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On an Intrusion of Muscovite-biotite Gneiss in the South-eastern Highlands of Scotland, and its accompanying Metamorphism

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Notes

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[Plates XV. & XVI.]

Contents.

I. Introduction.

The area to which attention is directed in the following pages lies in the north-eastern corner of Forfarshire, and forms part of the singularly flat table-land of the South-eastern Highlands. It is essentially a moorland district, much covered with peat and heather, and is drained by two rivers, the North Esk and the South Esk. The rocks of which the area is composed consist principally of gneisses and schists; these are clearly seen in the craggy sides of the valleys through which the two Esks and their tributaries flow. Boulders of these rocks may be noticed in the rough walls by the roadside as one drives up the glens, and their intensely crystalline aspect is a most striking feature. A brief visit to the crags and the flat-topped moorland speedily convinces the observer that this crystalline aspect is one of the chief characteristics of the district. It is proposed to show in the present communication that this area contains several masses of intrusive rock which are probably connected underground, and that the highly crystalline character of the surrounding schists is mainly the result of thermometamorphism.

II. Distribution and Mode of Occurrence of the Igneous Rocks.

The normal condition of the intrusive rock is that of a slightly foliated granite, with two micas; but there are considerable variations from this type, both as regards structure and composition, as will be seen from the detailed descriptions that follow. It is met with in masses which vary greatly in size, and the larger of these are more or less fringed with pegmatite, veins of which cut the schists in every direction. In one part of the area the gneiss occurs as thin bands, permeating the other rocks, and any crag- or scar-face will show clearly its intrusive nature. The foliation of the larger masses is rudely parallel to that of the surrounding schists, and their intrusive nature is not so obvious; but it is proved by detailed mapping, for these masses traverse different bands of the schists, the latter ending off against the igneous rock much in the same manner as in any ordinary case of intrusion.

The great crags at the head of Glen Clova are seen to be more or less permeated by small tongues or thin bands of a grey gneiss. In some cases this intrusive rock nearly equals in total bulk the surrounding metamorphic rocks, and to the district in which this is the case we have applied the term 'permeation-area.' This area commences at the north-western end of Glen Clova and stretches in a north-easterly direction for about 6 miles, No. 1 in the Map, Pl. XV. No strict boundary can be drawn to such an area, for, especially at its north-eastern end, it tails away by a continual decrease in the number of small intrusions, and consequently in the proportion of igneous material to the surrounding rocks.

Some distance to the south-east of this area the intrusion is met with again as a distinctly foliated granite. It is no longer minutely subdivided, but forms rather a continuous mass with many inclusions. The two types of igneous rock are connected by a narrow band, in which the decreasing proportion of the surrounding schists and the thickening of the separate intrusions may be fairly well made out, in spite of the covering of peat.

The mass (No. 2 in the Map, Pl. XV.) which is thus connected with the permeating gneiss is, on the whole, much less foliated and weathers more like a granite, especially towards its edges. Inclusions are more numerous on the western than on the eastern side, the latter edge being often fringed with pegmatite.

The next mass (No. 3 in the Map) is very irregular in shape. The appearance of the rock of which it is composed is that of a slightly foliated granite; but the most marked feature of the mass is the enormous fringe of pegmatite on its southern and eastern edges. There is also a slight fringe on the other edges.

Another outcrop (No. 4 in the Map) forms part of the high ground drained by the eastern branch of Rottal Burn. The foliation is always slight, and the rock passes insensibly on its south-eastern margin into a mass of aplite. Of the two masses shown in the Map on the western side of Glen Clova, No. 5 is identical with No. 3; while No. 6 is an inextricably-confused mass of foliated granite, pegmatite, and inclusions.

There are in the North Esk area, that is, north and east of these larger masses, many smaller patches of gneiss, granite, and pegmatite. The gneissose structure, never so well seen as in the permeation-area, is developed only when the outcrops have a breadth of 100 yards or more, and in all the more easterly patches the foliation is not easily seen in a hand-specimen. These small patches are, however, invariably accompanied by a fringe of pegmatite, which occurs in large masses. In the neighbourhood of Millden the intrusion is represented solely by large masses of pegmatite.

Thus it appears that the intrusive rock is most gneissose in the north-western portion of the area, and that, as we proceed towards the south-east, the gneissose character is gradually lost, while the amount of pegmatite is seen to increase until at last it occurs as isolated masses, and thus becomes the sole representative of the intrusion in that area. It must not be supposed that these isolated pegmatites are restricted to this district. Starting from the South Esk, they may be met with at intervals at least as far west as Pitlochry; and they are well known also on the east coast, a few miles north of Stonehaven.

III. Petrological Characters of the Igneous Rocks.

The gneiss of the permeation-area, when unweathered, has a grey colour. On a surface cut at right angles to the foliation, the felspars are seen to be somewhat rounded or pointed-elliptical in shape. A section made from a specimen taken from the head of the Lee Water shows the following features (4557 A)[1] :—It is composed of quartz, felspar, muscovite, and biotite. The lenticular crystals of felspar are mostly plagioclase (usually oligoclase); there is no microcline, and it is doubtful whether there is any orthoclase. A feature in the plagioclase is the very irregular way in which the polysynthetic twinning is rendered visible under crossed nicols. Part of a lenticle may show none, while in another portion of the same individual it is well marked; moreover, part of a crystal may be water-clear, while the rest is more or less clouded. The micas do not show any definite form, and the brown mica is not much less in amount than the white. The former contains numerous inclusions of small zircons, with marked pleochroic halos, and irregular patches of garnet, with a very fissured appearance. Apatite-inclusions appear to be totally absent. The areas of quartz, of which there is a considerable amount, break up under crossed nicols into small, irregularly-shaped patches with a tendency to undulose extinction. Small allotriomorphic garnets are scattered throughout the slide.

The aspect of the different minerals of the gneiss under the microscope suggests that the crystals of earlier consolidation underwent an appreciable amount of comminution; for, on the whole, they distinctly differ in size and shape from those seen where the intrusions are more or less massive. But there is no evidence of crushing after consolidation.

Thus it appears that in this area plagioclase is the dominant felspar; microcline is absent; and the white mica is about equal in quantity to the brown.

In the second area, where the intrusions are thicker, a slide

[1] The numbers of slides, referred to throughout this paper, are those of the slides preserved in the Museum of Practical Geology, Jermyn Street.

(4557) from a specimen taken near the western side of the mass shows the following characters:—The rock is a fine-grained, granitoid gneiss, composed of quartz, plagioclase, a little orthoclase (?), and two micas. There is no microcline. Its structure is more like that of a normal granite than the last. The plagioclase does not show the lenticular form, but is rather rounded in outline. The micas are in distinctly thicker flakes, especially the muscovite, which shows a tendency to idiomorphism. The dark-bordered inclusions in the biotite are hardly so numerous and are extremely small, still some can be clearly made out to be zircon. Irregular grains of garnet are also met with. There are no apatite-inclusions. The quartz fits into the rest of the rock as in a granite. A point of special importance is the occurrence of micropegmatite. The rock is essentially a foliated granite, and the foliation is even less marked under the microscope than in the hand-specimen. Several slides have been cut from this mass and they are mostly similar to the above. On approaching the eastern edge the rock has rather a pink tinge, and after one has crushed up a number of fragments it becomes clear that this part of the foliated granite contains a considerable amount of microcline, a mineral hitherto absent. It has already been stated that pegmatite, in which the bulk of the felspar is microcline, is often largely developed here.

The points in which this area differs from the former may therefore be summarized as follows:—White mica is more abundant than brown; micropegmatite occurs throughout; the structure is more granitic, and microcline begins to appear near the edges of the mass.

The third mass varies considerably in character. Small portions of the central and west-central parts, where the outcrop is broad, closely resemble the area last described; but the main mass has a different character, well represented by a specimen (4234) from the eastern side of Ben Tirran. It is composed of quartz, oligoclase, orthoclase (?), microcline, muscovite, and biotite. The quartz contains 'hairs,' and inclusions with bubbles. The 'hairs' may occasionally be seen crossing the junction of two quartz-grains without interruption or distortion. Zircon occurs as an accessory. Some of the oligoclase shows fairly well-marked zonal banding. This felspar and microcline are roughly equal in amount. The white micas are usually much larger than the brown. Inclusions of zircon and garnet occur only in a few crystals of biotite; the smaller individuals, which much predominate, usually contain none. Towards the edge of the intrusion a further increase of potash-felspar takes place. Thus a specimen from a point about a mile south-east of Loch Brandy (4232) is composed of microcline, oligoclase, quartz, muscovite, and biotite. This is distinctly less foliated than the two preceding, and the microcline exceeds the oligoclase in amount. Still closer to the edge a specimen (4236) taken from Rough Craig, about a mile east of Clova Hotel, shows under the microscope orthoclase, microcline, oligoclase (rare), quartz, and muscovite. The quartz contains 'hairs' and inclusions with bubbles. Magnetite occurs as an accessory. Thus the brown mica is almost absent, and oligoclase is quite subordinate in amount, white mica and potash-felspar being dominant. Finally the borders of the mass are fringed with pegmatite, of which there is a vast quantity on the south-eastern side, and of this rock microcline is the chief component. The pegmatite here often assumes the 'graphic' structure, and where this is the case the amount of muscovite is always small. A section (4233) shows microcline and albite in microperthitic intergrowths, with some quartz. The 'graphic' structure is seen in portions only of the slide.

The special points to be noticed in this area are as follows:—The centres of the broader portions contain oligoclase to the exclusion of microcline, and are more foliated than the rest of the mass (which is essentially a slightly foliated granite, and contains the two felspars in nearly equal parts); white mica is here much in excess; while close to the edges microcline is the dominant felspar, and muscovite the dominant mica.

A typical specimen (4241) of the fourth mass, taken from the head of Kennel Burn, may be described as a fairly coarse granitic rock, composed of quartz, microcline, plagioclase, and two micas. Microcline is the dominant felspar. A tendency on the part of the micas to flow round the plagioclase is well marked in a few places, otherwise the structure approximates very closely to that of a normal granite. On the south-east of the mass all trace of foliation disappears, and the rock is an aplite. This last, from its composition, probably represents the pegmatite, which now forms a fringe on the northern and western edges. The feature, then, of this fourth mass is that microcline much exceeds plagioclase, and brown mica occurs only in very small quantity.

The facts enumerated above conclusively prove that this great intrusion becomes steadily more and more acid as we follow it from the north-west to the south-east; and further, that the acid character of each outcrop is more pronounced on its southern and eastern edges than in the rest of the mass; except perhaps in the case of the fourth mass, which is very acid throughout. This conclusion may be tabulated as follows:—

North-western Area	1. Maximum plagioclase, minimum microcline. 2. Maximum biotite, smallest white micas.
South-eastern Area	1. Minimum plagioclase, maximum microcline. 2. Minimum biotite, largest white micas.

The meaning of this distribution of the component minerals is made intelligible by examining one of the larger apophyses of any of the post-metamorphic Highland granites shown in Sir Archibald Geikie's Geological Map of Scotland (2nd ed. 1892). At the junction with the granite the dyke is very coarse in texture, but farther from the parent mass it gradually becomes less and less coarse, till eventually it consists of porphyritic crystals set in a fine-grained matrix. These crystals, which belong to the earlier phase of consolidation, consist of bipyramidal quartz, oligoclase, and brown mica, while the bulk of the finer material consists of potash-felspar and quartz, the minerals of later consolidation.[1] By applying these facts to the distribution of the minerals in the area under consideration, we see that those which are most abundant in the north-west belong to the first phase of consolidation, while those which are most abundant in the south-east belong to the second phase. Thus the earlier-formed minerals appear to have been retained or strained off, while the still liquid potash-bearing material travelled on in a south-easterly direction. Hence it may be inferred that the source of origin lies to the north-west, and that the intrusion ends with the formation of the masses of pegmatite, which are the acid or potash-bearing residuum. Further, the fact that in one area the intrusion is minutely subdivided while in the south-east it hangs together, finally consolidating as aplite, suggests that the rocks to the north-west must have had a higher initial temperature than those farther south-east. It will be found that this view is strongly corroborated by the evidence adduced later on. The high temperature was probably due to the intrusion of slightly older gneisses, of the same type as the muscovite-biotite gneiss, in which white mica is rare or absent. It was intended to give a brief account of the intrusion, but the idea has been abandoned on account of the writer's reluctance to lengthen what is already a long paper.

The igneous origin of these pegmatites having been placed beyond reasonable doubt, a few additional details may be given here as to their chief petrographical characters. They are most commonly composed of quartz, microcline, and muscovite, and the smaller veins are nearly all of this type. An important feature is that there are always at least two faces of the prism developed in the last-named mineral, often more; but we know of no case in which all six sides are shown in a large crystal. Moreover, the white mica is not often in immediate contact with the microcline. It is usually separated from the latter by a very variable amount of quartz. The other types of pegmatite are a rude kind of graphic granite, quartz-microcline rock common in the larger veins and masses, and a quartz-muscovite rock which occurs only in small patches. In addition to these normal constituents, garnet and schorl are associated with the pegmatites. The former is locally abundant, though absent over considerable areas; the latter also is abundant locally, and is the black variety, brown in thin section.

We may conclude the petrographical description of this intrusion with a short account of some of the special features of the minerals which enter into the composition of the rocks. The brown mica has been isolated and analysed. The iron occurs as $FeO=20{\cdot}87$ and $Fe_2O_3=2{\cdot}56$ per cent. The magnesia averages only 4·32 per cent. As the mineral is approximately uniaxial, the mica may be fairly classed as haughtonite. The inclusions in it are grains of garnet and zircon, and the latter has always a black 'skin' in addition

[1] See a paper by the present writer on the 'Origin of certain Gneisses,' Geol. Mag. for 1892, pp. 64–65.

to a pleochroic halo. Apatite has not been observed, and its absence distinguishes this brown mica from that of the newer (pre-Old Red Sandstone) granites, in which apatite occurs abundantly.

The white mica contains 8·47 per cent. of potash, and only 0·91 per cent. of soda. As it is widely biaxial, it may be fairly claimed as typical muscovite. The large micas of the pegmatites have the same composition as the small individuals of the 'permeation-area.'

The plagioclase has in the majority of cases been proved to be oligoclase, but it is often impossible to determine accurately its true nature. Traces of zonal banding are common in the plagioclase of the larger masses of the intrusion. This plagioclase-banding is often very puzzling. A part of a crystal is well-twinned oligoclase; the rest may show no twinning at all and be water-clear. The twinned portion merges insensibly into the untwinned. A common phenomenon is a binary twin, with little patches of plagioclase-banding in one half only, and from this we pass to the simple binary twin, identical as regards state of decomposition with the undoubted oligoclase. The passage strongly suggests that the binary twin is not orthoclase, and for that reason a note of interrogation is often put after 'orthoclase' in describing the specimens.

The analyses of the microcline are not satisfactory. The variation in the proportion of potash to soda is such as to suggest that some albite is invariably intergrown with the microcline proper. The individual crystals in the pegmatite fringing the third igneous mass are often of enormous size.

The highly crystalline condition of the rocks into which the above-described igneous masses have been intruded has been already referred to. Their grain is coarser than in most other areas, and the micas are especially large. The general aspect of the north-western portion of the district is distinctly gneissose. Proceeding in a south-easterly direction, this gneissose character is gradually lost, the rocks become finer in grain and more like the ordinary schists of the Southern Highlands. Eventually they assume the phase of phyllites in the case of the originally fine-grained sediments, and of more or less crystalline arkose grits in the case of the coarser deposits. This decrease in crystalline aspect is most rapid when measured in a south-easterly direction from the pegmatites, which have been proved to form the outer edge of the intrusion. Further, the variation in crystalline aspect has been found to be accompanied over a large area by a change in the minerals of which the rocks are composed. This is especially well-marked in the case of the aluminous silicates (sillimanite, cyanite, and staurolite), minerals which have been clearly recognized as the products of thermo-metamorphism (so-called contact-metamorphism). In the area in question the three minerals mentioned above characterize three more or less distinct zones, the boundaries of which are sensibly parallel with a line joining the most southerly or south-easterly exposures of the igneous intrusion at the surface. Thus the distribution of the minerals, as well as the crystalline phase of the rocks, is seen to be dependent on nearness to or remoteness from the igneous masses; and in presence of such evidence it seems only reasonable to attribute both the minerals and the crystallization to the thermometamorphism of the intrusion.

IV. Minerals of the Metamorphic Rocks.

In the following petrological descriptions, the minerals that are especially suggestive of this mode of origin will first be dealt with, and a brief account will then be given of the rocks in which they occur.

(1) *Sillimanite* or *Fibrolite*.—This mineral occurs so abundantly in the region of greatest metamorphism as to justify the application of the term 'sillimanite-zone' to the area in which it occurs. Over at least 50 square miles fully one half of the rocks contain this silicate of alumina, and usually in considerable quantity. Its distribution in the north-west is probably limited by a huge fault shown in the Map (Pl. XV.), but to the south-east sillimanite does not occur far from the acid edge (pegmatite) of the great intrusion. As the mineral has hitherto been so little known to most British geologists, it may not be out of place to give a brief summary of the previously published accounts of it. Of the earlier writers,[1] Dr. E. Kalkowsky, in a paper on the 'Gneissformation des Eulengebirges,' Leipzig, 1878, notes the presence of sillimanite-needles in quartz (*faserkiesel*). Several communications by different authors appeared soon after, but it seems that Michel-Lévy was the first to recognize its mode of production. In a paper of two pages in the Bull. Soc. Franç. Minéral. (1880) he gives an account of its optical properties and chemical composition. Its origin is then traced to 'contact'-action; and he concludes by stating that Sainte-Claire Deville had succeeded in producing it artificially by heating to redness a mixture of aluminium fluoride and silica. The contact-origin of this mineral has been further proved by Dr. Barrois's papers on the Guémené and Rostrenen Granites, published in the Annales Soc. Géol. du Nord.[2] In these cases the sillimanite occurs in sandstones of Lower Silurian age. In the Hautes Pyrénées Lacroix found sillimanite in the andalusite of the maclites (massive andalusite-rocks), and he also ascribed it to contact-action.[3] In this country Prof. Heddle recorded sillimanite from Pressendye Hill in Aberdeenshire, and also from Glen Clova. Soon afterwards Prof. Bonney published an account of its occurrence in the Rock of the Black Dog, again in Aberdeenshire; but neither of these writers made any suggestion as to its mode of origin. In 1890 Miss Gardiner communicated to this Society the results of her work on the contact-

[1] A list of the German memoirs is given in Rosenbusch's 'Mikroskopische Physiographie' (art. Sillimanite, 3rd ed. 1892, vol. i. p. 440).

[2] 1884, vol. xi. pp. 134 *et seqq.*, and vol. xii. pp. 1 *et seqq.*

[3] 'Roches métamorphiques et éruptives de l'Ariège,' Bull. Serv. Carte Géol. France, No. 11, vol. ii. (1890); see also 'Note sur une association de sillimanite et d'andalousite,' Bull. Soc. Franç. Minéral. vol. xi. (1888) p. 150.

metamorphism due to the Galloway Granite.[1] Her investigations have an important bearing on the origin of the crystallization of the Highland schists. Sillimanite is shown to occur close to the granite both in altered grits and shales, and is associated with quartz and two micas.[2]

In the area under consideration sillimanite occurs in two phases. First and by far the most abundant mode of occurrence is that known as *quartz sillimanitisé* or *faserkiesel*. This substance consists of minute glassy needles of sillimanite embedded in quartz. The centre of a patch is seen, under the microscope, to be made up of a great number of massed needles. Where the needles are fresh, they produce the effect of ice-needles in snow; that is, the centre of a patch is opaque snow-white. Away from the centre the needles decrease in number, and at the edges isolated needles are seen. Under crossed nicols the mineral gives high polarization-tints, and the usual linear arrangement is well brought out in the centre of the mass, giving the whole a more intense *flaser*-appearance. The patches of *faserkiesel* weather out on the surface of the rocks. They appear as quartz with a silky, pearly, or nacreous lustre, the tint varying from pure white to yellowish or greenish. The aspect of a fresh hand-specimen is perfectly characteristic, and quite unmistakable after it has once been clearly recognized. The second mode of occurrence of the mineral is that in which it is more or less independent of quartz. The needles in this case are arranged in wavy threads and films, and somewhat resemble spun silk. They are massed in the film except at the ends, where the needles diverge, and are fewer in number, thus producing the impression of a frayed edge. This frayed edge interlocks with a similar edge of some other mineral, usually brown mica. Sillimanite in this form occurs chiefly in small patches, and is not often recognizable on a hand-specimen.

(2) *Cyanite* or *Disthene*.—Like the last-described mineral, this is also a silicate of alumina, and is met with abundantly on weathered faces of the rocks in which it occurs. The detailed mapping has shown that a more or less interrupted belt of cyanite-bearing rocks follows the south-eastern edge of the 'sillimanite-zone' in such a way as to form an outer zone of metamorphism. The interruptions of the belt are due to its being crossed by rocks that are not likely to contain free silicate of alumina in any great quantity, such as siliceous rocks; for these zones are not rigidly coincident with the strike of the rocks of the district. The general trend of this zone is shown in the Map (Pl. XV.), and specially good places for collecting are indicated by the letter *c*. Cyanite occurs macroscopically in two forms: first, as single crystals scattered fairly evenly through the mass of the rock, and secondly, as more or less segregated or aggregated crystals. The single crystals show very little variation in form. They may be briefly described as follows:—Take a piece of common lead-pencil half an

[1] Quart. Journ. Geol. Soc. vol. xlvi. p. 569.

[2] Since I wrote the above, Mr. W. M. Hutchings has kindly lent me some slides of highly-altered ash, taken a few feet from the edge of the Shap Granite. In these sillimanite-needles are seen, embedded in quartz.

inch long; cut off two slips along the length of the pencil, so that the flat faces are parallel and the distance between them is roughly half that of the diameter of the pencil; then round the ends a little, and a fair model is produced of all the isolated crystals of cyanite in the district. This rounding of their angles and ends is a never-failing character. As the crystals become smaller, the tendency to roundness in outline becomes more marked; but while the brachypinacoid (0 1 0) is often obliterated in this manner, the macropinacoid (1 0 0) never is quite lost. All crystals of cyanite cleave with extreme facility parallel to the latter face, and fairly well parallel to the former. They break easily, but at irregular intervals, nearly at right angles to the macropinacoid, across the length of the prism. These planes of fracture are the well-known 'gliding-planes' parallel to the basal pinacoid. Further, these evenly-distributed crystals are never twinned, so far as has been observed in this district. An interesting feature in the larger isolated crystals is that, instead of showing the typical blue colour to which the mineral owes its name, they seem to be coated with a black dust, having the appearance of graphite or 'black lead.' As such crystals are extremely abundant over large areas, they may be conveniently designated 'black-leaded,' to distinguish them from the normally blue-coloured specimens. The graphitic aspect of the black dust is, however, deceptive; for, on examining a cleavage-flake under the microscope, it is seen that these crystals have a vast number of grains (sometimes crystals ?) of iron ore scattered through them in a fairly even manner. It is impossible not to feel that the structure thus produced is of the same character as those described by Dr. Salomon, as occurring in the inclusions in the tonalite of Adamello; and these 'black-leaded' cyanite-crystals exhibit 'typical contact-structure.' Sections of this mineral under the microscope are easily recognized. In the first place, they have a clear glassy appearance, very rarely showing the blue colour of the large crystals. Then their high refractive index, which makes their borders and characteristic cross-jointing or cleavages stand out in bold relief, assists largely in the determination. A section parallel to the length of the crystals extinguishes almost straight, if it be also parallel to the face 0 1 0, and at about 30° if parallel to the face of easiest cleavage (1 0 0). Under crossed nicols they give moderately high polarization-tints. It may be here added that the isolated crystals tend to lie with their broadest face (1 0 0) parallel to the dominant foliation of the rock; but it is doubtful how far this holds good in the case of very small crystals. Cyanite also occurs as segregations or aggregations. In both cases the blue colour is well shown; but by far the most beautiful crystals occur in quartz-segregations, from which, unfortunately, it is impossible to extract them, as they break so much more easily than quartz.

My colleague, Mr. J. J. H. Teall, F.R.S., in addition to kindly helping me with the petrological descriptions of the slides, has further drawn my attention to some very remarkable literature bearing on the points here discussed, and has shown me the following passage in Dana's 'System of Mineralogy,' 6th ed. 1892, p. 499:—"Vernadsky shows that cyanite is transformed at 1320°–1380° into sillimanite" (Bull. Soc. Franç. Minéral. vol. xii. p. 447, 1889, and vol. xiii. p. 256, 1890). Thus the experience of the laboratory furnishes an explanation of the fact that sillimanite characterizes the inner, and cyanite the outer, zone in an area of thermometamorphism. Further, we obtain a general idea of the high temperature to which great masses of the Central Highland rocks have been raised. This temperature was probably greater than that suggested by Vernadsky's experiments; for as the specific gravity of sillimanite (3·23) is less than that of cyanite (3·56–3·60), the temperature required to effect the change would almost certainly be increased by pressure.

(3) *Staurolite.*—In addition to the zones already described, there is a third still farther removed from the igneous rocks, characterized by the presence of staurolite. This is the best marked of all; for, with the exception of an interval of a few hundred yards, the zone is nowhere interrupted by siliceous rocks throughout a distance of nearly 10 miles. This is probably due to the fact that the zone very nearly corresponds with the actual outcrop of a particular bed. Moreover, if a line be drawn joining up all the most southerly outcrops of the intrusion, then this zone is roughly parallel with that line. In hand-specimens staurolite usually weathers out as yellow-tinged crystals. In the more crystalline areas these are of large size, and twinning is the rule, the exception being to find untwinned crystals, in which respect staurolite is the reverse of cyanite. For some undiscovered reason, twinning takes place so that the crystals cut one another at an angle of 60°. In other districts in the Central Highlands the twins frequently assume the form (roughly) of a Maltese cross; but here they rarely do so. The crystals may be seen, from the part projecting from the rock, to be mostly eight-sided or six-sided. Under the microscope they vary in colour from pale yellowish-brown to red, and are distinctly pleochroic. Their refractive index is a little higher than that of quartz, and they are much cracked, the cracks standing out in strong relief. The mineral is composed of silica, alumina, and iron, thus differing from sillimanite and cyanite in composition, and approaching the garnets. It is essentially an unstable mineral, in marked contrast with its ally, the garnet, which is unusually stable. It is rare to find a crystal of staurolite which has not decomposed more or less to a 'shimmer'-aggregate; and if a weathered-out crystal be pounded up, scarcely a single grain will be found to possess the optical properties of the original mineral.

(4) '*Shimmer'-aggregates.*—Sillimanite, cyanite, and staurolite all tend to pass over to a fine-grained material giving a 'shimmer' of high polarization-tints under cross nicols. Dr. Barrois, *op. jam cit.*, says they have been altered (*épigénisé*) into white mica. But though the shimmer of colour may be due to very minute scales of this mineral, they must be cemented by some hard substance, possibly quartz; otherwise the replacing material would not project, but

would fall out and leave hollows. Moreover, in many cases the pseudomorphs after staurolite are often harder than white mica. In staurolite and cyanite the replacement starts from the outside, and then frequently proceeds into the interior along cracks so as to leave cores of the unaltered mineral, thus reminding one of the well-known mode of alteration of olivine into serpentine. In the case of sillimanite in quartz the reverse happens. The sillimanite, where massed, practically reaches the outside of the quartz-lenticle and decomposes; but the projecting needles round the edges of a felted mass are buried in quartz, and so protected. In consequence, a 'shimmer'-aggregate may be proved to be sillimanite by carefully examining its edges for the ends of the needles under a high power. The fine *flaser*-aspect of the sillimanite may often be recognized under crossed nicols, even when complete alteration has taken place.

(5) *Micas.*—Brown and white micas occur more or less abundantly in nearly every rock in the district. In the most altered areas the crystals are usually large, and arranged parallel to the foliation-planes. They are rarely, if ever, idiomorphic. The brown mica has been isolated and analyzed. It is rich in ferrous oxide, and low in ferric oxide and magnesia. As it is also approximately uniaxial, it may be classed as haughtonite. Seen in sections at right angles to the basal plane, it is always strongly pleochroic. There are two well-marked tints observed in such crystals: the first is pale brown, changing to blackish brown on rotating the nicol 90°; and the second is very pale red-brown, changing to a deep red-brown. This mineral has a curious mode of occurrence in the less highly-altered schists. Oval grains of brown mica are seen in the angles of the puckers of fine schists, so that the basal cleavage of the mineral is at right angles to the foliation-planes. The puckering may be frequently traced through the grains by means of minute inclusions of iron ores. A special point of importance is the occurrence in many cases of numerous pleochroic spots in the red-tinted micas (rare in the brown). In sections parallel to the vertical axis these spots are almost invisible when the short axis of the polarizer lies at right angles to the trace of the cleavage, and the crystal is very pale in colour. When the short axis is parallel to the cleavage, the spots are deep black and the mica is deep red-brown. These spots are seen to have tiny grains in their centre: in some cases these are iron ores; in others they have been extracted and proved to be epidote. In a thin section the epidote-grains can be distinguished from grains of zircon by the fact that the latter (in igneous rock at least) always have a black 'skin' round them, independently of the pleochroic halo; but this black 'skin' does not appear to ever surround the inclusions of epidote. This type of mica, with its pleochroic spots, has been so often recorded in contact-rocks, such as those of Shap and New Galloway in this country, and those of the Britanny granites in France, that it may be fairly claimed as a 'typical mineral' produced by thermometamorphism. In the most highly-altered rocks white mica often occurs in considerably larger flakes than brown; but in the finer sericite-schists it is always the smaller of the two minerals.

Oval grains, similar to those of brown mica, are rare; but when they do occur the rocks containing them are always intensely crystalline. The only inclusions of importance in this mineral are minute flecks of brown mica lying parallel to the basal cleavage of the enclosing mica. Chemical analysis shows that potash and soda occur in the proportion of 7·56 : 3·2 per cent., so that the soda is considerably higher than in the muscovite of the igneous rocks. The white mica of these highly-altered rocks is frequently more or less embedded in the brown, in such a way that the basal plane of the latter makes an angle of about 60° with the former. When the muscovite appears in section as a number of tiny laths, these laths bear the same relation to the brown mica as the felspars do to the augite in an ophitic dolerite.

(6) *Garnets.*—The garnets in this area do not differ from those so abundant all over the Highlands, until we approach one of the igneous masses, or are well within the area of intense thermometamorphism. In this case they are of a weak port-wine colour, and remarkable for their transparency; such garnets do not habitually show the usual crystalline form (dodecahedron) when large, but are often like drops of transparent red gum. Both under the microscope and in the hand-specimen, they exactly resemble the garnets which Miss Gardiner has shown to be produced by the intrusion of the Galloway granite in the surrounding rocks.

(7) *Tourmaline* or *Schorl.*—This mineral has not been largely developed; but there seems good ground for stating that when it occurs in the pegmatites it is also developed in the adjacent schists. The number of instances is too small to enable one to speak confidently. The schorl of the igneous rock is brown in thin sections; it is dark olive-green in the schists (slide 4865). The blue schorl of the limestone is not specially connected with the pegmatites.

(8) *Quartz.*—Over an area of at least 60 square miles the larger grains of quartz possess a curious character. Under crossed nicols they do not extinguish as a whole; but neither can the extinction be fairly called undulose. There is a difference of several degrees in the extinction-positions of different parts of a large grain. Thus a grain will break up sometimes into five or six parts; while half are dark, the remainder are very nearly so; but there is no definite boundary to the patches, which fade into one another. This phenomenon is so constant in the area surrounding the intrusions, and so uncommon elsewhere, that it seems unreasonable to doubt that this curious optical property has been produced by intense heating. As is well known, the optical properties of many minerals are liable to be entirely changed by being kept at a high temperature for a considerable time.

(9) *Lime-silicates.*—A distinct group of minerals has been developed in the calcareous rocks of this district. The chief members of this group are malacolite, a green pyroxene, zoisite, epidote, idocrase, and sphene. A variety of pale-brown mica also occurs, but not in sufficient quantity to enable us to determine its composition; it has a somewhat different appearance from, and is less

pleochroic than, the ordinary form of that mineral. Most of these minerals are well known to occur in *cipolino* and in varieties of *kalksilicat-hornfels*.

(10) *Felspar.*—Microcline occurs in the principal band of the group of calcareous rocks mentioned above. With this exception, almost the whole of the felspar developed in the metamorphosed rocks is plagioclase; and, where the identity of the species can be established, it is mostly oligoclase. This fact is of extreme importance, because the bulk of the felspar-pebbles in the grits of the less-altered areas are also oligoclase; and these grits can be clearly seen to pass into gneisses as they approach the great intrusion. Fresh specimens of the oligoclase are seen under the microscope to be water-clear,[1] a feature which appears to be characteristic of these rocks. The larger grains are not only twinned, but the twinning-planes usually pass right across the crystal. In the oligoclase of the igneous rocks the twinning-planes frequently stop short of the edge of the crystal, *i. e.* the edge is more or less completely untwinned. No trace of zonal banding has been met with in the felspars of the metamorphosed rocks.

V. Rocks of the Metamorphic Area.

A brief description may now be given of the principal types of rock in which the minerals above described occur. They may be divided into four groups: firstly, those of the sillimanite-zone; secondly, those of the cyanite-zone; thirdly, those of the staurolite-zone; and lastly, those lying between the third zone and the Great Highland Fault, as seen on the banks of the North Esk.

(a) *The Sillimanite-zone.*

Quite in the north-western corner of the area here described the dominant rock is a coarse felspathic gneiss, of which the felspar is almost exclusively oligoclase. The felspar occurs in lenticles of variable size, more or less associated with quartz. These lenticles are separated one from another by felted masses of mica, both brown and white. As the lenticles get more and more elongated, and of greater thickness (they are at times 2 feet thick), a rudely parallel-banded, coarse gneiss is produced. Into this the tongues of igneous gneiss are intruded, and so inextricably are the two rocks interwoven that it frequently becomes impossible to say how much of the mass is igneous and how much of metamorphic origin. In such rocks sillimanite is rare. By an increase of the silica or alumina, these coarse gneisses pass insensibly into fine-grained, grey, siliceous rocks on the one hand, or into still gneissose, though less coarse, sillimanite-bearing rocks on the other. The former siliceous type occurs abundantly on the Driesh, the highest mountain

[1] Messrs. Harker and Marr have drawn attention to the clearness of the minerals in the metamorphic rocks surrounding the Shap Granite, Quart. Journ. Geol. Soc. vol. xlvii. (1891) p. 266.

in the district. A microscopic section (4881) shows this rock to be composed of quartz, felspar, biotite, and muscovite. Structurally it is a fine gneiss or schist; but the amount of free silica in the dominant rock of this mountain places the sedimentary origin of the schist beyond reasonable doubt.

The most gneissose phase of the sillimanite-bearing rocks is seen close to the outcrop of the limestone, in the crags south of the stables on the Lee Water. A microscopic section (4531) shows it to be composed of plagioclase (mostly oligoclase), quartz, and white and brown mica. The micas occur in films, and are associated with a considerable amount of sillimanite, which interlocks with the frayed edge of the brown mica. A few garnets are also present.

These three types, the coarse felspathic, the siliceous, and the coarse sillimanite-bearing gneiss, are very abundant in the western part of the sillimanite-zone. A less coarsely gneissose phase occurs in the great pass of the Unich, above Loch Lee, and extends almost down to the Loch. A specimen (4544) taken from Craig Maskeldie is a puckered, grey, gneissose rock in which segregation of felspar-lenticles is still fairly well-marked, and the surface is coated with *quartz sillimanitisé*. It is composed of quartz, felspar, sillimanite, muscovite, biotite, garnets, and iron ores (sillimanite-gneiss). Farther down the glen, and farther from an outcrop of the igneous gneiss, the same band shows still less segregation of the felspars, and a smaller quantity of sillimanite; indeed, Mr. Teall describes one specimen (4541) as a schist containing sillimanite rather than a gneiss.

Some garnetiferous varieties of the sillimanite-bearing rocks are seen on the top of the crags above Loch Brandy, and stretching thence down a narrow ridge to the Unich. The first of these is a very coarse garnet-schist (? gneiss) with minute patches of *quartz sillimanitisé*. Proceeding towards the igneous gneiss which crops out close to the Unich, a segregation of the components takes place. Siliceous patches with a silky lustre are interlaminated with more garnetiferous portions of the rock. A microscopic section of the former (4540) shows sillimanite-needles embedded in quartz. This is a perfectly typical specimen of *faserkiesel* or *quartz sillimanitisé*. Close to the Unich, where it is joined by the Longshank Burn, is a considerable mass of extremely garnetiferous coarse-grained rock, somewhat gneissose in aspect, and associated with much sillimanite. Seen in section (4543) it is composed of quartz with a little felspar, white and brown mica, and large, irregularly shaped wine-clear garnets. Iron ores and sillimanite also occur. Some of the sillimanite is enclosed in garnet, but most of it is of the filamentous type, fraying out on the edges and interlocking with brown mica. The garnets in this case form nearly one half of the rock, which is obviously so rich in silicate of alumina and iron as to place its sedimentary origin beyond dispute.

Some sillimanite-bearing rocks, with a peculiar mode of weathering, occur on the hill about $\frac{1}{2}$ mile E.N.E. of the church of Loch Lee. In these the *quartz sillimanitisé* projects from the weathered micaceous surfaces almost in the form of little cones from which the apex has been broken with a jagged fracture. These conical projections vary in colour from green to yellow. They give the rocks a very jagged or roughened surface, which can be easily noticed several yards off. A cross-fracture of such a specimen is generally compact, and, if fresh, not a trace is seen of the structure brought to light by weathering. About Tarfside, a rock very similar to the last in weathering, but with a still more compact fracture, keeps close to the outcrop of the limestone which was at one time extensively quarried. There is every reason to believe that a large proportion of the rocks to the eastward contain sillimanite in the 'film' phase, associated with frayed brown mica.

In the neighbourhood of Millden, on the North Esk, the little projections of *quartz sillimanitisé* are frequently met with on the weathered surfaces of the rocks. Fine examples of rather highly crystalline sillimanite-bearing rocks rise almost like dykes out of the ground, close to the Meallie Burn. This is on the northern side of the main river. On the southern side, somewhat similar rocks are seen above the large farmhouse of Dalhastnie, while in the little Dalscampie Burn, farther south-east, the least crystalline variety of sillimanite-bearing rocks is seen. It is a fine crystalline schist in which segregated quartz occurs in very thin films. A specimen (5107) is seen to be composed of quartz, chlorite, and white mica, with larger patches of quartz fairly free from the other components of the rock. Lying parallel with the schistosity are certain faintly-yellow lenticular patches, closely resembling 'shimmer'-aggregates. Their centres are invariably very finely fibrous, and a comparison with other slides leaves little doubt that these patches are *faserkiesel* or *quartz sillimanitisé*. No other sillimanite-bearing rocks are known to occur south-east of this locality.

There is in this zone a sill of basic igneous rock, which always occurs close to the limestone (see below, p. 350). In the most altered areas, *i. e.* the most gneissose, this sill is a more or less coarse, hornblendic gneiss, while in the areas where the felspar-segregations are of a less coarse type, it becomes a more ordinary hornblende-schist.

In addition to the rocks described above, a band of impure crystalline limestone is frequently met with. Its colour and appearance vary little if unweathered, but there is a good deal of difference in the decomposed rock, depending on the presence in greater or less quantity of iron-bearing silicates. Along the Lee Water it is bright bluish-grey, and a microscopic section shows it to be composed of calcite, green hornblende, zoisite, felspar, quartz, sphene, and pyrites. Blue tourmaline is rare.

The zoisite is well marked by the weak indigo tint under crossed nicols. The mica, or some of it, does not look like the ordinary brown mica of the district, but it is not easy to isolate a sufficient quantity for analysis. Much of the sphene is in roundish grains. A very interesting type of the limestone is seen in an old quarry at Stylemount, halfway between Loch Lee and Tarfside, going by the old road.

Since the quarry was opened, the rock has decomposed to a depth of several inches to a soft, brown, ferruginous mass; the unweathered rock is a bluish-grey limestone. A specimen of this (4869) shows calcite, green hornblende, malacolite, zoisite, sphene, felspar (including microcline), and iron ores. The microcline is very remarkable, because we have never yet found it in any of the metamorphosed rocks of the Central Highlands, except where it was part of an original crystal of an igneous rock, as the Ben Vuroch granite. There is no white mica in the limestone, and further there is very little in the rocks next to the limestone, though they contain much brown mica. White mica increases rapidly in amount as we leave the limestone: it is, indeed, doubtful whether this mineral is ever absent from the altered sediments of this area, except close to the calcareous rocks. Microcline continues to be abundant in the limestone over all the Tarfside area. The malacolite has no idiomorphic boundaries, but it occurs in much larger individual crystals than the other constituents.

At the base of this little calcareous series are one or more bands of siliceous rocks, which weather like very massive quartzites. They are exclusively confined to the north-eastern side of the North Esk, where they cover a great area and are the lowest rocks yet known to occur in the Southern Highlands. From a nearly pure quartzite they vary to a felspathic phase, in which both white and brown mica are present. Such a rock is seen under the microscope to be markedly foliated. The felspar occurs in little patches shaped rather like a double wedge: these are joined together by their taper ends and so give a well-marked foliated aspect to the rock, quite independently of the micas. It can only be fairly called a muscovite-biotite gneiss, but its extremely high percentage of free silica puts its sedimentary origin beyond doubt.

(b) *The Cyanite-zone.*

Though highly crystalline, the rocks of this zone are not so coarse in texture as those of the sillimanite-zone in the same neighbourhood. This is shown both by the size of the micas and also by that of the individual grains composing the felspar-segregations. To begin with the rocks in which the characteristic mineral is met with: cyanite is shown in a slide made from the schist close to the old limestone-quarry in Glen Clova; it is not visible in a hand-specimen. This schist is fairly soft and finely puckered, being practically a sericite-schist, and is dotted over with specks of brown mica. Under the microscope it is seen to consist of quartz and two micas, the flakes of white mica frequently meeting so as to form a number of small angles; and in these angles the brown micas, seen on the surface of the rock, mostly lie. They are the typical red-brown contact-mica, and are full of intensely pleochroic spots. In addition to these micas, a few crystals of garnet, and crystals (or more often aggregates) of cyanite occur. Farther up the glen larger crystals of cyanite are seen in the fallen blocks of gneiss, above the farm-steading of Alton. The gneiss consists of large flakes of brown and white mica lying in layers in a fine gneissose matrix, mostly of quartz and felspar. In Bonhard Corrie, a short distance north-west of the Clova Hotel, the weathered surfaces of some of the finer-grained rocks are coated with a vast number of tiny crystals of blue cyanite. The same is true of the fine gneisses at the head of Saughs Burn. About Loch Lee rather coarsely-micaceous rocks (fine gneisses) frequently show cyanite-crystals on their weathered surfaces. A specimen (4547) is composed of quartz, muscovite, and chlorite, with a little garnet and iron ores. In this as a matrix are set glassy crystals of cyanite, the high refraction and cross-cleavage cracks being well shown.

A section was also made of a rock-specimen (4539), occurring close to the last, in which the cyanite is not so well preserved. The matrix is composed of quartz, chlorite, muscovite, and a little felspar, with iron ores, garnet, and tourmaline as accessories. In this are set a number of vividly-polarizing aggregates, in the centre of which small patches of cyanite may still be recognized. Comparing slide No. 4539, containing cyanite, with No. 4541, containing sillimanite, in what can be clearly proved to have been originally the same rock, the transverse section shows that in the latter a further segregation of felspar has taken place, and the rock is on the whole more crystalline and gneissose. That is, the development of sillimanite in place of cyanite in the same band is accompanied by a higher phase of crystallization in the whole rock.

Some of the finest and most interesting specimens of cyanite are seen on the weathered rock-surfaces on the northern flank of Glen Effock, about halfway up the hill. Almost every crystal, and they are both numerous and large, shows in perfection the regular dissemination through it of iron ore-grains (ilmenite). They probably form about one fourth of the whole, as seen under the microscope. The structure is best marked in thin cleavage-flakes, which can be taken off with a blunt knife. At the head of Glen Effock (a little north of the word 'Cruys' on the one-inch Ordnance map, Sheet 66) there are some rather coarse quartz-segregations, in which are embedded the most perfect specimens of bright blue cyanite-crystals to be met with in the whole district. On Bulg, a mountain close to the main stream of the North Esk, some way below Keeny or Millden, a finely-marked horizon of cyanite-schist is met with, striking E.N.E. across the river. The cyanite here occurs principally as 'blackleaded' crystals in a fine-grained schist composed of felted mica cemented by little grains of quartz and felspar. The amount of this rock is very large, and specimens of it occur abundantly as drifted boulders in the fields between the Wood of the Burn (on the North Esk) and Fasque. A section of such a rock shows crystals of cyanite full of black inclusions, set in a matrix of quartz and brown and white mica. The cyanite is surrounded by the typical 'shimmer'-aggregate. In addition to these evenly-distributed crystals, cyanite is also to be found on Bulg in aggregated masses, sometimes as large as a man's head. A microscopic section (5105) was made from the edge of one of these aggregates. The cyanite is clear and glassy, and only one little spot shows the blue colour.[1] It is set in a matrix of chlorite (after biotite), white mica and iron ores, associated with a curious dusty material, probably quartz full of minute inclusions. Some of these are large enough to be made out as garnets, but most of the dust is black and probably consists of iron ores.

Now, comparing the rocks of this neighbourhood with those seen about Loch Lee and the watershed of Glen Clova, there is a very great difference between the matrix in which the cyanite is set in the southern and northern areas. In the latter the micas are frequently large, and each individual may be easily seen by the unaided eye; so that it is not correct to say that *any* cyanite-bearing rock is less crystalline than *any* sillimanite-bearing rock. But it is absolutely true that a specimen of the former is *invariably* less crystalline than a specimen of the latter lying between that cyanite-rock and the nearest outcrop of igneous gneiss.

In addition to the cyanite-bearing rocks described above as occurring in this zone, there are some gneisses, quartzites, and grits. The former are felspathic in the northern area; but though lenticles of felspar, or quartz and felspar, are often met with, the individual grains are much smaller than those composing similar lenticles in the sillimanite-zone close by. The quartzites are thin bands occurring near the Clova Hotel and in Glen Effock. They have a very bedded look, due to the presence of thin layers of white and brown mica. But these layers have nothing to do with original bedding, for they are entirely parallel to the planes of strain-cleavage. The grits are especially interesting. On the eastern side of Loch Brandy, as well as in Ben Reid on the west, there are some rather gneissose felspathic rocks, which from their weathering appear to be intensely altered felspathic grits, traces of the incompletely-absorbed felspar-pebbles being still visible. Moreover, at the former locality these pass gradually into more siliceous rocks, in which much-deformed quartz-pebbles can be recognized in a highly siliceous matrix of quartz-schist. The high percentage of silica was not favourable to the development of new minerals, and the original clastic character of the rock can still be made out. Again, starting from the southern side of Glen Effock and proceeding along the low ridge between the head of Keeny Burn and the main stream of the North Esk, this phenomenon is repeated far more slowly. The rocks gradually become less gneissose, and traces of pebbles are seen here and there, every little infolded patch with an originally siliceous matrix being an unquestionable pebbly grit. Gradually even the felspathic grits show clearly their original clastic character, till, as we approach Bulg, the whole mass of the group of pebbly grits is clearly recognizable.

On Cairn Caidloch, a mountain due south-east of Loch Lee, is a mass of pure white quartzite. On breaking the loose blocks, they

[1] The blue colour is hardly ever seen in microscopic slides; when it is, the colour occurs only in isolated spots, like the yellow specks in cordierite, etc.

are found to contain little crystals of an emerald-green mica. The extreme purity of this quartzite, coupled with the presence of this very rare mica, enables us to recognize the rock instantly. It is here quite close to the rock containing the largest isolated crystals of cyanite, with ilmenite-inclusions, that occur in the whole district.

(c) *The Staurolite-zone.*

The first staurolite-bearing rock was met with on the south-western side of Glen Clova, just where the pack-road to Glen Prosen reaches the crest of the hill. The staurolite weathers out of the rock in six-sided crystals, which are frequently twinned. The crystals are embedded in a matrix of fine sericite-schist, spotted over with specks of brown mica similar to those seen in the schist close to the limestone. This outcrop is separated from the main mass of staurolite-bearing schist by a great development of the pebbly grits of the Southern Highlands. The pebbles in the grits can still be clearly recognized, in spite of the profound alteration which the rocks have undergone.

The main mass of staurolite-schist commences on the ridge that forms the watershed between Glen Effock and the West Water (Burn of Saughs in its upper part). A specimen taken from the Cruys (4862) is a silvery mica-schist, with conspicuous staurolite-crystals on the weathered surface. Under the microscope only a few small patches of staurolite are left as kernels to 'shimmer'-aggregates, which are set in a schist-matrix composed of quartz, white mica, and chlorite (? after biotite). Small garnets and iron ores are scattered through the slide, while blue tourmaline is occasionally seen.

Following the outcrop of this staurolite-schist along the ridge, the crystals that weather out are seen to diminish in size. They show also a tendency to aggregate together, so that several smaller crystals are twinned obliquely with a larger one.

Staurolite-bearing rocks are abundant in the north-western face of Bulg; these are mostly compact schists with little crystals of staurolite weathering out as small yellow projections. Under the microscope the matrix is seen to be composed of brown and white mica and quartz. The latter occurs as evenly-distributed grains with the micas, and also as clear patches in the small segregations. These,under crossed nicols, show the signs of optical strain common to nearly all the larger grains in the contact-rocks. In the schist-matrix are set a great number of what were once staurolite-crystals. For the most part they are replaced by 'shimmer'-aggregates, in some of which cores of staurolite are still visible; the boundaries of the aggregates are those proper to the mineral replaced. A specimen from the south-east of Bulg, close to the 949 bench-mark, shows the typical yellow projections on the surface. The matrix (5100) is composed of white and brown mica and a little quartz. In this are embedded a considerable number of quite fresh garnets, and still more numerous grains and crystals of staurolite. The latter mineral is a good deal altered in the usual manner.

The most southerly outcrop of staurolite-bearing rock is seen on a narrow ridge north-west of Cornescorn Farm, rather less than half-a-mile from the house. Comparing this rock with a specimen (4862) from the Cruys, it is seen that while the latter contains large crystals of staurolite and the matrix is coarsely crystalline, in the former the crystals are quite small and set in a fine schist-matrix.

These staurolite-bearing rocks are frequently seen on the ridge to be close to a mass of pebbly grits, just as in Glen Clova. At the north-western end of the ridge the grits cannot be recognized as such; they are here represented by distinctly coarse schists or fine gneisses, often garnetiferous. As we recede from the area of intrusion little patches occur, in which the pebbles begin to be recognizable, and at the great gap in the ridge where it is crossed by the old road to the West Water, the bulk of the rocks are unmistakably of clastic origin. They are, of course, much altered, and the matrix in which the pebbles are set is thoroughly schistose. The pebbles are also granulitized.

In addition to these grits there is in this zone a little band of very pure quartzite, containing bright emerald-green crystals of mica. This rock is unmistakable wherever seen, and it follows the staurolite-schist continuously for some miles, after which it is frequently met with as small infolds, fixing accurately the horizon of the surrounding rocks. It is no exaggeration to say that this quartzite gives the clue both to the structure of the country and to the succession of the rocks, for it is the same rock as that described on Cairn Caidloch (see pp. 348–349); and it follows that this long outcrop of staurolite-schist is the *same bed* as the far more highly-crystalline cyanite-gneiss in Glen Effock. The latter rock is *much nearer* the igneous gneiss than the former.

The area close to the North Esk between the staurolite-zone and the Great Fault that bounds the Southern Highlands is chiefly composed of the massive pebbly grits and slates (or phyllites) so well known along the Highland border. In addition there are two rocks occurring close to the Great Fault, not known west of this district. These are the red-and-yellow jaspers, and a sill of basic igneous rock. The sill, when uncrushed, is a massive ophitic dolerite or fine gabbro, in which the augite is singularly fresh. The jaspers are essentially limestone and chert, altered by the contact-action of the sill.

We may ask, what further evidence is there of the effects of the great intrusion on these rocks? In the case of the grits the metamorphism is considerably greater in the north-western portion of their outcrop than in the south-eastern; but the effect of contact-alteration on coarse grits has not yet been sufficiently worked out to justify our ascribing the increased metamorphism to that cause. However, a band of fine grey phyllite, folded in with the grits at the Mooran Burn, contains little rounded grains of brown mica closely resembling the brown contact-mica described above. The only other rock which affords clear evidence of increasing metamorphism to the north is the old basic sill. Near the Great Fault, where sharply folded, this is a dark green, fine-grained, schistose rock, mainly composed of chlorite, epidote, and carbonates. Half-a-mile north of the Great Fault it has gradually passed into a distinctly crystalline chlorite-schist.[1]

VI. Sedimentary Origin of the Metamorphic Rocks.

The sedimentary origin of the group of rocks last described will probably be admitted without question, but in the case of the more highly-altered rocks it is not so clear, and we have to depend rather on the broader structural features due to original stratification and on the chemical composition of the rocks for information as to their original characters. Thus the lowest rocks, the quartzites of the North Esk valley, are highly siliceous. Like the quartzites of Ben-y-Ghlo (North-eastern Perthshire), they contain a certain amount of felspar, and differ from the latter chiefly in the greater reconstruction that they have undergone. These highly siliceous rocks form nearly one-fifth of the whole area described. The quartzite is succeeded by the limestone—a perfectly normal sequence—while the character of, and the minerals contained in, this calcareous rock are such as the researches of Prof. Brögger and others would lead us to expect. Next to the limestone in the Tarfside area is a bluish-grey *hornfels*-like rock which contains sillimanite, and its cross-fracture is suggestive of its being an altered shale or clay; but it has not yet been analysed. There is, however, a mass of sillimanite-bearing rocks extending along the southern side of the North Esk for a considerable distance, as to the origin of which it is impossible to speak with certainty. But it may be fairly said that the evidence of the area as a whole points to their sedimentary origin, and there is nothing to suggest that they have been formed of crushed igneous material. The great mass of pebbly grits that can be traced to fairly coarse gneisses has already been mentioned; it may, however, be here added that the felspar, both in the grits and the gneisses, is almost exclusively oligoclase.

There are only two other bands of importance in the highly altered area. One of these forms the long outcrop of staurolite-schist already referred to. This rock contains no less than 36·4 per cent. of alumina;[2] consequently it could only have been shale or clay originally. The other is the green-mica quartzite, which often consists almost entirely of silica. Thus it will be seen that the greater part of the series was probably of sedimentary origin.

[1] [It has been suggested that the alteration of these jaspers and green chloritic phyllites (they are not truly crystalline schists) is no greater than that known to be produced by earth-movement alone, unaccompanied by igneous intrusions. It is doubtful whether such may not be the case, but the extreme clearness of the minerals in fresh specimens of the chloritic rocks suggests incipient thermometamorphism, as well as mechanical deformation.—May 29th, 1893.]

[2] See Table of Analyses, p. 355.

Moreover, it appears that the entire area is formed of some seven, or at most eight bands of rock, not one of which need originally have been of any great thickness. The detailed evidence for these statements is too long and complicated to be given here, and must be reserved for the official Survey memoir on the district.

VII. Evidence of Progressive Metamorphism.

The green-mica quartzite, which has been so often referred to, is seen on the eastern flank of Bulg. Ascending this hill and keeping along the ridge overlooking Keeny Burn, one meets with the quartzite at intervals infolded in staurolite-schist. On the same ridge farther north it can be followed continuously for some miles, while the metamorphism in the surrounding rocks is seen to be steadily increasing. Quartzite traverses the zone of cyanite-schists, and finally at East Craig, near the head of Inchgrundle Burn, it enters the sillimanite-zone, where it is penetrated by the third mass of the great igneous intrusion. Thus this quartzite, which is easily recognized and is not liable to undergo important alteration in consequence of its composition, may be followed through the various metamorphic zones. The band of rock adjacent to the quartzite, at the point farthest from the igneous mass, is a staurolite-schist. As we approach the intrusion, it becomes first of all a cyanite-gneiss, and finally, close to the contact, a coarse-grained sillimanite-gneiss. A more conclusive proof of progressive metamorphism in one and the same bed is not easily conceivable.

VIII. General Conclusions, and Summary of Results.

In concluding this account of the thermometamorphism of the South-eastern Highlands, there are two features that call for special explanation. These are, firstly, the great extent of the area affected, and secondly, the intensity of the alterations produced.

Much light is thrown on the first of these by the wide distribution of the pegmatites. The connéxion between these pegmatites and the muscovite-biotite gneiss has been established in the first part of this paper. They have been shown to represent that part of the magma which consolidated last, and penetrated farthest into the overlying rocks. Their occurrence in any area may therefore be reasonably supposed to indicate the presence of an underlying mass of muscovite-biotite gneiss; as they increase or decrease in quantity, it becomes obvious that this gneiss is nearer to or deeper below the surface. But the area over which they occur is so great that, viewed on a large scale, the upper surface of this igneous mass must be roughly horizontal. And so we are led to the conclusion that these gneisses occur in huge sills or laccolites having approximately horizontal upper surfaces. That this is the true explanation of their mode of occurrence is rendered almost certain by the fact that we have already mapped a sill of muscovite-biotite gneiss, closely resembling the gneiss of the permeation-area in its mode of intrusion, in which both the top and the base keep at a fairly uniform horizon. This permeating sill is so inextricably interwoven with the cyanite-schists and other rocks with which it is associated that it was not until Mr. Teall showed how the minute structures of the thin intrusions were largely those of original igneous rocks that it became possible to believe that the whole complex mass was not of one age and of one mode of origin. If this mode of intrusion as sills or laccolites be admitted, it follows that one of the chief factors in increasing or decreasing metamorphism of the rocks affected must be the variation in depth of the sills below the surface. In the case of ordinary granite-intrusions it is customary to measure the metamorphism by the distance from the edge of the granite at the surface; but in the special case under consideration it must rather be measured by the height above the top of the intrusion.

The intensity of the metamorphism is doubtless largely due to the great depth below the surface of the rocks affected by the intrusion. The importance of this factor is conclusively shown by Dr. Barrois in his papers on the granites of Britanny. The same mass is there proved to have affected Cambrian, Silurian, and Devonian rocks; but the metamorphism in the Cambrian strata is more pronounced than in the Silurian and still more than in the Devonian. In other words, the lowest rocks are most affected.

In estimating the difference in depth at which the change took place in the rocks of the different periods, account must be taken not only of the thickness of the deposits, but also of the folding to which they had been subjected before the intrusion of the granite. If the folds were of great depth, the older rocks would be buried under a cover of newer strata, the original thickness of which would be enormously increased. Now, in the area to which this paper refers, it can be shown that the rocks affected are the lowest in the series and that they have been enormously folded, the depth of the major folds being apparently never less than 2000 feet. Thus the occurrence of sillimanite and coarsely crystalline gneisses over large areas may be easily explained by the great depth at which the metamorphism took place.

Rocks of the kind described in this communication are usually of great antiquity, and their especial features are regarded by some geologists as evidence of the existence in early geological times of physical conditions distinctly different from those which now prevail. The considerations which have been advanced above suggest that these special features may after all be due to the depth in the earth's crust at which the metamorphism took place, rather than to any physical conditions peculiar to early geological time. A comparison of the rocks of Shap and New Galloway with those of the district under consideration shows that the difference between them is one of *degree*, not one of *kind*, and strengthens Dr. Barrois's conclusion that "regional metamorphism and contact-metamorphism are much the same thing." The great geological age of most, if not of all, of the areas where phenomena similar to those we have referred to may be observed receives a simple explanation in the fact that an enormous amount of time is required to remove the overlying material by denudation.

Summary of Results.

1. In the area drained by the higher branches of the Forfarshire North Esk and South Esk, there are a number of outcrops of an igneous rock varying both in structure and composition.

2. The variations in structure are due to the presence or absence of foliation; while those of composition are due to changes in the relative proportions of the potash-bearing constituents (microcline and white mica) and those constituents in which the characteristic bases are soda and iron (oligoclase and biotite).

3. As the various intrusive masses are followed towards the south-east the amount of potash-bearing constituents increases, and the soda-felspar (oligoclase) diminishes.

4. The masses are frequently fringed with pegmatite (in which the potash-bearing constituents attain a maximum), especially on their southern and eastern borders.

5. The fact that these pegmatites occur over a very large area in the South-eastern Highlands suggests that a great portion of the district must be underlain by the intrusion of which they form a part.

6. The rocks that surround the areas in which the intrusive masses are exposed at the surface, are in a coarsely-crystalline condition.

7. This coarsely-crystalline character decreases as the rocks are followed towards the south-east.

8. Three zones characterized by the abundance of the three minerals, sillimanite, cyanite, and staurolite, may be roughly mapped out in the North-west Forfarshire area.

9. The sedimentary character of the metamorphic rocks as a whole is established by their chemical composition. Limestones, shales, quartzites, and coarse grits may all be recognized in the metamorphic zones.

10. A special feature in the altered rocks is the abundance of oligoclase. This is explained by the frequent occurrence of this mineral in the grits of the Highland border, and by the presence of a high percentage of alkalis in the phyllites. The potash which was present in the original rocks is entirely absorbed in the formation of the micas.

IX. Analyses of the Rocks.

The appended table of analyses[1] shows the composition of

A. The brown mica of the igneous rock.
B. The white mica of the igneous rock.
C. The brown mica of contact-metamorphism.
D. The white mica of contact-metamorphism.
E. The grey slate or phyllite, north of the Great Highland Fault.
F. The staurolite-schist north of Bulg.

[1] Analyses E and F were made by Mr. A. Dick, Jun., who moreover kindly helped me with the others.

The brown micas are both rich in ferrous oxide and low in magnesia. They belong to the haughtonite group. The white mica of the altered rocks contains appreciably more soda than that of the igneous rock; but the water of crystallization in the igneous mica is more than twice as great as in the contact-mica. This is true of both brown and white mica, but it is more noticeable in the latter case.

The grey slate or phyllite shows the high percentage of alkalis (6·41) which the finer sediments of the Central Highland Series contain. This rarely falls below 5, and often reaches 7 per cent.

The staurolite-schist affords a perfect example of a rock that can be proved to be a sediment by analysis. The percentage of alumina shows that it must have been a clay or a shale. No known igneous rock could have even approximately such a composition. The iron is about the same as that given in Prof. Renard's analyses of the Ardennes phyllite, and was originally in the form of pyrites.

	A.	B.	C.	D.	E.	F.
SiO_2	34·90	43·08	35·00	45·80	58·00	39·70
Al_2O_3	23·27	32·85	25·06	31·84	20·16	36·40
FeO	20·87	2·76	15·30	......	......	......
Fe_2O_3	2·56	·73	3·94	5·86	7·64	9·60
CaO	1·20	1·07	1·50	Trace	·73	1·20
MgO	4 32	·33	6·48	1·15	2·49	3 20
K_2O	6·94	8·78	9·31	7·56	3·91	3·60
Na_2O	2·01	1·00	1·84	3·19	3·41	2·58
Loss	3·60	9·12	1·72	4·90	3·03	4·50
Total	99·67	99·72	100·15	100·30	99·37	100·78

EXPLANATION OF THE PLATES.

(Map) Plate XV.

For many miles to the S.W. the Central Highland rocks have been found to be pierced by a number of coarse pegmatite-veins, the origin of which was uncertain. They have now been clearly traced to the parent mass, a muscovite-biotite gneiss, from which they proceed. The Map shows the only known outcrops of this parent mass in the South-eastern Highlands. To the N.W. the gneiss is let down by an enormous fault, but in all other directions it is sinking very slowly beneath the crystalline schists, the *upper limit*, however, being extremely uneven.

The small patches in the sillimanite are upward prolongations of the type of No. 2 or the centre of No. 3. No other outcrop of No. 4, the southerly termination of the intrusion, is known. The zones of staurolite- and cyanite-gneiss or schist really represent the variation in *height above* the upper limit of the underlying gneiss.

The great fault, shown to the N.W., crushes and greatly alters these metamorphic rocks, while the newer granite and diorite are more recent than this fault, as the Map clearly shows in the case of the diorite. Further, these newer intrusions largely destroy the older crystallization, as may be seen in Glen Clova. (Shown in the scars a little above 'G' of 'Glen' on the Map.)

Specially good places for observing the minerals sillimanite, cyanite, and staurolite are shown by the letters S, C, and St., and good outcrops of limestone by the letter L.

PLATE XVI.

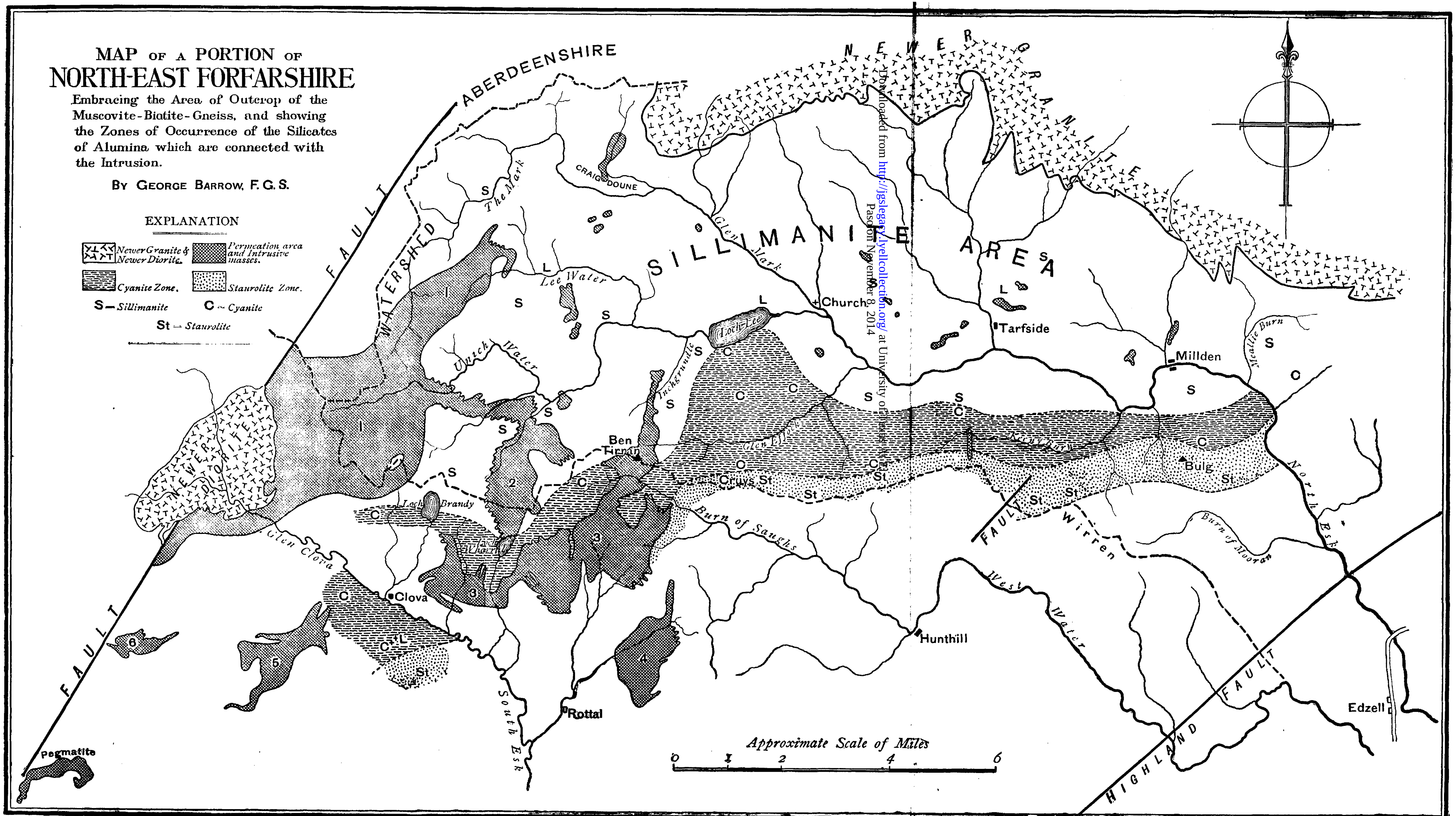
Fig. 1 (Slide No. 4540). Sillimanite-needles in quartz. × 40 diameters.
Fig. 2 (Slide No. 4531). Sillimanite associated with mica. Close to the Lee Water, North Esk. × 40 diameters.
Fig. 3 (Slide No. 4547). Cyanite-schist or gneiss. In the centre of the field is a crystal of cyanite enclosing a small garnet. The cyanite shows the planes of easiest cleavage, and the gliding-planes parallel to the base. The garnets are very similar to those shown in pl. xxiii. vol. xlvi. of this Journal, which have been developed by the contact-metamorphism of the Galloway Granite. × 20 diameters.
Fig. 4. Iron-ore inclusions in cyanite. 'Contact-structure.' Bulg, North Esk. × 20 diameters.
Fig 5 (Slide No. 5101). Staurolite surrounded by 'shimmer'-aggregate. × 20 diameters.
Fig. 6. Brown contact-mica, in the position of maximum and minimum absorption of light. One half shows the pleochroic spots in the most marked manner, in the other half the spots are almost invisible. Some cyanite (glassy-white mineral) is also present, showing the typical high refractive index by its strongly-marked borders.

DISCUSSION.

The PRESIDENT said that it was of great advantage to the Society to have communications from the Officers of the Geological Survey now engaged in the work of mapping the Highlands of Scotland. In this paper the Author suggested solutions of some geological puzzles. He (the speaker) asked for fuller information as to the relations between the oligoclase- and microcline-bearing portions of the intrusive masses; as to the effects of the later granite; and as to the nature of the original rocks. Why was sillimanite found in one area, cyanite in a second, and staurolite in a third?

Prof. JUDD called attention to the circumstance that the district described by the Author of the paper is near Kinnordy, the birthplace and home of the late Sir Charles Lyell. A year or two before Lyell's death, the speaker had spent some days in Glen Clova, in company with the veteran geologist, examining the geological structure of the district, and they had been greatly impressed by the intricacy as well as the suggestiveness of that structure. He complimented the Author of the paper on the thoroughness and excellence of his work in the district, and was pleased to find that the Officers of the Geological Survey, in carrying on their important studies of the Highland rocks, were ready to accept and weigh all evidence, without any reference to preconceived opinions. He remarked, in conclusion, that the paper constituted a splendid vindication of the principles so long ago enunciated by Lyell concerning the mode of formation of the 'hypogene rocks.'

Mr. RUTLEY fully endorsed the statements of the last speaker with reference to the value of the paper. He considered that some of the rocks exhibited bore a resemblance to those met with in the Malvern range, and that the latter had probably been altered under conditions similar to those which the Author had indicated. He thought it likely that both sillimanite and cyanite might be developed in the same rock, but that staurolite would be formed in a



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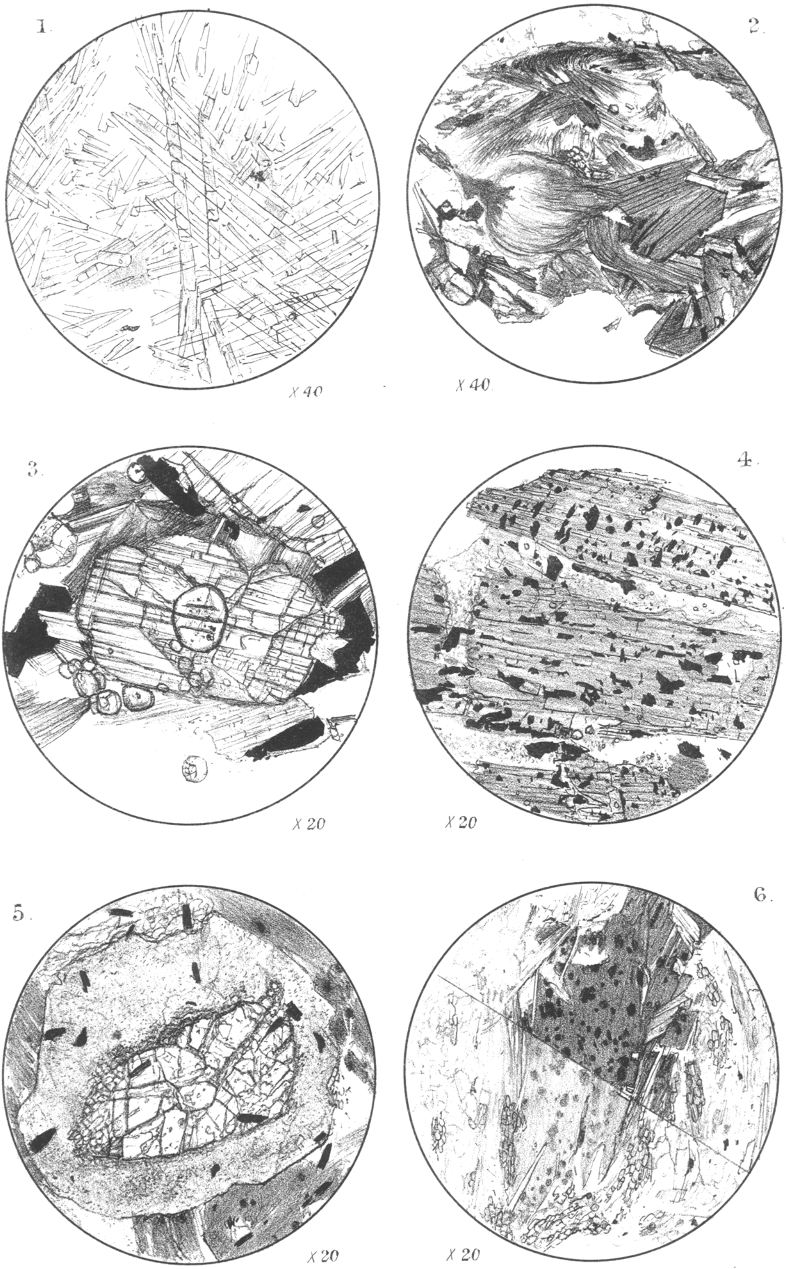

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MINERALS DEVELOPED BY THERMOMETAMORPHISM OF MUSCOVITE BIOTITE-GNEISS.

rock differing in composition from that in which the sillimanite and cyanite were developed.

General McMahon congratulated the Author on the interest and importance of his results. Of late years the geological mind had been so fascinated with the doctrine of dynamo-metamorphism that thermo-metamorphism and the foliation of igneous rocks prior to their complete consolidation had not received adequate consideration. It was encouraging to find that the tide had now turned. In the Himalayas, where the eruptive gneissose granite was of a strongly porphyritic type, he had observed in some places that the porphyritic structure was well maintained in veins sent off from the main mass into the adjoining sedimentary rocks. When an eruptive rock had been moved into position after the partial crystallization of the magma, such a result might be expected; and when a mass full of crystals was forced through the jaws of a fissure, parallelism of structure and the crushing and crumpling of crystals would inevitably result.

General McMahon also alluded to observations at the Lizard made by Prof. Bonney and himself, where the very coarse-grained gabbro was not in the main mass but in small dykes—a state of things analogous to the Author's observations regarding his 'giant granite'; and it pointed to a similar cause, namely, to the moving up at a later stage in an eruption of deeper-seated portions of a magma, the crystallization of which had considerably advanced.

Dr. Hicks said it was clear the results referred to by the Author could not have originated from one cause, but during a period when a combination of circumstances tended to favour such changes. Mechanical movements were necessary, if only to produce the fractures through which the magma and the heated waters and vapours permeated the rocks. The recent intrusions could have had little or no influence in producing the main results, as the evidence clearly pointed to their having taken place at a much earlier period. Similar pegmatite-veins were found traversing not only the rocks in the Central Highlands, but also those of the North-western Highlands, and fragments which must have been derived from such veins occurred frequently in the Torridon Sandstone. He was satisfied that the metamorphism of these rocks dated back to pre-Cambrian time; but there was no reason, of course, why such changes should not have taken place since that time. What he maintained was that for hundreds of square miles rocks of similar composition, and showing a similar state of change, were to be found, and that, under the circumstances, it was legitimate to attempt here a correlation by petrological characters. The differences observed were in the main due to the original character of the sediments, and to the readiness of the materials to undergo change. He congratulated the Author on the broad and liberal manner in which he had dealt with the several questions involved.

Mr. Marr said that, in their joint paper on the Shap Granite, he and Mr. Harker had expressed the hope that their work would be found to have a bearing on the general question of metamorphism.

The present communication showed that this was the case. He mentioned a letter from Mr. Greenly, who stated his belief that great masses of gneiss behave as igneous rocks, chiefly as sills, and that their foliation was acquired at the time of their intrusion. He (Mr. Greenly) had observed junctions and inclusions of schists in gneiss similar to those figured by Lawson, and had noticed the development of sillimanite and cyanite in such of the sedimentary schists as could have furnished material for the growth of these minerals.

Dr. Du Riche Preller wished to ask the Author whether and how far the more recent eruptive rock shown in the diagram, and marked 'newer diorite,' had affected the contiguous older igneous (granitic) mass. He congratulated the Author on his paper, and on the ingenious and conclusive way in which he had worked out the process of the potash-bearing part of the magma being forced out, and of the potash being subsequently consolidated and crystallized into microcline and muscovite. In this connexion, Dr. Preller asked what, according to the analysis made, was the relative proportion of silica and potash in the rock in which the latter formed so large a constituent. He also wished to express his entire concurrence in Dr. Hicks's view that the metamorphic phenomena described in the paper were due not only to thermal but also to dynamic agency. Indeed, it could not be otherwise, for, physically speaking, one agency involved the other.

Mr. Teall said he had watched the growth of this paper, and could testify to the great amount of important detail contained in it. It was almost impossible to give an idea of such a paper in the short time available for reading. Vernadsky had shown that cyanite could be converted into sillimanite by heating to about 1300° centigrade, and the latter mineral had been proved by Mr. Barrow to occur in the most highly altered area. It appeared probable, therefore, that the line separating the sillimanite-zone from the cyanite-zone was an isothermal.

The Author only claimed credit for holding fast to Lyell's principles of uniformitarianism. In answer to the President, he said that the metamorphism of the newer granites could be easily separated from that which he had described. Its effect was to destroy many of the characters due to the earlier action.

In reply to Dr. Preller, he remarked that the microcline of the pegmatites was perfectly normal in its composition, but that owing to the coarseness of the grain he had not determined the relative proportions of felspar and quartz.