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PROGRESSIVE METAMORPHISM OF AMPHIBOLITES FROM THE CLONCURRY AND PETERMANN RANGES AREAS

by

R.N. England

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SUMMARY

Electron probe analyses of calciferous amphibole, plagioclase, and some other phases from greenschist to middle amphibolite facies basic rocks of the Cloncurry and Petermann Ranges areas are presented. By plotting amphibole compositions onto a diagram first used by Hallimond (1944), a general trend with increasing grade from tremolite-actinolite towards pargasite-ferropargasite is observed. Hornblende analyses are absent from regions near edenite and tschermakite, but there is no obvious solid-solution gap between tremolite-actinolite and pargasite. Hornblendes with about 7.0 Si atoms per formula unit are rare.

Hornblende grains from many of the Cloncurry rocks are continuously zoned, with magnesian actinolitic cores and Fe-rich pargasitic rims at their contact with plagioclase. Reactions involving Fe-oxide minerals are suggested as an important means of introducing (Al, Fe^{3+}) into calciferous amphibole. The feasibility of some isochemical reactions is tested by plotting total Fe against Al^{VI} and comparing the slopes of the zoning trends with the theoretical slopes produced by the reactions. A further test is obtained in quartz-free rocks; a reaction introducing one mole of Na^{X-XII} liberates 4 moles of SiO_2 which, under isochemical conditions, must be accounted for by SiO_2-consuming reactions. Na^{X-XII} is plotted against Al^{VI} and the slopes of the zoning trends are compared with those generated when SiO_2-consuming, $(Al, Fe^{3+})^{VI}$-producing reactions are coupled so that SiO_2 is balanced.

With the possible exception of one specimen, a peristerite gap is not developed and it seems probable that plagioclase rich in anorthite component is of relict igneous origin. The extent to which hornblende has taken up $(Al, Fe^{3+})^{VI}$ seems to be determined by the amount of anorthite component available from plagioclase. Na^{X-XII} enters hornblende as edenite or richterite component during reaction with albite component

in plagioclase. Although large amounts of albite component are generally available, anorthite may be in short supply. Under such conditions entry of $(Al, Fe^{3+})^{VI}$ into hornblende is inhibited and the compositional trend of the amphibole is towards edenite. Because of the instability of edenitic amphiboles under the conditions encountered, the trend is limited and the amphibole remains poor in both $(Al, Fe^{3+})^{VI}$ and Na^{X-XII} compared with those that become pargasitic by reactions involving anorthite component in plagioclase.

The Ti content of hornblende increases with metamorphic grade but it is not sufficiently predictable to be useful as a petrogenetic indicator. The distribution of K between hornblende and plagioclase does not vary systematically with metamorphic grade, but partitioning seems to favour hornblende at higher temperature. The effect of bulk composition on all aspects of hornblende composition is probably great enough to prevent its use as an accurate petrogenetic indicator.

INTRODUCTION

The change in the composition and optical properties of calciferous amphibole during progressive metamorphism is well known. The best-known of the early systematic studies of the mineralogy of basic rocks in metamorphic terrains is that of Wiseman (1934) in his work on the South-west Highlands 'epidiorites'. The first modern studies of hornblende in basic metamorphic rocks were those of Shido (Shido, 1958, Shido & Myashiro, 1959). They noted the probable existence of a miscibility gap between actinolite and hornblende at low grade; their work also showed that Al^{VI} does not necessarily increase with metamorphic grade in the amphibolite facies. The work of Engel & Engel (1962) and Binns (1965a, b) was mainly concerned with rocks in the amphibolite facies and above and did not cover the major changes in calciferous amphibole composition which occur at lower temperatures during the transition from actinolite to hornblende. In a more recent study by Cooper & Lovering (1970) of greenschists from the Haast River area in New Zealand, electron probe analyses of calciferous amphibole showed a sharp discontinuity between actinolite and hornblende and probable exsolution of one phase from the other.

The use of hornblende and its relationship with other phases as a precise petrogenetic indicator has been speculated upon by many authors (e.g. Barth, Correns & Eskola, 1939), but few have proposed schemes in which the conditions of metamorphism can be deduced from the compositional relationships between hornblende and co-existing phases. However, Perchuk (1966) in a necessarily greatly oversimplified treatment proposed the use of the distribution of $\frac{Ca}{Ca+Na+K}$ between amphibole and plagioclase as a temperature indicator. He has shown that it works well for common amphibole compositions at high temperatures, but when applied to the amphibolites of the present study, the results give only an approximate indication of the temperature range over which they crystallized and give widely differing temperatures for rocks known to be of identical grade. Statistical studies like those of Kostyuk (1970) and Saxena & Ekstrom (1970) give useful generalizations about amphiboles from different P - T environments and parageneses. They indicate the coupled substitutions most likely to take place, but do not enable us to arrive at very precise conclusions about the P.T. environment of a particular calciferous amphibole-bearing rock. Experimental work to date has been mainly concerned with the P - T range of stability of various individual amphibole phases out of the context in which they are normally found in nature (see Ernst, 1968).

The compositions of minerals in amphibolites from progressive metamorphic terrains in the Cloncurry region of northwest Queensland and the Petermann Ranges in Central Australia have been studied. A purpose of the study was to search for some parameter of equilibrium between amphibole and plagioclase which changes systematically with metamorphic grade and is largely independent of whole rock composition. The equilibrium relationships between calciferous amphibole and other phases are complicated by variation of hornblende composition in response to the variation in whole rock composition. However, disequilibrium relationships yield information about reactions leading to the formation of hornblende. In amphibolites from Cloncurry, zoning from magnesian actinolitic cores to Fe-rich hornblende rims is a common feature. In one example from the Petermann Ranges (P2B), hornblende forms in reaction rims between plagioclase and olivine. In such cases it is possible to make meaningful guesses at the reactions responsible for the formation of hornblende.

GEOLOGICAL SETTING

(a) Cloncurry Area

Specimens C1 and S1 to S11 were collected by Dr A.Y. Glikson of the Bureau of Mineral Resources in 1969 during investigations of the Cloncurry 1:100 000 Sheet area. Specimens S1-S11 come from the Middle Proterozoic Soldiers Cap Formation (Carter et al., 1961), which consists of pelitic and psammitic sediments, basic volcanics, and intrusive dolerites. Specimen C1 was collected from the Corella Formation, a series of bedded, brecciated, and metamorphosed impure calcareous and dolomitic rocks which unconformably overlies the Soldiers Cap Formation (Carter et al., 1961).

Specimens from the Soldiers Cap area, S1-S11 (Fig. 1), are numbered in probable order of increasing metamorphic grade. S1 to S5 come from intrusive and extrusive rocks in the Toole Creek volcanics, the uppermost of the three members of the Soldiers Cap Formation. S6 to S8 come from basic intrusives and extrusives in the Mount Norna quartzite, the middle member of the Formation, and S9-S11 from the Snake Creek meta-turbidities, the lowermost member. The three divisions of the Soldiers Cap Formation are those of Glikson & Derrick (1970).

The mineral assemblages of the pelites interbedded with the basic rocks indicate intermediate pressure metamorphism from low greenschist to middle amphibolite facies. The important mineral assemblages of all the rocks collected, including those pelites collected in the immediate vicinity of the specimens studied in detail, are listed in Table 1.

Specimen C1 (regd. no. 69200063A) is from the Corella Formation 20 km north west of Soldiers Cap. It has the assemblage diopside + actinolite + albite + calcite + quartz without wollastonite and probably belongs to the lower amphibolite facies. However, its grade could be lower if $P_{E_{CO_2}}$ was considerably lower than P_{load}, which would be the case if much water was available during metamorphism.

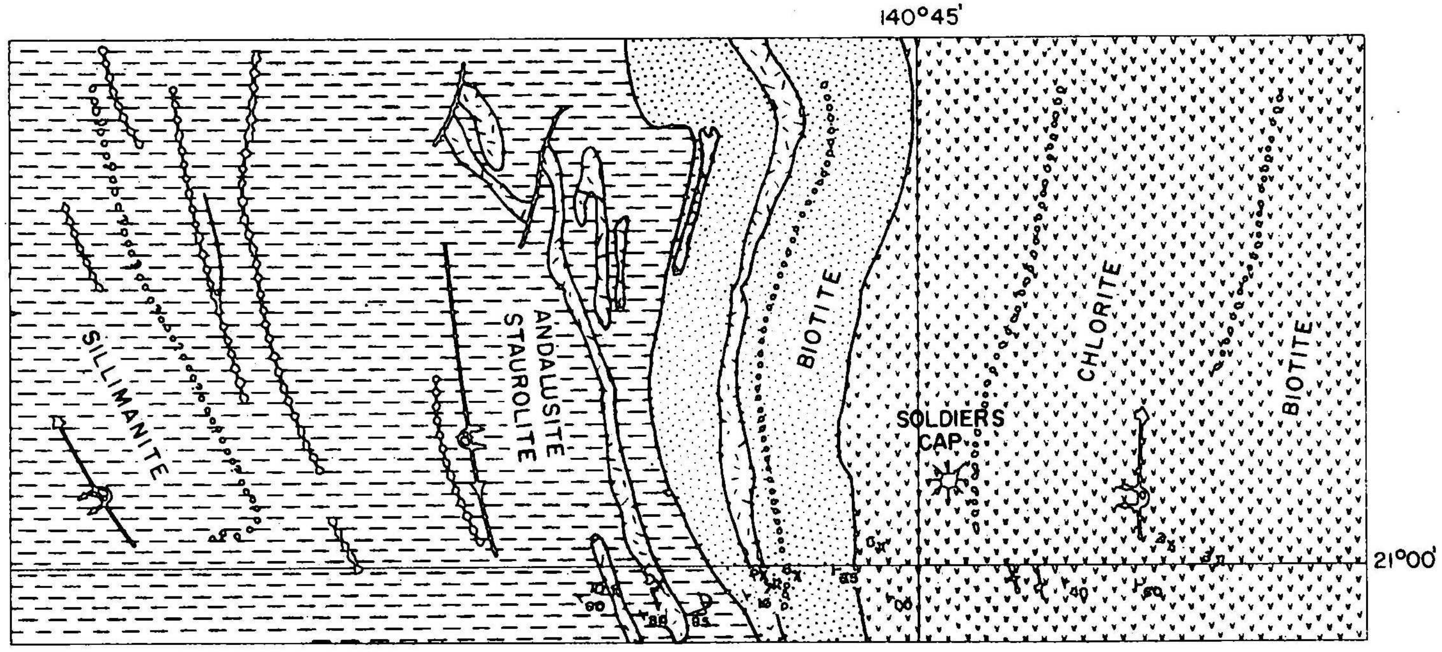

FIG.1 **Soldier's Cap. Specimen Locations.**

Adapted from Cloncurry 1:100,000 geological map (Glikson and Derrick 1970)

▨ *Extrusive and intrusive basic rocks*

▨ *Toole Creek Meta-Volcanics*

▨ *Mount Norna Quartzite*

▨ *Snake Creek Meta-Turbidities*

Basic Dyke

Isograd

0 1 2 3 4 Km

F54/A2/105

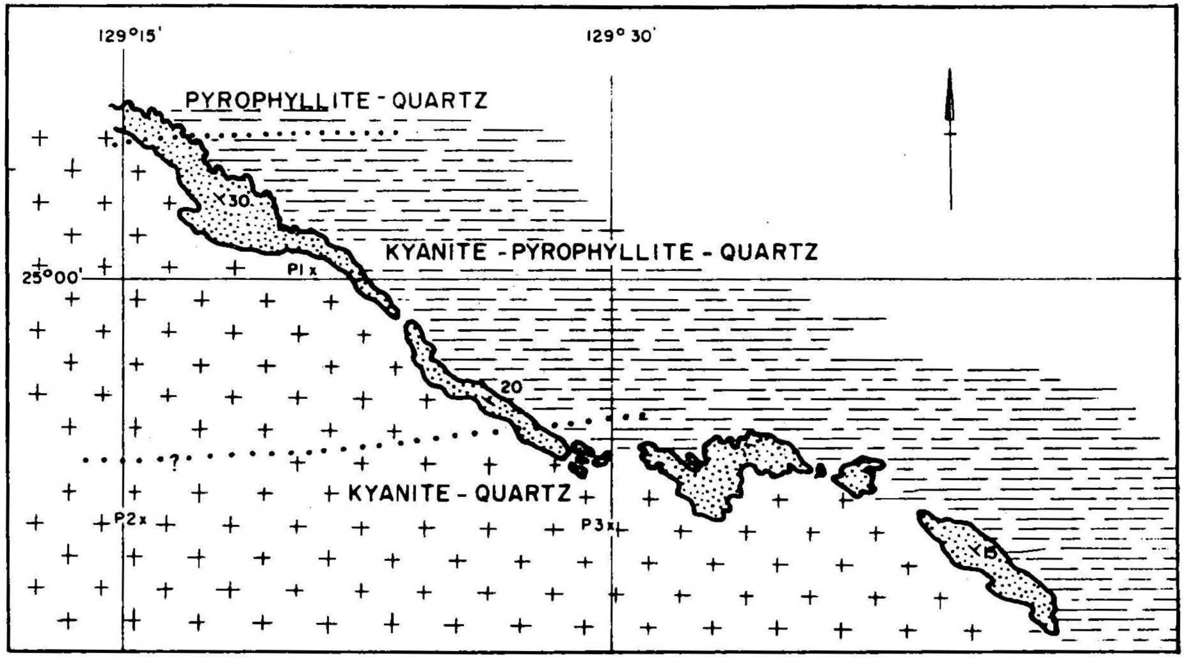

FIG. 2

PETERMANN RANGES
Specimen Locations

(map after Forman, 1966)

▤ Isolated outcrops of Amadeus Basin sediments

▨ Dean Quartzite

+ Isolated outcrops of Pottoyu Granite Complex

⋰ Approximate position of isograd

0 5 10 15 km

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Table 1.

Mineral Assemblages of Soldier's Cap Rocks

Metamorphic grade	Number given in this study	BMR Registered Number	Mineral Assemblage
Chlorite	S1	69200026	Actinolite + oligoclase + albite + calcite + magnetite + haematite + sphene + Kspar + chlorite.
		69200027	Quartz + albite
	S2	69200030	Hornblende + andesine + Ilmenite + sphene
Biotite	S3	69200031	Hornblende + albite + ilmenite + biotite
	S4	692000107	Hornblende + andesine + quartz + ilmenite + biotite + chlorite
	S5A	69200032A	Hornblende + biotite + albite + quartz + ilmenite + sphene
	S5B	69200032B	Hornblende + oligoclase + microcline + quartz + ilmenite + biotite + apatite
		69200033	Biotite+muscovite+quartz
	S6	69200028	Hornblende + andesine + epidote + ilmenite + sphene
Andalusite-Staurolite	S7	69200035A	Hornblende + oligoclase + andesine + quartz+ilmenite + sphene
		69200035B	Garnet + staurolite + muscovite + biotite + quartz
	S8	69200036A	Hornblende + oligoclase + quartz + ilmenite + sphene
		69200036B	Garnet + staurolite + muscovite + biotite + quartz
		69200040	Garnet + staurolite + muscovite + biotite + quartz
		69200041	Andalusite + staurolite + muscovite + biotite + quartz
		69200042	Garnet+biotite+muscovite+quartz
	S9A,B	69200043A	Hornblende + oligoclase + quartz + ilmenite
		69200043B	Hornblende + oligoclase + quartz + ilmenite + sphene
		69200044A	Garnet + gedrite + chlorite + plagioclase + quartz
		69200044B	Garnet + gedrite + staurolite + biotit
		69200044C	Garnet + staurolite + biotite
	S10	69200045	Hornblende + cummingtonite + oligoclase + quartz + ilmenite
Sillimanite	S11	69200048	Sillimanite + garnet + biotite + quart
		69200047	Hornblende + oligoclase + andesine + ilmenite + sphene

Although the specimens of pelitic rocks to the east of sample S7 do not contain assemblages diagnostic of the biotite zone, they are known to belong to that zone because of the presence of biotite in those of suitable composition and the absence of any sign of garnet or staurolite in all the rocks observed during traverses in the region.

(b) Petermann Ranges

In the Petermann Ranges, the Upper Proterozoic Dean Quartzite the basal unit in the south-western Amadeus Basin, overlies older granite and minor basic intrusives of the Pottoyu Granite Complex (Forman, 1966). The specimens studied were collected during a visit to the area made with Dr D.J. Forman in 1968. Typical pelites are rare, but highly aluminous assemblages in the Dean Quartzite are good indicators of metamorphic grade. They are, in order of increasing grade, (i) pyrophyllite-quartz, (ii) kyanite-pyrophyllite-quartz and (iii) kyanite-quartz. The persistence of the apparently univariant assemblage kyanite-pyrophyllite-quartz over some 20 km of outcrop is problematical (England, 1972). The amphibolite-greenschist facies boundary is thought to be slightly up-grade of the beginning of the kyanite-quartz zone.

Specimen P1 definitely belongs to the upper greenschist facies and P3 is probably close to the greenschist-amphibolite boundary (Fig. 2). The metamorphic grade of P2 is less well known because of the large distance separating it from the Dean Quartzite. It is probably close to and may be slightly lower than that of P3.

METHOD OF ELECTRON PROBE ANALYSIS

All analyses were made on a JEOL JXA-3A electron probe using an operating voltage of 20 kV and a specimen current close to 0.1 A. Corrections for absorption and fluorescence were made using a program developed by Frazer, Fitzgerald, & Reid (1966). The JXA-3A microprobe has a take-off angle of only 20° and errors due to surface irregularities and inaccuracies in the correction method tend to be amplified when compared with the results from more modern instruments. Because of the inherently poor precision of the instrument, totals lying between 96 and 100% were considered acceptable.

An analysed mineral standard was used in order to minimize the magnitude of corrections. The hornblende chosen was a kaersutite from Spring Mountains, Nevada, kindly supplied by Mr N.G. Ware of the Australian National University. Homogeneous hornblendes are rare and are generally of high-temperature origin. For this reason they are usually more magnesian and aluminous and poorer in silica than hornblendes from amphibolites. A previously analysed kaersutitic hornblende from Delegate, NSW, supplied by Dr A.J.R. White was analysed on the JXA-3A microprobe in the same manner as the hornblendes in Tables 3-20. The results appear in Table 2 and compare well with the original analysis.

The compositions of all the hornblendes in Tables 3-20 show more variations from the standard than the Delegate hornblende, therefore errors are expected to be higher in them. Although statistical uncertainties can be calculated, they are much less important than errors brought about by uncertainties in the correction method.

The analyses (Tables 3-20) that are high in total iron have totals around 98 and 99% when Fe is calculated as FeO despite the fact that most are bound to contain significant amounts of Fe_2O_3. The reason for this lies in the correction method, which, because it calculates all Fe as FeO, underestimates the amount of oxygen in an analysis which should contain a significant amount of Fe_2O_3. When the program recalculates the analysis

TABLE 2 : MICROPROBE ACCURACY

	Hornblende standard; wet chemical analysis	Delegate Hornblende XRF analysis	Delegate Hornblende Microprobe Analysis
SiO_2	39.51	41.06	40.66
TiO_2	5.64	4.87	4.37
Al_2O_3	14.26	14.58	14.65
FeO (total Fe)	12.50	10.84	10.95
MnO	0.09	0.09	0.09
MgO	11.36	13.16	12.97
CaO	10.12	9.95	9.87
Na_2O	2.80	2.86	2.98
K_2O	1.59	1.55	1.39
Total	97.87	98.96	97.93

to 100% before calculating $f(\chi)$ it arrives at a composition with excess of metals over oxygen. Values for $f(\chi)_{spec.}$ thus calculated are therefore underestimated. The correction factor, which is very nearly equal to $\frac{f(\chi)std}{f(\chi)spec}$, is then overestimated, especially for light elements, giving a high total for the analysis. Neglect of trivalent Fe, because it causes an underestimate of the amount of oxygen, is responsible for an overestimate of all the other elements when they are calculated with respect to a certain number of oxygens (an anhydrous basis of 23 oxygens for microprobe analyses). The method involves filling the smaller sites first and the problem becomes acute in the case of Na, which is assigned to either the x of A sites. The amount of $Na^{VI-VIII}$ is generally only small and is underestimated by as much as 100%. Na^{X-XII} is overestimated by the same absolute amount but is relatively more accurate because of its larger absolute value.

Plagioclase analyses were carried out using the same kaersutite standard as the hornblende analyses. Although differing considerably in chemical composition from plagioclase, the hornblende standard has very similar values of $f(\chi)$ for Ca and K to members of the plagioclase series and corrections are therefore quite small. Plagioclases were analysed for Ca and K and corrections were made using a curve calculated by assuming plagioclase to be a two-component system containing a very small amount of K. Analyses are then expressed in terms of An and Or components.

Whole rock analyses of rocks from the Cloncurry region were carried out by Dr J.W. Sheraton on a Philips PW1210 automatic x-ray spectrometer. FeO determinations on whole rocks were made by Australian Mineral Development Laboratories. Approximate values of the average FeO contents of hornblendes were calculated where possible using the micrometric analyses.

POSSIBLE REACTIONS LEADING TO THE FORMATION OF HORNBLENDE IN PLACE OF ACTINOLITE

Structural Formulae and Site Allocation

Amphibole compositions are expressed in terms of molecular formulae calculated on an anhydrous basis of 23 oxygens. Site allocation is made in the following order (after Shido, 1958).

Site	Species	Total
Z (4 - fold)	Si Al	8
Y (6 - fold)	Al, Fe^{3+} Ti Mg, Fe, Mn	5
X (6 - 8 - fold)	Mg, Fe, Mn Ca Na	2
A (10 - 12 - fold)	Ca Na K	0 - 1

Classification of calciferous amphiboles is not discussed here, but where names are used, such as tschermakite, pargasite, etc., they adhere approximately to the scheme of Leake (1969).

With a few exceptions the compositional changes expected are essentially those that occur during the transition from actinolite to hornblende. The most important changes are:

1. Increase Al^{VI} and $Fe^{3+\ VI}$
2. Increase in alkalis in the A site
3. Increase in Ti^{VI}
4. Decrease in Si with complementary increase in Al^{IV}.

In all these, coupled substitutions are made, in order to maintain charge neutrality. In general $(Al, Fe^{3+})^{VI}$ seems to be accompanied by Al^{IV}, although in high-pressure terrains it may be coupled with $Na^{VI-VIII}$ (Coleman & Papike, 1968). Alkalis in the A site are generally balanced by Al^{IV} and in some cases by $Na^{VI-VIII}$. Ti^{VI} is generally balanced by Al^{IV} but it is possible that in rocks with very sodic plagioclase it may be balanced by $Na^{VI-VIII}$. In many cases a small amount of (Fe, Mg, Mn) must be allocated to the X site and in some cases there is an overflow of Ca from the X site into the A site. However, such small values are subject to very large percentage error and are therefore difficult to use.

Increase in $(Al, Fe^{3+})^{VI}$

In the reactions suggested below isochemical metamorphism is assumed.

To produce hornblende from actinolite by $(Al, Fe^{3+})^{VI}$. Al^{VI} substitution, reaction with (i) a Ca-bearing phase and (ii) a (Fe, Mg)-bearing phase is necessary, and at least one of these phases must contain Al (Fig. 3).

The most commonly suggested reaction producing $(al, Fe^{3+})^{VI}$ in hornblende is

$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + 14(Mg,Fe)_5(Al,Fe^{3+})AlSi_3O_{10}(OH)_8 + 24Ca_2Al_3Si_3O_{12}(OH)$
Actinolite + Al-poor Chlorite + epidote
$+ 28SiO_2 \longrightarrow 25Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2 + 44H_2O$ ——(1)
+ silica tschermakite + water
(after Shido, 1958)

or, if chlorite is more aluminous

$8Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + 14(Mg,Fe)_4(Al,Fe^{3+})_2Al_2Si_2O_{10}(OH)_8$
Actinolite + aluminous chlorite
$+ 24Ca_2Al_3Si_3O_{12}(OH) + 28SiO_2 \longrightarrow 32Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2 + 44H_2O$ —(2)
+ epidote + silica tschermakite + water

Considering the abundance of relict(?) calcic plagioclase it is reasonable to expect the following reactions to have occurred in some rocks:

$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + 2(Mg,Fe)_5(Al,Fe^{3+})\ AlSi_3O_{10}(OH)_8 + 8CaAl_2Si_2O_8$

Actinolite + Al-poor chlorite + anorthite

$\longrightarrow 5\ Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2 + 4H_2O$ ——(3)

tschermakite + water

$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + (Mg,Fe)_4(Al,Fe^{3+})_2\ Al_2Si_2O_{10}(OH)_8 + 4CaAl_2Si_2O_8$

Actinolite + aluminous chlorite + anorthite

$\longrightarrow 3\ Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2 + 2H_2O$ ——(4)

tschermakite + water

Epidote, and especially chlorite, are not common in amphibolites from Soldiers Cap. Chlorite-grade metadolerites from areas not covered in the traverse generally contain a small amount of epidote but very little chlorite. Relict (?) patches of calcic plagioclase are generally present instead of epidote, which is only present in significant quantity in specimen S6. It is unlikely that hornblende in the Cloncurry area has formed from relict ferromagnesian minerals because of their complete absence from even the lowest grade basic rocks. Ilmenite is the opaque oxide mineral in all the rocks studied in detail except specimens S1 and C1, which contain magnetite (coexisting with sphene). The rarity of chlorite, the ubiquity of opaque minerals, and the sharp iron enrichment towards the outer zone of hornblendes suggest possible reactions by whith $(Al, Fe^{3+})^{VI}$ may be entering the hornblende lattice. These involve opaque oxide minerals.

(a) Magnetite

$Fe_3O_4 + 2CaAl_2Si_2O_8 + 2SiO_2 + H_2O \longrightarrow Ca_2Fe_3Al_4Si_6O_{22}(OH)_2 + O$ ——(5)

magnetite + anorthite + silica + water **ferro-tschermakite + oxygen**

$5Fe_3O_4 + 6CaAl_2Si_2O_8 + 3Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 + 3H_2O + O$

magnetite + anorthite + actinolite + water + oxygen

$\longrightarrow 6Ca_2\ (Fe,Mg)_3Fe_2^{3+}\ Al_2Si_6O_{22}(OH)_2$ ——(6)

Ferri-tschermakite

$14Fe_3O_4 + 12Ca_2Al_3Si_3O_{12}(OH) + 42SiO_2 + 6H_2O$

magnetite + epidote + silica + water

$\longrightarrow 3Ca_2Fe_5Si_8O_{22}(OH)_2 + 9Ca_2Fe_3Al_4Si_6O_{22}(OH)_2 + 14O$ ———(7)

ferro-actinolite + ferro-tschermakite + oxygen

$10Fe_3O_4 + 6Ca_2Al_3Si_3O_{12}(OH) + 3Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 + 3H_2O + 12SiO_2$

magnetite + epidote + actinolite + water + silica

$\longrightarrow 9Ca_2(Mg,Fe)_3\ (Fe^{3+})_2\ Al_2Si_6O_{22}(OH)_2 + O$ ———(8)

ferri-tschermakite + oxygen

$CaTiSiO_5 + 2Fe_3O_4 + 3SiO_2 + H_2O + CaAl_2Si_2O_8$

sphene + magnetite + silica + water + anorthite

$\longrightarrow FeTiO_3 + Ca_2(Mg,Fe)_3\ (Fe^{3+})_2\ Al_2Si_6O_{22}(OH)_2 + O$ ———(9)

ilmenite + ferri-tschermakite

(b) <u>Ilmenite</u>

$6FeTiO_3 + 14CaAl_2Si_2O_8 + 3\ Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 + 4H_2O$

ilmenite + anorthite + actinolite + water

$\longrightarrow 7Ca_2(Mg,Fe)_3\ Al_4Si_6O_{22}(OH) + 6CaTiSiO_5 + 4SiO_2$ ———(10)

tschermakite + sphene + silica

$5FeTiO_3 + 7CaAl_2Si_2O_8 + 6Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 + H_2O + 7O$

ilmenite + anorthite + actinolite + water + oxygen

$\longrightarrow 7Ca_2(Mg,Fe)_3\ Fe^{3+}{}_2\ Al_2Si_6O_{22}(OH)_2 + 5CaTiSiO_5 + 15SiO_2$ ———(11)

ferri-tschermakite + sphene + silica

$4FeTiO_3 + 4CA_3Al_2Si_3O_{12}(OH) + Ca_2\ (Mg,Fe)_5\ Si_8O_{22}(OH)_2 + 2SiO_2$

ilmenite + epidote + actinolite + silica

$\longrightarrow 3Ca_2(Mg,\ Fe)_3\ Al_4Si_6O_{22}(OH)_2 + 4CaTiSiO_5$ ———(12)

tschermakite + sphene

$20FeTiO_3 + 14Ca_2Al_3Si_3O_{12}(OH) + 17Ca_2\ (Mg,\ Fe)_5\ Si_8O_{22}(OH)_2 + 11O$

ilmenite + epidote + actinolite + oxygen

$\longrightarrow 21Ca_2(Mg,\ Fe)_3\ Fe^{3+}{}_2Al_2Si_6O_{22}(OH)_2 + 20CaTiSiO_5 + 32SiO_2 + 3H_2O$ —(13)

Ferri-tschermakite + sphene + silica + water

Increase in Alkalis in the A-site

The only important reactions by which Na may enter the A-site of the hornblende lattice are -

$$\mathrm{Ca_2(Mg,\ Fe)_5Si_8O_{22} + NaAlSi_3O_8}$$

actinolite + albite

$$\rightarrow \mathrm{NaCa_2(Mg,\ Fe)_5\ AlSi_7O_{22}(OH)_2 + 4SiO_2} \qquad \text{———(14)}$$

edenite + silica

and

$$\mathrm{Ca_2(Mg,\ Fe)_5\ Si_8O_{22}(OH)_2 + NaAlSi_3O_8}$$

actinolite + albite

$$\rightarrow \mathrm{Na_2Ca\ (Mg,\ Fe)_5\ Si_8O_{22}(OH)_2 + CaAl_2Si_2O_8 + 4SiO_2} \qquad \text{———(15)}$$

richterite + anorthite + silica

In general, the amount of Na in the X site in both the Soldiers Cap and Petermann Ranges amphiboles is small and reaction (15) is of much less importance. When K is present in significant amounts it probably enters the lattice by the following reactions:

$$\mathrm{KAlSi_3O_8 + Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 \rightarrow KCa_2(Mg,Fe)_5AlSi_7O_{22}(OH)_2 + 4SiO_2} \text{———(16)}$$

Kspar + actinolite K-edenite + silica

$$\mathrm{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2 + 2CaAl_2Si_2O_8 + Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2}$$

phlogopite-annite + anorthite + actinolite

$$\rightarrow \mathrm{Ca_2(Mg,Fe)_3\ Al_4Si_6O_{22}(OH)_2 + KCa_2(Mg,Fe)_5\ AlSi_7O_{22}(OH)_2 + 2SiO_2} \text{———(17)}$$

tschermakite + K-edenite + silica

Increase in $\mathrm{Ti^{VI}}$

The reactions by which Ti enters hornblende depend on the assemblage of Ti minerals. For example -

Rocks with sphene + magnetite (e.g. C1, S1):

$$\mathrm{3CaTiSiO_5 + 4Fe_3O_4 + 3CaAl_2Si_2O_8 + 9SiO_2 + 3H_2O}$$

sphene + magnetite + anorthite + silica + water

$$\rightarrow \mathrm{3Ca_2(Fe,Mg)_4\ TiAl_2Si_6O_{22}(OH)_2 + 4O} \qquad \text{———(18)}$$

titanoamphibole + oxygen

$3Ca_2(Mg,Fe)_5\ Si_8O_{22}(OH)_2 + 4CaAl_2Si_2O_8 + 6FeTiO_3 + Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2$

actinolite + anorthite + ilmenite + tschermakite

$+2H_2O \longrightarrow 6Ca_2(Mg,Fe)_4\ TiAl_2Si_6O_{22}(OH)_2$ ——(19)

+ water titanoamphibole

$3CaTiSiO_5 + 4Ca_2(Mg,Fe)_3\ Al_4Si_6O_{22}(OH)_2 + SiO_2$

sphene + tschermakite + silica

$\longrightarrow 5CaAl_2Si_2O_8 + 3Ca_2(Mg,Fe)_4\ Ti,Al_2Si_6O_{22}(OH)_2 + H_2O$ ——(20)

anorthite + titanoamphibole

DESCRIPTION AND ANALYSIS OF INDIVIDUAL SAMPLES

Petrographic notes are given, the analytical data for each specimen are tabulated, and the hornblende compositions are plotted on a diagram first used by Hallimond (1943), which is still probably the least inadequate two-dimensional representation of hornblende composition. The number of silicon atoms is plotted against the number of atoms in the A site, with axes at 60 degrees. Hornblende compositions are approximately contained by a quadrilateral with the following 'end members' at its apices (clockwise from actinolite).

Tremolite - Ferro-actinolite	$Ca_2 (Mg, Fe)_5 Si_8O_{22} (OH)_2$
Edenite - Ferro-edenite	$(NaCa_2 (Mg, Fe)_5 AlSi_7O_{22} (OH)_2$
Pargasite - Ferro-pargasite - Magnesio-hastingsite - Hastingsite	$NaCa_2(Mg,Fe)_4 (Al,Fe^{3+}) Al_2Si_6O_{22}(OH)_2$
Tschermakite - Ferro-tschermakite - Ferri-tschermakite	$Ca_2(Mg,Fe)_3 (Al, Fe^{3+})_2 Al_2 Si_6O_{22}(OH)_2$

The Hallimond diagram has a number of inadequacies -

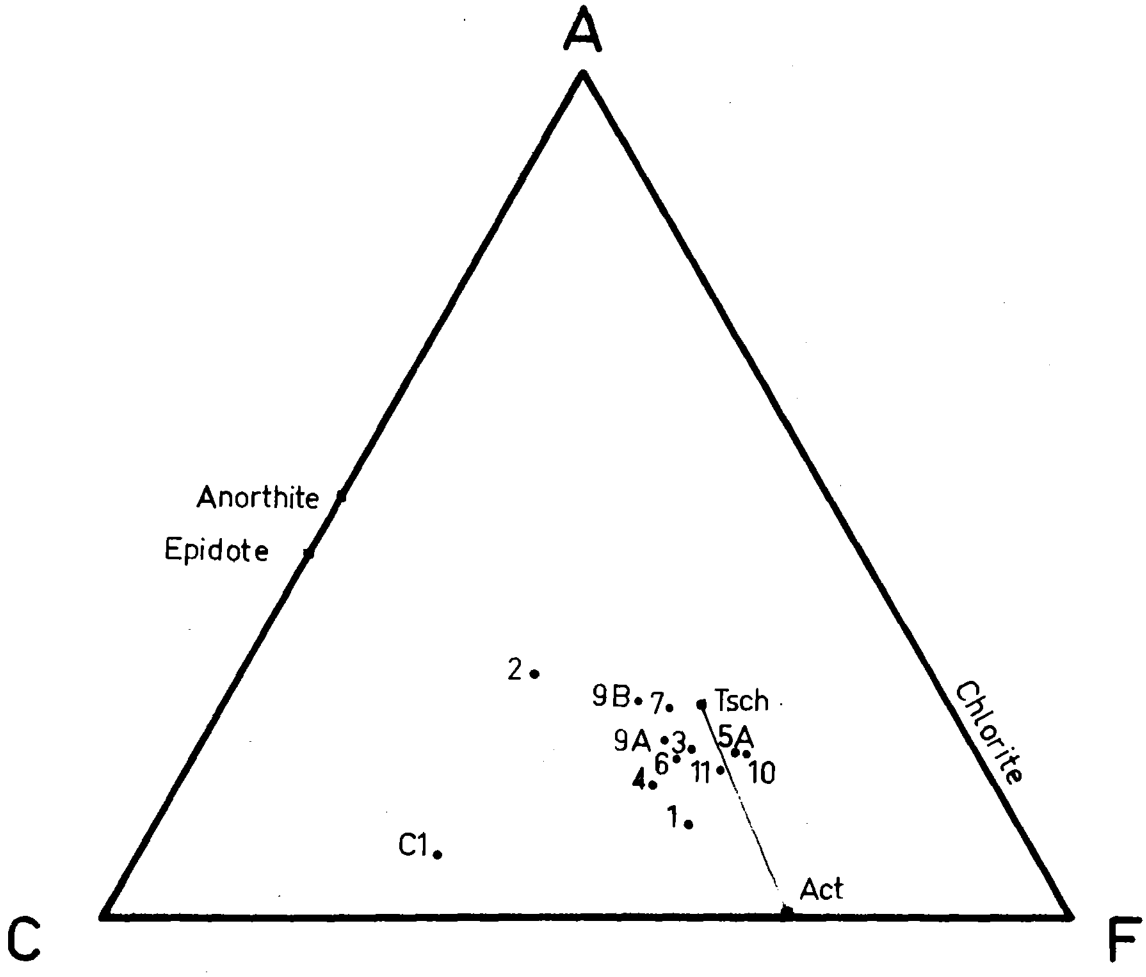
(i) it does not discriminate between Fe-rich and Mg-rich hornblendes,

(ii) it does not discriminate between Na, K or Ca in the A site,

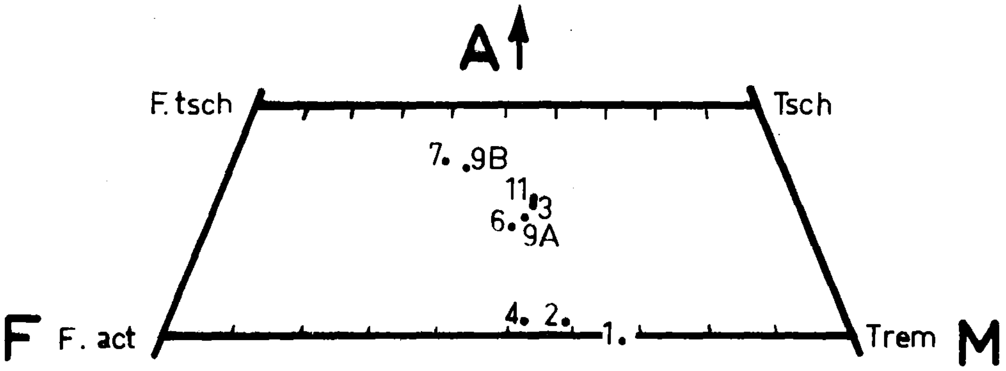
(iii) it does not show the amount of (Fe, Mg) or Na in the X sites,

(iv) it does not show the amount of Ti or Mn present in the Y sites.

Neglect of trivalent iron causes an underestimate of the amount of oxygen, hence an overestimate of the number of atoms per 23 oxygens in the A site, and its effect on the position of an analysis on the diagram is shown in Fig. 4(a). Hallimond plots of individual amphiboles are shown in Figs. 5 and 6.



ACF diagram showing analysed amphibolites from the Soldier's Cap area



AFM projection through anorthite onto the hornblende plane

FIG. 3

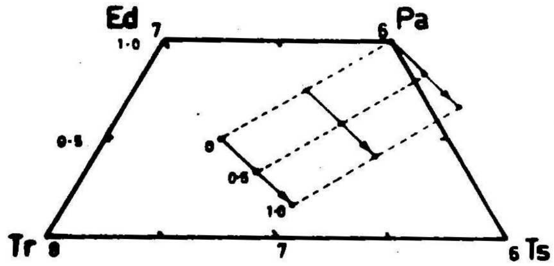


Fig. 4(a). Displacement towards tschermakite on the Hallimond diagram of three typical hornblende compositions after 0.5 and 1.0 atoms of trivalent iron are taken into account.

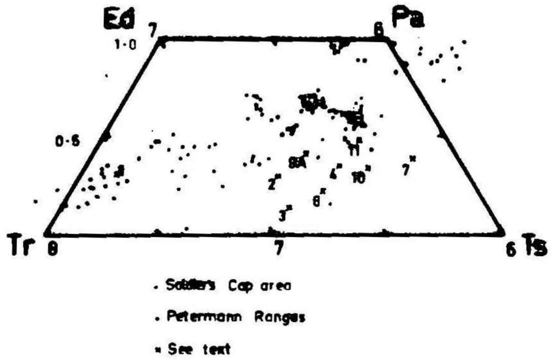


Fig. 4(b). Plot of all hornblende analyses in this study. Points marked by a cross are averages of hornblende analyses from Soldier's Cap specimens where a whole rock analysis was carried out. Fe^{3+} is included and was calculated from the whole rock analysis.

TABLE 3. SPECIMEN C1. ANALYTICAL DATA

	Whole* Rock		Amphiboles												
			a	b	c	d	e	f	g	h	i	j	k	l	Average
SiO_2	47.13		55.30	54.90	52.80	55.94	55.37	53.72	55.35	53.09	53.41	53.04	52.67	55.45	54.25
TiO_2	0.54		.07	.08	.15	.07	.17	.03	.10	.13	.07	.10	.17	.10	.10
Al_2O_3	8.12		1.12	1.22	3.14	1.08	.49	.98	.98	2.74	2.06	2.55	3.21	.59	1.68
Fe_2O_3	3.04		-	-	-	-	-	-	-	-	-	-	-	-	-
FeO	3.45		10.24	10.74	12.62	10.34	21.71	17.56	20.13	12.31	11.45	11.55	12.25	20.27	14.26
MnO	0.25		.19	.17	.19	.18	.51	1.00	.93	.20	.18	.17	.19	1.20	.43
MgO	4.54		17.53	17.24	15.67	17.78	9.82	12.02	10.83	16.33	16.51	16.09	15.82	10.33	14.66
CaO	17.81		12.69	12.45	12.08	12.69	8.37	10.81	7.08	12.69	12.43	12.16	12.11	7.45	11.08
Na_2O	2.85		.64	.65	1.09	.58	2.65	1.02	2.83	.96	.73	.87	.99	3.12	1.34
K_2O	0.11		.16	.16	.35	.17	.11	.16	.15	.34	.26	.27	.37	.11	.22
P_2O_5	0.21	Total	97.94	97.61	98.10	98.82	99.20	97.28	98.37	98.81	97.09	96.79	97.78	98.62	98.02
total H_2O	5.17	Si	7.857	7.844	7.604	7.871	8.125	7.955	8.120	7.594	7.723	7.672	7.598	8.207	7.844
CO_2	5.70	Al^{iv}	.143	.156	.396	.129	-	.045	-	.406	.277	.308	.402	-	.156
Total	98.92	Al^{vi}	.045	.049	.137	.052	.086	.124	.168	.056	.074	.128	.144	.101	.131
mg	.686	Ti	.007	.009	.016	.007	.020	.043	.011	.014	.007	.011	.018	.011	.011
(with total Fe as FeO)	.557	Fe^{3+}	-	-	-	-	-	-	-	-	-	-	-	-	-
		Fe^{2+}	1.217	1.284	1.520	1.217	2.665	2.174	2.470	1.473	1.384	1.401	1.478	2.492	1.724
		Mn	.024	.020	.024	.022	.064	.126	.115	.025	.022	.021	.024	.149	.053
		Mg.	3.714	3.670	3.364	3.727	2.146	2.656	2.368	3.482	3.556	3.478	3.402	2.265	3.160
		Ca	1.932	1.906	1.866	1.911	1.317	1.714	1.114	1.945	1.923	1.890	1.873	1.173	1.717
		Na	.176	.177	.305	.156	.755	.293	.803	.265	.204	.246	.275	.890	.375
		K	.029	.029	.064	.031	.020	.029	.029	.063	.047	.049	.067	.020	.041
		Asite	.145	.145	.296	.123	.073	.158	.077	.322	.216	.225	.281	.102	.212
		mg	.75	.74	.69	.75	.44	.54	.48	.70	.72	.71	.69	.46	.64

Micrometric Analysis	Act	Plag	Qtz	Mag	Sph	Cal	Diops
	24	43	10	2	1	14	6

*Analyst, J. Sheraton

In a discussion of hornblende zoning, Fe is plotted against Al^{VI} (Fig. 8) and the slopes of the trends are compared with the theoretical slopes given by equations in the previous section. Na is plotted against Al^{VI} in rocks without or with very little free quartz (Fig. 9). Reactions 14 and 15 liberate large amounts of SiO_2 which must be accounted for by silica-consuming reactions in rocks without or with very little free quartz. The slopes of these trends where reaction 14 and 15 are coupled with the various silica-consuming reactions to produce no free quartz are plotted in the inset.

Each rock is dealt with separately, and an attempt has been made to discuss the most important reactions controlling hornblende composition in each individual case.

(a) Cloncurry area

C1 Albite + actinolite + diopside + calcite + quartz + sphene + magnetite amphibolite (from Camel Hill, an outlier of Corella Formation 20 km northwest of Soldiers Cap).

Very pale actinolite with slightly darker patches is rimmed by deep Prussian-blue amphibole. The metamorphic grade is uncertain; the presence of diopside would indicate temperatures of over 500°C if the $P_{E_{CO_2}}$ were above about 10% of the load pressure (Winkler, 1967, p. 34). However, flushing of the system with nearly pure water would cause a drop in $P_{E_{CO_2}}$ well below this value, thus causing the reaction

$$Ca_2(Mg, Fe)_5\ Si_8O_{22}\ (OH)_2 + 3CaCO_3 + 2SiO_2 \longrightarrow 5Ca\ Mg\ Si_2O_6 + 3CO_2$$

actinolite + calcite + silica diopside + carbon dioxide,

to go to the right at lower temperatures. It seems probable, however, that this rock was formed near the greenschist-amphibolite boundary.

Edenite solid solution, which could occur by reaction 14

(actinolite + albite $\longrightarrow$ edenite + silica)

has not occurred to any great extent despite the presence of both reactants. A trend towards edenite-pargasite solid solution is shown in the Hallimond diagram (Fig. 5) but it has stopped far short of the extent attained in the hornblende from specimen S5B, which was probably subject to similar temperatures but was able to accept a much greater amount of Al and presumably Fe^{3+} because greater availability of An in the plagioclase enabled reactions such as 5, 6, 10, and 11 to proceed.

A steep increase in Fe content with Al^{VI} in the amphibole (Fig. 8) strongly suggests that reaction with magnetite is responsible for the introduction of Al^{VI} by reaction 5 (the limited extent to which this reaction proceeded even when compared with reaction 14 probably reflects the small amount of An component which was available in the plagioclase). The slope of the Fe versus Al^{VI} trend in amphibole for reaction 5 is 3/2 (Fig. 8). This is less than the actual trend in the amphibole from specimen C1. It is likely that reactions such as

$3Ca_2(Mg, Fe)_5\,Si_8O_{22}(OH)_2 + 5Fe_3O_4 + 6CaAl_2Si_2O_8 + 3H_2O + O$

actinolite + magnetite + anorthite + water + oxygen

$\longrightarrow 6Ca_2(Mg, Fe)_3\,Fe^{3+}_2\,Al_2Si_6O_{22}(OH)$ ——(21)

ferri-tschermakite

and

$5Fe_3O_4 + 6CaCO_3 + 24SiO_2 + 3H_2O \longrightarrow 3Ca_2Fe_5Si_8O_{22}(OH)_2 + 6CO_2 + 5O$ ——(22)

magnetite + calcite + silica + water   ferro-actinolite + carbon dioxide

(which does not consume the scarce anorthite component in plagioclase) may have occurred.

The Prussian-blue amphibole (analyses e, g, l in Table 3) is subcalciferous and much richer in Fe and alkalis and even poorer in aluminium than the actinolite. When total Fe is calculated as FeO, the values for Si are as high as 8.21 and there is a corresponding deficiency in charge of the cations occupying the X site, of which a considerable proportion is Na. It is concluded that this error is due largely to the neglect of the presence of Fe^{3+}, which would occur as riebeckite component. Reactions producing riebeckite component involve the introduction of Na without accompanying Al and are difficult to understand in an isochemical process without postulating the breakdown of albite to more aluminous phases and the release of Na. Albite is thickly clouded with Fe-stained clay minerals and it may be possible for riebeckitic amphibole to have formed at the same time as the breakdown of albite by a reaction such as -

$$\underset{\text{albite}}{2\,NaAlSi_3O_8} + \underset{\text{actinolite}}{Ca(Mg,Fe)_5\,Si_8O_{22}(OH)_2} + \underset{\text{water}}{2H_2O} + \underset{\text{carbon dioxide}}{2CO_2} + \underset{\text{oxygen}}{2O} \longrightarrow$$

$$\underset{\text{riebeckite}}{Na_2(Mg,Fe)_3Fe^{3+}{}_2\,Si_8O_{22}(OH)_2} + \underset{\text{calcite}}{2CaCO_3} + \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} \qquad (23)$$

If this is the case, then it is probable that the riebeckitic rims formed at a late stage at lower temperature.

S1. Actinolite + oligoclase + albite + calcite + magnetite + hematite + sphene + K-feldspar + chlorite schist

Actinolite is pale green (analyses a - e, h - j, n: Table 4) with some darker green rims (analyses, f, g, k-m: Table 4). Plagioclase is of two distinct compositions, $An_{1.5}\,Or_{0.2}$ (average of 9 analyses) and $An_{29}\,Or_{2.1}$ (average of 10 analyses). The amphibole zoning shows a steep trend of limited extent towards edenite-pargasite composition on the Hallimond diagram (Fig. 5). There is also rapid increase in Fe with Al^{VI} (Fig. 8), suggesting reaction between magnetite and anorthite component of plagioclase as a means of introducing Al^{VI} (reaction 5). As with specimen C1 it is necessary to postulate an additional reaction such as 22 in order to account fully for the steepness of the Fe versus

TABLE 4. SPECIMEN 81. ANALYTICAL DATA

	Whole Rock	Amphiboles a	b	c	d	e	f	g	h	i	j	k	l	m	n	Average	Average with Fe_2O_3
SiO_2	52.32	52.07	52.68	53.68	52.75	53.05	50.39	50.59	52.32	52.57	54.55	48.39	47.91	48.68	51.84	51.53	51.53
TiO_2	0.90	.08	.08	.08	.05	.08	.13	.15	.13	.12	.12	.07	.17	.17	.12	.11	.11
Al_2O_3	12.26	2.68	2.26	1.44	2.28	2.09	4.46	3.81	3.37	3.58	2.48	5.65	5.87	5.30	2.49	3.41	3.41
Fe_2O_3	5.47	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00
FeO	6.10	12.43	11.68	10.78	11.31	11.20	15.08	14.06	13.16	13.38	11.93	16.48	16.04	15.46	12.55	13.25	13.25
MnO	0.05	.08	.08	.08	.05	.08	.09	.06	.09	.08	.08	.08	.06	.06	.08	.07	.07
MgO	6.33	16.40	16.40	17.42	16.36	16.60	14.12	12.43	14.88	15.68	15.97	11.83	12.22	12.70	15.43	14.90	14.90
CaO	8.32	12.73	12.58	12.08	12.82	12.73	12.96	12.73	12.53	13.12	13.03	12.26	12.51	12.61	12.92	12.69	12.69
Na_2O	4.65	.54	.43	.33	.61	.62	1.06	.97	.59	.60	.51	1.24	1.23	1.16	.63	.79	.79
K_2O	0.38	.19	.16	.11	.21	.19	.39	.37	.16	.13	.13	.65	.68	.57	.16	.29	.29

	Whole Rock
P_2O_5	0.11
Total H_2O	0.58
CO_2	0.50
Total	98.92
mg =	.686
(with total Fe as FeO) =	.557

	a	b	c	d	e	f	g	h	i	j	k	l	m	n	Average	Average with Fe_2O_3
Total	97.53	96.35	96.02	96.65	96.65	98.70	97.21	97.25	99.28	98.79	96.67	96.68	96.63	96.19	97.04	97.04
Si	7.554	7.679	7.792	7.670	7.684	7.346	7.443	7.605	7.509	7.741	7.269	7.193	7.279	7.623	7.542	7.542
Al^{iv}	.446	.321	.208	.330	.316	.654	.557	.395	.491	.259	.731	.807	.721	.377	.458	.458
Al^{vi}	.013	.066	.039	.061	.041	.111	.102	.183	.113	.155	.268	.231	.212	.056	.130	.130
Ti	.009	.009	.009	.006	.009	.015	.017	.015	.013	.013	.008	.019	.019	.013	.012	.012
Fe^{3+}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.000
Fe^{2+}	1.506	1.425	1.303	1.375	1.357	1.839	1.730	1.602	1.599	1.417	2.072	2.014	1.924	1.544	1.622	1.622
Mn	.010	.010	.010	.006	.010	.011	.008	.011	.013	.009	.010	.008	.008	.010	.009	.009
Mg	3.549	3.566	3.770	3.546	3.627	3.066	3.171	3.225	3.340	3.379	2.649	2.735	2.829	3.380	3.250	3.250
Ca	1.930	1.965	1.880	1.996	1.977	2.026	2.008	1.951	2.008	1.963	1.973	2.013	2.021	2.037	1.990	1.990
Na	.239	.120	.096	.231	.173	.298	.277	.166	.167	.139	.358	.358	.333	.179	.224	.224
K	.037	.030	.020	.039	.036	.071	.069	.030	.025	.024	.127	.129	.107	.030	.054	.054
Acite	.345	.193	.132	.268	.231	.440	.322	.133	.264	.146	.464	.500	.461	.249	.291	.291
mg	.70	.71	.74	.72	.73	.62	.65	.67	.67	.70	.56	.57	-	.69	.67	.67

CIPW	NORM
Qtz	1.45
Or	2.25
Plag	51.80
(% An)	23
Di	20.78
Hy	11.09
C1	-
Mag	7.93
Ilm	1.71
Ap	0.26
Cal	1.14

Micrometric Analysis	Act	Plag	Mag	Hae	Sph	Chlor	Cal
	38	60	5	1	1	1	3

* Analyst. J. Sheraton

Al^{VI} trend. A reaction such as 22 is also necessary to account for the absence of quartz which would otherwise be produced by the combination of reactions 5 and 14 in the proportion in which they appear to be occurring (see Fig. 9).

Specimen S1 is the only low-grade amphibolite which appears to have approached some degree of textural equilibrium, and in which no trace of igneous texture remains. The plagioclase compositions may lie on either side of the peristerite solvus. Because chlorite is rare the only possible way actinolite can be transformed into hornblende by isochemical means in a rock such as this is by reactions 5 and 6 combined with 14 and 15.

S2. Bluish-green hornblende + andesine + ilmenite + sphene metadolerite

Specimen S2 is moderately coarse-grained, with scattered patches consisting of an aggregate of scapolite, clinozoisite, and prehnite (which may be of later origin). Pale actinolitic patches (e.g., Table 5, analysys d) are moderately common in the cores of the slightly ragged, sheaf-like amphibole grains. The fine needles projecting into plagioclase are the most aluminous and alkali-rich (Table 5, analysis f). The plagioclase composition is An_{44} $Or_{0.3}$ (an average of 18 analyses varying from $An_{29 \text{ to } 61}$ and $Or_{0.2 \text{ to } 0.5}$). The plagioclase in contact with the hornblende whose analysis (a) appears in Table 5, is An_{40} $Or_{0.3}$. Ilmenite has been largely replaced by sphene and there is little doubt that iron from this source now resides in the hornblende.

Zoning in hornblende involves only a moderate increase in Fe with Al^{VI} (Fig. 8), and Na^{X-XII} with Al^{VI} (Fig. 9). The slope of the Fe versus Al^{VI} trend is too small for reaction with ilmenite to account entirely for the introduction of Al^{VI} and it seems probable that some chlorite has taken part. Lower grade rocks from the area with similar textures generally contain a variable but small amount of chlorite, some epidote and sphene with ilmenite, or in some cases magnetite. However, it is certain that any further isochemical increase in $(Al, Fe^{3+})^{VI}$ which would occur with increasing temperature could result only from reactions 10 and 11.

S3. Bluish-green hornblende + albite + ilmenite + biotite metadolerite

Specimen S3 resembles S2 except for (i) the absence of sphene, (ii) absence of calcareous patches, (iii) coarse grainsize and better preserved doleritic texture, (iv) only rare actinolite cores in amphibole grains, (v) much more sodic plagioclase, (vi) the presence of red-brown biotite.

Of the hornblende analyses (Table 6), a - c are from a traverse from a pale actinolite core to a darker rim, f is of a pale actinolite patch, and d, e, g, h, and i are more or less blue-green. Plagioclase has an average composition of An_4 $Or_{0.1}$ but ranges from $An_{1.8}$ to $_{12.8}$ and $Or_{0.1}$ to $_{0.3}$.

The Na^{X-XII} content of zoned amphibole increases at a greater rate with respect to Al^{VI} than in Specimen S2. This is almost certainly related to the more sodic plagioclase composition of S3. The absence of sphene indicates that reactions 10 - 13 could not have taken place and the moderate increase in Fe with Al^{VI} suggests a situation similar to that of S2, where chlorite may have taken part in the introduction of tschermakite component. Hornblende analysis (a) is unusual in that it appears to contain a large amount of cummingtonite component. Repeat analyses yield similar results.

S4. Blue-green hornblende + andesine + quartz + ilmenite + biotite + chlorite metabasalt

Scapolite is moderately common and appears to be replacing the original minerals in patches. However, ilmenite appears unaffected and its texture within the scapolite-rich patches is identical with that in the rest of the rock. Actinolite cores (Table 7, analysis a) occur in only

TABLE 5. SPECIMEN S2, ANALYTICAL DATA

		Whole * Rock
	SiO_2	47.82
	TiO_2	1.00
	Al_2O_3	17.89
	Fe_2O_3	1.74
	FeO	8.45
	MnO	0.15
	MgO	6.14
	CaO	12.52
	Na_2O	1.98
	K_2O	0.99
	P_2O_5	0.11
Total	H_2O	1.04
	CO_2	-
Total		99.83
	mg	.560
	(with total Fe as FeO)	.518
	CIPW	NORM
	Or	5.85
	Plag	53.75
	(% An)	69
	Di	20.04
	Hy	4.43
	Ol	10.04
	Mag	2.52
	Ilm	1.90
	Ap	0.26

	Amphiboles a	b	c	d	e	f	Average	Average with Fe_2O_3
	47.69	47.06	47.88	47.63	46.58	41.87	46.45	46.45
	.37	.32	.34	.30	.37	.37	.35	.35
	9.52	10.16	8.60	7.59	9.12	15.55	10.09	10.09
	-	-	-	-	-	-	-	3.22
	16.11	16.03	15.28	15.08	15.74	17.04	15.88	12.98
	.17	.18	.18	.19	.17	.19	.18	.18
	11.80	11.16	11.08	11.54	10.85	7.66	10.68	10.68
	12.85	12.46	12.39	12.78	12.93	12.58	12.67	12.67
	.84	.96	.85	.67	.82	1.34	.91	.91
	.24	.23	.19	.22	.26	.44	.26	.26
Total	99.60	98.56	96.79	96.01	96.73	97.03	97.47	97.79
	6.910	6.887	7.097	7.130	6.945	6.307	6.882	6.829
Si	1.090	1.113	.903	.870	1.055	1.693	1.118	1.171
Al^{iv}	.537	.640	.600	.471	.552	1.069	.644	.577
Al^{vi}	.040	.035	.037	.034	.041	.042	.039	.039
Fe^{3+}	-	-	-	-	-	-	-	.356
Fe^{2+}	1.952	1.962	1.895	1.890	1.966	2.146	1.967	1.596
Mn	.021	.022	.023	.025	.021	.025	.022	.022
Mg	2.550	2.434	2.448	2.576	2.415	1.720	2.358	2.340
Ca	1.995	1.955	1.969	2.050	2.070	2.031	2.011	1.995
Na	.239	.271	.244	.196	.238	.390	.262	.260
K	.045	.043	.036	.042	.048	.083	.049	.049
Asite	.378	.363	.252	.288	.356	.505	.353	.304
mg	.56	.55	.56	.57	.55	.44	.54	.59

Micrometric Analysis	Hbd	Plag	Ilm	Sph	Ep	Scap	Prehnite
	40	27	1	3	2	6	22

* Analyst, J. Sheraton.

TABLE 6. SPECIMEN S3, ANALYTICAL DATA

	Whole* Rock	Amphiboles a	b	c	d	e	f	g	h	i	Average	Average with Fe_2O_3
SiO_2	47.56	50.33	46.35	42.34	46.42	47.85	48.84	44.87	48.45	43.14	46.51	46.51
TiO_2	2.89	.07	.34	.17	.42	.25	.33	.27	.20	.37	.27	.27
Al_2O_3	12.57	7.80	2.97	12.85	10.55	6.01	5.57	11.05	6.11	13.56	8.50	8.50
Fe_2O_3	5.40	-	-	-	-	-	-	-	-	-	-	7.61
FeO	12.90	20.10	23.34	21.08	20.29	20.36	17.73	21.05	19.83	21.90	20.63	13.76
MnO	0.30	.05	.27	.13	-	-	-	-	-	-	-	-
MgO	4.79	11.71	10.18	7.69	9.35	10.06	13.05	8.64	11.23	6.87	9.86	9.86
CaO	8.78	7.15	11.17	11.90	11.21	10.60	11.82	10.90	11.46	11.77	10.89	10.89
Na_2O	2.89	.49	1.22	1.74	1.09	.99	.05	.31	.13	.30	.20	.20
K_2O	0.59	.09	.21	.33	.22	.17	.05	.31	.13	.30	.20	.20
P_2O_5	0.28	97.79	96.06	98.21	99.56	96.27	97.66	98.89	98.35	99.81	98.02	98.78
Total H_2O	0.26	7.371	7.269	6.427	6.833	7.281	7.236	6.709	7.207	6.443	6.977	6.849
CO_2	-	.629	.550	1.573	1.167	.719	.764	1.290	.793	1.557	1.023	1.151
Total	99.21	.717	.000	.725	.664	.360	.207	.659	.278	.831	.480	.324
mg	.393	.007	.041	.019	.047	.028	.037	.030	.022	.042	.031	.030
(with total Fe as FeO)	.321	-	-	-	-	-	-	-	-	-	-	.843
CIPW	NORM	2.461	3.061	2.677	2.497	2.591	2.196	2.633	2.468	2.734	2.588	1.697
Qtz	1.29	.006	.035	.016	-	-	-	-	-	-	-	-
Or	3.49	2.556	2.379	1.741	2.049	2.282	2.881	1.926	2.492	1.527	2.205	2.164
Plag	44.03	1.122	1.876	1.937	1.767	1.728	1.877	1.747	1.826	1.883	1.750	1.718
(An content)	45	.139	.371	.512	.311	.290	.080	.527	.276	.549	.337	.331
Di	18.46	.016	.040	.062	.040	.032	.009	.057	.025	.057	.038	.037
Hy	17.72	.025	.768	.690	.376	.311	.287	.578	.386	.624	.428	.144
Mag	7.83	.51	.43	.39	.45	.47	.57	.42	.50	.36	.46	.56
Ilm	5.49											
Ap	0.66											

Micrometric Analysis	Hbd	Plag	Ilm
	46	50	4

Analyst, J. Sheraton.

TABLE 7. SPECIMEN S4, ANALYTICAL DATA

	Whole* Rock	Amphiboles a	b	c	d	Average	Average with Fe_2O_3
SiO_2	47.67	49.27	43.55	41.54	42.72	44.27	44.27
TiO_2	1.16	.19	.43	.48	.45	.39	.39
Al_2O_3	13.79	6.02	14.01	15.41	13.23	12.17	12.17
Fe_2O_3	2.13	-	-	-	-	-	3.79
FeO	10.40	14.46	18.59	20.75	18.03	17.96	14.65
MnO	0.21	.18	.18	.19	.17	.18	.18
MgO	7.02	13.19	9.15	6.86	8.87	9.52	9.52
CaO	12.21	12.48	11.99	12.07	12.47	12.25	12.25
Na_2O	2.08	.42	1.19	1.10	1.23	.99	.99
K_2O	0.37	.15	.53	.90	.89	.62	.62
P_2O_5	0.13						
Total H_2O	0.27						
CO_2	0.80						
Total	98.24	96.34	99.59	99.28	98.05	98.35	98.83

	a	b	c	d	Average	Average with Fe_2O_3
Si	7.300	6.411	6.230	6.415	6.591	6.527
Al^{iv}	.700	1.589	1.710	1.585	1.409	1.473
Al^{vi}	.349	.843	.954	.758	.727	.642
Ti	.020	.047	.054	.051	.044	.043
Fe^{3+}	-	-	-	-	-	.421
Fe^{2+}	1.792	2.288	2.604	2.265	2.236	1.806
Mn	.023	.022	.024	.021	.022	.022
Mg	2.915	2.008	1.534	1.987	2.113	2.093
Ca	1.982	1.892	1.940	2.007	1.954	1.935
Na	.120	.341	.320	.357	.285	.283
K	.027	.098	.173	.171	.118	.116
Asite	.229	.539	.603	.617	.499	.361
mg	.62	.47	.37	.47	.48	.53

mg = .541

(with total Fe as FeO) .500

CIPW	NORM
Or	2,19
Plag	44.79
An content	61
Di	26.8
Hy	11.53
Ol	6.26
Mag	3.09
Ilm	3.20
Ap	0.31

Micrometric Analysis

Hbd	Plag	Qtz	Ilm	Sph	Biot	Chlor	Scap
60	21	4	2	1	[illegible]	1	13

* Analyst, J. Sheraton.

a few large grains of amphibole. Chlorite is present as very rare fine veins and extremely rare flakes. Plagioclase composition in An_{33} $Or_{0.4}$ (an average of 8 analyses which range from $An_{20\ to\ 48}$ and $Or_{0.3\ to\ 0.7}$). The steep increase in zoned grains of Fe versus Al^{VI} (Fig. 8) is similar to that expected from reaction 5, but less than the slope expected from a combination of 5 and 6. It is possible that small amounts of chlorite or biotite may have taken part in reactions such as 3 and 4 or 17.

S5A. Blue-green hornblende + biotite + albite + quartz + ilmenite + sphene amphibolite

S5B. Deep blue-green hornblende + oligoclase + microcline + quartz + ilmenite + biotite + apatite amphibolite

Both of these rocks show good evidence of equilibration. Although the hornblende of specimen S5A has a slightly variable composition, that of S5B is homogeneous (Fig. 5, S5A, S5B). Only a trace of relict igneous texture is present in specimen S5A. The plagioclase is S5A is An_3 $Or_{0.3}$ (an average of 19 analyses ranging from $An_{2\ to\ 6}$ and $Or_{0.1\ to\ 0.5}$). The plagioclase from S5B is more calcic (An_{15} $Or_{0.2}$ - an average of 12 analyses ranging from $An_{12\ to\ 17}$ and $Or_{0.1\ to\ 0.3}$). The hornblende of S5A coexists with a more sodic plagioclase than that of S5B, yet it is poorer in Na (Tables 8, 9). It appears that Al has been unable to enter the Y sites of the hornblende in S5A because of the lack of anorthite component in the co-existing plagioclase and entry of much Na^{X-XI} into the hornblende would move it into the edenite field, which is apparently forbidden to upper greenschist/lower amphibolite facies amphiboles (see Fig. 4B).

The Ti content of hornblende from specimen S5A is slightly higher than that from S5B (Tables 8, 9). This probably reflects the fact that S5A contains both ilmenite and sphene, whereas S5B contains only ilmenite. In other words, Ti is probably entering hornblende by reaction 19 in S5B and both 19 and 20 in S5A.

S6. Green hornblende + andesine + epidote + ilmenite + sphene metabasalt

Amphibole grains which have replaced earlier ferromagnesian minerals have moderately common actinolite cores (Table 10, analysis g). Plagioclase composition is $An_{31}\ Or_{0.2}$, an average of 20 analyses which range from $An_{21}\ Or_{0.2}$ to $An_{41}\ Or_{0.2}$. Hornblende zoning involves a marked increase in Fe with Al^{VI}, but there is no zonal relationship between Na and Al^{VI} (Figs. 8, 9). In general the hornblende is tschermakitic and poor in alkalis - probably reflecting the calcic plagioclase composition and the presence of epidote. The presence of 3% sphene indicates that reactions such as 10-13 could have occurred, but about 8% sphene would have been produced if they were entirely responsible for the transition from actinolite to hornblende. It is unlikely that the extra 5% sphene could occur as fine clouding. Magnetite and a small amount of chlorite would also be needed as reactants.

S7. Green hornblende + (oligoclase-andesine) + quartz + ilmenite + sphene meta-basalt

An average of 20 analyses in quite close agreement indicates that the plagioclase composition is $An_{30}\ Or_{0.3}$. Plagioclase next to hornblende (analyses b and f, Table 11) has a composition $An_{28}\ Or_{0.2}$. Hornblende is homogeneous (Fig. 5, 57) but is a good deal richer in total Fe than any of the low-grade actinolites or relict actinolite cores in moderate grade rocks. It has probably originated in a similar manner to the hornblendes which show a history of iron enrichment during the introduction of Na^{X-XII} and Al^{VI}.

S8. Green hornblende + oligoclase + quartz + ilmenite + sphene metadolerite

The plagioclase is $An_{16}\ Or_{0.2}$ (an average of 11 analyses in close agreement). One actinolite core (Table 12, analyses, d, e) is present in the section and there is a sharp increase in Fe with Al^{VI} and a moderately sharp increase in Na^{X-XII} with Al^{VI} towards the hornblende rim (Figs. 8 and 9).

TABLE 8. SPECIMEN S5A* ANALYTICAL DATA

	Whole* Rock		a	b	c	d	e	f	Average
SiO_2	46.10		46.89	46.22	47.12	46.73	44.94	43.49	45.90
TiO_2	2.64		.45	.40	.39	.40	.54	.54	.45
Al_2O_3	12.06		8.25	7.22	6.22	6.40	9.73	8.42	7.71
Fe_2O_3	4.22		-	-	-	-	-	-	-
FeO	13.50		21.42	21.10	20.28	20.67	21.93	22.52	21.32
MnO	0.33		.28	.32	.31	.28	.31	.28	.30
MgO	4.92		8.17	8.67	9.14	9.11	7.74	7.27	8.35
CaO	7.16		11.68	11.91	12.19	12.17	12.28	12.26	12.08
Na_2O	2.16		1.25	1.05	1.05	1.07	1.51	1.58	1.25
K_2O	2.57		.67	.41	.33	.33	.61	.69	.51
P_2O_5	0.26	Total	99.05	97.27	96.99	97.16	99.59	97.06	97.87
Total H_2O	0.49	Si	7.026	7.055	7.181	7.127	6.754	6.773	6.986
CO_2	1.25	Al^{iv}	.974	.945	.819	.873	1.246	1.227	1.014
Total	97.66	Al^{vi}	.484	.354	.297	.277	.477	.318	.369
mg	.388	Ti	.050	.045	.043	.045	.061	.064	.050
(with total Fe as FeO)	.332	Fe^{3+}	-	-	-	-	-	-	-
CIPW	NORM	Fe^{2+}	2.685	2.695	2.584	2.637	2.756	2.934	2.713
Cr	15.18	Mn	.036	.041	.040	.036	.039	.037	.038
Plag	33.89	Mg	1.823	1.972	2.074	2.072	1.732	1.688	1.894
(An content)	46	Ca	1.877	1.949	1.991	1.990	1.976	2.045	1.970
Di	15.24	Na	.364	.308	.311	.316	.443	.479	.369
Hy	13.27	K	.130	.079	.063	.063	.117	.135	.099
Ol	6.61	Asite	.449	.444	.403	.437	.603	.700	.502
Mag	6.12	mg	.40	.42	.44	.44	.38	.36	.41
Ilm	5.01								
Ap	0.62								

Micrometric Analysis	Hbd	Plag	Qtz	Ilm	Biot
	33	40	10	2	15

* Analyst, J. Sheraton.

TABLE 9. SPECIMEN S5B. ANALYTICAL DATA

Amphiboles

	a	b	c	d	e	f	Average
SiO_2	41.39	41.02	38.93	40.49	39.70	39.97	40.25
TiO_2	.39	.30	.34	.33	.42	.42	.37
Al_2O_3	13.20	13.84	13.42	13.50	13.35	13.57	13.48
Fe_2O_3	-	-	-	-	-	-	-
FeO	25.14	24.67	26.39	24.47	26.02	25.03	25.29
MnO	.20	.24	.22	.22	.26	.23	.23
MgO	3.42	3.93	2.67	3.50	2.78	3.25	3.26
CaO	11.37	11.35	11.34	11.43	11.66	11.52	11.45
Na_2O	2.03	2.09	2.13	1.95	2.01	2.07	2.05
K_2O	.90	.72	.98	.82	1.33	1.22	1.00
Total	98.03	98.17	96.38	96.70	97.52	97.30	97.38
Si	6.442	6.361	6.254	6.386	6.295	6.309	6.341
Al^{iv}	1.558	1.639	1.746	1.614	1.705	1.691	1.659
Al^{vi}	.867	.892	.796	.894	.789	.834	.845
Ti	.046	.034	.042	.039	.051	.051	.044
Fe^{3+}	-	-	-	-	-	-	-
Fe^{2+}	3.271	3.201	3.546	3.227	3.450	3.304	3.266
Mn	.027	.032	.029	.029	.034	.031	.030
Mg	.792	.910	.638	.822	.656	.765	.764
Ca	1.896	1.885	1.953	1.930	1.981	1.949	1.932
Na	.613	.623	.662	.597	.616	.634	.624
K	.180	.143	.199	.165	.269	.246	.200
Asite	.693	.723	.865	.702	.866	.812	.705
mg	.19	.22	.15	.20	.16	.19	.19

Micrometric Analysis	Hbd	Plag	Kspar	Qtz	Ilm	Biot	Apatite
	45	11	15	25	1	1	2

TABLE 10. SPECIMEN S6, ANALYTICAL DATA

	Whole* Rock
SiO_2	48.16
TiO_2	1.38
Al_2O_3	13.76
Fe_2O_3	2.67
FeO	11.70
MnO	0.23
MgO	6.77
CaO	11.58
Na_2O	1.99
K_2O	0.26
P_2O_5	0.14
Total H_2O	0.46
CO_2	-
Total	99.10
mg	.503
(with total Fe as FeO)	.457
CIPW	NORM
Or	1.54
Plag	44.68
(An content)	62
Di	23.75
Hy	20.07
Ol	1.79
Mag	3.87
Ilm	2.62
Ap	0.33

	Amphiboles a	b	c	d	e	f	g	Average	Average with Fe_2O_3
SiO_2	42.67	41.92	46.56	44.82	43.05	44.78	51.92	45.10	45.10
TiO_2	.37	.44	.29	.37	.37	.42	.08	.33	.33
Al_2O_3	14.07	14.67	10.22	13.09	12.85	13.42	2.52	11.55	11.55
Fe_2O_3	-	-	-	-	-	-	-	-	3.98
FeO	19.05	19.40	16.94	19.36	19.12	18.73	19.51	18.87	15.29
MnO	-	-	-	-	-	-	-	-	-
MgO	7.71	7.43	10.03	7.87	7.61	7.92	13.43	8.86	8.86
CaO	12.18	12.12	12.40	11.89	12.25	12.30	12.17	12.19	12.19
Na_2O	1.07	.87	1.20	.46	1.22	1.20	.14	.88	.88
K_2O	.26	.19	0.33	.09	.32	.29	.01	.21	.21
Total	97.37	97.03	97.95	97.95	96.77	99.05	99.78	97.99	98.39
Si	6.439	6.355	6.891	6.671	6.549	6.605	7.559	6.729	6.664
Al^{iv}	1.561	1.645	1.109	1.329	1.451	1.395	.433	1.271	1.336
Al^{vi}	.940	.975	.673	.969	.853	.941	-	.761	.676
Ti	.041	.049	.031	.041	.041	.046	.009	.037	.036
Fe^{3+}	-	-	-	-	-	-	-	-	.442
Fe^{2+}	2.404	2.460	2.097	2.410	2.432	2.312	2.376	2.354	1.889
Mn	-	-	-	-	-	-	-	-	-
Mg	1.735	1.681	2.213	1.746	1.727	1.740	2.915	1.971	1.952
Ca	1.968	1.967	1.969	1.897	1.996	1.942	1.898	1.949	1.930
Na	.312	.255	.345	.131	.358	.340	.038	.255	.252
K	.048	.037	.061	.016	.060	.054	.002	.040	.040
Asite	.450	.424	.388	.148	.467	.375	.238	.366	.222
mg	.42	.41	.51	.42	.42	.43	.55	.46	.51

	Hbd	Plag	Ilm	Sph	Ep	Ap
Micrometric Analysis	63	24	1	3	7	2

*Analyst, J. Sheraton

TABLE 11. SPECIMEN S7, ANALYTICAL DATA

	Whole* Rock
SiO_2	49.40
TiO_2	2.18
Al_2O_3	13.54
Fe_2O_3	4.81
FeO	13.20
MnO	0.41
MgO	3.98
CaO	8.69
Na_2O	2.09
K_2O	0.38
P_2O_5	0.20
Total H_2O	0.57
CO_2	-
Total	99.45
mg	.503
(with total Fe as FeO)	.457
CIPW	NORM
Qtz	7.20
Or	2.25
Plag.	44.12
(An content)	60
Di	12.95
Hy	20.80
Mag	6.97
Ilm	4.14
Ap	0.47

	Amphiboles							
	a	b	c	d	e	f	Average	Average with Fe_2O_3
SiO_2	41.26	42.18	40.68	41.26	41.13	41.49	41.33	41.33
TiO_2	.47	.43	.47	.42	.33	.40	.42	.42
Al_2O_3	14.58	13.14	14.41	14.32	14.76	12.91	14.02	14.02
Fe_2O_3	-	-	-	-	-	-	-	7.27
FeO	21.79	21.62	22.28	22.40	21.83	21.48	21.90	15.36
MnO	.35	.33	.33	.33	.35	.32	.34	.34
MgO	5.87	6.43	5.59	5.77	5.58	6.43	5.95	5.95
CaO	11.64	11.87	11.79	11.73	11.79	11.75	11.76	11.76
Na_2O	1.80	1.67	1.87	1.82	1.85	1.69	1.78	1.78
K_2O	.34	.28	.35	.30	.32	.23	.30	.30
Total	98.10	97.96	97.78	98.35	97.95	96.69	97.80	98.53
Si	6.297	6.438	6.261	6.299	6.292	6.421	6.335	6.182
Al^{iv}	1.703	1.562	1.739	1.701	1.708	1.579	1.665	1.818
Al^{vi}	.921	.800	.876	.877	.954	.776	.867	.751
Ti	.053	.050	.054	.048	.038	.047	.048	.048
Fe^{3+}	-	-	-	-	-	-	-	.818
Fe^{2+}	2.781	2.758	2.867	2.861	2.793	2.760	2.807	1.921
Mn	.045	.043	.044	.043	.045	.042	.044	.043
Mg	1.335	1.464	1.283	1.314	1.274	1.485	1.359	1.326
Ca	1.904	1.940	1.942	1.919	1.933	1.950	1.931	1.822
Na	.534	.494	.559	.539	.547	.506	.530	.516
K	.066	.054	.069	.059	.064	.045	.060	.058
Asite	.640	.604	.694	.659	.648	.630	.646	.395
mg	.32	.34	.31	.31	.31	.34	.32	.40

Micrometric Analysis	Hbd	Plag	Qtz	Ilm	Sph
	56	29	10	4	0.5

Analyst, J. Sheraton.

TABLE 12. SPECIMEN S8, ANALYTICAL DATA

Amphiboles

	a	b	c	d	e	f	Average
SiO_2	40.32	42.37	42.49	47.18	47.87	43.77	44.00
TiO_2	.57	.73	.83	.45	.35	.61	.59
Al_2O_3	12.98	12.03	11.44	6.56	4.71	9.98	9.62
Fe_2O_3	-	-	-	-	-	-	-
FeO	25.38	20.41	20.29	18.65	17.88	19.71	20.39
MnO	.23	.22	.21	.19	.22	.22	.22
MgO	5.77	7.17	7.23	9.53	11.18	8.08	8.16
CaO	11.90	12.17	12.20	12.17	12.52	12.37	12.22
Na_2O	1.84	1.86	1.88	1.30	1.02	1.55	1.58
K_2O	.79	.75	.69	.37	.30	.52	.57
Total	99.77	97.71	97.26	96.40	96.07	96.81	97.35
Si	6.194	6.481	6.529	7.177	7.292	6.716	6.737
Al^{iv}	1.806	1.519	1.471	.823	.708	1.284	1.263
Al^{vi}	.547	.649	.602	.353	.138	.521	.474
Ti	.065	.083	.095	.052	.040	.070	.068
Fe^{3+}	-	-	-	-	-	-	-
Fe^{2+}	3.262	2.611	2.606	2.374	2.278	2.528	2.611
Mn	.030	.029	.027	.025	.028	.029	,028
Mg	1.323	1.634	1.657	2.162	2.539	1.846	1.862
Ca	1.957	1.994	2.008	1.905	2.045	2.037	2.005
Na	.547	.551	.559	.382	.300	.457	.469
K	.155	.146	.134	.070	.059	.100	.111
Asite	.667	.697	.701	.436	.426	.595	.605
mg	.29	.38	.39	.47	.52	.42	.42

Micrometric Analysis	Hbd	Plag	Qtz	Ilm	Sph
	52	39	5	3	0.5

The scarcity of sphene shows that ilmenite could not have taken a major part in reactions leading to hornblende rich in (Al, $Fe^{3+})^{VI}$, and magnetite appears to be a better choice as an important reactant.

S9A. Green hornblende + oligoclase + quartz + ilmenite metagabbro

S9B. Green hornblende + oligoclase + quartz + ilmenite + sphene amphibolite

All traces of igneous texture have been obliterated in specimen S9B, which also has the more calcic plagioclase (An_{26} $Or_{0.5}$) compared with that of S9A (An_{15} $Or_{0.25}$): Plagioclase is homogeneous in both rocks. Both hornblendes are homogeneous (Tables 13, 14). Specimen S9A is poorer in Na^{X-XII} (if the analyses are recalculated taking Fe^{3+} into account) as well as (Al $Fe^{3+})^{VI}$ and the pair is analogous to S5A and B, (Fig. 5, S9A and S9B). A higher Ti content of the amphibole co-existing with sphene as well as ilmenite is also observed.

S10. Green hornblende + cummingtonite + oligoclase + quartz + ilmenite amphibolite

The presence of cummingtonite is expected from the position of this rock on the ACF diagram (Fig. 3). Specimen S5A, which plots close to S10 on the ACF diagram, contains biotite instead because of its much higher K_2O content. Plagioclase is An_{18} $Or_{0.2}$ (an average of 15 analyses in close agreement). Hornblende is homogeneous (Table 15). At lower grade Specimen S10 may have contained chlorite or a large amount of magnetite with a magnesian actinolite.

S11. Green hornblende + (oligoclase-andesine) + ilmenite + sphene amphibolite

Specimen S11 comes from a rock containing alternating layers of hornblende + ilmenite + sphene and hornblende + quartz + ilmenite + sphene with a little plagioclase. The homogeneous plagioclase is An_{30} Or_5. Hornblende is homogeneous (Table 16). The whole rock is high in normative pyroxenes, poor in normative albite, and quite magnesian. It may be a metamorphosed igneous cumulate but its near monomineralic nature and prominent layering suggest that its chemistry may have been affected by metamorphic differentiation.

(b) Petermann Ranges Area

Specimens P1 and P3 are amphibolites typical of their respective grades, but P2A and P2B are partly metamorphosed troctolitic gabbros, which were probably metamorphosed under conditions of $P_{E_{H_2O}} \ll P$ total. Hornblendes from basic rocks from the Petermann Ranges have been analysed so that amphibolites from a moderately high pressure terrain may be compared with those of low-intermediate pressure (Cloncurry). Previous studies have shown the amount of Na in the X sites to be higher in the low to medium grade hornblendes of high pressure terrains compared with hornblendes of lower pressure origin (e.g., Shido & Myashiro, 1959). However, uncertainty in Fe^{3+} content of hornblende leads to very large relative errors in the amount of $Na^{VI-VIII}$ (which is generally small) and precludes a meaningful comparison in terms of $Na^{VI-VIII}$.

The homogeneity of low-grade hornblendes from the Petermann Ranges is in marked contrast to those in the Soldiers Cap amphibolites; this may reflect the longer time available for equilibration in the more deeply buried Petermann Ranges amphibolites.

P1. Very pale green hornblende + epidote + biotite + oligoclase + ilmenite + chlorite + quartz schist

Both green and brown biotite are present. Epidote contains about 0.45 Fe^{3+} ions per formula unit and homogeneous plagioclase is $An_{23}\ Or_{0.5}$.

Specimen P1 is probably equivalent in grade to S2 or S3. However, the hornblende combines a high value of Mg/(Mg + Fe) with fairly large amounts of Al^{VI} and Na, and is also homogeneous (Table 17).

TABLE 13. SPECIMEN 59A ANALYTICAL DATA

Amphiboles

	Whole* Rock	a	b	c	d	e	f	Average	Average with Fe_2O_3
SiO_2	53.73	44.11	43.91	44.48	45.35	44.91	44.13	44.48	44.48
TiO_2	1.09	.65	.68	.67	.65	.65	.57	.65	.65
Al_2O_3	15.70	9.17	9.52	9.42	8.42	9.02	8.96	9.09	9.09
Fe_2O_3	2.43	-	-	-	-	-	-	-	6.27
FeO	7.55	22.24	21.85	22.31	21.70	22.22	22.44	22.13	16.49
MnO	0.22	.29	.32	.27	.33	.28	.26	.29	.29
MgO	3.18	8.50	8.27	8.23	8.78	8.70	8.61	8.52	8.52
CaO	6.12	11.37	11.11	11.22	11.28	11.57	11.36	11.32	11.32
Na_2O	5.47	1.67	1.82	1.70	1.60	1.60	1.70	1.68	1.68
K_2O	.76	.46	.49	.48	.40	.41	.50	.46	.46
P_2O_5	0.40								
Total H_2O	0.42								
CO_2	0.05								
Total	97.12	98.46	97.97	98.77	98.52	99.37	98.53	98.62	99.25
mg	.422								
(with total Fe as FeO)	.363								

	a	b	c	d	e	f	Average	Average with Fe_2O_3
Si	6.718	6.711	6.740	6.863	6.765	6.725	6.753	6.649
Al^{iv}	1.282	1.289	1.260	1.137	1.237	1.275	1.247	1.351
Al^{vi}	.367	.426	.421	.366	.362	.334	.379	.250
Ti	.092	.079	.076	.074	.074	.064	.074	.073
Fe^{3+}	-	-	-	-	-	-	-	.705
Fe^{2+}	2.833	2.793	2.827	2.747	2.797	2.859	2.809	2.061
Mn	.038	.042	.035	.043	.036	.033	.037	.037
Mg	1.931	1.885	1.862	1.979	1.954	1.955	1.928	1.899
Ca	1.854	1.819	1.822	1.830	1.867	1.855	1.842	1.813
Na	.493	.539	.499	.470	.468	.502	.494	.487
K	.089	.094	.091	.077	.079	.096	.089	.088
Asite	.698	.676	.633	.586	.637	.699	.653	.413
mg	.40	.40	.39	.41	.41	.40	.40	.48

CIPW	NORM
Qtz	0.13
Or	4.49
Plag	63.31
(An content)	26
Di	9.50
Hy	13.63
Mag	3.52
Ilm	2.07
Ap	0.95
Cal	0.11

Micrometric Analysis	Hbd	Plag	Qtz	Ilm
	50	39	9	2

TABLE 14. SPECIMEN S9B, ABALYTICAL DATA

	Whole * Rock	Amphiboles a	b	c	d	e	f	Average	Average with Fe_2O_3
SiO_2	49.20	42.15	42.65	42.70	42.43	42.35	42.84	42.52	42.52
TiO_2	1.92	.75	.80	.82	.78	.98	.83	.83	.83
Al_2O_3	17.78	13.09	13.26	13.25	13.15	12.36	12.65	12.96	12.96
Fe_2O_3	3.40	-	-	-	-	-	-	-	5.60
FeO	10.90	19.56	19.87	19.79	19.90	19.64	19.89	19.78	14.71
MnO	0.30	.27	.28	.29	.29	.27	.27	.28	.28
MgO	3.88	6.78	6.74	6.63	6.61	6.88	6.72	6.73	6.73
CaO	9.13	12.30	12.00	12.31	12.20	12.34	12.07	12.20	12.20
Na_2O	3.59	1.74	1.73	1.77	1.75	1.72	1.86	1.76	1.76
K_2O	0.47	.74	.75	.75	.74	.70	.70	.73	.73
P_2O_5	0.10								
Total H_2O	0.35								
CO_2	0.05								
Total	101.07	97.40	98.06	98.32	97.85	97.26	97.84	97.79	98.32

	a	b	c	d	e	f	Average	Average with Fe_2O_3
Si	6.436	6.450	6.456	6.451	6.482	6.509	6.466	6.378
Al^{iv}	1.564	1.540	1.544	1.549	1.518	1.491	1.534	1.622
Al^{vi}	.794	.826	.817	.806	.713	.773	.788	.669
Ti	.085	.090	.092	.089	.113	.095	.094	.094
Fe^{3+}	-	-	-	-	-	-	-	.632
Fe^{2+}	2.498	2.518	2.503	2.532	2.513	2.527	2.515	1.845
Mn	.036	.037	.039	.039	.036	.035	.037	.035
Mg	1.544	1.520	1.494	1.499	1.570	1.525	1.525	1.505
Ca	2.012	1.946	1.995	1.988	2.024	1.965	1.988	1.960
Na	.515	.506	.517	.512	.507	.544	.517	.512
K	.143	.147	.144	.143	.136	.135	.141	.140
Asite	.670	.653	.656	.643	.667	.644	.646	.612
mg	.38	.37	.37	.37	.38	.37	.37	.44

	Whole Rock
mg	.382
(with total Fe as FeO)	.327
CIPW	NORM
Or	2.78
Plag	61.38
(An content)	51
Di	11.42
Hy	9.82
Ol	6.47
Mag	4.93
Ilm	3.65
Ap	0.24

Micrometric Analysis	Hbd	Plag	Qtz	Ilm	Sph
	40	45	10	1.5	3

*Analyst, J. Sheraton

TABLE 15. SPECIMEN S1C ANALYTICAL DATA

			Amphiboles											
	Whole* Rock		a	b	c	d	Cummingtonite e	f	g	h	i	Cummingtonite j	Average Hornblende	Average Hb with Fe_2O_3
SiO_2	50.60		43.31	43.23	42.95	43.05	53.17	43.27	43.34	43.17	42.20	53.05	43.07	43.07
TiO_2	1.91		.66	.60	.63	.58	.03	.43	.58	.55	0.17	0.14	.45	.45
Al_2O_3	13.15		12.19	11.48	11.91	11.76	.63	11.79	11.31	11.79	12.21	0.94	11.81	11.81
Fe_2O_3	4.21		-	-	-	-	-	-	-	-	-	-	-	7.56
FeO	13.70		23.05	23.35	23.50	23.61	31.06	23.38	23.62	23.13	23.53	31.25	23.40	16.60
MnO	0.33		.27	.32	.28	.31	.86	.23	.23	.24	0.23	0.79	.26	.26
MgO	4.79		7.40	7.10	6.97	7.03	12.74	6.93	7.10	6.94	6.51	12.36	7.00	7.00
CaO	7.08		10.60	11.38	11.16	11.24	.73	11.62	10.96	11.74	11.57	1.02	11.28	11.28
Na_2O	3.39		1.71	1.62	1.62	1.72	.31	1.61	1.64	1.61	1.66	0.35	1.65	1.65
K_2O	0.26		.34	.35	.35	.34	.01	.41	.34	.38	0.44	0.04	.37	.37
P_2O_5	0.19	**Total**	99.53	99.42	99.37	99.63	99.75	99.68	99.12	99.55	98.50	99.95	99.29	100.05
Total H_2O	0.18	**Si**	6.515	6.541	6.502	6.505	7.926	6.531	6.573	6.520	6.465	7.888	6.524	6.409
CO_2	-	**Al^{iv}**	1.485	1.459	1.498	1.495	.074	1.469	1.427	1.480	1.535	.112	1.476	1.591
Total	99.79	**Al^{vi}**	.676	.586	.626	.599	.036	.628	.596	.619	.670	.053	.633	.481
mg	.378	**Ti**	.075	.068	.072	.066	.004	.049	.066	.062	.019	.016	.051	.050
(with total Fe as FeO)	.324	**Fe^{3+}**	-	-	-	-	-	-	-	-	-	-	-	.847
		Fe^{2+}	2.898	2.954	2.975	2.984	3.946	2.950	2.996	2.922	3.016	3.886	2.964	2.065
CIPW	NORM	**Mn**	.035	.041	.036	.040	.109	.030	.030	.031	.030	.099	.034	.033
Qtz	2.44	**Mg**	1.662	1.601	1.571	1.584	2.829	1.559	1.605	1.560	1.489	2.742	1.580	1.552
Cr	1.54	**Ca**	1.709	1.844	1.809	1.820	.116	1.878	1.780	1.900	1.900	.165	1.830	1.798
Plag	48.57	**Na**	.500	.474	.475	.502	.090	.473	.480	.471	.493	.101	.484	.476
(An content)	41	**K**	.065	.067	.067	.065	.002	.079	.065	.072	.085	.007	.035	.035
Di	11.75	**Asite**	.618	.635	.632	.659	.132	.646	.619	.637	.702	.068	.612	.337
Hy	25.15	**mg**	.36	.35	.34	.34	.41	.34	.35	.346	.33	.41	.35	.43
Mag	6.10													
Ilm	3.63													
Ap	0.45													

Micrometric Analysis	Hbd	Cum	Plag	Qtz	Ilm
	37	9	32	19	3

*Analyst, J. Sheraton

TABLE 16. SPECIMEN S11 ANALYTICAL DATA

	Whole* Rock	Amphiboles a	b	c	d	e	Average	Average with Fe_2O_3
SiO_2	45.47	42.97	43.74	43.61	43.10	43.52	43.39	43.39
TiO_2	1.93	.77	.79	.84	.85	.78	.81	.81
Al_2O_3	10.03	11.23	11.13	11.42	11.71	11.22	11.34	11.34
Fe_2O_3	6.48	-	-	-	-	-	-	7.36
FeO	13.30	19.61	19.63	19.65	20.17	19.86	19.78	13.18
MnO	0.35	.22	.24	.24	.23	.23	.23	.23
MgO	8.06	9.42	9.66	9.23	9.23	9.39	9.39	9.39
CaO	10.90	12.08	12.14	12.11	12.27	11.99	12.12	12.12
Na_2O	1.00	1.55	1.51	1.63	1.68	1.59	1.61	1.61
K_2O	0.67	.59	.56	.60	.63	.56	.59	.59
P_2O_5	0.18							
Total H_2O	0.53							
CO_2	-							
Total	98.90	98.44	99.39	99.34	99.86	99.25	99.26	99.43

	a	b	c	d	e	Average	Average with Fe_2O_3
Si	6.485	6.525	6.512	6.430	6.513	6.493	6.377
Al^{iv}	1.515	1.475	1.488	1.570	1.487	1.507	1.623
Al^{vi}	.484	.482	.524	.489	.492	.494	.341
Ti	.086	.087	.093	.095	.088	.090	.089
Fe^{3+}	-	-	-	-	-	-	.814
Fe^{2+}	2.475	2.448	2.454	2.515	2.486	2.476	1.620
Mn	.028	.031	.031	.029	.029	.030	.028
Mg	2.119	2.146	2.057	2.051	2.094	2.093	2.057
Ca	1.954	1.940	1.938	1.960	1.922	1.943	1.908
Na	.451	.438	.474	.485	.490	.468	.458
K	.110	.105	.113	.119	.105	.110	.110
Asite	.710	.678	.683	.743	.706	.703	.477
mg	.46	.46	.45	.45	.45	.46	.56

	Whole* Rock
mg	.513
(with total Fe as Feo)	.424
CIPW	NORM
Qtz	1.63
Or	3.96
Plag	30.36
(An content)	71
Di	26.30
Hy	23.66
Mag	9.40
Ilm	3.67
Ap	0.43

Micrometric Analysis	Hbd	Plag	Qtz	Ilm	Sph
	72	1	23	2	2

Analyst, J. Sheraton.

Neither of these characteristics is observed in the Soldiers Cap hornblendes. It is clear that reaction with iron oxides cannot have been responsible for the formation of the hornblende. Chlorite and epidote still remain and are most likely to have been the principal reactants forming tschermakite component.

P2. Specimens P2A and P2B come from a body of metamorphosed olivine gabbro which occurs in an upper greenschist or lower amphibolite facies terrain. The body is distinguished from other basic intrusions by its larger size and the lack of alteration at its centre. P2A, which was collected close to the contact with granite, contains chlorite and abundant biotite. Specimen P2B, which was collected from near the centre of the body, is much less altered and contains relict olivine.

P2A. Hornblende + cummingtonite + biotite + chlorite + andesine + K-feldspar meta-gabbro

Although some of the plagioclase is primary, most has been made over to sodic andesine. A small amount of K-feldspar is present. Both olivine and augite have completely given way to hornblende, cummingtonite, and biotite. Former olivine sites are recognizable as patches of pale tan biotite and moderately coarse prismatic colourless cummingtonite, more or less surrounded by coarse and fine prismatic hornblende. Some amphibole prisms are made up of both hornblende and cummingtonite growing in structural continuity.

As in P2B the hornblende is pale despite its aluminous composition (Table 18). Because it contains components of broken-down augite, it is less aluminous and alkali-rich than the hornblende of P2B. Chlorite occurs as scattered large flakes: it shows no signs of disequilibrium with other phases and in most places contains included euhedral prisms of both hornblende and cummingtonite.

P2B. Hornblende + almandine + plagioclase + hypersthene + cummingtonite + magnetite metamorphosed troctolitic gabbro

Plagioclase (about An_{59} $Or_{0.4}$) and especially augite appear to be largely unaltered, but relict olivine is separated from plagioclase by rims, firstly of fine-grained magnetite, then cummingtonite which may contain scattered anhedral grains of hypersthene, and finally hornblende studded with a few small garnet crystals. Despite its pale colour (x = pale straw yellow, y = very pale apple green, z = pale greenish blue) it is extremely aluminous and its vacant site is almost filled with alkali atoms (Table 19). It is notably poor in Ti and may be low in Fe^{3+}, factors which are probably responsible for its pale colour. Hypersthene has a moderate negative 2V and is very slightly pink. It is granular in habit, with no sign of optical continuity between adjacent grains. It appears that the corona structures were produced by the following reaction:

$$\text{Olivine} + \text{plagioclase} + H_2O + O \longrightarrow \text{hornblende} + \text{garnet} + \text{cummingtonite} + \text{hypersthene} + \text{magnetite}.$$

To test whether the coronas developed by such an isochemical reaction, a CIPW norm of the reaction products was calculated. Hornblende, cummingtonite, hypersthene, and garnet were analysed (Table 20), their proportions by volume, together with magnetite, were measured by point count analysis, and mole proportions were calculated, using data estimated from Robie et al., (1967). Fe in magnetite was recalculated in the divalent state. The results appear in Table 21. Olivine and plagioclase make up about 97% of the normative constituents. Diopside (3%) and nepheline (only 0.2%) remain. The measured olivine composition, Fo_{44}, corresponds with the normative composition, $Fo_{46.5}$. The measured plagioclase composition (An_{59}) is more sodic than the calculated composition (An_{65}), which is entirely determined by the composition of the hornblende in the corona. The hornblende probably contains the maximum possible Na, and

TABLE 17. SPECIMEN P ANALYTICAL DATA

Amphiboles

	a	b	c	d	e	f	Average
SiO_2	45.60	45.36	45.05	45.83	44.87	45.49	45.53
TiO_2	.31	.32	.36	.34	.41	.38	.35
Al_2O_3	12.11	11.86	11.73	11.98	11.91	11.33	11.82
Fe_2O_3	-	-	-	-	-	-	-
FeO	12.02	12.23	12.14	12.34	12.70	12.17	12.27
MnO	.37	.35	.37	.34	.39	.32	.36
MgO	13.50	13.23	13.07	13.20	12.73	12.89	13.10
CaO	11.88	12.01	12.06	12.12	12.09	12.02	12.03
Na_2O	1.62	1.53	1.40	1.61	1.55	1.56	1.54
K_2O	.23	.23	.26	.24	.27	.23	.24
Total	97.65	97.11	96.43	98.02	96.92	96.38	97.24
Si	6.635	6.648	6.649	6.657	6.617	6.716	6.654
Al^{iv}	1.365	1.352	1.351	1.343	1.383	1.284	1.346
Al^{vi}	.713	.697	.691	.707	.687	.687	.697
Ti	.035	.035	.039	.037	.045	.041	.039
Fe^{3+}	-	-	-	-	-	-	-
Fe^{2+}	1.462	1.499	1.499	1.499	1.565	1.502	1.504
Mn	.046	.044	.047	.044	.050	.042	.046
Mg	2.928	2.891	2.878	2.857	2.799	2.838	2.865
Ca	1.852	1.885	1.908	1.885	1.910	1.901	1.890
Na	.459	.436	.402	.455	.445	.448	.441
K	.044	.044	.049	.046	.051	.044	.046
Asite	.539	.532	.512	.532	.551	.503	.528
mg	.66	.65	.65	.65	.63	.65	.65

Micrometric Analysis	Hbd	Flag	Qtz	Ilm	Biot	Chlor	Epidote
	14	34	15	3	26	4	7

TABLE 18. SPECIMEN P2A ANALYTICAL DATA

	Hornblende						Cummingtonite					
	a	b	c	d	e	Average	f	g	h	i	j	Average
SiO_2	42.72	42.74	42.21	42.28	43.06	42.60	53.57	54.00	53.42	53.96	53.68	53.73
TiO_2	.53	.63	.50	.53	.50	.54	0.02	0.13	.05	.03	.02	.
Al_2O_3	14.92	15.05	14.68	15.15	14.74	14.91	1.19	0.95	.97	.86	.91	.98
Fe_2O_3	-	-	-	-	-	-	-	-	-	-	-	-
FeO	15.34	15.84	15.85	15.54	15.26	15.57	23.23	23.82	23.44	23.57	23.78	23.57
MnO	-	-	-	-	-	-	-	-	-	-	-	-
MgO	9.73	10.07	10.00	9.98	9.78	9.91	17.19	17.58	17.53	17.77	17.60	17.53
CaO	11.27	11.20	11.06	11.16	10.98	11.13	.91	.71	.76	.72	.62	.74
Na_2O	1.85	1.74	1.68	1.67	1.73	1.73	-	-	-	-	-	-
K_2O	.23	.23	.24	.28	.22	.24	-	-	-	-	-	-
Total	96.59	97.49	96.21	96.57	96.27	96.63	96.10	97.19	96.17	96.91	96.61	96.60
Si	6.381	6.338	6.359	6.322	6.437	6.367	7.947	7.924	7.918	7.931	7.924	7.927
Al^{iv}	1.619	1.662	1.641	1.678	1.563	1.633	.053	.076	.082	.069	.076	.073
Al^{vi}	1.009	.970	.966	.993	1.034	.995	.154	.090	.089	.081	.082	.097
Ti	.060	.071	.057	.060	.056	.061	.002	.015	.006	.004	.002	.005
Fe^{3+}	-	-	-	-	-	-	-	-	-	-	-	-
Fe^{2+}	1.917	1.964	1.960	1.944	1.907	1.938	2.845	2.923	2.904	2.897	2.936	2.908
Mn	-	-	-	-	-	-	-	-	-	-	-	-
Mg	2.166	2.225	2.246	2.225	2.180	2.208	3.804	3.843	3.870	3.894	3.874	3.855
Ca	1.803	1.779	1.784	1.787	1.761	1.783	0.144	0.112	0.122	0.114	.098	.117
Na	.535	.500	.488	.485	.504	.502	-	-	-	-	-	-
K	.044	.044	.046	.057	.041	.046	-	-	-	-	-	-
Asite	.534	.552	.546	.547	.484	.533	-	-	-	-	-	-
mg	.53	.53	.53	.53	.53	.53	.57	.57	.57	.57	.57	.57

TABLE 19. SPECIMEN P2B ANALYTICAL DATA

										Cummingtonite						Cummingtonite		Average	Average
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	Hornblende	Cummingtonite
SiO_2	42.27	40.82	40.24	40.06	39.90	39.59	39.20	39.51	39.19	54.69	39.68	40.31	39.33	38.78	38.30	55.58	55.31	39.8	55.2
TiO_2	.04	.04	.03	.04	.05	.03	.03	.04	.04	-	.05	.05	.02	.03	.03	-	-	.04	-
Al_2O_3	16.52	17.84	18.97	19.30	19.99	19.76	20.37	21.30	20.94	0.43	16.87	18.21	19.39	20.52	20.61	.46	.61	19.2	0.36
Fe_2O_3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FeO	15.69	15.61	16.40	16.08	15.74	16.56	16.67	16.16	16.92	21.56	15.66	15.05	15.95	15.59	17.04	22.47	21.49	16.1	21.8
MnO	.09	.11	.14	.07	.10	.15	.07	.11	.11	.21	.09	.10	.14	.10	.10	.24	.30	0.11	.28
MgO	10.47	9.61	9.45	9.44	8.87	9.28	9.33	8.57	8.61	19.50	10.15	10.15	9.42	9.07	8.97	20.41	20.89	9.4	20.3
CaO	11.35	10.86	11.26	11.04	10.89	11.05	10.89	10.83	10.51	.58	10.96	10.50	10.05	10.68	10.62	.41	.55	10.8	.51
Na_2O	2.64	2.71	2.83	3.00	2.80	2.90	2.90	2.81	2.97	.17	2.86	2.79	2.86	2.79	2.92	-	-	2.84	.17
K_2O	0.89	0.40	0.48	0.36	0.41	0.44	0.44	0.44	.51	.03	.46	0.38	.35	.40	.45	-	-	0.46	.03
Total	99.96	98.01	99.79	99.47	98.73	99.70	99.99	99.73	99.80	97.17	96.79	97.54	97.51	97.97	99.05	99.57	99.15	98.7	98.7
Si	6.156	6.047	5.891	5.881	5.859	5.807	5.736	5.763	5.740	7.951	5.989	5.985	5.866	5.836	5.670	7.899	7.871	5.88	7.91
Al^{iv}	1.844	1.953	2.109	2.119	2.141	2.193	2.263	2.237	2.260	.049	2.011	2.015	2.134	2.164	2.330	.077	.101	2.12	.08
Al^{vi}	.994	1.162	1.165	1.221	1.313	1.223	1.249	1.423	1.355	.026	.990	1.173	1.274	1.251	1.268	.000	.000	1.22	.00
Ti	.004	.004	.003	.004	.006	.003	.003	.004	.004	-	.006	.006	.002	.004	.004	-	-	.00	.00
Fe^{3+}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe^{2+}	1.912	1.934	2.008	1.975	1.934	2.028	2.040	1.971	2.072	2.621	1.978	1.869	1.989	1.962	2.109	2.671	2.557	1.99	2.62
Mn	.011	.013	.018	.018	.008	.013	.018	.008	.013	.025	.011	.013	.018	.013	.013	.028	.036	.01	.03
Mg	2.275	2.124	2.063	2.066	1.942	2.030	2.032	1.864	1.879	4.225	2.283	2.246	2.094	2.034	1.980	4.325	4.432	2.07	4.33
Ca	1.771	1.724	1.767	1.737	1.713	1.736	1.706	1.692	1.649	.091	1.772	1.672	1.605	1.721	1.685	.063	.085	1.71	.08
Na	.746	.778	.804	.856	.798	.824	.822	.797	.842	.047	.840	.803	.826	.814	.840	-	-	.81	.05
K	.166	.077	.090	.068	.077	.083	.083	.081	.095	.004	.088	.071	.066	.076	.084	-	-	.09	.01
Asite	.879	.816	.918	.945	.791	.908	.953	.840	.910	.039	.968	.854	.874	.876	.983	-	.109	.90	.12
mg	.54	.52	.50	.51	.50	.50	.50	.49	.47	.61	.53	.54	.51	.51	.48	.62	.63	.51	.62

Micrometic Analysis.	Hbd	Cummingtonite	Plag	Ilm	Mag	Biot	Hypersthene	Olivine	Garnet
	23	7	48	2	1	1	5	3	3

TABLE 20 : MICROPROBE ANALYSES OF REACTION RIMS IN SAMPLE P2B.

	Hornblende (average of 14 analyses)	Hypersthene (average of 3 analyses)	Cummingtonite (average of 3 analyses)
SiO_2	39.8	52.1	55.2
TiO_2	0.04	-	-
Al_2O_3	19.2	0.38	0.36
FeO	16.1	27.3	21.8
MnO	0.11	-	0.28
MgO	9.4	19.7	20.3
CaO	10.8	0.16	0.51
Na_2O	2.84	-	0.17
K_2O	0.46	-	0.03
	98.7	99.6	98.7

Structural formula calculated on an anhydrous basis

	Hornblende		Hypersthene		Cummingtonite	
Si^{4+}	5.88	8.00	0.99	1.00	7.91	7.99
Al^{3+IV}	2.12		0.01		0.08	
Al^{3+VI}	1.22	7.90	0.00	1.00	0.00	7.12
Ti^{4+}	0.00		-		0.00	
Fe^{2+}	1.99		0.44		2.62	
Mn^{2+}	0.01		-		0.03	
Mg^{2+}	2.07		0.56		4.33	
Ca^{2+}	1.71		0.00		0.08	
Na^{+}	0.81		-		0.05	
K^{+}	0.09		-		0.01	
O (assumed value)	23.00		3.00		23.00	

Semi-quantitative analyses.

Olivine: Fo_{56}

Garnet : Alm_{66} Py_{20} Gr_{10} $Spess_{3}$

TABLE 21 : COMPOSITION OF REACTION RIM MATERIAL AND RELATED DATA IN SAMPLE P2B

	Vol.% in corona structures	Estd Molar Volume (cm^3)	Mole %	CIPW norm of corona material		
Hornblende	55.8	275	24.3	Ilm	0.02	
				Ab	12.6	41.3
Hypersthene	12.8	32.2	47.6	An	27.3	
				Or	1.5	
Cummingtonite	18.7	272	8.2	Di	1.3	3.2
				Hd	1.9	
Garnet	8.7	115	9.1	Fo	20.2	55.3
				Fa	35.1	
Magnetite	4.1	44.5	11.0	Ne	0.2	

Approximate Modes

Rock

Hornblende	21
Cummingtonite	7
Hypersthene	5
Olivine	3
Garnet	3
Ilmenite	2
Biotite	1
Plagioclase	50
Augite	8

Original Gabbro Parent

Olivine	26
Plagioclase	64
Augite	8
Ilmenite	2

TABLE 23. SPECIMEN F3. ANALYTICAL DATA

	a	b	c	d	e	f	Average
SiO_2	40.13	40.38	40.14	39.83	40.24	40.05	40.13
TiO_2	.99	1.10	1.11	.98	.98	.96	1.02
Al_2O_3	12.06	12.18	12.29	12.65	12.58	12.48	12.37
Fe_2O_3	-	-	-	-	-	-	-
FeO	25.52	25.64	25.25	25.98	25.71	26.02	25.69
MnO	.39	.36	.37	.37	.37	.37	.37
MgO	4.99	5.08	5.03	4.87	5.08	5.15	5.03
CaO	11.59	11.52	11.50	11.55	11.53	11.62	11.55
Na_2O	1.88	1.85	1.92	1.86	1.81	1.79	1.85
K_2O	1.52	1.59	1.52	1.52	1.46	1.55	1.53
Total	99.09	99.67	99.17	99.62	99.77	99.99	99.54
Si	6.260	6.258	6.247	6.192	6.224	6.200	6.230
Al^{iv}	1.740	1.742	1.753	1.808	1.776	1.800	1.770
Al^{vi}	.479	.484	.502	.509	.520	.478	.495
Ti	.117	.128	.130	.115	.114	.112	.119
Fe^{3+}	-	-	-	-	-	-	-
Fe^{2+}	3.329	3.324	3.286	3.376	3.326	3.370	3.335
Mn	.053	.048	.050	.050	.050	.050	.050
Mg	1.169	1.174	1.165	1.128	1.169	1.189	1.166
Ca	1.939	1.913	1.918	1.925	1.912	1.929	1.923
Na	.570	.556	.581	.561	.543	.535	.558
K	.303	.308	.302	.302	.289	.305	.302
Asite	.959	.934	.934	.967	.964	.968	.954
mg	.26	.26	.26	.25	.26	.26	.26

	Hbd	Plag	Kspar	Qtz	Sph
Micrometric Analysis	35	16	16	31	2

abstraction of a small amount of An component from the surrounding plagioclase during the formation of the corona may have been necessary.

The persistence of relict olivine and the formation of metamorphic hypersthene in the lower amphibolite facies suggest that an extremely small amount of water was available during metamorphism. Hornblende is poorer in Al and richer in Si, Mg, and Ca at its contact with cummingtonite than at its contact with plagioclase.

Calculation of a CIPW norm of the corona structures shows that they have resulted from a very nearly isochemical reaction between olivine and plagioclase with the addition of very limited amounts of water and oxygen.

P3. Deep green hornblende + K-feldspar + oligoclase + quartz + sphene amphibolite

Homogeneous plagioclase has the composition An_{22} $Or_{1.4}$. Hornblende (Table 22) is very rich in Fe and in some respects it resembles the hornblende of specimen S5B. Both are Fe and K-rich and both have 2V less than 20°. Hornblende P3 is, however, much richer in Ti despite the absence of co-existing ilmenite. Analyses a - e are near a grain boundary with plagioclase. Analysis f comes from the interior of a large grain.

DISCUSSION

Range of Compositions Encountered

The hornblendes encountered fall along a broad trend from tremolite towards pargasite (Fig. 4b). The hornblende from specimen P2B lies in the region beyond pargasite. The subcalcic riebeckitic actinolites from the calc-silicate specimen C1 do not plot in the quadrilateral and their compositions are far removed from that of normal calciferous amphiboles.

There are two large regions in the quadrilateral where no analyses fall. The more notable is the edenite region. It is reasonable to conclude that a large solid-solution gap exists in the region of edenite in the greenschist and lower to middle amphibolite facies. Therefore there may in certain cases be very **strict** limits to the extent to which the reaction

$$\text{Albite} + \text{Actinolite} \longrightarrow \text{Edenite} + 4SiO_2 \qquad \text{———}(14)$$

can proceed. In these cases, because of unsuitable host rock composition hornblende cannot obtain sufficient quantities of $(Al, Fe^{3+})^{VI}$ to become pargasitic with increasing grade. Consider samples S5A, S5B, S9A, and S9B. S5A has a more sodic plagioclase and a less sodic hornblende despite the fact that it belongs to the same grade as S5B. S9A and S9B have a similar relationship. It appears that hornblendes S5A and S9A are unable to become more sodic by reactions 14 and 15 because unsuitable bulk composition prevents the hornblende obtaining sufficient amounts of $(Al, Fe^{3+})^{VI}$ for its composition to move in the direction of pargasite. The relationship between the hornblende and plagioclase compositions in samples S5A, S5B and S9A, S9B is the opposite to that predicted by Perchuk (1966). He does not take into account the possibility that the amount of edenite or richterite component is dependent on the amount of (Al, Fe^{3+}, Ti) in the Y-site in moderate grade amphiboles.

No hornblende compositions from the present study plot in the tschermakite region. It is well known that hornblendes with composition close to tschermakite do not occur.

Although no solid-solution gap is obvious between actinolitic compositions and hornblendes, there is a scarcity of compositions with about 7 Si atoms per unit cell. It is possible that the few hornblendes with compositions in that region are out of equilibrium, because all are found in zoned grains with actinolite cores and pargasitic rims. However,

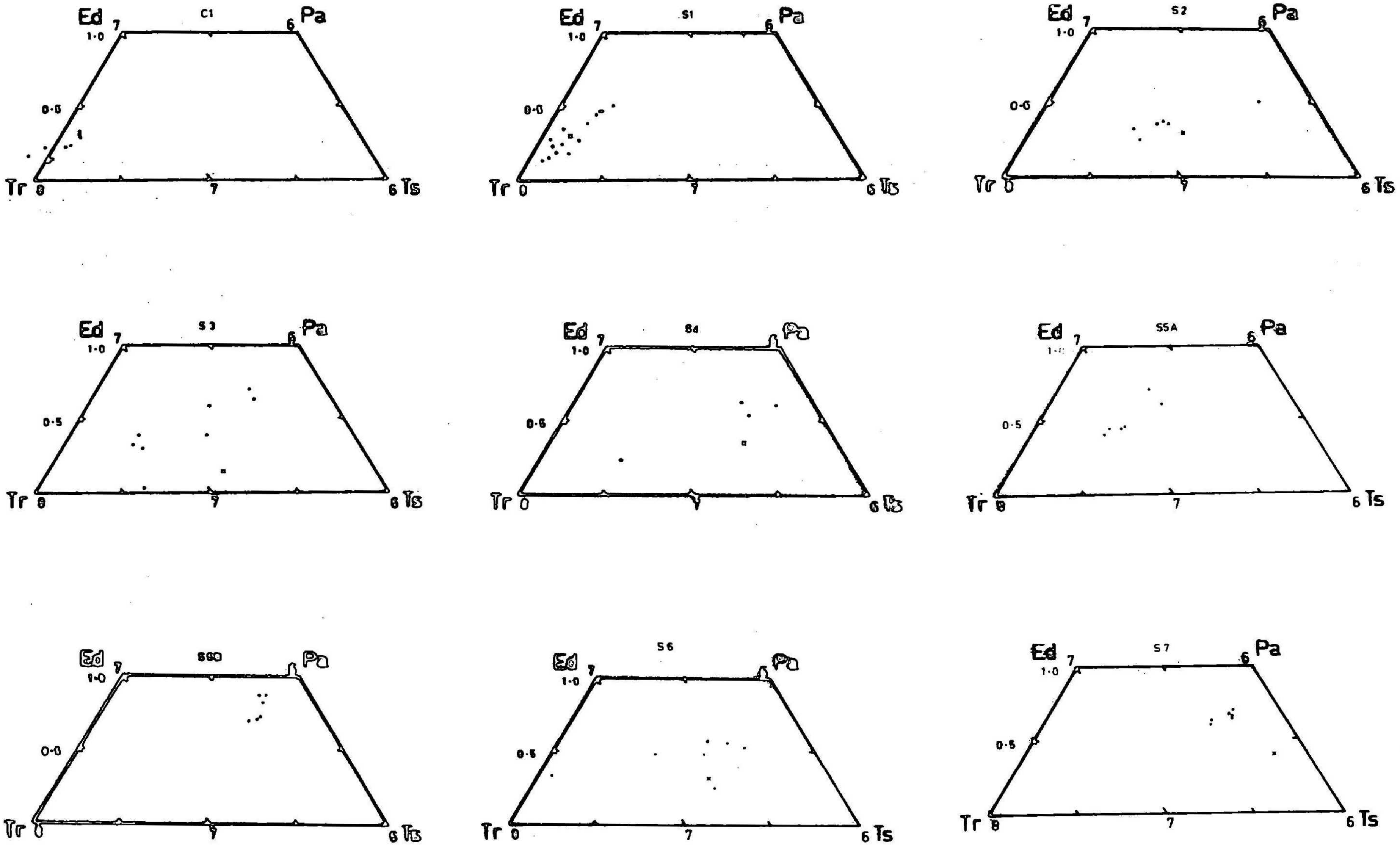


Fig. 5. Hallimond diagrams. Specimens C1 and S1-S7. Crosses have the same meaning as in Fig. 4 (b).

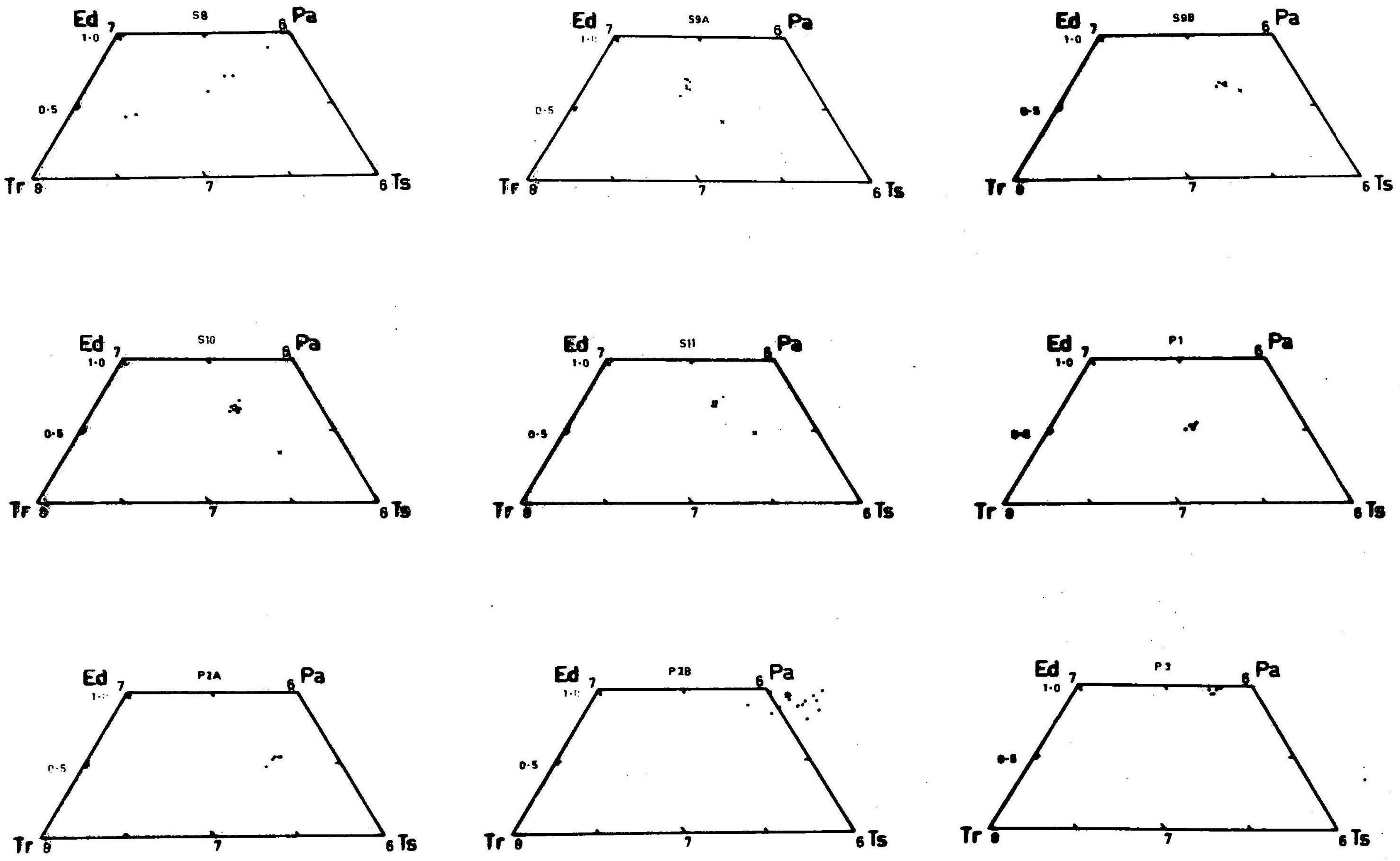


Fig. 6. Hallimond diagrams. Specimens S8-S11, P1-P3. Crosses have the same meaning as in Fig. 4 (b).

the sharp boundaries found between actinolite and hornblende in basic rocks from the Haast River, New Zealand (Cooper & Lovering, 1970), the Grampian Highlands (Shido & Myashiro, 1959), California (Compton, 1958), and the Abukuma Plateau (Myashiro, 1958; Shido, 158) and Tanzawa Mountains (Sugi, 1931) in Japan do not occur.

Introduction of $(Al, Fe^{3+})^{VI}$

In amphibolites containing only hornblende + plagioclase + quartz + K-feldspar the amount of $(Al, Fe^{3+})^{VI}$ in hornblende is largely determined by bulk composition. The fraction of tschermakite component can be approximately estimated by projecting from anorthite through the bulk composition onto the actinolite-tschermakite line in an ACF diagram (Fig. 3). However, almost all the hornblende + plagioclase + quartz + K-feldspar amphibolites contain ilmenite + sphene and the amount of $(Al, Fe^{3+})^{VI}$ is determined partly by reactions 8 and 9.

The $(Al, Fe^{3+})^{VI}$ content is always less than that implied by the amount of tschermakite component indicated by the Hallimond diagram. Ti in the Y site and Ca in the A site require additional replacement of Si by Al^{VI} over that dictated by (Al, Fe^{3+}) in the Y site, causing the composition to trend in the direction of tschermakite on the diagram without addition of $(Al, Fe^{3+})^{VI}$.

Introduction of Na^{X-XII}

Na^{X-XII} probably enters hornblende by reaction 14 and possibly 15, both of which use albite component of plagioclase, in contrast with reactions leading to the introduction of $(Al, Fe^{3+})^{VI}$, which use anorthite component. Therefore it is not surprising that hornblendes in rocks with sodic plagioclase trend towards edenite and those in rocks with calcic plagioclase tend to be pargasitic. Fig. 7 shows a plot of $\frac{\text{total Na in amphibole}}{Al^{VI}\text{ in amphibole}}$ against the Ab content of plagioclase for hornblende-plagioclase pairs. The extent to which edenite component enters hornblende is generally small compared with pargasite component. In other words hornblende in a rock with sodic plagioclase generally remains more actinolitic.

Zoned Amphiboles

(a) Al^{VI} and Fe

The compositional trends of zoned amphiboles with actinolitic cores that are relics of lower grade are mostly close to a straight line between tremolite-actinolite and pargasite-ferropargasite composition on the Hallimond diagram. They do not curve upwards as might be expected if reactants forming $(Al, Fe^{3+})^{VI}$ were exhausted and Na continued to enter the lattice by reactions 14 and 15. Trends of Na^{X-XII} versus Al^{VI} in some zoned hornblendes appear in Fig. 9. The magnitude of their slope depends largely on the albite content of the reacting plagioclase.

An Fe versus Al^{VI} diagram (Fig. 8) shows straight-line trends of varying slopes leading from magnesian composition at zero Al^{VI} to more iron-rich compositions where larger amounts of Al^{VI} are present. The general trend of amphibole composition throughout the metamorphic sequence is from magnesian compositions at low grade to more Fe-rich compositions at higher grade.

An increase in Fe^{2+} and Fe^{3+} content with grade has been noted by most authors working on low to medium grade amphiboles. Wiseman (1934) attributed the increase in iron content of hornblende in the southwest Highland epidiorites to the breakdown of chlorite, which he was able to show was richer in Fe than the co-existing actinolite. Shido (1959) also mentions the more magnesian composition of low-grade actinolites from the Abukuma Plateau. Leake (1968) suggests that iron-oxide minerals co-exist with magnesian actinolite in low-grade basic rocks with normal Fe contents. It is apparent from Leake's (1968) catalogue of calciferous and subcalciferous

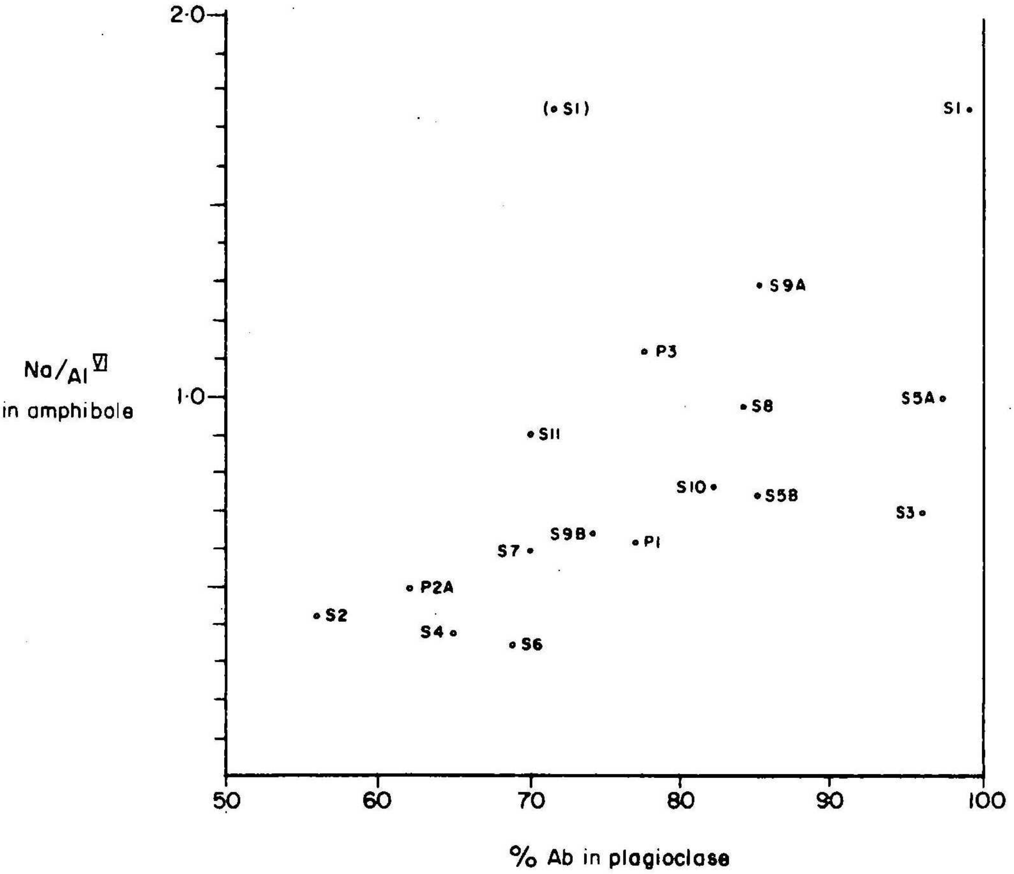


Fig. 7. Effect of albite content of plagioclase on the Na/Al^{VI} ratio of amphibole.

amphiboles that actinolitic amphiboles are rarely able to accommodate a large amount of Fe^{2+}. Of all the calciferous amphiboles with $Si<7.25$, 212 have values of $Mg/(Mg + Fe^{2+} + Fe^{3+} + Mn)$ greater than 0.50 and only 9 less than 0.50 (6 of the latter are considered to be poor analyses). It would seem that the Y sites are too small for Fe^{2+} unless the chains are expanded by replacement of some Si and Al.

The suggestion that reactions such as 5 to 13 are largely responsible for introduction of Al^{VI} into hornblende in specimens C1, S1, S4, S6, and S8 and probably S7 and S9B requires further explanation. Consider an amphibolite containing 50% hornblende with 0.7 Al^{VI} and 0.4 $(Fe^{3+})^{VI}$ as a typical example. Using the molar volume data of Robie et al. (1967) the modal amounts of selected reactants and products required by reactions 1-13 can be calculated from the molar amounts required in the reactions (Table 23).

The amounts of magnetite and ilmenite required by reactions 5, 6, 9 and 10 are comparatively small and quite possible in terms of the modal amounts of these phases found in the low-grade actinolite-bearing rocks. The amounts of chlorite and epidote required by reactions 1-4 are generally large compared with the amounts present in the low grade Cloncurry rocks. However, in nearly all cases in those rocks which contain zoned hornblende showing marked Fe-enrichment, insufficient of the normative ilmenite has been consumed to account for all the $(Al, Fe^{3+})^{VI}$. Magnetite must therefore be called upon in such cases as a reactant (as it certainly is in samples C1 and S1). However, there is a possibility that some movement of Fe and or Mg has occurred during increasing grade, in response to the general preference of hornblende for Fe as it becomes more aluminous. Fig. 10 shows what may be a significant decrease in whole rock $Mg/(Mg + \text{Total Fe})$ with increasing grade. The hornblende-producing reactions involving anorthite component of plagioclase and iron oxide minerals are hydration reactions and water must be supplied from outside the system where other hydrous minerals are absent. Actinolitic amphiboles may persist in such cases when external water is unavailable.

(b) Na^{X-XII} and Al^{VI}

The only probable reactions responsible for introduction of Na^{X-XII} produce 4 moles of SiO_2 for every mole of Na^{X-XII} introduced. Despite this, specimens S1, S2, S3, S4, and S6 contain no modal quartz and S8 only 5%. Clearly, silica must have been consumed by other reactions if the formation of hornblende is an isochemical process. Na^{X-XII} is plotted against Al^{VI} in Fig. 9 and obvious sympathetic trends can be observed in all cases except S6. The slopes of the trends can be compared with the slopes produced by coupling the various Al^{VI}-producing reactions (and reactions 8, 9, and 22) with reactions 14 or 15 in such a proportion as to neither produce nor consume silica (inset in Fig. 9). The information in Figs. 8 and 9 has been used in elucidating the most probable reactions producing hornblende in those rocks with zoned amphiboles.

Behaviour of Titanium during Metamorphism

Ilmenite does not appear to be stable in the lowest-grade amphibolites (specimen S1), where the assemblage sphene-magnetite is stable, but it is not certain whether low temperature or high f_{O_2} is responsible for its absence. Ilmenite is the only opaque mineral present in all the higher grade rocks from Soldiers Cap and it occurs with or without sphene. Ilmenite is always extremely poor in Mg, and generally consists of aggregates of small, optically discontinuous grains. It is therefore concluded that ilmenite is not relict but has equilibrated with the metamorphic conditions. The reason why sphene does or does not occur depends on a large number of

Fig. 8. Increase in Fe with Al^{VI} in zoned Ca amphiboles. Inset shows the calculated Fe/Al^{VI} slopes produced in zoned amphiboles by reactions referred to in text.

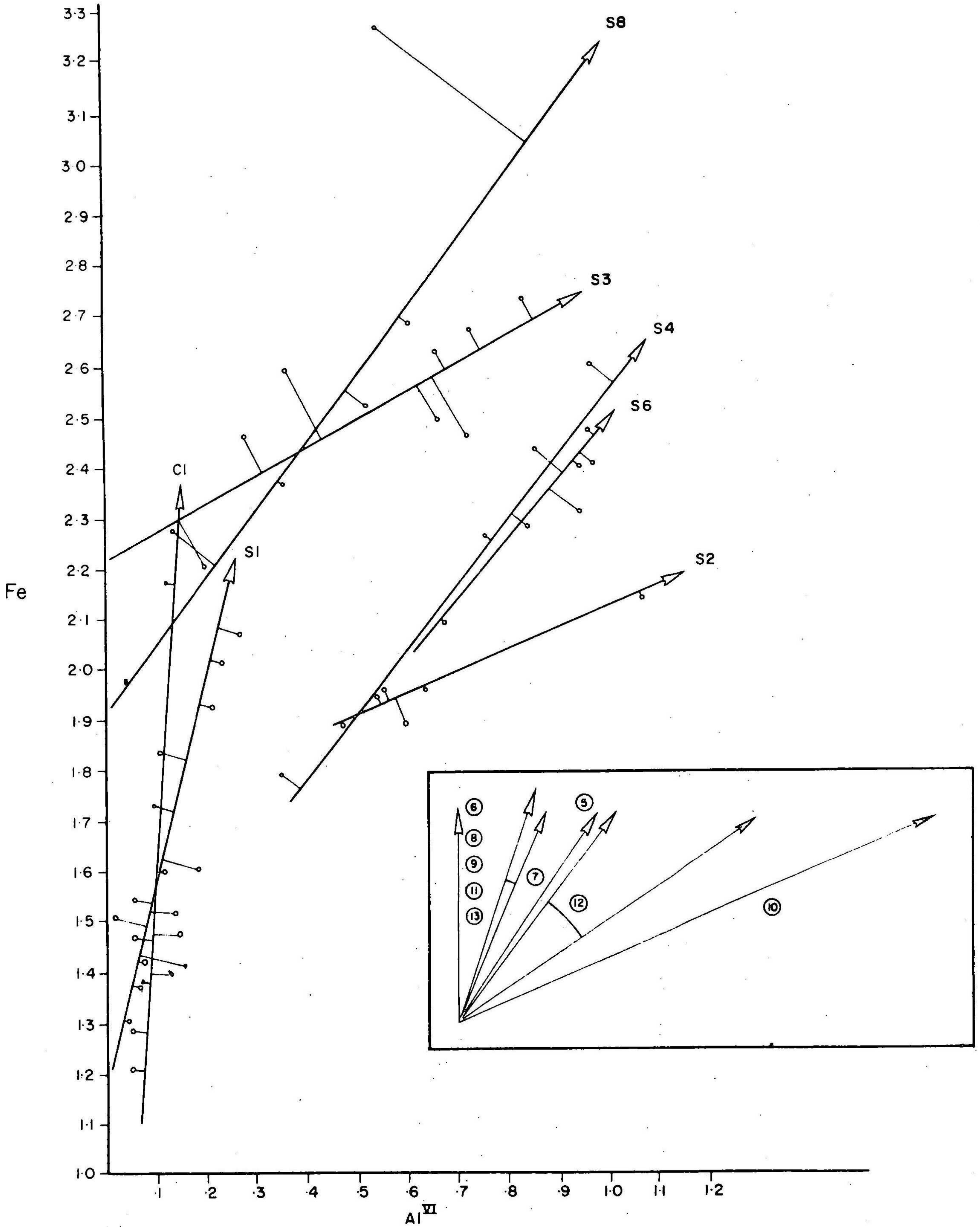


TABLE 23: MODAL PERCENTAGES OF REACTANTS AND PRODUCTS IN SOME HORNBLENDE-FORMING REACTIONS IN A TYPICAL AMPHIBOLITE

Phase	Chlorite	Epidote	Magnetite	Ilmenite	Sphene
Molar Vol (ml.)	200 (estd)	137	44.5	31.7	55.7
Reaction					
1	11.2	13.1			
2	8.4	9.8			
3	8.0				
4	6.0				
5			2.8) 4.1		
6			1.3)		
7		15.5) 18.8	5.8) 7.5		
8		3.3)	1.7)		
9			3.2	1.2(+)	2.0) 6.4(+)
10				1.7) 2.5	4.4)
11				0.8)	
12		10.7) 14.0		2.7) 3.8	6.7) 8.6(+)
13		3.3)		1.1)	1.9)

The estimated partial molar volume of all components of hornblende is 175 ml. (+) signifies product, while all others are reactants.

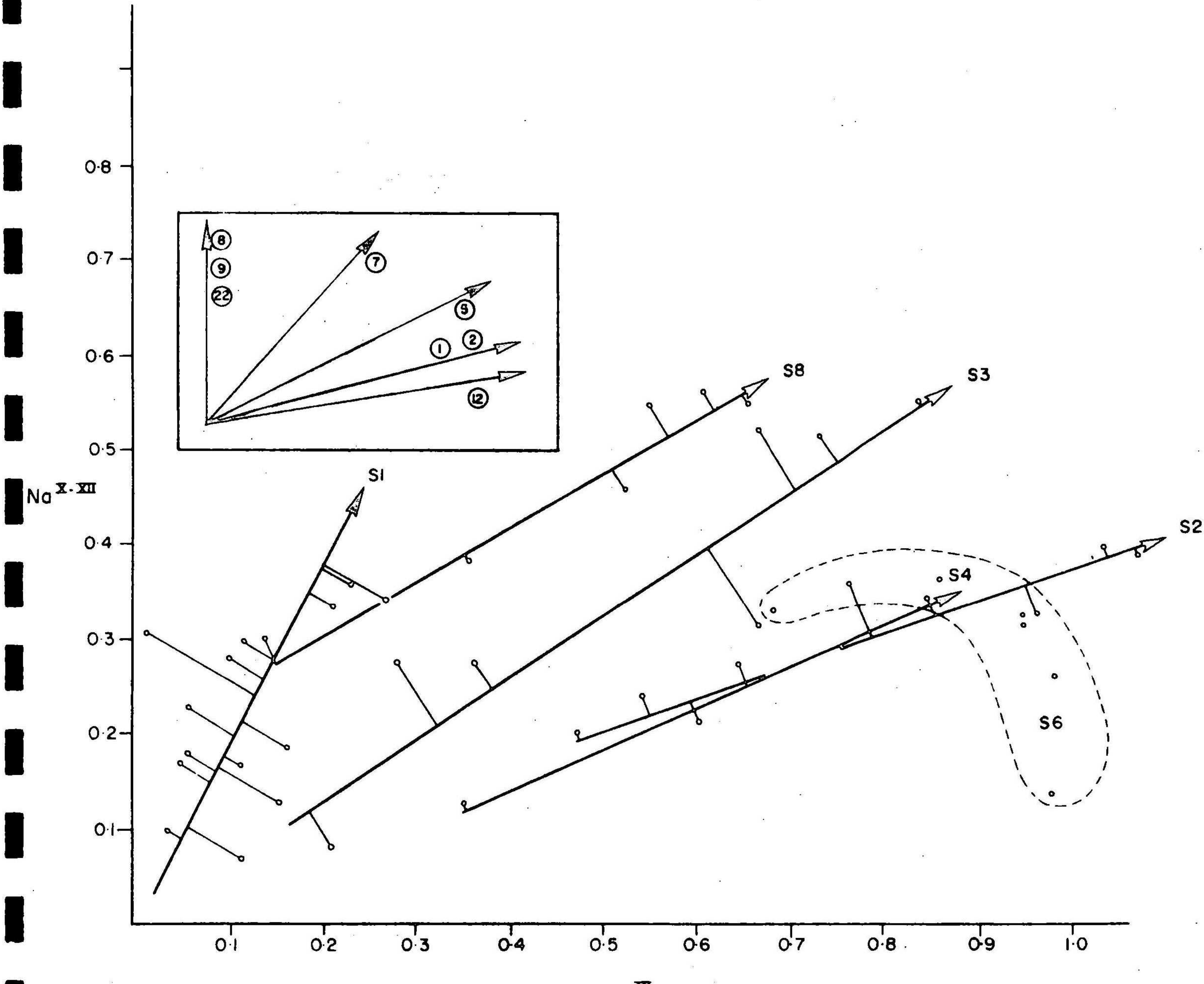


Fig. 9. Trends of Na^{X-XII} versus Al^{VI} in zoned amphiboles from quartz-free rocks and S8 which contains only a few percent quartz.

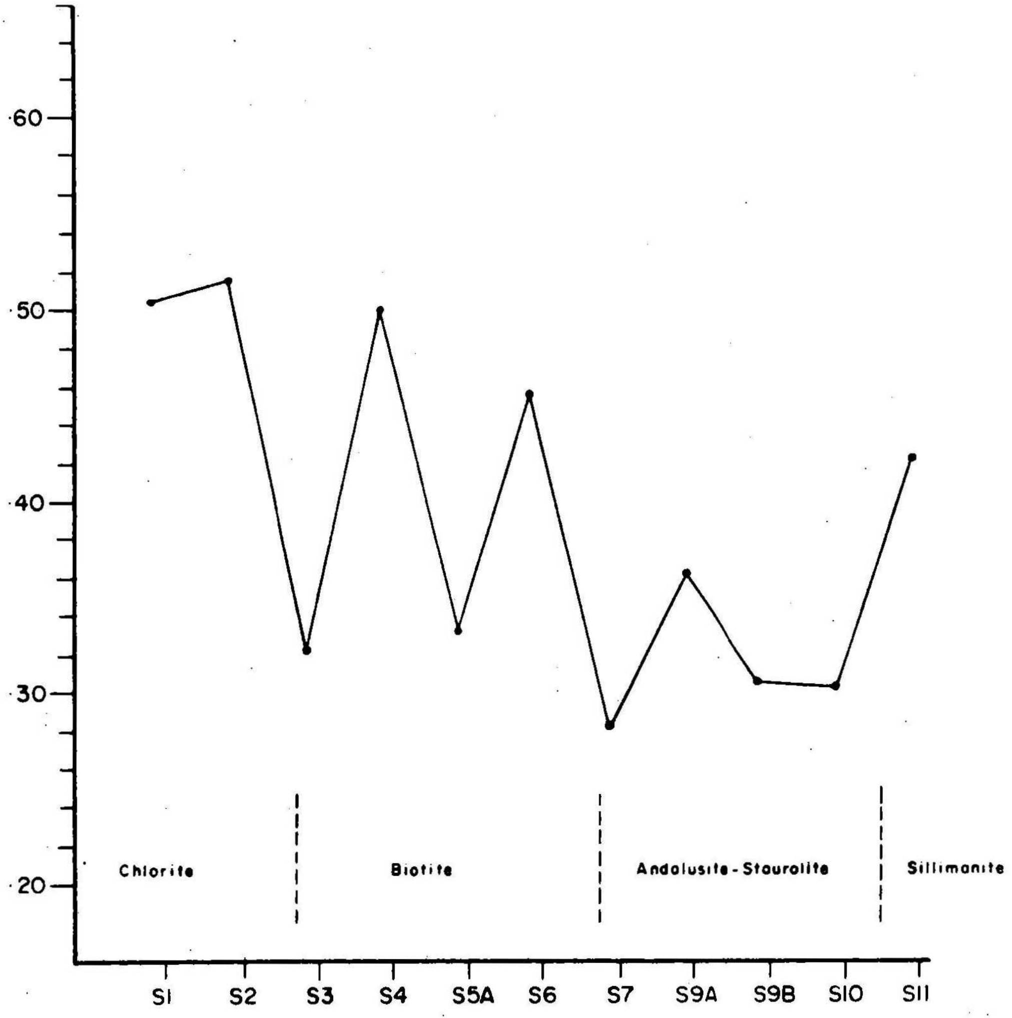


Fig. 10. Possible decrease in $Mg(Mg + Fe^{2+} + Fe^{3+})$ for whole rocks with increasing grade.

factors, but in general it is likely to occur in more calcium-rich rocks, and may also be favoured by high f_{O_2}. The large number of factors controlling the amount of Ti which enters the hornblende lattice can be appreciated by inspection of equations 18, 19 and 20. It is the variation of the equilibrium constant of these reactions with temperature that determines the amount of Ti in hornblende. It is well known that hornblende is able to accommodate larger amounts of Ti at high temperature than at low temperature. Fig. 11 shows the increase in Ti content of Soldiers Cap hornblendes with metamorphic grade. At locations S5 and S9, rocks containing sphene have more titaniferous hornblendes than do rocks of identical grade without sphene. This is almost certainly a consequence of reaction 20 occurring as well as 19.

Co-existing hornblende and cummingtonite

Cummingtonite is found in one sample from Soldiers Cap (specimen S10) and two from the Petermann Ranges (specimens P2A and P2B). Specimen S10 combines a low K content with a basic composition (Fig. 3) and would be expected to contain a (Mg, Fe)-rich phase such as cummingtonite. Samples P2A and P2B are metamorphosed troctolitic gabbros and would also be expected to contain cummingtonite and Si-poor hornblende in the amphibolite facies.

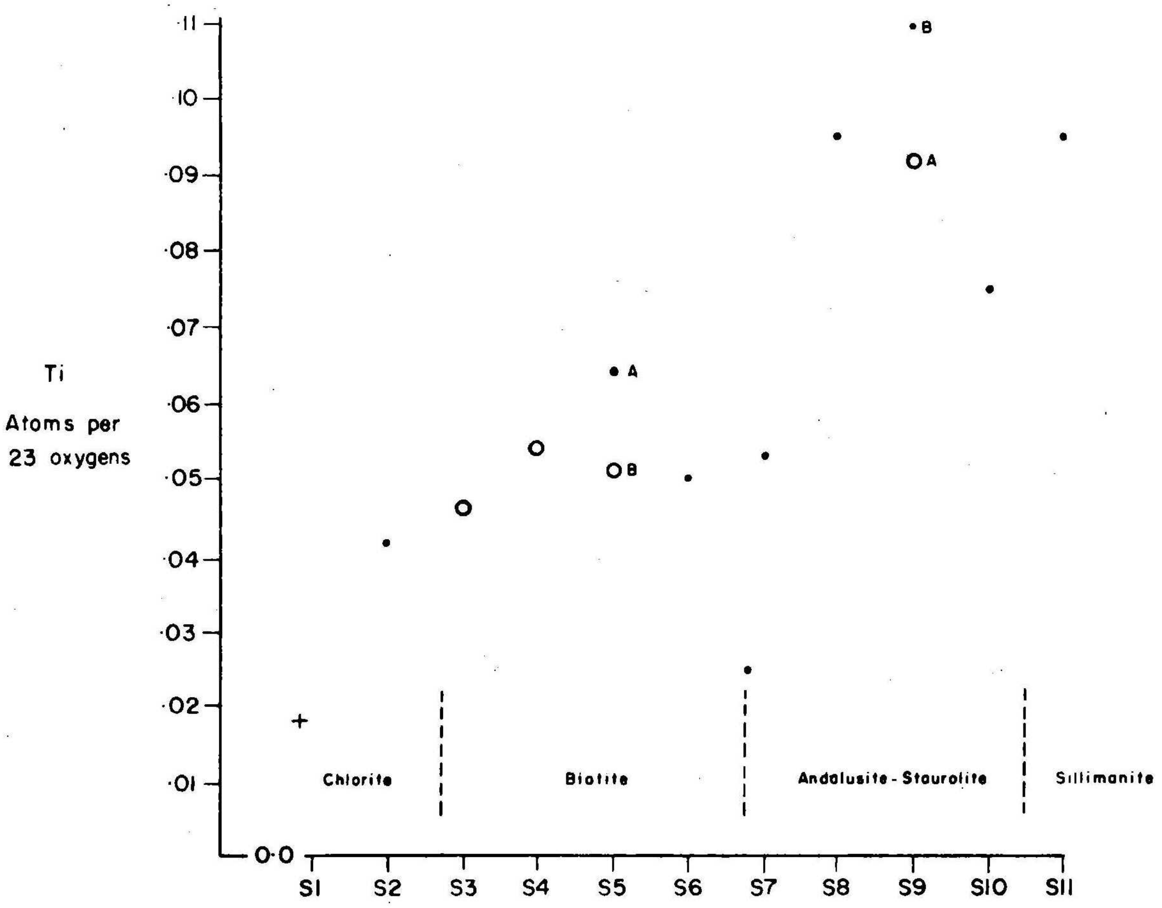
Binns (1965) noted that hornblende from rocks with large ratios of normative enstatite to normative diopside are more likely to have a large excess over 5 to cations generally found in the Y site. One might expect such an excess of Y-type cations in hornblende from cummingtonite amphibolites. However, the average number of Y-type cations in the hornblende in specimen 10 is only 5.03 when Fe^{3+} is taken into account. This figure rises to 5.26 if total Fe as Fe^{2+} is used in the calculation, and there is a possibility that the estimated Fe^{3+} content of the co-existing hornblende is excessively high.

In sample P2B there is further evidence that equilibrium with cummingtonite need not imply a larger excess of Y-type cations. There is a distinct zoning of hornblende in the reaction rims from its contact with plagioclase to its contact with cummingtonite. If anything, the hornblende close to cummingtonite has a smaller excess of Y-type cations than does the hornblende close to plagioclase (Fig. 12). In this case the high Al^{VI} content of hornblende close to plagioclase seems to have more affect on the excess of Y-type cations than saturation with cummingtonite component. It should be remembered that Fe^{3+} is not taken into account in the analyses from sample P2B and that a decrease in the amount of Fe^{3+} from the cummingtonite boundary to the plagioclase boundary would have a false effect, similar to that observed on the calculated Y cation excess. However, total Fe increases in that direction and it would therefore seem unlikely that Fe^{3+} would decrease. The colour of the hornblende remains pale blue-green throughout, suggesting that the Fe^{3+} content is low and fairly constant.

The distribution of $Mg/(Mg + Fe^{2+})$ between hornblende and cummingtonite is affected significantly by neglect of Fe^{3+} in the microprobe analyses and meaningful comparisons with other authors are difficult.

Plagioclase

The distribution of plagioclase compositions is shown in Fig. 13 together with the approximate position of the peristerite solvus found by Cooper (1971) in the Haast River greenschists from New Zealand. A large proportion of plagioclase analyses in this study fall within Cooper's solvus. The only specimen to contain plagioclase of two distinct compositions is specimen S1. The two types, $An_{1.5}\ Or_{0.2}$ and $An_{29}\ Or_{2.1}$, are close to the compositions expected on either side of the peristerite solvus. The high K content in the more calcic phase is notable and could be interpreted



M(Pt)117

Fig. 11. Increase in the maximum Ti content of Ca amphibole with increasing grade in Soldier's Cap rocks.
+ coexisting with magnetite and sphene
● coexisting with ilmenite and sphene
O coexisting with ilmenite without sphene

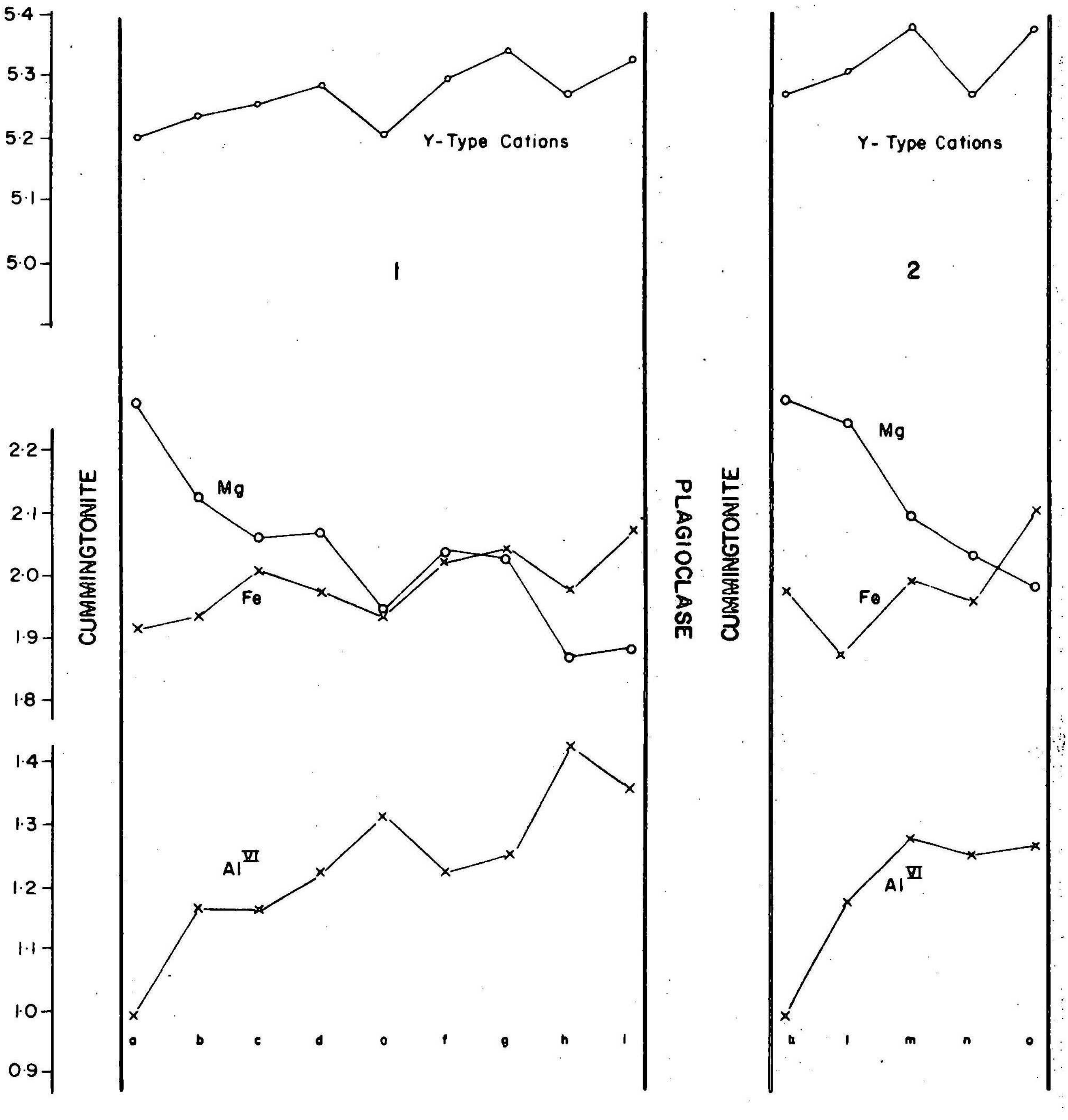


Fig. 12. P2B: Zoning of 2 hornblende rims from boundary with cummingtonite to boundary with plagioclase. Note that although Mg increases towards cummingtonite boundary, the total number of Y type cations appears to decrease slightly.

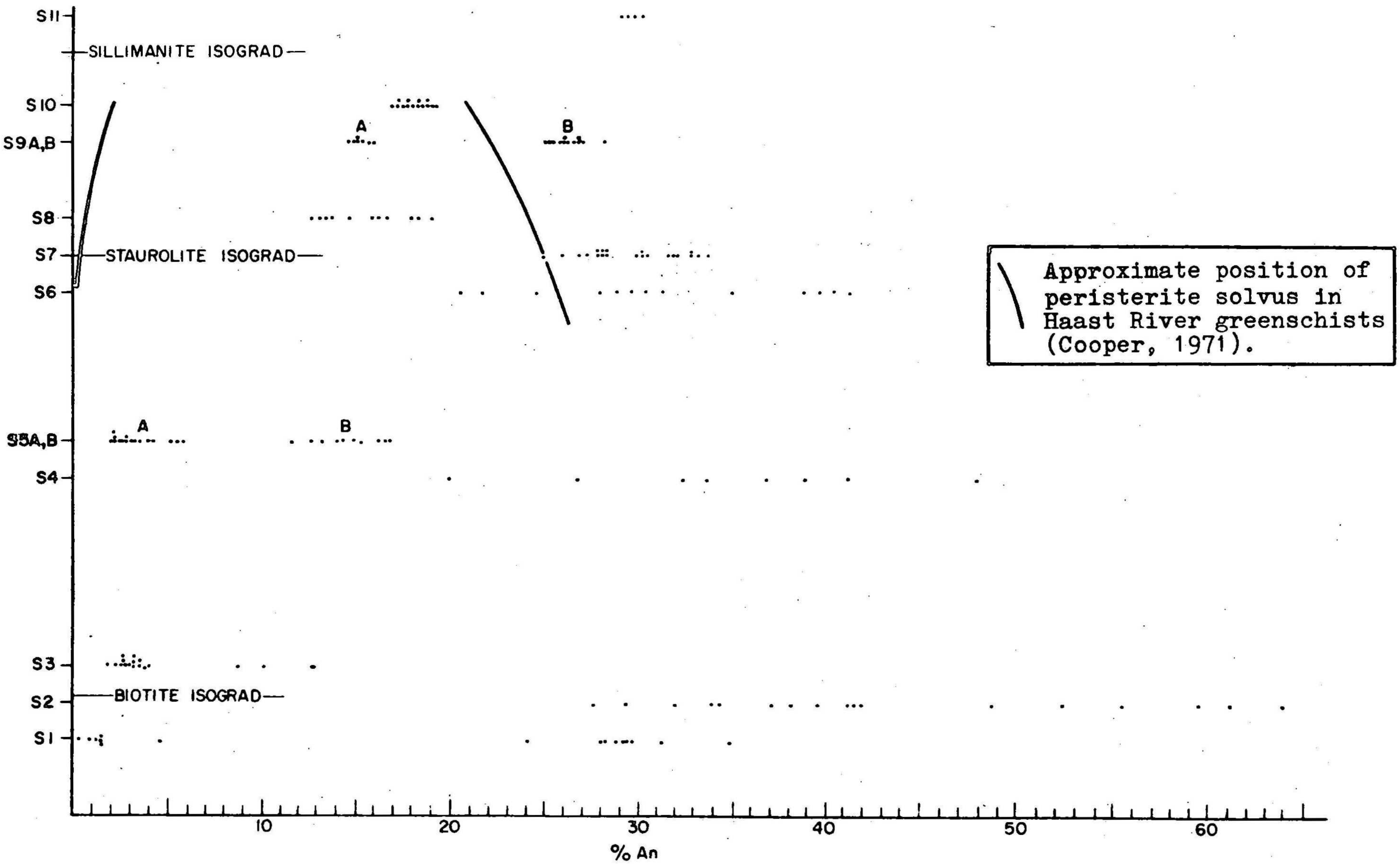


Fig. 13. Approximate order of increasing grade plotted against An content of plagioclase.

as indicating an igneous origin. Nevertheless, specimen S1 is the only low-temperature basic rock which has been thoroughly recrystallized and which does not contain plagioclase with any trace of relict igneous habit and twinning.

The plagioclase of the other low-grade amphibolites may be quite calcic and is generally normally zoned. The zoning appears to have been caused by reaction of the plagioclase closest to amphibole during the formation of hornblende. (Inspection of the equations of formation of hornblende from actinolite and plagioclase shows that more anorthite than albite is consumed.) It is probable that the most calcic centres in plagioclase grains in specimen S2 and S6 have survived unaltered from their igneous beginning, whereas compositions ranging down to more typical low-grade metamorphic values represent various stages of incomplete albitization. Whether a peristerite gap would appear under conditions so far from equilibrium is doubtful. Perhaps such plagioclases inherited a metastable disordered structure from the original igneous calcic plagioclase and formed out of equilibrium without a peristerite gap. The necessity of an ordered state for the formation of the two separate compositions is discussed by Brown (1962).

Although some authors have found a gap in plagioclase compositions, others have noted a continuous increase in An content with grades in the oligoclase region. Amongst them are Shido (1958) and Myashiro (1958) in their work on the Central Abukuma Plateau and Compton (1958) in California. However, James (1955) found a gap between An_{20} and An_{30} in rocks of a metamorphic terrain very similar to the Soldiers Cap district (andalusite-staurolite).

HORNBLENDE AS A PETROGENETIC INDICATOR

The following changes in hornblende composition are known to occur with increasing grade in the Soldiers Cap and Petermann Ranges areas:

(i) an increase in $(Al, Fe^{3+})^{VI}$ (Soldiers Cap only) - Fe^{3+} is estimated from the bulk composition,

(ii) an increase in Na and K in the A site,

(iii) a decrease in Si (accompanying (i) and (ii)),

(iv) an increase in Ti.

There are many exceptions to these general rules. Before the composition of hornblende and its co-existing minerals can be used as an accurate petrogenetic indicator, parameters must be found which depend very largely on temperature and are independent of bulk composition.

The amount of $(Al, Fe^{3+})^{VI}$ increases from very low values in the actinolites in specimens C1 and S1 to values which are largely determined by bulk composition in the hornblendes from the rest of the rocks of the Soldiers Cap area. A good estimate of $(Al, Fe^{3+})^{VI}$ in hornblende in specimens S2-S11 can be made on an ACF diagram (Fig. 3) by projecting a line joining An and the bulk composition onto the line joining actinolite and tschermakite. There is no way in which the amount of $(Al, Fe^{3+})^{VI}$ in hornblendes can be used as an indicator of metamorphic grade in such rocks.

The amount of Na in the A site in hornblende appears to depend on the following factors:

(a) The albite content of the co-existing plagioclase (Na^{X-XII} enters the hornblende lattice by reaction with the albite in plagioclase).

(b) Temperature.

(c) μ_{SiO_2}, which is variable in rocks without free quartz (Shido, 1958).

(d) The (Al, Fe^{3+}, Ti)^{VI} content of the hornblende. The proposed dependence of Na^{X-XII} on the (Al, Fe^{3+}, Ti)^{VI} content is a consequence of the existence of a solid solution gap in the edenite region. On the Hallimond diagram boundary slopes upwards from slightly edenitic actinolite to slightly edenitic pargasite. The forbidden region prevents amphiboles poor in (Al, Fe)^{VI} from accepting much Na^{X-XII} (e.g., the hornblende in specimen S5A), whereas others (e.g., the hornblende in specimen S5B) can accept larger amounts of Na^{X-XII} under identical P-T conditions. Because the An component of plagioclase is an important reactant in the introduction of (Al, Fe^{3+})^{VI} into hornblende, amphibolites with An-poor plagioclase tend to have hornblendes poor in both (Al, Fe^{3+})^{VI} and Na^{X-XII}. This appears to be the explanation for the apparent anomaly of the alkali-rich hornblende of specimen S5A co-existing with An_{15} and the less alkali-rich hornblende of specimen S5B co-existing with An_3.

Perchuk (1966) has constructed a diagram in which $\frac{Ca}{Ca+Na+K}$ in hornblende is plotted against $\frac{Ca}{Ca+Na+K}$ in plagioclase and in which the temperature of formation of a hornblende-plagioclase pair is uniquely fixed. He does not take into account the effect of (Al, Fe^{3+})^{VI} in hornblende on the amount of Na^{X-XII} which it can accept, and consequently there is substantial disagreement in the temperature at which the pair S5A and S5B and the pair S9A and S9B equilibrated (Fig. 14). It is therefore, concluded that bulk composition, through its effect on (Al, Fe^{3+})^{VI}, has an important control on the amount of Na in hornblende co-existing with plagioclase of a given composition.

It was hoped that the partitioning of K between hornblende and plagioclase would vary systematically enough to be a temperature indicator largely independent of bulk composition. The results in Fig. 15 show little more than a general preference of K for hornblende at high temperatures. Even amongst the higher grade rocks, where equilibrium between hornblende and plagioclase must have been very nearly achieved, there is no smooth relationship between the distribution co-efficient and temperature.

The Ti content of hornblende in equilibrium with ilmenite increases with temperature but still does not afford a reliable measure of temperature (Fig. 11). The equilibrium maintaining Ti in hornblende in rocks containing ilmenite differs from that in rocks containing ilmenite + sphene or sphene alone (a probable explanation for the differing Ti contents of the hornblendes from specimens S5A and S5B, and S9A and S9B). Inspection of equations 19 and 20 shows that both the An content of plagioclase and the $(Al, Fe^{3+})^{VI}$ content of the hornblende are likely to exert an influence on the Ti content of hornblende.

The influence of bulk composition on the Fe content of hornblende is obvious and although Fe in hornblende does tend to increase with grade because of reaction with opaque minerals, it is obviously of little or no use as an indicator.

It appears, therefore, that even when equilibrium has been very nearly attained, the influence of whole rock composition on equilibrium between hornblende and co-existing phases is great enough to frustrate attempts to obtain any reasonably accurate measure of temperature based on the major element composition of the co-existing phases in the Soldiers Cap and Petermann Ranges amphibolites.

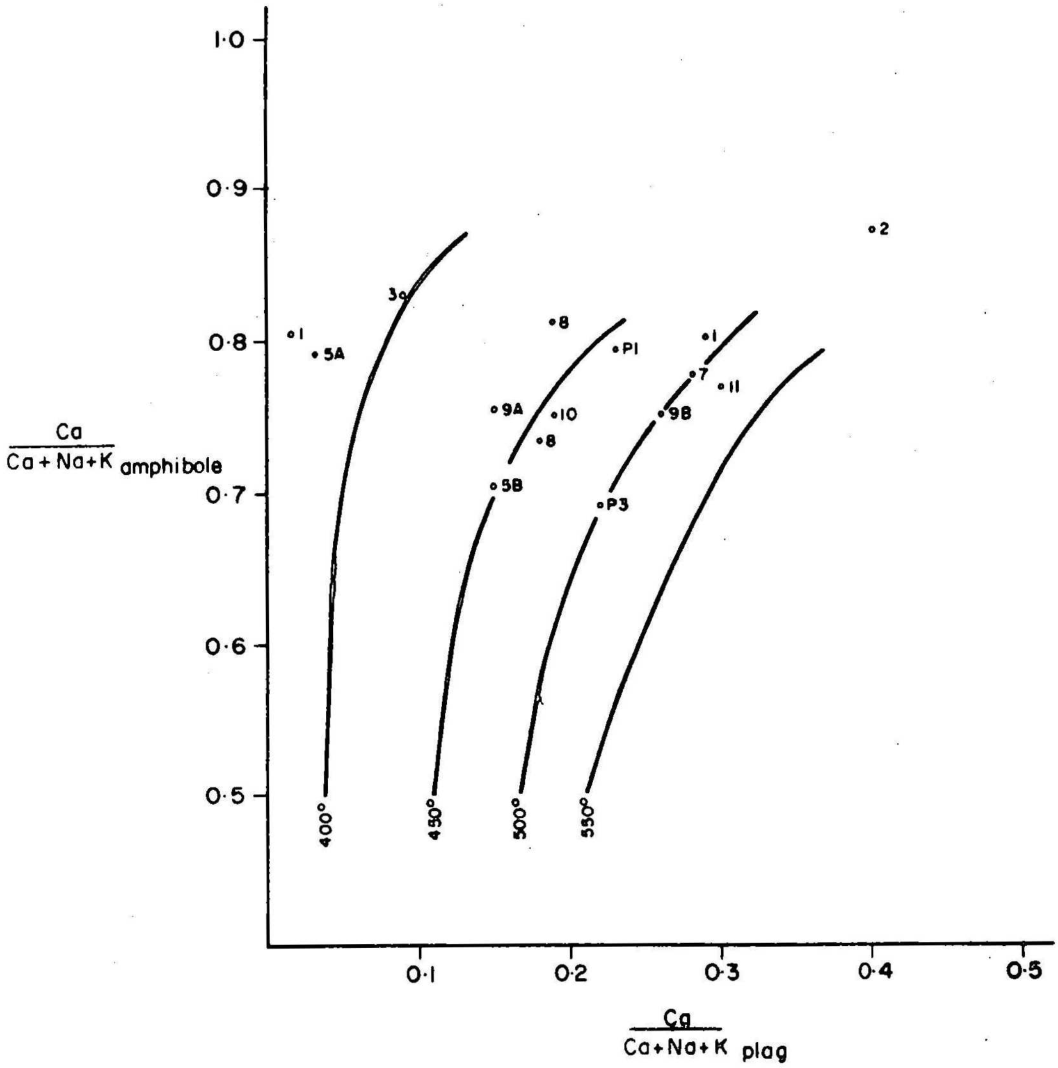


Fig. 14. Distribution of Ca/(Ca+Na+K) between plagioclase and Ca amphibole. Isotherms after Perchuk (1966). Note the poor temperature agreement between the pairs 5A, 5B and 9A, 9B. Amphibole-plagioclase pairs are from adjacent grains and less than 20 microns apart.

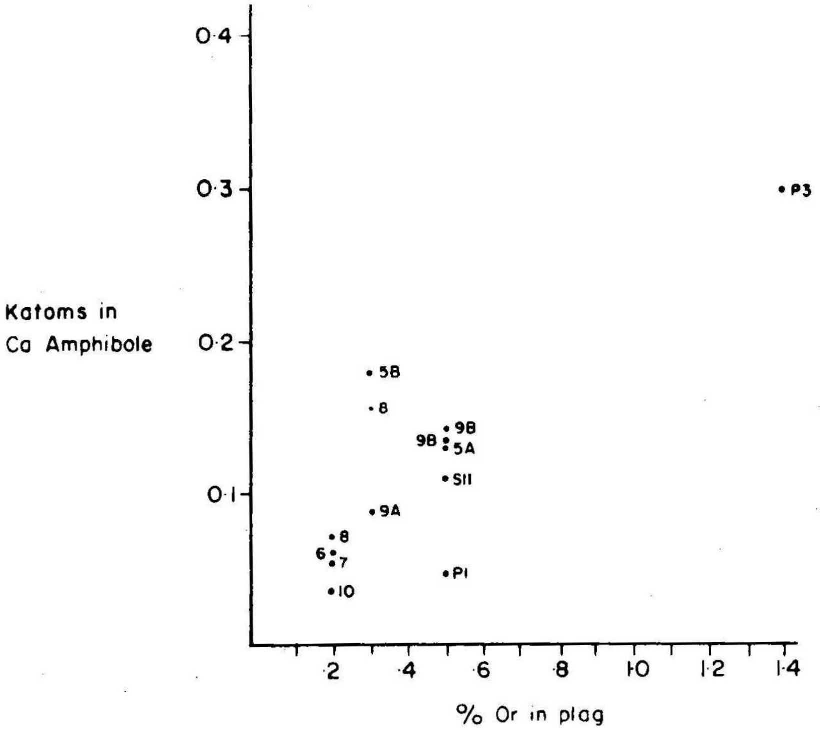


Fig.15. Distribution of K between plagioclase and Ca amphibole.

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