle anticline and these two monoclinical folds are parallel to each other and change direction from north-north-east to almost east. They occur within

¹ "The Foundation of the Pennines," *Manch. Geol. Assoc. Journ.*, i, 1927, p. 1.

² Marr, Dr. J. E., "The Geology of the Appleby District," *Proc. Geol. Assoc.*, vol. xx, 1907, p. 129.

³ The old 1 in. map shows a faulted junction with the Trias.

⁴ "The Canonbie Coalfield," *Trans. Roy. Soc. Edin.*, vol. xl, 1903, p. 835.

each other in the order described and may be regarded as a group of crescentic folds of the same age and origin.

Another anticline, with an approximately E.-W. trend, crosses the South Tyne near Featherstone Castle; evidence of its age is lacking.

Other anticlines are probably associated with the tear-faults to be described later. The trend of their axes, as a group, is similar to that of the crescentic folds.

The lie of the strata on the Alston Block is in striking contrast to that in the adjoining area to the north of the Stublick Fault, for no folding of considerable magnitude is discernible on it. The similarity of this area with that of the Rigid Block of North-west Yorkshire is apparent. There, as here, the folded strata outside the block are in marked contrast with those upon it. Indeed the analogy may be carried still further, for the tear-faults of the Carnforth district,¹ outside the Rigid Block, may be compared with those developed in the strata adjoining the Alston Block (below). The comparatively unfolded sediments on both of these blocks are evidence of a rigid core, possibly Archean, which protected the Carboniferous cover during the Hercynian compression. There is, however, some evidence of compression on the Alston Block, for slight folding can be detected on it, and in the crests and troughs of these folds the Whin Sill increases in thickness (p. 445). It would appear, therefore, that the intrusion of the Sill was contemporaneous with, or later than, the compression which produced the folds.

Still further evidence of compression is apparent. A group of small acute folds of a different order and arrangement from those described above fringe the western and north-western marginal areas of the Alston Block (see Fig. 1). They are restricted to resistant beds, particularly limestones, and die out vertically within the individual beds. The axis of these folds progressively change from S. 30° E.-N. 30° W. near Croglin to S.-N. near Castle Carrock and to S. 15° W.-N. 15° E. near Tindale Tarn, thus maintaining a general parallelism with the margin of the Block and with the direction of the larger crescentic folds.

TEAR-FAULTS.

A series of faults fringe the north-west margin of the Block in the sediments of the trough to the north of it. As a group they change in direction from W.S.W.-E.N.E. in the south-west to N.W.-S.E. in the north-east. They have the following characteristics in common.

- (1) They are dip faults.
- (2) Their throw is southward, so that as a group they would have the effect of depressing the Block in pre-Triassic times, relatively to the area north of it.

¹ Marr, Dr. J. E., *The Geology of the Lake District*, Camb. Univ. Press, 1916, p. 119.

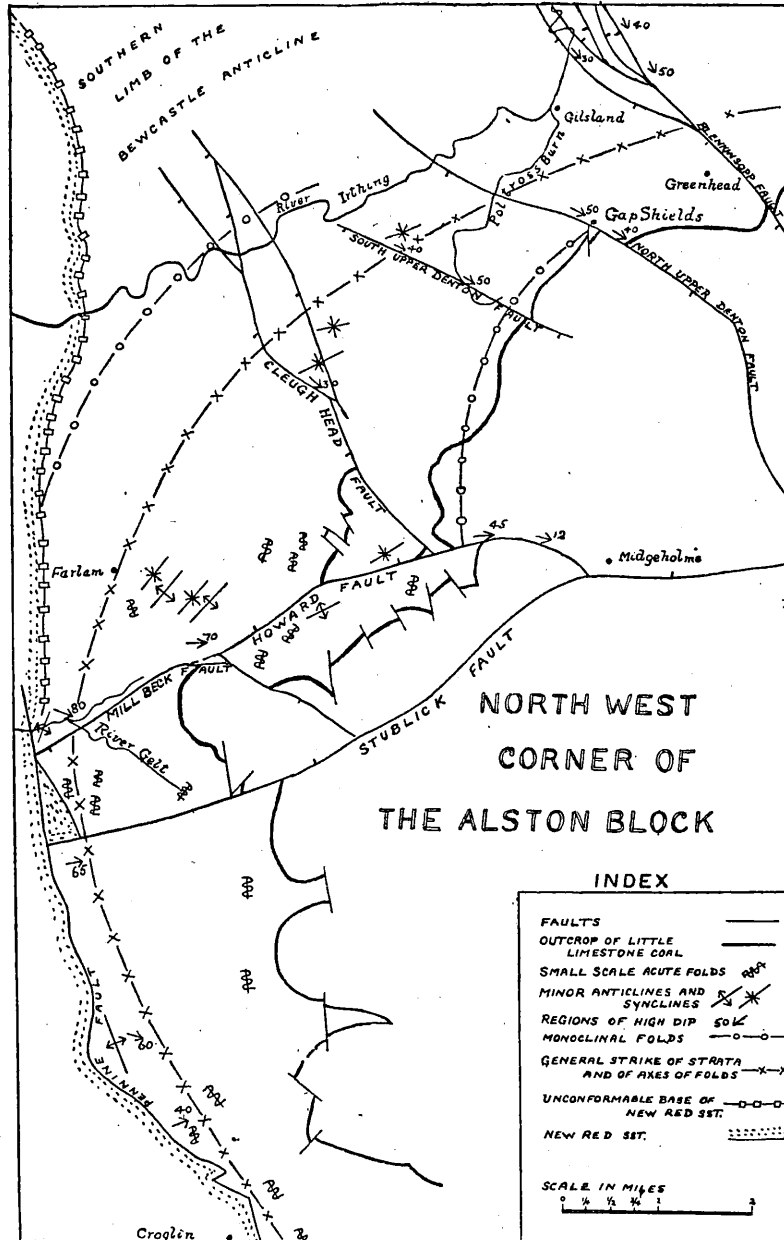


FIG. 1.—Structural map of the North-west Corner of the Alston Block and adjoining areas.

(3) The strata on the north side of the faults are folded into a series of anticlines and synclines with axes making high angles with the faults (see Fig. 1), the beds as a whole having a general dip to the south-east. These folds gradually die out when traced north-westwards from the north side of one fault to the south side of the next. Frequently high dips to the south-east alternating with comparatively low dips in the same direction are found on the northern sides of the faults. These are interpreted as asymmetric folds in an area of general south-easterly dip off the southern limb of the Bewcastle anticline.

These facts indicate a horizontal compressional movement eastward on the northern side of each fault. The faults must therefore be considered to be tear-faults. They will be briefly described in order from south to north.

The *Mill Beck Fault* (see Fig. 1) shows to best advantage the striking difference in dip on the two sides of the fault. On the north side a strong anticlinal fold is developed immediately adjacent to the Trias overlap in the River Gelt and the dip maintains high angles of from 45° to 90° in the River Gelt and to the north-east. On the south side horizontal beds crop out. The continuation of this fault in an easterly direction as the Howard Fault is reversed in throw, but high dips are developed on the north side near Cardiff, and again at Roachburn Colliery. The reversal of the throw of the fault in this area is considered to be the result of a second movement associated with the elevation of the Northumbrian Fault Block in post-Triassic times (see p. 448). The steepened dips and the folding in the Gelt are in marked contrast with the gentle dip and the absence of folding in the Trias which here unconformably overlies the Carboniferous. Similarly $1\frac{1}{2}$ miles north of Farlam highly inclined Carboniferous strata dipping E.S.E. are overlain by the New Red Sandstone series dipping gently to the west. There is thus definite evidence that these movements are earlier than the deposition of the New Red Rocks.

East of Farlam, in the area between the Mill Beck and Clough Head Faults, several folds can be recognized.

The *Clough Head Fault* is probably a tear-fault, for it has the trend and throw common to the tear-fault system, and has an associated fold on its north side near Highfield.

The *South Upper Denton Fault* is well exposed in a small stream near Chapel Burn, where high dips are associated with a fold on the north side. High dips are again observable in Poltross Burn, where the fault has a maximum "vertical" throw of 100 feet.

Across the *North Upper Denton Fault* near Gapshields high dips exist at both sides of the fault as it is here crossing the pre-existing inner crescentic fold. The throw decreases south-eastward from 460 ft. near Gapshields, where the dip is 45° to 180 feet in the Coal Measures at West Coanwood, where the dips are about 15° .

A narrow fan-shaped group of five faults well exposed in the

Irthing north of Gilsland converges to the south-east to form the *Blenkinsopp Boundary Fault*. In Blenkinsopp Colliery the fault has a throw of 250 feet down south-west, but this decreases in a south-easterly direction to 100 feet across the South Tyne. High dips occur immediately to the north of this fan-shaped group of faults near Barn House. In the Thirlwall Colliery the dip has been proved to decrease rapidly when traced north-east along the strike away from this fault. The Whin Sill is definitely at the same geological horizon—that of the Five Yard Limestone—on each side of this fault.

THE WHIN SILL.

Historical.—Phillips held the view that this igneous sheet was interbedded with the strata and so occurred at a constant horizon. Tate¹ later proved its intrusive character, and was supported by Topley and Lebour,² who considered, on negative evidence, that it was intruded into the Carboniferous before the deposition of the Permian. Its petrography has been described by Teall.³

Some positive evidence of the age of the Whin Sill has been obtained recently by Dr. Holmes⁴ who has found a pebble of it in the Upper Brockram near Appleby. It is, therefore, definitely older than that deposit. As the Whin has not been recorded from the Lower Brockram Professor Gilligan⁵ considers that its date may be restricted to the interval between the formation of the Lower and Upper Brockrams.⁶

Mr. Versey places the date of the intrusion of the Whin Sill in the interval between two periods of faulting considered by him to be of Hercynian age.

Phacolitic Character.—The term phacolite has been used by Dr. Harker for lenticular sills which are the result of intrusion into folded strata. Similar lenticular forms would result if folding and faulting took place simultaneously. In general, pressure will tend to produce folding, and if a sill were intruded contemporaneously, the liquid magma would accumulate as a thickened sill in areas of relative relief from pressure (the incipient crests and troughs) and so develop a lenticular cross section, although the compression might not be sufficiently intense to produce appreciable folding. The term phacolite is used here to include such lenticular forms, where no direct evidence of folding is seen.

¹ Tate, G., "The Basaltic Rocks of Northumberland," *Proc. Ber. Nat. Club*, vol. vi, 1871, pp. 197–217.

² Topley, W., and G. A. Lebour, "On the Intrusive character of the Whin Sill of Northumberland," *Quart. Journ. Geol. Soc.*, vol. xxxiii, 1877, pp. 406–22.

³ "The Chemical and Microscopical Characters of the Whin Sill," *Quart. Journ. Geol. Soc.*, vol. xl, 1884, pp. 640–57.

⁴ Gilligan, Professor A., *The Geology of the Appleby District*, Whitehead and Son, Appleby, 1926, p. 21.

⁵ *Op. jam. cit.*, p. 21.

⁶ On account of the excessive rarity of the Whin pebbles in any of the Brockrams, this conclusion does not appear to be warranted.

The Whin Sill usually outcrops as a continuous sheet to the north of the Alston Block and along its western margin, but within a limited area of the Brampton Sheet it has been proved to occur as a series of discontinuous lenticular outcrops. It is possible that these lenticular sills may be true laccolites, but no feeders have been proved. A number of dykes of similar characters to the Whin Sill have, however, been mapped, and these may have acted as feeders.

The phacolitic character of the Whin Sill in this area is considered to be a consequence of localized pressure on the north-west corner of the Alston Block during the intrusion of the Sill acting in conjunction with the general northward directed Hercynian pressures. Evidence of phacolitic thickening produced by the latter has been brought forward by Mr. Versey in the case of the Whin Sill of the Teesdale anticline.

A fine example of a phacolite is seen in Black Burn, south-east of Midgeholme. The Sill, 140 feet thick in the burn, thins rapidly along the hillside to the east and disappears completely within a distance of $\frac{1}{2}$ mile. Lenticular sills or phacolites have also been mapped in the Coal Measures near Midgeholme, and in the South Tyne drainage at Tows Bank, and Thinhope Burn. Their petrography will be discussed in the forthcoming memoir.

Variation in Horizon.—In the north-western part of the Alston Block the Whin Sill makes great changes in horizon, the essentially localized character of which is brought out by a consideration of its geological horizon in the areas to the south and north-east.

On the Pennine Escarpment at High Cup Nick, the Whin Sill lies below the Tyne Bottom Limestone; from this point it gradually rises to the horizon of the Scar Limestone when traced northwards to Croglin, where it dies out, a change of only 100–150 feet in 20 miles. From Croglin northwards for a distance of 4 miles there is a rapid change upward in horizon; thus when it reappears it is above the Great Limestone, a change of horizon of 450 feet, and farther north on the south side of the Stublick Fault it lies some 1,050 feet above the Tyne Bottom Limestone. To the north of this fault it is absent for a distance of $2\frac{1}{2}$ miles, and when it reappears it lies beneath the Four Fathom Limestone—500 feet above the Tyne Bottom Limestone. Immediately north of this it is in the Coal Measures—2,600 feet above the Tyne Bottom Limestone; farther north it occurs below the Five Yard Limestone—some 300 feet above the Tyne Bottom. From this point north-eastward the region of rapid change of horizon is left and for a distance of 20 miles it outcrops within 100 feet of the Five Yard Limestone. This remarkable variation of horizon which takes place as the north-west corner of the Block is approached is illustrated in Fig. 2, in which isohypses of the position of the Whin above the Tyne Bottom as a base line are drawn.

The figure also shows the general westward rise in horizon of the Whin toward the escarpment throughout the northern half of the

Alston Block. The following example illustrates this, and also shows the progressive thinning of the Sill on approaching the western margin of the Block. In Rotherhope Fell Mine the Whin Sill is 192 feet thick, and occurs below the Tyne Bottom Limestone; it is 80 feet thick (base not seen) in Gilderdale, where it is some 70 feet above the same limestone, and in Croglin Water, where it is divided by 6 feet of strata into two beds each 20 feet thick, it immediately underlies the Scar Limestone. Still farther west in a quarry north-west of Croglin the Sill thins from a bed 10 feet thick to thin strings, totalling less than 2 feet thick, within the Scar Limestone. In this quarry where the Whin is dying out the most easterly acute folds characteristic of the western margin of the Alston Block are first developed.

The close connection of the acute folds with the Whin Sill in the north-west corner of the Alston Block is significant, for no such folds have been found within the area in which the whin occurs. Indeed, a curved line can be drawn separating the known occurrences of Whin Sill from the marginal area of acute folds. One may conclude that the conditions of pressure over the Alston Block during the intrusion of the Whin Sill were such that the liquid magma found relief by lateral extension in sill form. The presence of strong compression and its associated folding on the western margin of the block caused the sill to thin westward, and probably proved, in the northern part of the Alston Block at least, an effective barrier to further extension in that direction. The folding and faulting around the north-west part of the block indicate that this corner was subjected to particularly intense earth pressure. This localization of stress is intimately connected with the local abnormalities in the behaviour of the Whin Sill, for it is here that this magma developed its markedly discontinuous phacolitic character, and found relief from the stress by great upward changes of horizon.

THE RELATION OF THE WHIN SILL TO FAULTING AND ITS ECONOMIC ASPECTS.

The abnormal characteristics of the Whin Sill are displayed in an area where numerous limestone coals are, and have been worked, viz. the coals below the Oakwood, Little, Four Fathom, Three Yard, Five Yard, and Scar Limestones. The intrusion has influenced the exploitation of these coals, and a knowledge of its behaviour is of the utmost importance to mining engineers. This can be better appreciated by a study of the following examples.

The Little Limestone Coal near Tows Bank is overlain at a distance of 30 feet by a Whin Sill 20 feet thick which has completely coked the coal, and driven off all the volatile constituents.

The influence of the Whin is again seen by comparing the analyses of the Little Limestone Coal at Gair's Colliery and Venture Pit.

	Gair's Colliery.	Venture Pit.
	%	%
Fixed carbon	79.6	63.83
Volatile matter	16.6	34.3
Ash	3.8	1.87

At Gair's Colliery where the whin is 350 feet above the Little Limestone Coal, the analysis shows a striking loss of volatile constituents compared with that at Venture Pit, where there is no Sill within at least 1,000 feet of the coal. This example shows that the Whin Sill can affect coal where it lies as much as 350 feet above the seam. The relation of the Whin Sill to faulting is also economically important, for if the whin is intruded *after* faulting it may change its horizon in crossing a fault and so lie much nearer to a particular coal on one side of the fault than the other.

Mr. Versey gives three examples in the Brampton district of whin occurring at a different horizon on opposite sides of faults. He interprets this as the result of faulting of the strata *prior* to the intrusion of the sill. Our observations, however, do not support this interpretation. We propose therefore to discuss briefly the field evidence in each of these cases.

1. The original 1 inch geological map of the Brampton district (Sheet 18) shows a change of horizon of the Whin Sill on opposite sides of the North Upper Denton Fault, which has been accepted by Mr. Versey, but the identification of the individual limestone on the south side of the fault during the resurvey of the sheet has shown that there is no such change of horizon. As in the case of the Blenkinsopp Fault (see p. 442), it lies below the Five Yard Limestone on both sides of the fault.

2. The whin occurs above the Scar Limestone $\frac{1}{2}$ mile north of the South Upper Denton Fault. At the fault it is obscured by drift. Immediately south of it a section is seen in Poltross Burn. Here the Scar and the underlying Cockleshell and Single Post Limestones are exposed, but no trace of whin is seen. The higher limestones are under drift. The whin, therefore, does not change its horizon in crossing this fault to below the Scar Limestone—the position assigned to it in Mr. Versey's sketch.¹

3. The resurvey has shown that the Stublick Fault has a downthrow to the north in the Trias as well as in the Carboniferous (see Fig. 1). It is, therefore, of post-New Red age, but earlier movement along it is by no means improbable. The whin occurs to the south of the fault, but no whin is seen for $2\frac{1}{2}$ miles to the north of it, although the strata from 600 feet below the Tyne Bottom to 500 feet above the Little Limestone are well exposed. Mr. Versey has figured the whin as being intruded after faulting, occurring above the Little Limestone on the south side of the Fault, and below the Four Fathom on the north side, and calculates a pre-whin throw

¹ Versey, H. C., *op. cit.*, p. 10.

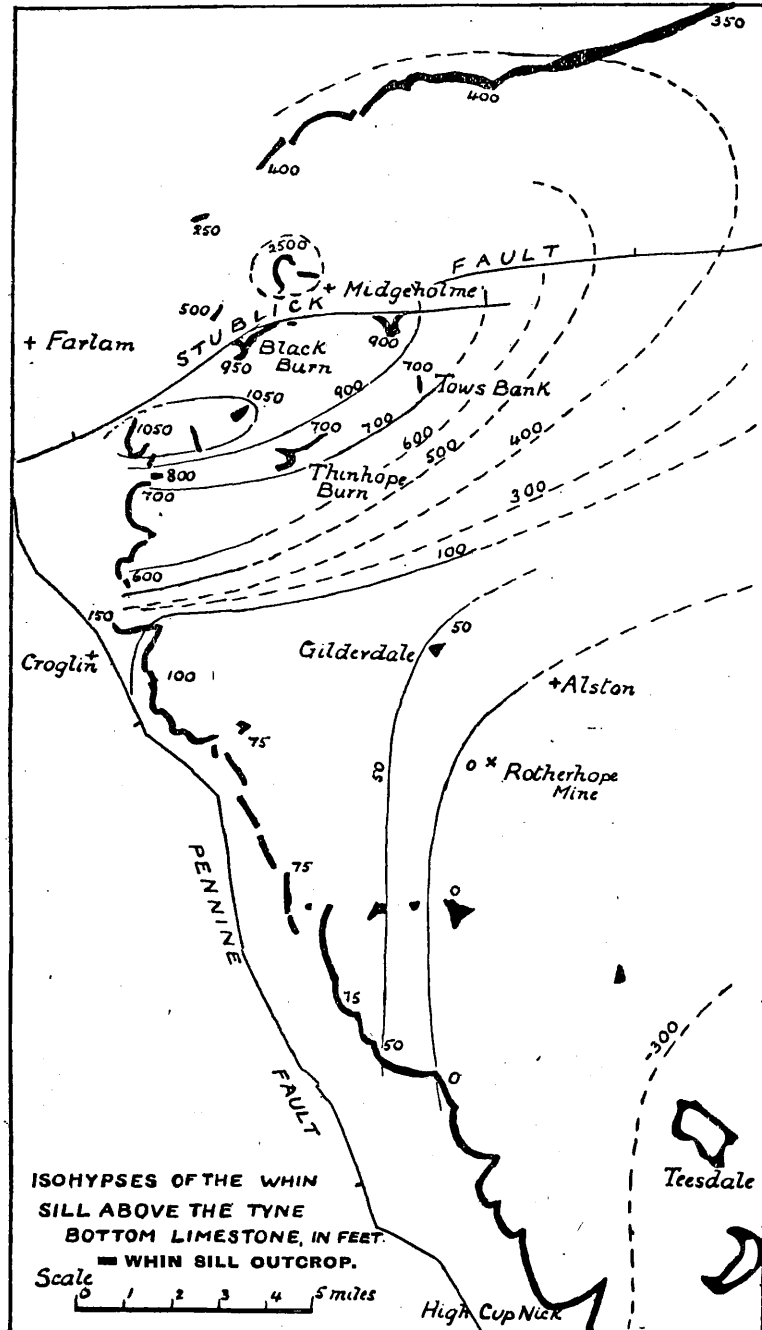


FIG. 2.

of 250 feet, as the whin is actually 300 feet above the Little Limestone on the south side his explanation necessitates a downthrow *to the south* of 600 feet. His inference that this faulting represents the initiation of the uplift of the Block by a downthrow *to the north* is therefore clearly invalid.

To sum up, we have found no evidence to support the view that faulting took place in this area before the intrusion of the Whin Sill, hence there is no reason to expect that it will be nearer a coal seam on one side of a fault than on the other. It must be remembered, however, that at the north-west corner of the Alston Block the Whin varies rapidly in horizon independently of faulting.

AGE OF THE WHIN SILL.

At least two of the Hercynian tear-faults have been proved to displace the whin (p. 440); the intrusion, therefore, is earlier than the faulting. There can be little doubt that the Whin Sill was intruded later than, or contemporaneously with, the pressure which produced the large crescentic folds outside the Alston Block and the small acute folds around its north-western corner. Hence it must have been intruded in the interval between the initiation of the folding and the later faulting of Hercynian age.

HERCYNIAN MOVEMENTS (SUMMARY).

The following brief explanation of the observed facts due to Hercynian movements is suggested.

In the general northward movement of the earth's crust the comparatively rigid masses forming the underlying cores of the Alston Block and the Lake District-Isle of Man mass are considered to have moved northwards at a greater rate than the Southern Uplands Horst of Scotland because they were nearer the southern source of compression. As a consequence the Bewcastle-Mid-Northumberland geosynclinal trough, lying in advance of the more rigid Alston Block, was folded along approximately east-west lines. The Lake District encountered greater resistance than the Alston Block in the northward movement as it was nearer to the Southern Uplands. Its resultant direction of movement then became east of north, a direction which caused it to converge relatively towards the Alston Block and compress the intervening strata against it, and thus form the acute folds. This compression eventually produced a movement of the strata north-eastward and eastward around the north-west corner of the Block. The strata adjacent to the Block encountered greater resistance than that farther to the north and so moved more slowly. This differential movement ultimately produced the series of successive tear-faults by relative movement eastward on the northern sides of the faults. A close analogy may be drawn between the movement producing these tear-faults and that forming the marginal crevasses in a glacier. The trend of

the fractures in both cases is backward from the margins towards the source of movement at an angle of 45° to the lateral margin.

The authors wish to express their thanks to Dr. Bernard Smith for helpful criticism of this paper. He has suggested that the system of faults and folds here described is such as would be expected from a clockwise rotation of the Alston Block in its travel northwards. It is possible that the general northerly and local north-easterly forces acting on the Block would produce such a rotation, but the final explanation of these movements must await further detailed work in the tectonics of a much larger area.

THE ALSTON BLOCK IN PERMO-TRIASSIC TIMES.

In the core of the Bewcastle Anticline, near Kirkcambek, the basal breccia of the St. Bees Shales rests on the upper beds of the cementstones. This shows that enormous denudation had taken place before the deposition of the Trias, for the Coal Measures ? 3,000 feet thick, the "Millstone Grit" 280 feet, the Upper Limestone Group 1,500 feet, the Middle Limestone Group 1,250 feet, the Lower Limestone Group 850 feet, Birdoswald Limestone Group 1,500 feet, Craighill Sandstone Group 800 feet, Fell Sandstones 1,000 feet, amounting in all to 10,000 feet, of strata, had been eroded. On the other hand 500 feet of Coal Measures at Midgeholme and the greater part of the Upper Limestone Group on the Alston Block are even now preserved to the south of the anticline. This indicates that the northern end of the Block was depressed relatively to the Bewcastle Anticline in pre-Triassic times. The throw of the tear-faults yields confirmatory evidence of this depression (p. 439). Recently Mr. Turner¹ has brought forward evidence that the southern part of the Alston Block in the Westmorland Pennines was depressed in pre-Permian times relatively to the Eden Valley on the west. It is reasonable to conclude that the whole of the Alston Block was depressed as the result of the Hercynian movements.

This view necessitates a reconsideration of the origin of the Permian Brockram of the Vale of Eden. These have been interpreted by Professor Kendall, whose view is generally accepted, as torrential deposits derived from high ground on the east, which towered above the Vale as a fault scarp, and was renewed by uplift during the formation of the Penrith Sandstone. Mr. Turner has given reasons to suppose that the Vale of Eden was elevated relatively to the area to the east. He has questioned the eastern origin of the Brockram and suggests their derivation from high ground on the site of the present Lake District. While not entirely accepting

¹ Turner, J. S., "The Lower Carboniferous Succession in Westmorland Pennines and the Relations of the Pennine and Dent Faults," *Proc. Geol. Assoc.*, vol. xxxviii, 1927, p. 371.

his view of the source of the Brockram, we are in agreement with the conclusion that the Brockram was not derived from the east. Mr. Turner has shown that the Brockrams do not become coarser or more angular towards the Pennine Escarpment. On the other hand they thin out when traced from south to north. Additional evidence is available to support his view. North of Armathwaite lenticular beds of conglomerate in the Penrith Sandstone are made up almost entirely of limestone pebbles. These cannot have been derived from the Escarpment, for in this district the Carboniferous Limestone Series shows a typical Yoredale facies in which sandstone beds are as thick as the limestones. Indeed, this deposit is in striking contrast with the local basal conglomerates of the New Red which have been derived from areas of Yoredale facies. In these sandstones predominate, although limestone pebbles are present. The limestone pebble conglomerate can only have been derived from massive limestone country which lay to the south.

It has been shown that the Bewcastle-Mid-Northumberland trough was elevated into an anticline by Hercynian earth movements, the southern or Bowland trough was also folded. An east-west anticline runs from Middleton Dyas in the east through the Howgill Fells to south of St. Bees Head. This anticline was formed as a result of the Hercynian earth movements, for in the east the Magnesian Limestone rests successively on the Coal Measures, Millstone Grit, and Carboniferous Limestone when traced from north to south. In the Vale of Eden Mr. Turner has shown that the Penrith Sandstone rests on successively lower divisions of the Carboniferous Limestone when traced from north to south. Similarly in West Cumberland the Brockram overlaps the Carboniferous on to the Older Palaeozoics from north to south.

We prefer to regard this uplifted anticlinal axis as the source of the Brockrams of the Vale of Eden, particularly as the anticline passes through the thick limestones in the Ravenstonedale trough of Carboniferous sedimentation. South of the anticline, the conglomerates of the Ingleton Permian outlier may be considered to support this view, for Professor Kendall¹ has shown that they were derived from the north.

It may be noted here that the Middleton Dyas and Bewcastle Anticlines have a pronounced pre-New Red pitch to the east, for the oldest rocks of these anticlines appear in the cores at their western ends, where they are unconformably overlain by the New Red. The conception of the Alston Block depressed between two easterly pitching anticlines on its northern and southern margins has a necessary corollary, viz. that the Pennine axis, which separated the Yorkshire and Lancashire Coalfields in the south, did not extend to the Alston Block in Permo-Triassic times.

¹ Kendall, Professor P. F., "The Geology of the Districts around Settle and Harrogate," *Proc. Geol. Assoc.*, vol. xxvii, 1911, pp. 46-7.

POST-TRIASSIC HISTORY OF THE BLOCK.

It has been shown that the Block was not uplifted by the Hercynian earth-movements or during the deposition of the New Red rocks.

The Stublick Fault, forming the present northern boundary of the Block, has a downthrow to the north in the Trias (see Fig. 1).

Similarly the Tyne Bottom (or Tynemouth) Fault, which may be regarded as an expression of its northern margin in the east, throws down the Magnesian Limestone to the north. The Pennine Fault also affects the Trias. The available evidence then, is wholly in favour of the post-Triassic age of the elevation of the Block.

The later Mesozoic appears to have been a period of quiescence and the uplift of the Alston Block—the last great stage in its evolution—probably formed part of the widespread crustal movements of earlier Tertiary times.

The Petrography of the Triassic Sandstone of North-East Ireland.

By DORIS L. REYNOLDS, M.Sc.

- I. INTRODUCTION AND LOCALITIES VISITED.
- II. MINERALOGY.
 - (a) Method of examination.
 - (b) Description of the minerals.
 - (c) Distribution of the minerals.
- III. DESCRIPTION OF THE CONGLOMERATE AND PEBBLE BEDS.
- IV. THE SOURCE OF THE PEBBLES.
- V. HEAVY MINERALS PRESENT IN THE PEBBLES.
- VI. HEAVY MINERALS IN NEIGHBOURING OLDER FORMATIONS.
- VII. THE SOURCE OF THE HEAVY MINERALS IN THE TRIASSIC SANDSTONE.
- VIII. THE GEOGRAPHY OF NORTH-EAST IRELAND IN TRIASSIC SANDSTONE TIMES AND THE MODE OF ACCUMULATION OF THE MATERIAL.
- IX. THE CORRELATION OF THE SANDSTONE.

I. INTRODUCTION.

BETWEEN the years 1869–83 the Triassic sandstone of North-East Ireland was examined and mapped by the Geological Survey under the direction of Hull. The rocks were correlated with those of similar age in Lancashire and Cheshire, the lithological characters described and the exposures noted. Later the Belfast district was resurveyed under the direction of Lamplugh, who suggested, in the Memoir published in 1904, that the Triassic sandstone should be correlated with the St. Bees sandstone rather than with that of Lancashire and Cheshire. Attention was also drawn to the probable incorrect mapping of the Trias near Belfast.

No attempt has yet been made to tackle the problem of the origin of the Trias in Ireland and the present investigation was undertaken in the hope of attaining something in that direction. It is concerned mainly with the mineralogical constitution of the Triassic sandstone

and includes additional information concerning the conglomerate beds.

The rocks of Triassic age in Ireland are entirely restricted to the

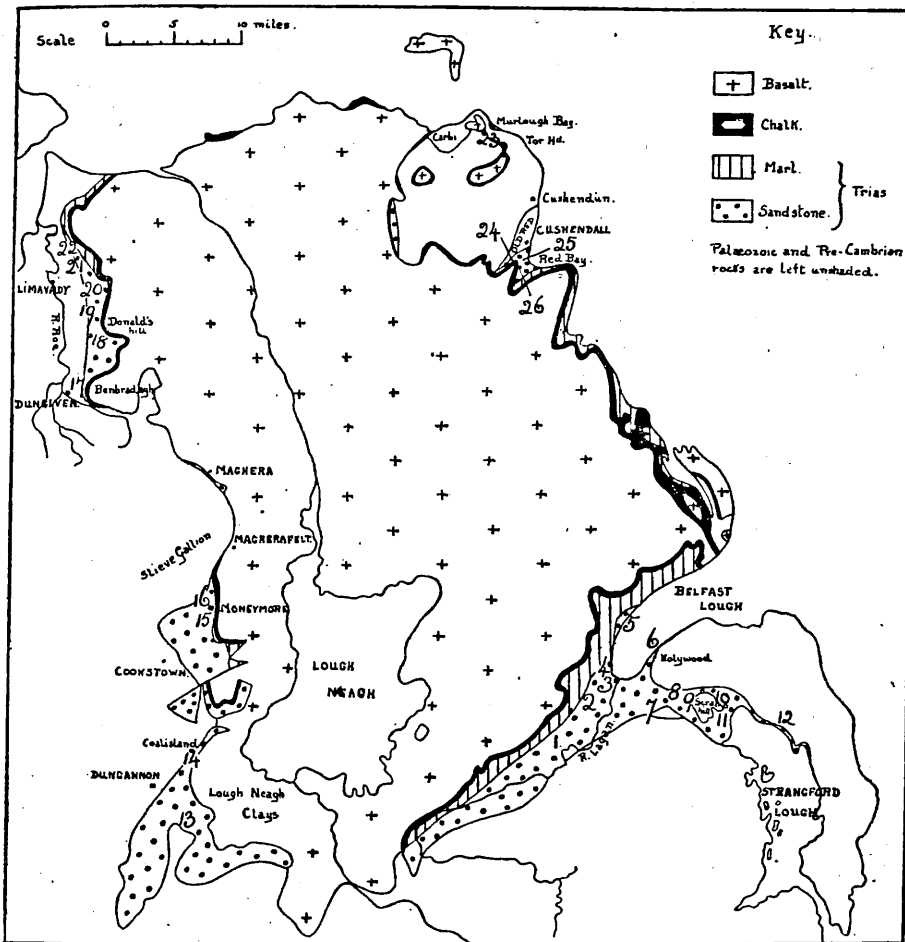


FIG. 1.—Sketch-map of N.E. Ireland showing the distribution of the Triassic sandstone. The numbers refer to the localities from which material has been collected. (See Table I.)

north-eastern counties, where they emerge in an almost continuous outcrop at the base of the Chalk and basalt escarpment of the Antrim plateau, in Antrim, Down, Armagh, Tyrone, and Londonderry.

A small faulted outlier occurs, farther south, near Kingscourt, on the borders of the counties of Cavan and Meath.

Although the area over which Triassic sandstone is known to occur is of considerable extent, the number of exposures is exceedingly small. This is due to the general association of these soft rocks with the larger valleys and depressions of the region and the thick covering of drift which everywhere conceals their floors. One has in consequence to rely on artificial excavations, stream sections, and occasional coast exposures. In many cases the sections noted by the Survey are no longer visible, the old quarries being frequently filled with water, and the small stream sections grassed over.

Localities visited.

Samples of sandstone have been collected from the following localities:—

Co. Antrim.—Belfast District: Falls Road, Skegoniel, Fortwilliam Park; White Abbey (north of Belfast Lough); Milltown (near Dunmurry). Cushendall district: Glenariff, Red Bay, Ballyeamon River, Murlough Bay.

Co. Down.—Marino (coast near Holywood); Dundonald: stream dividing the townlands of Ballybeen and Ballyhaywood, stream west of Dunlady House. Red stone quarry between Dundonald and Newtownards. Scrabo Hill. Ards Peninsula: Ballyhaft Cottage.

Co. Tyrone.—Red Ford (near Dungannon). Torrent River, Coalisland.

Co. Londonderry.—Moneymore: stream near Maple Lodge, Boherboy Cottage. Benbradagh (near Dungiven). Donald's Hill. In the following streams which flow westward into the Roe:—

1. The stream east of Drumagosker.
2. The stream flowing from Kready mountain to Drummond bridge.
3. Curly River.
4. The stream which flows under Artikelly Bridge (near Limavady).

Co. Cavan.—Enniskeen River (near Kingscourt).

II. MINERALOGY.

A. *Method of examination.*

The sandstone was crushed, passed through sieves, boiled in 30% HCl., washed, dried, and separated by means of bromoform. It is usually highly ferruginous, so that it was necessary to boil it for several hours in HCl. Since this would cause the complete disappearance of some minerals, e.g. apatite, an additional separation, without preliminary boiling in HCl., was made in the case of the paler sandstones. A quantity averaging about 60 gms. was separated at a time, larger amounts being panned, previous to separation in bromoform in the case of samples deficient in heavy

minerals. This was found advisable in order to verify the presence or absence of minerals that are only represented by one or two grains in each separation. A bar magnet and electromagnet were sometimes used for further separations.

Several specimens were thus examined from each locality, to ensure that an average sample had been taken and to note any variation at different horizons.

B. Description of Minerals.

The following is a list of the minerals identified :—

- | | |
|-----------------|-------------------|
| (1) Cubic— | (4) Orthorhombic— |
| Garnet. | Brookite. |
| Magnetite. | Staurolite. |
| (2) Tetragonal— | (5) Monoclinic— |
| Anatase. | Biotite. |
| Rutile. | Chlorite. |
| Zircon. | Hornblende. |
| (3) Hexagonal— | Muscovite. |
| Apatite. | Orthoclase. |
| Calcite. | (6) Triclinic— |
| Hematite. | Microcline. |
| Ilmenite. | Plagioclase. |
| Quartz. | |
| Tourmaline. | |

In addition an authigenic mineral was found in the sandstone from Benbradagh.

Garnet.—This mineral is most abundant in the coarser beds. It occurs, for example, almost to the exclusion of the other minerals in the coarse sandstones near Dundonald railway station, where the grains average .15 mm. in diameter, some being .5 mm. Under the microscope the smaller grains are seen to be colourless, the larger ones, however, vary from pale to deep salmon pink. They are angular and commonly diamond shaped, both angularity and shape being due to the excellent development of the dodecahedral cleavage. In appearance they recall those figured by Bosworth (1)¹ from the Coal-Measure sandstones of Scotland.

The garnets frequently show inclusions, which occasionally are so crowded that the garnet does not appear isotropic. The inclusions are small stumpy prismatic crystals with well-marked boundaries. Their refractive index is lower than that of garnet and the double refraction is low and extinction straight. They are probably apatite.

Magnetite, recognizable by its magnetic properties and bluish-black colour in incident light, is never abundant. It occurs as rounded or ragged grains.

Anatase occurs as aggregates of small crystals growing from grains of leucoxene, and more rarely as isolated rectangular crystals

¹ Figures in parentheses refer to Bibliography at the end of the article.

of tabular habit averaging about .05 mm. This form results from the combination of a broad basal plane and exceedingly narrow pyramid faces. The crystals vary from colourless to pale yellow and are usually clear. The crystal angles are always perfectly sharp, which would seem to indicate that the whole of the anatase was derived from leucoxene after the deposition of the sandstone.

Rutile was observed as ovoid grains averaging .1 mm. in length and less frequently as worn prismatic crystals, often striated parallel to the vertical axis and showing the following forms:—100, 110, 111. In the sandstone east of Drumagosker, near Limavady, grains as large as .37 mm. by .2 mm. occur. Genuiculate and polysynthetic twins are rarely present. The colour varies from golden-yellow to deep reddish-brown, the former predominating: pleochroism is strongly marked, in yellow crystals O pale yellow, E deep amber, and in brown crystals O reddish-brown, E dark red.

Zircon is most abundant in the finer sandstones, where it forms the predominant heavy mineral. It occurs as oval grains and also as prismatic crystals, the two types occurring together in almost every sample. The crystals and grains vary from .075 mm. to .37 mm. in length.

In the sandstone of Scrabo Hill the zircons are perfectly formed, fairly uniform in size with an average length .075 mm. They show the following forms recorded in order of frequency:—

- 100 and 110 terminated by 111.
- 100 and 110 terminated by 111 and 311.
- 100 terminated by 111.
- 110 terminated by 111 and 001.

Zoning is not uncommon in the larger grains. Inclusions are numerous and in the case of the zoned crystals are zonally arranged. They consist of zircon prisms, prisms and occasional needles of rutile, slender prisms of apatite and long tubular glass inclusions. The zircons are generally clear, but some are cloudy, possibly as the result of decomposition, whilst others are brownish. Purple zircons, oval in shape and sometimes of considerable size, have been found in samples of sandstone from Cos. Londonderry, Antrim, and Cavan. These evidently belong to the type described by Mackie (2) as originating in the Lewisian gneiss.

Apatite is probably characteristically present, though its occurrence could only be ascertained in the pale coloured sandstones which it was possible to examine without a preliminary boiling in HCl. In these it forms one of the most abundant of the heavy minerals, occurring in colourless well-rounded grains, often perfectly spherical and occasionally exhibiting the imperfect cross cleavage. The grains vary from .075 mm. to .1 mm. in diameter.

Calcite is present as a cementing material and also occurs filling cavities in the sandstone near Limavady and in veins at Scrabo Hill, in both localities exhibiting the scalenohedral form.

Hematite.—In addition to its occurrence as a cementing material, hematite is frequently present as large ragged plates.

Ilmenite was observed as rounded and ragged grains, forming often one of the most abundant of the heavy minerals. It shows signs of alteration to leucoxene, which not infrequently has entirely replaced it.

Leucoxene as an alteration product of ilmenite is abundant in rounded opaque grains, which are white, yellow, or brown in colour. Anatase can frequently be observed growing from the surface of the grains.

Quartz occurs as rounded, sub-rounded and angular grains, the larger ones only showing complete rounding.

Strain shadows were very frequently noticed and a large number of the fragments are composite, consisting of interlocking grains which sometimes show an elongation in one direction. These have evidently been derived from metamorphic rocks.

The researches of Mackie (3) on the quartz of the Scottish granites, gneisses, and schists have shown that the type of rock from which quartz grains have been derived can be determined from the nature of the inclusions. An examination of the inclusions in the quartz grains of the Triassic sandstone of this area shows the following types to be present:—

1. Regular: zircon, tourmaline, rutile, biotite, and possibly apatite.

2. Acicular: needles of rutile.

3. Irregular: glass (occasionally with enclosed bubbles), and very fine black inclusions, not determined.

Of these the regular type of inclusion is the most frequent.

Dr. Mackie says that "It may be stated as a fairly general law that acicular and irregular inclusions pre-eminently abound in the quartz of granite; that the regular group is to be found in various proportions, but always in relatively large numbers in the quartz of gneiss and the younger schistose rocks."

Tourmaline.—Its most common variety is of a deep brown colour and occurs as almost spherical grains, less frequently as prismatic crystals with rhombohedral and rounded terminations. Occasional striations parallel to the *c* axis were observed, and strong pleochroism is shown: O dark brown, E pale yellow. Blue tourmaline, exhibiting less strongly marked pleochroism, is also present in small amount. It occurs as splinters and small subangular grains. Pinkish tourmalines are frequently present, occurring as prisms with rounded terminations; they are usually smaller in size than the grains of brown tourmaline.

The blue tourmaline is free from inclusions as in the case of that described by Travis and Greenwood (4) in the Wirral Trias. The brown, however, is often crowded with inclusions, of which the most common are glass and iron-ore, while small crystals of rutile and zircon were also noted.

The brown tourmaline is common and frequently abundant, the pinkish is frequent, whilst the blue, though almost always present, is only represented, in each separation, by a few grains.

Brookite.—Only two or three grains are present in a few samples of sand that have been examined. The grains are usually well rounded and show marked striations. They are pale yellow in colour and sometimes very faintly pleochroic. A very imperfect cleavage was noted in one or two grains parallel to the direction of striation. The nature of the grains is readily determined from the interference figure, the crossing of the optic-axial planes for red and blue light usually being very clearly shown.

Staurolite.—This mineral, though almost invariably present, is never abundant, a few grains only being obtained as a rule from each separation. It occurs in pale yellow or reddish grains, sometimes showing slight pleochroism and a very characteristic toothed outline, due to fraying along the 110 cleavage, as described by Bosworth (5) in connection with the staurolite from the Keuper Marls around Charnwood. The grains average about .1 mm. in diameter, though in the sandstones rich in garnets from Dundonald they measure as much as .4 mm.

Micas.—Both muscovite and biotite are present, the former invariably. Muscovite, occurring generally in perfectly oval flakes, forms one of the principal heavy minerals in some of the flaggy sandstone. Biotite is less frequently present.

Chlorite is sometimes represented, especially in the finer sandstones, but is rarely abundant.

Hornblende.—This mineral is very rare, but was found in slight amount in the sandstones from Co. Londonderry, while one grain was detected in the sandstone from Red Ford, near Dungannon, Co. Tyrone. It occurs in small compact grains showing a tendency to prismatic habit due to breaking along the 110 cleavage. It is strongly coloured and shows marked pleochroism from yellowish green to bluish green. The extinction angle varies from 2° to 8° and a convergent light picture can always be obtained, with an optic axis emerging near the margin of the field. One or two green grains have been noted in the samples from Skegoniel and Falls Road, Belfast. They show the prismatic form of hornblende, but exhibit aggregate polarization and are possibly due to the decomposition of original hornblende.

Felspar.—Orthoclase is the most common variety. It occurs in rounded and angular grains and is always more or less kaolinized.

Microcline is always present and is most abundant in the Roe valley. It is usually fresher than the orthoclase.

Grains of plagioclase were occasionally seen, which gave extinction angles indicating albite and oligoclase as the species present.

An Authigenic Mineral.—The discovery of this mineral in the sandstone from Benbradagh was rather fortuitous, since it is normally lost with the fine rock powder in washing the sand before separation

in bromoform. It is most easily separated from the rock by crumbling the sandstone over a watch glass, until the glass is covered with a thin layer of sand. If the glass is then tilted and all the sand allowed to fall off, a fine powder remains, which, on microscopic examination proves to consist of perfectly developed crystals resembling dolomite in form and cleavage and averaging .05 mm. in diameter.

This mineral is insoluble in strong acid (except hydrofluoric) even after prolonged boiling, and microchemical tests show it to be an aluminium silicate probably with potash. The average refractive index is 1.52 and the double refraction is low. The extinction varies on different faces, it is either straight with the diagonals or makes a low angle with a crystal edge. The fast ray, in the former case, vibrates parallel to the short diagonal. Possibly the crystals have a slight tendency to be tabular, for in every case when a convergent light picture has been obtained the same result is found. This face is approximately normal, either to an obtuse bisectrix or an optic normal, since the hyperbola leave the field of the microscope rapidly. Serious difficulties are encountered in determining the specific gravity of so small a mineral and an accurate figure cannot yet be given, although it is thought to be roughly equal to that for orthoclase.

Lath-shaped forms have also been noted, which show straight extinction with their length, the vibration direction of the slow ray.

The Benbradagh sandstone is very friable and had to be specially treated before a thin section could be made. It is a fine-grained rock composed of angular and subangular grains of quartz with a little orthoclase, microcline, and oligoclase and occasional flakes of biotite and muscovite. Each grain is surrounded by a pellicle of hematite. The rhomb-shaped crystals cannot be seen over the greater part of the slide, but towards the edge, where the rock has been almost rubbed away, they occur abundantly.

The mineral is evidently authigenic and its properties indicate a feldspar (possibly orthoclase), but this requires confirmation and further investigations are being made.

C. *Distribution of the Minerals.*

1. *The heavy minerals.*—Examination of material collected from successive layers in various localities shows that variation in the relative abundance of the heavy minerals takes place from layer to layer and may be correlated with the coarseness of the sandstone. Garnet and, to a lesser degree, staurolite are more abundant in the coarser sands, whilst zircon, rutile, and apatite predominate in the fine. Consequently great variation in the relative abundance of the heavy minerals is sometimes found within a few feet. In view of this, the tabular summary of the distribution of heavy minerals was compiled to show the average abundance of each species, at the various localities, as determined from a number of samples.

TABLE I.—TABULAR SUMMARY OF THE DISTRIBUTION OF HEAVY MINERALS.

8 = superabundant; 7 = very abundant; 6 = abundant; 5 = common;
4 = frequent; 3 = scarce; 2 = rare; 1 = very rare.

Locality.		Garnet.	Anatase.	Rutile.	Zircon.	Apatite.	Ilmenite and Leucocoxene.	Tourmaline.	Staurolite.	Brookite.	Hornblende.
Co. Antrim.	1. ¹ Milltown	6	—	6	6	—	6	6	3	—	—
	2. Falls Road	6	4	3	4	5	6	6	1	1	1(?)
	3. Fortwilliam Park	1	1	5	7	4	6	6	1	1	—
	4. Skegoniel	5	1	5	6	4	5	7	3	—	—
	5. White Abbey	6	—	4	7	—	4	5	2	—	—
Co. Down.	6. Marino	6	3	5	6	—	7	5	3	—	—
	7. Dundonald. Stream near railway station	8	—	2	2	1	1	7	6	—	—
	8. Dundonald. West of Dunlady House	2	5	3	3	5	7	2	—	—	—
	9. "Redstone" quarry	—	—	6	6	—	8	—	—	—	—
	10. Scrabo Hill	1	3	4	4	3	8	1	—	—	—
	11. Scrabo railway cutting	6	—	4	3	3	8	5	—	—	—
12. Ards Peninsula	1	4	4	6	6	6	8	2	—	—	
Co. Tyrone.	13. Red Ford	1	2	4	7	—	7	4	1	—	1
	14. Coalisland	1	3	4	7	—	7	6	—	—	1
Co. Londonderry.	15. Near Maple Lodge	6	—	3	4	—	6	4	2	—	—
	16. Boherboy Cottage	6	3	5	6	—	7	4	1	1	—
	17. Benbradagh	2	—	3	5	—	7	5	—	—	1
	18. Donald's Hill	8	1	3	3	4	5	4	—	—	—
	19. Near Drumagosker	4	1	3	5	—	7	1	2	—	1
	20. Stream from Kready mountain to Drum- mond Bridge	2	1	4	7	—	7	3	2	—	1
	21. Curly River	7	—	3	6	—	6	4	—	—	1
	22. Lyn-burn	6	1	3	3	4	6	3	1	—	—
Co. Antrim.	23. Murlough Bay	1	1	3	4	—	8	4	1	—	—
	24. Ballyeamon River	2	—	6	8	—	8	2	1	—	—
	25. Red Bay	6	—	2	3	—	7	3	2	—	—
	26. Glenariff	4	1	6	8	—	3	2	1	—	—
Border of Cos. Cavan & Meath.	Enniskeen River	5	2	4	4	5	6	6	1	1	—

¹ The numbers are the same as those used on the map, Fig. 1, to indicate the localities from which material was collected.

NOTE.—Muscovite, chlorite, and magnetite are not shown in the table, although they are usually present. This is on account of the difficulty of estimating the amount of muscovite and chlorite present, since much of these minerals is lost whilst washing the sand. No estimate is given for magnetite on account of its solubility in HCl, although it is usually present and less abundant than ilmenite. The presence of apatite is only shown in the case of the pale sands which could be examined without preliminary boiling in HCl.

The table shows no regular lateral variation of heavy mineral content, even the blue and pinkish varieties of tourmaline, not shown separately in the table, are found in small amounts at all localities. Hornblende is the only mineral with a definite restricted occurrence. Although represented only by one or two grains in each sample, yet it is characteristic of the sandstone to the west of the plateau in Londonderry and Tyrone. The only grains recorded from the east are those from the Lagan Valley, which are decomposed and doubtful.

It should be mentioned, however, that whilst in general the heavy residue from one locality is indistinguishable from that of another, certain districts are characterized by bands rich in ilmenite with zircon, rutile, and apatite in subordinate amounts, almost and sometimes quite to the exclusion of other minerals. This is noticeably the case at Scrabo Hill. Samples were collected from all horizons in the excellent quarry exposures at Scrabo, yet not more than two or three grains of garnet and tourmaline and no staurolite have been found in the whole thickness of about 120 feet. Only at the extreme base in the railway cutting do garnet and tourmaline appear in any quantity and staurolite is still absent. The sandstone from "Redstone" quarry on the Belfast and Newtownards road to the north-west of Scrabo is exactly similar. Bands rich in ilmenite but never quite so deficient in other species, have been found in the higher beds at Red Bay, Benbradagh, and at Murlough Bay. It is noticeable that these bands, with the exception of Murlough Bay, where tourmaline and garnet are never entirely absent, come from the higher part of the series, yet such a composition is not characteristic of the higher horizons everywhere, as is seen from the samples examined from the Lagan Valley not far from the junction with the marl.

2. *The light minerals.*—Felspar is usually abundant. Rough estimates were made, by counting, of the percentage of felspar present in the light residue in various specimens from the Lagan and Dundonald valleys. It was found to form as much as 30% to 40% of the bulk of the rocks. In some of the sandstones from the Roe Valley it appeared to be so abundant that a special examination was made. A portion of the light residue of the sand from the stream flowing under Artikelly bridge was suspended in potassium-mercuric-iodide to separate quartz from felspar. As a result 51% of felspar, by weight, was found to be present. Not only is felspar more abundant in the Roe Valley, but the proportion of microcline to orthoclase increases, although orthoclase is always the more common.

III. DESCRIPTION OF THE CONGLOMERATE AND PEBBLE BEDS.

Conglomerate and pebble beds are recorded in the Survey Memoirs as occurring at Murlough Bay (13), Red Bay-Cushendall (14), in the Roe Valley near Limavady (15), at Cookstown (16), and in

the Dundonald Valley (17). The conglomerate and pebble beds of Murlough Bay, Red Bay, and the Roe and Dundonald Valleys were examined and rock fragments collected from them for identification, but the conglomerate beds at Cookstown could not be located. These conglomerate beds will now be briefly described together with the rock types represented in them.

1. *Murlough Bay.*

The small exposure of sandstone in Murlough Bay contains angular fragments of mica schist, pebbles of brown quartzite, vein quartz, and occasional gneiss pebbles. All of these have evidently been derived from the underlying Dalradian.

2. *Red Bay.*

The Triassic sandstone is well exposed in the cliffs skirting Red Bay, between Cushendall and Waterfoot. A coarse basal conglomerate appears near the coastguard station, Cushendall; fragments of schist are most abundant, varying in size from blocks measuring 1 foot or more across to small chips about 1 inch across. The schist fragments are arranged with their foliation planes parallel to the bedding planes of the red sandstone in which they are embedded. Pebbles of quartzite, vein quartz, gneiss, and rarely felspar porphyry are also present. About 40 feet from the arch quartzite becomes the predominant rock in the conglomerate, and occurs in well-rounded boulders measuring as much as 1½ feet in diameter. The matrix of the conglomerate is a hard dull red sandstone. Viewed from the cliff behind the quartzite conglomerate appears as a tumbled mass of boulders, bedding planes being no longer apparent. The higher horizons exposed in the cliff are pebble beds alternating with thin beds of sandstone. These pebble beds proved more interesting than the massive conglomerate. Angular fragments of mica schist predominate, but in addition pebbles of vein quartz, brown quartzite, pink felspar-porphry, grey felspar-porphry, and grey gneiss were collected. A pebble measuring about 4 to 5 inches in diameter of white quartzite containing pink felspars was also found. Pebbles of black schist become fairly common in the higher layers.

The more interesting of these pebbles were sectioned for microscopic examination and are described below.

(a) *Pink Felspar-Porphry.*—This rock is of a type easily recognized. In the pebbles large crystals of pink felspar measuring as much as ½ inch across and rounded quartz blebs can be seen surrounded by a fine pink ground-mass. When examined in section the most abundant phenocrysts are found to be oligoclase. Porphyritic crystals of orthoclase are scarce and rounded quartz crystals showing signs of corrosion are fairly common. Biotite is the only ferro-magnesian mineral in the section, though hornblende has been distinguished in the hand

specimens. The oligoclase shows a marked zonal structure and is usually very fresh except for the development of a fine white mica along the junction of the zones. The ground mass is a microcrystalline aggregate of quartz and felspar.

(b) *Grey Felspar-Porphry*.—The hand specimens show closely packed phenocrysts of white felspar averaging about $\frac{1}{16}$ inch across and occasional flakes of biotite in a compact grey groundmass. When examined microscopically this rock is found to be allied to the pink felspar-porphry. The phenocrysts are again well-zoned oligoclase with white mica developed along the limit of the zones. A few idiomorphic crystals of orthoclase are present and the groundmass is a microcrystalline quartz-felspar aggregate.

(c) *Black Schist*.—On sectioning, the black schist was found to consist of fine angular quartz grains and very much kaolinized felspar, in a matrix of ilmenite and magnetite. The iron ores appeared to form rather more than half of the bulk of the rock. This was confirmed by pounding the rock to separate the individual grains and then separating in bromoform. The heavy residue of specific gravity greater than 2.9 was found to form more than half of the bulk of the rock and to consist of ilmenite and magnetite.

(d) *Grey Gneiss*.—This rock is closely related to the black schist, ilmenite being very abundant. It is coarser in grain than the schist and the quartz is crowded with inclusions. The inclusions are mainly of irregular quartz, elongated in the direction of schistosity, but in addition zircon, apatite, and garnets are frequent. The felspar is very much kaolinized.

(e) *Felspathic Quartzite*.—This is a coarse white quartzite with pink feldspars and in places rounded opalescent grains of quartz. In section the felspar proves to be microcline which is usually slightly kaolinized. It occurs in rounded grains which average about 2.5 mm. in diameter. The microcline together with rounded grains of quartz is embedded in a microcrystalline groundmass. This matrix is mainly quartzose, but some microcline and a little oligoclase are present. The quartz grains have crenulate edges and exhibit strain shadows. They show the dot and hairlike type of inclusion.

3. *The Roe Valley.*

East of Limavady pebble beds are exposed in the Lyn-burn which flows under Artikelly bridge. At the marked bend in the stream south of the Coleraine road the section is follows:—

- Boulder-clay.
- Red sandstone.
- Pebble bed, about 2 feet thick.
- Red sandstone, about 4 feet thick.
- Pebble bed forming bed of stream.

The pebbles rarely exceed 3 inches in length and are usually smaller. The rock types represented among the pebbles are in order of frequency:—brown, green and grey quartzite, pink and white gneiss, which is always very rotten, vein quartz, and rarely small pebbles of brown sandstone like the local Carboniferous, and of coarse grit or arkose in which pink felspar is abundant.

Some of these pebbles are described in more detail:—

(a) *Pink Gneiss*.—This rock has a granitic appearance in the hand specimen and a very noticeable foliation. Where it is most rotten in the bed of the stream it tends to crumble and break along the foliation planes. On sectioning, the rock was found to contain more or less rounded grains of microcline and quartz averaging about 1 mm. in diameter, in a microcrystalline matrix of quartz with a little microcline. In places the matrix becomes almost cryptocrystalline. The grains have crenulate margins and the larger ones have frequently broken down round their edges to a microcrystalline or cryptocrystalline aggregate.

(b) *Green Quartzite*.—This is a fine-grained quartzite or quartz schist with abundant ilmenite. As in the gneiss, microcline is characteristic. The other colours of quartzite were not sectioned, but small portions were pounded up and examined. As a result microcline was found to be present in every type.

(c) *Arkose*.—This rock closely resembles the Torridon sandstone. The pebbles shade from pink to grey and pink felspar is very evident. Some of the feldspars measure as much as $\cdot 2$ inch across. In section it is found to consist of well-rounded grains of quartz, microcline, and more rarely perthite and oligoclase. The grains average about 1 mm. in diameter. Many of the grains have finely crenulate edges and intercrystallization can be seen in places, giving a mosaic structure. Generally speaking, however, the grains are distinct and are separated from one another by a fine white mica. Microcline is strikingly abundant, distinctly more so than in the gneiss and quartzites previously described, and is exceedingly fresh. The relative abundance and high degree of rounding of the various heavy minerals present in the arkose, which are recorded in another part of this paper, also indicate that this is a distinct type and not a variety of the quartzites.

4. Cookstown.

As already mentioned, the conglomerate beds at Cookstown could not be located: this was possibly due to the flooding of the streams in which exposures occur. From the following description given by Egan (16), however, they appear to be local in character: "The lower portions are composed of a coarse sandy red breccia with some thin layers of sandstone, the former containing fragments of the underlying granite and schists, and a few quartz pebbles. Higher up they become finer and less compacted; and at the top they

become quartzose and assume the form of a fine conglomerate with interstratified beds of sandstone."

5. *Dundonald Valley.*

In the pebble beds near Dundonald railway station, which are exposed in the small streams flowing into the Dundonald Valley, only angular chips of slate and pebbles of vein quartz are present. These have evidently been derived from the underlying Palaeozoic slate.

IV. THE SOURCE OF PEBBLES.

In connection with the Cushendall conglomerate beds the rocks exposed to the north of the area between Cushendun and Tornamoney were examined.

At Cushendun a red felspar-porphyry, which is intrusive in the Dalradians, is exposed in small quarries. This is the rock described by M. Henry (14*b*) as "quartziferous porphyry" and cited by Harker (6) as a good example of a quartz-monzonite-porphyry. Sections of this rock proved to be identical with those of the red felspar-porphyry found in the pebble beds at Red Bay, the abundance of zoned oligoclase with fine mica delimiting the zones being unmistakable.

On the north side of Cushendun Bay several dykes of grey porphyry with abundant crystals of white felspar traverse the schists. Microscopic examination of this rock shows it to be closely allied to the red porphyry. The oligoclase phenocrysts have, however, undergone a curious type of decomposition and become entirely cryptocrystalline, so that they are no longer recognizable as felspar crystals. That oligoclase similar to that in the red felspar-porphyry was the original mineral is indicated by the presence of the white mica which still shows the concentric arrangement parallel to the edges of the crystal and so gives evidence of the original zonal character of the mineral. A few very fresh crystals of orthoclase are present and rounded, much corroded crystals of quartz. Biotite and chlorite are present in small amount. A fresher type of this dyke rock must have furnished the material for the grey felspar-porphyry pebbles in the conglomerate.

The silver mica schist which predominates in the Red Bay conglomerate beds is the normal type of schist exposed in the Dalradians of the Tor Head Series, whilst the grey gneiss can be matched in the same series. The quartzites are also derived from the Dalradians, although some of the boulders have doubtless been derived via the Old Red Conglomerate of Cushendun.

Although the black schist pebbles were not exactly matched in the Tor Head Series, yet it seems probable that this is a variety of

the dark schists exposed to the north of Cushendun. These are hornblende biotite schists, with a considerable quantity of ilmenite and some iron pyrites present. Continued search would doubtless reveal a type similar to the iron ore schist pebble.

The most characteristic feature of the pebble beds near Limavady is the abundance of microcline in pebbles of all types, whether gneiss, quartzite, or arkose. In the case of the gneiss and quartzite pebbles the rounding of the larger grains which are enclosed by a matrix of secondary quartz is also characteristic. Both these features are shown by the Dalradian quartzites in Jura and Argyllshire. A comparison of slides of these quartzites, in the Geological Survey collection, with those made from quartzite and gneiss pebbles found in Lyn-burn and the felspathic quartzite from Cushendall brings out an exact similarity.

Unfortunately an examination of the Irish quartzites has not been possible. The quartzites from several localities in Ireland, however, are described in the Survey Memoirs as being felspathic (18) and at times grading into gneiss (19). In the petrographical notes on Inishowen (20) the quartzites of Ineuran Bay are described as "pink in colour and very fresh. In section under the microscope the original quartz grains are seen to have been mostly well rounded, some are subangular but the fragmental structure is still preserved. The rocks contain a large quantity of felspar which often shows microcline or micropertthitic structure. The form of the felspar is often remarkably well defined."

Thus the quartzite and gneiss pebbles are allied to the Dalradian quartzites both in structure and in the presence of microcline and were evidently derived from the quartzite ridge which extended from Argyllshire, through Jura to Donegal in Triassic times.

The arkose pebbles, as has already been shown, are very similar to the Torridon sandstone, except that in microscopic section they do not show the iron staining which is characteristic of the Torridonian and it is possible that they might be matched amongst the grit bands which occur in Donegal. Whether they originated in the Torridonian or the Dalradian Series, however, makes no difference to the direction from which they were derived. If Dalradian they originated, with the quartzites, in the ridge of metamorphic rocks which existed to the north and if Torridonian they were probably derived from a southerly extension of the Islay Torridon.

The pebble beds of other localities, as already stated, are quite evidently local in origin.

V. HEAVY MINERALS PRESENT IN THE PEBBLES.

Several examples of various types of pebbles found in the pebble beds were pounded up, separated in bromoform, and the heavy residue examined. The result of this examination, showing the minerals present and their relative abundance, is tabulated below:—

8 = superabundant; 7 = very abundant; 6 = abundant; 5 = common; 4 = frequent; 3 = scarce; 2 = rare; 1 = very rare.

	Garnet.	Rutile.	Zircon.	Apatite.	Ilmenite and Leucocene.	Magnetite.	Tourmaline.	Staurolite.	Chlorite.	Muscovite.
Schist—from Cushendall and Murlough Bay .	7	1	5	7	8	1	1	—	8	7
Black schist—Cushendall	—	—	4	4	8	6	—	—	—	—
Grey gneiss—Cushendall	5	1	5	7	3	8	3	1	4	—
Pink gneiss—near Limavady	3	2	5	5	8	4	1	—	—	—
Arkose—nr. Limavady .	6	3	5	7	4	8	3	—	—	—
Green quartzite—near Limavady	6	4	5	2	3	6	—	—	1	—
Brown quartzite—near Limavady	4	1	5	2	3	8	1	—	—	—
Felspathic quartzite—Cushendall	5	1	4	4	1	8	1	—	1	—
Brown quartzite—Cushendall	5	2	4	5	2	7	—	—	1	—
Slate—Dundonald	6	5	6	4	7	6	3	—	5	—

The schist, gneiss, and quartzites were all found to contain a high percentage of heavy minerals, whilst the slate, although less rich in the amount of heavy minerals present, showed exactly the same species. The principal characteristics of the heavy minerals from the pebbles may be summarized as follows:—

Garnets occur in the pebbles of all types as small and medium sized grains which are either pink or colourless, the former predominating. They are frequently crowded with inclusions so that they do not always appear to be completely isotropic. In the pebbles of grey gneiss the small garnets show perfect dodecahedral form.

Rutile is not common in any of the pebbles except the slate, but when present it shows a rounded prismatic form and is reddish-brown in colour.

Zircon is common and occurs as well-formed crystals, resembling those recorded from the Triassic sandstone in form, and as oval grains. It frequently shows zonal structure and sometimes has a cloudy appearance. Purple zircon is present in the heavy residue from the arkose, schist, and green and brown quartzite pebbles. In the quartzites and arkose it is oval in shape, whilst in the schist pebbles, although usually oval, it sometimes shows good prismatic form.

Apatite is sometimes more abundant than zircon and usually shows prismatic form with rounded terminations, or else is terminated by the basal plane; at other times it occurs as irregular

grains. In the arkose the apatite is well rounded and frequently almost spherical.

Magnetite and Ilmenite are very abundant and occur usually in irregular grains. The ilmenite is fresh compared with that in the sandstone, though some leucoxene can be seen. In the arkose and the green quartzite both magnetite and ilmenite grains are well rounded and sometimes almost spherical.

Tourmaline is scarce in all the pebbles that have been examined. In the schist it occurs as well-formed brown or pinkish-brown prismatic crystals with the trigonal pyramid predominant at one end and the base at the other. In the grey gneiss irregular and rounded grains of brown and pinkish-brown tourmaline are present and in addition a few irregular grains of blue tourmaline have been seen, whilst grains of brown and green tourmaline are present in some of the quartzites and the arkose.

Staurolite does not appear in the heavy residues from any of the pebbles except the grey gneiss and in that case only one small grain was found.

VI. HEAVY MINERALS PRESENT IN NEIGHBOURING OLDER FORMATIONS.

In order to ascertain whether or not the neighbouring older sediments may have contributed to the Triassic sandstone, a few samples of Ordovician slate, Old Red sandstone, and Carboniferous sandstone were examined. The Carboniferous sandstone was collected from near Ballycastle and from the Roe Valley, the Old Red sandstone from between Cushendall and Cushendun, and the Ordovician slate from near Newtownbreda.

Each yielded the same suite of heavy minerals as the Triassic sandstone, with the exception of staurolite, which was not found in any of the heavy residues. Also the same type of quartz was found in each. The fact that staurolite was not found in the heavy residues cannot be taken to prove its absence from these formations. In the Triassic sandstone staurolite is a very rare mineral, only one or two grains being found in large quantities of sand, so that its non-appearance may be due to the small number of samples that have been examined.

The following table shows the average relative abundance of the various heavy minerals in the specimens examined, but should not be regarded in any case as typical of the whole formation.

8 = superabundant;	7 = very abundant;	6 = abundant;
5 = common;	4 = frequent;	3 = scarce;
2 = rare;	1 = very rare;	x = present, but relative abundance not determined.

	Garnet.	Rutile.	Zircon.	Apatite.	Ilmenite and Leucocoxene.	Magnetite.	Tourmaline.	Staurolite.	Chlorite.	Muscovite.
Ordovician slate	4	4	4	3	7	1	2	—	x	x
Old Red sandstone	1	1	5	x	8	x	3	—	—	x
Carboniferous sandstone, from the Roe Valley	2	5	7	2	6	x	2	—	—	x
Carboniferous sandstone, from Ballycastle	4	5	8	x	7	x	3	—	—	x

VII. THE SOURCE OF THE HEAVY MINERALS IN THE SANDSTONE.

The derivation of the sandstone is clearly indicated by the assemblage of minerals present. It has already been shown that, according to the principles enunciated by Mackie (3), the quartz was derived from gneiss or schist, a conclusion which is upheld by the frequency of strain-shadows and schistose grains. The presence of the metamorphic mineral staurolite and the abundance of muscovite point in the same direction. This suggests that the local Dalradian series forms the most likely source of the material.

With the exception of staurolite, a mineral suite similar to that found in the sandstone was found to characterize the fragments of Dalradian schist, gneiss, and quartzite found in the pebble beds. Not only are the mineral suites similar, but each mineral species shows the same characteristics in the Dalradians as in the sandstone. Although staurolite was not found in the pebbles examined, yet it is certainly present in the local schists, since it was recorded by Geikie (13*b*) as occurring in the schists at Ballycastle. The only difficulty appears to be the relative abundance of tourmaline in the sandstone and its relative scarcity in the heavy residues from the pebbles examined. In spite of this, the fact that all the varieties of tourmaline found in the sandstone are present in the metamorphic rocks strongly suggests that they were derived from these rocks. Also tourmaline evidently becomes characteristic of the schists in certain localities, having been recorded by the Survey from near Ballycastle (13*b*) and the schistose ridge north-west of Maghera (21).

The neighbouring older sediments are also characterized by the same suite of heavy minerals as the Triassic sandstone and the same type of quartz, so that the question arises as to whether the greater part of the material was derived directly from the Dalradian Series or indirectly via the older sediments. Near Limavady fragments of the local Carboniferous sandstone in the pebble beds clearly indicate that this formation was providing some material. Similarly in the neighbourhood of Cushendall the underlying Old Red Sandstone contributed at least to the basement beds. In the south

the Ordovician and Silurian were yielding material, as shown by the presence of slate fragments in the small conglomerate beds in the Dundonald Valley.

In the north of the area there can be little doubt that the main part of the sandstone was derived directly from the metamorphic rocks. The percentage of felspar is there so high as to make it seem unlikely that it can have been derived from pre-existing sediments, whilst the fact that microcline is most abundant in the north indicates that it was there derived directly from the quartzites and gneiss. That these rocks played an important part in providing material even in the south of the area is rather suggested by the fact that the Triassic sandstone is richer in the percentage of heavy minerals present than the neighbouring older sediments. This implies a general drift of material from north to south, a view which is upheld by the greater abundance of felspar and particularly microcline in the Roe valley as compared with the south and the presence of fresh hornblende in Cos. Londonderry and Tyrone with an absence of fresh hornblende in the south. Additional strength is perhaps given to the idea of a flow from north to south by the degree of rounding of the quartz grains. In the northern localities they vary from angular to subangular, whilst in the south a larger percentage are subrounded to rounded. This is capable, however, of other interpretation.

A record was kept of the direction of current-bedding observed in various localities, in the hope of learning something definite as to the direction of drift of the material, but it was found to be of little value, since the directions are very variable, though the balance of evidence is in favour of flow along the Dundonald Valley in the direction of Strangford Lough.

VIII. THE GEOGRAPHY OF NORTH-EAST IRELAND IN TRIASSIC SANDSTONE TIMES AND THE MODE OF ACCUMULATION OF THE MATERIAL.

From the evidence of the conglomerate beds, it is apparent that, in Triassic sandstone times, the rocks of the Tor Head Series formed part of a ridge from which material was carried both to the north and the south. Further evidence of this ridge is to be found in the thinning of the sandstone. The sandstone reaches its greatest development in the Lagan Valley, where bores in Belfast and near Lisburn have revealed a thickness exceeding 500 feet, whilst in the neighbourhood of Carrickfergus the thickness has been estimated by Doyle as between 800 and 1,000 feet. The estimate given by M. Henry of the combined thickness of the sandstone and marl near Cushendall, however, is only 700 feet; moreover, at the head of the Ballyeamon Valley the Trias overlaps the Old Red Sandstone and thins out. North of the ridge in Murlough Bay and on the north-east slope of Carnamore Mt. the Geological Survey give the total thickness of the sandstones and marls as only 60 feet. The outcrop



FIG. 2.—Map showing the physical geography of N.E. Ireland in early Triassic times.
The unshaded portion represents the basin of deposition.

of sandstone in Bush River, about 10 miles west of Cushendall, probably marks the western termination of this ridge, which may have been continuous with the rocks of Kintyre.

According to Jukes-Browne (7), a landmass extended across from Scandinavia, through Scotland to the north-west of Ireland and probably far into the area of the north Atlantic. The southern part of this landmass, where it adjoined the Irish Triassic deposits, was formed by the Dalradian Series of schist, quartzite, and gneiss which extended across from Scotland to Ireland. It is from this elevated area that the main part of the Irish Triassic sandstone must have been derived. In view of the occurrence of pebbles resembling the Torridon sandstone and Dalradian quartzites in the pebble beds near Limavady it is probable that a river entered the area of deposition from the north. This river need not have been either long or powerful, for the metamorphic rocks are close at hand, whilst Torridon sandstone occurs in Islay, and a slight extension of this outcrop to the south-west would bring it very close to the pebble beds. Also these pebble beds are small in extent and the number of pebbles is not very large, since they are scattered at intervals through sandstone rather than forming a massive conglomerate.

It seems likely that the sandstone never extended much farther westward than its present boundary, for the rocks of the Slieve Gallion district provided material for the conglomerate beds of Cookstown to the south-east. Very little information can be gained as to the original southerly extension of the sandstone. That deposition took place far to the south of the Lagan Valley is known from the occurrence of the isolated outlier of sandstone and marl near Kingscourt. From the presence of chips of slate in the sandstone of the Dundonald Valley, however, it may be inferred that such rocks were exposed close at hand, so that part of the Ordovician and Silurian slates must have risen above the level of deposition, at least in early sandstone times, and the Trias of the Dundonald Valley was accumulated in an old depression in the Palaeozoic rocks.

An examination of the degree of rounding of the quartz grains leads to the conclusion that whereas water played the greater part in the deposition of the sand in the north, wind action was more prevalent in the south. The sandstone bounding the metamorphic rocks is composed for the most part of subangular and angular grains, though some of the coarse sandstone which forms the matrix of the massive conglomerates of Cushendall contains a fair percentage of grains which are subrounded to rounded. In the Lagan Valley rounding is more common and some of the beds may be largely composed of wind-blown sand. Yet even there beds composed of subangular and angular grains are not wanting.

Current-bedding is particularly characteristic in the south, the

best examples being found at Scrabo Hill and at Milltown near Derriaghy, though it also occurs in the north at Waterfoot (near Cushendall) and near Dungiven. The current-bedding is of the irregular type described by Grabau (8) as characteristic of Eolian deposits, and the examples figured by him can easily be matched in the Irish Triassic sandstone. The bedding is characterized by variation in the angle and direction of slope of the laminae in the same stratum or successive strata and by lack of parallelism of the dividing laminae.

Clay galls are characteristic of much of the sandstone in the Lagan Valley and are best developed at Scrabo Hill and in sections seen in Falls Road, Belfast. According to Grabau (9) clay galls may "be regarded as practically positive evidence of a subaerial origin of the rock containing them". He regards them as being formed from thin mud layers which, when exposed to the heat of the sun, become dry and curl up into masses resembling shavings. When dry these shavings may be blown into neighbouring sand-dunes where they are buried. During the rainy seasons when the dune is saturated with water the clay shavings are softened and become compressed into clay pellets. In support of this view I have found that the clay galls are frequently associated with the best rounded sands.

Thus it appears that a basin of deposition extended over north-east Ireland in Triassic sandstone times, and probably reached its greatest depth in the region of what is now the Lagan Valley. Possibly a river entered this basin from the north and small streams drained the surrounding Pre-Cambrian and Palaeozoic highlands at least in times of heavy rainfall. These streams spread out their debris over the basin floor. In early Triassic times boulders and pebbles were washed down the slopes of the surrounding highlands, particularly from the north, where the land reached its greatest elevation. As the heights were progressively lowered the streams moved smaller and smaller fragments, until finally, they were only capable of carrying sand.

Deposition may have been intermittent, taking place mainly during periods of heavy rainfall. The thin beds of sandstone, intercalated in the conglomerates, which usually vary from a few inches to a foot in thickness, possibly represent the drier periods.

Towards the south wind action was more prevalent and the sand was blown over the basin floor and in places piled up into dunes. At times, probably after periods of greater rainfall, pools must have collected over the lower southern part of the basin and in these pools the thin marl bands which can be found intercalated in the sandstone were formed, or thin marl layers which provided material for clay galls collected. Ripple marks were formed in the shallow water and on the drying of the pools sun cracks and rain prints developed. Into these same pools the more angular sands may have been washed directly by the streams.

In connection with the river claimed by Professor Bonney (10)

as having carried pebbles from Scotland to the English midlands in Bunter times, it should be mentioned that no evidence of such a river exists in Ireland. Although there may have been a southerly drift of the finer material in Ireland, there was no transportation of pebbles from the north to the southern localities, so that if such a river existed its course must have lain to the east of Ireland.

IX. THE CORRELATION OF THE SANDSTONE.

The Geological Survey correlated the Irish Triassic sandstone with the complete development in Lancashire and Cheshire. They recognized the following horizons:—

Lower Keuper sandstone.

Upper Mottled sandstone.

Middle Bunter sandstone (Pebble beds).

In the Lagan and Dundonald Valleys where the sandstone shows its greatest thickness it was at first assigned to the Upper Mottled sandstone. Exception to this classification was made in the case of the sandstone of Scrabo Hill (17*b*) and that round Dundonald railway station (17*c*), where, in each locality, it is protected by a sill of dolerite. Here correlation with the Lower Keuper sandstone was made. The sandstone of other isolated exposures was also correlated with the Lower Keuper, namely, the small outcrop on the south-east shore of Belfast Lough, about 1 mile north-east of Holywood (17*d*); the beds exposed near Falls Road Cemetery, Belfast (22*a*); in a quarry about 2 miles north-west of Lisburn (22*b*); and at the base of the marls north-east of Hullstown (22*b*).

In 1904 Lamplugh (26) noted that "to the west of the Lagan the Keuper Marls rest directly upon soft sandy beds presenting the lithological characters of the Bunter Sandstone without the intervention of beds like those of Scrabo Hill" which are regarded as Keuper in age. He suggested the correlation of the Triassic sandstone of the Lagan Valley with that of Cumberland and the Isle of Man, rather than with the more distant area of Lancashire and Cheshire, and pointed out that "if this course be followed, the Triassic sandstones of this part of Ireland may be regarded as the equivalent of the St. Bees' Sandstone, underlain as in Cumberland by the Lower Marls and with an attenuated representative of the Permian, comparable to that at Whitehaven and in the Isle of Man, occurring in places at their base." The presence of the Lower Marl was proved in various borings in Belfast.

An examination of the classification over the rest of north-east Ireland brings out the curious fact that all the northern sandstone, viz. that which outcrops in the neighbourhood of Cushendall (14*c*) and Murlough Bay (13*a*) in Co. Antrim and that outcropping to the west of the plateau in the Roe Valley (15*b*) has been classed as Lower Keuper, whilst the southern sandstone exposed in the Lagan and

Dundonald Valleys and in Counties Armagh, Tyrone, and Londonderry as far north as Magherafelt, was, with the exception of that of a few isolated exposures, classed as Bunter. All the Bunter was regarded as Upper Mottled sandstone with the exception of the conglomerate beds of Cookstown, which were classed as Middle Bunter Pebble beds (16). Yet in both the north and the south of the area the sandstone passes up gradually into the overlying Keuper marls, so that this classification seems unnatural.

The lithological characters of the sandstone, with the exception of that of Scrabo Hill, are everywhere similar. Usually it is bright red in colour with the occasional intercalation of buff-coloured beds, and it varies from a fairly compact sandstone to a friable sand. Current-bedding and clay galls are common. At Scrabo Hill the sandstone is more compact and harder and is quarried for building stone. This greater hardness is probably due to the intrusion of the dykes and sills of dolerite with which the rock is here riddled. The sandstone of Scrabo Hill is also more variegated in colour, varying from the usual bright red and buff to dull red, purple, and green, and shows excellently current-bedding, ripple marks, sun cracks, rain prints, and clay galls. Thin beds of green or chocolate-coloured marl are intercalated here and there. At the base of the hill, in the railway cutting, the usual bright red and more friable type of sandstone again appears.

Nowhere in Ireland, with the exception of Scrabo Hill, can any change in the lithological characters be found in the sandstone as it passes to higher horizons, nor can any break be seen in the sequence, apart from insignificant local pebble beds, which would give evidence of a lower Bunter and upper Keuper member.

It has been pointed out by Sherlock (11), in the case of the Belfast area, that since the rock salt of Carrickfergus may be correlated with the Cheshire salt, the marl is evidently the Keuper marl and the underlying beds may represent both Bunter and Keuper sandstone. This might equally well be said of the sandstone throughout the Lagan Valley.

Similarly the sandstone of the northern localities which has been classed as Keuper, may also have some Bunter component. Since the sandstone is here thinner and nothing representing the Magnesian Limestone has been recorded, however, it is possible that deposition did not take place in the north at quite so early a date as in the southern basin round Belfast.

It was shown by Travis and Greenwood (12) in the case of the Triassic sandstone of Wirral that although the Bunter and Keuper are alike in the mineral assemblage present, yet they differ as to the physical condition of their component grains. The Bunter there shows a regularity of grain size and a high percentage of rounded grains, whilst the Keuper is composed of an agglomerate of grains of widely different dimensions, a large percentage of which are angular and subangular. The Keuper is also characterized by the occurrence

of large grains of felspar in quantity in the lower beds and by a greater average size of grain.

In view of this a careful watch has been kept for any change in the physical condition of the grains in examining samples from different horizons in Ireland. It has not, however, been found possible to distinguish between sandstone of Bunter and Keuper age in this way. The only generalization that can be made with regard to the physical conditions of the grains is that the sandstone of the northern outcrops is characteristically more angular than that of the southern, but this feature is to be attributed rather to nearness to the source of the material and the greater part played by water in its deposition than to difference in age.

With regard to the distinction made by the Survey between Bunter and Keuper at Scrabo Hill, mineralogical investigation shows that the upper part of the "Bunter" sandstone shown at the base of the quarries, although so different lithologically from the "Keuper", is indistinguishable from it mineralogically, being characterized by the superabundance of ilmenite with zircon and apatite and an almost complete absence of other heavy minerals. The sandstone at the extreme base of the hill and exposed in the railway cutting, however, although identical lithologically with that exposed at the base of the quarries, shows the complete assemblage of heavy minerals characteristic of the normal sandstone. Also, the sandstone exposed in Red Stone quarry on the Belfast and Newtownards Road, classed by the Survey as Bunter, is identical with the Scrabo Keuper mineralogically. Hence, it seems that change of lithological character, such as colour change or greater hardness or compactness, does not necessarily indicate change of physical conditions at the time of deposition.

Stated briefly, the Triassic sandstone in Ireland forms one continuous series in which no lithological or mineralogical change (which may be regarded as anything but local in character) can be found in tracing the beds from their base to the junction with the marls.

In conclusion the writer would like to express her thanks to Professor P. G. Boswell and Professor J. K. Charlesworth for suggestions in the early stages of the research, to Dr. L. Hawkes for kindly reading and criticising the manuscript and to H.M. Geological Survey for allowing certain of the slides in their possession to be used for comparison with those made from some of the Irish pebbles.

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MEMOIRS OF THE GEOLOGICAL SURVEY OF IRELAND.

- (13) Explanation of Sheets 7 and 8, 1888, (a) p. 17; (b) p. 11.
 - (14) Explanation of Sheet 14, 1886, (a) p. 14; (b) p. 26; (c) p. 11.
 - (15) Explanation of Sheet 12, 1885, (a) p. 15; (b) p. 14.
 - (16) Explanation of Sheet 27, 1881, p. 25.
 - (17) Explanation of Sheets 37 and 38 and part of 29, 1871, (a) pp. 38 and 39; (b) p. 12; (c) pp. 13 and 39; (d) p. 19.
 - (18) Explanation of Sheets 3, 4, 5, 9, 10, 11, 15, and 16, 1891, p. 158.
 - (19) Explanation of Sheet 25, 1887, p. 9.
 - (20) Explanation of Sheets 1, 2, 5, 6, and 11, 1890, p. 51.
 - (21) Explanation of Sheet 19, 1882, p. 13.
 - (22) Explanation of Sheet 36, 1871, (a) p. 23; (b) p. 26.
 - (23) Explanation of Sheets 21, 28, and 29, 1876, p. 9.
 - (24) Explanation of Sheet 35, 1877, p. 67.
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 - (26) Memoir on the Country around Belfast, 1904, p. 20.
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REVIEWS.

LES PLATEAUX DU JURA CENTRAL: ÉTUDE MORPHOGÉNIQUE.
By GEORGES CHABOT. Publications de la Faculté des Lettres
de l'Université de Strasbourg, Fascicule 41. Paris: Les
Belles Lettres; Great Britain: Humphrey Milford, 1927.
pp. 350, 85 text-figures, 4 plates. Price in Great Britain,
12s. 6d. net.

THIS is a detailed geomorphological study of the plateau region of the Central Jura, in which an attempt is made to trace the evolution of the present plateaux. Briefly, the author's conclusion is that the plateaux are the remains of a single peneplain which after its formation was broken up by faulting. The erosion which has taken place since the dislocation of the original peneplain is also dealt with in detail, and there is an interesting section on karst phenomena.

The work is very thorough. The views of previous writers are fully discussed, and there is an excellent bibliography. It is a very useful volume.

The book is printed on paper which is free from loading and is accordingly exceptionally light for its size. The views in the text and most of the sections have been drawn to suit the paper, but in some of the maps and sections the lines are too fine for the rough surface, and there is some loss of clearness. Plate I is a relief map of part of the area, and the other plates are photographic views.

P. L.

OEUVRES GÉOLOGIQUES DE MARCEL BERTRAND. Edited by EMM.
DE MARGERIE, and published under the auspices of the Académie
des Sciences. Vol. I. pp. xxii 708, + 184 text-figures, 12
plates, and a frontispiece in heliogravure. Paris: Dunod, 1927.

THE death of Marcel Bertrand in 1907 deprived geology, and especially tectonic geology, of one of its most brilliant investigators. He was extraordinarily original and fertile in ideas, and remarkably clear and logical in expounding them. But his fertility had one disadvantage. He was so much occupied in developing his conceptions that he never had time to combine them, and they still lie scattered in the journals in which they originally appeared. Many of his papers, however, have had a profound influence upon geological thought, and in 1922 the International Geological Congress expressed a hope that they might be republished in book form. It is in response to this expression of feeling that the Académie des Sciences undertook the work.

The number of articles and memoirs collected for the purpose is 163. All the publications that bear the name of Marcel Bertrand are to be reproduced, except the sheets of the *Carte géologique détaillée de la France* on the scale of 1 : 80,000 and two long memoirs already published by the Académie (*Mémoires présentés par divers savants à l'Académie des Sciences*, xxx, 2, 1889, and 1, 2, 1908). The first of these is a study of the Mesozoic and Tertiary rocks of Granada and Malaga, and the second is a more general memoir on the folding of the earth's crust and the rôle of horizontal displacements.

Three volumes have been found necessary to contain the rest of Marcel Bertrand's work, and the preparation for publication has been entrusted to M. de Margerie. The extent and accuracy of M. de Margerie's knowledge and—perhaps even more—his sympathy make him an ideal editor in such a case.

The various articles and memoirs have been grouped according to subject and the first volume includes those dealing with the Jura and with Provence. As an introduction there is a summary of Bertrand's scientific work up to 1894, written by himself. The volume is beautifully produced. There are many figures in the text, and the maps and the longer sections are reproduced as plates, which are mounted so as to open out clear of the text. Three of the maps and three of the plates of sections are in colour. The frontispiece is a photograph of Marcel Bertrand reproduced in heliogravure.

P. L.

WELLS AND SPRINGS OF WARWICKSHIRE. By L. RICHARDSON.

Mem. Geol. Survey. pp. vi + 204, with 5 figures. Price 5s.

THE county of Warwick is not on the whole very well provided with underground water, and as is well known to all geologists, most of the Birmingham supply is derived from a distant source in central Wales, while Nuneaton gets a supply by arrangement with the Corporation of Leicester. This memoir contains an account, arranged on the usual plan, of the underground water resources actually derived from the county itself, giving a large amount of detail. There is an interesting description of the medicinal waters of Leamington, which are derived from the Keuper sandstones, and are therefore naturally somewhat saline. The water of the Pump Room is said to be radioactive. There are a fair number of deep borings in the county, made in search of water, many of which are very fully described. All these water memoirs are valuable sources of information for stratigraphical purposes, owing to their good accounts of well-sections and borings.

INTRODUCTION TO SCIENTIFIC STUDY OF THE SOIL. By N. M. COMBER. Arnold and Co.

PROFESSOR COMBER has produced in his *Introduction to the Scientific Study of the Soil* an elementary text-book which presents the most recent views on soil science. The work of Hissink, Oden, Robinson, Keen, and the author himself, has profoundly affected the whole trend of recent work on soil problems. Professor Comber is the first author to produce a readable and concise account of the present-day views on the subject in a form suitable for students. Soil science should be based on pure geology, and Professor Comber's book shows very well the application of soil physics and chemistry to the data supplied by geologists. It may fairly be considered that the trend of soil research in the future will follow pure geology and mineralogy to a much greater extent than was the case a few years ago. The book may be safely recommended to students of agricultural science and will provide information useful to field geologists interested in applied work.

L. F. N.

EVOLUTION AND CLASSIFICATION OF SOILS. By E. RAMANN. Translated by C. L. Whittles. Heffer and Sons.

THE work of Dr. E. Ramann exercised a profound effect on agricultural soil science and geology. The publication of his small work, *The Evolution and Classification of Soils*, translated by Dr. C. L. Whittles, is of great value in placing one of the classics of soil science within the reach of the student; and Messrs. Heffer and Sons, of Cambridge, have shown great enterprise in issuing the work at a price which makes it available for everyone. Dr. Whittles' translation is quite adequate, and he has preserved the spirit of Ramann's original work in a marked degree. The translation was made some years ago, and the introduction and footnotes were obviously written at the same time. The explanatory notes and introduction would have gained in value had they been brought up to date at the time of publication in view of the recent advances on methods of soil classification and examination. With the exception of one or two misprints the book has been well produced.

L. F. N.

PRINCIPLES OF SOIL MICROBIOLOGY. By S. A. WAKSMAN. Bailliere, Tindall and Cox.

RECENT work on the flora and fauna of the soil has led to the production of a large number of papers published in various journals in this and other countries, and Professor Waksman may be congratulated on the success which has attended his attempt to collect the scattered literature into one volume of reasonable size.

The author deals almost entirely with the changes in the organic

content of the soil due to the activity of the micro-flora, and the book contains little of interest to the geologist. The debatable question of rock-weathering by bacteria only occupies some twenty-three pages of the volume. The author has dealt with that subject in a very interesting way, and most of the information at present available is included in the one chapter. It is, however, too brief to do justice to the importance of the theories of biological rock-weathering. The volume contains a full index of authors and a general bibliography of book literature. Recent publications are quoted in copious footnotes, and the only criticism that can be made of Professor Waksman's book is that a general bibliography of papers is not given as a separate section.

L. F. N.

REPORT OF THE COMMISSION ON PLOCIENE AND PLEISTOCENE TERRACES, edited by K. S. SANDFORD. Union Géographique Internationale, pp. 123, 1928.

AS will be seen from its title this publication appeals to geologists as well as to geographers. In point of fact it contains so much valuable matter in a condensed form that it cannot be reviewed in the ordinary way. The only possible course seems to be to give a list of the contents, for the information of geologists who may desire to read the papers for themselves.

The following are the titles of papers, some of which are abstracts only :—

1. Raised Beaches and Terraces of Egypt. By W. F. Hume and O. H. Little.
2. Changes of Level on the Palestine Coast. By Sir W. M. Flinders Petrie.
3. Terraces of the Nile in Upper Egypt. By K. S. Sandford and W. J. Arkell.
4. Les terrasses marines de la Grèce. By Ph. Negrin.
5. Relazione sui Terrazzi fluviali e marini d'Italia. By M. Gortani.
6. Der Monte Argentario in Toscana. By G. Braun.
7. Les Terrasses fluviales de l'Espagne. By E. Hernández-Pacheco.
8. Les Zones d'Abrasion maritime ou lacustre de l'Èbre moyen. By L. Garcia-Sáinz.
9. Les Terrasses des Régions atlantiques françaises. By E. Chaput.
10. Evidences of Change of relative level between Land and Sea in Southern England since the Pliocene Period. By H. Dewey.
11. Raised Beaches of the British Isles. By W. B. Wright.
12. On the Climatic Equivalent of Raised Beach Mollusca. By D. Baden-Powell.
13. Land Oscillations in England at the close of the Neolithic depression. By C. J. Gilbert.
14. Post-Pliocene Movements in the Vicinity of Cambridge. By J. E. Marr.
15. Raised Beach Levels, Ayrshire Coast, from Ardrossan to Girvan. By V. A. Eyles.
16. A Raised Beach on the Outer Hebrides. By J. W. Gregory.
17. Les Terrasses alluviales de deux grands Fleuves asiatiques; l'Euphrate et le Mékong. By C. Dépéret.
18. Pleistocene Movements in Sierra Leone. By F. Dixey.
19. An Examination of the Tertiary and Quaternary Changes of Sea-level in South Africa, with special stress on the evidence in favour of a Recent World-wide Sinking of Ocean Level. By A. V. Krige.

THE IKUNO-AKENOBE METALLOGENETIC PROVINCE. By T. KATO.
Japanese Journal of Geology and Geography, vol. v, 1927,
p. 121.

IN this paper Professor Kato describes the geology of the Ikuno mining area, and to some extent revises his former work on Akenobe. The chief points of interest are that he has established the existence of the normal sequence of mineralization, viz. tin, tungsten, copper, zinc, and then gold in quartz. The country rock is largely rhyolite and andesite of Tertiary age, these being cut by the veins. But the author clearly states his view that the real ore-bringer is a plutonic intrusion lying below at no great depth, and not exposed at the surface owing to the comparatively late date of the intrusion. This is important in connection with the supposed volcanic or hydrothermal origin of certain tin deposits elsewhere.

R. H. R.

TIN MINING. By C. G. MOOR. pp. xi + 171, with 14 figures.
London: Sir Isaac Pitman and Sons, Ltd., 1928. Price 8s. 6d.

THIS little book is clearly intended mainly for those who wish to gain a knowledge of the practical side of tin mining. The sections dealing with geology are necessarily brief, but they appear to be accurate as far as they go. The author has apparently had a wide experience in various countries, and he gives some interesting details of different types of tin-mining, if indeed it is justifiable to apply the term mining to the commonest methods of winning this metal, such as ground-sluicing, gravel pumping, and the different types of dredging. Tin working in alluvial deposits is in reality the making of more or less complicated forms of mud pies. It is only lode-workings that are truly mines, and these yield only a fraction of the world's output, though they are likely to increase in relative importance as the alluvials become exhausted.

R. H. R.

CORRESPONDENCE.

THE MAGMATIC ORIGIN OF ORES.

SIR,—The interesting letter of Mr. H. C. Sargent published in our last issue creates a somewhat anomalous situation, because the author of the paper referred to in it is also the editor of this Magazine, and it seems rather irregular for the editor in his private capacity to write a letter to himself in his editorial capacity. But our readers will perhaps excuse this unusual proceeding.

It may be well to confess that the suggestion of a granite batholith underlying the mineralized area of Derbyshire was put forward mainly in default of a better explanation. The presence of great quantities of fluorspar must be accounted for somehow, and according to the accepted canons of geology fluorine is associated with acid intrusions, whereas the only known igneous rocks of that area are decidedly basic. However, the facts disclosed by the data supplied in Mr. Sargent's letter do seem to afford a possible explanation of the presence of fluorspar in that area as the result of the differentiation of a magma rich in potash and silica, with granitic affinities, though far from being a granite magma in the ordinary sense. It is of course obvious that a lava-flow cannot account *directly* for the formation of minerals higher up in the rock-series, which are necessarily of much later date than the lava. It should be remembered that fluorspar is also found in quantity in the northern part of the Pennine area, where the only igneous rock that could be concerned in its formation is the Whin Sill. The publication of Mr. Sargent's detailed work will be awaited with interest: till this occurs further speculation on the subject may well be deferred.

R. H. RASTALL.

THE SILURO-DEVONIAN JUNCTION IN ENGLAND.

SIR,—No apology is needed from Dr. Robertson for reopening this controversy; on the contrary, his paper in the August number of the GEOLOGICAL MAGAZINE is a welcome indication of the progress towards general agreement. Reviewing the subject from still another angle, he has expressed agreement with the main conclusion put forward by de Dorlodot, Barrois, myself, and others, that the Ludlow Bone-bed or the equivalent horizon elsewhere is the most generally satisfactory base for the Devonian. Dr. Robertson mentions that he does not accept certain statements in my 1923 paper in this MAGAZINE, and that he disagrees with certain of the reasons given for the selection of the Ludlow Bone-bed as the Devonian base. I think there are only two points of apparent disagreement. I showed that the Ludlow Bone-bed passes laterally when traced southwards

from Shropshire into a bone-bed conglomerate below which there is an unconformity of varying importance. Although a break in the succession is a help in mapping, Dr. Robertson is undoubtedly right in arguing that the limit should be determined where the sequence is unbroken and the presence of an unconformity which is frequent at about the Ludlow Bone-bed horizon away from Shropshire is really no argument for the choice of this horizon as the base of the Devonian. Dr. Robertson is also justified in hinting that I have tended to overemphasize the absence of fish in pre-Bone-bed strata. Their absence is comparative rather than complete! So far as I can see, only one other point of disagreement remains, and that is not one vital to the general conclusion. I was puzzled, and still am, over the interpretation of the sequence in Central Wales—the Afon Sawdde sections and the Llandilo district. The Geological Survey's reading of the succession in the latter area is perfectly clear, but I do not think the possibility of contemporaneity between part of the Green Beds and the Tilstones further east is entirely eliminated. Mr. S. H. Straw's recent work, from the brief abstract available, seems to confirm the possibility. When working over the ground in 1920-1, I was unable to satisfy myself as to the position of the Devonian base in Central Wales and Mr. Straw is no doubt right in stating that my tentative suggestion placed it too low.

Evidently much work remains to be done before agreement is reached between workers in this particular area, and it is desirable that it should be perfectly clear that the main question of the fixation of the Siluro-Devonian boundary is not dependant thereon.

L. DUDLEY STAMP.

LONDON SCHOOL OF ECONOMICS, W.C. 2.
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