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Some mineralogical and chemical changes induced by progressive metamorphism in the Green Bed group of the Scottish Dalradian.

(With Plate X.)

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INTRODUCTION.

THE petrology of the igneous rocks has for the last quarter of a century been established on a sound quantitative basis, largely as a result of the body of experimental work available on silicate melts. In the field of metamorphism, however, progress has been much less marked, and the difficulties of the laboratory development of stresses comparable with those acting during regional metamorphism must for some time leave our knowledge of the crystalline schists far behind that even of the hornfelses. A quantitative approach, however, is not confined to the experimental side. The introduction of the conceptions of facies and grade[1] raises a new need for exact knowledge of the compositions of the various minerals, both of those constituting the different isophysical assemblages of a given grade, and of the isochemical assemblages representing a given rock under the grade-conditions of the various facies established. The need is for fuller chemical investigation, where possible, of individual minerals

[1] P. Eskola, Norsk Geol. Tidsskr., 1920, vol. 6, pp. 143–194; C. E. Tilley, Geol. Mag., 1924, vol. 61, pp. 167–171.

as well as of the rock in bulk.[1] With increasing knowledge of the effects on optical properties of the various components which enter into solid solution in natural minerals it is becoming increasingly possible to determine a mineral accurately from optical data, so that where actual separation is not feasible a full statement of these data, even for the commonest constituents, is of value.

The universal stage affords the readiest means of carrying out a full investigation of individual crystals in a thin section, yet it is still regrettably rare for a petrologist to avail himself of this opportunity in routine descriptive work. In the felspar group, much work has been done on the well-formed phenocrysts in andesites and allied igneous rocks, but application of the method even to this group of minerals in the crystalline schists is practically untouched. The account presented below is to be regarded as an indication of desirable lines of research, rather than as a complete contribution in itself.

General character of the Green Beds.

The Green Beds of the Scottish Dalradian succession form a series of widespread development which is readily distinguishable by marked characteristics, and has the advantage of occurring in an area in which the zoning of progressive metamorphism as determined in pelitic rocks rests on a fairly firm basis.[2] From their characteristic bedding and jointing, intercalated pelitic bands, lateral passage into other types, and the frequent presence of pebbles of quartz they are readily seen, at least in the lower grades, to be of sedimentary origin; yet they possess distinctive chemical characteristics, most readily explained by fairly direct derivation from basic igneous rocks and deposition without much admixed material. In proportion as the amount of foreign material increases, they pass from their own distinctive isochemical group towards normal psammitic or pelitic rocks. This view was long ago put forward by the Geological Survey,[3] but the published evidence seems to consist of a single analysis of a rock from Ardlui, Loch Lomond.[4] Five new analyses have therefore been obtained of material from various grades, (Anal. I–V), and with these is quoted the Survey analysis. The first glance reveals wide variation in the silica-content, a constituent whose passive role

1 C. E. Tilley, Min. Mag., 1926, vol. 21, p. 46.
2 C. E. Tilley, Quart. Journ. Geol. Soc. London, 1925, vol. 81, pp. 100–112.
3 Mem. Geol. Survey, Scotland, Sheet 37, 1905, p. 18.
4 Geol. Survey Summary of Progress for 1903, 1904, pp. 57–58.

in many metamorphic changes has been emphasized.[1] The essential chemical resemblances and differences are more readily appreciated if the Niggli values for *al, alk, fm, c* and *k, mg* are calculated (Table II) and plotted (figs. 1 and 2). The *si* numbers, of course, show considerable variation (112–353), but the points in the *al-alk-fm-c* tetrahedron fall close together, and within the field of composi-

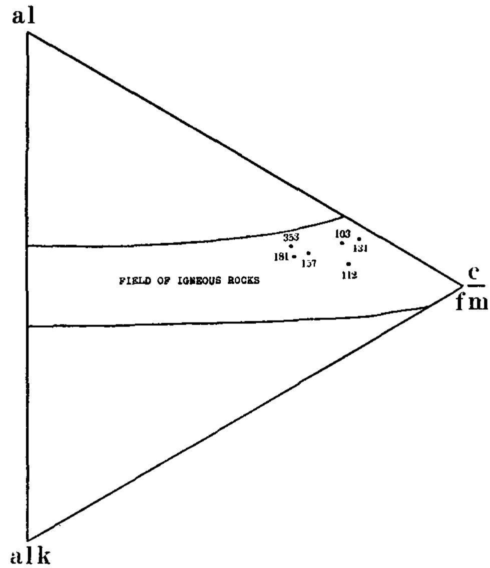


Fig. 1. Plot of analyses I–VI on section of the *al-alk-fm-c* tetrahedron.

tion of igneous rocks in a position corresponding in general to a gabbro magma-type. The close resemblance of analysis VI to that of many ‘ diabases ’ was pointed out by Sir J. S. Flett; the clustering of the points in fig. 1 brings out well the essentially isochemical character of the series under investigation.

Sediments of Green Bed character occur at several horizons in the outer part of the Dalradian succession, but the main development is between the Loch Lomond and Loch Tay series, not far below the Loch Tay Limestone. A zone in which they occur abundantly, though with intercalations of other sediments, can be followed more or less continuously from Kintyre north-eastwards to Glen Clova, in

[1] C. E. Tilley, Min. Mag., 1926, vol. 21, p. 38.

which direction it thins gradually. Its non-appearance farther north-east than Glen Clova might be due to various causes, and no evidence at present available enables a decision to be made.[1] During this course the Green Beds pass gradually from the lowest grades just to the kyanite-sillimanite boundary, as determined in pelitic sediments. In the higher grades their separation from the intrusive rocks with which they are frequently associated is often difficult, but crushed

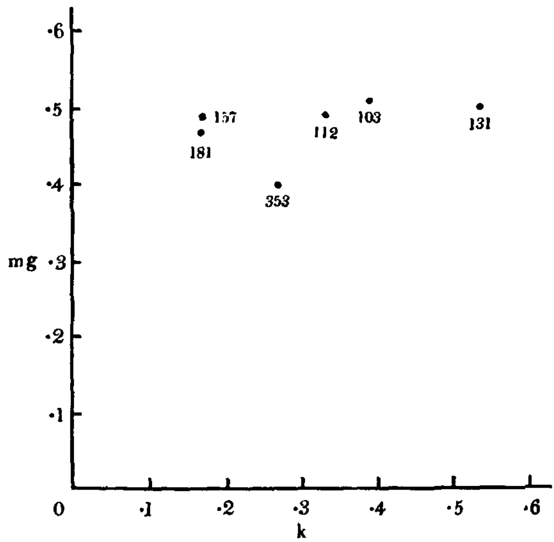


FIG. 2. *k-mg* diagram for analyses I–VI.

sills usually show a more lenticular structure, inconstant jointing, and rusty weathering. A sketch-map is appended, showing their approximate distribution in relation to the one-inch maps of the Geological Survey (fig. 3).

No extended account of the Green Beds as a group has been published. They receive attention in the various official memoirs covering the areas in which they occur (see especially those for sheets 37, 46, 47, 55, and 65), and in many of the Summaries of Progress issued during the mapping (particularly from 1897–1903). They are also referred to briefly in many publications on the tectonics of the Dalradian area, and on the regional metamorphism of this and other districts.

[1] H. H. Read, Trans. Roy. Soc. Edinburgh, 1928, vol. 55, p. 770.

General account of Progressive Metamorphism.

The chlorite zone.

In its lowest grade of metamorphism the typical Green Bed presents itself as a chlorite-albite-epidote-schist. Abundant *chlorite*, to

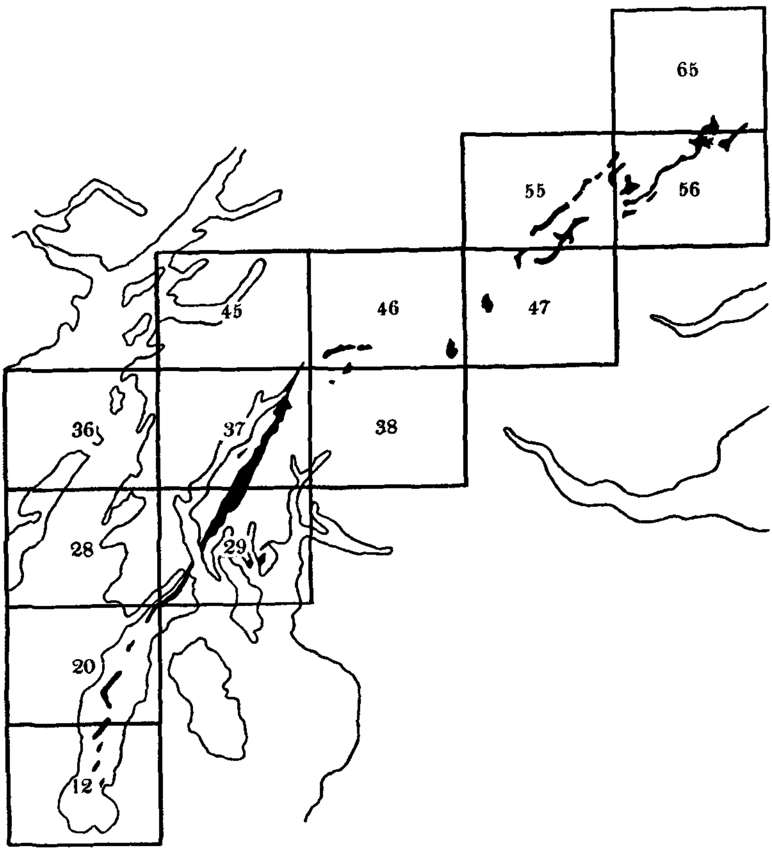


Fig. 3. Sketch-map showing the approximate distribution of the Green Beds in relation to the one-inch maps of the Geological Survey.

which the colour of the rock is mainly due, occurs as long lath-shaped crystals or as scaly aggregates. It is of greenish-yellow colour, but the depth of colour and strength of pleochroism are quite variable; where larger crystals wrap around opaque iron-ores they often acquire a deeper colour and stronger pleochroism from green to yellow. The double refraction rises slightly, too, and whereas much of the material may be sensibly isotropic these areas give deep brownish-purple anomalous interference colours. Occasionally the chlorite builds stumpy porphyroblasts set across the schistosity.

The *albite* occurs as rounded crystals showing considerable variation in size, the structure varying from strongly porphyroblastic to equigranular; and in finer aggregates with quartz in the groundmass. Many of the larger crystals show a cloudy zone of inclusions in the interior; lamellar twinning is not common, occasionally a trace of zoning can be seen.

The amount of *epidote* varies fairly widely, and from many slides it is almost or entirely absent. It may occur as aggregates of pale yellow-green granules giving a cloudy appearance under low powers, or as larger well-formed crystals, yellowish-green to greenish-brown and often showing zoning between crossed nicols. Its irregular distribution in streaks and bands often shows up prominently the original sedimentary character of the rock.

A variable and often large quantity of *quartz* is seen in most slices, and the larger lenticular patches of partially recrystallized aggregates sometimes obviously represent original quartz pebbles partly broken down. Opaque iron-ores—magnetite, pyrite, and a titaniferous iron-ore associated with granular sphene—rutile, idiomorphic apatites, and occasional tourmaline needles are all accessory minerals of the normal rock. A carbonate mineral is frequently present, and its habit and relationships suggest in many cases that it is a primary mineral of the metamorphic assemblage.

A constituent of sporadic occurrence, but notably abundant in certain types, is an almost colourless *mica*. Even when present only in very occasional flakes amongst the chloritic ground it is easily detected by its high polarization-colours, and examination in ordinary light then usually reveals that it is distinctly coloured a very pale green, and is pleochroic between this tint and colourless. In extreme cases this coloration approaches that of a pale chlorite. The mica is finely divided and evenly distributed throughout the groundmass; in types in which it becomes more abundant it contributes to a felted structure of the whole micro-section.

The appearance of a dark mica in these low-grade rocks signalizes a slightly increased grade of metamorphism, but begins well below the biotite isograd of pelitic rocks.[1] Its first appearance is usually

[1] C. E. Tilley, Quart. Journ. Geol. Soc. London, 1925, vol. 81, p. 103.

as small green-brown streaks bridging larger chloritic patches and readily distinguished by their more pronounced pleochroism. As it becomes more abundant, it acquires a deeper colour and a pleochroism from yellow-brown to a deep brownish olive-green. It usually follows the schistosity closely, but may also form radiating sheaves, or more rarely be set in porphyroblasts across the cleavage. In these the elongation is much less, cross-sections being practically square; lines of epidote granules may continue the schistosity through these porphyroblasts. The early appearance of biotite may be seen in the middle of the chlorite zone in the south-west, on the shores of Loch Striven; and again farther north-east in numerous localities in the neighbourhood of Loch Lubnaig and the eastern half of Loch Earn.

The biotite zone.

As described above, the Green Beds begin to develop a dark mica considerably in front of the biotite isograd in pelitic rocks, and the passage into the biotite zone itself is not marked by any pronounced new mineral development. In all the rocks of normal composition biotite is now an abundant constituent, and from localities farther north-west, in the direction of higher grade, as, for example, in material from the head of Hell's Glen, Cowal, it can be seen to be acquiring a more brownish tinge, marking a gradual approach in appearance to the normal red-brown mica. In the more melanocratic rocks chlorite is still present, often deeply coloured and strongly pleochroic, but it is scarce or absent in the case of more gritty varieties. A rock from Ballochandrian, near Glendaruel, Cowal, may be described in detail, as a partial mineral separation has been carried out (p. 251); the bulk analysis is given (anal. I). The rock is coarse-grained and gritty, with abundant quartz n rudely lenticular patches. Greenish biotite, with pronounced elongation, forms crystals up to 1 mm. long. The other important dark mineral is a yellow epidote in granular aggregates tending to occur between the more quartzose patches; chlorite is practically absent. The fairly abundant albite shows a strong tendency to porphyroblastic habit, with lamellar twinning not uncommon and occasionally a very slight degree of zoning. Calculation of an approximate mode gives quartz 54, epidote 20, albite 14, and biotite 12 %.

Less siliceous varieties from this zone show the usual accessories, and passage types a similar type of greenish muscovite to that described from the lower-grade rocks above.

The garnet zone.

The Green Beds are found within the garnet zone in the south-west near Loch Tarbert and Loch Fyne, and pass again completely across the zone in Perthshire. With their considerable variations in composition, they may themselves show the almost immediate development of garnets; as, for example, near the junction of the Cur and the Cab, south of Strachur, Loch Fyne (memoir for sheet 37, p. 20), and west of Loch Fender, Amulree; but the areal distribution of garnet is decidedly irregular and single thin sections may show it confined to narrow bands. Biotite is fairly constantly present, and is now a more brown or typical red-brown colour. Hornblende now becomes important, usually with a marked acicular habit, and only occasionally as platy crystals, which latter sometimes show zonary extinction. The colour and pleochroism are fairly constant, and the γ axial tint in particular is characteristic; α yellowish, β brownish-green, γ bluish-green. The extinction $\gamma : c$ is usually about 20 °.

Epidote, sometimes accompanied by zoisite, is present only in diminished amount, and may be associated with the biotite in eyes and lenticles. Chlorite may have survived in small amounts, sometimes intergrown with the biotite; a colourless mica is rare. Clastic structures are not often seen, except where large pebbles remain as patches of recrystallized quartz; the structure is pronouncedly schistose. In the dominantly hornblendic types, however, the garnets do not usually form the centres of marked eyes, this appearance being confined to the micaceous examples.

Higher zones.

Between Pitlochry and Kirkmichael the Green Beds run in the broad expanse of the garnet zone in this district, and pass on the south-west side of Glen Clova within the higher zone of kyanite and just up to or across the boundary with that of sillimanite, but do not themselves show the development of aluminium-silicate minerals. The texture becomes increasingly coarse, and hornblende is the predominant or only ferromagnesian mineral, and it is here that great difficulty is experienced in separating them from doleritic intrusions. A pebbly example from the south of Caddam, Clova, shows small rounded garnets in certain layers only. The felspar is now an oligoclase or andesine (p. 250).

The felspars.

It was early established that of the plagioclase isomorphous series the pure albite end-member is a characteristic stress mineral, whilst anorthite is anti-stress.[1] In low-grade dynamic metamorphism the reconstituted felspar is a pure albite, but as the metamorphic grade increases a more calcic member of the series becomes stable. From this view-point a special study has been made of the composition of the plagioclases of the Green Beds by means of the universal stage.

The newly-developing conception of the facies classification of metamorphic rocks is vitally concerned with the degree to which equilibrium is maintained in the various mineral assemblages, and such rocks as the Green Beds are suggested as indicators,[2] in view of their apparently high sensitivity to changes of temperature and stress. The first sets of measurements were therefore made on duplicate slides of material, both in the case of low- and high-grade localities, and suggest that so far at least as the felspars are concerned the adjustment to equilibrium is close. Within the chlorite zone no felspar has been measured showing more than 3 or 4 % of anorthite, which within the limits of error of the method can be considered pure albite. A succession of measurements of material from Glen Clova showed a composition constant between the limits 29–35 % of anorthite.

Much of the felspar is of course untwinned, but results can always be obtained from measurements of cleavages or (much less reliably) the optic axial angle 2V. Twinning when present is usually simple, the complicated twinning of the phenocrysts of igneous rocks being rarely if ever observed. It is rare, too, to find association on more than two laws in a single crystal, and of these laws a high percentage are well-known twins. As in igneous rocks, twins associated on (010) are usually much the commonest, and of these albite twinning the most frequent. The pericline twin, however, becomes important much nearer the albite end of the series in these metamorphic rocks than is the case in igneous rocks, and this fact is likely to lead to error in determination by orthodox methods.[3] The percentage frequencies of the various laws as observed in these Green Beds are for all the measurements: albite 60, pericline 17,

[1] F. Becke, Denkschr. Akad. Wiss. Wien, Math.-naturw. Kl., 1913, vol. 75, pp. 42–43.

[2] C. E. Tilley, Quart. Journ. Geol. Soc. London, 1923, vol. 79, p. 200.

[3] F. Coles Phillips, Min. Mag., 1930, vol. 22, p. 225.

Carlsbad 16, and other laws 7%. Of the pericline twins, however, 80 % contain more than 25 % anorthite.

The cleavages are sometimes interesting, for the good cleavages (001) and (010) of idiomorphic felspars are less frequently seen in these porphyroblasts than a cleavage (110) or a series of cracks approximating to this direction. A similar observation has been made by Carstens,[1] who attempts to correlate rarity of the (001) and (010) cleavages with the surface forms of the porphyroblasts. The same writer found in general no parallel arrangement of the felspars. Though no attempt has yet been made to investigate this systematically in the case of the Green Beds on the lines developed by Sander and Schmidt,[2] work with the universal stage makes it quite apparent that there is some regularity of arrangement. If a particular section happens to be so cut that for the first felspar investigated two particular axes such as α and β can be directly determined, then it is frequently found that the majority of the other felspars of that section will give the same pair. Schmidt has found a similar regularity in felspars as well as in quartz.[3]

Two other features in the felspars call for comment. The reconstituted albite is usually water-clear except for foreign inclusions, which are often zonally arranged. Occasionally, however, a felspar is seen which shows between crossed nicols a variety of wavy, perthitic, or chequer intergrowth ; in some cases the pattern of these is extremely regular, but no intergrowth of two minerals could be seen in ordinary light, even with careful manipulation of the condenser and diaphragms. Becke described similar appearances in chequer-albites,[4] where newly-formed albite is homoaxially arranged in conjunction with original potash-felspar. He describes the similarity of oblique sections to sections of anorthoclase, and the frequent presence of a later fringe of normal twinned albite, both of which features have been observed in the felspars of the Green Beds and confirmed by universal stage measurements. No case has been seen, however, in which an obvious difference of refractive index between the two felspars (if such they be) could be observed, nor has it so far proved possible to correlate the presence of these possible chequer-albites with any indications of a potassic character in the rock.

[1] C. W. Carstens, Norsk Geol. Tidsskr., 1924, vol. 7, pp. 241–242.
[2] W. Schmidt, Min. Petr. Mitt. (Tschermak), 1925, vol. 38, pp. 392–423.
[3] W. Schmidt, Neues Jahrb. Min., Abt. A, 1928, Beilage-Band 67, pp. 203–222.
[4] F. Becke, Denkschr. Akad. Wiss. Wien, Math.-naturw. Kl., 1913, vol. 75, p. 125.

The zoning of felspars in metamorphic rocks also first received detailed attention from Becke, who demonstrated that very frequently the zonary arrangement is the reverse of that familiar in crystallization from a melt, a more albitic kernel being surrounded by a more anorthitic shell. The Green Beds of the lowest grades contain nearly pure albite, in which there is no measurable zoning, although in many sections the extinction is not quite uniform throughout each crystal. Where an oligoclase or oligoclase-andesine becomes stable a moderate degree of zoning is sometimes present; and, by measurements of optical orientation, optic axial angles, or extinctions from determined directions, it was confirmed that the core was less anorthitic than the outer shell, with differences of composition of the order of a few per cent. of anorthite. A similar reversed zoning has been observed by Carstens in his material from the Trondhjem district.[1] As the observations of Becke have not been always confirmed by later writers, one possible cause of failure to detect the true direction of the zoning may be suggested. A frequent combination of twinning in the oligoclase-andesines of the Green Beds is multiple pericline twinning, with rare albite lamellae making with the pericline lamellae an angle of less than 90°. If cleavage is not visible and the direction of frequent twinning be assumed as the (010) direction, orthodox determinations of extinctions would give a reversed interpretation of the zoning over a certain range of composition.

Grubenmann and Niggli[2] have put forward an explanation of this reversal in terms of the solubility relationships of the plagioclases. Anorthite being the more soluble, pure albite will separate first from aqueous solutions, and anorthite will thus be successively enriched outwards. With a given kernel, more of the soluble anorthite will pass into solution, and on the Riecke principle will crystallize out in places of low pressure. Becke has himself observed that the calcic shell does not always completely surround the acid core, but may be developed on one or two sides only.

Composition of the plagioclases.

It has been observed that the plagioclase throughout the lower grades is uniformly albite. Measurements have been made on

[1] C. W. Carstens, loc. cit., p. 242.

[2] U. Grubenmann and P. Niggli, *Die Gesteinsmetamorphose*, I. Berlin, 1924, p. 425.

material from various localities in the chlorite zone in the districts of Loch Katrine, Strathyre, and Loch Earn, and in slightly higher grades from Ballochandrian, Balquhidder, &c. The anorthite molecule only begins to enter noticeably into the composition of the plagioclase when the garnet isograde is passed. Measurements of material from localities around West Loch Tarbert, Loch Fyne, and south of Aberfeldy give compositions of $Ab_{95}An_5$ to $Ab_{90}An_{10}$. As the grade increases farther, the plagioclase is taking part actively and the composition changes rapidly. The most calcic felspars measured occur near the summit of the Hill of Strone, south-west of Glen Clova (2778 feet), near the kyanite-sillimanite boundary, with a composition of $Ab_{63}An_{37}$, medium andesine. At the north-east side of Glen Clova, near Loch Brandy, the average composition of a large number of measurements was $Ab_{68}An_{32}$.

It is interesting to compare with these results a series of measurements on the felspars of the associated epidiorite sills. Though of closely similar composition to the Green Beds chemically, they differ in the important feature that they represent a high-temperature association only partly accommodated to low-temperature conditions.[1] In the lowest grades, the original felspar has undergone saussuritic change, and the plagioclase now present is pure albite, but the calcic portion is represented by epidote, zoisite, &c., usually forming a core of inclusions in the albite. The change in the Green Beds from a chlorite-albite-epidote assemblage to that of hornblende and plagioclase is paralleled in these rocks by the gradual re-absorption of the calcic minerals to give a more calcic plagioclase. The actual compositions of the felspars are closely similar in the two series; averages for the epidiorites are: St. Catherine's Ab_{100}, Balquhidder $Ab_{95}An_5$, Kinloch Rannoch $Ab_{83}An_{17}$, Pitlochry $Ab_{76}An_{24}$, Glen Clova $Ab_{63}An_{37}$.

Mineralogical changes on metamorphism.

It has been observed that the Green Beds in their lowest grade consist mainly of recrystallized chlorite, with lime present largely as epidote, pure sodic felspar, and a white mica in the more pelitic varieties. One of the earliest changes is the production of a green-brown biotite. The genesis of biotite at this stage usually involves interaction of chlorite and sericite, and in these highly chloritic rocks the available sericite is often rapidly consumed. It has been suggested,

[1] C. E. Tilley, Geol. Mag., 1924, vol. 61, p. 170.

in fact, that the mica-like mineral which forms in rocks low in potash is not a true potash-mica, but the optically similar stilpnomelane.[1] A separation was carried out on a rock from Ballochandrian, Cowal (p. 245) and the greenish-brown material analysed (Anal. VII, p. 255).

In view of the urgent need of many more analyses of this kind, it may be valuable to outline the methods of separation employed. The particular rock was chosen as being fairly simple in mineralogical constitution, but the chief difficulty lay in the inconsistent behaviour of the dense but flaky mica, which ruled out the use of heavy liquids. The average grain of the rock was measured in thin sections, and a quantity crushed to a mesh-size likely to avoid composite grains. This material was then run through a Hallimond magnetic separator, and the medium magnetic concentrate, already largely mica, put through a second time. The chief foreign material at this stage was granular epidote, and an effective separation was achieved by the use of a glazed pasteboard tray, perforated at one corner, as a primitive 'shaking-table'. A small quantity of the concentrate was spread along one side of the tray, which was then tapped rapidly by the fingers of one hand, whilst held slightly inclined. The granular epidote travelled more rapidly over the surface than the tabular mica and could readily be manœuvred to fall through the perforation in advance of the latter. Finally, the material was picked over, a small quantity at a time, under a binocular microscope, and any foreign grains removed on a moistened camel-hair brush.

The mineral is a true potash-mica, fairly high in ferric iron; its composition can be represented almost exactly by a Tschermak mixture of muscovite and olivine. Quite comparable analyses are recorded by Doelter.[2] The refractive index, γ 1·63, was determined by immersion and accords fairly well with the graph given by Grout,[3] who also notes that a green colour in a mica is at least suggestive of a considerable content of ferric oxide. (Compare the reverse change, from brown to green, on weathering, without lowering of the double refraction.)

In the subsequent change of the biotite towards the normal red-brown tint it is customarily assumed that there is an increase of the FeO content.[4] It has not yet been found possible to effect a satisfactory separation of a mica of this type, which tends to occur as poorly-developed crystals in rocks of fairly complex mineralogical constitution. An impure specimen separated from a garnetiferous rock from Pittiely Burn, south of Duntaggart, east-south-east of Aberfeldy, gave an FeO content of 15·8%, and a refractive index γ greater than

[1] A. F. Hallimond, Min. Mag., 1924, vol. 20, p. 196.
[2] C. Doelter, Handbuch der Mineralchemie, 1917, vol. 2, part 2, p. 691.
[3] F. F. Grout, Amer. Min., 1924, vol. 9, p. 163.
[4] C. E. Tilley, Min. Mag., 1926, vol. 21, p. 40.

1·63. Analysis VIII is that of a biotite from a high-grade rock, from the Hill of Strone, but the colour in this case is a greenish-brown allied to that of the low-grade mineral.

It has been noted that garnet is sporadically developed. Dr. Tilley has argued that the normal genesis of almandine in pelites is from chlorite, often with exchange of magnesia for ferrous oxide.[1] The variable degree to which excess of chlorite survives and recrystallizes in higher zones may be correlated with this variability of occurrence of garnet. An analysis of a garnet from a garnetiferous hornblende-schist from Dalnacarn Craig, near the Kirkmichael road, five miles north-east of Pitlochry, is given (Anal. IX), and shows a molecular ratio of FeO to MgO of 3·1, with lime figuring equally prominently with magnesia.

In carrying out separations on these high-grade rocks, a magnetic separator or the usual heavy liquids were employed initially to remove the lightest minerals. For the final separation it was found that very good results could be obtained by means of fused mercurous nitrate. If a quantity of the salt was allowed to melt undisturbed in a large boiling-tube immersed in a water-bath, a diffusion-column with small differences of density was established. When the concentrate had been gently poured in, the boiling-tube was revolved between the palms of the hands about a vertical axis, and under the action of the slight disturbance thus set up in the melt the minerals arranged themselves in sharply-defined layers. In this way, for example, the garnet was obtained practically pure as a layer separated by an inch of the solidified salt from the darker ferro-magnesian minerals above and below it. The difference of colour made removal of the few foreign grains by hand-picking an easy matter, yielding an absolutely pure garnet concentrate.

Hornblende normally appears after garnet, and represents the calcareous content which contributed to the formation of epidote in earlier stages, this latter mineral now disappearing. At this stage, too, the albite, which has remained practically unaffected, begins to give place rapidly to a plagioclase containing notable amounts of the anorthite molecule:

$$\text{epidote} + \text{albite} \rightarrow \text{amphibole} + \text{more calcic plagioclase.}$$

Dr. Tilley has discussed the genesis of hornblende in green schists, and has shown that the potash-content is important in determining the grade of its first appearance. In the non-potassic green schists of the Start, South Devon,[2] as in the altered spilites of Cornwall[3]

[1] C. E. Tilley, loc. cit., 1926, pp. 43–44.
[2] C. E. Tilley, Quart. Journ. Geol. Soc. London, 1923, vol. 79, p. 185.
[3] F. Coles Phillips, Geol. Mag., 1928, vol. 65, p. 554.

and Finland,[1] hornblende appears before biotite. With admixed sericitic material, as in a tuff or derived sediment of the nature of the Green Beds, the higher potash-content leads to the formation of biotite, and hornblende appears much later, often after garnet, as noted in the petrographic descriptions above. In this connexion material from localities in the Loch Earn district is of special interest. Rocks from Creagan nan Gabhar, south of Loch Earn, and from the south side of Loch Boltachan, one mile north of St. Fillans, Loch Earn, although occurring in the middle of the chlorite zone of pelitic rocks, show the development of an amphibole. The mineral is finely fibrous, pale green or almost colourless (and lacking the characteristic blue-green axial tint of the hornblende of higher-grade rocks), with positive elongation and marked oblique extinction. A bulk analysis of one of these rocks is given (Anal. II), and shows a molecular ratio for CaO to K_2O of 27, this ratio for the Cowal rock (Anal. I) being only 8. An alkali estimation of the other Loch Earn rock showed a K_2O content of only 0·41.

Conclusion.

The tracing of these changes progressively on passing from south-west to north-east may serve as an excuse for pleading in conclusion that renewed attention should be paid to the significance of the Older Granite intrusions. Mr. Barrow wrote in 1912[2] 'the Highland area, south of the Caledonian Canal, is essentially built up on the lines of an aureole of metamorphism round a granite intrusion ; but instead of aureoles we have zones or belts which diverge more and more from a . . . highly crystalline nucleus'. This simple view has been combatted, but the reduction of the Older Granites to 'merely an incident'[3] may tend to obscure the fact that they represent the focus of high temperature and high pressure conditions. An interesting comparison has been effected between this Dalradian area and the Jutogh series near Simla, India.[4] The metamorphic changes in the latter series are essentially regional in character, but a modifying zonal relationship can be traced within the region influenced by the Chor granite. Dr. Harker, writing of normal regional metamorphism, has recently shown how 'the zones recognised are primarily temper-

[1] P. Eskola, Fortschr. Min. Krist. Petr., 1927, vol. 11, pp. 63–66.

[2] G. Barrow, Proc. Geol. Assoc. London, 1912, vol. 23, p. 277.

[3] C. E. Tilley, Quart. Journ Geol. Soc. London, 1925, vol. 81, p. 112.

[4] G. E. Pilgrim and W. D. West, The structure and correlation of the Simla rocks. Mem. Geol. Surv. India, 1928, vol. 50, pp. 60–72.

ature-zones',[1] and how, though the metamorphism is essentially regional in kind, the bounding lines are in a certain sense isothermals.

A considerable portion of the expenses of analyses in connexion with this work has been met by a grant from the Royal Society. I wish also to record my indebtedness to Prof. A. Hutchinson and Dr. A. Harker for encouraging and assisting the investigation in many ways: to Dr. C. E. Tilley and Mr. W. D. West for supplying me with hand-specimens, and to Mr. W. Campbell Smith for initial instruction in the use of the universal stage.

Table I. Rock analyses.

	I.	II.	III.	IV.	V.	VI.
SiO_2 ...	73·25	50·80	58·90	46·10	56·20	48·28
TiO_2 ...	0·35	1·26	1·02	1·90	1·17	1·37
Al_2O_3 ...	10·06	14·21	14·28	17·42	15·26	13·20
Fe_2O_3 ...	2·80	4·57	1·08	3·47	3·75	2·60
FeO ...	2·44	6·49	8·28	9·73	6·40	11·35
MnO ...	trace	0·40	0·13	0·44	0·22	0·77
MgO ...	1·88	6·08	4·58	7·60	5·25	7·67
CaO ...	5·14	10·55	4·40	9·18	6·38	7·35
Na_2O ...	1·80	0·36	3·64	1·36	3·30	2·63
K_2O ...	1·08	0·66	1·09	1·28	1·05	2·02
H_2O- ...	0·10	0·20	0·50	nil	0·30	0·07
H_2O+ ...	1·00	3·58	1·90	1·60	0·70	2·14
CO_2 ...	nil	0·72	nil	nil	nil	0·91
P_2O_5 ...	trace	trace	0·05	trace	0·05	0·21
S	trace	nil	trace	nil	trace	0·03
Cr_2O_3 ...	—	—	—	—	—	0·02
(Co,Ni)O ...	nil	nil	nil	nil	nil	0·04
V_2O_5 ...	—	—	—	—	—	0·05
	99·90	99·88	99·85	100·08	100·03	100·71

I. Biotite-epidote-albite-schist, near Ballochandrian, west of Glendaruel river, Cowal, Argyllshire. Anal. W. H. Herdsman.

II. Epidote-biotite-hornblende-schist, south side of Loch Boltachan, one mile north of St. Fillans, Loch Earn, Perthshire. Anal. W. H. Herdsman.

III. Garnetiferous biotite-hornblende-schist, Pittiely Burn, ESE. of Aberfeldy, Perthshire. Anal. W. H. Herdsman.

IV. Garnetiferous hornblende-schist, Dalnacarn Craig, Kirkmichael road, five miles NE. of Pitlochry, Perthshire. Anal. W. H. Herdsman.

V. Hornblende-biotite-plagioclase-schist, Glen Clova, Forfarshire. Anal. W. H. Herdsman.

VI. Biotite-hornblende-schist, west side of railway cutting, ¼ mile north of Ardlui station, Dumbartonshire. Anal. W. Pollard.

[1] A. Harker, Fennia (Helsingfors), 1928, vol. 50, no. 36, pp. 6–7.

Table II. Niggli values of rock analyses.

Analysis.	*si.*	*al.*	*fm.*	*c.*	*alk.*	*k.*	*mg.*	*c/fm.*	Section of Tetrahedron.
I.	353	28·5	33·5	26·5	11·5	0·27	0·40	0·80	V.
II.	131	22·0	47·0	29·0	2·0	0·54	0·50	0·61	IV.
III.	181	26·0	45·5	15·0	13·5	0·17	0·47	0·32	III.
IV.	103	23·0	50·0	22·0	5·0	0·39	0·51	0·44	IV.
V.	157	25·0	45·0	19·0	11·0	0·17	0·49	0·42	III.
VI.	112	18·0	55·0	18·0	9·0	0·33	0·49	0·33	III.

Table III. Mineral analyses.

	VII.	VIII.	IX.
SiO_2	38·14	38·20	38·40
TiO_2	0·23	1·72	nil
Al_2O_3	16·92	18·57	21·28
Fe_2O_3	7·37	1·73	6·07
FeO	11·25	13·23	21·34
MnO	0·53	nil	2·84
MgO	9·84	14·93	3·75
CaO	1·27	1·85	6·30
Na_2O	0·20	3·01	-
K_2O	7·60	4·88	—
H_2O-	(6·65)	0·10	trace
H_2O+		1·60	
	100·00	99·82	99·98
Sp. gr.	—	—	4·00
Refr. index ...	1·63	—	1·80

VII. Green biotite, Ballochandrian, Cowal, Argyllshire. Anal. F. Coles Phillips (p. 251).

VIII. Greenish-brown biotite, Hill of Strone, Forfarshire. Anal. W. H. Herdsman (p. 252).

IX. Garnet, Dalnacarn Craig, near the Kirkmichael road, five miles NE. of Pitlochry, Perthshire. Anal. W. H. Herdsman (p. 252).

Explanation of Plate X, on p. 256.]

EXPLANATION OF PLATE X.

FIG. 1. Biotite-epidote-albite-schist, Ballochandrian, Cowal, Argyllshire; from the chlorite zone. Elongated crystals of greenish-brown mica, granular epidote, and cloudy albite porphyroblasts. The clear areas are quartz.

FIG. 2. Chlorite-albite-schist, Glen Fyne, Argyllshire; from the chlorite zone. Abundant albite in a ground of chlorite and iron-ores.

FIG. 3. Chlorite-epidote-albite-schist, Balquhidder, Perthshire; from the biotite zone.

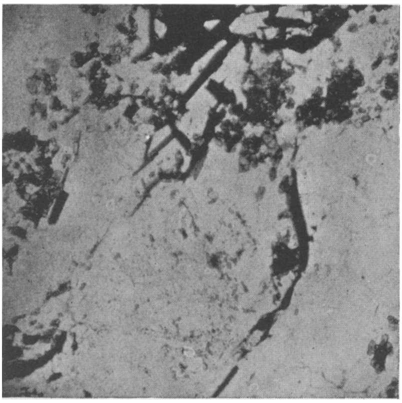
FIG. 4. Garnetiferous biotite-epidote-albite-schist, Pittiely Burn, ESE. of Aberfeldy, Perthshire; from the garnet zone. Lath-shaped sections of normal-reddish-brown biotite.

FIG. 5. Garnetiferous hornblende-biotite-plagioclase-schist, Hill of Strone, Forfarshire; from the kyanite zone.

FIG. 6. Garnetiferous hornblende-plagioclase-schist, south of Caddam, Glen Clova, Forfarshire. A pebbly variety; the clear area is a portion of a lenticular patch of recrystallized quartz.

Magnification in each case $\times 28$. Note the general increase in coarseness of crystallization towards higher grades.

Department of Mineralogy,
Cambridge, November, 1929.



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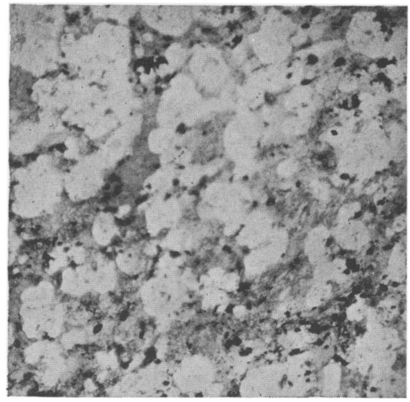

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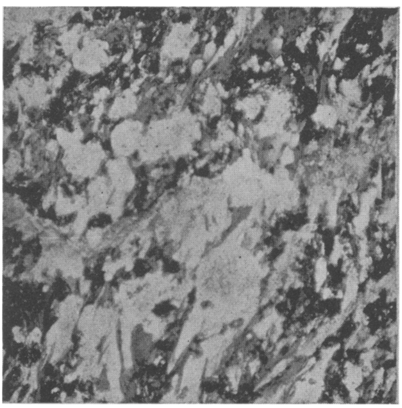

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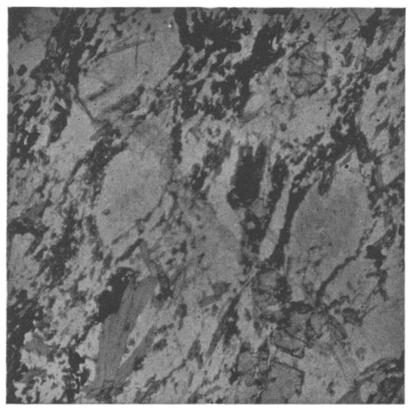

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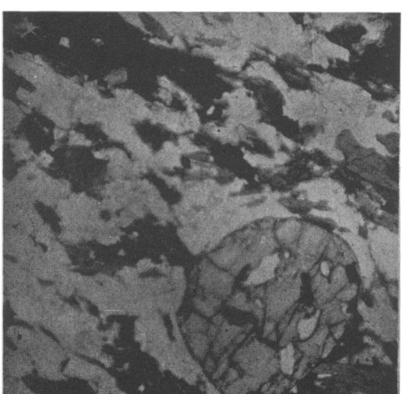

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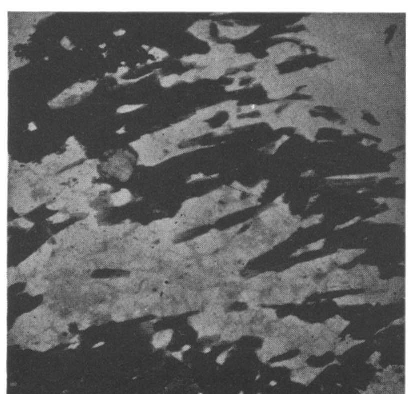

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F. COLES PHILLIPS: GREEN BEDS OF THE SCOTTISH DALRADIAN.