The aegirine-granulites of Glen Lui, Braemar, Aberdeenshire.

(With Plate XI.)

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I. Introduction.

In the explanation of sheet 65 of the Geological Survey of Scotland an outcrop of aegirine-granulites was described from Glen Lui, 1¼ miles SSE. of Derry Lodge. Brief descriptions of some of the rocks were given and it was suggested that they might be metamorphosed igneous rocks having distinct affinities with the borolanites of Assynt. Such a correlation, it was felt, would be of importance in assessing the age of metamorphism in the Central Highlands. Harker (1932) made the further suggestion that these rocks might originally have been a tuff which had subsequently become metamorphosed.

Unfortunately, the results of the present investigation do not tend to support these theories and the granulites are regarded as the resultant products of localized metasomatism of the associated metamorphic schists.

Just south of Derry Lodge in Glen Lui, the eastern side of the valley is dominated by a 400-foot hill which rises fairly steeply from the river. It is near the top of this rise that the granulites are located. Across the Glen, about half a mile to the westward is a limb of the Cairngorm granite mass. The intervening ground is unfortunately drift-covered so that the contact between the granite and the Moine gneisses is obscured, but it almost certainly lies to the west of the river. North-east of Derry Lodge this granite has intruded limestones with the production of grossular, idocrase, and wollastonite.

II. Lithological succession.

The aegirine-granulites form a relatively insignificant horizon in the hillside as they extend laterally for some 400 yards and vertically for, at most, 20 feet. Fortunately they are in general well exposed and even build small crags in places. Several faults tend to complicate the lateral correlation of the beds, but with the aid of one or two well-marked horizons it is possible to form a fairly accurate picture of the succession. An idealized section built up from the better exposed cliffs is given in fig. 1.

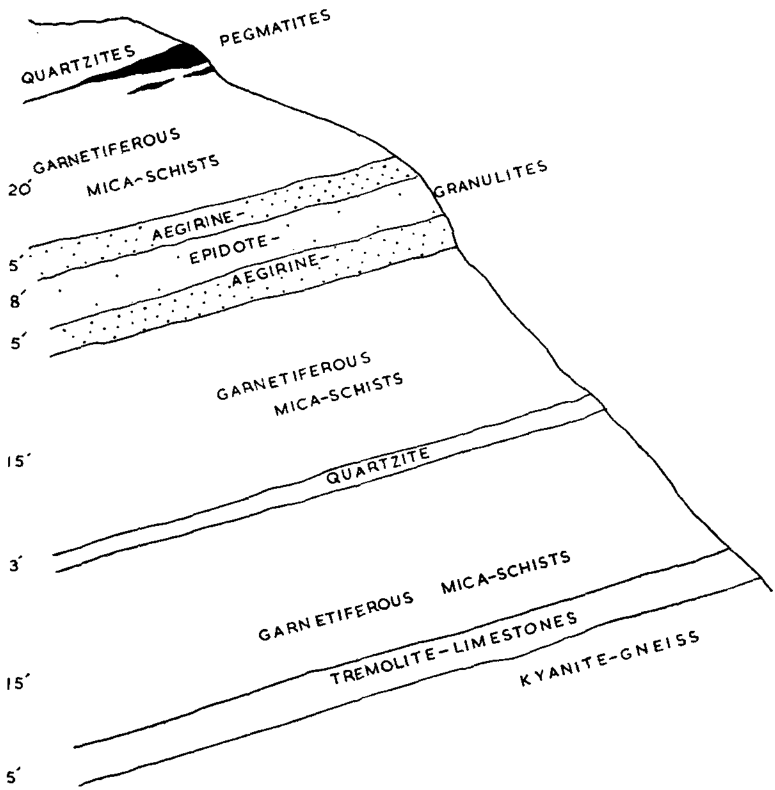

FIG. 1. Idealized section of rock succession in cliffs of Glen Lui, Aberdeenshire.

As the associated metamorphic rocks are of particular interest and have a bearing on the origin of the granulites, they will be described briefly in ascending order.

1. *Kyanite-gneisses.*—The first rocks to appear above the drift-covered lower slopes of the hill are small outcrops of kyanite-gneiss and intercalated limestones and quartzites. The gneisses are coarse, very

acid rocks consisting of quartz lenticles enveloped in felted biotite and containing large porphyroblasts of kyanite or almandine. Their most interesting feature is that they have been subjected to thermal metamorphism which is superimposed on the regional metamorphism responsible for their formation. This is reflected in the alteration of the kyanite porphyroblasts to andalusite, cordierite, and muscovite. A typical example of this polymetamorphic assemblage is shown in pl. XI, fig. 1.

MacKenzie (1949) has described rather similar gneisses from Mull, but he does not mention the presence of cordierite, the change being simply from kyanite to andalusite. MacGregor (1928) found the same alteration to cordierite and andalusite in the aureole of the Lochnagar granite. Tilley (1935) has described the reverse process round the Carn Chuinneag granite where chiastolite suffers replacement by kyanite.

The alteration of kyanite to cordierite suggests that there may have been introduction of Mg and Fe into the gneisses from the granite. Moreover, there are often minute, idiomorphic crystals of tourmaline enclosed in the resultant cordierite and these also suggest the introduction of similar elements. However, tourmaline occurs as a common minor accessory in the main fabric of these gneisses and shows no sign of replacing the other constituents, being present as small rounded crystals. Goldschmidt and Peters (1932) have shown that pelitic sediments may contain up to 0·1 % of B_2O_3, and this would be ample for the formation of the, at most, 1 % of tourmaline present in these rocks. It is therefore almost certain that the small tourmaline prisms in the cordierite were formed by recrystallization of pre-existing tourmaline.

Without introduction of Mg and Fe, the most feasible mode of formation for the cordierite is by reaction between kyanite and its surrounding felt of biotite. Occasionally, as in pl. XI, fig. 1, the kyanite becomes armoured by a mantle of cordierite and is compelled to change directly to andalusite. This strongly suggests that the reaction is local in origin and has not been assisted by elements from the granite. The fact that the biotite in these rocks is usually associated with almandine shows that it is a magnesian type, so that the only constituent necessary is SiO_2 which is present in excess. The following equation requires a change in volume of only 5 % and represents the relative volumes of cordierite and muscovite as closely as can be estimated from thin sections.

$$3H_2O + 7SiO_2 + \underset{\text{(kyanite)}}{8Al_2SiO_5} + \underset{\text{(biotite)}}{2K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} \longrightarrow \underset{\text{(cordierite)}}{3(Mg,Fe)_2Al_4Si_5O_{18}.H_2O} + \underset{\text{(muscovite)}}{2KAl_3Si_3O_{10}(OH)_2}.$$

The kyanite-gneisses are very variable and many carry andalusite which shows no sign of having been derived from kyanite. The more calcareous bands have hornblende and almandine with or without α-zoisite and clinozoisite. Large segregations of quartz and kyanite, similar to those described by Read (1933) in the Shetlands, also occur and even in the hand-specimen the kyanite is seen to have pink centres of andalusite. In the Survey Memoir of this area, Barrow (1912) repeatedly states that the intrusion of the 'Newer Granite' masses was not responsible for any marked thermal metamorphism. On the other hand, MacGregor (1928) ascribes similar polymetamorphic phenomena to the intrusion of the Lochnagar mass, and in Glen Lui it seems only reasonable to assume that the same effects were induced by the Cairngorm mass.

Intercalated with the gneisses are narrow horizons of limestone and quartzite, the latter being of particular interest as it often contains abundant octahedra of fluorite particularly in the neighbourhood of faults.

2. *Limestones.*—At about 350 feet above the floor of the valley the kyanite-gneisses give way to some 5 feet of impure limestones. These include bands rich in diopside or tremolite, while others are almost pure marbles.

3. *Micaceous schists and quartzite.*—The next 33 feet are occupied by an almost infinite variety of micaceous schists. The central 3 feet are of pure white quartzite. The micaceous schists are typical medium-grained schists consisting of quartz, blackish-green or brown biotite, muscovite, almandine, and andalusite. Muscovite may form up to 60 % by volume, while biotite may be absent or present with or without muscovite. Almandine is common, usually as small pin-head crystals showing a certain amount of alteration to biotite or chlorite and magnetite. Some of the larger garnets show signs of rotation in the presence of S-shaped lines of iron-ore inclusions. In some bands almandine is present up to 15 % by volume. These schists are of particular importance as they represent types similar to those which appear to have been metasomatized to give the aegirine- and epidote-granulites. Six feet from the top of the garnetiferous schists is an horizon rich in hornblende, and it is particularly useful as a marker because the granulites begin 6 feet above it.

4. *Aegirine-granulites and epidote-granulites.*—As shown in fig. 1, the granulites occur as a triple band, the outer two horizons being aegirine-bearing and the centre one more epidotic. In the field the granulites

are white or pink, some retaining a crude foliation while others are more massive felspathic rocks. They are uniformly fine-grained and frequently show narrow transgressive or concordant veins of green aegirine or pale-blue riebeckite-crossite, making their identification in the field quite easy. The granulites are extremely variable and the distinction between aegirine- and epidote-bearing types is by no means clear-cut or always present, indeed in the central area of the outcrop the granulites pinch out to a narrow band of épidote-granulite about 2 feet thick, the place of the other granulites being taken by micaceous schists similar to those described in the last section.

Above the 20 feet or so of granulites there is a return to garnetiferous mica-schists for another 20–25 feet and intercalated with these are flaggy quartzites which become more massive towards the top of the hill.

5. *Soda-pegmatite.*—Intruded into the quartzites in the eastern sector of the exposures is a highly sodic pegmatite which extends laterally for some 30 feet and is up to 3 feet in depth. The exposures are rather poor in this area, however, and the body is probably larger than this.

The pegmatite is composed almost entirely of albite which shows very fine twin-lamellae confined chiefly to the edges of the crystals. In addition there are a few flecks of biotite, chlorite (vermicular pennine), pyrite, and a little tourmaline. The rock is slightly fractured and the fractures are filled first by silica and then by calcite. Since the latter mineral does not appear to have been derived by the alteration of plagioclase and preserves sharp contacts with the albite, a portion of the rock was crushed, treated with dilute hydrochloric acid to remove the calcite, and then analysed (table III, p. 490). As may be seen from this analysis the Na_2O content is high and the ratio Na_2O/K_2O remarkably so. The alkali determination was repeated to minimize any possibility of error.

Judging by the field evidence this pegmatite is not itself a metasomatic product because the quartzites surrounding it have been arched to accommodate the granitic material. The peripheral twinning of the albite crystals also suggests some movement of the body when almost solid. Peripheral twinning is not seen in any of the granulites.

The quartzites surrounding the pegmatite have been albitized for a distance of at least 4 feet above it and in places the contact between igneous and sedimentary material is scarcely distinguishable. The resulting metasomatic product is very like a fine-grained acid igneous rock through which run siliceous replacement veins often carrying pyrite and sphene. Small zircons are also abundant.

The micaceous schists towards the eastern end of the hill are intruded by numerous small veins and lenticles of albite and in the field these appear very similar to the main, larger body of pegmatite. One of the small bodies in particular merits fuller description. It is injected into an acid muscovite-biotite-schist about 10 feet below the general level of the granulites. As a result of the injection of the felspathic material an area about 1 foot by 6 inches in size has become highly felspathized with

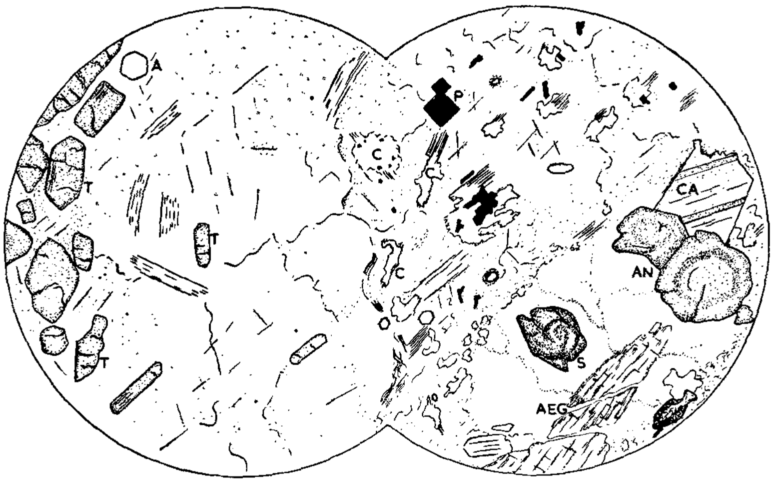

FIG. 2. Aegirine-augite (Aeg) and andradite (An) produced in a micaceous schist by the intrusion of a tourmaline (T)-bearing pegmatite. The groundmass is mainly albite with apatite (A), chlorite (C), pyrite (P), calcite (Ca), and sphene (S). Muscovite and zircon are also present.

the formation of albite, andradite, aegirine-augite, sphene, and abundant tourmaline (fig. 2). The presence of dense tourmaline aggregates shows that this vein is not a simple metamorphic segregation, so that we have here an example of aegirine-augite developed in a micaceous schist by the intrusion of pegmatitic material. Other much narrower veinlets of plagioclase and tourmaline intrude the schists for some distance from the pegmatite, up to 50 yards or so, but their effect on the schists is usually confined to felspathization for an inch or two on either side.

The intrusion of the micaceous schists by these veinlets of albite has frequently produced a texture which can only be described as micro-migmatitic, and throughout the granulites themselves the same texture persists though often on a microscopic scale. This is particularly true of the aegirine-granulites, the epidote-bearing varieties being usually more homogeneous rocks.

Petrography of the Granulites.

Petrographically the granulites display an almost bewildering variety of types ranging from slightly felspathized mica-schists to aegirine- and epidote-bearing highly felspathic granulites. Every gradation between these three types exists and may even be present within the compass of one slice.

1. *Felspathized mica-schists.*—These are schists in which orthoclase and albite have been developed at the expense of the original quartz and mica. Folia of biotite and muscovite, particularly the latter, may be seen to fade into orthoclase, so that the original extent of the mica can only be inferred from the lines of black flecks extending into the felspar. The grain-size of these rocks and the granulites averages about 0·25–0·5 mm., so that they are fine-grained except in the pegmatitic patches where the felspars may be up to 1 or 2 cm. in length.

As the amount of felspar developed increases, minerals such as andradite, aegirine-augite, epidote, and sphene begin to appear and the schistosity is lost, giving rise to the following rock types.

2. *Aegirine- and epidote-granulites.*—The main fabric of the aegirine- and epidote-granulites consists once again of a granulitic fine-grained groundmass of orthoclase and albite, while quartz has usually disappeared completely. The texture formed by the felspars may be judged by the groundmass of pl. XI, fig. 2. Staining of a typical epidote-granulite with sodium cobaltinitrite after the method of Gabriel and Cox (1929) showed that the potash and sodic felspars occurred in definite layers. Moreover, when the bands rich in potash were traced across the schistosity into less felspathic areas of the specimen, the corresponding bands were found to be rich in muscovite. This restriction of the orthoclase to definite layers suggests very strongly that it was formed by metasomatism of muscovite, since it is difficult to imagine the original igneous rock or tuff being intimately stratified into bands alternately rich in soda and potash, two or three to the centimetre.

The albite (An 7–11) between the bands of orthoclase is pink in the hand-specimen and intensely clouded in thin section. It is seldom twinned except in some of the aegirine-granulites, where it occurs as clear well-twinned crystals forming minute veins and pegmatite-like patches.

The potash-felspar was described in the Memoir of the Geological Survey (1912) as 'an alkali-felspar containing both potash and soda, and therefore probably belonging to the anorthoclase group'. This statement was presumably based on the low optic axial angle of these felspars, as the slide 8217 described in the Memoir contains potash-felspar with a 2V of 54° measured on the universal stage. Similar values for the aegirine- and epidote-granulites analysed and given in table III are 51° and 49° respectively. In the more migmatitic aggregates the 2V may rise to 65°, and in these cases the felspar is distinctly perthitic, whereas the small crystals of the groundmass with lower 2V values extinguish almost perfectly uniformly.

A conspicuous feature of the aegirine-granulites of the cliffs nearest Derry Lodge is a line of large porphyroblasts of potash-felspar. These may reach a length of 15 cm., are white in colour, and have been replaced peripherally and along cracks by pink albite. The 2V of these porphyroblasts is 58°, so that they are comparable with the smaller felspars of the groundmass. Moreover, the fact that they are not microcline suggests that they are products of the thermal metamorphism and metasomatism rather than relict crystals from the Moine schists. Since E. Spencer (1937) has shown that potash-felspars of the orthoclase-microperthite series may have low optic axial angles, one of these large porphyroblasts was analysed to determine the ratio of K_2O to Na_2O. This was found to be 14·9:1·4 %, so that allowing for a probable 1·5–2·0 % of anorthite, the content of soda-lime-felspar would not exceed 12 %. This is in fairly close agreement with the curves drawn up by E. Spencer (1937), and since Alling (1921) restricts the term anorthoclase to types containing over 30 % of albite, the term orthoclase will be used here. A careful comparison of the modes and chemical analyses of the granulites does not indicate any large amount of soda in the orthoclase as there is usually insufficient potash-felspar in the mode to satisfy the potash of the analysis. This discrepancy is due in some cases to the presence of muscovite and in others more probably to the difficulty in distinguishing small crystals of orthoclase from untwinned albite.

A feature common to both the aegirine- and epidote-granulites is that they frequently carry two distinct garnets. It is often difficult, in thin section, to determine the exact types of garnet involved, and to prove the existence of two types a typical felspathic granulite was crushed and the heavy residue above 3·6 was further fractionated in Clerici solution of sp. gr. 3·85. This process yielded 0·4 gm. of a pink almandine and 1·6 gm. of a yellowish andradite. In view of the very small amount of almandine recovered, further purification of this mineral was not attempted. Both garnets were analysed (table I), but the analysis of the almandine is not too satisfactory, owing to the small amount available and its probable impurity. The significant fact, however, in the present discussion is that there are clearly two distinct garnets present in the same rock.

TABLE I. Chemical analyses of two garnets from the same rock (granulite) from Glen Lui, Aberdeenshire.

1. Almandine (Analyst, J. H. Scoon). 2. Andradite (Analyst, G. R. McLachlan).

	1.			2.		
SiO_2	39·69	3·10	3·10	36·2	2·99	2·99
Al_2O_3	20·59	1·89	1·89	4·95	0·49 }	1·95
Fe_2O_3	2·77	0·17 }		23·25	1·46 }	
FeO	24·06	1·57 }		1·33	0·09 }	
MnO	2·64	0·17 }		0·43	0·03 }	
MgO	1·07	0·12 }	2·80	—	— }	2·99
CaO	8·37	0·70 }		30·86	2·74 }	
TiO_2	1·25	0·07 }		1·88	0·13 }	
H_2O— ...	0·21			0·33		
	100·65			99·23		
Sp. gr. ...	4·13			3·76		
n	1·807			1·87 approx.		

In some cases the difference between the two garnets is quite obvious, as yellowish andradite may be seen moulded on colourless cores of almandine (pl. XI, fig. 2). The andradite is then fresher than the almandine which is cracked and frequently altered to biotite and chlorite. Occasionally the andradite may form large ragged porphyroblasts, but it is then, in part at least, anisotropic, yellow, and not altered to biotite and chlorite.

Andradite also occurs in the aegirine-granulites as minute idiomorphic crystals, which, with the pyroxene, may form long winding trails through the rocks. These small crystals are pale yellow, generally isotropic, but often marginally anisotropic. Larger crystals up to 2 mm. are characteristic of the felspathic veins near the pegmatite, and these are uniformly anisotropic and often show beautiful sector twinning. Some are heavily zoned, presumably with varying tenor of the grossular molecule, and this forms a distinguishing feature when almandine is also present.

The coexistence of two distinct garnets, one characteristic of acid metamorphic schists and the other more typical of contact metamorphic and replacement deposits, is probably the most significant feature of the granulites, as it is difficult to imagine their being produced by metamorphism of an igneous rock or tuff. On the other hand, if the granulites are regarded as the result of metasomatism of an almandiferous schist, the almandine may be regarded as a relict mineral. The virtual identity of the almandine of the granulites with that of the underlying schists is shown by the similarity of their refractive indices. That of the former is 1·807 and of the latter 1·811.

The greater persistence of the almandine in the micaceous bands of the granulites is in support of its inferred relict nature, while the frequent association of andradite with aegirine-augite in the felspathic veins shows that the calcic garnet is the stable mineral under the metasomatic conditions.

Epidote is a common constituent of the granulites, occurring as small sub-idiomorphic crystals, colourless or pale yellow, with 2V negative about 85°. It reaches its greatest development in the felspathic veins near the pegmatite and the crystals may reach a length of 6 mm. Epidote is not often associated with aegirine in the granulites, the significance of which will be dealt with later. In general the two minerals characterize different bands, but a few grains of diopside may be present in the epidote-granulites.

The aegirine-augite of the granulites occurs in three distinct forms. Firstly, as interstitial allotriomorphic masses which often extend laterally and form pyroxene-rich bands parallel to the general schistosity of the outcrop. Secondly, the mineral appears as sub-idiomorphic skeletal crystals up to 3 mm. in length which often grow round aggregates of chlorite, felspar, or foxy-red biotite. Invariably when the crystals are of this type they are associated with very clear twinned albite and quartz which may project as perfect crystals into cavities later filled by calcite. A typical example of these skeletal forms is represented in pl. XI, fig. 3.

The third mode of occurrence of the pyroxene is as small, often minute, idiomorphic prisms which are once again associated with clear albite. The dark-green, often radiating acicular crystals may be scattered at random throughout the albite, but more often they tend to form aggregates or dense bands parallel to the general schistosity of the granulites. It is also as needles of this sort that the aegirine-augite is present with andradite in narrow trains ramifying through the rocks.

Alteration products of the pyroxene include a pale-blue sodic amphibole (riebeckite-crossite), while inclusions of magnetite are characteristic of the denser masses. The sodic amphibole may either form peripheral fringes on aegirine-augite, or it may be found independently as fine tufts which combine to form narrow bands as with the pyroxene. It also occurs as hair-like tufts in quartz. When some of the granulites are cleaved, the schistose surfaces may appear quite blue from the abundance of riebeckite-crossite, so that they may be easily recognized in the field. The amphibole, however, is not as common a mineral as the pyroxene, but like the latter it attains its maximum development in association with large veinlets of albite, the strings of riebeckite-crossite often outlining the felspathic body as if forced aside by the growing albite.

Both the pyroxene and the amphibole were separated and analysed; the analyses together with the optical data are given in table II. The intense colour of the amphibole made it impossible to assess the 2V accurately.

TABLE II. Chemical analyses and optical data of pyroxene and amphibole from granulite, Glen Lui, Aberdeenshire.

1. Aegirine-augite (Anal. G .R. M.). 2. Riebeckite-crossite (Anal. G. R. M.).

	1. Wt. %.	1. No. of metal atoms to 6 oxygens.			2. Wt. %.	2. No. of metal atoms to 24(O,Oh,F)	
SiO_2	51·68	1·961		2·000	51·02	7·499	7·834
Al_2O_3	1·28	0·059	0·039		1·93	0·335	
			0·020	1·033			
TiO_2	1·59	0·045			1·41	0·158	4·848
Fe_2O_3	19·10	0·546			13·05	1·446	
FeO	5·17	0·164			10·96	1·340	
MnO	0·45	0·014			0·14	0·009	
MgO	4·29	0·244			8·62	1·895	
CaO	9·56	0·389	0·927		4·85	0·776	2·328
Na_2O	7·25	0·538			4·95	1·429	
K_2O	—	—	—	—	0·74	0·123	—
H_2O+	0·05	—	—	—	2·43	2·346	2·434
H_2O-	0·05	—	—	—	0·25	—	
F ...	—		—	—	0·2	0·088	
	100·47				100·55		

	1.	2.
Sp. gr. (20° C.)	3·561	3·192
α	1·741 deep green	1·668 pale blue
β	1·767 yellowish-green	— yellowish
γ	1·789 brownish-green	1·680 bluish-mauve
$2V_\alpha$	85°	50° ± (axial plane ⊥ (010))
$\alpha : c$	12°	14°

The aegirine-augite is homogeneous and never shows any sign of zoning beyond a slight irregular patchiness of colour in the larger crystals of the allotriomorphic aggregates.

Sphene is a very common accessory in all the Glen Lui rocks and shows considerable variation in colour and mode of occurrence. In the granulites it varies from small colourless blebs to typical greyish lozenge-shaped crystals and aggregates. When it occurs in the clearer quartz-albite pegmatitic veinlets in association with aegirine-augite, it often shows reddish patches around what appears to be an earlier core on which more idiomorphic crystals have moulded themselves (fig. 3).

Many of the granulites are very rich in small rounded crystals of zircon. These are often concentrated along definite horizons and even in one slice they may be traced through the section in lines parallel to the general schistosity. Their abundance, rounding, and stratification suggested that they might be relict sedimentary crystals. To establish this on a more quantitative basis, the length/breadth ratios of 200 crystals from a felspathic granulite were plotted against similar ratios for 200 crystals from an underlying garnet-muscovite schist. These values are given in fig. 4 according to the method of Poldervaart and von Backström (1950) and Poldervaart (1950). The close similarity of the curves with maxima at a point between 1·65 and 1·85 suggests that the zircon in both rocks has been subjected to a comparable degree of rounding. Moreover, the curves are fairly similar to those obtained by Poldervaart (1949, 1950) for schists and gneisses in the Kakamas area.

FIG. 3. Aegirine-augite in micropegmatite with sphene showing two stages of growth.

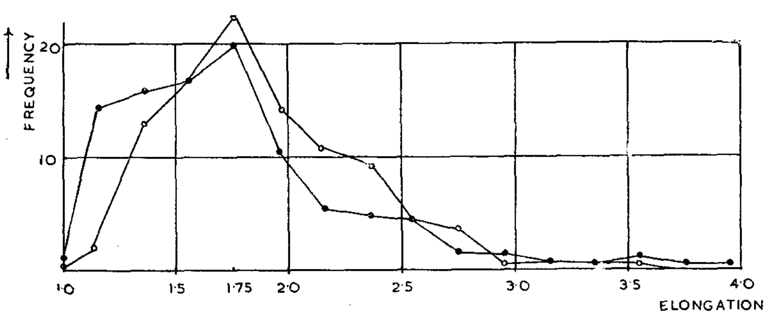

FIG. 4. Percentage frequency of zircon length/breadth ratios from a felspathic granulite (solid dots) and an underlying garnetiferous muscovite schist (open dots).

Reynolds (1936) has shown that zircons in xenoliths may retain their sedimentary characteristics during metasomatism, so that in Glen Lui the rounded crystals may be regarded as relict minerals from the original schists. If, on the other hand, the granulites were formed by metamorphism of an igneous rock, the zircons should show igneous features and the same would be true if they had crystallized from metasomatizing fluids. A tuff might be expected to show some rounding of its zircons, but in view of the restricted field distribution of the Glen Lui rocks, it is unlikely that the tuffaceous material could have been transported far, and this would have prevented the zircons from suffering any considerable attrition.

Some of the muscovite in the granulites, particularly that in the neighbourhood of the tourmaline veins, is clearly of metasomatic origin. Much of it, however, preserves a distinct schistosity identical with that of the associated schists. Aegirine-augite is frequently found associated with muscovite and quartz, and this assemblage would be difficult to imagine in a purely metamorphic rock, since aegirine is characteristic of peralkalic rocks and muscovite of peraluminous acidic types. It is extremely unlikely that an igneous rock or tuff would give rise to such a combination even under metamorphism. If, however, it is accepted that the granulites are metasomatic in origin, then the persistence of muscovite as a relict mineral is merely dependant on the ability of the sodic metasomatizing agents to convert it to felspar. Failing such a conversion, or subsequent to it, the soda would enter the pyroxene.

The biotites of the granulites are usually dark-brown or green varieties variously bleached and altered to yellowish and green chlorites, some showing anomalous and others normal interference colours. That these chlorites are derived from biotite is shown by their inclusions of minute octahedra of magnetite, which may congregate in masses or form long winding strings with chlorite. Apart from these types, secondary after biotite, there are large interstitial masses of pale green pennine often beautifully vermiculate or gathered into rosettes and showing a distinct tendency to be associated with andradite. Identical material is present in the pegmatite and associated veinlets and in most cases is clearly of late formation, as the aggregates are bounded by sharp contacts against the surrounding minerals. Apatite is another common accessory of the granulites and may be present in amounts up to 1 % by volume.

3. *Silicified granulites.*—Many of the aegirine-granulites show unmistakable signs of silicification as the last stage in their formation. This is most pronounced in the bands of clear albite and aegirine-augite and of some cavities in the granulites which have become filled with quartz or calcite into which albite or pyroxene crystals project. As might be expected, andradite is unstable under these conditions and the idiomorphic crystals are replaced by iron-ore as is shown in pl. XI, fig. 4.

Aegirine-augite may also disappear, so that its former presence can only be inferred from the 'ghost' outlines of black flecks which remain in the quartz. Two of the 'ghosts' may be seen in pl. XI, fig. 4 near the upper left-hand corner.

The silicification of the granulites is most pronounced in the horizon at the top of the upper aegirine-granulite band and closely resembles that produced in the quartzites in contact with the soda-pegmatite. In both cases the silicification is clearly the last stage of the metasomatism, replacing all the previously formed minerals.

Before considering the chemical implications of the metasomatism under discussion it might be as well to summarize the purely petrographic evidence in favour of a metasomatic origin for the granulites.

(1) The great mineralogical and textural variety of the granulites. Had they been formed by metamorphism of an igneous rock or tuff, greater uniformity might have been expected.

(2) The presence of the pegmatite shows that a source of soda was available.

(3) The fact that tourmaline-bearing veins have produced aegirine and andradite in the underlying schists shows that the mineral assemblage of the granulites could be produced in those schists.

(4) The presence in felspathic granulites of two garnets, one similar to those in the associated schists and the other typical of contact metamorphic rocks.

(5) The occurrence of the orthoclase in definite bands which appear to correspond to the muscovite folia of the schists.

(6) The coexistence of muscovite and aegirine, the former characteristic of peraluminous and the latter of peralkalic rocks.

(7) The widespread dissemination of hydatogenic minerals, characteristic of hydrothermal replacement, throughout the granulites and associated schists and felspathic veins. These minerals include tourmaline, fluorite, pyrite, andradite, and aegirine-augite.

(8) The sedimentary nature of the zircons, and the comparable degree of rounding shown by the zircon of the granulites and the underlying schists.

Chemistry of the metasomatism.

Having considered the petrographic evidence in favour of metasomatism, it is now necessary to decide the type of metasomatism involved. In table III, six analyses are given. The first is that of the soda-pegmatite which is composed almost entirely of albite (An 3 %), some 15 % of quartz, largely in the form of narrow veins filling cracks between the felspar crystals, and about 4 % of sericite, tourmaline, and pyrite. This is reflected in the analysis since all the values except SiO_2, Al_2O_3, and Na_2O are less than 0·7 %. The extremely sodic nature of this pegmatite suggests that it was intruded very late in the differentiation of the Cairngorm mass.

TABLE III. Chemical analyses and mineral composition of rocks from Glen Lui, Aberdeenshire.

	1.	2.	3.	4.	5.	6.
SiO_2	69·94	62·72	61·79	56·84	67·77	60·70
Al_2O_3	19·02	17·33	16·90	18·78	16·42	19·79
Fe_2O_3	0·62	3·23	3·10	3·98	1·37	3·63
FeO	0·38	1·30	1·07	2·76	3·68	3·63
MgO	0·01	0·90	0·90	1·22	1·50	0·98
CaO	0·46	1·75	2·44	3·84	1·23	0·68
Na_2O	8·99	5·87	5·26	4·75	2·28	0·42
K_2O	0·52	4·48	6·96	6·26	3·58	6·44
H_2O+	0·34	0·60	0·29	0·72	0·74	1·70
H_2O-	0·02	0·16	0·14	0·17	0·04	0·18
TiO_2	0·03	0·97	0·90	0·39	1·04	1·32
P_2O_5	—	0·15	0·34	0·47	0·15	0·15
MnO	0·12	0·04	0·19	0·04	0·33	0·18
	100·45	99·50	100·28	100·22	100·13	99·80
$\frac{Na_2O+K_2O}{Al_2O_3}$	0·81	0·84	0·96	0·78	0·47	0·38
Sp. gr.	2·58	2·65	—	2·72	—	—
Quartz	15·0	—	—	—	—	—
Orthoclase	—	26·0	35·0	35·0	—	—
Albite	81·0	53·0	45·0	47·0	—	—
Muscovite	3·0	8·5	—	—	—	—
Aegirine-augite ...	—	7·0	9·0	—	—	—
Riebeckite-crossite ...	—	3·0	—	—	—	—
Almandine	—	—	6·0	—	—	—
Andradite	—	0·5	3·0	—	—	—
Epidote	—	—	—	9·0	—	—
Sphene, ores, apatite, &c.	1·0	2·0	—	6·5	—	—
Chlorite	—	—	2·0	2·5	—	—
	100·0	100·0	100·0	100·0		

1. Soda-pegmatite from the upper quartzites of Glen Lui. (Analyst, G. R. M.)
2. Aegirine-granulite from the lower granulite contact, Glen Lui. (Analyst, G. R. M.)
3. Aegirine-granulite, no. 8217, Mem. Geol. Surv. Braemar, 1912. (Analyst, W. Pollard.)
4. Epidote-bearing felspathic granulite. Glen Lui. (Analyst, G. R. M.)
5. Garnetiferous muscovite-biotite-schist, Glencalvie Lodge, Mem. Geol. Surv. Ben Wyvis, Ross-shire, 1912, p. 112. (Analyst, W. Pollard.)
6. Mica-schist, Banffshire, Mem. Geol. Surv. Banffshire, 1923. (Analyst, E. G. Radley.)

The second analysis is of a felspathic granulite with some persistent schistose lamellae of muscovite and biotite, while aegirine-augite, riebeckite-crossite, and andradite are also present. No. 4 is of a homogeneous very felspathic epidote-granulite, once again with some micaceous bands.

Analysis 3 is from the Memoir of the Geological Survey, slide 8217. It is a typical aegirine-granulite with both almandine and andradite. Accompanying the analyses are the percentages by weight of the component minerals. In some cases these may not appear to correspond too well with the analyses. This is in part due to the banded nature of the granulites, so that the slide on which the mode is based may not cover parts of the specimen which are crushed for analysis.

Numbers 5 and 6 were chosen from analyses of Scottish schists to show the approximate chemical composition of the Glen Lui garnetiferous mica-schists. Since they vary from biotite-muscovite-schists to others containing 20–40 % of muscovite, no. 5 should represent the former accurately enough, while no. 6 is higher in K_2O and Al_2O_3, consistent with a higher percentage of muscovite. Since some of the Glen Lui schists contain small amounts of andalusite, Al_2O_3 probably reaches 20 % and may be down to 14 % in the less micaceous bands. The Al_2O_3 of the granulites also lies roughly between those two values, so that it seems unnecessary to postulate introduction of alumina. The values for K_2O, varying from 3·7 to nearly 7·0 %, would also be covered by the muscovite content of the original schists and, in addition, the almost complete absence of K_2O in the pegmatite suggests that the metasomatizing fluids did not contain any significant amounts of potash.

The status of calcium is more difficult to assess since its low value in the pegmatite makes its introduction unlikely, but the granulites contain up to 3·84 % of CaO. That the associated schists contain a certain amount of calcium is shown by the fact that in a narrow vein of felspar and tourmaline intruded into them, the albite has become basified to oligoclase (An 28). The bands of tremolite also point to the presence of calcium in many of the schists. It is therefore unnecessary to assume introduction of calcium. The calcite which is present both in the pegmatite and the granulites may be ascribed to the circulation of groundwater.

The only major constituent which appears to have been introduced, or at any rate fixed, in the granulites is sodium, since the Na_2O content of the original schists is unlikely to have exceeded 1·5 %, whereas in the granulites it rises as high as 5·87 and does not fall below 4·75 %.

It would seem as if the granulites were formed by some process such as the following. During the intrusion of the Cairngorm granite the schists on the eastern side of Glen Lui were subjected to thermal metamorphism sufficiently intense to induce the conversion of kyanite to andalusite and cordierite. In the later stages of the intrusion a highly sodic pegmatite was injected into the quartzites while associated sodic solutions permeated the underlying schists parallel to their schistosity. By hydrolysis of biotite and muscovite, Na became fixed with the formation of albite, the K of the micas similarly forming orthoclase. As the available alumina became exhausted the Na was compelled to crystallize as aegirine-augite and riebeckite-crossite with Mg and Fe derived from the hydrolysis of biotite. Moreover, as the temperature fell and the metasomatizing power of the solutions was reduced, muscovite was no longer converted to felspar, and soda-pyroxene was formed in spite of the presence of the mica.

Epidote might be expected to form when alumina was available after the formation of the felspars and provided calcium was also present. A schist rich in muscovite would provide these conditions and the banding of the orthoclase in the epidote-granulites and the persistence of some muscovite-rich layers show that the epidote-granulites were formed from schists of this sort.

All the Glen Lui analyses show a high ratio of Fe_2O_3 to FeO, and this is particularly noticeable in the riebeckite-crossite and the aegirine-augite. The formation of andradite may be attributed to this change in the state of oxidation of the schists, while paucity of alumina kept the grossular content of the garnet low. The fact that calcium was available shows that under the particular conditions prevailing, an almost pure albite was the stable plagioclase and little calcium entered into its formation.

There is an important difference in the mode of replacement of the two types of granulite. In the epidote-granulites the replacement is on a volume-for-volume basis, the resulting product being a dense homogeneous rock, whereas in the aegirine-granulites the replacement has been accompanied by a decrease in the specific volumes of the minerals with consequent cavernous replacement. As a result the aegirine-granulites are porous and frequently contain cavities filled later by silica or calcite. Furthermore, the epidote-granulites have not been silicified, so that the aegirine-bearing rocks may be said to have a longer metasomatic history than the others.

According to Turner (1948) soda-pyroxenes may be expected in a metamorphic rock when the ratio Na_2O+K_2O/Al_2O_3 approximates unity. The values for this ratio in the Glen Lui rocks are given below the analyses on page 490, but the results are somewhat anomalous. Aegirine-augite here begins to appear when the ratio is only 0·84, but this is due to the fact that aegirine-augite and muscovite are found together in this particular rock. As a result, had complete reaction occurred between the sodic solutions and the muscovite, aegirine-augite would not have appeared. In this way its formation at a ratio of 0·84 may be explained, whereas in stable rocks it would probably not appear until a ratio of 0·90–0·95 had been reached.

Since the granulites follow a definite horizon in the succession and do not occur as random patches scattered throughout the schists, it seems necessary to assume that a pegmatite is either concealed deeper in the hillside at the same horizon, or else that one has been removed by erosion on the side of the hill towards the river. The band of silicification at the top of the granulites suggests this very strongly, as a similar effect may be observed in the neighbourhood of the pegmatite intrusive into the quartzites.

Examples of soda-metasomatism are common enough in the literature, but none can be said to be identical with the situation at Glen Lui. Goldschmidt (1914) attributes the formation of riebeckite and aegirine-diopside in hornfels to the introduction of soda from the larvikites and nepheline-syenites of Langesundfjord. The same author (1921) in the Stavanger area describes the formation of albite porphyroblasts in phyllite by the introduction of soda, but here, although the Al_2O_3 percentage is of the same order as in Glen Lui (15–20 %), the soda content does not rise above 3·1 %, so that aegirine-augite is not produced. Taliaferro (1943) shows that the glaucophane-schists of California have been produced by introduction of soda, iron, magnesia, lime, and alumina into sandstones, shales, and cherts. Suzuki (1934) describes quartzose rocks from Hokkaido in which soda-metasomatism has produced schistose bands of aegirine-augite and glaucophane, but here the rocks are so siliceous that Al_2O_3 only rises to 2·73 %, so that the amount of soda introduced is very small.

The work of King (1943) in the Cnoc nan Cuilean area forms the closest parallel to Glen Lui. Here, according to King, siliceous granulites have been metasomatized to hybrid syenites containing anorthoclase, albite, aegirine-augite, and sodic hornblendes. The effects at this locality, however, are on a much larger scale and there is more intimate mixing of the igneous and metamorphic material than in Glen Lui.

The material described in the foregoing pages was largely collected by Dr. S. O. Agrell and this was supplemented by the present writer in two short field trips. The writer wishes, in particular, to record his thanks to Dr. Agrell for allowing him to work on this problem and for considerable advice and assistance during its elucidation.

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EXPLANATION OF PLATE XI.

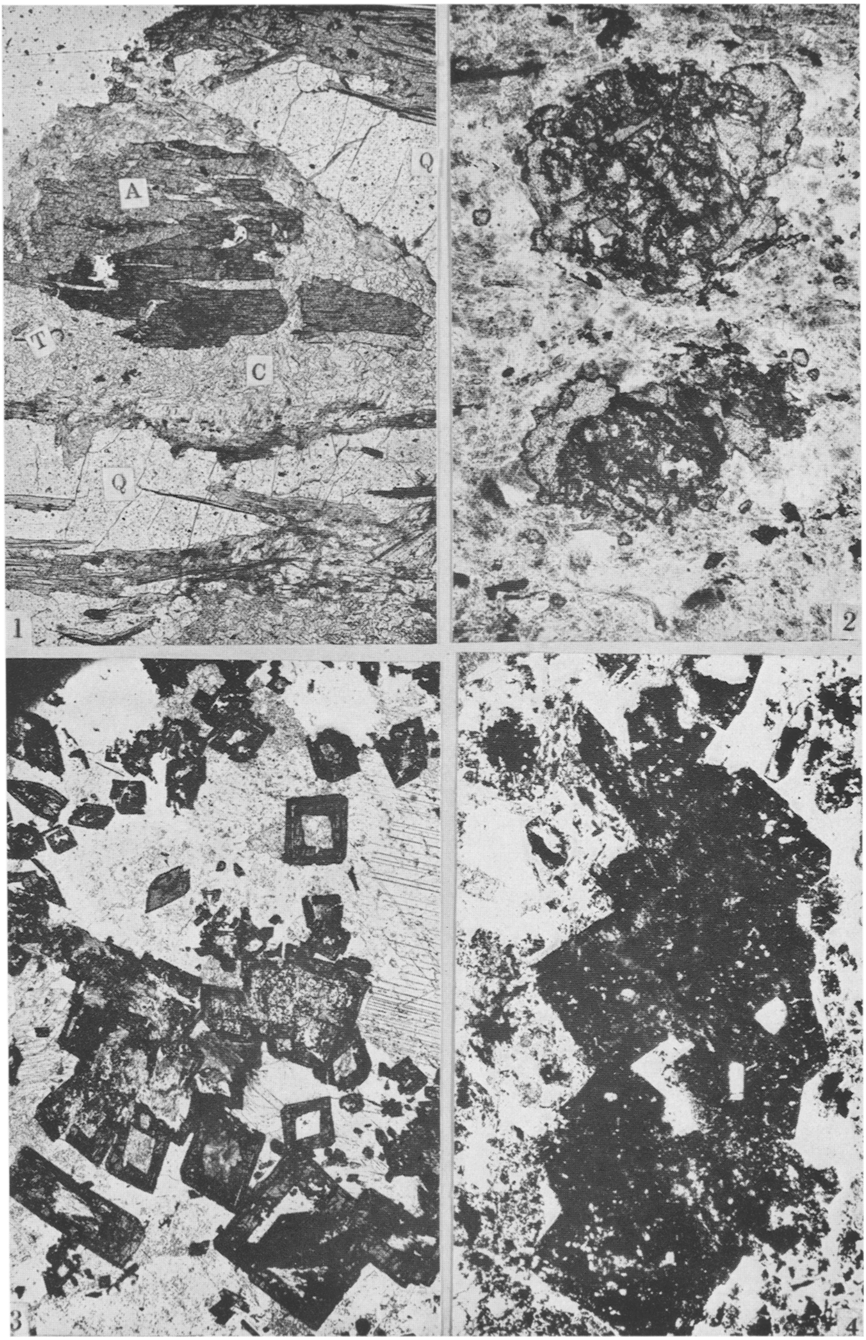
Photomicrographs of aegirine-granulites from Glen Lui, Braemar, Aberdeenshire.

FIG. 1. Kyanite (dark) altered to andalusite (A) and surrounded by cordierite (C) and muscovite. Quartz (Q) and tourmaline (T). ×23.

FIG. 2. Yellowish andradite moulded on almandine. Ordinary light. ×32.

FIG. 3. Aegirine-augite forming skeletal crystals round foxy-red mica. Calcite at right. Ordinary light. ×27.

FIG. 4. Andradite and aegirine-augite in silicified granulite. Andradite pseudomorphed by haematite and limonite. Aegirine-augite appearing as 'ghost' crystals. Ordinary light. ×27.



G. R. McLACHLAN: AEGIRINE-GRANULITES, GLEN LUI, ABERDEENSHIRE