STUDIES IN METAMORPHISM AND ASSIMILATION IN THE COOMA DISTRICT OF NEW SOUTH WALES.

PART I. THE AMPHIBOLITES AND THEIR METASOMATISM.

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(With four text-figures.)

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CONTENTS.

I. INTRODUCTION.

In his account of the general geology of the Cooma District W. R. Browne (1914)[3] recorded a roughly circular mass of amphibolite, about 50 yards in diameter, in the town of Cooma 200 yards south of the R.C. church. Smaller masses, measuring a couple of yards in diameter, were recorded from the western end of the town on the Berridale Road, Por. 3, Par. of Cooma; from Pine Valley and from west of the Mittagong Road near the south-west corner of Por. 108, Par. of Binjura.

With the exception of the Pine Valley occurrence the amphibolite outcrops are completely surrounded by an acid gneiss, termed by Dr. Browne the Cooma gneiss. Furthermore, it was noted that a coarse type of amphibolite, with interstitial white felspar, passed abruptly into finer grained types, and that the former was closely associated with intrusive pegmatite.

The relative ages of the amphibolite and Cooma gneiss, with its associated pegmatite, are rather obscure, as there are apparent contradictory lines of field evidence, and it was suggested in the 1914 paper that the relation between the amphibolite and pegmatite required laboratory investigation.

I should like to take this opportunity of thanking Dr. Browne for allowing me to undertake this work, for making available his specimens and field notes, and for his interest and helpful discussion during the progress of the investigation. To Mr. H. F. Whitworth, Curator of the Mining Museum, I am indebted for the loan of a specimen and slide of the Cooma amphibolite analysed by Mr. H. P. White.(19) For financial assistance I gratefully acknowledge a grant from the Commonwealth Research Fund which is administered by the University of Sydney.

II. Field Relations.

Reference to Dr. Browne's map will show that the country about Cooma is composed of Ordovician and Silurian rocks which are partly overlain by Tertiary basalts. The Ordovician series has suffered intense folding and the schists are injected by acid gneisses and associated pegmatites. Among the schists there is a hornblende-pyroxene-bearing type, and in a later communication it will be shown that this bears no relation to the amphibolites at present under discussion. The amphibolites, therefore, appear to be a distinct type, possibly representing a small intrusion which either antedated or postdated the Cooma gneiss.

On three occasions I have been to Cooma with geological parties led by Dr. Browne, so have had his field observations on the amphibolites pointed out to me. Recently I paid two further visits to the district and spent several days collecting and making a detailed study of the field relations in the small quarries on the south-western side of Soho Street between the intersections of Murray and Victoria Streets.

The following is a summary of the most important field observations that Dr. Browne and I have made on the amphibolites :

(1) Close field relation between coarse amphibolite and pegmatite.

(2) Numerous quartz-plagioclase veins cutting amphibolite and apparently related to pegmatite (see Fig. 1).

(3) Coarse amphibolite not a homogeneous rock, but showing all gradations between a coarse hornblende-quartz-plagioclase rock with inclusions of fine amphibolite, and coarse hornblende-quartz-plagioclase veins threading fine amphibolite (see Fig. 2).

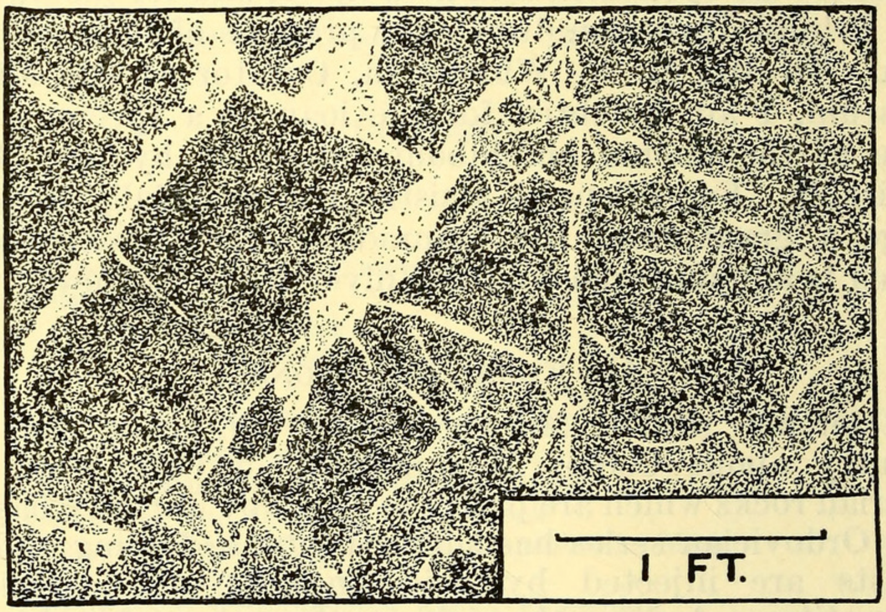

Fig. 1.—Quartz-plagioclase Veins cutting Amphibolite. Drawn from photograph by W. R. Browne.

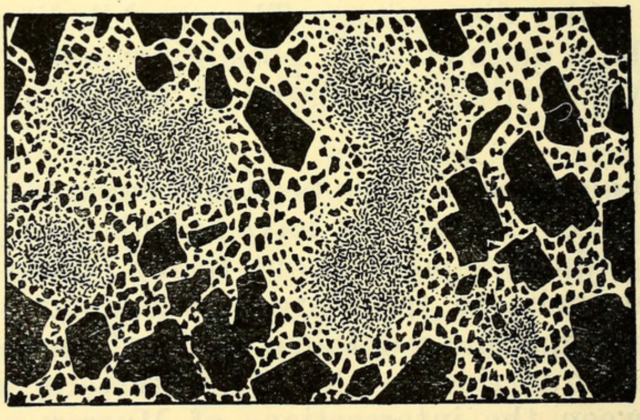

Fig. 2.—Drawing of Polished Surface of Heterogeneous Amphibolite. Natural size.

(4) Coarse amphibolite apparently intrusive into fine type, and possibly into Cooma gneiss.
(5) Occasional inclusions of amphibolite in gneiss.
(6) Basification of gneiss in the vicinity of amphibolite suggested by the development of abundant biotite.

III. Proposed Lines of Investigation.

To interpret the above field facts the following lines of laboratory investigation suggest themselves before the question of the age and origin of the amphibolite can be discussed.

(1) To ascertain if there be any relation between the fine inclusions and the coarse veins in the heterogeneous type.
(2) To investigate any relation between the fine amphibolite and the fine-grained inclusions in the heterogeneous rock.
(3) To investigate any relation between the quartz-plagioclase veins and the hornblende-quartz-plagioclase veins of the heterogeneous amphibolite.
(4) To ascertain if there be any relation between the pegmatite and the quartz-plagioclase veins.

In the following pages a detailed description of each rock-type is given with a view to establishing these relations.

IV. Petrography.

(i) Amphibolites.

(*a*) Relict Gabbro.

In the hand specimen these are even medium grained rocks with a high density and very dark green colour. Under the microscope a relict structure indicates an igneous plutonic rock, with subidiomorphic prisms or irregular grains of plagioclase interspersed with groups of small crystals or granules of hornblende, diopside, epidote, and plagioclase, which suggest the recrystallisation of the larger crystals of a ferromagnesian mineral—possibly of augite.

The plagioclase prisms are about 1·5 mm. in length. Extinction measured on the albite twinning in sections normal to 010 is $35\frac{1}{2}°$, $\alpha=1{\cdot}561$ and $\gamma=1{\cdot}570$. The composition is therefore basic labradorite ($Ab_{37}An_{63}$). The mineral is much saussuritised and sometimes shows alteration along cracks to an isotropic mineral which may be a chlorite.

Hornblende forms subidioblastic prisms (1 mm.) or small rounded grains (0·1 mm.) and inclusions of apatite and sometimes of magnetite and sphene may be present. The hornblende is light yellowish-green in colour with $Z > Y > X$, $Z \wedge c = 22°$, $\alpha = 1 \cdot 643$, $\gamma = 1 \cdot 660$.

Diopside is variable in amount, being very abundant in some types and absent in others. Like epidote, which is also rather sporadic in its development, the diopside always occurs in small rounded subidioblastic crystals or grains. Apatite is sometimes present in small stout prisms.

Large irregular grains of quartz are numerous, and these are either vein-like or interstitial in their occurrence, and may surround and isolate the plagioclase crystals. Sometimes small radiating filaments of quartz or minute strings of quartz beads are present in the plagioclase, suggesting a myrmekite-like[16] replacement (see Fig. 3 (*c*)).

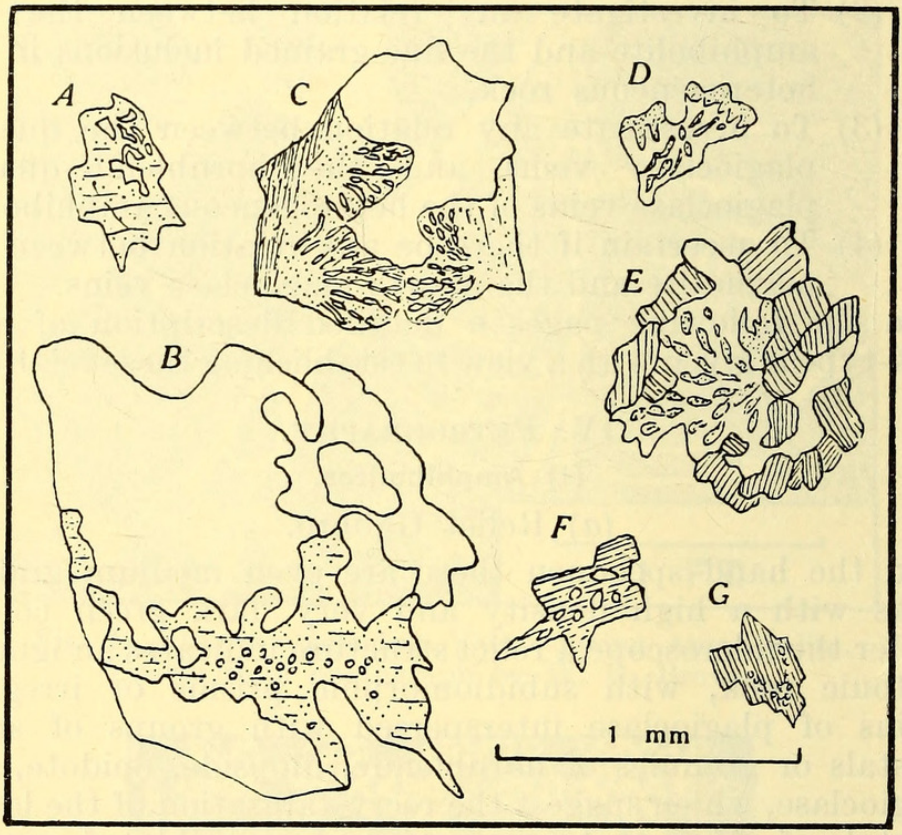

Fig. 3.

A and B. Various stages in the replacement of labradorite by quartz. The quartz is attacking along cleavage planes in this type. (A) Labradorite with angular inclusions of quartz. (B) Large quartz grain enveloping resorbed angular skeleton of felspar.

C, D and E. Myrmekite-like replacement of labradorite by quartz. (C) Filaments and beads of quartz in labradorite, surrounding large quartz grain which was possibly introduced by displacement. Note strain cracks in felspar on left. (D and E) Bead-like remnants of plagioclase surrounded by quartz.

F and G. Hornblende crystals showing drop-like inclusions of quartz.

Although most of the quartz seems to have been introduced by replacement, small local areas of parallel cracks indicate strain and suggest that some displacement of the other minerals may have taken place. One rock contains interstitial micropegmatite, which points to the addition of a little orthoclase with the quartz.

A rather unusual rock has been analysed by Mr. H. P. White. This contains no quartz, large tabular sub-idiomorphic crystals and irregular grains of labradorite up to 3 mm. across, hornblende crystals averaging 1 mm., but occasionally attaining a size of 6 mm. and thus closely resembling the large hornblendes of the heterogeneous rock described on p. 93. The plagioclase shows slight alteration, but there is no evidence of recrystallisation or of silicification, and the rock appears to be a relict gabbro of somewhat coarser grainsize than those mentioned above. The large crystals of hornblende may represent original hornblende crystals which have not been recrystallised, or, what seems more likely, they may have grown at a late stage in the rocks' history as a result of the concentration of volatiles along certain channels. The presence of these large hornblende crystals would place this rock among the heterogeneous types, but as it shows relict structures and differs from all the other heterogeneous rocks in the absence of quartz and acid plagioclase, it seems more fitting to describe it here. The analysis is given below, and, as no introduced material can be detected, it is assumed that this represents the composition of the original rock from which the amphibolite was derived.

SiO_2	52·50
Al_2O_3	11·72
Fe_2O_3	2·30
FeO	5·94
MgO	10·44
CaO	13·04
Na_2O	0·97
K_2O	0·53
H_2O+	1·66
H_2O-	0·28
TiO_2	0·22
MnO	0·11
NiO . CoO	0·01
P_2O_5	0·07
Cr_2O_3	0·02
V_2O_3	0·05
CO_2	0·06
	99·92
Sp. Gr.	2·993

Relict gabbro (slightly heterogeneous). Behind Dodds' Hotel, Cooma. Anal. H. P. White. *Ann. Rept. Dept. Mines*, 1909, 198.

(*b*) Even-grained Amphibolites.

In the hand specimen these rocks appear to be even-grained and both fine and medium types may be recognised, the latter closely resembling the relict gabbros. They are often intersected by quartz-plagioclase veins (see Fig. 1).

Under the microscope the even grainsize is not so apparent, and crystalloblastic structures are evident, the most common being a poikiloblastic development of plagioclase. The large (3-5 mm.) optically continuous sheets are quite clear and free from saussuritisation but enclose small granules or subidioblastic prisms of hornblende and often of diopside as well. The felspar is sometimes untwinned but usually both albite and pericline twinning are developed. Extinction on the albite lamellæ in sections normal to 010 is 35°, $\alpha = 1 \cdot 560$ and $\gamma = 1 \cdot 570$, so the composition is basic labradorite ($Ab_{37}An_{63}$).

In the fine-grained amphibolites the ferromagnesian crystals measure about 0·15 mm. and in the medium-grained types the hornblende crystals vary from 0·5-1 mm. and may show a slight schiller-structure and a brownish core. The hornblende is optically negative with positive elongation, $Z \wedge c = 22°$, X = yellowish-green, Y = pale yellowish-green and Z = bluish green. Sphene is often present as inclusions in the hornblende, magnetite is conspicuous by its absence, and apatite, though rare, may be present in small stout prisms associated with quartz. Tiny flakes of biotite have been noted in the hornblende of a few rocks.

Quartz varies in amount and occurs interstitially or as ill-defined veins. Two types of replacement of plagioclase by quartz are shown. First, a myrmekite-like growth with fingers of quartz penetrating the felspar, followed by a more advanced stage when only threads and beads of felspar remain in a quartz host (see Fig. 3 (*c*), (*d*), (*e*)). Secondly, a replacement along cleavages, which first appears as a series of angular inclusions of quartz in basic felspar resembling a micrographic intergrowth. This is followed by various stages, the most advanced showing rather angular skeletons of felspar surrounded by large grains of quartz. At this stage the felspar and the accompanying hornblende often contain drop-like inclusions of quartz (see Fig. 3 (*a*), (*b*), (*f*), (*g*)).

Some of the even-grained types have a granoblastic structure, but it is difficult to say whether this represents a true crystalloblastic structure or whether it is due to a partial replacement of poikiloblastic plagioclase by irregular grains of quartz. Fine- (0·15 mm.) and medium-grained (1 mm.) granoblastic rocks occur, and in the hand specimen these cannot be distinguished from the poikiloblastic types.

Evidence of local strain is often shown by an alignment of the hornblende crystals and by a series of parallel cracks in the quartz and felspar.

The following is an analysis of a fine-grained granoblastic rock, containing 10·44% of quartz and very little felspar (see Fig. 4 (*a*)).

SiO_2	59·13
Al_2O_3	7·92
Fe_2O_3	0·98
FeO	4·06
MgO	14·29
CaO	12·37
Na_2O	0·44
K_2O	0·15
H_2O+	0·31
H_2O-	0·15
TiO_2	0·32
P_2O_5	abs.
MnO	0·10
Cr_2O_3	tr.
	100·22
Sp. Gr.	3·039

Fine-grained granoblastic amphibolite containing 10·44% of quartz (found by Rosiwal measurement and calculated to wt. %). Anal. G. A. Joplin.

(*c*) Heterogeneous Amphibolites.

These rocks vary from fine-even-grained amphibolites veined by a coarse hornblende-quartz-plagioclase rock to coarse hornblende-quartz-plagioclase types with inclusions of fine amphibolite (see Fig. 2).

The fine patches are usually rounded and measure about ½ inch across. They are similar to the fine amphibolites described above and may show either a poikiloblastic (see Fig. 4 (*b*)) or a granoblastic structure, the plagioclase showing varying degrees of replacement by quartz. The hornblende is optically identical with that of the even-grained rocks, and usually the plagioclase has the same composition ($Ab_{37}An_{63}$). In some rocks, however, a more acid variety of felspar has been noted—$Ab_{40}An_{60}$ to $Ab_{50}An_{50}$. Diopside may or may not be present in the fine-grained inclusions. Magnetite is absent and apatite rare. A few of the heterogeneous rocks contain very basic

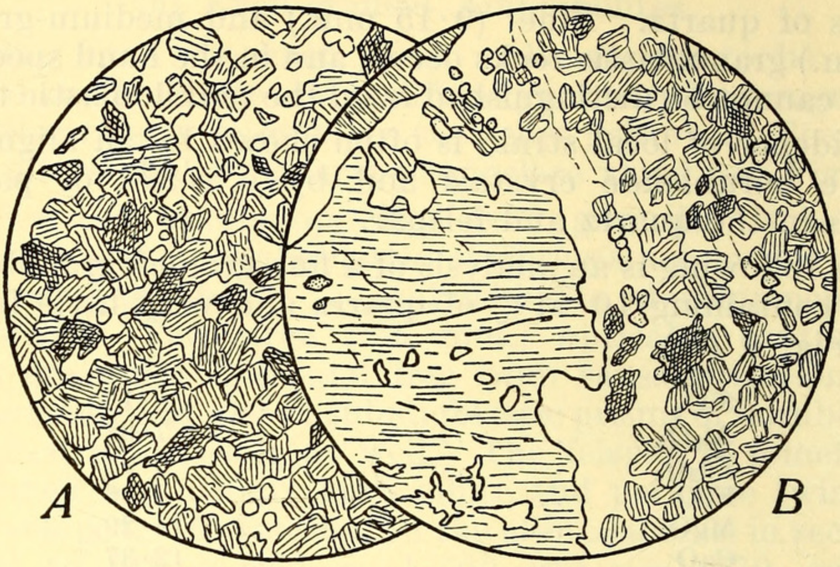

Fig. 4.

A. Fine grained granoblastic amphibolite showing intergrowth of hornblende and quartz. A very small quantity of diopside and plagioclase is also present. ×10.

B. Heterogeneous amphibolite showing corner of large hornblende crystal surrounded by quartz and andesine and associated fine poikiloblastic type. The right-hand top corner consists of a single crystal of labradorite with small inclusions of hornblende and diopside. ×10.

inclusions consisting almost exclusively of small (0·15 mm.) crystals of hornblende. The absence of both felspar and quartz suggests that only the felspar is being silicified.

The coarse phase of the heterogeneous rock consists of large subidioblastic crystals of hornblende, often over 7 mm. in length, adjacent to or partly surrounded by large grains of quartz and andesine ($Ab_{54}An_{46}$) with $\alpha = 1 \cdot 550$ and $\gamma = 1 \cdot 560$. Hornblende crystals of intermediate size (1-2 mm.) often occur between the large crystals and the fine inclusions (see Fig. 2), but this is not always the case and a large crystal of hornblende may be in direct contact with the fine type. A unique rock, which contains a few large crystals of hornblende and no quartz, has been described with the relict gabbros. The possible origin of this type will be discussed later (see p. 102).

The large hornblende crystals may have a slightly brownish core, but otherwise appear identical with the hornblende of the finer grained types. The hornblende from the coarse phase of a heterogeneous rock has been analysed, and a calculation based on Warren's formula[18] shows that it is very rich in the tremolite-actinolite molecule, with Fe/Mg 1/4·17. A small amount of aluminium replaces silicon in the tetrahedral chain and a comparable amount is present in the Y group. The mineral is negative with positive elongation, $Z \wedge c = 22°$, $Z > Y \geqslant X$, with X = yellowish-green, Y = yellowish-green and Z = bluish-green, $\alpha = 1·643$, $\gamma = 1·660$ and $(\gamma - \alpha) = 0·017$.

	Wt. %	No. of metal atoms on basis of 24(O, OH, F).		
SiO_2	50·08	7·15	0·85	8·00
Al_2O_3	9·42	1·57	0·72	
TiO_2	0·36	0·04		
Fe_2O_3	1·14	0·12		
MgO	16·00	3·42		5·16
FeO	6·89	0·82		
MnO	0·33	0·04		
Na_2O	1·09	0·31		
CaO	12·53	1·81		2·15
K_2O	0·21	0·03		
H_2O	1·49	1·42		1·42
F	nd	—		
	99·54			
Sp. Gr.	3·119			

Anal. G. A. Joplin.

The andesine associated with the large hornblende crystals often surrounds cores of corroded labradorite and may show a peculiar mottling which seems to indicate replacement by a more sodic felspar.(6) Apatite is often present in small stout crystals, and quartz, which is usually very abundant, occurs in large irregular grains. Occasionally the quartz is accompanied by granular epidote and in these types andesine is not abundant.

A type rich in quartz was crushed and the fine and coarse phases separated and analysed (see Table I, columns I, II). As there is no essential mineralogical difference between the phases except for a greater abundance of quartz in the coarse type, the analyses have been re-calculated on the basis of equal silica, and the close chemical relation is shown in columns III, IV below.

Special mention should be made here of a rock occurring at Pine Valley. It closely resembles the amphibolite, but consists chiefly of fibrous amphibole and chlorite. As it occurs among the schists, and appears to have suffered dynamic metamorphism, the discussion on this type will be reserved until the schists are further examined.

TABLE 1.

	I.	II.	III.	IV.
SiO_2 ..	52·06	62·12	51·73	51·73
Al_2O_3 ..	14·83	10·51	14·75	13·47
Fe_2O_3 ..	1·08	1·62	1·07	2·08
FeO ..	4·51	3·89	4·47	4·98
MgO ..	11·75	9·16	11·68	11·73
CaO ..	12·31	10·06	12·24	12·89
Na_2O ..	1·19	0·87	1·18	1·11
K_2O ..	0·98	0·61	0·97	0·78
H_2O+ ..	0·60	0·29	0·95	0·68
H_2O- ..	0·36	0·24		
TiO_2 ..	0·29	0·32	0·29	0·41
MnO ..	0·67	0·11	0·67	0·14
P_2O_5 ..	abs.	abs.	—	—
Cr_2O_3 ..	tr.	tr.	—	—
	100·63	99·80	100·00	100·00
Sp. Gr. ..	3·100	2·821	—	—

I. Fine phase of Heterogeneous Amphibolite. Soho Street, Cooma. Anal. G. A. Joplin.

II. Coarse phase of Heterogeneous Amphibolite associated with fine phase of analysis I. Anal. G. A. Joplin.

III. Analysis I re-calculated to 100%.

IV. Analysis II re-calculated to 100% after deducting 10·39% of SiO_2.

(ii) Quartz-plagioclase Veins.

These veins (see Fig. 1) intersect all types of the amphibolite. Occasionally narrow strips of the amphibolite are isolated between two parallel veins or rifted off by converging ones. In the small strip-like rafts of heterogeneous amphibolite both coarse and fine phases may be identified. The veins are white in colour ; the larger ones are a couple of inches in width but the majority are about ½ inch across. They appear to be intimately related to the pegmatite dykes which are adjacent to the amphibolite, but the exact relation cannot be satisfactorily determined in the field. That is, no vein can be actually traced from the pegmatite, nor can the dyke be seen cutting the smaller veins.

Under the microscope the veins are seen to consist almost exclusively of the three minerals—quartz, plagioclase and apatite. The relative abundance of quartz and felspar varies greatly, and many of the veins consist almost entirely of quartz. Hornblende and labradorite sometimes occur as xenocrysts, and there is sometimes a slight suggestion that some of the hornblende may have crystallised from solution. The plagioclase is very variable in composition, independent crystals and borders around labradorite xenocrysts ranging from andesine ($Ab_{64}An_{36}$) to oligoclase ($Ab_{72}An_{28}$).

In most cases the margin of the vein is quite sharp against the invaded rock, but occasionally poikilitic plates of andesine occur in the amphibolite adjacent to the vein, and, except for their more sodic nature, might easily be mistaken for the poikiloblastic crystals in the metamorphosed basic rocks.

(iii) Tourmaline Pegmatite Dykes.

The largest of the pegmatite dykes have been mapped by Dr. Browne,(3) who has also given an account of their field occurrence and macroscopic characters. In the vicinity of the Soho Street quarries the dykes are a couple of feet in width, with the outer part consisting of a coarse graphic intergrowth of quartz and felspar and passing inwardly into a zone rich in felspar with a rude comb-structure. A few large crystals of biotite and of tourmaline may be present in this zone, and the centre of the dyke is infilled with quartz, sometimes associated with large crystals of tourmaline.

Under the microscope the felspar proves to be microcline-microperthite. Although albite is apparently intergrown with the microcline, the potash felspar shows evidence of albitisation, suggesting that soda-rich solutions were active towards the close of crystallisation.

V. Nature of the Original Basic Rock.

The foregoing petrographical descriptions and chemical analyses indicate that the amphibolites have suffered silicification, and that the coarse heterogeneous types differ from the even-grained only in that they usually contain more quartz and often a more sodic felspar, indicating a late introduction of albite. There is abundant evidence to show that much of the silicification was a replacement process, and it is of interest to note that some of the structures observed in the partly silicified labradorite are comparable to structures noted in metalliferous replacements (Bateman,[2] Anderson,[1] and Schouten[15]). Nevertheless, the occasional vein-like occurrence of the quartz in the less replaced rocks, and sometimes the local areas of strain, suggest that some of the quartz may have been introduced by displacement.

As the relict gabbro, whose analysis is quoted on p. 91, contains neither quartz nor acid felspar, it is assumed that it represents the composition of the original rock. Furthermore, the fine inclusions analysed from the heterogeneous rock contain very little introduced material, and, although they have been recrystallised, it is unlikely that they have changed much in composition. Reference to the other analyses, however, show that these rocks, on account of the metasomatic processes, possess very unusual chemical characters, with comparatively high silica, lime and magnesia, and low alumina. In considering the origin of the rocks, therefore, it is necessary to make allowance for the material which has passed in and out of the system. It was shown in Table I that the coarse phase of the heterogeneous rock differed from the fine phase only in its greater amount of quartz, and that the two rocks were chemically similar when re-calculated on an equal silica basis. It was thus tacitly assumed that the quartz had been introduced by displacement, although such an assumption is not entirely justified. With regard to the fine even-grained amphibolite there is abundant evidence to show that much of the felspar has been replaced by quartz, although some of the quartz may have been introduced by displacement. For the purpose of re-calculating the analysis on the most accurate basis possible, Rosiwal measurements were made to ascertain the amount of quartz present and the weight percentage was found to be 10·44%. On account of the possibility of some displacement it could not be assumed that there was a volume for volume replacement of felspar by quartz; so after 10·44% of SiO_2 had been deducted sufficient labradorite ($Ab_{37}An_{63}$) was added to make the silica percentage equal to that of the relict gabbro, and the whole analysis was re-calculated to 100%.

Although much has been assumed in re-calculating these analyses there is good petrographical evidence for the assumptions that have been made, and reference to Table II will show that the rocks show a consanguinity which was

TABLE 2.

	I.	II.	III.	IV.	V.	VI.	VII.
SiO_2 ..	52·50	52·06	51·73	52·50	48·91	51·50	52·00
Al_2O_3 ..	11·72	14·83	13·47	10·86	8·81	10·89	11·59
Fe_2O_3 ..	2·30	1·08	2·08	1·04	1·04	1·75	2·72
FeO ..	5·94	4·51	4·98	4·34	9·52	6·86	7·18
MgO ..	10·44	11·75	11·73	15·29	15·19	13·91	12·87
CaO ..	13·04	12·31	12·89	14·05	14·69	10·19	10·49
Na_2O ..	0·97	1·19	1·11	0·82	0·64	1·18	1·06
K_2O ..	0·53	0·98	0·78	0·16	0·10	0·24	0·92
H_2O+ ..	1·66	0·60	0·37	0·33	0·52	2·40	0·37
H_2O- ..	0·28	0·36	0·31	0·16	0·07	—	0·18
TiO_2 ..	0·22	0·29	0·41	0·34	0·37	0·20	0·99
P_2O_5 ..	0·07	abs.	abs.	abs.	tr.	tr.	tr.
MnO ..	0·11	0·67	0·41	0·11	0·16	tr.	tr.
Etc. ..	0·14	—	—	—	0·15	0·76	0·04
	99·92	100·63	100·00	100·00	100·17	99·86	100·41

I. Relict gabbro (slightly heterogeneous), Cooma. Anal. H. P. White.

II. Fine phase of Heterogeneous Amphibolite. Cooma. Anal. G. A. Joplin.

III. Coarse phase of Heterogeneous Amphibolite, Cooma. Re-calculated as explained above.

IV. Even-grained Amphibolite re-calculated to 100% after deducting 10·44% of quartz and adding 7·07% of labradorite as explained above.

V. Olivine gabbro (IV.1.2.2.2), Orange Grove, Baltimore Co., Maryland. Anal. W. F. Hillebrand. G. H. Williams, *U.S. Geol. Surv. Ann. Rept.*, *15*, 674, 1895. In W.T. No. 7, p. 709.

VI. Diorite (III.5.4.(4)5), Mazaruni River, British Guiana. Anal. J. B. Harrison. J. B. Harrison, *Goldf. Bri. Gui.*, *49*, 1908. In W.T. No. 65, p. 647.

VII. Norite (III.5.4.(3)4), Cow Creek, near Bridger Peak, Wyoming. Anal. E. T. Allen. H. C. Spencer, *U.S. Geol. Surv. Prof. Paper*, *25*, 32, 1904. In W.T. No. 46, p. 645.

not so apparent before. Moreover, they are now comparable with other normal basic rocks. These rocks are all characterised by low alumina and high magnesia, and the Cooma rocks are particularly rich in lime. This suggests the former presence of olivine and/or hypersthene, and possibly of diopsidic pyroxene. On whatever basis the analyses may be re-calculated, it is obvious that II and III were slightly more aluminous than the other Cooma rocks and that IV was a slightly more melanocratic type ; thus there appears to have been some differentiation in the original rock mass, which possibly consisted of norites and olivine gabbros. The presence of relict structures confirms this supposition.

VI. Metamorphic History of the Amphibolite Mass.

It has been shown that the amphibolite mass consists of relict gabbros, fine and medium even-grained amphibolites and coarse grained heterogeneous amphibolites, and that the whole mass is invaded by small quartz-plagioclase veins and by a dyke of granite pegmatite. Furthermore, it has been shown that the original rock, from which all types of amphibolite were derived, was of the nature of a gabbro or norite.

The various metamorphic processes which brought about the change from gabbro to amphibolite will now be considered, and it will be shown that the development of the present amphibolite mass, with its several types, took place in a number of stages :

(*a*) By contact metamorphism.
(*b*) By metasomatism involving replacement of the felspar by quartz.
(*c*) By albitisation and further silicification of the felspar accompanied by a simultaneous increase in the size of the hornblende crystals, and sometimes by a deposition of epidote.
(*d*) Finally by the injection of small quartz-plagioclase veins.

(*a*) The development of poikiloblastic and granoblastic structures and the reduction of grainsize (Tilley,[17] Joplin,[7] Grout[5]) in the amphibolites indicate an initial thermal metamorphism of the gabbro, which no doubt was due to the intrusion of the Cooma gneiss. No foliation appears to have accompanied this metamorphism, although the enveloping acid rock has a primary gneissic structure. That the amount of amphibole so greatly exceeds pyroxene suggests that the metamorphism was a medium grade "wet" type.

Evidence of relict igneous structures in the gabbro indicates that the basic rocks had not been stressed before the thermal metamorphism took place, and it seems evident that the gabbro was intruded before the folding or before it reached its maximum. The maximum possibly synchronised with the intrusion of the Cooma gneiss, and the solid gabbro was partly suspended in the acid magma as a roof-pendant; so was thus protected and remained unstressed.

(*b*) At this stage, however, the gabbro was subjected to intensive silicification and the greater part of the basic felspar was dissolved and stored up in the aqueous solutions which were the agents of metasomatism. The exact nature of these solutions is unknown, but it is evident that they contained large volumes of silica, and that at a later stage soda became concentrated; thus aqueous siliceous and waterglass solutions are indicated. It is possible that some of the ferromagnesian minerals may have been removed also, but there is very little petrographical evidence for this. The completeness of the silicification of the felspar in many of the rocks points to the maintenance of a fairly high temperature and concentration of these solutions over a long period.

(*c*) The formation of the heterogeneous rock appears to have occurred at a slightly later stage than the silicification of the even-grained amphibolites and possibly after the complete solidification of the enveloping gneiss and the intrusion of the pegmatite. It has been pointed out that the microcline of the pegmatite has been albitised, and, although albite solutions were becoming sufficiently concentrated to be precipitated in the heterogeneous amphibolite, it is likely that the albitisation of the pegmatite belongs to a later period. The felspar of the heterogeneous amphibolites is andesine and acid labradorite of somewhat variable composition. Some of this plagioclase was no doubt deposited from solution, the potential albite having been basified by the anorthite-molecules that had been stored up in the liquid. The more basic types of felspar, however, represent the reaction between these solutions and the solid labradorite. Read and Phemister(11) (12) have pointed out that albite solutions cannot react with a lime-rich basic rock to give a more calcic felspar unless sufficient alumina be available. In the case of the Cooma rocks the anorthite molecule must have been available either in solid labradorite or in solution after its replacement by quartz. Epidote was no doubt formed by the addition of lime to this anorthite-molecule, the lime having been released by the amphibolisation of the pyroxene.

The development of the large hornblende crystals is rather difficult to explain. Some of the medium grained rocks show a slight indication of the growth of hornblendes, and here it appears to have taken place in the solid and to be a metamorphic phenomenon. The very large crystals of the heterogeneous rock, however, are usually adjacent to large crystals of quartz or andesine; and apatite is usually present in stout crystals. Their growth thus appears to have been promoted by volatiles.

The chemical composition of the hornblende indicates that it is a metamorphic rather than an igneous type,[8] and this is further suggested by its similarity to the hornblende of the metamorphosed even-grained amphibolites. Therefore, the large crystals cannot have crystallised from solution, but may have formed as the result of the coalescence of the small hornblende inclusions in the felspar porphyroblasts that have been replaced by quartz and more sodic felspar. Volatiles have promoted this coalescence, which was not possible during the earlier stage of silica replacement owing to an insufficient concentration of volatiles. Read[11] in describing the Ach'uaine hybrids notes a similar development of large hornblende crystals in and along the margins of intrusive felspathic veins, and Deer[4] records large porphyroblasts of hornblende at the contact of granite and hornblende-schist " especially in proximity to the narrow permeating veins of volatile-rich emanations from the granite ". The association of quartz and acid plagioclase with the large hornblende crystals is to some extent fortuitous and occurs only because these more acid minerals were being precipitated when volatiles are sufficiently concentrated to promote the growth of the hornblende. In the case of a heterogeneous relict gabbro (see p. 89) neither quartz nor acid felspar are associated with the large hornblende crystals, but their abnormal growth is nevertheless probably due to the escape of volatiles along sinuous channels in the rock-mass. A similar development of large hornblende crystals along cracks where volatiles were escaping was observed in a hybrid hornblende-gabbro at Hartley. At Hartley, as at Cooma, the large hornblende crystals occur in vein-like segregations, and, although Grout[5] criticises the use of the term " segregation " with regard to a hybrid rock, there seems to be no other way of describing or accounting for these vein-like occurrences.

(*d*) As the quartz-plagioclase veins usually show a sharp contact with all types of amphibolite, they belong to a still later period. Their felspar is more sodic than that of the coarse phase of the heterogeneous rock, which would indicate a greater enrichment of albite in the invading solutions. These veins seem to be connected with a late stage in the crystallisation of the adjacent pegmatite, the microcline of which is partly albitised ; though the onset of albitisation possibly synchronised with the formation of the heterogeneous amphibolite. The pegmatite dykes were probably intruded at about the time of the initial silicification of the gabbro, and the presence of a little micropegmatite in one of these rocks further points to this period. Moreover, the pegmatite dykes are in general parallel to the grain of the country and were evidently injected before the decline of shearing stress, although crystallisation took place after compression had ceased. The small quartz-felspar veins are neither orientated nor ptygmatic and suggest a state of tension rather than of compression.

VII. Age of the Amphibolites.

In tabulating the field relations it was recorded that there were some apparent contradictions regarding the relative ages of the amphibolite and Cooma gneiss. These, however, may be explained.

The basification of the gneiss near the amphibolite and the presence of basic inclusions in the acid rock indicate that the amphibole antedates the gneiss. Moreover, it has been shown that the basic rock has been metamorphosed and metasomatised by the gneiss. Whether the gabbro represents an earlier crystallisation phase of the granite magma, or whether it is of still earlier origin is impossible to ascertain.

The evidence for its post-gneissic age was based on the apparent close association with the pegmatite and a possible intrusive relation against the gneiss. These observations apply to the coarse amphibolite which has resulted from emanations derived at a late stage from the acid magma. This type would therefore post-date the gneiss ; thus the observed facts would be explained.

VIII. Comparison with Similar Rocks Elsewhere.

Heterogeneous hornblendic rocks containing quartz and alkaline felspar have been described from various parts of

Scotland and from Ireland. Their origin has been variously ascribed to fractional crystallisation accompanied by filter-press action,[9] to the assimilation of quartzite xenoliths by an ultrabasic magma[13] [14] and to reaction between quartz-felspar solutions derived from an acid magma and a solid ultrabasic rock.[11] [12]

So far as the Cooma rocks are concerned the explanation of differentiation accompanied by pressure is quite untenable. First, there is evidence of metamorphism in the amphibolite pre-dating the formation of the heterogeneous rock ; in the second place the rocks have obviously been silicified ; thirdly the hornblende is not an ordinary igneous variety ; and, finally, when the heterogeneous rocks were formed they were probably in a state of tension, whereas filter-press action requires compressional forces.

Regarding the explanation put forward by Miss Reynolds[13] it must be admitted that the enveloping gneiss at Cooma contains many inclusions of quartzite and quartz-schist, and it is possible that the earlier intrusion of gabbro may have picked up similar inclusions. Nevertheless, careful search has not revealed any trace of such xenoliths. At Colonsay the transfusion of quartzite, poor in alkalies, has caused an enrichment of potash, which is precipitated as orthoclase in the appinite. At Cooma, however, no orthoclase has been noted and only a silica and soda enrichment occurs. Moreover, the country rocks which form the xenoliths in the Cooma gneiss usually contain a high percentage of biotite, which would tend to bring about a potash enrichment in the contaminated rock. The absence of potash felspar in the Cooma amphibolite and its presence in the associated pegmatite excludes this rock from being the leucocratic end-member of a transfusion process. Furthermore, the bulk of pegmatite as compared with amphibolite, and the association of gneiss and pegmatite in regions where amphibolite is absent, make such a suggestion quite untenable. If the small quartz-plagioclase veins are to be regarded as the final products of transfusion, then it must be borne in mind that most of the end-members of the gneissic magma have suffered albitisation.

It is believed that the heterogeneous rocks at Cooma were formed by the action of granitic or trondhjemitic emanations on a gabbroid rock, an explanation very similar to that put forward by Read to account for the Ach'uaine hybrids.

Read and Phemister[12] and MacGregor and Kennedy[10] have suggested a correlation between the Ach'uaine hybrids of Sutherland and the appinites of the west coast of Scotland. Though these authors were agreed that mineralogically and texturally the rocks are very similar, they hold very different views regarding their origin.

There seems to be reliable field evidence for each of the explanations put forward concerning the origin of these heterogeneous hornblendic rocks, and the question arises, can a rock of similar mineral composition and fabric be formed in different ways? The answer surely appears to be in the affirmative, and it would seem that these rocks are not a unique type, but may be formed under a variety of physical and chemical conditions. The complex and variable nature of hornblende itself favours such a suggestion, and the fact that it occurs in both igneous and metamorphic rocks of very diverse composition would necessarily make it a common mineral. Moreover, quartz and alkaline felspar (both albite and orthoclase) are ubiquitous minerals, which are stable over a wide range of physical conditions, and these minerals are frequently precipitated at a time when volatiles are concentrated and when physical conditions favour the growth of hornblende crystals.

IX. Summary.

It has been shown that the Cooma amphibolites have a very simple mineral composition and consist almost entirely of hornblende, plagioclase and quartz. Even-grained and heterogeneous types occur, the latter consisting of the even-grained type cut by hornblende-quartz-plagioclase veins, which have originated by reaction between the original basic rock and late solutions from the adjacent gneiss and pegmatite. The amphibolites have suffered recrystallisation and intense silicification, and when due allowance is made for these processes it is evident that the original rock was a gabbro or norite which was intruded before the gneiss.

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