

37. *On FOLIATED GRANITES and their RELATIONS to the CRYSTALLINE SCHISTS in EASTERN SUTHERLAND.* By J. HORNE, Esq., F.R.S.E., F.G.S., of H.M. Geological Survey of Scotland, and E. GREENLY, Esq., F.G.S., formerly of H.M. Geological Survey. (Communicated by permission of the Director-General of H.M. Geological Survey. Read June 10th, 1896.)

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I. INTRODUCTION.

THE detailed mapping of the eastern portion of the County of Sutherland by the Geological Survey has shown that the crystalline schists of that region are extensively penetrated by granites, more or less foliated, which are apparently linked to some extent with the present crystalline characters of these schists. Some of the features presented by these foliated granites have already been described by previous observers.

In 1862 Prof. Harkness remarked that the mode of occurrence of the granites in the east of Sutherland rather tends to the conclusion that the sedimentary rocks were elevated, flexured, and contorted previous to the period when the granites made their appearance in the sedimentary rocks, and that these granites have conformed in their course to the strike of the previously elevated strata. He further observes that here are abundant features which would support the conclusion that granite is in this district rather the result of an excessive amount of metamorphic action than a plutonic rock as regards its origin.¹

In 1869 the Rev. Dr. Joass stated that he was inclined to regard the granites in the Kildonan region as partly intrusive and partly metamorphic. He further noted that in the most richly auriferous localities certain granitoid rocks, chiefly felspathic, are so intimately connected by interlamination with the flaggy quartzose strata that they almost appear to be the result of metamorphic action upon true sedimentary rocks of the quartzose series, or contemporaneous effusions of plutonic rock. This granitiform rock appears at least in one instance to run across the strike of the decomposed gneissose strata.²

¹ 'On the Metamorphic Rocks of the Banffshire Coast, the Scarabins, and a Portion of East Sutherland,' Quart. Journ. Geol. Soc. vol. xviii. p. 331.

² 'Notes on the Sutherland Goldfield,' Quart. Journ. Geol. Soc. vol. xxv. p. 317.

The minute penetration of gneiss, schists and sedimentary deposits altered by contact-metamorphism, by granitic materials in the form of excessively thin folia along the planes of schistosity was first clearly described by Michel-Lévy. In his paper 'Sur l'Origine des Terrains Cristallins Primitifs' he makes the following observations: 'J'ai, le premier, appelé l'attention sur le phénomène de pénétration intime, lit par lit, des roches granitiques et granulitiques éruptives suivant les plans de schistosité des gneiss et des schistes . . . Mais en outre, dans les zones de contact immédiat sur la roche éruptive, le quartz et les feldspaths s'insinuent, lit par lit, entre les feuillets des schistes micacés; on est parti d'un schiste argileux détritique, on le trouve en définitive transformé en un gneiss récent, bien difficile à distinguer des gneiss anciens.'¹

In 1890 Miss Gardiner described some of the contact-phenomena produced by the granite near New Galloway, and showed how the Silurian sediments pass into crystalline schists and gneiss with various contact-minerals at the granite-junction.²

In the same year, while referring to the gneisses of central Aberdeenshire, our colleague Mr. Hinxman states that the granitoid character of the gneiss at certain points is due to the intrusion of granitic material along the planes of foliation.³

In 1893 our colleague Mr. Barrow described in detail the metamorphism produced by an intrusion of muscovite-biotite-gneiss in the South-eastern Highlands. He showed that the normal condition of the intrusive rock is that of a slightly foliated granite with two micas, but with considerable variation as regards structure and composition, the larger masses being more or less fringed with pegmatite. The foliation of the larger masses is rudely parallel to that of the surrounding schists, and though their intrusive nature is therefore not so obvious, it has been proved by detailed mapping that these masses traverse different bands of the schists. The crystalline gneisses and schists with the contact-minerals, sillimanite, cyanite, and staurolite, arranged in zones according to the stages of metamorphism, are held to be due to the intrusion of muscovite-biotite-gneiss.⁴

In 1890 the Geological Survey first broke ground in the east of Sutherland from Melvich as a centre: the coast-line between Strath Halladale and Armadale having been assigned to Mr. Greenly. On the shore at Portskerry he observed minute granitoid folia radiating from the larger granite masses and traversing the granite-like schists. Mr. B. N. Peach mapped the larger sills of acid igneous rock in Strath Halladale and clearly recognized their intrusive character, ascribing the foliation of the granite to dynamic action. In the

¹ Bull. Soc. Géol. France, ser. 3, vol. xvi. (1888) pp. 104, 107.

² 'Contact-Alteration near New Galloway,' Quart. Journ. Geol. Soc. vol. xlv. p. 569.

³ Geol. Surv. Scotl. Explanation of Sheet 76, p. 12.

⁴ 'On an Intrusion of Muscovite-biotite-gneiss in the South-eastern Highlands of Scotland and its Accompanying Metamorphism,' Quart. Journ. Geol. Soc. vol. xlix. p. 330.

same year (1890) Mr. Horne obtained confirmatory evidence of the 'lit par lit' introduction of granitic materials into the crystalline schists south-west of Strath Halladale. In the autumn of 1891 and 1892 Mr. Horne surveyed the coast-section between Kirkatomy and Armadale and the tract extending south-eastward towards the Armadale burn, where there is a group of complex gneisses formed by alternating folia of granitoid materials and granulitic or coarsely granulitic gneisses or schists, recalling some of the Lewisian types between Cape Wrath and Laxford. These phenomena, which seem to have been developed at a later date than granulitic schists of the 'Moine' type, were briefly summarized in the Annual Report of the Geological Survey for 1892.

From the northern coast of Sutherland these intrusive granite-masses and pegmatites have been traced across the county by Forsinard, Kinbrace, and Kildonan to the Ord, Helmsdale, and Upper Strath Brora: Mr. Greenly having mapped the Kinbrace and Kildonan area, and our late colleague, Mr. Hugh Miller, the tract between the Ord and Upper Strath Brora. During 1893-94 Mr. Hugh Miller observed the phenomena resulting from the minute penetration of the eastern schists by granite on an extensive scale in the outlying parts of Rogart and Clyne. His observations in Upper Strath Brora led him to the following conclusions. The structures in the granites and granitic gneisses were supposed by him to be 'to a large extent imitation-structures, due to a simulation of the form and structural features of the country rock (the eastern schist) by granites that have by some means crept into their place. The process by which this replacement has been effected seems to have been a development of crystalline matter among the granulitic materials of the pre-existing schists and quartzites. In the earlier stages of metamorphism the granitic substance has entered or by some means suffused the structure of the stone, appearing first as a fine mottling of granitic particles. In further stages of metamorphism the granitic matter, keeping for the most part to the folia of the pre-existing rock, has increased into knots and knotty strings, has entered planes, slide-planes, and the lines of contortion in the contorted schists, and so thickens into bands and sills at the expense of the original rock, till the latter is represented only by inclusion-planes and ultimately by inclusion-structures. The crystalline matter of the granitic gneisses and granites remains optically complete, and the inclusion-structures and the inclusion-planes everywhere retain the same dip and strike as that of the country rock, not only in Upper Strath Brora, but also in Rogart and wherever present in the granite massifs of Helmsdale and the Ord of Caithness. Parts of these granites are in fact pseudomorphs or granite-casts preserving as replacement-structures remains of the structure of the pre-existing rock.'

II. KIRKTOMY TO ARMADALE.

The various types of crystalline schists with which the granitic rocks are associated in this area may be grouped as follows :—

1. Granulitic schists or gneiss.
2. Biotite-schists and gneiss.
3. Granular gneiss.
4. Hornblende-gneiss or schist.
5. Cipolin group (crystalline limestones containing silicates).

The members of the first two groups display in a remarkable degree the introduction of granitic materials in the form of granitoid folia; thus giving rise to a series of complex gneisses, composed partly of granulitic and partly of granitic constituents. The evidence in the area between Kirkatomy and Armadale seems to point to the conclusion that these constructive processes operated after the formation of certain granulitic schists allied to the type of the 'Moine' schists, and yet the series of complex gneisses recalls some of the features of the Lewisian gneiss between Cape Wrath and Laxford.

The granite occurs in the form of branching sills, veins, and minute folia, penetrating the schists and gneiss along the planes of foliation, and in places it merges into massive pegmatite. It is usually foliated, the foliation being parallel to that of the schists, though in some instances it is clearly transgressive.

The essential constituents of the granitoid rocks are orthoclase, oligoclase, quartz, and biotite. A specimen of gneissose granite, taken from the shore at the edge of the outlier of Old Red Sandstone, $\frac{1}{2}$ mile north of Kirkatomy, shows under the microscope orthoclase, oligoclase, quartz, and biotite, with apatite and zircon as accessories.¹ Both feldspars occur as allotriomorphic grains, but there are occasional signs that oligoclase may be idiomorphic with respect to an untwinned feldspar which is presumably orthoclase. Here and there indications of a micropegmatitic intergrowth of quartz and feldspar may be observed. The biotite does not occur as a rule in the form of detached plates, but usually in aggregates of several individuals which mutually interfere with each other. In a specimen of granitoid gneiss between Kirkatomy Point and Geodh na Muice muscovite occurs, though not in any great abundance, together with biotite, orthoclase, oligoclase, and quartz. These foliated granites and granitic gneisses are well displayed in the massive form between Kirkatomy Point and Pollsain, about $\frac{1}{2}$ mile east of the headland.

The granitoid folia, alternating with folia of granulitic schists and biotite-gneiss, may be studied near Kirkatomy Point and about a mile to the east near Poulouriscaig. Their constituents resemble those of the larger veins and sills, with the exception that biotite

¹ Microscopic sections of rocks from the Kirkatomy area have been examined by Mr. J. J. H. Teall, M.A., F.R.S., who supplied notes on the various rock-specimens and sections.

is sparingly developed. They contain orthoclase, oligoclase, quartz, and occasionally biotite. Indeed, the remarkable feature of the granitoid rocks as a whole, both in the case of the larger masses and in the granitoid folia, is the abundance of oligoclase. A specimen taken from a locality about 100 yards from the edge of the cliff S.S.E. of Kirkatomy Point, in which the granite-bands can be seen cutting across the folia of the darker granulitic rock, shows under the microscope that the granitic bands consist of quartz, oligoclase, and orthoclase, with garnet and apatite as accessories. So minute are these layers of granitic materials that in some instances they do not exceed $\frac{1}{4}$ inch in breadth: and hence in a specimen, say a foot across, there may be several granitoid bands alternating with layers rich in biotite or with granulitic bands containing quartz, felspar, and mica. It is further observable that the granitoid folia follow the various folds, and even the minute puckerings of the biotite-gneiss and the granulitic gneiss, without any apparent crushing or deformation of the constituents. The size of the grains does not vary with reference to the margin of the band, and there is no trace of chilled margins. Still more noteworthy is the fact that along the junction-line separating the granitoid from the other folia the minerals interlock just as they do in the interior of the different folia.

It is obvious that these phenomena do not resemble those of an igneous rock penetrating pre-existing strata along cracks and fissures where chilled margins may be readily detected. Indeed, an unbiased observer would almost infer at first sight that the granitoid bands are not in reality later than the gneisses and schists which they traverse. But in many excellent sections the quartzo-felspathic folia, which are identical in structure and composition with the quartzo-felspathic portions of the larger granite-masses, can be seen branching from the latter and following the contorted foliation-planes of the pre-existing strata. It seems reasonable to infer, therefore, that these igneous materials were introduced when earth-movements were in progress and when the pre-existing rocks were at a high temperature.

Throughout the area, numerous lenticles of granulitic schist occur as isolated masses in the foliated granite, the foliation of the schist being parallel to that of the granite. An excellent example is met with on the shore south of Uamh Dhom near Pollsain, east of Kirkatomy Point. Here small lenticles of highly siliceous schist of the 'Moine' type occur, with the planes of schistosity parallel to that of the granite. This instance further shows minute granitoid folia branching from the main mass and traversing the foliation-planes of the inclusions of granulitic gneiss. Under the microscope this siliceous schist or gneiss is composed of quartz, felspar, and biotite, with garnet as an accessory. Some of the quartz occurs as irregular patches.

In the belt of garnetiferous biotite-schist or gneiss extending southward from Kirkatomy Bay to Creag Meadie, foliated granite and pegmatite occur as lenticular masses varying from a few feet

to several yards or more in length. Their constituents resemble those of the larger veins and sills already described. Immediately to the west Mr. Peach has traced a great series of thin sills of foliated granite traversing the biotite-schist and granulitic gneiss.

Where the granitoid rocks traverse the biotite-schist or gneiss on the moor about 2 miles south of Armadale, the contact-mineral sillimanite was observed in the latter, associated with the biotite. This mineral was likewise found in an inclusion of biotite-gneiss in a granite-vein. The occurrence of the quartz in the biotite-gneisses in large, almost ophitic patches may also point to contact-metamorphism—if we may judge from an instance of the change produced in siliceous gneiss at the point of contact with an intrusive mass of augite-biotite-diorite at Sandside, Reay, in Caithness.

The foliated granite and the complex of gneisses between Kirkatomy and Armadale are traversed by veins of pink microgranite, which, so far as observation goes, are never foliated. These veins probably represent the last phase of igneous activity, which culminated in the introduction of the broad sills of foliated granite.

Reference may now be made to some of the other groups of crystalline schists represented in the area under consideration.

Group 4, composed of hornblende-gneiss or schist, is likewise traversed by gneissoid granite and pegmatite. It occurs in lenticular bands or masses, which are represented on the eastern side of Kirkatomy Bay, and on the moor to the south-east. A specimen from the eastern cliff of Geodh Acrah, $\frac{1}{2}$ mile north of Kirkatomy, examined under the microscope by Mr. Teall, shows felspar, mostly striated, quartz, and green hornblende, with biotite and sphene as accessories. The three principal constituents occur for the most part as allotriomorphic grains. Now and then the quartz appears to form inclusions in the felspar and hornblende. The microstructure is granitic, not granulitic. Mr. Teall adds that there is no doubt a close resemblance between this rock and basic portions of the Lewisian Gneiss occurring between Laxford and Cape Wrath.

The granular gneiss (group 3), which extends from Armadale Bay westward for a distance of $\frac{3}{4}$ mile, is a rather fine-grained granular rock, containing quartz, felspar (including oligoclase), biotite, and sometimes hornblende. This group is associated with highly quartzose schists or gneiss, with magnetite in well-formed octahedra.

The Cipolin group (no. 5) is in some respects the most interesting of this series. The rocks included in this group are exposed in a burn draining into the sea, about $\frac{3}{4}$ mile W.N.W. of the village of Armadale. In the lower part of its course, where it flows through a rocky gorge, a band of crystalline limestone is exposed at the base of the cliff. One specimen from this locality has been named by Mr. Teall a banded cipolin, one band being mainly composed of crystalline calcite. Under the microscope it shows scapolite, calcite, quartz, a pale green pyroxene, and sphene. Scapolite is the most abundant mineral in that portion of the rock from which the

section is taken. The principal constituents occur in allotriomorphic grains.

The crystalline limestone is associated with a green crystalline granular rock, composed mainly of allotriomorphic grains of pale green pyroxene (omphacite), with altered scapolite, sphene, and pyrite. Along the strike of these rocks, on the sea-cliff at the mouth of the stream, flaggy hornblende-schist with omphacite is exposed; and in the walls of the gorge flaggy biotite-gneiss occurs with felspar (including oligoclase), quartz, and biotite. Apatite, zircon, and garnet appear as accessories. The foregoing series is pierced by veins of pink microgranite and pegmatite.

While in the foregoing pages we have adduced evidence suggesting a close relation between the granitoid folia of the complex gneisses and the foliated granites, it ought to be frankly admitted that there is a striking resemblance between the mineralogical constituents of the granulitic biotite-gneiss and the granitic gneiss.

III. PORTSKERRY TO ARMADALE.

The crystalline schists into which, in this region, the granitoid rocks have been introduced are of three types:—

1. Granulitic, seen on the coast from Portskerry to Baligal.
2. Wavy biotite-gneiss. On the coast this is concealed by the Old Red Sandstone of Baligal; but it is well exposed on the hills about Beinn Ruadh and Bowside.
3. Granular gneiss of Strathy Point.

The granulitic type is an ordinary fine-grained flaggy schist, composed of quartz, felspar, and biotite, arranged in a mosaic. No traces of clastic structure can be seen, but the rock is very quartzose.

The second type is a highly crystalline gneiss composed of felspar (chiefly oligoclase), quartz, and large wavy flakes of very black mica. It will be described in more detail in the section devoted to the Kinbrace area.

The 'granular' gneiss is an even, medium-grained rock, also composed of striated felspar, quartz, and biotite; but of an exceptional crystalline type, allied to the granulitic, the constituents, however, being on a scale too large for it to be described by that name. Seams of both the other types occur in it, and also peculiar quartzose schists rich in idiomorphic magnetite.

The granitoid rocks are composed of quartz, felspar, and biotite. The felspar is chiefly oligoclase, but those in the eastern part of the area (Portskerry) contain also porphyritic orthoclase.

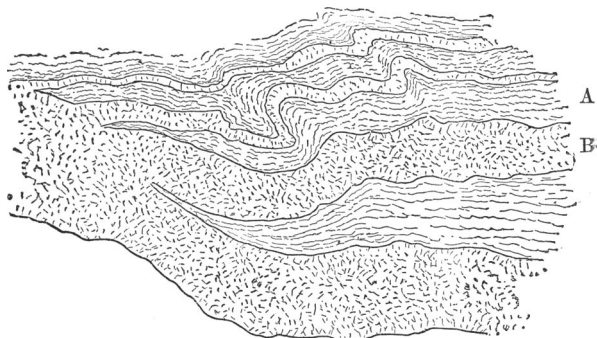
Basic rocks (amphibolites and hornblende-schists) also occur. Their relations are not perfectly clear, but need not be dealt with in this paper.

In all the schists the granites occur as anastomosing lenticular sills. They are exceedingly numerous, even those large enough to

be mapped occupying about one-third of the surface in the well-exposed parts, while the smaller outcrops are innumerable.

The relations to the various types of schists are slightly different. The gneisses and the granulitic rocks, however intimately inter-banded, are sharply distinguished from each other. The cliffs of Portskerry display a strongly banded series (fig. 1), composed of rapid

Fig. 1.—*Gneisso-granitic complex, Rudha Ghoidh, Portskerry.*



A = Gneiss.

B = Granite.

The granite is slightly foliated.

alternations of grey granulitic schist and pink granite, with here and there lenticular sills of foliated porphyritic granite from 2 to 3 yards thick. The thin bands are true veins, for though at first sight conformable with the gneiss, they can be proved to truncate its folia and to anastomose. Of their connexion with the granites there can be no doubt, for the whole series is traversed by precisely similar veins at right angles, which can be seen to be continuous with some of the bands, while cutting others. These veins usually lie along planes of dislocation which fault many of the granite-bands, but these old faults are completely 'healed up,' the crystals interlocking along them, and there being no sign of cataclastic structure.

With regard to foliation :

1. The granite is almost always foliated, the structure being marked out, not only by the orientation of the mica-flakes, but by that of the porphyritic feldspars. Sometimes there are feldspar 'augen,' and even bands, the whole mass being there very complex. But generally the feldspars are angular, and even zonal.
2. The foliation usually follows the cheeks of the sill or vein. Sometimes it is discordant to that of the schist ; sometimes it folds rapidly, without the sill folding as a whole ; and again here and there, though rarely, a foliation parallel to that of the schist appears to pass through a vein. Finally, in the

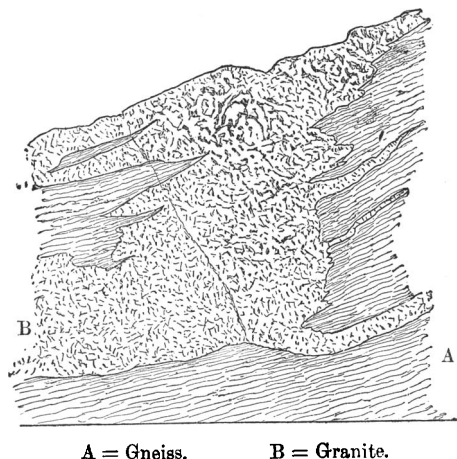
ends of a sill are sometimes seams of biotite whose flakes have the peculiar oblique orientation which they possess in the gneiss.

There are no chilled edges; the margins, indeed, are often fringed with pegmatite; while the thinnest seams are wholly pegmatite.

In the granular gneiss of Strathy Point, the relations of the granite are more intimate. The granites differ slightly in character, as well, porphyritic feldspars not being developed. There is an absence of the parallel interbanding that is so marked at Portserry, the small sills being lenticular, like the large ones. The sills are extremely irregular in form; they sometimes run right across the gneissic folia for 20 or 30 feet, inosculating, however, along the edges. In and near the basic rocks of Armadale Bay there is an amazing development of highly complex veining, though sills are also common. But most important are the apparent passages between gneiss and granite. Sometimes a sill will have distinct transgressive junctions on one side, while on the other it is difficult to decide where the boundary shall be drawn.

The behaviour of the granular gneiss is singular. Throughout the Point the coarse granitoid rock cuts it; and yet here and there it appears itself to give off veins, and cut granulitic and basic rocks. Indeed, this 'granular' gneiss is the most perplexing of all the types. Very likely it includes rocks of various nature and origin.

Fig. 2.—Part of base of great sill, Strathy Bay.



There is a faint foliation in the granite, rudely parallel to that of the gneiss.

On the cliffs of Glas Eilean and Boursa Cove, magnificent sections, 250 feet high, expose the internal structure of the great sills. They are highly complex synthetic gneisses, consisting of foliated granite,

full of inclusions of all sizes, up to 100 feet long, round and between which the granite passes in gently undulating curves, retaining its own independent foliation, which often truncates that of the inclusions.

In Strathy Bay sills of very massive grey rock, with clear fresh oligoclase and a beautiful waxy lustre, are seen. The junctions are perfectly exposed, showing forms intermediate between sills and dykes (fig. 2, p. 641). Within this mass granites indistinguishable in hand-specimens can be seen to vein each other, both rocks being independently foliated.

Both at Strathy and Portskerry, the whole foliated series is traversed by dykes of pink microgranite. They are unfoliated, and, though compact, have no chilled edges. They cut all the other rocks very sharply.

IV. KINBRACE AND KILDONAN AREA.

Although the exposures in this district are far less complete than those on the northern coast, they have especial interest, because the less altered condition of the rocks at Kildonan allows us to see that some, at any rate, of the crystalline schists into which the granites have been introduced must be of sedimentary origin.

The following groups or types can be distinguished:—

1. Quartz-schist.
2. Granulitic biotite-schist.
3. Wavy mica-schist.

All these are truly crystalline schists, composed of interlocking minerals; the structure of Nos. 1 and 2 being that of a granulitic mosaic.

There can, however, be no doubt that No. 1, at any rate, is a highly altered quartz-felspar grit. Not only are clastic grains clearly recognizable in certain parts, but the highly quartzose character, maintained over a large area, makes its sedimentary origin practically certain. There are always some felspar and white mica, and seams of iron ores are a characteristic feature.

Group 2 resembles the granulitic schist of Portskerry, differing only in that a few bands contain muscovite as well as biotite. But its relations to the quartz-schist throw light on its origin. Not only do seams of Group 2 occur constantly within the main mass of Group 1, but the main masses of each always pass one into another through a series of alternations in such a way as to leave little doubt of their common origin. The boundaries on the map are, indeed, quite arbitrary, and it is often difficult to decide how to colour the intermediate types.

Group 3 is different in texture. It is a very wavy foliated schist, composed of both micas, quartz, and felspar (sometimes certainly oligoclase). The micas are much larger than in the granulitic rocks, and the biotite is a deep brown ferruginous variety. Garnet and sillimanite are generally present. The sillimanite is usually in the mica, but sometimes in quartz (*Faserkiesel*). This group passes

into Group 2 in the same way as that does into Group 1. From this, and from the abundance of sillimanite, it seems reasonable to infer that it also is of sedimentary origin. Seams of quartz-schist occur within it.

Granites occur in all these rocks as veins and sills. Those in the quartz-schist are red pegmatitic-looking veins, composed of oligoclase, microcline, quartz, and muscovite; while those in the other schists about Suisgill contain biotite and very little muscovite, their felspar being (so far as determined) oligoclase, and sometimes probably natron-orthose. All these rocks have sharply-defined margins, and are hardly ever foliated.

Groups 1, 2, 3 follow in order north-westward from Kildonan, till, about Borrobol, a large mass of Group 2 comes in again. When we approach the north-western margin of this, we find that a change has set in. The granites, which hitherto have not been very numerous, now appear in great numbers, and 'injected lit par lit,' as well as along old faults, now completely healed up by interlocking crystallization, just as on the coast of Portskerry, forming with the granulitic schists a 'synthetic gneiss.' A little distance farther on, however, we leave the granulitic type, and enter a tract of coarse, wavy, highly crystalline gneiss, like that of Bowside near the northern coast. It is composed of quartz, felspar, and very black mica (often olive-green by transmitted light). The felspars are large and well striated. They are chiefly oligoclase, but albite and orthoclase also occur. Garnet is not uncommon, and sillimanite occurs locally, sometimes most beautifully crystallized.¹

In spite of the coarsely crystalline texture of this rock, especially the large size of its beautiful striated felspars, there is a general resemblance in structure to the wavy mica-schists of Suisgill, and in places it could not be distinguished from these; and I am inclined to believe that, although it may contain other material as well which has not yet been separated, nevertheless the greater part of it is the Suisgill mica-schist in a more highly crystalline condition. It occupies a very large area, extending, with only one interruption of $1\frac{1}{2}$ mile of granulitic gneiss, across the strike, all the way to the Naver.

Now it is in this rock that the most wonderful granitic intrusions occur. The phenomena so clearly seen in the cliffs of Strathly Point are here repeated in their highest intensity. Great sills of granitoid rocks, often a mile in width, range for miles along the country, and every gradation exists between these and the very thinnest bands and seams.

The felspars of these granites are in all cases so far determined oligoclase, often inclining to andesine, except certain porphyritic crystals of rather rare occurrence, which are natron-orthose. Albite and microcline occur in some small pegmatites. The large porphyritic crystals only are idiomorphic, the rest having the form called by

¹ These and other minerals were determined during field-work from crushed fragments under the microscope; laboratory tests being used afterwards, for confirmation in doubtful cases.

Mr. Barrow 'round-grained,' whether in foliated or unfoliated rocks. The micas are almost always biotite, muscovite being very rare.

Most of the sills are full of inclusions, the smaller sills behaving in every respect like the largest. There are no chilled edges whatsoever.

The junctions are of three kinds :—

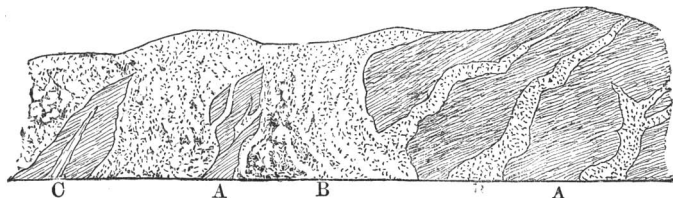
- (a) 'Lit par lit' injection of a kind more subtle still than that where we see parallel beds of schist and granite, for the margins of a sill fade off into the gneiss through a series of thinner and thinner lenticles.
- (b) The ends of a sill fading off into the gneiss by a dovetailing of biotitic folia into the granite.
- (c) True transgressive junctions, where the granite truncates the folia of the biotite-gneiss.

All these three types can be seen in one and the same sill.

Finally, large masses occur in which these relations are carried to such a degree of intimacy as to render it very difficult to decide whether to regard them as granite or as gneiss, difficult even to produce a consistent map, all lines being wholly arbitrary.

The granites are for the most part foliated, the foliation being generally, as on the northern coast, parallel both to that of the gneiss and to the sides of the sill. Cases, however, occur of transgressive junctions where the foliation of the granite follows the cheeks of the sill or dyke, and so truncates that of the gneiss (fig. 3). Foliated granitoid rocks can also be seen to truncate each other, as in Strathy Bay.

Fig. 3.—*Foliated granite and biotite-gneiss, southern bank of Allt Tom na Bradh, Kinbrace.*



[Length of section = about 27 feet.]

A = Biotite-gneiss.

B = Granite.

Note.—By an error of the draughtsman, the thin dyke of granite (O) at the left end of the above section has been 'shaded' with lines parallel to the sides of the dyke, instead of lines at right angles to the sides.

The intimate relations here described do not exist in Kildonan. The granites there are not only smaller and fewer in number, but they have well-defined margins. As we pass north-westward they increase, but even in the wavy mica-schists at Suisgill every dyke and sill is sharply separated from the country rock. The inter-

felting and amalgamation come on only in the Kinbrace gneisses. It is clear, therefore, that even allowing that the structure of the wavy mica-schists may have been favourable to these types of injection, the following phenomena are coincident:—

- α. Increase in quantity of granite.
- β. Intimacy of relation.
- γ. Increase of coarseness of crystalline texture in the schists.
- δ. Appearance and perfection of crystallization of sillimanite.

V. SUMMARY AND CONCLUSIONS.

The foregoing facts suggest important considerations with regard to the nature of intrusion, foliation, and metamorphism.

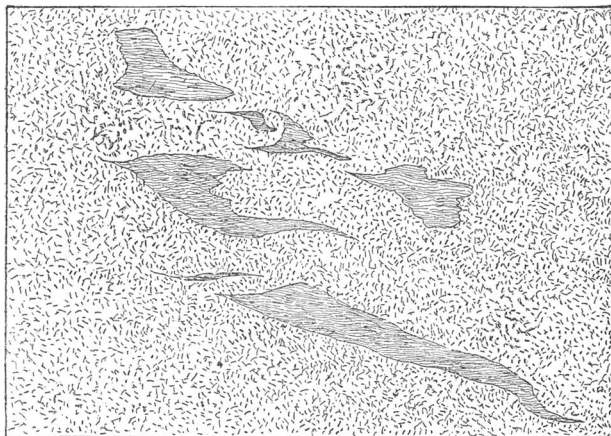
It is certain that sedimentary rocks enter into the crystalline complex, but igneous 'contact' in the ordinary sense cannot be held to be the sole cause of the regional metamorphism. For schists closely resembling some of these (especially Group 2 of Kildonan) cover large areas in which no granite is to be seen (see the description of the schists above the Moine Thrust-plane in Geol. Surv. Report on N.W. Highlands, Quart. Journ. Geol. Soc. vol. xlv. 1888, p. 378). The whole series, however, is powerfully folded, and can be shown to have been subjected to shearing stresses, which perhaps points to the initial cause of metamorphism. That the granitic injections were closely associated with the metamorphic processes we have little doubt; but it appears probable that they found the schists already crystalline.

What part 'contact-metamorphism' actually played is not perfectly clear. It is true that as we pass from Kildonan, where granites are small and few, to Kinbrace, where they are numerous and large, we do find what has generally been called a 'progressive metamorphism' in all rocks which could be expected to show it; that the intrusive relations at the same time become more and more intimate; and that sillimanite appears as we pass in, and is most beautifully crystallized in the final stages. From which it seems reasonable to infer that the cause which brought about the introduction of the granite also resulted in these high and peculiar types of crystallization.

Of foliation in the granites there are several conceivable causes. Many of the parallel structures are certainly the remains of biotite-folia belonging to gneisses whose quartzo-felspathic elements have been incorporated with those of the granite, for every gradation can be traced from inclusions retaining their natural orientation (fig. 4, p. 646) down to the merest trains of mica-flakes. Probably much of the foliation is of this nature, at any rate where the gneisses lent themselves readily to it. But neither this nor dynamo-metamorphism can always be appealed to. The numerous cases where the foliation of the granites can be seen to truncate that of the gneiss must be borne in mind. How difficult it would be to distinguish this from the other structure in cases where transgressive junctions cannot be observed, the margins consisting of ranges of lenticles!

The orientation of the porphyritic felspars in the granites of Portskerry, again, can hardly be other than a truly igneous structure; also the phenomenon of foliated granites cutting each other's foliation.

Fig. 4.—*Inclusions of hornblende-schist in foliated granite, Altiphurst, Strathy Point.*



[Area represented = about 8 square feet.]

Introduction of granite was without doubt the final term in the production of the gneissose complex, but everything points to that process having been long and elaborate. Single sections, even, can be seen showing schists powerfully folded, foliated veins intruded, the whole faulted, and new and complex veins introduced (figs. 5 & 6). It is clear that movement must have continued, or recurred from time to time, from the very first glimpse we get of the metamorphic process till nearly its close, for all veins except the microgranites are cut by faults which are completely 'healed up' by crystallization.

But it is also clear that the whole mass must have remained at a high temperature till the very last, not only from the last quoted fact, but from the absence of any chilled edges whatever, even to these microgranites, which cut every other rock sharply, and are the last members of the whole crystalline series.

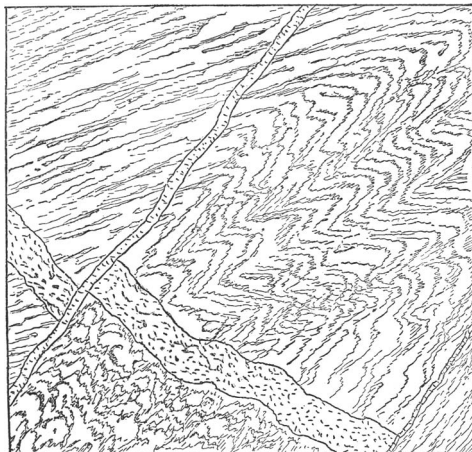
If, therefore, the rocks ever passed through a stage of mere mechanical crushing as a result of these movements (and of this the sections observed afford no evidence), such cataclastic structures have been wholly effaced during the later stages of metamorphism.

The evidence of powerful movement which these schists everywhere present certainly suggests that such movement was the initial cause of the whole series of phenomena.

With regard to the granites, it is difficult to believe that they are wholly foreign matter; though here it is necessary to observe the utmost caution, the chemical difficulties being so great.

In all probability, we must wait for satisfactory solutions of these

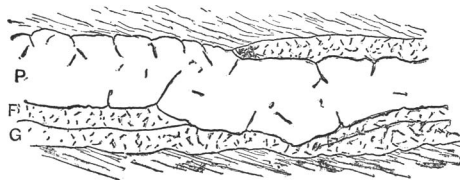
Fig. 5.—*Veins of granite and pegmatite in hornblende-schist, north-eastern corner of Armadale Bay.*



[Face of cliff = about 4 feet square.]

and other problems in metamorphism until much more is known of the behaviour of the compounds of silicon under high temperature and pressure. The chemical analogies between silicon and carbon are known to be close, but whereas the carbon compounds are

Fig. 6.—*Details of the smaller vein in fig. 5.*



P = Pegmatite.

F G = Foliated granite.

singularly tractable under conditions attainable in experiment, those of silicon are as strikingly intractable. It is not unreasonable to suppose that the silicon atom may have powers of forming groups and compound radicals comparable to those of the carbon atom,

giving rise to similar series of Protean changes¹; but that these powers are exerted only under conditions which, as yet, preclude experimental investigation. If we consider, however, what amazing results have followed the successful investigation of such a series as C_nH_{2n+2} , for example, it may well give us pause to reflect on what may happen under conditions which set the silicon atom also free to move.

Let us hope that the door to further knowledge of these matters may not always remain closed, though of its opening there is yet no sign.

Meanwhile the facts described render certain :

1. The existence of relations between granites and crystalline schists so intimate as to amalgamate the two rocks into one gneissose complex.
2. That in such regions the schists become more coarsely crystalline than they are elsewhere.
3. That some of these schists are of sedimentary origin, and that aluminous silicates abound in the most highly crystalline varieties.
4. That the foliated structures in the granites are assignable to at least two modes of origin.
5. That, in spite of powerful earth-movements, there is a general absence of cataclastic structure.

DISCUSSION.

Sir ARCHIBALD GEIKIE remarked that it was curious to see how the oscillations of geological theory were reviving the views formerly held, but more recently abandoned, as to the metamorphic origin of some granites. The Authors of the record of careful observations contained in this paper were cautious in drawing deductions, but it was obvious that they were disposed to believe that the granite described by them, though an eruptive rock, had assimilated the surrounding schists and was not separated from them by any sharply-defined differences of composition or structure. Their work ran on lines closely parallel to that of the French Geological Survey under M. Michel-Lévy. They were evidently dealing with the same class of phenomena that had been so closely studied in the Plateau Central of France. A new line of research had in recent years been opened up by the study of the intimate blending of granitic laminæ with granulitic and other schists, and though it was still perhaps too early to formulate a definite theory, a marked advance had been made towards a comprehension of the conditions under which granitic intrusions and regional metamorphism are linked together.

Gen. McMAHON congratulated the Authors on their interesting paper, and concurred with them in their main conclusions. He

¹ It is not meant that 'hydrosilicons' play the part of the hydrocarbons, but merely to suggest how much we may have yet to learn regarding silicon.

was interested to see a large specimen on the table illustrating the fine-grained injection of a rock by granite in thin parallel veins, as it closely resembled Prof. Bonney's 'granulitic series' at the Lizard, for which the speaker, in his first paper on that region, had suggested a similar origin. He felt some difficulty in criticizing the paper on one or two points. The Authors suggested that the 'initial' metamorphism of the schists into which the granite had intruded was 'perhaps' due to 'shearing stresses'; but the paper, as read, did not disclose any evidence to prove this contention. The hypothesis might or might not be true, but he was not prepared to accept it without sufficient evidence. The metamorphism might be anterior or posterior to the shearing.

As regards the last point in the paper, the Authors said that the granite was intrusive, but suggested that it was itself a product of the metamorphism of the schists. As the Authors had not attempted to unfold this theory, it would be idle to attempt to criticize it. He would only remark that granite contained highly heated steam, or water, under great pressure, charged with the mineral matter of the granite, and as this solution penetrated into the rocks in contact with the granite, they became impregnated with the minerals of the granite, and might thus appear to blend into granite.

Mr. TEALL said that the Authors had clearly proved that 'lit par lit' injection and other allied phenomena occurred on an extensive scale in the area in question; but they wisely refrained from speaking as if they had solved all the problems connected with the origin of the schists of the district. It was a curious fact that in several areas granitic rocks were found to be intrusive into gneissose rocks which closely resembled them in mineralogical composition.

Speaking on the subject of dynamic metamorphism, he remarked that the rocks into which the granitic magma had been intruded gave abundant evidence of having been folded and sheared—they must at one time have been, so to speak, alive with movement—and he doubted whether a single cubic inch could be found which had not suffered deformation. At the same time the crystalline grains were not fractured, so that crystallization must have taken place during or after the movement. Some critics would apply the theory of dynamic metamorphism only to those rocks which now possessed cataclastic structures; but this limitation had never been contemplated or accepted by those who were mainly responsible for its introduction.

Prof. JOHNSTON-LAVIS remarked that the evidence offered by the Authors as to the high temperature of the matrix-rocks into which the granite was injected probably inferred also a comparatively plastic state, which would favour the extraordinarily complicated ribbon-and-vein structure so characteristic of such regions. High temperature and the approach to fluidity of materials are, as is well known, conditions most favourable to chemical interchange and osmotic diffusion, which are further increased by diversity of chemical composition of the matrix and the injected material and by the affinities between the elements of the one and the other. The

tendency will be, by chemical interchange and osmotic action, to bring the intrusive rocks and those into which they are intruded more and more to resemble each other. Granite in small veins, dykes, and sills can have been formed only in a very hot matrix, in which heat would remain during long periods of time—conditions most favourable to the extensive physico-chemical changes of the intrusive and the intruded rocks. The Authors show how much material of the granite has been derived from the matrix of the intrusions, and we must also consider the loss of components from the granite to the advantage of the matrix. Notwithstanding such evidence as this, and much more of the same nature, a large school of geologists persist in referring all the variations in igneous rocks to internal differentiation and ignore chemical and physical osmosis.

The PRESIDENT also spoke.

Mr. GREENLY, in reply, adduced cases where lenticles of granite occurring in the schists could not be seen to have any communication with any other granite-masses. These supported the view that the granite might not be wholly foreign matter. Referring to remarks by Gen. McMahon and Mr. Teall, he had never yet seen any region of crystalline schists in which there was not abundant evidence of intense earth-movement and deformation. This seemed a fact of the first importance in the study of these rocks. But the time was probably still far distant when it would be possible to generalize concerning them without considerable reserve. He much regretted the absence of Mr. Horne.