Chapter (13)

THE AGNES GREYWACKE AND REGIONAL METAMORPHISM AT MOONA PLAINS

Introduction

The majority of the greywackes and slates of this subdivision have suffered only slight reconstitution, however three areas within the Agnes Greywacke have been metamorphosed to biotite grade or above. These areas are outlined on Map 2 and are located:

(1) Near Mt Agnes where a trace of biotite is found in the matrix of the greywackes,

(2) In the headwaters of the Mummel River within a small area adjacent to the Mummel River Fault,

(3) At Moona Plains, where a large area of greywackes and slates contain metamorphic biotite. The previously emplaced intrusive igneous rocks of the Garibaldi Complex have also been deformed and regionally metamorphosed. These metamorphics of regional extent at Moona Plains are associated with several granitic intrusions, the petrology and chemistry of which is currently under investigation by E. Hobson.

Mineral Assemblages

The greywackes and slates without biotite contain a low grade metamorphic assemblage consisting of quartz, albite, epidote, chlorite and white mica, with patches of minor calcite and streaks of finely divided opaque and semi-opaque material.

With the appearance of biotite, chlorite disappears and the assemblage quartz, albite or sodic plagioclase, biotite, white mica and epidote is stable. The majority of the greywackes above the biotite isograd carry this assemblage. It is virtually impossible to determine the plagioclase compositions in the matrix of these metamorphosed greywackes, however it is inferred that a slightly more calcic plagioclase crystallizes at higher grade. Adjacent to the granitic intrusions at Moona Plains white mica disappears and the following assemblages are found:

(1) Quartz - Plagioclase - Potassium feldspar - Sillimanite - Biotite

(2) Quartz - Plagioclase - Potassium feldspar - Cordierite - Biotite

(3) Quartz - Plagioclase - Potassium feldspar - Biotite.

Petrography

Low Grade Rocks

The majority of the greywackes are of lithic character, with mudstone, siltstone and acid to intermediate volcanic rock fragments predominant and minor chert fragments. Clastic quartz grains and coarse (1 - 2 mm) plagioclases with well developed Albite twinning are subordinate. Euhedral grains of detrital brown hornblende of volcanic aspect are a widespread and common minor constituent and appear to be an important characteristic of these greywackes. Detrital epidote is rare. A minor plutonic contribution is indicated by rare fragments containing graphic quartz-feldspar intergrowths.

Low grade metamorphic crystallization has affected both the matrix and the coarser material. The matrix has recrystallized to a low grade assemblage in which the platy minerals show a vague to strongly developed preferred orientation parallel to S1. Similar crystallization takes place within the coarse lithic fragments which also show flattening and a preferred orientation parallel to S1. Plagioclase is clouded with fine grained metamorphic minerals and quartz commonly shows undulatory extinction and marginal cataclasis. The overall relationship between the low grade metamorphic minerals and the S1 cleavage suggest that this low grade metamorphism more or less coincided with the F1 deformation throughout much of the Agnes Greywackes.

The lighter coloured, isolated pod-like inclusions in the greywackes have textures that show clearly they were originally igneous rocks. The outlines of plagioclase laths and mafic minerals are still discernible but are replaced by the following assemblage:

Tremolitic amphibole - Clinozoisite - Talc -
Chlorite - (Albite - Quartz - Sphene)

These rocks are believed to be intermediate to basic dyke rocks metamorphosed and deformed along with the greywackes. Their similarity with the metamorphosed igneous rocks of the Garibaldi Complex suggests they are related and were therefore probably emplaced at about the same time.

Adjacent to the faults bounding this subdivision the greywackes become progressively more sheared. Adjacent to the Yarrowitch Fault the greywackes have been mylonitized, with a strong cleavage parallel to a fine mylonitic layering.

Biotite Zone Rocks

Fine grained metamorphic biotite crystallizes initially within the matrix of the greywackes where it rapidly becomes a major constituent. The remainder of the matrix recrystallizes to granoblastic quartz and feldspar and minor white mica. At the same time the outlines of coarser detrital material become blurred as they also undergo progressive reconstitution. Biotite crystallizes as aggregates of large numbers of small flakes either as streaks or lenses parallel to S1 in which the biotite may show a moderate to weak schistosity, or as irregular equidimensional patches in which biotite tends to crystallize without any preferred orientation. These biotite rich areas are commonly found to have a nucleus of small rounded sphene grains, and it is probable that the crystallization of biotite at these sites was enhanced by nucleation at the surface of this sphene.

East of Moona Plains the biotite-bearing greywackes approaching the Yarrowitch Fault have been strongly mylonitized. Biotite has not retrogressed to a lower grade assemblage during mylonitization, but has been ground up into tiny flakes which are concentrated in biotite-rich laminae within the layered mylonite. Throughout the remainder of these regional metamorphics, no other layering or lamination of any sort is developed. All the metamorphosed greywackes have a black, massive hornfelsic appearance, and the strong slaty cleavage of the pelitic bands also disappears at biotite grade.

Closer to the granites at Moona Plains the original greywackes are transformed to a homogeneous siliceous biotite-cordierite hornfels. At this grade muscovite has disappeared and the rock consists of granoblastic quartz, plagioclase and potassium feldspars, schistose red-brown biotite and highly poikiloblastic fresh cordierite. Fibrolitic sillimanite associated with biotite is also found in these rocks slightly closer to the contact. The immediate contact rocks of the granites contain abundant potassium feldspar showing microcline cross-hatched twinning. The bent and kinked biotite and undulatory extinction of the quartz of these contact rocks shows they have undergone some cataclastic deformation.

A single horizon of metamorphosed basic rock was found in these greywackes. This has recrystallized to a massive dark green hornfels containing blue-green hornblende, calcic plagioclase and quartz. It has a typical hornfelsic texture consisting of randomly oriented ragged plates of hornblende between which granoblastic quartz and plagioclase has crystallized. Unfortunately this horizon could not be traced to higher or lower metamorphic grades, but it is possibly a metamorphosed basic igneous rock belonging to the Garibaldi Complex.

The Garibaldi Complex has been briefly described in Part 1. The heterogeneous assemblage of rocks of this Complex show good evidence of having been metamorphosed along with the enclosing greywackes and slates. A foliation and lineation homegeneous with respect to S1 and L1 of the Agnes Greywacke are variously developed throughout. All the rock types show partial or complete recrystallization to a lower grade mineral assemblage. The original minerals of the gabbro are replaced by a quartz, albite, epidote, actinolite, chlorite assemblage with varying amounts of sphene and opaque oxide. Original pyroxenes have a fringe of acicular, pale green actinolite and a spong~~e~~y appearance resulting from its penetration by numerous needles of actinolite. Where it has been completely replaced, the site of the original pyroxene is occupied by a mixture of acicular or platy actinolite, prisms of epidote, and chlorite. Although some plagioclase from the middle of the gabbroic phase of the intrusion was still relatively unclouded and was found to be a relatively calcic variety, the majority of the original plagioclase is heavily saussuritised. The granophyric and pegmatitic phases showed similar mineralogic evidence of partial or complete adjustment to low grade metamorphic conditions.

The fine grained biotite adamellite constituting the other major phase of the Garibaldi Complex has also been metamorphosed. The original feldspars are virtually completely replaced by a finely divided granular mixture of albite, epidote, white mica and biotite. The original pale red-brown biotite has brown semi-opaque rod-like inclusions and shows marginal recrystallization to patches of fine-grained, randomly oriented brown metamorphic biotite of very similar character to that found in the metamorphosed greywackes.

Close to the Yarrowitch Fault these igneous rocks have been mylonitized but these effects are quite distinct from the recrystallization attributed to regional metamorphism.

Summary

The contrast between the style of deformation and metamorphism at Moona Plains and at Tia is obvious. The metamorphism at Moona Plains has largely been a regional "static" recrystallization. Some overlap of deformation and metamorphism is apparent in the low grade greywackes, but crystallization of biotite and higher grade minerals appears to have taken place either in a hydrostatic environment or under the influence of a relatively weak non-hydrostatic stress. Only one recognizable major period of deformation has affected these rocks, in contrast to the multiple deformation recognized throughout the Tia Complex. In addition cordierite and sillimanite are found within the higher grade metamorphics at Moona Plains whereas muscovite is absent. This also contrasts with the assemblages of the higher grade metamorphics at Tia, where cordierite and sillimanite are absent, and a white mica is an important constituent of the high grade schists.

Chapter 14.

MINERALOGY

HORNBLENDE

Introduction

The primary aim of this study of the hornblendes of the metabasic rocks of the Tia Complex was to elucidate the amount and nature of their chemical variation with metamorphic grade. The determination of the bulk rock chemistry of the host amphibolites also permitted a study of the effect of host rock composition on hornblende chemistry. From Zones C and D four hornblendes (Hbl - 4) and the amphibolites in which they occur (MB1 - 4) have been analysed. The localities of these analysed samples are shown on Map 2.

Rocks representing a range in metamorphic grade were selected. MB1 (S9554) is from the higher metamorphic grade amphibolite adjacent to the Tia Granodiorite (Zone D). MB2 (S9551) and MB3 (S9548) come from the upper and middle grade parts of Zone C, while MB4 (S9539) from Zone C is of the lowest metamorphic grade.

Separation

MB1 was crushed to -300 mesh and MB2 - 4 to -400 mesh for separation. This was necessary to eliminate the finely divided opaque material occurring either as inclusions or adhering to hornblende to form composite grains. Separation was achieved using a Frantz magnetic separator and by repeated centrifuging in Clerici's solution.

The purity of Hb1 and Hb2 was very high (99.5%). Hb3 and Hb4 still contained a trace (<1%) of opaque material (mainly ilmenite). No corrections were considered necessary for these slight impurities.

Optical Properties

The refractive indices and absorption colours of the four analysed hornblendes and of other amphiboles from the Oxley and Wybeena Metamorphics are given in Table 2. Two generalizations based on the variation of the colours of the hornblendes may be made:

(1) There is an overall deepening of the colour of the amphiboles with increasing metamorphic grade. The actinolitic amphiboles of Zones A and B are, in general, very pale green varieties. The presumably Al-bearing hornblendes in the upper part of Zone B are also pale coloured varieties, with some showing a pale blue-green γ tint. The Zone C hornblendes show considerable variation but they are still relatively pale coloured, with pale blue-green γ tints more common. Towards the top of Zone C and with Zone D

there is a significant deepending in colour, with olive green and blue-green colours along β and γ respectively. The α tint of pale yellow or straw colour shows only slight variation throughout.

(2) The hornblendes with blue-green tints along and the more strongly coloured Zone D hornblendes have, in general, higher refractive indices than the paler hornblendes from Zones B and C.

Similar variations in hornblendes from regionally metamorphosed basic rocks have been reported by Wiseman (1934) from the Scottish Highlands, Shido (1958) and Miyashiro (1958) from the Abukuma Plateau, Engel and Engel (1962) from the Adirondacks, and Binns (1964, 1965) from the Willyama Complex.

Chemistry

Calculation of Structural Formulae

The structural formulae of the analysed hornblendes were calculated according to the general formula:

$$A_{0-1} \quad X_2 \quad Y_5 \quad Z_8 \quad O_{22} \quad (O, OH)_2$$

The site occupancies have been calculated on both a 24 (O,OH) hydrous basis and a 23 (O) anhydrous basis, (Table 3). The calculation on the 23(O) basis gives a better fit to the ideal formula with respect to the Y occup-

Table (2)

Optical Properties of Hornblendes from the Oxley Metamorphics

Zone	Thin Section No.		Refractive Indices			Absorption Colours		
			α	β	γ	α	β	γ
D	9555	HbL	1.657	-	1.675	Yellow	Green	Blue green
C	9551	Hb2	-	1.640	-	V. pale yellow green	Pale green	Pale green
C	9548	Hb3	1.645	-	1.671	Pale yellow	Pale green	Pale blue green
C	9539	Hb4	-	1.654	-	Pale yellow	Pale green	Pale blue green
C	9459		1.627	-	1.655	Pale yellow	Pale green	Pale green
C	9460		-	-	1.666	Pale yellow	Pale green	Pale blue green
C	9483		1.626	-	1.654	Pale yellow	Pale yellow green	Pale green
C	9506		-	-	1.663	Pale yellow	Pale green	Pale green
C	9507		-	-	1.679	Pale yellow	Pale green	Pale blue green
C	9509		1.645	-	1.670	Pale yellow	Pale green	Pale blue green
C	9523		1.641	1.658	1.664	Pale yellow	Pale yellow green	Pale green
C	9526		1.642	1.660	1.665	Pale yellow	Pale yellow green	Pale green
D	9535		1.659	-	1.678	Yellow	Green	Blue green
D	9560		-	1.683	-	Yellow	Olive Green	Emerald green

ancy. Binns (1965) advocates calculation on this basis as inaccurate determination of H_2O^+ results in substantial errors which accumulate in the partly occupied A site of the structural formulae. Calculation on the 23(O) anhydrous basis was criticised by Borg (1967), who pointed out that the 23(O) calculation produces ΣX, ΣY, and ΣZ closer to the ideal only because of compounding and cancellation of errors, as amphibole analyses almost always add up to approximately 100 percent. Although the analyses of hornblendes Hbl - 4 total close to 100 percent, the H_2O^+ value of each is low, and this is probably due to an inaccurate determination in each case. For such hornblendes the 23(O) calculation is preferable, (Borg, 1967, p. 589) although without measurements of unit cell volume and density, both methods of calculation are subject to ambiguities (Binns, 1965, p. 316; Ernst, 1968, p. 19). In the discussion that follows all references are to the structural formulae calculated on a 23 (O) anhydrous basis.

Chemical variation of the Hornblendes

(1) Dependent on Host Rock Composition

In Table 4, the $Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn)$ ratios and the $Fe^{2+}/(Fe^{2+}+Fe^{3+})$ ratios of the hornblendes and the host rocks are compared. As expected, the ratio of these

Table (3)

CHEMISTRY OF HORNBLENDES FROM THE TIA COMPLEX

Chemical Analyses of the Hornblendes

	Hb1	Hb2	Hb3	Hb4
SiO_2	43.92	45.08	44.34	47.94
TiO_2	0.86	0.63	0.73	0.75
Al_2O_3	11.31	13.13	12.53	9.83
Fe_2O_3	3.91	1.60	2.71	1.36
FeO	12.54	14.08	14.00	14.08
MnO	0.24	0.24	0.20	0.22
MgO	10.66	11.15	10.23	11.26
CaO	12.93	11.09	12.21	12.34
Na_2O	1.55	1.40	1.37	1.00
K_2O	0.35	0.18	0.27	0.20
H_2O^+	1.38	1.46	1.36	1.49
H_2O^-	0.09	0.08	0.07	0.11
P_2O_5	0.05	0.05	0.05	0.04
	99.79	100.17	100.07	100.62

Structural Formulae on a 23(O) Anhydrous Basis

	Hb1	Hb2	Hb3	Hb4
Si	6.49	6.56	6.51	6.94
Al^{iv}	1.51	1.44	1.49	1.06
Al^{vi}	0.46	0.81	0.68	0.62
Ti	0.10	0.07	0.08	0.08
Fe^{2+}	1.55	1.71	1.72	1.70
Mg	2.35	2.42	2.24	2.43
Mn	0.03	0.03	0.02	0.03
Ca	2.05	1.73	1.92	1.91
Na	0.44	0.40	0.39	0.28
K	0.07	0.03	0.05	0.04
ΣY	4.92	5.22	5.04	5.01
Edenite Alkalis	0.45	0.34	0.36	0.14

Structural Formulae on a 24(O, OH) Hydrous Basis

	Hb1	Hb2	Hb3	Hb4
Si	6.56	6.64	6.60	7.02
Al^{iv}	1.44	1.36	1.40	0.98
Al^{vi}	0.56	0.92	0.80	0.72
Ti	0.10	0.07	0.08	0.08
Fe^{3+}	0.44	0.18	0.30	0.15
Fe^{2+}	1.57	1.73	1.74	1.72
Mg	2.38	2.45	2.27	2.46
Mn	0.03	0.03	0.03	0.03
Ca	2.07	1.75	1.95	1.94
Na	0.45	0.40	0.40	0.28
K	0.07	0.03	0.05	0.04
OH	1.38	1.43	1.35	1.45
ΣY	5.08	5.38	5.22	5.16

Table (3) Cont'd.

CHEMISTRY AND CIPW NORMS OF THE HOST AMPHIBOLITES

	MB1	MB2	MB3	MB4
SiO_2	45.45	47.42	48.74	49.83
TiO_2	0.78	0.96	0.83	1.02
Al_2O_3	16.91	17.34	15.97	15.52
Fe_2O_3	2.72	1.20	1.72	0.96
FeO	9.19	10.91	10.20	10.31
MnO	0.18	0.18	0.14	0.13
MgO	7.86	8.30	7.28	7.09
CaO	13.19	10.45	10.77	10.90
Na_2O	2.18	2.67	2.95	3.00
K_2O	0.25	0.15	0.20	0.15
H_2O^+	0.72	1.10	1.10	0.90
H_2O^-	0.08	0.04	0.10	0.06
P_2O_5	0.13	0.09	0.62	0.56
	99.64	100.81	100.62	100.43

CIPW NORMS

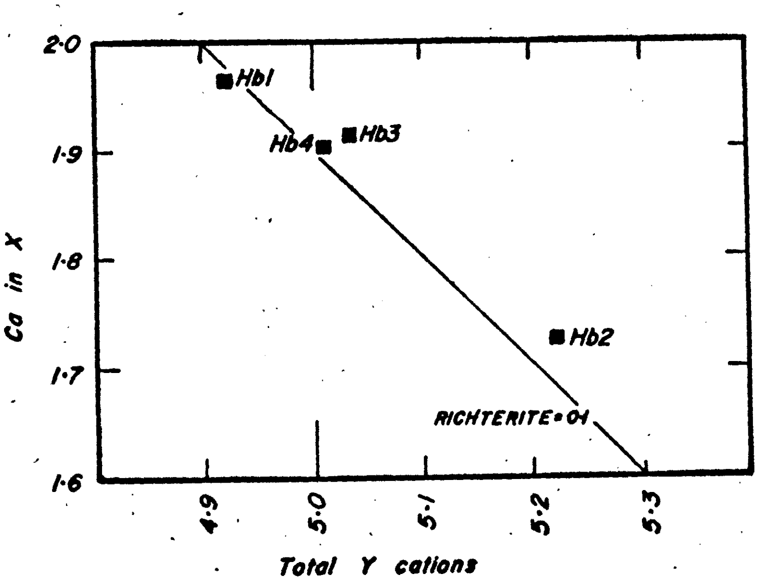
Or	1.7	1.1	1.1	1.1
Ab	13.6	23.1	25.2	25.2
An	35.6	34.5	29.8	28.4
Ne	2.6	-	-	-
Di	23.9	13.7	16.5	18.4
Hy	-	1.1	8.5	12.7
Ol	15.9	22.4	13.1	9.2
Ilm	1.5	1.8	1.5	2.0
Mt	3.9	1.9	2.6	1.4
Ap	0.3	0.3	1.3	1.3
F	34	38	40	41
An	72	60	52	53

TABLE. 4.

	MB1	Hb1	MB2	Hb2	MB3	Hb3	MB4	Hb4
$\frac{Mg}{Mg.\ Fe^{2+}\ Fe^{3+}\ Mn}$	0·543	0·540	0·550	0·556	0·523	0·523	0·530	0·560
$\frac{Fe^{2}}{Fe^{2+}\ \ Fe^{3+}}$	0·790	0·783	0·915	0·905	0·868	0·853	0·922	0·918

Ratios showing a strong correlation between bulk rock composition and hornblende composition.

FIG. 8.



Illustrates the complementary relationship between amount of Ca in the X sites and the sum of the Y group cations at a relatively constant richterite content of 0.I.

elements in the hornblends parallels closely that in the host rocks. A slight discrepancy is found in the case of Hb4 - MB4, and is probably attributable to minor analytical error. The Fe^{2+}-Fe^{3+} substitution is also clearly controlled by host rock composition, in which the Fe^{2+}/Fe^{3+} ratio is dependent on the oxidation-reduction conditions during metamorphism. In addition, Hb1 with Fe^{3+} of 0.43 per formula unit co-exists with magnetite and sphene while the other three with Fe^{3+} 0.30 per formula unit co-exist with ilmenite, in agreement with Binns (1965) p. 320.

Binns (1965) p. 319 showed that the nature of the cations occuping the X site is also dependent on host rock chemistry. Fig 8 shows the complementary variation between the amount of calcium in the X site and the total Y group cations for the Tia hornblendes. Hb2 contains the largest excess of Y group cations and Ca is correspondingly low. The host rock, MB2 contains low normative diopside content but a relatively high normative diopside/normative hypersthene ratio. Hb1 is deficient in the Y site and Ca in X is correspondingly high. This correlates with the very high normative diopside content of the host amphibolite. As suggested by Binns (1965), this ΣY deficiency is possibly made up by octahedrally co-ordinated calcium. Hb3 and Hb4 have intermediate values of ΣY and Ca in X, and intermediate normative diopside host rock values. In addition, the Tia hornblendes, like those from the Willyama Complex (Binns, 1965), plot very close to a line denoting a constant richterite content of 0.10, (i.e. atoms of sodium replacing calcium in X).

Binns (1965) showed that the largest excesses in Y site occupancy occur in rocks with a relatively low ratio of normative diopside to normative hypersthene, whereas the excess is small in hornblendes from rocks relatively rich in Ca. In the case of the hornblendes from the Tia complex, the complementary relationship between Ca in X and Σ Y occupancy appears to be related to the amount of normative diopside of the host rocks rather than the normative diopside/normative hypersthene ratio as shown by Binns (1965) p. 319 for the Willyama hornblendes.

(2) Inferred Grade Dependent Variation

Previous work

Much has been written of the possible grade dependent chemical variation of metamorphic hornblendes. Wiseman (1934) detected increases in the total Al and Al^{iv} replacing Si with increasing grade. Harry (1950) proposed that the Al^{iv} content of hornblendes increases regularly with metamorphic grade. Shido (1958) and Shido and Miyashiro (1959) demonstrated that the alkali content increases with metamorphic grade. The Abukuma Plateau hornblendes were also found by Shido (1958) to show no regular increase in Al^{iv} with metamorphic grade; to show an increase in Ti with increasing metamorphic grade; and to show a decrease in $Fe^{3+}/Fe^{2+}+Fe^{3+}$ at higher metamorphic grades. In the Adirondacks, Engel and Engel (1962) found that with increasing metamorphic grade, the hornblendes showed increases in Ti, Na and K and decreases in Mn, (OH+F+Cl) and the ratios Fe_2O_3/FeO and Fe/Mg. That the maximum Ti content of hornblende increases at higher temperatures was also proposed by Leake (1965), who also suggested that the amount of Al^{vi} appears to be related to the pressure acting during crystallization. Binns (1965) found that Al^{vi} decreases steadily with metamorphic grade and that there is an increase in "edenite alkalis" occupying the A site at higher metamorphic grade.

Grade Dependent Variation of the Tia Hornblendes

The Tia hornblendes show only a very slight increase in Ti with increasing grade (from 0.07 to 0.10) however the host rocks show a regular decrease in TiO_2 with increasing metamorphic grade, from 1.02 in MB4 to 0.78 in MB1. In addition, these Ti contents are significantly lower than the Ti contents of the metamorphosed basic rocks of the Willyama Complex, (Binns, 1964). This suggests that the Ti of the Tia hornblendes (especially Hbl) may not have reached its maximum possible value at the T-P conditions of metamorphism because of the limited Ti of the host rock. The Ti content (and colour) of the Tia hornblendes is not therefore a reliable indicator of metamorphic grade. In Fig 9a, 2Ti is plotted against Fe^{3+} (after Binns, 1965, p. 313) showing the slight increase in Ti with grade and indicating that the deeper blue-green colours of the highest grade hornblende Hbl are predominantly a result of its higher Fe^{3+} content.

The distribution of Al between the tetrahedral and octahedral sites is shown in Fig 9B. The highest grade hornblende (HB1) has the lowest Al^{vi} content and plots in the field of the Zone C hornblendes from the Willyama Complex. The lower grade hornblendes (Hb2-4) have higher Al^{vi} while Hb4 has significantly less Al^{iv} than Hbl-3. Although the data are scattered, there is general agreement with Binns (1965), p. 320, that Al^{vi} decreases at high metamorphic grade.

By plotting Fe^{3+}+2Ti against Al^{iv}, Binns (1965) showed that Ti and Fe^{3+} substitution in the Y sites of the Willyama hornblendes is balanced by Al replacing Si in the Z site. With the exception of Hb2, the Tia hornblendes plot very close to those of the Willyama Complex (see Fig 10a). After balancing Fe^{3+} and Ti, Hb2 contains

FIG. 9a.

Titanium plotted against ferric iron in the Tia hornblendes, showing the negligible increase in titanium with increasing metamorphic grade. The colours shown are those of the Willyama hornblendes described by Binns, (1965).

FIG. 9b.

Octahedrally coordinated aluminium plotted against tetrahedrally coordinated aluminium in the Tia hornblendes. Fields A, B, and C are from Binns, (1965) for the hornblendes of these zones of the Willyama Complex.

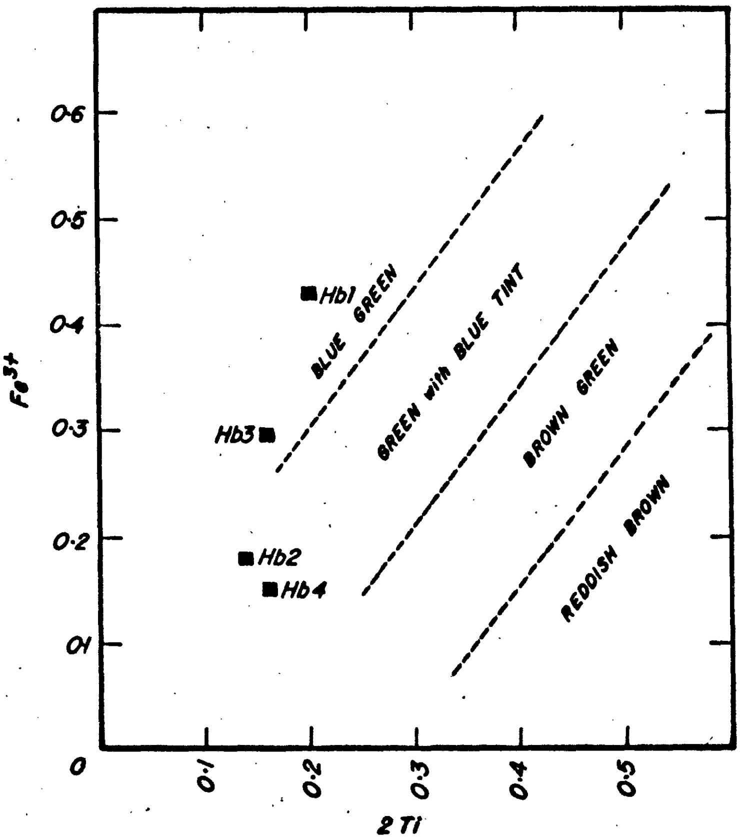

0·6
0·5
0·4
0·3
0·2
0·1
0
Fe^{3+}
0·1
0·2
0·3
0·4
0·5
2 Ti
Hb1
Hb3
Hb2
Hb4
BLUE GREEN
GREEN with BLUE TINT
BROWN GREEN
REDDISH BROWN

FIG. 9a.

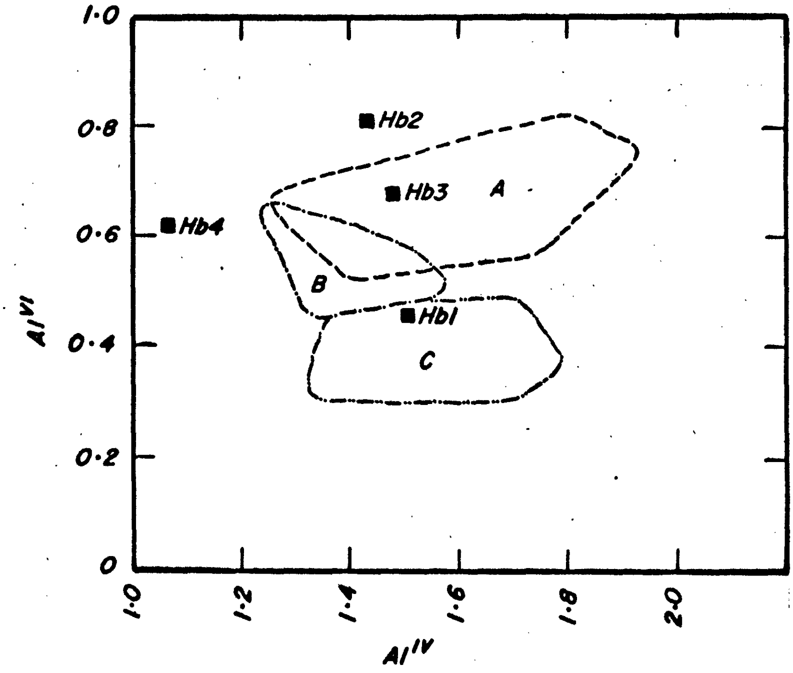

1·0
0·8
0·6
0·4
0·2
0
Al^{VI}
1·0
1·2
1·4
1·6
1·8
2·0
Al^{IV}
Hb2
Hb3
Hb4
Hb1
A
B
C

FIG. 9b.

substantially more remaining Al^{iv} than the other Tia hornblendes. This is balanced by the octahedral Al^{vi} which is also significantly higher in Hb2. The high aluminium content of Hb2 may be a consequence of the MB2 bulk chemistry which has a relatively higher Al_2O_3 (17.34%) and lower CaO and normative diopside than the other amphibolites.

Binns (1965) showed that the alkalis occupying the A and X sites may be divided into richterite and edenite alkalis. Richterite alkalis fill the X and A sites in a 1:1 ratio and show little variation with increasing metamorphic grade (see Fig 8). The excess alkalis occupying the A sites are known as edenite alkalis and the Willyama hornblendes show increasing occupancy of the A site by edenite alkalies with increasing metamorphic grade, (Fig 10b). This is balanced by a decrease in the octahedrally co-ordinated Al^{vi}. The Tia hornblendes show similar behaviour to the Willyama hornblendes. Hb2-4 plot in and adjacent to the field of the Zone A Willyama hornblendes, while Hb1 plots close to the field of the Zone C hornblendes. In addition, there is a significant increase in the K content of the hornblendes with metamorphic grade.

Summary

This limited study shows that the Tia hornblendes

FIG. IOa.

Plot of tetrahedrally coordinated aluminium against the charge excess resulting from substitution of ferric iron and titanium into the Y sites.

FIG. IOb.

Plot of edenite alkalis against octahedrally coordinated aluminium in the Tia hornblendes. Fields A,Band C encompass the hornblendes from these zones in the Willyama Complex described by Binns,(I965).

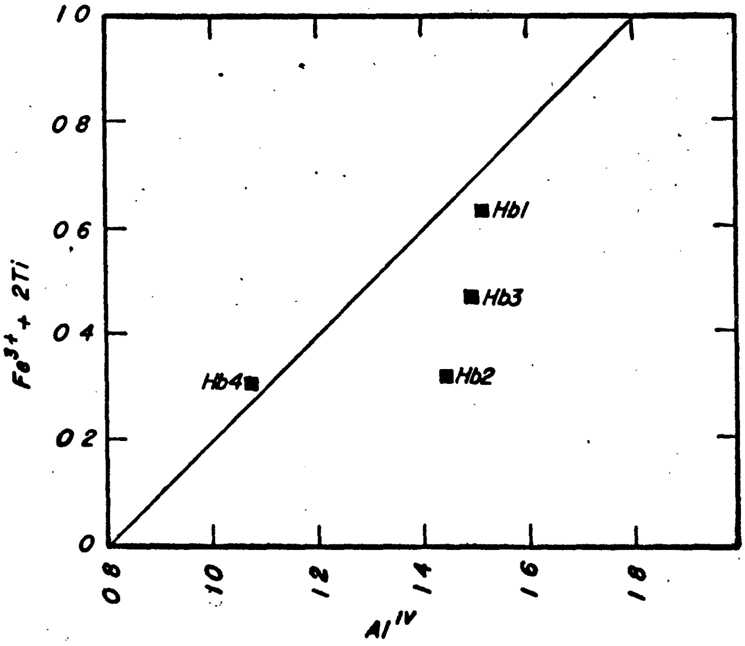


FIG. 10a.

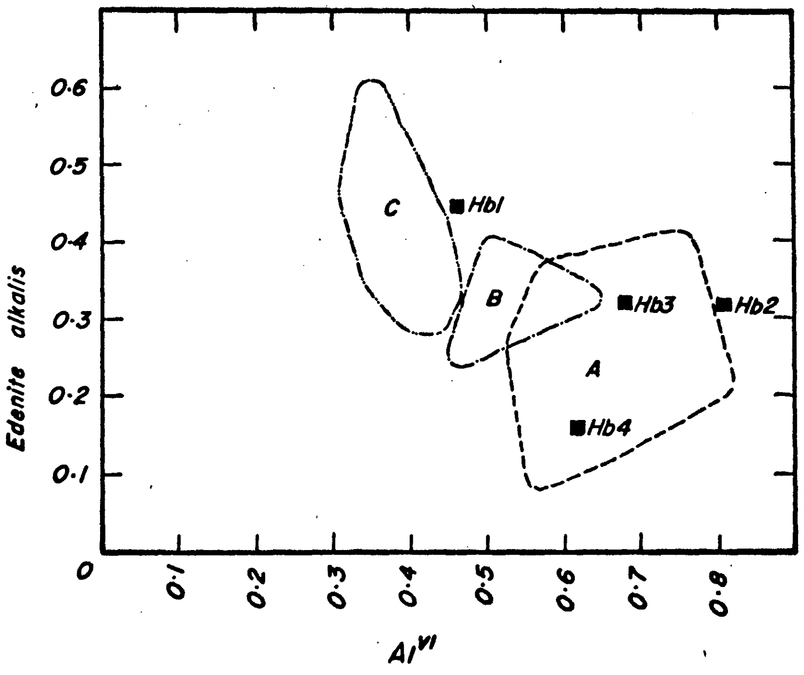


FIG. 10b.

show similar chemical variation to that reported by other workers. With increasing metamorphic grade the Tia hornblendes show:

(1) Overall decrease in Al^{vi}

(2) Slight increase in Al^{iv}

(3) Increase in Fe^{3+}

(4) Overall increase in edenite alkalis.

The $Mg/Mg+Fe^{2+}+Fe^{3+}+Mn$ and $Fe^{2+}/Fe^{2+}+Fe^{3+}$ ratios of the hornblendes are shown to depend on these ratios in the host rock.

The pale green and pale blue-green colours of the Zone C hornblendes appears to result from low Ti combined with low Fe^{3+}. The deeper blue green tints of the Zone D hornblende Hbl appears to be almost wholly the result of a higher Fe^{3+} value, as the increase in Ti is only slight.

The various maximum absorption colours of hornblendes have been noted by many workers to be a useful indicator of metamorphic grade, however as Miyashiro (1968) p. 818 has pointed out, these colour changes show quite different behaviour in different metamorphic terrains. The progression from blue-green to brown green and brown hornblendes with increasing metamorphic grade has been described by Wiseman, (1934), Shido (1958), Miyashiro

(1958), Engel and Engel (1962), and Binns (1965). This colour variation has been shown to result from increasing Ti substitution in the hornblendes at higher metamorphic temperatures, coupled with a decrease in Fe^{3+} in this direction. This is illustrated in Fig 9a, taken from Binns, (1965), p. 313).

Two features distinguish the hornblendes and amphibolites described by the above workers from those of the Tia Complex.

(1) The amphibolites of the Tia Complex from which the analysed hornblendes were extracted contain, in general, considerably less TiO_2 (0.78-1.02%) than the amphibolites from the metamorphic terrains described by the above workers.

(2) There is an overall increase in the Fe^{3+} of the Tia hornblendes and Fe_2O_3/FeO ratio of the amphibolites with increasing metamorphic grade.

In the work cited above by others (with the exception of Wiseman, 1934), the TiO_2 content of the analysed amphibolites is, in general, well in excess of 1%, and in each case the Fe^{3+} of the hornblendes tended to decrease with metamorphic grade, corresponding to a decrease in the Fe_2O_3/FeO ratios of the host rocks with metamorphic grade, (Shido, 1958, p. 183; Miyashiro, 1958, p. 240; Engel and Engel, 1962, p. 1506; Binns, 1965, p. 312).

These differences can explain the slightly different behaviour of the Tia hornblendes. Hb2, 3 and 4 co-exist with ilmenite, thus according to Leake (1965) p. 305 these hornblendes should be saturated with Ti to the extent permissible at that metamorphic grade. Their Ti contents cover the same range as the Zone A hornblendes of the Willyama Complex (Binns, 1965), but the coupling with much lower Fe^{3+} results in the pale-green and pale-blue green colours. In Figs 9b and 10b Hb2, 3 and 4 also plot in the field of the Zone A Willyama hornblendes, so their Ti content is probably at its maximum for their respective metamorphic grade at Tia.

Hbl co-exists with magnetite and sphene, and the Ti of Hbl is probably less than its possible maximum. Its other chemical characteristics suggest Hbl is of about the same metamorphic grade as the Zone C Willyama hornblendes (see Figs 9b and 10b), however it still has a Ti content more typical of the Zone A Willyama hornblendes. This, combined with the higher Fe^{3+}, gives it the deep blue-green colour. The co-existence of Hbl with sphene may mean that in rocks such as Mbl, containing high CaO and normative diopside, Ti is preferentially incorporated in sphene, thereby reducing the Ti content of the coexisting hornblende.

OTHER MINERALS OF THE METAMORPHOSED BASIC ROCKS

Actinolite

This was referred to briefly in the account above of hornblende. It is a characteristic amphibole of the Zone A and lower Zone B metabasalts and is a major mineral phase of the metamorphosed basalts of the Woombi Greenstones.

Throughout Zones A and B it is a pale coloured variety with an acicular or fibrous habit. The following pleochroic scheme is typical:

α - V. pale yellow to almost colourless

β - V. pale yellow green

γ - Pale green.

An actinolitic amphibole from S9568 has $\beta = 1.637$, $\gamma = 1.657$ ($\pm .002$). A common textural feature, described in Chapter (10), is its occurrence as zoned grains, the cores of which contain crossite.

The actinolitic amphibole of the Woombi Greenstones is similar, but may also show slightly deeper colours, with a blue green tint along γ corresponding with a slightly higher refractive index (n γ in the range 1.650-1.655).

Crossite

This is a common minor constituent of the Zone A metabasalt. An attempt to separate crossite from these rocks for analysis was unsuccessful because of its fine grainsize and tendency to occur as zoned grains.

It is strongly pleochroic, with the following scheme:

α - Pale yellow
β - Lavender blue
γ - Blue

Refractive Indices

Thin Section No.	α	β	γ ($\pm$.002)
9568	1.646	1.662	1.666
9592	-	-	1.664
9595	-	1.660	1.664

It is optically negative with a low 2v ($< 20^\circ$), shows moderately high dispersion, and the optic axial plane is oriented normal to (010).

According to Deer, Howie and Zussman, v. 2, (1963), p. 333, these are typical properties of an amphibole intermediate between glaucophane and riebeckite in composition, known generally as crossite.

Plagioclase

The plagioclase of Zone A is a fine grained albite resulting from the breakdown of the calcic plagioclase of the basalts. Its precise composition could not be determined however its mean refractive index is less than co-existing quartz, so an albitic composition is inferred. The composition of the plagioclase in the other metamorphic zones is shown in Table 5. It is clear that with increasing metamorphic grade, the plagioclase becomes enriched in anorthite molecule.

At the boundary between Zones B and C the disappearance of epidote coincides with the crystallization of an anorthite bearing plagioclase. The crystallization of more anorthite rich plagioclase in Zone D coincides with increasing sodium as edenite alkalis entering the co-existing hornblende at higher metamorphic grade.

Diopsidic Clinopyroxene

This is found in some parts of the highest grade amphibolite horizon. It is also abundant in the outer zones of the patchy alteration described earlier (page 85). The diopside of the amphibolite (S9563) is colourless with $\beta = 1.684$ ($\pm .002$) and a relatively high 2V(55-60°). These values suggest a diopside close to the end member Ca Mg Si_2O_6, (Deer, Howie and Zussman, v. 2, 1962, p. 132).

Table (5)

Composition of the Plagioclase from the Metamorphosed Basic Rocks

Thin Section No.		Plagioclase (± 0.002)	Plagioclase Composition
Zone B	9568	1.532	An_o
	9617	1.533	An_o
Zone C	9448	1.556	An_{46}
	9463	1.551	An_{36}
	9464	1.550	An_{35}
	9466	1.552	An_{38}
	9476	1.552	An_{38}
	9478	1.547	An_{29}
	9489	1.554	An_{42}
	9532	1.551	An_{36}
	9534	1.553	An_{40}
	9535	1.550	An_{35}
	9680	1.548	An_{30}
Zone D	9554	1.557	An_{48}
	9556	1.558	An_{50}
	9563	1.555	An_{46}

Epidote

No determination of the compositions of the abundant fine grained epidote of Zones A and B was attempted. Its pale yellow colour and slight pleochroism in sections of normal thickness, along with its relatively high birefringence suggest it is a relatively ferrian variety.

The epidote from the patchy alteration within the highest-grade amphibolite horizons is a yellow, poikiloblastic variety with $\beta = 1.760$. According to Deer, Howie and Zussman, v. 1, (1962), p. 203, this indicates a content of approximately 33 mol. percent $Ca_2Fe_3^{3+}Si_3O_{12}(OH)$.

Pumpellyite

The X-ray powder patterns of two pumpellyites from Zone A are given in Appendix 2. They are both pleochroic varieties with the following colour scheme,

α -	Pale yellow to colourless
β -	Emerald green to brownish green
γ -	Pale yellow green to pale green

and with anomalous birefringence colours.

De Roever (1947) and Coombs (1953) showed that the absorption colours of pumpellyite can be correlated with iron content. Their data suggest that the pumpellyites of Zone A are iron-rich varieties.

Chlorite

Both optically positive and negative varieties are present. They vary from almost colourless to pleochroic from pale yellow to pale green, and show a wide variety of anomalous birefringent colours such as blues, purples, browns and greys.

The chlorite from S9568 is pleochroic from pale yellow to pale green with $2V < 10^{\circ}$, optically negative and with $\beta = 1.629$ ($\pm .002$). It shows anomalous violet birefringent colours. According to the optical properties and nomenclature of the chlorites given by Deer, Howie and Zussman, V. 3, (1962), p. 137 and p. 151 this is a variety known as brunsvigite.

Stilpnomelane

This was identified by X-ray powder photography carried out on specimens plucked from thin sections. All these photographs carry the characteristic strong reflection from the 12.1Å (001) basal spacing of stilpnomelane.

The stilpnomelane of S9568 (illustrated in Plates 8C) has the following optical properties:

α - V. pale cream

β, γ - Pale green-brown = 1.582 ($\pm .002$)

According to Deer, Howie and Zussman, V. 2, (1962) p. 106, these properties are typical of ferro-stilpnomelane. In other thin sections deeper browns and red-browns are developed. According to Hutton (1938) p. 185 this is the result of decreasing Fe^{2+}/Fe^{3+} ratio, i.e. an increase in ferri-stilpnomelane component.

Green Biotite

This rare mineral component of the low grade metabasalts has the following optical properties:

α - Pale yellow-green
β, γ - Deep green = 1.638 (±.002)

According to the work of Hall (1941), Hayama (1959) and Chinner (1960) these properties suggest this biotite has a very low TiO_2 content and relatively high ferric iron.

Sulphides and Opaque Oxides

The identity of the various opaque phases was determined by reflected-light microscopy and X-ray powder photography.

It was found:

(1) Pyrrhotite and pyrite are common minor constituents of the metamorphosed basalts at all metamorphic grades.

(2) Ilmenite is the most common opaque oxide of Zones B and C, where it may be accompanied by minor magnetite. The highest grade amphibolites contain magnetite as the sole opaque oxide.

Other Minerals

The following are also found in the metamorphosed basic rocks, but will not be discussed in detail:

Quartz
Calcite
Sphene
Minor red-brown biotite
White mica
Grunerite (discussed in Chapter 15).
Relict igneous clinopyroxene (discussed in Chapter 16).

Chapter 15.

MINERALOGY OF THE SILICEOUS METASEDIMENTARY ROCKS

BIOTITE

Introduction

The maximum absorption colours of the biotites of these rocks show wide variation, ranging from green-brown to deeper browns and red-browns and deep olive-browns to black. From the work of Hall (1941), Hayama (1959) and Chinner (1960), this variation indicates a wide range in their chemical composition especially with regard to TiO_2, MgO, FeO and Fe_2O_3 content. Chinner (1960) also found a correlation between the colour of the biotites and the variety of opaque oxide with which it co-existed.

This colour variation is partly dependent on metamorphic grade, as the red-brown tints are generally absent from lower grade biotites. From the work of Engel and Engel (1960), Oki (1961) and Banno (1964) this variation in chemical composition is inferred to be, in part, the result of grade dependent chemical changes, however it is also known that the host rock composition is of great importance (Chinner, 1960; Binns, 1969, p. 328).

Chemistry

Two biotites from the higher grade metamorphics were analysed. The analyses and structural formulae of these two biotites, together with one from the Tia Granodiorite is given in Table 16, Chapter (19). B3 comes from a high grade schist, whose bulk chemistry is also known, adjacent to the analysed high grade metabasalt MB1. B2 comes from a migmatitic contact schist situated at the south-west contact of the granodiorite. These localities are also shown on Map 2.

Discussion

Biotite B2 is of very similar composition to biotite B1 from the granodiorite. The migmatitic nature of the B2 host rock is inferred to have arisen by partial melting by the granodiorite of some of its immediate contact rocks. The chemical composition of biotite B2 has therefore been strongly influenced by its crystallization in equilibrium with the migmatitic fluid phase, which was itself in equilibrium with that of the adjacent granodiorite.

The composition of the co-existing mineral phases of biotite B3, as well as the bulk chemistry of its host rock, have been determined. B3 contains unusually high Si, low tetrahedral Al and high octahedral Al. In addition, Ti is relatively low compared with other metamorphic biotites (see Binns, 1969, p. 328). Further discussion of the chemistry of this biotite will take place in Part VI.

MUSCOVITE

Introduction

White mica is an ubiquitous constituent of the siliceous metasedimentary rocks at all metamorphic grades. Its variation in habit with metamorphic grade has been described in Chapter (10).

Optical Properties

The majority of the white micas of Zones 1 and 2 are colourless, whereas many of those white micas of the Transition Zone and of some horizons in Zone 1 are slightly pleochroic with pale green or yellow maximum absorption tints and with a relatively low 2V. It is inferred that the latter are of phengitic composition, (Ernst, 1963, p. 1347).

Refractive Indices

Thin Section No.	N γ ($\pm$.002)	
9608	1.602	Zone 1
9815	1.605	Transition Zone
9841	1.597	)
9886	1.593	) Zone 2
9789	1.596	)

The two white micas from the lower grade schists have significantly higher refractive indices than those from Zone 2.

X-Ray Study

Two factors may cause a decrease in the basal spacing of white micas:

(1) Increasing substitution of Na for K, (paragonite substitution).

(2) Increasing substitution of Fe^{2+}, Fe^{3+} and Mg for Al, (phengite substitution).

The d(002) spacings measured using silicon as an internal standard are listed in Table (6). A difference between the values of the higher grade (Zone 2) and low grade (Zone 1 and Transition Zone) white micas is apparent. The limited data for the latter suggest that two varieties are present in Zone 1 and the Transition Zone. From their basal spacings and optical properties these are inferred to be a phengitic variety (e.g. 9806, 9810) and a variety close to relatively pure muscovite, (eg. 9843, 9844, 9808).

The basal spacings of the Zone 2 white micas have intermediate d(002) values. The analyses of two Zone 2 muscovites (Table 7) show they have rather unusual compositions, and their basal spacings are not a clear guide to their composition.

Chemistry

Three muscovites from these rocks were separated and analysed. Separation was easily achieved in each case, and the analyses were performed on samples of high purity (99.5%). Mu1 co-exists with biotite B3, orthoclase Kf1, quartz, minor plagioclase and garnet G5 and comes from a high grade schist adjacent to the granodiorite. Mu2 is from an upper Stage 2 schist of the Brackendale Metamorphics, co-existing with biotite, orthoclase Kf2, plagioclase and quartz. Both these muscovites have crystallized as coarse, randomly oriented porphyroblasts, as described in Chapter (II). Mu3 is a lower grade muscovite from the upper part of Zone 1 within the Oxley Metamorphics. These localities are also given on Map 2.

Dioctahedral muscovite has the following ideal formula, (Deer, Howie and Zussman, V. 3, 1962, p. 7).

$$X_2 \ Y_4 \ Z_8 \ O_{20} \ (OH,F)_4$$

where X is mainly K, with Na, Ca and possibly H_3O^+

Y is mainly Al, with possibly some Mg, Fe^{2+}, Fe^{3+}, Mn and Ti.

Z is mainly Si and Al, and possibly Ti and Fe^{3+}.

Replacement of K by Na gives paragonitic white mica. Entry of Mg, Fe, Mn and Ti into the Y site is balanced

Table (6)

Basal Spacings of White Micas from the Tia Complex

(Measured using Silicon as an internal standard)

Thin Section No.	d(002)Å(±.008Å)	Absorption Colours
9806 (Mu3)	9.972)	V. pale green
9843	10.031) Zone 1	Colourless
9844	10.034)	Colourless
9808	10.027) Transition	Colourless
9810	9.943) Zone	Pale yellow-green
9819	9.996)	)
9667	10.020)	)
9665	10.005) Zone 2	) Colourless
9841 (Mu2)	10.023)	)
9789 (Mu1)	10.016)	)

by increasing Si in the octahedral site to give phengitic muscovite. Both these types of substitution are exhibited to some extent by the analysed white micas. The structural formulae have been calculated on the assumption that all 8 Z sites are occupied by Si and Al. Occupancies have been calculated on a 24(O,OH) hydrous basis as the analytically determined H_2O^+ gives OH contents relatively close to the ideal 4. Calculation on a 22(O) anhydrous basis would not significantly change the occupancies.

Discussion

Previous Work

Butler (1965) found that adjacent to the biotite isograd of the Moine Schists near Ardnamurchan the muscovites contain large amounts of Fe^{3+}, Fe^{2+} and Mg. Towards higher metamorphic grades the amount of Al^{iv} and Al^{vi} increases as the white mica becomes closer to ideal muscovite in composition. Similar compositional variation of the white micas from the Morar and Knoydart districts was reported by Lambert (1959).

Ernst (1963, 1964) showed that many dioctahedral micas from glaucophane schists and green schists are of phengitic composition and also demonstrated a change to

Table (7)

Chemistry of the Muscovites from the Tia Complex

	Mu1	Mu2	Mu3
SiO_2	50.61	54.67	47.26
TiO_2	0.10	0.45	0.10
Al_2O_3	33.04	27.97	29.79
Fe_2O_3	0.92	1.62	2.05
FeO	0.43	1.18	3.45
MnO	0.03	-	-
MgO	0.75	1.20	2.58
CaO	0.08	-	0.11
Na_2O	0.50	1.38	-
K_2O	9.75	7.75	9.45
H_2O^+	3.87	3.48	4.76
H_2O^-	0.07	0.09	0.21
P_2O_5	0.02	-	-
	100.08	99.79	99.76

Structural Formulae calculated on a 24(O,OH) Hydrous Basis

	Mu1	Mu2	Mu3
Si	6.67	7.21	6.36
Al^{iv}	1.33	0.79	1.64
Al^{vi}	3.81	3.56	3.08
Ti	0.01	0.04	0.01
Fe^{3+}	0.09	0.16	0.21
Fe^{2+}	0.05	0.12	0.39
Mg	0.15	0.24	0.52
Ca	0.01	-	0.02
Na	0.13	0.35	-
K	1.64	1.30	1.62
H_3O^+	-	-	0.28
OH	3.40	3.06	4.00
X	1.78	1.65	1.92
Y	4.11	4.02	4.21

Refractive Indices

	Mu1	Mu2	Mu3
γ ($\pm$.002)	1.596	1.598	1.602

more muscovitic compositions at higher grade. Low grade white micas of similar composition have also been reported by Van der Plas (1959) and McNamara (1965). The latter denied that there was any good evidence of a grade dependent change in muscovite composition. Muscovites from higher grade metamorphic rocks have been studied by Evans and Guidotti (1966). These muscovites contain much less Fe^{2+}, Fe^{3+}, Mg and Ti than those typical of lower grade. This supports the former suggestion above that the compositional field of white mica is diminished at higher metamorphic grades.

This Study

The structural formulae of all three muscovites analysed depart quite radically from the ideal formula. Considering the purity of the material analysed and the care with which the analyses were performed, there is no reason to doubt their validity.

The low grade muscovite Mu3 contains substantial Fe^{2+}, Fe^{3+} and Mg in the octahedral layer, balanced by higher Si substitution in the tetrahedral sites. The excess negative charge of the tetrahedral layer is balanced by the interlayer cations K and Ca. This still leaves an excess negative charge on the octahedral layer which must be balanced by H_3O^+ as interlayer cations, (Ernst, 1963), in which case the OH^- occupancy is set at its maximum of 4, see Table 7. This departure from ideal formula results from phengite-type substitution and Mu3 may be referred to as a phengitic muscovite. The higher Si, lower Al^{iv}, octahedral Mg, Fe^{2+} and Fe^{3+}, deficiency of X site alkalies and high water content are all characters of phengitic muscovites described by Ernst (1963).

The refractive index ($n\gamma = 1.602$) and low d(002) basal spacing (= 9.972Å) are also typical of phengitic muscovites. Limited X-ray data of other low grade muscovites (see Table 6) suggest that not all are of phengitic composition. The composition of the white mica at this grade is therefore probably also strongly dependent on its paragenesis.

The high grade muscovites Mu1 and Mu2 also depart radically from the ideal formula. Both are strongly enriched in Si and correspondingly low in Al^{iv}, and both are deficient in alkalies occupying the X site, (see Table 7). The Y site occupancy is very close to the ideal 4 in each case, the majority of which is Al^{vi}.

This muscovite chemistry may be explained in terms of substitution of pyrophyllite molecule (Al_4

$(Si_8\ O_{20})(OH)_4)$ in the muscovite lattice. Diffractometer scans of the analysed mineral concentrates showed they are homogeneous, giving only the characteristic reflections of muscovite. The possibility that a physical mixture of muscovite and pyrophyllite was analysed can therefore be dismissed. Pyrophyllite-type substitution in muscovite results in an increase in the Si of the tetrahedral layer and decrease in tetrahedral Al, with a decrease in the interlayer or twelve co-ordinated alkali cations to maintain the charge balance. This substitution may possibly take the form of an interlayering of muscovite and pyrophyllite sheets in the same manner as other interstratified platy minerals such as the pyrophyllite-montmorillonite described by Kodama (1958). Its development in these rocks is believed to be dependent on the paragenesis and metamorphic history of the host rock, (see Chapter 26).

There is a significant difference between the Na contents of Mu1 and Mu2, which appears related to their differing host rock compositions. Mu1, with 0.13 atoms of Na, comes from a potassium rich contact schist adjacent to the granodiorite, while Mu2, with 0.35 atoms of Na in the X site, comes from a more normal psammitic schist further from the granodiorite, (see Table 15, Chapter 18).

Summary

The white micas of the Tia Complex show the following characteristics:

(1) The low grade white micas may have a phengitic composition, however this probably depends on paragenesis and host rock composition, as muscovites of more ideal composition also appear to be present at lower grades.

(2) The higher grade white micas are less phengitic, in agreement with the findings of other workers such as Butler (1965), Ernst (1963).

(3) The white micas that have crystallized with a porphyroblastic habit within the higher grade schists have an unusual chemical composition which may be interpreted to result from substitution of pyrophyllite molecule in the muscovite lattice.

GARNET

The composition of five garnets from the Zone 2 schists of the Oxley Metamorphics were determined by partial analysis for MnO, and measurement of their refractive indices and cell dimensions. The compositions were then determined from these three parameters using charts modified from Winchell (1958).

The determinative data and the composition derived

Table (8)

Composition of Garnets from the Tia Complex

Determinative Data

Thin Section No.	Wt% MnO	a_o Å	n_d
9657	18.30	11.581	1.815
5111	19.20	11.575	1.811
9773	16.30	11.586	1.813
9674	16.54	11.568	1.814
9789	16.03	11.566	1.810
5123		11.574	1.814
5119			1.809
5132			1.815

Composition

(Mol% End members)

		Almandine	Spessartine	Pyrope	Grossular
G1 (9657)	Zone C	54.5	42.5	-	3.0
G2 (5111)		50.0	45.0	3.0	2.0
G3 (9773)		56.0	38.0	-	6.0
G4 (9674)		57.0	39.0	2.0	2.0
G5 (9789)	Zone D	55.0	37.5	6.0	1.5

are given in Table 8.

Discussion

The garnets are arranged in approximate order of increasing metamorphic grade, i.e. in order of decreasing distance from the granodiorite. G5 comes from the high grade schist from which biotite B3 and muscovite Mu1 are analysed. G1-4 come from lower metamorphic grades, and their localities are given on Map 2. The only clearly defined compositional variation with metamorphic grade is a slight decrease in the MnO or spessartine content. Grossular decreases slightly with metamorphic grade while the almandine component does not appear to show any clear trend. The higher pyrope content of the highest grade garnet G5 may not be significant as their compositions by the above method are only approximate.

The grade dependent chemical variation of garnet is reasonably well documented, (Miyashiro, 1953; Lambert, 1959; Engel and Engel, 1960; Sturt, 1962; Atherton, 1954). In rocks of essentially pelitic composition it is found that there is a decrease in Mn and Ca and an increase in Mg and Fe with increasing metamorphic grade. It is also known that the composition of the garnet is strongly dependent on host-rock composition and paragenesis eg. Binns (1969) p. 330.

The slight chemical variation of the garnets of the Tia Complex with increasing metamorphic grade is in general agreement with this previous work. The Tia garnets are much richer in MnO compared with garnets of comparable metamorphic grade in other metamorphic areas (eg. see Miyashiro, 1953), and this is probably a consequence of the host rock compositions. The influence of host rock composition may also be seen in the tendency for the Tia garnets to crystallize as small rounded grains confined to thin layers parallel to the lithologic layering. Minor concentrations of nodular manganese ore (psilomelane) are common in the interbedded quartzites, and the minor but related manganese content of the accompanying schists is believed to be important in promoting the crystallization of these garnets. The absence of garnet in the Brackendale Metamorphics is also believed to be important in this respect, as this subdivision lacks quartzites with concentrations of manganese and it is inferred that the schists of this subdivision are overall poorer in MnO than those of the Oxley and Wybeena Metamorphics.

It is also of interest to compare these garnets with those reported by Binns (1966) p. 13 from the Wongwibinda district. These garnets are much richer in almandine and pyrope (60-72 and 12-14 mol. percent of the end members respectively), and poorer in spessartine (11-24 mol. percent) than those from Tia.

ORTHOCLASE

Potassium feldspar is a major mineral phase of the higher grade schists of Zone 2 and is even more abundant in the contact rocks of the granodiorite. A potassium feldspar (kf1) from a contact schist (co-existing with biotite B3, muscovite Mu1 and garnet G5) and one from a slightly lower grade (Kf2, co-existing with Mu2) were separated. Diffractometer scans over the 131 reflections of these feldspars show monoclinic symmetry with no perceptible line broadening. A further sample from a migmatitic schist from the south west contact shows a distinctly triclinic intermediate state, (Fig 18, Chapter 19). This aspect is further discussed in Chapter (19).

The composition of Kf1 and Kf2 was estimated by the X-ray diffraction method of Orville (1958, 1963), using potassium bromate as an internal standard. Kf1 has a composition Or88Ab12, and the slightly lower grade Kf2 is of composition Or92Ab8.

Monoclinic orthoclase from upper amphibolite facies rocks is relatively common, described for example by Heald (1950), Binns (1964), Evans and Guidotti (1966) and Lundgren (1968). Heier (1957), (1961) has suggested that the transition from triclinic to monoclinic potassium feldspar takes place at P.T. conditions just below the amphibolite-granulite facies boundary. In view of later work this is subject to doubt, as the composition of the feldspar, its paragenesis and host rock composition, and the ~~Ph_2O~~ P_{H_2O} conditions during crystallization are all known to influence the final structural state, (Mackenzie and Smith, 1961; Tomisaka, 1962; Binns, 1964; Evans and Guidotti, 1966).

PLAGIOCLASE

The refractive indices of plagioclase from the schists of the Tia Complex were measured and their compositions estimated using the determinative chart of Chayes (1952). Their compositions are given in Table 9.

The overall change in composition of the plagioclase with metamorphic grade is similar to that reported from many other areas of metamorphic rocks. The plagioclase of the lower grade Zone 1 and Transition Zone appears to be virtually pure albite. In Zone 2 it becomes more anorthite rich and shows a relatively wide range in composition. This variation did not correlate well with increasing grade within this zone, and it appears that the composition of the plagioclase may have depended

Table (9)

Plagioclase Compositions from the Siliceous Metasedimentary Rocks of the Tia Complex

	Thin Section No.	n_β ($\pm$.002)	Composition (Mol%)
Zone 1 and Transition Zone	9815	1.532	An_0
	9856	1.531	An_0
	9884	1.531	An_0
Zone 2	9629	1.550	An_{35}
	9672	1.549	An_{33}
	9799	1.540	An_{13}
	9805	1.536	An_6
	9885	1.540	An_{13}
	9886	1.542	An_{17}
	9891	1.539	An_{12}

on host rock composition, i.e. on the amount of Ca in the host rock available to make anorthite molecule.

MINERALOGY OF THE METAMORPHOSED QUARTZITES

The majority of the quartzite horizons of the Tia Complex have only minor amounts of opaque oxides and sulphides, although many contain scattered small nodules and pockets of manganese ore, predominantly of psilomelane. One of these horizons accompanying the Zone D amphibolites contains an unusual mineral assemblage which is irregularly distributed throughout a layer in the quartzite adjacent to an amphibolite horizon. The silicate assemblage Quartz-Grunerite-Garnet-Biotite-Stilpnomelane has crystallized in this layer (illustrated in Plate 13C), while the adjacent amphibolite in contact with this layer contains a hornblende-grunerite-rich assemblage (Plate 11B). Similar quartzite layers are found at lower metamorphic grade (in Zone C) in which a garnet and a blue-green hornblende rather than grunerite have crystallized. Unfortunately these lower grade examples are poorly exposed and, in general, deeply weathered. All the known localities of these rock types are shown on Map 2.

The grunerites from the two adjacent high grade horizons were separated and analysed, (see Table 10).

The co-existing hornblende in the amphibolite could not be sufficiently purified for analysis in the time available. The composition of the garnet from the quartzite has been estimated using its cell dimensions, refractive index and MnO content.

Grunerite

The chemical composition and structural formula of the two analysed grunerites are given in Table 10. Both calculated structural formulae fit very closely the ideal grunerite formula, given by Deer, Howie and Zussman, V. 2, 1962, p. 234 as:

$$(Fe^{2+},Mg)_7Si_8O_{22}(OH)_2$$

The trace of potassium in Gr1 is probably the result of an insignificant biotite impurity in the analysed sample. Gr1 contains substantial (0.43 atoms) of Mn in the Y site and may be more specifically termed a manganoan grunerite. A grunerite containing 0.96 atoms Mn/formula unit has been given the specific name dannemorite by Sundius (1931), and it is suggested by Troger (1967) p. 437 that this name be used for grunerites with excess of 0.7 atoms Mn/formula unit, (see also Klein, 1964).

Garnet

The garnet accompanying the grunerite possessed

Table (10)

Chemistry of the Grunerites

	Gr1	Gr2
SiO_2	49.86	49.46
TiO_2	-	-
Al_2O_3	0.07	0.04
Fe_2O_3	0.49	1.36
FeO	37.73	40.52
MnO	3.16	0.42
MgO	5.87	5.24
CaO	0.80	0.73
Na_2O	-	-
K_2O	0.04	-
H_2O^+	1.60	1.52
H_2O^-	0.02	0.13
P_2O_5	-	-
	99.64	99.52

Structural Formulae calculated on a 23(O) anhydrous basis

	Gr1	Gr2
Si	7.95	7.94
Al^{iv}	0.01	0.01
Fe^{3+}	0.06	0.16
Fe^{2+}	5.03	5.44
Mn	0.43	0.06
Mg	1.40	1.25
Ca	0.14	0.13
K	0.01	-
ΣY	7.07	7.04
$(Mg/(Mg+Fe^{2+}+Fe^{3+}+Mn)$	0.20	0.18

Gr1 - From garnet-grunerite quartzite

Gr2 - From adjacent amphibolite horizon, co-exists with hornblende.

the following physical and chemical properties:

$n_d = 1.803$

$a_o = 11.638 (\text{Å})$

MnO =13.74 wt%

Using these data the following composition is derived from determinative charts modified from Winchell (1958):

Almandine	46.5
Spessartine	32.5
Grossular	19.5
Andradite	1.5

expressed as mol% of the ideal end member garnet molecules.

Other Minerals of the Siliceous Metasedimentary Rocks

The following mineral species are also found in these rocks but will not be discussed in detail:

Quartz
Epidote
Calcite
Chlorite
Tourmaline
Stilpnomelane
Graphite
Minor opaque oxides and sulphides
Minor Sphene

Chapter 16

BULK CHEMISTRY OF THE METAMORPHOSED BASALTS

Introduction

Bulk rock analyses of nine metabasic rocks (MB1-9) from the Oxley and Wybeena Metamorphics along with their C.I.P.W. norms and a calculated average composition are given in Table 11. All metamorphic grades are represented and the sample localities are shown on Map 2. The hornblendes from samples MB1-4 were separated and analysed and have been discussed in Chapter (14).

These bulk chemical data were collected for three main purposes:

(1) To elucidate the broad chemical features of the original basalts and their magmatic parentage, although the latter can only be discussed in very general terms.

(2) To determine the extent of bulk chemical variation and whether this can be correlated with, for example, redistribution of elements during or before metamorphism, or during the development of veins throughout the Zone A metabasalts.

(3) To provide a firm chemical basis for interpreting the metamorphic mineral assemblages found in these rocks.

Table (11)

Bulk Chemistry of the Metamorphosed Basalts

Zone	D	C	C	C	C	B	A	A	C	
	MB1	MB2	MB3	MB4	MB5	MB6	MB7	MB8	MB9	Average
SiO_2	45.45	47.42	48.74	49.83	48.65	40.60	45.42	43.18	47.18	46.27
TiO_2	0.78	0.96	0.83	1.02	1.28	4.24	2.38	1.70	1.38	1.62
Al_2O_3	16.91	17.34	15.97	15.52	12.68	15.51	15.99	15.16	14.81	15.54
Fe_2O_3	2.72	1.20	1.72	0.96	1.91	2.58	1.20	3.45	1.64	1.93
FeO	9.19	10.91	10.20	10.31	13.44	13.13	9.62	10.66	11.46	10.99
MnO	0.18	0.18	0.14	0.13	0.20	0.33	0.18	0.24	0.14	0.19
MgO	7.86	8.30	7.28	7.09	6.56	8.08	8.67	6.28	6.58	7.41
CaO	13.19	10.45	10.77	10.90	11.38	7.41	7.90	13.16	9.53	10.52
Na_2O	2.18	2.67	2.95	3.00	1.64	2.53	3.70	1.66	3.20	2.61
K_2O	0.25	0.15	0.20	0.15	0.14	0.83	0.05	0.04	0.50	0.26
H_2O^+	0.72	1.10	1.10	0.90	1.40	4.14	3.97	4.48	2.58	2.26
H_2O^-	0.08	0.04	0.10	0.06	0.13	0.14	0.20	0.16	0.07	0.11
P_2O_5	0.13	0.09	0.62	0.56	0.04	0.29	0.39	0.05	0.80	0.33
	99.64	100.81	100.62	100.43	99.45	99.81	99.67	100.22	100.27	100.04

C.I.P.W. Norms

Qz	-	-	-	-	1.2	-	-	-	-
Or	1.7	1.1	1.1	1.1	0.6	5.0	0.6	-	2.8
Ab	13.6	23.1	25.2	25.2	13.6	18.9	29.9	14.2	27.3
An	35.6	34.5	29.8	28.4	27.2	28.6	26.7	34.0	24.5
Ne	2.6	-	-	-	-	1.1	0.9	-	-
Di	23.9	13.7	16.5	18.4	24.6	5.1	8.0	25.4	14.7
Hy	-	1.1	8.5	12.7	25.6	-	-	0.6	7.3
Ol	15.9	22.4	13.1	9.2	-	24.4	22.4	14.6	14.4
Ilm	1.5	1.8	1.5	2.0	2.4	8.1	4.6	3.2	2.7
Mt	3.9	1.9	2.6	1.4	2.8	3.7	1.9	5.1	2.3
Ap	0.3	0.3	1.3	1.3	-	0.7	1.0	0.2	2.0
F	34	38	40	41	50	36	31	40	44
An	72	60	52	53	67	60	47	70	47

Table 11 (Cont'd.)

Summary Description of Analysed Metabasalts

MB1	Zone D amphibolite containing blue-green hornblende, plagioclase, quartz, sphene, and magnetite, (Plate 10C).
MB2	Zone C amphibolite containing pale green hornblende, plagioclase, quartz and ilmenite, (Plate 10B).
MB3	Zone C amphibolite containing pale blue-green hornblende, plagioclase, quartz and ilmenite.
MB4	Lower Zone C amphibolite containing pale green hornblende, plagioclase, quartz and ilmenite.
MB5	Lower Zone C amphibolite with pale green hornblende, plagioclase, quartz and ilmenite, (Plate 10A).
MB6	Lower Zone B amphibolite containing pale green actinolite, crossite, epidote, chlorite, stilpnomelane, quartz, albite and a trace of green biotite, (Plate 9A).
MB7	Zone A metabasalt with relict igneous clinopyroxene and a metamorphic assemblage of actinolite, epidote, chlorite, albite and quartz, (Plate 7B).
MB8	Zone A metabasalt with relict igneous clinopyroxene and a metamorphic assemblage of actinolite, crossite, epidote, pumpellyite, chlorite, stilpnomelane, quartz and albite(?) (Plate 7A).
MB9	Amphibolite of Zone C collected adjacent to the Tiara Fault, (see Map 2).

Sample Selection and Preparation

No real sampling problems were encountered as the majority of the metabasalt horizons are fine-grained and homogeneous. Nothing resembling pillow structure is found at any metamorphic grade. The sort of redistribution of material described by Smith (1968) and chemical inhomogeneities associated with pillow structures such as those described by Vallance (1965, 1969) are not obvious in these rocks. Some metabasic horizons of Zone A have substantial post-tectonic veining as described in Chapter (10), but these are not highly developed in the horizons from which the two analysed Zone A metabasalts were collected. In addition, the highest grade amphibolite horizon (MB1) was sampled well away from the late, cross-cutting alteration zones described earlier.

The samples for analysis were sawn into slabs and about 1 kilogram of each crushed to -150 mesh by hand in a steel mortar and pestle, of which the pestle was tipped and the mortar lined with tungsten carbide.

Broad Chemical Features

The essentially basaltic composition of the metabasic rocks of the Tia Complex is clear from the nature and proportions of the C.I.P.W. normative minerals, and the position in which they plot in an ACF diagram

(Fig 11). This diagram shows that MB1-9 plot within or very close to the field of average basalt composition. Taken at face value, the C.I.P.W. norms suggest that the original basalts varied from mildly alkaline, i.e. nepheline normative, to distinctly tholeiitic (eg. quartz normative MB5). In addition, diagrams conventionally used to distinguish alkali and tholeiitic basalts show also a spread from mildly alkaline to tholeiitic, (Figs 12a and b). This however, ignores the possibility that the chemical composition of these rocks may have been changed by migration and redistribution of elements. It is well known that the composition of ancient mafic lavas may depart quite markedly from normal basalt chemistry, and Vallance (1960, 1965, 1969) and Smith (1968) have shown that substantial redistribution of material may take place throughout such lavas.

All the analysed samples except the quartz-normative MB5 contain substantial normative olivine. Throughout all the partially reconstituted basalts of Zone A there is little textural evidence that olivine was as abundant in the original basalts as these C.I.P.W. norms suggest. MB7 (See Plate 7B) has 22.4% normative olivine and 8.0% normative diopside whereas it clearly mainly consists of large clinopyroxene remnants partially replaced by later minerals. There is no textural evidence that olivine was ever a major mineral phase. The same

FIG. II.

ACF DIAGRAM CONTAINING THE ANALYSED METABASIC ROCKS OF THE TIA COMPLEX.

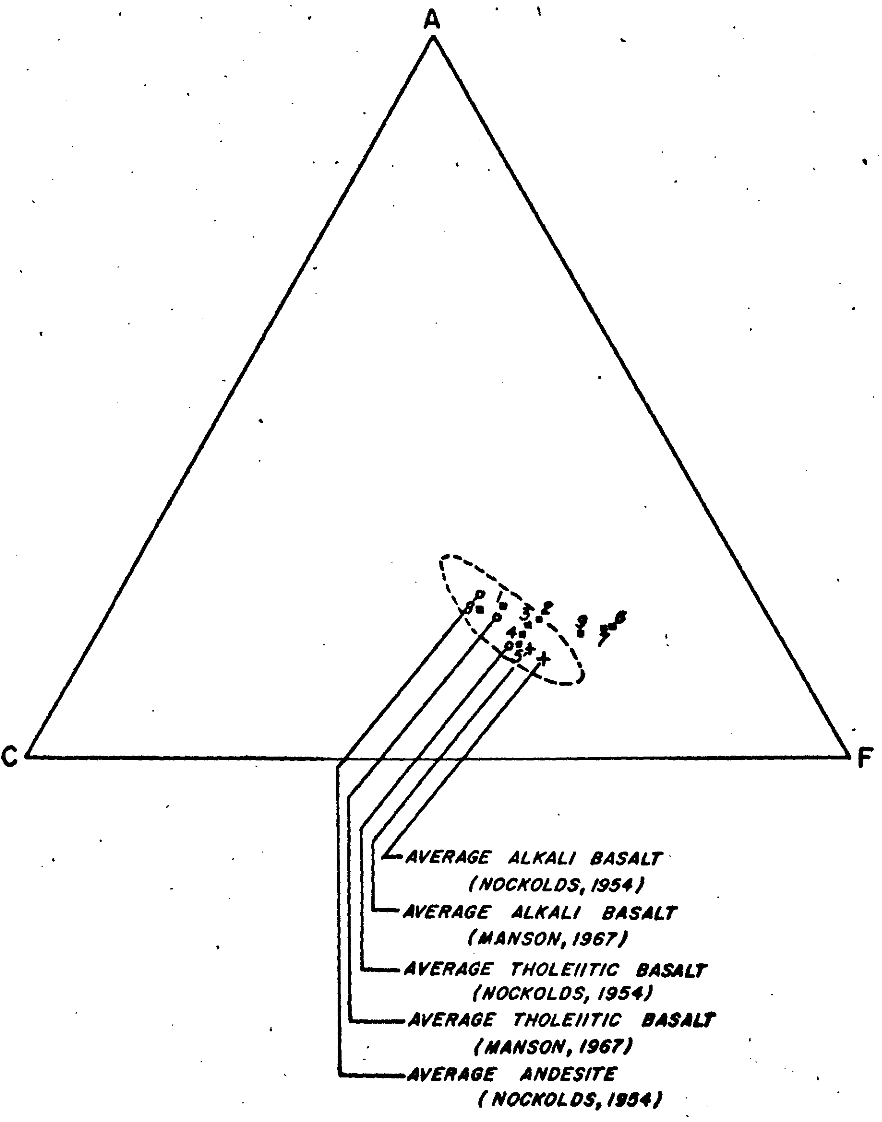
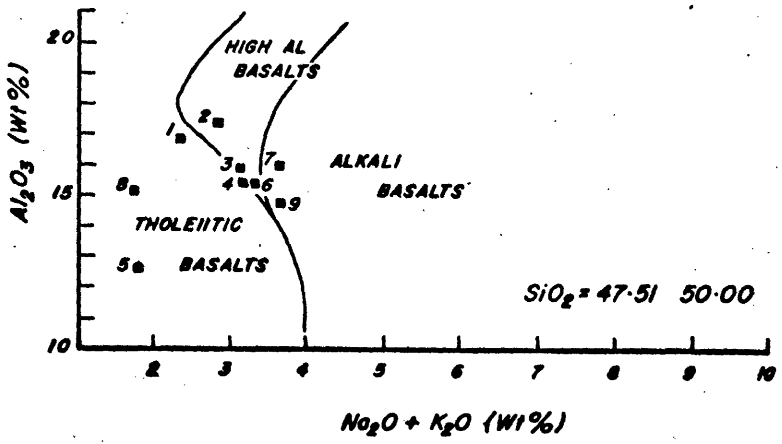
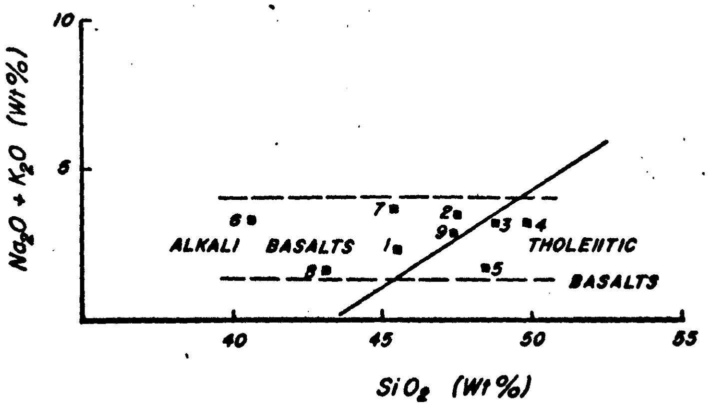


FIG. I2a.



(after Kuno, I968).

FIG. I2b.



(after Macdonald and Katsura, I964).

argument applies to MB8 (see Plate 7A) with 14.6% normative olivine and 25.4% normative diopside.

This discrepancy suggests that the metabasalts have undergone some compositional change subsequent to extrusion. Two possible explanations for this discrepancy are offered:

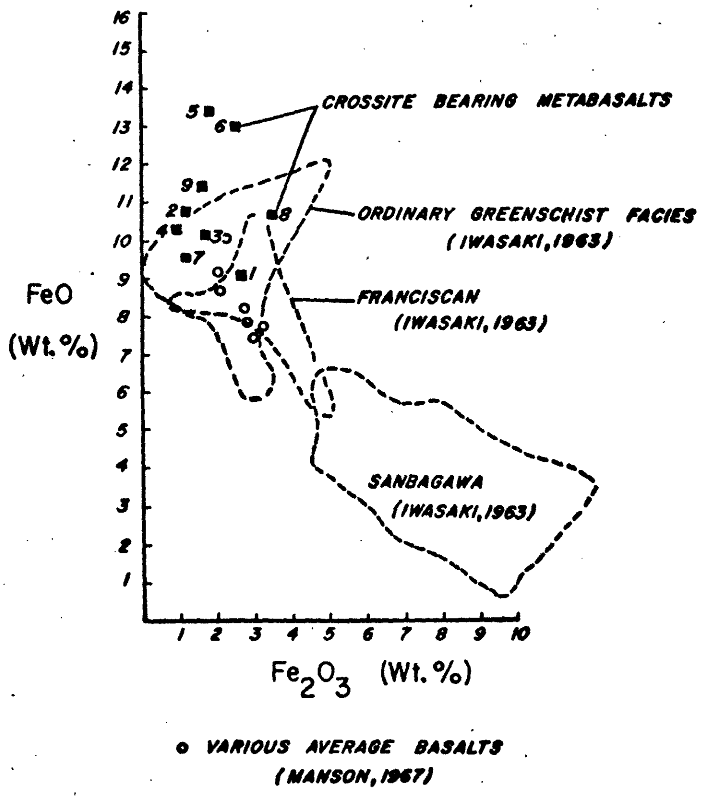
(1) Normative olivine would increase if the basalt became depleted in SiO_2. This may be, in part, the explanation for the high normative olivine of MB6 (SiO_2 =40.60) and MB8 (SiO_2=43.18) as both these metabasalts contain significantly less SiO_2 than the remainder.

(2) Reduction of iron during metamorphism increases the normative olivine, i.e. Fe^{3+} formerly allocated to normative magnetite upon reduction gives Fe^{2+} which combines with available SiO_2 to increase the normative olivine Fig (13) illustrates relatively higher Fe^{2+}/Fe^{3+} ratios of the Tia metabasalts compared with the average basaltic compositions of Manson (1967) and the compositional fields of metabasalts from other metamorphic terrains, taken from Iwasaki (1963).

Na_2O - FeO·MgO and CaO - FeO - MgO Diagrams (Fig 14a and 14b)

The metabasalts plotted on Fig 14a show that there is no enrichment in Na_2O relative to MgO and FeO in the crossite bearing metabalts MB6 and MB8. The analyses

FIG. 13.


16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
FeO
(Wt.%)
1
2
3
4
5
6
7
8
9
10
Fe2O3 (Wt.%)
5
6
9
2
4
3
7
1
8
CROSSITE BEARING METABASALTS
ORDINARY GREENSCHIST FACIES
(IWASAKI, 1963)
FRANCISCAN
(IWASAKI, 1963)
SANBAGAWA
(IWASAKI, 1963)
○ VARIOUS AVERAGE BASALTS
(MANSON, 1967)

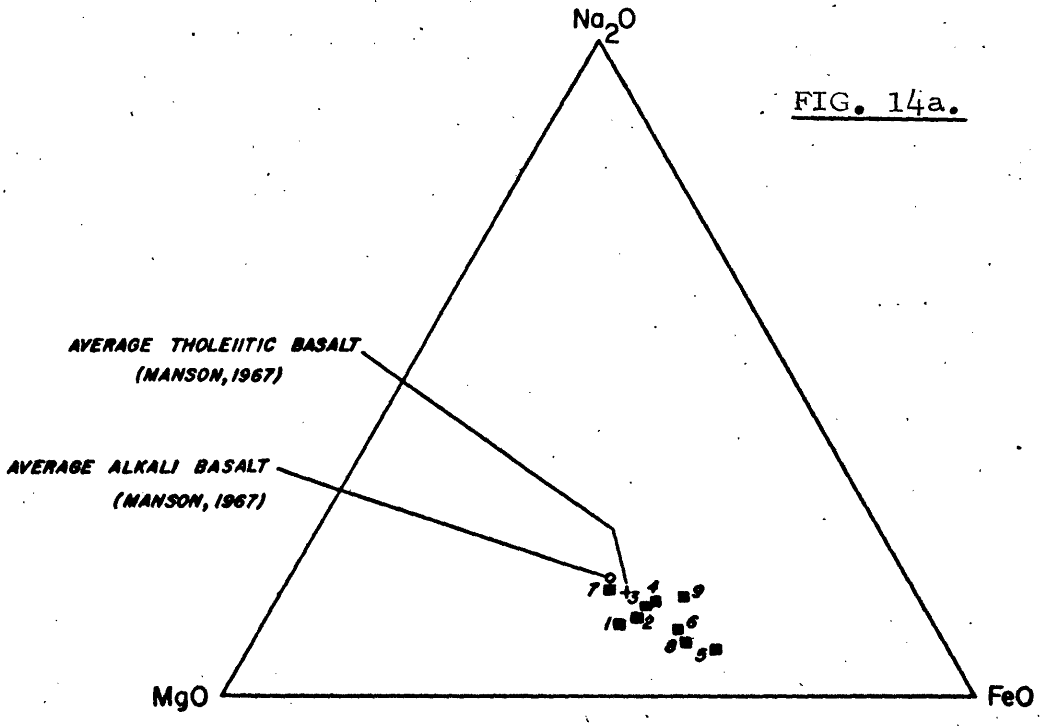


FIG. 14a.

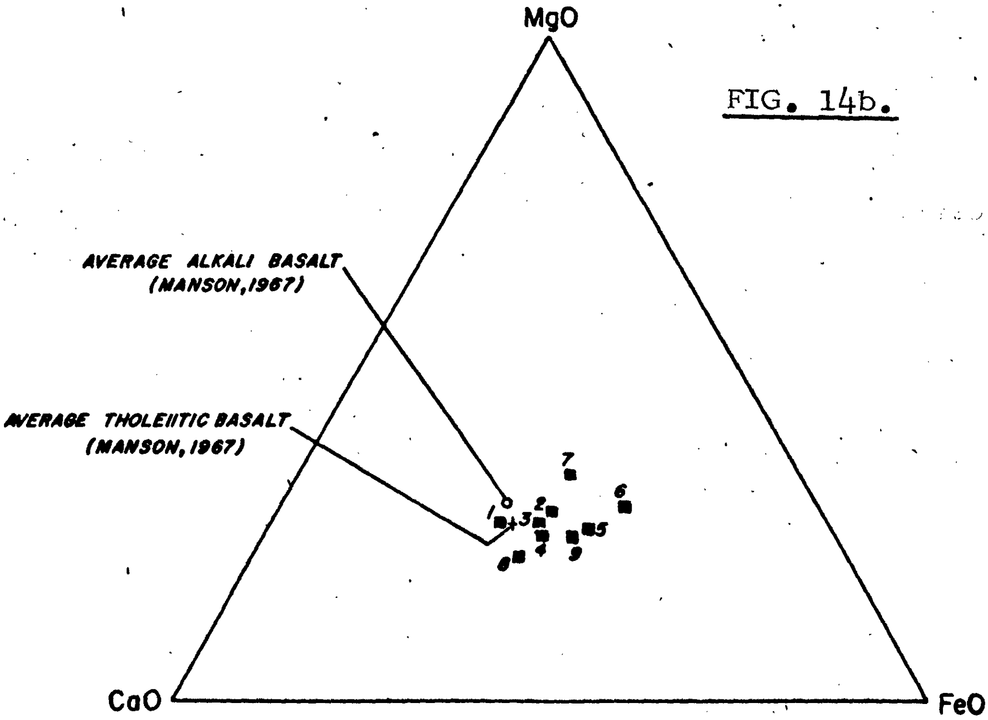


FIG. 14b.

are displaced towards the FeO vertex compared with the average basalt compositions, and this is believed to be a consequence of the higher Fe^{2+}/Fe^{3+} ratio of the Tia metabasalts.

The metabasalts show a slightly wider spread in Fig (14b), and by analogy with Vallance (1965) p. 478, this suggests that there has been some redistribution of CaO. It appears that MB6 and MB7 have been depleted in CaO relative to MgO and FeO, and MB8 enriched in CaO relative to FeO and MgO (see also Fig 11). The remainder plot close to the average basalt compositions of Manson (1967) but again slightly displaced toward the FeO vertex.

Relict Igneous Clinopyroxene

The measured optical properties of the relict clinopyroxenes of the metabasalts of Zone A are given in Table 12. 2V was measured orthoscopically on a Leitz 4-axis Universal Stage using sodium light.

When referred to the determinative diagram of Hess (1949) these data indicates that the pyroxenes show variable composition, trending from calcic augite to calcic ferro-augite. This is not inconsistent with pyroxenes of a tholeiitic basaltic suite however it is not diagnostic without a detailed study of their chemical composition, (cf Vallance, 1969). The slight pinkish brown colouration of some of these pyroxenes described

Table (12)

Optical Properties of the Relict Igneous Clinopyroxene

Thin Section No.	$n\beta(\pm.002)$	$2V(\pm2^{\circ})$
9499	1.700	53°
9574	1.713	52°
9576	1.709	-
9580	1.696	54°
9582	1.692	48°
9587	1.699	-
9588	1.694	-
9589	1.693	-
9596	1.693	-
9598	1.697	50°
9608	1.695	-
9611	1.692	-
10004	1.696	52°

earlier could be a secondary colour aquired during the low grade metamorphism of the basalts, however augites of tholeiitic suites not uncommonly also show such colours, e.g. McDougall, (1962).

Bulk Chemical Variation with Metamorphic Grade

Although as a first approximation these basalts are of similar chemistry, there are slight but significant differences that appear to correlate with metamorphic grade. These are outlined below:

(1) TiO_2 is higher in the lower grade (Zones A and B) metabasalts compared with those of Zones C and D.

(2) Although the data is limited, it appears that the low grade basalts of Zones A and B have lower SiO_2 values than those of Zones C and D.

(3) Within Zones C and D, CaO reaches its highest value in the highest grade amphibolite MB1. Throughout Zones A and B, the limited data available shows a wide range of CaO values, (see Fig 14b).

(4) H_2O^+ shows an overall decrease with increasing metamorphic grade.

(5) The Fe_2O_3/FeO ratio is highest in the highest grade amphibolite MB1, suggesting either that slight oxidation accompanied metamorphism, or alternatively that MB1 is less reduced relative to the original composition than the remainder.

Discussion and Conclusions

The redistribution of material revealed by these analyses appears to be divisible into that taking place at low metamorphic grade in Zones A and B, and into a more limited redistribution at high grade (Zone D) involving mainly CaO. The former may be caused in part by the migration of material into the post-tectonic veins, which are mainly epidote or pumpellyite and quartz. The outcrops from which the analysed material came show only minor veining, however the possibility of this type of redistribution cannot be dismissed. This can explain the lower overall SiO_2 and CaO of MB6 and MB7. Another possibility arises from the observation that the higher CaO of MB8 complements MB7 and is analogous to the redistribution reported by Vallance (1965) to be characteristic of pillow lavas. This suggests that pre-metamorphic redistribution of material may have also occurred but that any original pillow structure with which this may have been associated has been obliterated by deformation and metamorphism.

The redistribution of elements at high metamorphic grade is less clearly defined and appears to have mainly involved an increase in CaO.

The probably original composition of the basalts is not clear, as the higher grade basalts may have also undergone some redistribution of elements prior to regional metamorphism. During metamorphism and deformation involving the transposition of these metabasic horizons, the effects of early redistribution would, however, tend to be removed suggesting that perhaps the analyses of the Zone C metabasalts most closely approach those of the original basalts. All the Zone C metabasalts are hypersthene normative, of essentially tholeiitic chemistry.

A further indication and probably the best guide to the original magmatic character appears to be the original mineralogy of the Zone A metabasalts. The optical properties and derived compositions of the relict clinopyroxenes along with the apparent paucity of olivine in the original basalts also suggest a tholeiitic parentage rather than alkaline.

The structural evidence shows that the development and infilling of the veins cutting the low grade metabasalts was a post-regional deformation phenomenon. The assemblages of these veins are therefore envisaged as representing a post-regional metamorphism episode of essentially burial metamorphic style.