The mineralogy of amphiboles in amphibolites

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THE MINERALOGY OF AMPHIBOLES IN AMPHIBOLITES.

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by

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PREFACE AND ACKNOWLEDGEMENTS:

The work set out in this thesis is a development of the published Bulletin No. 24 of the Ghana Geological Survey. This bulletin is totally the work of the present writer and covers a hitherto completely unmapped area of Ghana. It is included in the thesis as Part 2.

Owing to a number of practical difficulties, the analyses of the writer's amphiboles were completed after the graphs in the thesis had been developed. Tests show, however, that the writer's data fits closely with the graphs derived from published work.

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CHAPTER 1

THE MINERALOGY OF AMPHIBOLES IN AMPHIBOLITES.

Introduction.

The amphiboles, which are amongst the most common minerals of igneous and metamorphic rocks, have an extremely complex chemical constitution. Their relations to the environment in which they were formed, and indeed, the factors affecting the correlation of their physical properties and chemical constitution are not fully understood. The complex nature of the amphibole molecule is more easily appreciated when it is remembered that all eight of the elements, which together make up 99% of the earth's crust, are important constituents of the common amphiboles. It will be clearly essential, therefore, to make a general examination of the chemical composition and physical properties of the amphiboles before analysing the mineralogy of the group in a particular environment.

The terminology of the amphibole group is extensive and varied. One of the first tasks of this investigation will be to set down the present, generally accepted, classification and nomenclature. Due attention will be paid to the derivation of the various type names and an examination of their suitability will be made.

The amphibole classification, so introduced, will be discussed in relation to the chemical constitution and X-ray structure of the individual members. It is naturally impossible to examine every amphibole by X-ray and chemical methods. Some classification on the basis of correlation of physical and chemical properties must be worked out. The work of Winchell, Ford, Sundius and others has been examined to see if such a classification and correlation is possible. On the basis of this earlier work and more recent work by the present writer, a somewhat revised classification is presented.

The general physical and chemical properties of the amphibole group having been studied and an alternative classification and nomenclature suggested, it is then possible to consider the natural environment of the amphiboles, with particular reference to those occurring in the amphibolites. 'Amphibolite' is a wide and varied term of reference and an attempt is made to define the term and suggest limitations for its use.

The geology of the Winneba District of Ghana, which was mapped, for the first time, by the present writer during a contract appointment with the Ghana Government, is described. The geology here represents a typical environment of amphiboles in amphibolites and associated rocks. The Winneba District is compared geologically with similar amphibolite provinces in the literature.

A selection of ten analysed amphiboles and their parent rocks from the Winneba District is compared with similar types from other sources. Their physical properties and chemical composition have been fitted into the revised amphibole notation. It is convenient at this point to indicate that in many cases the chemical analyses of amphiboles from the literature are incomplete. Where they are complete it is often irritating to find that their physical properties have not been determined. No classification would be reliable without the consideration of the complete mineralogical characteristics and for this reason, many of the analysed amphiboles from the literature are useless for comparison and classification purposes.

Finally having considered the mineralogy and environment of the amphiboles in amphibolites, it remains to compare their mineralogical characteristics with those of amphiboles from other metamorphic environments and from igneous rocks. The obvious method of comparison is a graphical one. The validity of several types of graphical comparisons from the literature have been considered in relation to the general amphibole mineralogy.

CHAPTER 2

THE CLASSIFICATION AND GENERAL PROPERTIES OF THE AMPHIBOLE GROUP.

The term 'amphibole' was first used by Hauy in 1801 and its original meaning was 'a doubt'. In this thesis 'amphibole' is used as a comprehensive term to cover any silicate mineral of the double chain (inosilicate) type which has in its basic structure, the grouping, Z_8O_{22} (OH,O,F)$_2$ where Z consists of Si with or without Al. It is appreciated that some types of amphiboles, for example, the oxy-hornblende types, have rather less than two of the (OH) group units and also that some types have rather more. The terminology, as used in its present sense, covers these peculiarities but it does not cover the so-called triclinic amphiboles, enigmatite and rhonite. Enigmatite has, however, been shown by Gossner and Mussnug (1929) to be quite different from the amphiboles and is therefore not considered here.

Natural amphiboles lend themselves to division into three principal types; the anthophyllite type, the low calciferous and calciferous amphiboles and the alkali amphiboles. The basaltic or oxy-hornblende may be considered, for these purposes, as a type of calciferous amphibole. Some solid solution may exist between these groups, particularly, between the alkali and calciferous types and there is a wide range of solid solution within each group. These extensive solid solution relationships amongst amphiboles have led to a great confusion on nomenclature. There have been, in the literature, numerous suggestions for the clarification of the amphibole nomenclature. Often, these suggestions, tend to increase the terminology rather than to simplify it. It is proposed to give, at this juncture, an outline of the chemical and physical properties of the group as a whole, an indication of the chemical composition and usual classification (Fig. 1) of each member of the group and a description of current terminology.

2a The Chemical Characteristics and General Formula of the Amphibole Group.

The present accepted classifications of the amphibole group depend wholly on the chemical composition of its members. The major divisions of the group are, chemically, relatively clearly defined, although, there is still confusion over the terminology and composition of some of the end members within the various constituent series of the group.

The difficulties of the earlier workers, in their attempts to classify the amphiboles are obvious. The chemical analyses at their disposal, for example, were largely incomplete and to some extent inaccurate. Water was not regarded, until 1890 (Penfield), as being part of the molecular structure of the amphiboles. Allen and Clement (1908) found that, in tremolite, a considerable amount of water could be driven off with only slight change in optical properties and that even in the powdered state tremolite was not completely dehydrated at temperatures under

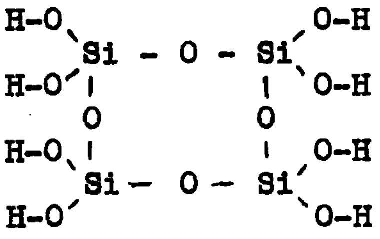
900°C. Allen and Clement regarded wafer and tremolite as being in solid solution with each other. They made the further point that amphiboles contained water as a characteristic component and also that they had several points of resemblance with zeolites. Tschermak (1871) regarded water as being present due to alteration processes and despite the work of Schaller (1916), who derived the correct formula for tremolite, the H_2O molecule was generally omitted from the amphibole formula until Warren (1929), by X-ray methods settled many, if not all, the problems of the times concerning the structure of tremolite.

Winchell (1924) argued that the pyroxenes and the amphiboles had so many characters in common, that it would seem reasonable to expect the same molecules to occur in each family. By way of examples, he stated that natural anthophyllite could vary from 70% $MgSiO_3$ to more than the same percentage $FeSiO_3$. Similarly Kupfferite and grunerite attained about 80% of $MgSiO_3$ and $FeSiO_3$ respectively. Pure artificial $MgSiO_3$ was believed to exist as (Winchell 1924) an amphibole in both the monoclinic and orthorhombic forms. All this evidence, it was claimed, showed that this molecule together with $FeSiO_3$ were constituent molecules of the amphiboles.

Prior to Winchell's (1924) paper, Penfield and Stanley, (1907) having attained reasonably reliable results for the chemical analyses of a series of amphiboles, showed for the first time that the water content was part of the amphibole molecule or molecules. Penfield and Stanley argued that the chemical composition of the amphibole could be explained by assuming that it was based on a very complex meta silicate molecule. They further argued that the presence in many amphiboles of considerable amounts of sesqui-oxides could be explained by their introduction into the meta-silicate molecule in the form of various basic radicals. In all cases the calcium oxide of the analyses, together with very small amounts of oxides of the alkalis available, formed closely 25% of the various radicals and bases. In other words they replaced one quarter of the hydrogen atoms of the amphibole acid.

Penfield and Stanley made three points in support of their interpretation of the amphibole structure. Firstly, in tremolite actinolite analyses the 1:1 ration between RO (where 'R' is Mg, Fe or Mn) and SiO_2 was very exact and indicated that the structure of the molecule was that of a meta-silicate and that small amounts of RO could not be introduced into the formula, without destroying this ratio. Secondly they indicated that the identity of the crystalline structure of the whole amphibole group pointed strongly to the assumption that the acid radical was the same throughout the group. Thirdly, they believed that the amphibole group had a basic ring structure and suggested, although they were not able to prove it, that it would be quite reasonable to speak of an amphibole ring in the same way as benzene rings of organic chemistry.

Penfield and Stanley (1908) were uncertain as to the number of silicon atoms in the ring structure of the amphibole acid. They suggested that a possible formula may be written thus:-



Later work of Warren (1929) showed that the structure of the amphibole group was, indeed, that of a ring or double chain type. Warren also demonstrated the position and type of the silicate component, and if this component $Si_8O_{22}(OH)$, could be regarded as the amphibole acid, then the interpretation of the structure of the amphiboles by Penfield and Stanley is not so misleading as might first appear.

Warren's work in 1929-30 and Warren and Modell (1930) derived the structure of tremolite, the other monoclinic amphiboles and anthophyllite, by X-ray analysis. It had been obvious for a long time that there was some form of very close relationship between the amphiboles and the pyroxene group. Winchell (1924) had already made considerable use of this similarity in his discussions concerning the structure of the amphiboles. The two groups of meta silicates are so closely related in optical properties, axial ratio and cleavage that it seems highly probable that there must be a close connection in the crystal structure of the typical magnesian pyroxene diopside and the typical magnesian amphibole tremolite. The structure of diopside had already been worked out by Warren and Bragg (1928), and using this work as a basis, the structure of tremolite was evolved.

It had been shown by Warren and Bragg (1928) that the tremolite structure is built up of silicon oxygen chains lying parallel to the 'c' crystallographic axis and closely related to the silicon oxygen chains which were found to exist in diopside. It was also shown that the size of the unit cell of tremolite was closely related to that of diopside.

Diopside	Tremolite
a = 9.71 Å	a = 9.78 Å
b = 8.89 Å	b = 17.8 Å
c = 5.24 Å	c = 5.26 Å
d = 105° 50'	d = 106° 02'

Each silicon atom in the tremolite structure is surrounded by four oxygen atoms, as in other silicates, but part of the oxygen atoms of each tetrahedral group are held in common with neighbouring groups (Fig. 2. From Warren 1929) The tetrahedral, thus linked together by shared oxygen atoms, form a set of double chains parallel to the 'c' axis of the crystal. The silicon-oxygen chains in tremolite represent two diopside chains side by side and linked by a further sharing of oxygen atoms. The peculiar relationship between the pyroxene and amphibole groups is therefore to be found in this arrangement of the two types of chains.

Daly's (1899) work with etch figures on tremolite showed that the mineral belonged to the monoclinic holohedral class. Tremolite has an axial angle $106^{o}02'$ and axial ratio 0.551 : 1 : 0.294. The three primitive translations of the unit cell were determined in the usual way by Warren from rotation photographs taken about the three principal axes. Warren calculated the following primitive translations from the layer line distances:

$a = 9.78\ A^{o}$

$b = 17.8\ A^{o}$

$c = 5.26\ A^{o}$

From the above measurements the axial ratio was calculated as 0.550 : 1 : 0.295 which can be seen to be in good agreement with the crystallographic axial ratios.

Warren and co-workers took rotation photographs about the 'c' axis of five of the monoclinic amphiboles, namely, tremolite, kupferrite, actinolite, hornblende and grunerite. All five of the photographs showed a remarkable similarity in both the positions and the intensities of the spots. It was concluded from this that the structures of the other four substances must therefore be essentially that of tremolite with appropriate substitution of cations. The grunerite photographs showed that a few spots differ in intensity from the corresponding tremolite ones. This was accounted for by replacing Ca and Mg by Fe to produce the grunerite structure.

The calculated structure factors for the two crystals were found to differ in exactly the same way as did the observed intensities.

The cell size having been determined it was now possible to calculate the number of molecules of tremolite per unit cell. For these purposes the density of tremolite was accepted as 3.00, a figure determined by Penfield and Stanley (1908) on a particularly pure sample of tremolite. From chemical analysis the formula was believed to be $Ca_2Mg_5Si_8O_{22}(OH)_2$. Thus the number of molecules per unit cell was determined from the cell size, the molecular weight and the density:

$$n = \frac{9.78 \times 17.8 \times 5.26 \times 10^{-24} \sin 73^\circ\ 58' \times 3.00 \times 6.06 \times 10^{23}}{812}$$

$$n = 2$$

There are accordingly two molecules of the above formula per unit cell.

In connection with the number of molecules per unit cell in the hornblendes, this is always quoted as 4 in the literature, (even in Winchell 1951). The source of this error is to be found in Structure Bericht 1928-32 Band II p. 537 where the amphibole molecule is taken to be $2MgSiO_3CaMg(SiO_3)_2$ which is smaller than that determined by Warren. Calculation on this basis thus gives a higher but incorrect number of molecules per unit cell.

From a complete set of 15 oscillation photographs about the 'b' axis indices were assigned to about 300 reflections and it was found that reflections occurred only for

$h + k + l = \text{even}$

The tremolite lattice was accordingly designated as body centred. It should be noted in this respect that the axes chosen in this case were the usual crystallographic axes.

Tremolite belongs to the monoclinic holohedral class and there are therefore only two possible space groups (C2/m) and (C2/c). The photographs showed that there were some 15 (h0l) reflections with both h and l odd. Warren concluded that the space group must therefore be (C2/m) and showed that the symmetry elements comprised:

1. Two-fold rotation axis parallel to 'b'.
2. Reflection planes perpendicular to 'b'.
3. Sets of symmetry centres.
4. There are eight asymmetric units in the general positions.

It was concluded that there were 78 atoms in all in the unit cell - 4Ca, 10Mg, 16Si and 48O. All that could be said directly from the space group was that the 4Ca and 8Mg atoms must have special positions on the symmetry elements and that the 2Mg atoms must lie at the intersection of a 2fold axis and a reflection plane.

The striking similarity between the measurements of the unit cell of tremolite and diopside has been shown earlier. There must therefore be a strong similarity in the two structures. Warren states that this is especially noticeable in their projection on the ac plane and although the 'b' axis in tremolite is just double the value for the same axis in diopside, equal volumes in the two crystals contain very nearly equal numbers of atoms.

A further very striking connection between the tremolite and diopside structures is found in the fact that a complete set of (h0l) reflections given by diopside was reproduced exactly in the corresponding reflections given by tremolite. In Table 1 the observed (h0l) reflections from tremolite are listed and the intensities compared with the corresponding diopside reflections. The table is taken from Warren (1929).

In diopside it will be noted (h0l) reflections appear when h and l are both even. In tremolite an additional set of weak reflections appear with both h and l odd.

The (h0l) reflections depend only on the projection of the structure on the ac plane and from their complete similarity it follows that the projection of the tremolite on such a plane must be practically identical to that of diopside. The arrangement of the atoms in the projection upon the ac plane was arrived at by the logical exclusion of all other possibilities (Warren and Bragg 1928) and it follows that the corresponding projection for tremolite must justifiably be regarded as proved. This makes it highly probable that the arrangements in space of the atoms in the two crystals must be essentially similar. Warren states that there must be in fact whole blocks of tremolite and diopside structures which are identical. Fig. 3 from Warren 1929 compares the projection on the ac face of the tremolite structure with the corresponding projection for diopside. The marked similarity between the two structures can be clearly seen. The main difference is that in diopside every two-fold axis has a calcium and magnesium atom situated upon it, whereas in tremolite only alternate axes contain calcium and magnesium, and the remaining axes magnesium alone. This fact explains the extra (h0l) feflections with both h and l odd which are found in tremolite and which have already been described.

It has been demonstrated earlier that the space group of tremolite is (C2/m) and it must therefore contain reflection planes. The very important difference between the structures of diopside and tremolite is that the space group for diopside is (C2/c) and only glide planes are present. To arrive at the tremolite structure, therefore, blocks of the diopside structure and reflection planes have to be incorporated within the tremolite unit cell.

The problem is to find a possible position for the reflection plane in the diopside cell without destroying the essential order of the grouping. Obviously it cannot cut the silicon-oxygen chains since these do not themselves possess reflection plane symmetry. To introduce such a plane would either change completely the scheme of the grouping, or would bring two silicon atoms too close together. Warren showed that this immediately excluded all but two possibilities - namely, either the reflection plane may pass through the oxygen atom O_2 or O_2', or O_2O_2' may touch the reflection plane. Warren pointed out that this latter possibility would lengthen the 'b' axis too much and must therefore be ruled out, and that there is therefore only one possible position for the reflection plane and it must pass through the oxygen atom O_2 or O_2' and must, in which case, have the position in Fig. 4 represented by the section R R. The large Ca atom being slightly moved in the new structure.

In the lower unit cell in Fig. 4, Warren has introduced the RR reflection plane and it is clear that that part of the cell above the plane remains unchanged and that the part below is the result of reflection on RR. The section R'R' passes very close to two calcium atoms and in the lower cell these have been shifted by very small amounts to positions A and B lying on the plane RR. The lower cell of Fig. 4 must therefore represent, essentially, the tremolite structure.

In the new structure the positions of 4Ca and 8Mg are already suggested and it remains only to locate the remaining 2Mg. It is apparent from the symmetry conditions that these must be at the intersection of a 2fold axis and a reflection plane. The positions A and B which correspond to the calcium positions in diopside, are just such positions. Position A however does not seem to be suitable for Mg since there are only two oxygen neighbours (O_2) and these oxygens are each bound to two silicons so that their valency requirements are satisfied. The position B on the other hand has six oxygen neighbours and is therefore quite similar to the positions of the other Mg atoms in the structure. Warren therefore located the two remaining Mg atoms in position B leaving position A vacant.

Fig. 4 demonstrates that there are whole blocks of tremolite and diopside structures which are identical. The upper part of the projection represents the diopside structure and the lower part the tremolite structure. It can easily be seen that the two overlap by an amount equal to the length of the 'b' axis in diopside.

Warren points out that there is another close connection between the two structures which seems particularly suggestive in view of the fact that pyroxene alters to amphibole. If the diopside structure in Fig. 4 is sheared along the plane R'R' so that the lower part is displaced by an amount a/2+c/2, a structure which is essentially tremolite is produced.

Prior to Warren's work in 1929 the accepted tremolite formula was $Ca\ Mg_3\ (SiO_3)_4$, which would require 12 atoms of Mg per unit cell rather than 10. It has been shown in the preceding paragraphs that there is definitely no other place in the structure where the additional 2Mg could be placed other than in position A of Fig. 4. This position has been shown to be highly improbable. The structure of tremolite is therefore quite incompatible with this early formula. Warren (1929) showed that in practice the chemical analyses agreed very well with the new formula. He showed that the two ideal compositions in the two cases were:-

$Ca\ Mg_3\ (SiO_3)_4$	$H_2\ Ca_2\ Mg_5\ (SiO_3)_8$
CaO = 13.5%	CaO = 13.8%
MgO = 28.8%	MgO = 24.7%
SiO_2= 57.7%	SiO_2= 59.2%
	H_2O = 2.2%

Five analyses of very pure tremolite from Allen and Clement (1908) showed an average ideal composition of:-

CaO = 13.9%
(MgFe) = 26.6%
($AlSiO_2$) = 58.8%
H_2O = 2.4%

This is seen to be in very good agreement with the new formula for tremolite $H_2Ca_2Mg_5\ (SiO_3)_8$.

The new formula shows that there are 48 oxygen atoms in the unit cell; however, only 44 are members of the Si_4O_{11} chains and bound to the silicon atoms. The remaining 4 oxygens, designated as O in Fig. 2 are not bound to silicon atoms but are bound to only three Mg atoms. Warren (1929) suggested that on the basis of Pauling's (1929) principle of electrostatic valence bonds the atom O must be singly charged and therefore an ion such as $(OH)^-$

rather than a doubly charged an ~~ion~~ anion such as O^{--}. From the tremolite composition there are 4 $(OH)^-$ ions per unit cell. It is interesting to note that each (OH) is equidistant from the three Mg atoms, situated approximately at the corners of an equilateral triangle. Warren suggests that the arrangement of Mg and (OH) is similar to the layer structure $Mg(OH)_2$ and there are threads of this grouping appearing through the tremolite molecule.

It has already been indicated that the rotation photographs of the five monoclinic amphiboles are essentially the same and it is also clear from the dimensions of the unit cells and their respective densities that all these substances must include water as part of the structure of the unit cell, as in tremolite. Tremolite must be regarded as typical of the structure of the monoclinic amphiboles and all others can be considered derived from it by suitable substitution of ions.

The possibility of isomorphous substitution of ions in a crystal structure depends primarily upon the sizes of the ions. It is also essential that the total positive and negative valences must balance. The elements commonly occurring in amphiboles are listed below in the order of increasing effective radius (from Goldschmidt).

Si^{++++}	0.39 Å	– Si
Al^{+++}	0.57	
Ti^{++++}	0.64	Mg
Fe^{+++}	0.67	
Mg^{++}	0.78	
Fe^{++}	0.83	
Mn^{++}	0.91	
Na^{+}	0.98	Ca
Ca^{++}	1.06	
K^{+}	1.33	
O^{--}	1.32	O, OH.
F^{-}	1.33	
$(\mathrm{OH})^{-}$	1.4-1.5	

It has been stated in many places in the literature that titanium can be included in the Z group. Positive proof of this has not so far been found by the writer. It is also seen in the table that Ti^{++++} is very little smaller than Fe^{+++}. If titanium can be included in the Z positionwhy not Fe^{+++}?

The neighbouring elements in the above table have been brought together into four sub-groups and designated by the ions in tremolite which they may replace. It will be noted athat aluminium falls between the Si group and the Mg group and could therefore be expected to replace either. This is, of course, actually the case in the hornblendes. The ion Mn also lies in the border region and canalso play a dual role. This fact which will be discussed later probably accounts for the relative importance of Mn in the cummingtonite group and its relative unimportance in the anthophyllite group.

The investigation has shown that there are 24(O,OH) groups per molecule. These are the largest ions and form the body work of the structure. Warren (1929) discussed the amphibole analyses in terms of the number of atoms of each kind in the amphibole structure. These were calculated on the basis of 24(O,OH,F). The number of atoms, so calculated, were then grouped in the manner of the tremolite structure. In this way a comparison of the various types of amphibole could be made. It is proposed to describe the Warren method of recalculation of the amphibole formula along with other methods later in the section.

Warren found that five hornblende analyses, when recalculated on the basis of 24(O,OH,F) and with the isomorphously replaceable atoms grouped together in the appropriate groups, fitted very well indeed with the simple formula already derived for tremolite, namely $H_2Ca_2Mg_5(SiO_3)_8$.

It was noted that the full amount of silicon, that is 8.00 atoms, was seldom present and that a fraction was always replaced by aluminium but that the sum of the two very closely makes up the ideal number of 8.00. It was found that the water content varied considerably from the ideal value of 2.00 but this was attributed to the difficulties of determining water and fluorine content and also the fact that excess water may also be present.

Warren found that the recalculated hornblende analyses showed a number of substitutions which had only been vaguely suggested in the tremolite analyses. For example, in the tremolite analyses there was always a small amount of replacement of silicon by aluminium but in the hornblende series as much as one quarter of the silicon could be replaced. It was also evident that although the greater part of the aluminium going into the amphibole molecule went as replacement for the silicon, some part of it was replacing atoms in the magnesium group. This was to be expected in view of the remarks concerning the table of ionic sizes when it was stated that the size of the aluminium ion was in the border line region between silicon and the magnesium group, and could therefore substitute for either.

It was also found that in all the hornblendes where approximately one quarter of the silicon was replaced by aluminium the (Na,Ca,K) group had risen from 2,00 to nearly 3.00. Thus it is clear that the position AA' which remains vacant in the tremolite structure, is in the hornblendes nearly filled by Na and/or K. The table below was produced by Warren to show that the amount of Na, Ca, K in excess of 2.00 atoms depends on the amount of aluminium replacing silicon.

Analysis	Al replacing Si	Na+Ca+K.
*8	0.73	0.26
+14	1.25	0.34
*9	1.46	0.77
*10	1.63	0.77
*11	2.02	0.87
*12	1.96	0.86
*13	1.53	0.89

* Analyses from Penfield and Stanley (1907).

\+ " " Heddle Doelter 2, 618, 43.

It can be shown that although the foregoing statement was true for the hornblendes chosen by Warren, it is far from being a general rule. Deer (1938) pointed out that more recent hornblende analyses from Wiseman (1934) and Nockolds (1935) did not agree with Warren's conclusion. In the case of the Glen Tilt amphiboles, Deer indicated that although they showed a slight tendency to increase the value of the (Ca, Na K) group from 2.0 to 3.0 with increasing replacement of silicon by aluminium there was no close relationship between these two factors. Deer stated that the amount of lime in the composition, not only of common hornblende but also of tremolite and actinolite, tended to be almost constant. Any increase therefore in the percentage of total alkalis is effective in increasing the value of the (Ca, Na, K) group, as was the case of those analyses chosen by Warren. The Glen Tilt hornblendes showed a re latively constant and moderately low amount of total alkalis, but a considerable range of alumina, with a consequently small variation in the (Ca, Na, K) group for a very much larger difference of silicon/aluminium replacement.

Deer stated that by plotting the amount of aluminium replacing silicon against the excess of the value of the (Ca, Na,K) group over 2.0, it was possible to demonstrate that the occupation of the vacant AA' positions of Warren in the amphibole structure by alkalis, was insufficient in itself to balance the negative valency excess caused by the replacement of silicon by aluminium. Deer did not reproduce his graph in his paper but a similar graph, Fig. 5, by the present author, with a selection of amphiboles from different sources shows precisely the same results as those obtained by Deer. It was suggested by Deer (1930) that the deficiency of positive ions could be compensated by the replacement of divalent magnesium by sesqui-oxides and tetravalent titanium. In an examination of the hornblende analyses, there are two complications to be dealt with. Firstly, there is a large amount of aluminium which mostly replaces silicon but which also partly replaces magnesium. Secondly, the position AA', which in the tremolite structure remains vacant, is partly occupied in the hornblendes by alkalis. In terms of these replaceable groups Warren (1929) derived the best simple formula, corresponding to the tremolite structure, for the hornblende analyses and presented it in the form:-

$$(OH,F)_2\ (Na\ Ca\ K\ Mn)_{2-3}\ (Mg,\ Fe\ Ti\ Mn\ Al)_5\ (Si\ Al)_8\ O_{22}$$

It has already been stated that one of the prime conditions for isomorphous substitution is that the total of positive and negative valences must balance. The excess alkali occupying the position AA' partly compensates the deficit in positive charge caused by the replacement of Si^{++++} by Al^{+++}. The remainder of the deficit is compensated by the replacement of Mg^{++} by Al^{+++}, Fe^{+++} and Ti^{++++}.

By way of summary it has been shown on the basis of the foregoing work by Warren that the structural formula of the amphibole group, as expressed in Machatschki's (1929) notation is:-

$$X_{2-3}\ Y_5\ Z_8\ O_{22}\ (OH,\ F,\ Cl)_2$$

In this formula the X group consists mainly of Ca, Na, K and Mn in part. The Y group is composed of Al, Ti, Cr, Fe", Mg, Li, Fe"' Zn and Mn in part. Finally the Z group is almost always composed of Si with or without Al, although occasionaly some Ti is included in the group.

The obviously large number of different ion sites in the amphibole structure together with the manner in which the basic structural units, the $Si_4\ O_{11}$ chains, are staggered permits extensive ionic substitution. The various combinations of substitutions together with their effects on the physical properties are to be discussed in later sections.

It should be noted that in the case of the anthophyllite series, the general formula given above required some modification. The X group disappears and the Y group is increased in value to 7. The formula thus reads:-

$$Y_7\ \ Z_8\ \ O_{22}\ \ (OH,\ F\ Cl)_2$$

Almost all analyses of amphiboles in the literature, where recalculated, have been on the basis of 24(O,OH,F) as originally described by Warren (1929). The method of calculation is simple. Each amphibole component with the exception of F is expressed in the analysis as a weight per cent of its oxide; by dividing this quantity by the molecular weight of the oxide the relative number of oxide molecules is obtained and recorded. This number is then multiplied in each case by the number of oxygens in the oxide molecule, giving the number of oxygen, (hydroxyl and fluorine) atoms contributed. These are again recorded and from their sum must be subtracted half the number of fluorine atoms, since for each two fluorines there has been an additional oxygen introduced into the analysis. The corrected sum is divided into 24.00 to put it on the basis of 24(O,OH,F). The values for the relative numbers of oxide molecules are then multiplied by this ratio and also by the number of metal atoms in the molecule, giving the number of metal atoms of each kind. The example given here was adapted from Warren (1929) and illustrates the calculation.

Calculation of Amphibole Analysis.

	1 % by wt.	2 No. of mol. % wt./mol. wt.	3 No. of (O,OH,F)	4 No. Metals, OH,F		
SiO_2	45.79	0.762	1.524 ~~0~~.524	6.47		8.00
					(1.53)	
Al_2O_3	11.37	.111	.333	1.88		
					.35	
TiO_2	1.20	.015	.030	.12		
Fe_2O_3	0.42	.003	.009	.05		
MgO	21.11	.524	.524	4.44		5.06
FeO	0.42	.006	.006	.05		
MnO	0.39	.006	.006	.05		
Na_2O	2.51	.040	.040	.67		
CaO	12.71	.226	.226	1.92		2.89
K_2O	1.69	.018	.018	.30		
H_2O	0.67	.037	.037	.63		1.87
F_2	2.76	.073	.146	1.24		
	101.14		2.899			
Less O for F--	1.16	F = ½x.146 =	-.073			
	99.88		2.826			

$$\frac{24}{2.826} = 8.49$$

The calculation described above assumes that there are 24 anions in the formula unit. It has also been shown that the structural unit of the amphiboles can have at most

2 (OH,F,Cl) atoms. In many published analyses however, the number of (OH) atoms is often seen to be in excess of 2 after recalculation on the basis of 24(O,OH,F,Cl). It has been suggested (Hutton 1940) that the extra (OH) units would occupy the 'A' or vacant positions. Nicholls and Zussman (1955) point out that this would imply an anion content of more than 24, which was the basis of the calculation in the first place. They further indicate that if the anion total does differ from 24, the calculation will yield incrrect results for the cation numbers. Any error in water determination thus causes a disproportionate error in recalculations of this sort.

The (OH) ion is a large one and possibly too big to be sited in the vacant AA' positions. It is possible to argue on this basis that the theoretical number of two for the (OH) ion is the correct one. Furthermore on the question of balancing charges a higher anion content than 24 is theoretically impossible. Francis (1955) in discussing gedrite with a high H_2O content suggested that some of the (OH) units take over vacant cation positions. This would appear unlikely in view of the differences in size between the cations and the (OH) ions, and also the proximity of negatively charged atoms. Francis also suggested that there may be vacancies in the tetrahedral lattice positions of the Si_4O_{11} chains, ($SiO_4 \rightleftharpoons (OH)_4$ replacement noted in the hydrogarnets and advocated by McConnell (1950) in several other silicates). The gedrite described by Francis (1955) can not be taken as an example of a hydrous anthophyllite because the mineral described was later found to be impure (Francis 1956) and it is clearly possible that the impurity was hydrous in view of the nature of the associated minerals.

Francis and Hey (1956), in an investigation of the unit cell contents of anthophyllite, showed that the total anions per unit cell O,OH,F,Cl could not be shown to depart significantly from 96 although the number of (OH,F,Cl) ions may be greater or less than 8. Francis and Hey demonstrated that in most of the so-called hydrous anthophyllites the excess water might well be absorbed water. In which case the use of the anion number of 24 for the calculation of the unit cell contents is probably not unreliable. Recalculation of the cell contents by the method of Francis and Hey shows that the (O,OH,F) group is rarely in excess of 96 (4x24). If it is then the excess (OH) is usually absorbed water. It seems clear that the number of (OH,F,Cl) ions can differ significantly from 2 provided the total number of anions remains 24. This would appear to be satisfactory on structural grounds. It eliminates the need to site the excess (OH) ions in the vacant AA' positions. The sizes of the (OH), F and O ions are not significantly different and the matter of the difference in charge can be adjusted. In support of this suggestion, an amphibole with high water content was examined by Nicholls and Zussman (1955) and it was shown that the AA' sites were in fact empty.

The work of Francis and Hey (1956) depended on having an alternative method for the calculation of the contents of the unit cell. Hey (1939, 1954) has discussed methods for calculating structural formulae without assumptions concerning the numbers of one type of ion. A method was evolved by which the numbers of different ions could be determined provided the volume and density were known with sufficient accuracy. The formula for the calculation is quoted below.

P = % oxide $R_m O_n$ of molecular weight M

$V \mathring{A}^3$ = cell volume = $(a \times b \times c \times \sin\beta)$

D = density in gm/cc.

R = number of R atoms in unit cell.

then

$$R = \frac{Pm}{100m} \times \frac{V.D.}{1.6603}$$

Hey (1954) also indicated the need, in calculations of this type, for correcting the density value for the presence of absorbed water. The correction is important because Hey points out that 1% H_2O- affects the density by as much as 2%. The density determinations in themselves present one of the greatest difficulties in the use of this method. It has been estimated (Rabbitt 1948) that density determinations have generally no greater accuracy than ±1%. Thus the method requires the use of a physical property which is difficult to measure exactly and the results must therefore be somewhat suspect if only on this account. One further point of interest is that very few of the published data on the amphiboles include measurements of cell size and whereas the majority of amphibole analyses from the literature have been or can be calculated on the basis of 24(O,OH,F), relatively few are available which have their cell contents calculated by the methods described above. On this basis alone, for comparison purposes, it would seem reasonable to adopt the system of calculation of cell contents, based on 24 (O,OH,F), in the present thesis.

2b The General Physical Characteristics of the Amphibole Group.

Morphologically the amphiboles are often finely fibrous or at least show a decided vertical elongation. In all of these fibrous amphiboles, the fibre direction is parallel to the direction of the silicon oxygen chains. The amphiboles have well developed prismatic cleavages at 124°. An explanation of the character of the cleavages in both the pyroxenes and the amphiboles is suggested by the two types of silicon oxygen chains. Warren (1929) points out that the binding between silicon and oxygen is probably the strongest in the crystal and furthermore this silicon-oxygen linkage exists only within the chains. It would thus be expected that the crystal would cleave around the silicon oxygen chains more readily than across them. Fig. 6 from Warren (1929) shows a projection on (001) of the silicon oxygen chains in diopside and tremolite and also a block of the two structures with the cross-sections of the chains outlined by properly shaped figures. A cleavage path, passing round these chains but not across them, is drawn in each figure. It is readily seen that the cleavage sections produced correspond to the cleavage of pyroxenes and amphiboles.

Twinning in the amphiboles is on (100). It is common and may be multiple. The specific gravity of the group ranges from 2.99 to 3.55 and the hardness from 4 to 6.5 in Moh's scale.

Amphiboles in thin section are usually coloured except in certain iron poor types. The colours range from green, brown, blue, blue-green to yellow. The pleochroism is usually distinct and may be intense in iron rich types. In the common varieties absorption is greatest parallel to the vibration direction Z and least parallel to the vibration direction X. The plane of the optic axes is parallel to (010) except in riebeckite, arfvedsonite and sometimes in crossite, when it is normal to (010).

In monoclinic amphiboles the Z ~~axis~~ vibration direction makes an angle with the vertical 'c' axis of 8° to 25° in the obtuse angle β with of course the exception of the alkaline types already specified. The various extinction angles in the monoclinic amphiboles are given in Winchell (1951). Despite the grouping given by Winchell in this diagram, the extinction angle alone has very doubtful value as a diagnostic property. This point is to be discussed in detail in a later section.

Throughout the group the axial angle is extremely variable but is found to decrease generally with increasing tenor of iron. The birefringence on the other hand, usually about 0.02 to 0.025 in the common types, tends to increase with increasing iron content.

It has already been mentioned that the amphibole group can be divided, crystallographically, into orthorhombic and monoclinic types. The anthophyllite series comprise the only known orthorhombic amphiboles all others being monoclinic. Cummingtonite which has a similar chemical composition to anthophyllite, was often in earlier work, grouped with the anthophyllite series. The work of Johansson (1930) showed that there were fundamental differences between the two series which could not be disregarded and this was confirmed by the present writer. The anthophyllite series is therefore classed separately in modern literature.

CHAPTER 3.

THE ORTHORHOMBIC AMPHIBOLES.

The Anthophyllite Series: General Formula $X_7 Z_8 O_{22} (OH)_2$

3a Terminology.

The term anthophyllite was derived from the Greek word meaning 'a clove'. The original material from Kongsberg, Norway was so named by Schumacher (1801) because of its clove brown colour. In later years a variety of new names was introduced, such as anthrogrammit (Breithaupt 1820), prismatic schiller spar (Jameson 1821) anthophyllite rayonne (Hauy 1822), antholite (Breithaupt 1820) and gedrite (Dufrenoy 1836).

Later the terminology was to increase even further, Breithaupt introduced two new synonyms, snarumit (1865) and thalackerite (see Des Cloiszeaux 1868). The term valleite was used by Cesaro (1895,1896), amosite by Hall (1918) and Peacock (1928), Picroamosite by Serdiuchenko (1936) and finally ferroanthophyllite by Shannon in 1921. Of these names, ferroanthophyllite assumed immediate importance. Shannon in his description of the ferroanthophyllite from Idaho included a note of the nomenclature of the anthophyllite series. He wrote as follows: 'Palmgren in 1917 found a similar amphibole in the eulysite of Sodermannland, Sweden.... Palmgren also emphasizes that this amphibole is distinct from anthophyllite, but, following Warren, whom he cites, he used the name eisen-anthophyllite, which becomes iron anthophyllite in English.' The present writer prefers the name ferroanthophyllite as the name for the iron end member of the anthophyllite group, despite the fact that the magnesium end member will then acquire the rather unwieldy name magnesio-anthophyllite. This nomenclature is in accord with that recently used by American mineralogists to designate the end members of isomorphous groups. The group name, anthophyllite, will then indicate intermediate mixtures of the two end members of the series, while gedrite will continue to indicate important admixture of the aluminous molecule. The possibility of the occurrence of lime and manganese members of this series is remotely indicated.

Rabbitt (1948) indicated that, in citing C. H. Warren, Palmgren had reference to Warren's description (1903) of a nearly pure iron anthophyllite from Rockport, Massachusetts. Material descfibed by Eckermann (1922) from Mansjo Mountain, Sweden was similar to that of Palmgren. Rabbitt states that all these high iron anthophyllites including that of Shannon are either hypersthene (Palmgren's and Eckermann's), grunerite (Warren's) or actinolite (Shannon's). He recommends that the term ferroanthophyllite and other synonyms denoting very high iron anthophyllites should be dropped.

The term antholite survived and was in use as late as 1946 (Winchell 3rd edition) where the antholite molecule is given as $H_2Na_2Ca\ (MgFe)_5Si_8O_{24}$. Gedrite was soon found to be an aluminium variety of anthophyllite and the term is currently used in this sense. The formula of the gedrite molecule is given by Winchell in two forms, $H_2MgFe_5Al_4Si_6O_{24}$

and ? $H_2Ca_2(MgFe)_3Al_4Si_6O_{22}$. The latter is clearly identical with the tschermakite molecule of the hornblende series.

The term amosite proposed by Hall (1918) for the ash-grey Transvaal asbestos which was identified by Peacock (1928) as a high iron orthorhombic amphibole but on account of the intermediate amounts of sesqui-oxides carried by the mineral, Peacock concluded that amosite could not properly be identified with anthophyllite, ferro-anthophyllite or gedrite. He suggested, that if there was justification for retaining the term crocidolite which differs from riebeckite only in its fibrous structure, then there were better grounds for retaining amosite as a mineral species. Strunz (1936) regarded amosite as monoclinic. Rabbitt (1948) stated definitely that the variety referred to at least two different monoclinic amphiboles.

X-ray analysis showed, that of the two Peacock samples in the Harvard collection one was clearly a member of the tremolite-actinolite series, whilst the other was almost identical to the cummingtonite of Johansson. Both samples of amosite were therefore monoclinic.

The picroamosite of Serdiuchenko (1936) contained 8.23% Fe_2O_3 and was so described because MgO almost completely replaced the FeO of amosite. On this basis Serdiuchenko proposed two branches of the isomorphous range in the anthophyllite series, thus:-

1. Ferro anthophyllite - amosite - gedrite.
2. Magnesioanthophyllite - picroamosite - ferrigedrite.

Winchell (1938) suggested that the whole series of the orthorhombic amphiboles should be called anthophyllite, the pure magnesian end member being called magnesio or mangam anthophyllite, the pure iron member ferro- or fer-anthophyllite, the high alumina types gedrite and the high soda variety antholite.

Rabbitt (1948) after an exhaustive and comprehensive examination of all the available 'anthophyllite' data decided that the term anthophyllite should be used for all members of the anthophyllite series and that the chemical suffixes, as proposed by Schaller (1930), should be used to indicate any known variations in the compositions. Aluminium rich members should be called aluminium anthophyllite and the term gedrite should be discarded. Members rich in ferrous iron should be called ferroan anthophyllite and those rich in ferric iron ferrian anthophyllite. This term would replace picroamosite which should be dropped. Ferro-anthophyllite and other synonyms denoting very high iron anthophyllites should be discarded.

The present writer is in general agreement with the terminology suggested by Rabbitt but can find no valid reason for the introduction of terms 'ferroan' and 'ferrian'. The equivalent terms 'ferrous' and 'ferric' are widely understood and in general use. The present writer feels that the Rabbitt terminology in this case is an unnecessary elaboration.

3b The Chemistry of the Anthophyllite Series.

Table 2 presented here consists of 46 chemical analyses which were collected by Rabbitt (1948). They form the most complete collected data on the anthophyllite series. They represent analyses from the period 1890-1946 and were selected on the following basis:-

1. The analysis must bear a date 1890 or later. Penfield's careful work on the anthophyllite of Franklin County, North Carolina, was published in 1890. Analytical results prior to 1890 are generally unreliable.

2. The summation of the analysis must be 100.00± 0.5%. This standard was set by Hillebrand and Washington on good grounds. Rabbitt points out that such a summation does not in itself assure the accuracy of the analysis.

3. In tha calculation of the formula on the basis 24(O,OH,F) and 8(Si,Al) the summation of (Ca,Na,K,Fe",Fe"&,Mn,Ti,Al) must be 7∓ 0.5. This figure will be called Y. If the value for Y is outside the limits indicated, then, there must be an error in the analysis of the material is impure, or both.

4. Although fulfilling the conditions above, the analysis must withstand a general inspection. For instance, some constituent such as SiO_2 or MgO might fall far outside the limits shown by the analyses as a group and no convincing evidence be presented to establish

the material as anthophyllite on optical or other grounds. In such a case the analysis would be listed as a doubtful variety.

A table of older analyses and those of doubtful varieties is given by Rabbitt but with the exception of those by Merrill, Table 3, is not reproduced here. Table 2 consists of part A, the chemical weights percent; part B the calculated formulae; and also columns for author, date, locality and analyst. Part A also contains a column showing the total weights per cent of $(FeO+Fe_2O_3+TiO_2+MnO)$. Column A $(MgO+CaO+Na_2O+K_2O)$, column B $(FeO+Fe_2O_3+TiO_2+MnO)$ and column C (Al_2O_3) show the weights per cent of these combinations of oxides, their combined total being 100%.

Part B of Table 2 shows the number of atoms in the formulae, claculated on the basis of 8 (Si,Al) and 24(O,OH,F) which is one quarter of the contents of the unit cell. It has been suggested by Berman (1937) and others, that a maximum of two silicon atoms can be replaced by aluminium. The present writer has found a number of examples in the literature where the total silica content is less than 6.0 but is unable to decide whether this was due to experimental error or not. (See Winchell and Hallimond lists Table 10, 9). The suggestion of Berman is, however, generally accepted. Where such a replacement of silica occurs an adjustment of valence must take place by the replacement of Mg or Fe" by ferric iron or other means. If such a replacement by Al occurred and if the anthophyllite series were a completely isomorphous one from the magnesium to the iron end, then the 'end members' with their weights per cent of constituent oxides would be:

1. $Mg_7\ Si_8\ O_{22}\ (OH)_2$
$MgO = 36.99\%$
$SiO_2 = 61.70\%$
$H_2O = 2.31\%$

2. $Fe_7\ Si_8\ O_{22}\ (OH)_2$
$FeO = 50.25\%$
$SiO_2 = 47.96\%$
$H_2O = 1.79\%$

3. $Mg_5\ Al_2\ Si_6\ Al_2\ O_{22}\ (OH)_2$
$Al_2\ O_3 = 26.08\%$
$MgO = 25.58\%$
$SiO_2 = 46.04\%$
$H_2O = 2.30\%$

$Fe_5\ Al_2\ Si_6\ O_{22}\ (OH)_2$
$Al_2O_3 = 21.66\%$
$FeO = 38.17\%$
$SiO_2 = 38.25\%$
$H_2O = 1.92\%$

and the possible range in the oxides would be :-

SiO_2	38.25 - 61.70%
H_2O	1.79 - 2.32%
FeO	up to 50.25%
MgO	up to 35.99%
Al_2O_3	up to 25.58%

Rabbitt points out that this is based on ideal considerations and that in the natural materials small amounts of Ca, Na, K, Ti and Mn are nearly always present in the crystal structure. It would be expected that Na and K would be less common and Ca, Ti and Mn more common in replacing Mg and Fe. The table of analyses shows this to be true.

A detailed examination of Table 2 was made. The following is a somewhat abbreviated discussion of the variation of the constituent oxides as given by Rabbitt.

SiO_2 - The table is arranged in order of increasing silica content and it is easy to see that there are no significant gaps in the silica range from 42.08% to 60.13% It will be observed that this nearly covers the theoretical limits of 38.25 - 61.70% given in the foregoing for the silica range in anthophyllites. Naturally, with increasing iron and aluminium, silica decreases; the greatest decrease coinciding with the increase in alumina. Analysis No. 4 represents the theoretical maximum replacement of silicon by aluminium. Nos. 44 and 46 show almost or no replacement of silicon by aluminium and are typical aluminium free anthphyllites. This point is illustrated in Fig. 7.

Rabbitt notes that in the aluminium-poor magnesium-rich range, the total of Al plus SiO_2 may sometimes be less than 8.00. Number 25 is the worst where the total is 7.65.

TiO_2 - Titania is present in small amounts in many, if not all, anthophyllites and particularly in the high-aluminium high-iron ones. Where alumina is about 10% or more, TiO_2 ranges from 0.41% to 1.11%. As the alumina decreases the TiO_2 falls off sharply (Fig. 8) to range from traces to 0.06%. Titanium thus seem to go with aluminium, iron or both.

CaO, Na_2O and K_2O - Calcium ranges by analysis up to 3.45%. There is some possibility that this represents impurity. The usual amount is about 0.5% and this seems to be definitely in the crystal structure. Soda, where determined, is present in amounts up to 1.34% with the average being about 0.5%. Rabbitt concluded that there was no doubt that some soda entered the crystal structure.

Potassium is clearly only present in negligible amounts or is completely absent and where more than 0.5% impurity should be suspected. Potassium on account of its large ionic radius as compared with magnesium and iron would not be expected to enter the anthophyllite structure to any large extent.

Al_2O_3 - Alumina, Rabbitt concluded, is more important in the anthophyllite series than has been realised. The series was regarded by Winchell (1931) as having an extremely simple composition with the absence of Ca, Na and Al atoms. Winchell (1938) continued to produce diagr ams correlating the chemistry and physical properties of the anthophyllite series without reference to the alumina content. Sundius (1933) does not stress the importance of aluminium although he does plot the Ca-poor amphiboles on a three component diagram with one component designated Fe_2O_3 plus Al_2O_3. Tilley (1939) used a similar diagram in which Al_2O_3 was one of the components. Of the 46 analyses given in table 2, 14 show more than 10% Al_2O_3 and 20 show more than 5%. The amount ranges up to 23.79% in analysis number 4.

The substitution of Al atoms for Si atoms and the accompanying substitution of Al (and Fe"') for Mg and Fe" is reflected in the formulae. The ratio of Al in the first case to Al plus Fe"' in the second should be, but rarely equals, one. Analysis number 4 which shows the maximum replacement, has a ratio of 1 but others, 6,7,11, 12,17,18, diverge widely from this.

In general high alumina means high iron but there are many exceptions. The peak of the alumina content seems to come about midway in the series, with equal quantities of iron and magnesia.

FeO and Fe_2O_3 - Ferrous iron ranges up to 26.53%. The series is in fact not complete to the magnesium end because numbers 41 and 43, which contain practically no FeO, have 2.53% and 2.77% MnO plus 0.25% and 0.29% Fe_2O_3 respectively. These members of the series, from Edwards, New York, are the purest anthophyllites (magnesium) known.

A pure iron end member of the series should contain 50.25% FeO and one with the maximum amount of alumina should contain 38.17% FeO (with 21.66% Al_2O_3). Number 2 shows the highest iron (FeO) content with 26.53% and FeO + Fe_2O_3+MnO equals 30.29% but with only 10.88% Al_2O_3. It is apparent therefore that the series is one of limited miscibility.

Ferric iron is present in limited amount in many anthophyllites. Rabbitt points out that it is doubtful if all the Fe_2O_3 reported in a chemical analysis is a true reflection of the original amount. The ease with which FeO is oxidised in the preparation of the sample makes any figure representing Fe_2O_3 subject to suspicion. For this reason, such figures as 0.20% (No.4) and 0.33% (No.12) are not important. However, amounts such as 7.03% (No.21) and 8.25% (No.25) must be accepted as representing the presence of Fe''' in the structure. It might be expected that high Fe_2O_3 would be accompanied by high Al_2O_3 but an inspection of Table 2 shows that this is not always the case. Ferric iron seems to follow ferrous iron as much as aluminium, a condition which seems to indicate that some oxidation is taking place.

MnO - Manganese is not important in the anthophyllite series; only four analyses 11,18,41 and 43 show more than 1.00%, MnO, the highest being about 2.77%. The rest average 0.25%. Some high Mn anthophyllites with up to 16.1% MnO have been described, but Rabbitt has shown by x-ray analysis that these varieties are in fact cummingtonites.

MgO - Magnesia ranges from 11.48% (No.2) to 31.53% (No.40). In the formulae, No. 40 shows the highest Mg content (6.38) but Y equals 7.20 atoms and Fe" 0.63. Number 41 on the other hand, has an Mg content of 6.13 and Mg+Ca+Na equals 6.67 where Y is 7.00. There is no Fe" and Fe'''+ Mn equals 0.33. This anthophyllite has a Ca+Mg+Na/Fe'''+Mn ratio of 6.67/0.33 and is therefore fairly close to an end member.

F, O, OH. No amphibole analysis is complete without a fluorine determination. In the complete list of anthophyllites in Table 2, there are only twelve complete with F determinations. These include the seven Montana specimens. Six of these latter show no fluorine but No. 1 shows 0.31% which seems to be about average for those containing this element.

Up to the year 1929-30 it was generally believed that anthophyllite was anhydrous. It has been shown that this was generally also the case with the other amphiboles. The findings of Francis and Hey (1956) have already been described in connection with the discussion of the validity of 24(O,OH,F) as a basis for the calculation of cell contents of amphiboles in general and anthophyllites in particular. It can be seen in Table 2 that analyses Nos. 38 and 39 have 3.76% and 4.95% H_2O respectively. This high percentage clearly gives more than 8(OH) units per molecule. Francis and Hey suggest that much of this water may in fact be absorbed. The calculation of the cell contents (Hey 1954) by the method descfibed by Hey (1939,1954) shows that they contain less than the allowable number of 96 (O,OH,F) units per molecule and are therefore not unusual.

The hydrous gedrite of Francis (1955) is impure and its nature is therefore definitely uncertain. In view of the mode of its occurrence the impurities are almost certainly hydrous. Francis and Hey (1956), however, suggest that an anthophyllite from Mainland, Shetland is probably hydrous. The calculation of the cell contents by Francis and Hey shows that (O,OH,F) = 99 or 3 units greater than the normal allowance. This mineral was excluded from

Rabbitt's table on the grounds of the early date (1890) and the high summation (100.68) of the analysis. Clearly before this mineral can be accepted a re-investigation is required.

Table 3 shows ten typical anthophyllite asbestos analyses by Merrill (1895). They have been grouped in this way to show clearly the composition of such asbestos. Most are not complete analyses, although they are complete enough to show that they are not commonly high in soda, although it is often said that amphibole asbestos is characterized by high soda content (Winchell third edition 1946, Elements of Optical Mineralogy.) Generally Merrill's specimens are low in iron and aluminium. This may be a reflection of their environment. All amphibole asbestos is not low in iron as one of the amosites of Peacock has 39.94% $FeO+Fe_2O_3$.

Spectrographic analysis.

Apart from Rabbitt's table of 10 spectrographically analysed anthophyllites, no further spectrographic data was available from the literature. The spectrographic analysis of anthophyllite-gedrite given by G.H. Francis (1955) proved to be an impure material (see Francis and Hey 1956). Rabbitt's table, is reproduced here, Table 4. Of the 35 metals determined, only 13 occurred in significant quantities, that is in amounts greater than 0.001%. Rabbitt concluded that there did not seem to be any definite variations of the minor metals with the major constituents. There did seem to be, however, a greater concentration of nickel and copper in the high magnesium anthophyllites (Nos. 29,53,59) and a lower concentration of lithium than in the others.

3c Physical Properties of the Anthophyllite Series.

1. Optical Properties.

The optical data for some of the analyses given in Table 2 is shown in Table 5. For convenience, specific gravity data is also included in this table. It will be noted that in many cases the optical data is most incomplete. The optical limits of the series in so far as the limited data available allows are given below:-

ND	F-C (Dispersion)
Np 1.598-1.674	0.017-0.029
Nm 1.605)-1.685	0.013-0.027
Ng 1.615 -1.697	0.013-0.022

Nz - Np 0.013 to 0.025

2V ranges from $(-)57^{\circ}$ to $(+)\ 59^{\circ}$

Dispersion of the indices is a property which appears to have been measured on very few anthophyllites. Data is available for seven of Rabbitt's Montana anthophyllites and on asbestiform material (Nos. 38 and 39) from Paakila, Finalnd by Rimann (1936). Rabbitt was unable to correlate the dispersion of the refractive index with the chemical composition. He did note, however, that the dispersion in all varieties was greater for Np than for Ng. The present writer, using statistical methods for the correlation of physical properties with chemical composition, was also unable to produce any satisfactory results using dispersion data.

The birefringence Ng-Np for the F, D and C lines is given for the seven Montana anthophyllites. Rabbitt noted, in general, that the birefringence increases with increasing magnesium. It is noteworthy that Hey (1956) uses the birefringence values Ng-Np and Np-Nm in his multiple regression equations for the estimation of Si, Al Mg and Fe". Hey points out that owing to the restricted range of the birefringences the results will always be rather inaccurate. With respect to Hey's equation for aluminium it is interesting to note that Rabbitt was unable to find any simple relationship between this metal and the birefringence.

Table 6 shows that with reference to the D line all the Montana anthophyllites with the exception of No. 29 are optically positive and have axial angles greater than 80°. All change sign for the F line and all decrease in 2V for the C line (except No. 1) but retain the same sign as that for the D line.

With reference to the optic sign, Winchell (1933) states that the optical sign is positive in mag-anthophyllite (magnesium anthophyllite) and antholite but is negative in gedrite and perhaps also in fer anthophyllite (ferrous anthophyllite). Dana (1932) also makes the point that gedrite is optically negative. If these suggestions by Dana and Winchell were true, then it would be a relatively easy matter to identify aluminium anthophyllites. Rabbitt points out however that many if not most such members of the series are, in fact, positive. Examples of these are numbers 2,3,6 and 10 and the Montana specimen numbers 1,8,9 and 14. Some aluminium members are negative, such as numbers 4, 12 and 20. The high magnesium members are generally negative but number 30 is positive.

2V is usually large in anthophyllites and an average figure would be above 80°. The lowest recorded are 59.3° in No. 22 by Sundius (1933) from Norway and 57° in No. 20 by Rama Rao (1937).

The optic orientation in all members of the anthophyllite series so far described is Z=c and Y=b. From the foregoing discussion on optic sign it is clear that in most aluminium members Ng is the obtuse ~~acute~~ bisectrix whilst in the high magnesium members Ng is usually the acute bisectrix.

In general the aluminium and feroan members of the anthophyllite series show pleochroism. The colours exhibited are usually shades of tan which have been named by different authors as clove, clove brown, buff, cream, yellow, straw yellow, brown, brownish yellow and so on. Rabbitt attempted to classify or standardise the colours on the basis of Ridgway's (1912) scheme. The method is based on colours in reflected light and is not wholly satisfactory. The possibility of the use of pleochroic colours as a means of classification of the amphiboles, has been indirectly suggested by many writers. So far it has proved impossible to link the axial colours with the composition. It is thought by the present writer to be extremely difficult to distinguish fibrous monoclinic amphiboles showing straight extinction from orthorhombic types. X-ray means probably the only possible method. There seems to be no satisfactory optical method for distinguishing between aluminium containing anthophyllites and the aluminium poor varieties. The writer suggests the use of Hey's statistical equations which are discussed fully in Chapter 8.

2. Density.

The densities of the seven Montana anthophyllites and also those from the literature are included in Table 2. Density provides no special features in the anthophyllite series and the density range, is well inside the range of densities for the amphiboles in general.

3d The Crystallography of the Anthophyllite Series.

1. Morphological Crystallography.

No terminated crystals of anthophyllite have been found. The crystals in any case are rare and usually fibrous. The sometimes appear as rosettes. Dana (1892) gives the axial ratio a:b 0.51375 :1. A later measurement by Cesaro (1896) on anthphyllite from Edwards, St. Lawrence County, New York, gave a :b:c=0.515:1:0.285 from the forms (100), (110), (920) and the cleavages (100), (010) and (021).

The cleavage (Winchell 1951) is perfect (110). Dana (1932) states that the cleavage on (010) is somewhat imperfect but that a further cleavage (100) is sometimes distinct.

The most useful diagnostic crystallographic measurement in the anthophyllite series is that of the cleavage angle. For orthorhombic amphiboles it is always near 54°30' and for the monoclinic amphiboles except those in the cummingtonite series, it is near 55°30'. Cummingtonite has a cleavage angle close to anthophyllite and is always less than 55°. Thus it is possible to distinguish between the calciferous amphiboles and the cummingtonite anthophyllite types.

The cleavage angles of the various anthophyllite types recorded in the literature are as follows. The numbers refer to the analyses given in Table 2.

Analysis Number	Cleavage Angle
1	54°10'
5	54° 41
8	54° 35'
9	54° 25'
12	56° 00 ?
14	54 21
15	54 41
16	55 10
17	54 40
26	54 21
29	54 06
30	54 37

Rabbitt (1946) was unable to find any correlation between the slight variation in the cleavage angle and chemical composition. It can be seen that while there are only twelve analysed anthophyllites with cleavage angle measurements, there are however, many such measurements on unanalysed fragments. The present writer constructed many correlation diagrams, composition plotted against cleavage angle size, but was unable to find any relationship between the variation in size of the cleavage angle and the chemical composition.

3d 2. X-ray Crystallography.

Johansson (1930) determined the cell constants for anthophyllite, actinolite and cummingtonite. The composition of the anthophyllite material which was from Falun in Norway, is found in Table 2 Number 26.

Crystallographic measurements on the Falun anthophyllite gave a:b=1.0267:1. For the cell constants he obtained the following data.

a_o= 18.52 A^o
b_o= 18.037 A^o
c_o= 5.270 A^o
which is clearly

1.02680 :1: 0.2922

Johansson (1930 pages 38/39) used the formula $MgSiO_3$ and suggested that there were 32 molecules per unit cell and that the space group for anthophyllites was Pnma. Johansson's powder photographs, taken with iron radiation, showed 47 indexed lines. The powder data for this mineral is reproduced in a later chapter.

Fibrous anthophyllites from Hrubschitz, Moravia (Jensen 1933) showed c:5.28A^{o}. Using the structural data of Warren and Modell (1930) Jensen also found that a_o=18.5A^{o}, b_o=17.9A^{o}.

Warren and Modell (1930), in a classic study on anthphyllite from Edwards, New York (Number 41 in Table 2), found by Weissenberg and oscillation methods that the cell constants, for their anthophyllite, were:-

$$a_o = 18.5A^{o}$$
$$b_o = 17.9A^{o}$$
$$c_o = 5.27A^{o}$$

The corresponding axial ratios were then found to be a: b: c 1.035 : 1 : 0.294.

Warren and Modell showed that the formula $H_2Mg_7(SiO_3)_8$ was the correct one, and that there were only four molecules to the unit cell. The space group was the same as that determined by Johansson (1930), namely Pnma. There were also 156 atoms in the unit cell.

The table below gives the cell dimensions for a number of anthophyllites from the literature. The reference numbers indicated refer to the numbers in Table 2.

Number	a_o	b_o	c_o
1	18.55	17.92	5.30
8	18.54	17.82	5.28
9	18.53	17.80	5.28
14	18.50	17.66	5.31
17	18.55	17.95	5.31
29	18.54	17.90	5.28
30	18.58	17.98	5.28
10	18.55	17.80	5.28
20	18.55	18.10	5.28

An inspection of the above list shows that the values for a_o and c_o are remarkable constant. The b_o values, on the other hand, show some differences between the maimum (18.10) and minmum (17.66) values. Rabbitt (1948) plotted these differences in b_o against the weight percentages of SiO_2, Al_2O and ($FeO+Fe_2O_3+MnO+TiO_2$). He could find no systematic variation in any of the relationships. Hey (1956) considering the correlation of physical properties with chemical composition in multivariate systems, indicated that the value of b in anthophyllite was lowered by the substitution of Al_2 for MgSi and further that the substitution Ca, Na or K for Mg appeared to increase b_o markedly. In view of the difference in ion size this latter effect would not be unexpected on structural grounds.

In the present writer's consideration of the hornblende series (Chapter 8) certain correlations between X-ray powder line spacing and chemical composition are noted. Sufficient data was not available for similar examination of the anthophyllite series but it is felt that this may well be a useful field for further research.

CHAPTER 4.

THE MONOCLINIC AMPHIBOLES.

4a Terminology:-

The naturally occurring members of this group are the most abundant of all amphiboles and they are also the most complex. Under the system of classification in current common usage (Winchell 1951) the hornblende series includes all the monoclinic amphiboles with the exception of the cummingtonite series. The term 'calciferous amphiboles' was used by Hallimond to cover the hornblende series excluding the soda hornblendes. The present writer suggests that the term 'calciferous amphibole' should be used only in this sense for amphiboles containing more than 1.5 atoms of Ca in their formulae units. The positions of the calciferous amphibole series in relation to the monoclinic amphibole is demonstrated in Fig. 9. The complete revised classification for the amphibole group, suggested by the present writer is given in Fig. 1a.

Sundius (1946) suggested that the hornblende series, excluding the oxy-hornblendes, could be divided into two principal types. These were the lime-alkali and the alkaline varieties. The salient features of the Sundius classification are shown below.

Richterite Ferrorichterite	Eckermannite Arfvedsonite	Glaucophane Riebeckite
	Tremolite	
	Actinolite	
Edenite Ferroedenite	Pargasite Hastingsite	Tschermakite Ferrotschermakite

It can be seen that the above terminology has one major difficulty. Richterite, which is classed as an alkaline type, contains up to one atom of calcium in its structure. Strictly therefore, it is not an alkaline variety but a lime-alkali type.

It is here suggested, as a basis for classification, that the calciferous amphibole series should only include the oxy-hornblendes as defined by Winchell (1951) and the hornblende series as defined by the present writer (see Fig. 9). The hornblendes series then, under the terms of the writer's definition, would thus include the common hornblendes of Winchell, i.e. the aluminous hornblendes, and the tremolite-actinolite series or non-aluminous varieties.

In the new classification it can be seen that the tremolite-actinolite series, although remaining in the hornblende series, has been divorced from the common hornblende series of other writers (Winchell 1951). The present writer finds this sub-division useful in that it allows the aluminous hornblendes to be referred to collectively and seperately from the non-aluminous types. The name 'hornblende' is still a collective term for the series in general.

Under the earlier classifications the alkaline varieties were known as alkali-hornblendes or soda-hornblendes. The present writer considers the term 'soda hornblende' a mis-nomer because, strictly speaking, it should include the pargasite and edenite types which both contain ~~soda~~ sodium. It is therefore suggested that this term be discarded.

The present writer has already strictly defined the term 'hornblende series' in his classification and suggests that to use it in the wider sense to include the alkaline varieties is unsatisfactory and unnecessary. It is therefore proposed that all the alkaline varieties, that is those containing two or more atoms of ~~soda~~ sodium in the 'X' position, should be called 'alkali amphiboles'. Apart from the obvious difference in chemical and physical properties between the hornblendes and the alkali-amphiboles, the term is a convenient one and satisfactorily provides the third sub-division in the present writer's suggested classification. Fig. 9 shows the principal features of this classification and it should be noted that where the writer uses terms defined by him in the following chapters, these terms will be underlined by dots to distinguish them from published definitions.

With reference to the oxy-hornblendes, a definite connection between them and the hornblende series was established by Barnes (1930). The writer suggests that the terminology of the oxy-hornblendes (as defined by Winchell 1951) should remain unchanged. Insofar as can be ascertained from the literature no 'freak' varieties of this series have been found or described from amphibolites. The series is therefore outside the scope of this thesis.

1. The Hornblende Series $Ca_2 Na_{0-1}(MgFe)_{3-5}Al_{0-2}Si_{6-8}Al_{0-2}O_{22}(OH)_2$

Terminology.
The Tremolite Series.
The Common Hornblende Series.

The term 'hornblende' originally referred to both hornblende in the modern sense and to tourmaline. In the first place the term seems to have been in use amongst early continental miners. The use of the mineralogical term 'hornblende' was regularised by Werner in 1798 (Dana 6th. Edition) and restricted to the lime and soda bearing monclinic amphiboles. In early writings 'Hornbarg' is sometimes synonymous with hornblende.

The Tremolite Series:

Tremolite. The term 'tremolite' was given by Pini to a non-aluminous amphibole of the hornblende type. The term alludes to material, of composition given below, from the Tremola valley on the south side of St. Gothard. The true non-aluminous soda poor amphibole of this type originates from Campolongo (Tessin) and occurs in granular white or grey dolomite. The term 'tremolite' is however, well established and by current definition means a non-aluminous soda and iron poor calciferous amphibole.

Tremolite Analyses.

	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	ign.	Total
St. Gothard I	58.40	.56	.26	-	24.82	13.63	1.85	99.52
II	58.50	.31	3.00	-	24.12	17.22	1.20	99.65

Ferrotremolite. This term was coined by Winchell in 1932 and refers to the iron rich analogue of tremolite. The term is not in common use and appears to serve no purpose other than to complicate the terminology of the tremolite series.

Actinolite. The term 'actinolite' was derived from two Greek words meaning a ray and a stone. This was apparently translated directly from the German 'strahlstein'. The name was changed by Hauy to 'actinote' for no apparent reason. This latter term has, however, fallen into disuse. In Winchell's 1951 classification actinolite is defined as a member of the tremolite series having 20-40% of the iron molecule.

Tremolite, ferrotremolite and actinolite are the principal terms used to describe the members of the tremolite series. Other terms included grammatite which was substituted by Hauy for tremolite and by description refers to the striations seen on transverse sections of some tremolite crystals. The term 'grammatite' appears to have fallen into general disuse although some German publications still use the term.

The designation 'hexagonite' refers to a pink tremolite from Edwards, New York. This mineral which contains small amounts of MnO_2 (1.54%) was originally thought to be hexagonal. Its true monoclinic character was later shown by Koenig. The term 'hexagonite' is not necessary if the mineral is simply referred to as pink tremolite.

Nephrite is, in some mineralogical textbooks, treated seperately from tremolite and actinolite. Rogers and Kerr (1942) devote one and a half pages to the description of this mineral. For the most part this consists of a repeat of the properties of the tremolite series. Rogers and Kerr say that nephrite can only be distinguished from the tremolite minerals by its greater compactness. The term 'nephrite' clearly has no chemical or crystallographic significance and should be dropped. Semi-nephrite (F. J. Turner) has been used as an intermediate between the compactness of tremolite and that of nephrite. This term should also be discarded.

The commercial term 'asbestus' or 'asbestos' incorporates in part, varieties of tremolite and actinolite as well as the alkali amphiboles anthophyllite, and members of the serpentine group of minerals. However useful the commercial designation of this term may be it has no pure mineralogical significance and refers to certain physical properties of the amphiboles in general. This term shoubd therefore be discarded.

The present writer considers that the only variety of tremolite which can be seriously admissable is actinolite. The reasons for this are partly historical in as much as the terms tremolite and actinolite were the original terms of the series before it became complicated by later additional terminology. The second reason is that these two terms cover chemically and mineralogically all the later additions.

It is appreciated that in view of their essentially similar ionic radii to iron and magnesium, small amounts of chromium, titanium or manganese can be introduced in to the tremolite-actinolite molecule. The terminology of such types would present no difficulty and they may simply be described by their characteristic element titanium, chromium or manganese tremolite. These types are rare and it is therefore unnecessary to coin special names for them.

At this point it is convenient to discuss the terminology of the special amphiboles described in the foregoing paragraph. It was seen earlier (Chapter 3) that Rabbitt (1948) used special terms for the magnesium, ferrous and ferric rich anhtophyllites. Schaller (1930) suggested that the terminology given here in the table (Table 7) may in general be adopted to designate mineral variety. It can be seen that this is done by the use of a suitable adjectival prefix. The prefixes given in the table have been generally adopted in Dana System of Mineralogy 7th. Edition.

The present writer whilst noting Rabbitt's nomenclature for the anthophyllites, suggests that the Dana/Schaller terminology is, in general, something of an unnecessary complication. For example, the mineral 'hexagonite' would be called by the Dana/Schaller system manganoan tremolite. The present writer cannot see any valid reason why the mineral cannot be called, simply, manganese tremolite. In the case of the iron minerals, both the terms ferrous and ferric are in common usage and the present writer considers that the introduction of further alternative terms unnecessary.

Similar arguments can be found for many if not most of the other terms given in the Schaller/Dana list.

The majority of the members of the tremolite-actinolite series occur at or near the magnesium rich end. It is probably convenient therefore to assign the term tremolite to those members with 10% or less of the iron molecule. This would allow the term tremolite to be used within its original meaning. The actinolite minerals have never been restricted to very narrow compositional limits and Sundius (1946) suggested that the term should be used as the other end member of the tremolite series. Winchell's limit of 20%-40% of the Fe molecules is probably the first attempt to limit the actinolite field. The Winchell notation has a disadvantage in that it can only be used with the introduction of new terminology for the iron molecule.

The present writer suggests that it is most convenient to define all members of the series with more than 10% of the Fe molecule as actinolites. This form, seems adequate in a general way, for routine descriptive mineralogy but for more precise work it is here suggested that the series should be divided into 10 equal parts. Section 0 to 1 should then be known as tremolite. Section 1 to 2 should be referred to as 2-actinolite and so on as far as the limit of the series at 10-actinolite. The tremolite end members are the most abundant of the naturally occurring members of the series and it is for this reason that the suggested general name for the series is the tremolite series.

The Common Hornblende Series.

This series, under the definition of the present writer, includes the following separate sub-series:

Edenite - ferroedenite.
(Pargasite) Hastingsite - ferrohastingsite.
Tschermakite - ferrotschermakite.

The series nomenclature given above is from Winchell (1951). The author proposes to discuss each series seperately and suggest certain simpler terminological designations.

Edenite - ferroedenite.

Edenite was described by Dana (6th. Edition) as a white to grey, occassionally pale green and sometimes colourless mineral from the Edenville locality of New York State. The minerals referred to in this description have less than 5% iron oxides. Winchell (1931) quotes an analysis of edenite from Edenville, New York. Presumably this specimen is meant to be a type specimen from the type area. A second analysis of a pargasite from the same locality is also given. The two analyses are set out below.

	Edenite	Formula				Pargasite			
SiO_2	56.87	7.88	8.04	46.46		6.54	2	8.00	
Al_2O_3	1.26	.21		13.70		2.27	1.46	~~0.910~~	1.05
Fe_2O_3	.11	.01	4.92	.38		.04	1.86 ~~.87~~		
FeO	2.26	.26		.99	.12	~~.09~~	4.~~38~~42		
MgO	22.47	4.64		20.48	4.24	~~4.22~~			
CaO	14.09	2.09	2.32	12.57	1.89	~~2.06~~	~~3.05~~ 2.67		
Na_2O	.15	.20		2.84		.77			
K_2O	.15	.03		.57	.01	~~.22~~			
H_2O	1.53	1.41		1.35	1.17	~~.58~~	~~1.10~~ 1.34		
F	.21	.09		.26	.12	~~.72~~			
TiO_2	.13	.01		.04		.01			
MnO	.13	.01		.05		.01			
	99.76			99.58					

It can be seen clearly that the edenite is a tremolite and that the pargasite is, in fact, correctly named under the original definition of the term (see pargasite section this chapter). This latter material is clearly not an edenite. A survey of the literature shows that very few of the so-called 'edenites' are in fact correctly named.

Edenite seems to have been first described by Glocker in 1839. It was certainly mentioned by Breithaupt in 1847 (Dana 6th. Edition). The first analysis of an amphibole designated 'edenite' from Edenville is given by Rammelsberg (1858) who recorded the mineral as edenite Breithaupt but prefers to call it horn blende.

Analysis:

SiO_2	51.67
Al_2O_3	5.75
Total Fe	2.86
MgO	23.37
CaO	12.42
Na_2O	.75
K_2O	.84

In current usage edenite is defined as a calciferous amphibole of the hornblende series, common hornblende sub-series, with one atom of sodium in the vacant space and one atom of aluminium in the 'Z' position. The 'Y' position being filled by magnesium atoms. The present writer considers that one of the best examples of this mineral is the brown hornblende from Usumbura, Urundi, V. ~~Der~~ de Putte (1939) The formula of the mineral is given below and shows that the theoretical compositions of the edenite series is closely approached.

$Ca_{1.99}\ Na_{0.83}\ (Mg_{2.89}\ Fe''_{1.52}\ Ti_{.10}\ Fe'''_{.16}\ Al_{.15})_5\ Al_{1.00}$

$Si_{7.02}\ O_{22}\ (OH)_{1.98}$

Francis (1958) considered the general case for the inclusion or exclusion of the term 'edenite' from the nomenclature of the hornblende series. He plots six hornblendes from Glen Urquhart, two edenites from the type locality and one Indian variety, on a Hallimond diagram. He shows Fig. 10 that none of these minerals, including the original edenite of Breithaupt (1847) and analysed by Rammelsberg (1858), approaches the end member edenite composition.

Francis also states that the Glen Urquhart minerals and the Rammelsberg edenite lay in the optically negative field of Winchell's (1945) diagram but that the composition $Na\ Ca_2\ Mg_5\ AlSi_7O_{22}\ (OH)_2$ lies in the optically positive field. Francis maintains that this theoretical composition is merely an unlabelled point in a variation diagram and is not represented by any amphibole analysis and therefore does not merit baptism under the name already given to an amphibole chemically and optically distinct therefrom. Francis recommends that the term 'edenite' should be discarded altogether.

The present writer considers that sufficient case has not been made for the discarding of the term 'edenite'. In the first place, the analyses quoted by Francis (1958) contain several percent of iron. The quoted 2V angles in all these cases are within a few degrees of 90°. The present writer believes thag this small quantity of iron could well be sufficient to cause 2V to measure less than 90° or in other words to make the minerals optically negative. The Glen Urquhart minerals ar e therefore not pure magnesian and members of any series.

With regard to the other points raised by Francis. The theoretical composition is not merely an unlabelled point on a variation diagram but is in fact a bona-fide end member (Sundius 1946, p. 5) having its vacant spaces filled and its charges balanced. It is not true to say, furthermore, that no analyses exist showing composition approaching this theoretical limit. Winchell list No. 45 is certainly an approach to this even although the iron content has to be included in the magnesium. The overall analysis is one which corresponds to the end member formula. In another case the pure end member with the exact theoretical formula has been synthesized (Carnegie Inst. Rep. 1953-54, p. 110). This in itself is sufficient justification for a suitable label to be applied to this end member.

The writer agrees with Francis that most of the so-called edenites, including the type variety, are not pure edenites. It is, however, a fact that earlier writers Hallimond (1943), Winchell (1945) and Sundius (1945) have established that edenite witht the formula $Na\ Ca_2\ Mg_5\ AlSi_7O_{22}(OH)_2$ is an emd member. It seems pointless to the present writer to introduce fresh terminology when a small amount of revision can clarffy the present nomenclature. It is suggested here, that there are good grounds for the naming of the end members with the composition $NaCa_2Mg_5AlSi_7O_{22}(OH)_2$ and it has been shown that the term edenite, as distinct from the mineral name, is clearly understood to have this composition. The term edenite should be maintained and applied only to minerals having the composition approaching this end member formula. Edenville should not be referred to as a type locality and mineral from this area should be renamed appropriately.

Ferro-edenite.

The term ferro-edenite was implied by Hallimond (1943). The properties of the mineral were predicted by Winchell (1945) and the name was finally coined by Sundius (1946). Winchell's Fig. 2 1945 shows that the iron rich members of the edenite series are even more rare than the magnesium end members. The present writer considers that even the existence of one natural or synthetic edenite is sufficient to justify the continued inclusion of the edenite series in the common hornblendes.

Pargasite.

The term 'pargasite' dates from 1815 (Steinheil) and refers to the type mineral from Pargas, Finland. The original description was somewhat vague and was later simplified by Laitakari (1918-1923) and Von Eckermann (1922) when pargasite became known as an optically positive hornblende, high in alumina and magnesia with some alkalis. In some cases a considerable amount of fluorine appears to be present in the molecule but this is by no means essential. The analyses of the pargasite from the type area correspond to the formula:

$$Na\ Ca_2\ Mg_{4.5}\ Al_2\ Si_{6.5}\ O_{22}\ (OH\ F)_2$$

Winchell (1945, 1951) uses the term hastingsite for any mineral with this formula. Optically positive minerals with both this composition and that of edenite as here defined are designate as pargasite. Under the Winchell definition 'pargasite' is therefore a collective term and somewhat different from the original meaning. It is proposed to consider the merits of the use of the term 'hastingsite' and pargasite in the 'hastingsite' sub-section.

Hastingsite.

The term 'hastingsite' was first used by Adams and Harrington (1896) to describe a hornblende rich in iron and aluminium with moderate amounts of alkalis. The mineral had a characteristically small optic axial angle. The constitution of the original hastingsite from Dungannon, Hastings County, Ontario, is given be low.

SiO_2	34,184	5.75	
Al_2O_3	11.517	2.29	H_2O loss after igniting 15 mins.
Fe_2O_3	12.621	1.60	
FeO	21.979	3.09	
MnO	.629	.09	
MgO	1.353	.34	
CaO	9.867	1.78	
Na_2O	3.290	1.07	
K_2O	2.286	.49	
H_2O	.348	.39	
TiO_2	1.527	.19	
Total	99.601		

Winchell (second edition) went so far as to place hastingsite as an intermediate member between grunerite and riebeckite, both of which are characteristically free from aluminium.

Billings (1928) and later Buddington and Leonard (1954) examined the hastingsite question and subdivided the group on the basis of their MgO:FeO ratios thus:-

Magnesio Hastingsite	$MgO:FeO > 2$
Femag Hastingsite	$MgO:FeO < 2 > \frac{1}{2}$
Ferrohastingsite	$MgO:FeO < \frac{1}{2}$

Billings does not seem to have appreciated the chemical similarity between the magnesio-hastingsite subdivision and the classical pargasite. This may be because the Billing's mineral was optically negative. Increases in magnesia content beyond that of Billing's sample but still within his definition would most certainly result in positive minerals of the pargasite type (see numbers 14, 15, and 16 in Table 8a).

In later classifications (Berman and Larsen 1931, and Berman 1937) the term 'hastingsite' was given the extensive meaning currently adopted by Winchell namely that it should include all amphiboles in which a quarter of the silicon atoms were replaced by aluminium with the corresponding readjustment of the valency balance by the introduction of alkalis.

Steiner Foslie (1945) agrees in principle with the findings of Billings and considers the use of the MgO:FeO ratio as effective in distinguishing the various types. The chemical and optical aspects of the series are to be discussed in a later section but it does seem that there is a considerable amount of terminological dead wood associated with the series.

The writer considers that the term pargasite is well established as a positive mineral with the composition $Na\ Ca_2\ Mg_4\ Al_3Si_6O_8\ (OH)_2$ and that it would be unfortunate to abandon a type end member mineral from a type locality. Historically the term pargasite certainly takes precedence over hastingsite. As a collective term, of Winchell definition pargasite is not satisfactory, edenite, optically positive, is relatively rare and it has yet to be proved that the magnesium end member of the tschermakite series is not optically positive. If it is, then 'pargasite', in the Winchell sense covers three different minerals.

The term 'hastingsite' is also well established as an iron rich mineral of the same type formula as pargasite. There is ample precedent for the use of different end member terms for the same series (Diopside-hedenbergite and others) and it would therefore seem unnecessary to discard either of these two well established terms.

To summarise, the series with the type formula $Na\ Ca_2\ (MgFe)_4\ Al_3Si_6O_{22}\ (OH)_2$ can be described as the pargasite series having pargasite of the Finland type as the characteristic magnesian end member and hastingsite of the Adams and Harrington type as the characteristic iron end member. Sundius (1946) gives two possible end members for the series. These appear to be entirely satisfactory and their formulae are given here.

Pargasite.

$NaK_{.99}\ Ca_{2.03}\ (Fe''Mg_{3.30}Mn,Ti)_{4.25}\ (Fe'''Al)_{1.02}\ Al_{2.02}\ Si_{5.98}\ O_{22}\ (OH,F)_{.95}$

Hastingsite.

$NaK_{1.05}\ Ca_{1.69}\ (Fe''_{3.42},\ Mg,Mn,Ti)_{3.98}(Fe'''Al)_{1.07}\ Al_{1.91}\ Si_{6.09}\ O_{22}\ (OH,F)_{2.17}$

It will be shown in a later section that there appears to be a more or less complete solid solution series between *pargasite* and *hastingsite*. The terminology of Billing's (1928) would therefore seem to be of little fundamental importance, serving only to complicate the notation. It is suggested that for routine mineralogical practice the subdivisions of the series should be:-

Pargasite — *Magnesio-hastingsite* — *Hastingsite*

The term magnesio-hastingsite has been maintained by the present writer because, in his definition, the term covers the point where the series changes from positive to optically negative. Fig. 11 shows the details of the author's classification of the series. The graph shows that there is very good correlation between the total iron content expressed as %FeO+%Fe2O3 in the analysis and the Ng refractive index. No. 15, a "schwarzer pargasite" (Laitakari 1918-1923), appears to be a marked exception. The writer is unable to account for this and suggests, in view of the general good agreement, that there may be an error in chemical analysis. No. 18 (Subramaniam 1956) shows a rather higher Ng than might be expected. An inspection of the analysis (Table 8) shows that this mineral contains 1.92% Cr_2O_3 which could well account for the high refractive index. Analysis No. 3 (Howie 1955) is a pargasite type. The mineral is assessed as optically negative with a 2V of 82. The present writer would expect from his classification that this mineral would be positive. A recalculation of Howie's optical data shows that this is the case.

Ng = 1.680

Nm = 1.671

Np = 1.163

$$\text{Tan } V = \sqrt{\frac{1/2.7655 - 1/2.7922}{1/2.7922 - 1/2.8224}} = \frac{.36312 - .35868}{.35868 - .35486} = \frac{.00444}{.00382} = \sqrt{1.16230}$$

Tan V = 1.0779

about X 2V = 94° 16'

In view of the position of this mineral and that of No. 18 in Fig. 11 it is suggested that the magnesio-hastingsite field should have as limits Ng = 1.656 to Ng = 1.685 or approximately from 6.0% to 14% $FeO+Fe_2O_3$.

It can be seen from this classification that magnesio-hastingsite is part pargasite and part hastingsite. The writer feels that the term should only be used when the optic sign is in doubt. In all other cases, in this series, all optically positive minerals are pargasite and all optically negative minerals are hastingsites.

Tschermakite.

The name for a calciferous amphibole containing little or no soda or potash but abundant alumina appears to have been coined by Hallimond (1943). It seems to have come into general use with the publication of Winchell's (1945) classification. Although $Ca_2 (Mg)_3Al_2Al_2Si_6O_{22}(OH)_2$ is not an end member in the true sense of the word, substitution rarely proceeds further and for all practical purposes tschermakite may be regarded as the natural limit. The terms tschermakite and the iron analogue ferro-tschermakite are useful and although the range of naturally occurring minerals, in this sub-series of the common hornblende series, is small it is proposed to include these terms in the revised nomenclature in the form of their common usage.

The writer appreciates that there may be some solid solution relationships between the various series and that these series are by no means as clearly defined as may be suggested by the foregoing. It is proposed to discuss the inter-relationships between the various series, in a seperate section.

Substitutions in the Hornblende series.

Warren's (1929) work indicated the contents of the unit cell of the amphibole molecule as well as the presence of the vacant space. He showed that this space could be occupied by atoms of Na and K, thus permitting aluminium to re place the silicon atom to some extent. Hallimond (1943) made use of these facts and showed that many hornblendes had a composition which could be expressed in terms of end members on a triangular diagram (Fig. 12).

The diagram was based on the two chief components introduced by the common substitutions in the calciferous amphiboles, namely NaAl for Si and 2Al for MgSi. From these substitutions the three formulae for the end members are obtained.

1. $Ca_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$
2. $Ca_2\ Mg_3\ Al_2\ Si_6\ Al_2\ O_{22}\ (OH)_2$
3. $Na_2\ Ca_2\ Mg_5\ Si_6\ Al_2\ O_{22}\ (OH)_2$

It should be noted that the operative part of Hallimond's triangle is a trapezium. This is due to the fact that formula 3 is not consistent with the general formula for the amphibole group and the substitutions extend only half as far as indicated by the complete triangle. The chief iron free members of the non-ferrous, hornblende series thus become:-

1.	$Ca_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Tremolite
2.	$Ca_2\ Mg_3\ Al_4\ Si_6\ O_{22}\ (OH)_2$	Tschermakite
3.	$Na\ Ca_2\ Mg_5\ Al\ Si_7\ O_{22}\ (OH)_2$	Edenite
4.	$Na\ Ca_2\ Mg_4\ Al_3\ Si_6\ O_{22}\ (OH)_2$	Pargasite

Hallimond plotted about 200 analyses of calciferous amphiboles on this partial triangle. He assumed that Mg stood for all the components of the Y group with the exception of Al. For the co-ordinates of the partial triangle Hallimond took the number of silicon atoms, calculated on th basis 2400 (O,OH,F) as one side and the number of NaK atoms in the vacant space as the other. Winchell (1945) pointed out that this method was probably not so satisfactory as using the formulae as a basis for determining the position of the amphiboles in the triangle. Winchell's point was that Na atoms could occupy places in the unit cell as the result of other types of replacement namely 2Na for Ca.

The basis of Winchell's representation (Fig. 13) of the relative positions of the various types of calciferous amphibole is, of course, the Hallimond partial triangle which has been extended to include the substitution Fe for Mg. It is thus possible to represent, in a three dimensional figure, all the most important variables in the composition of the calciferous amphiboles. It was also possible to show the relations between variations in compositions and physical properties.

Winchell stated that the diagram is an approximation because several of the minor variables have been disregarded in its development. It is worth while recording here, the method of determination of the position of any hornblende analysis in this partial triangular prism. The number of each kind of atom (on the basis 2400 O,OH,F) is calculated. Each side of the triangle is divided into 200 parts. Using

Si atoms - 600 as one co-ordinate, Ca+Na+K - 200 as a second co-ordinate and 200(Mg+Al) divided by Mg+Al'+Fe''+Fe'''+Ti+Mn as the third and vertical co-ordinate, the position of any given hornblende can be plotted. Al' was regarded as equal to the total Al atoms minus the Al atoms necessary to make Si+Al equal to 800.

It is interesting to note that although Hallimond included the oxy-hornblendes in his analysis of the data, Winchell finds it necessary to exclude them from the general interpretation of the calciferous hornblende data. He did this on account of their markedly different optical characteristics and constructed a second partial triangular prism to cover their variation in properties and composition.

It was seen, in the foregoing discussion, that the apparently large number of calciferous amphibole types, could in fact be expressed in a relatively small number of terms. Hallimond (1943), for example, related most calciferous amphiboles to three principal types. Winchell developed the process more fully and included the group in eight main types after having made due allowance for the iron components in the group.

Sundius (1946) indicated that it was possible to review the whole question of substitutions in the hornblende group. He showed that the chief types of substitution in the group were restricted to the following:

a. The introduction of alkalis by various means.

b. The exchange of Si and FeMg for Al.

In short, Sundius, by applying the well known principles of substitution in the amphibole group to the basic simple formula, either tremolite or actinolite, showed that it was possible to obtain a small number of formulae in which the substitution proper could not proceed further or which in practice, has not proceeded further than a certain limit in analysed samples. Of these so derived formulae Sundius considered that the former corresponded to 'end Members' and although the latter were not strictly speaking 'end members' by definition they tend to serve as such. Both kinds were termed standard types and formed the basis from which all members of the group could be derived.

The introduction of alkalis into hornblendes occurs in three principal ways. Commencing with the basic tremolite formula $Ca_2 Mg_5Si_8 O_{22} (OH)_2$ the commonest case is the occupation of the vacant spaces, as defined by Warren, by alkalis. In order to balance the valencies, a corresponding number of Al atoms must be exchanged for Si atoms. Warren has indicated that the maximum number of atoms allowed in the X position is three. When this process of substitution has proceeded as far as the introduction of one atom of Na and one atom of Al the process is complete and the vacant spaces are therefore filled. The resultant amphibole, edenite, was regarded by Sundius as an end member. There is also the case of the direct substitution of 2Na for Ca as in the *alkali amphiboles.*

It is relevant at this point to quote Warren's remarks concerning this substitution. He stated that in all hornblendes where approximately one quarter of the silicon has been replaced by aluminium the value of the (Na, Ca, K) group rose from 2.0 to nearly 3.0. He went on to say that the way in which this excess in (Na, Ca, K) over the required value of 2.0 depended upon the amount of aluminium replacing silicon was shown in a table for comparison. This data has been converted to a graphical representation by the writer and is shown in Fig. 5, Chapter 2.

It seems clear that further forms of substitution in the hornblende series are possible. Sundius (1946) showed that there was a fairly common substitution in the lime-bearing hornblendes of aluminium for Mg and Si without the introduction al alkalis into the vacant spaces. Thus, formulas $\overset{Na}{\wedge}Ca_2Mg_4\overset{Al}{\wedge}Si_6\overset{Al_2}{\wedge}O_{22}(OH)_2$ and $Ca_2Mg_3Al_2Si_6\overset{Al_2}{\wedge}O_{22}(OH)_2$ are obtained by the substitution of Al:Al for Mg and Si. The latter formula tschermakite is not an end member but in fact the substitution does not usually proceed beyond this point. Tschermakite could therefore be chosed as a standard formula. It was shown earlier that Warren's statement concerning the relative amounts of aluminium and alkalis which could be introduced into the lattice was incorrect. It is now suggested that a combination of the two types of substitution viz., Al:Al' for Mg and Si and Al Na for Si is probably most common. The graph Fig. 5, shows that there is nearly always more aluminium introduced into the structure than is required to satisfy the valence conditions brought about by the introduction of alkalis into the vacant spaces. It is suggested that the excess aluminium could well be accounted for by the form of double substitution described here. The general formula Na $Ca_2Mg_4Al_3Si_6O_{22}(OH)_2$ Pargasite is produced by this double substitution.

By the application of these kinds of substitution to the tremolite formula, Sundius showed that the six amphibole types indicated on page 55, could be produced. Mg and Fe were naturally regarded as being unlimitedly interchangeable, the name of the Fe member being quoted in the table below that of the Mg member, there being only one end member of each type. The table was conveniently divided into two parts corresponding to the alkali and the lime-alkali hornblendes. Sundius pointed out that it was logical that those hornblendes in which the Ca was exchanged for alkalis should be called alkali hornblendes. According to this principle, edenite pargasite and hastingsite are not alkali but limealkali hornblendes, whereas richterite belonged to the alkali group.

4b The Chemistry of the Hornblende Series.

Various writers, Eitel (1922), Kunitz (1931), Hallimond (1943), Winchell (1945) and others, have compiled lists of the chemical compositions of analysed amphiboles. Each author separately lists his own criteria for the selection of the analyses. Hallimond (1943), for example, confined his attention to fairly complete analyses of good material with more than 1.5 calcium atoms in the unit cell. In this way he was able to exclude the more calciferous members of the alkaline series, namely, the richterites of Sundius (1946).

A useful set of criteria for the selection of data has already been given in Chapter 3b. In a general way both Hallimond (1943) and Winchell (1945) follow this scheme. The modern authors Hallimond and Winchell consider the calciferous amphiboles on the basis of their unit cell contents.

In the modern literature, all the formulae units in the lists of analysed calciferous amphiboles are calculated on the basis of 24(O,OH,F). In this way a full comparison is possible. The use of the method of Hey (1939, 1954), which depended on having information on cell parameters, rarely available from the general literature, would reduce the number of amphibole analyses available for comparison by about 90%.

It is proposed, in the following paragraphs, to give a resumé of the quantity, position and importance of the various atoms in the hornblende series. The number of calcium atoms and the number of atoms in the vacant space give the series its identity. It is therefore proposed to consider these atoms first.

Calcium. Hallimond (1943) showed by means of a frequency diagram Fig. 14 that for the most part the calciferous amphiboles have less than 2.0 calcium atoms in the formula unit. There is an implied suggestion in Hallimond's comment on this, that the small number of amphiboles, with high calcium content, may be impure material or that the error has come about by imperfections in the methods of analysis.

The present writer has inspected Hallimond's list of analyses and finds that the calciferous amphiboles with Ca=2.0 atoms do not usually have more than 3.0 atoms in the 'X' position. Nos. 104, 165 and 168 are exceptions and the possibility is that these may be impure samples. There seems to be no reason to suppose, particularly on the basis of ionic radius, that calcium atoms in excess of two could not be accommodated in the vacant space. This however, does not seem to be the case.

In terms of percentage, the amount of calcium oxide present in hornblendes ranges from 7.94% to over 14.00%. The example with 7.94% is from the amphibolite-talc-chlorite schist of Kennedy and Dixon (1936). In this mineral the total for the 'X' group is only 1.28 atoms per formula unit and although it is included in Hallimond's list it must be regarded as atypical. For the most part, the percentage of calcium oxide present in the series lies between 9.00% and

11.50%.

Sodium and Potassium. These elements assume considerable importance in this series and may form a substantial part of the 'X' group. In the case of the sodium atoms Hallimond's list shows 14 analyses in which the number of sodium atoms per formula unit is equal to or greater than 1.00. Potassium is nearly always present in the structure and in 14 cases is more abundant than the sodium but in only five cases is the amount greater than 0.5 atoms per formula unit. A marked exception is number 72 in Hallimond's list, a barkevikite, which has 0.75 atoms of potassium in the structure.

In terms of percentage composition, the amount of soda may range from almost 0%, in some actinolites and tremolites to 4.58% in a magnesio-hastingsite from Iron Hill, Colorado (Billings 1928). This latter has only 1.54 atoms of calcium in the structure and is therefore approaching the alkaline types. For the most part the percentage Na20 is rarely greater than 2.8%.

The percentage of potash is very variable and ranges from about 0% to about 2.5%. The variation of the quantities of soda and potash will be discussed in a later section.

ALUMINIUM. The significance and importance of this element has already been discussed in Chapter 4,a, dealing with the substitutions in the series. It would be expected, from an examination of this section, that the maximum aluminium content would be found in minerals where there is maximum replacement by aluminium in both the 'Y' and 'Z' positions as in tschermakite $Ca_2Fe''Mg_3\ (Fe'''Al)_2\ Al_2Si_6O_8(OH)_2$ which shows a possible theoretical presence in the formula unit of four atoms of aluminium. In natural minerals this has proved to be the case and the maximum quantity of aluminium so far recorded is from a tschermakite (from Titianul, Hungary, Vendl, 1932) which has 3.25 atoms of aluminium per formula unit.

At the other end of the scale, the aluminium poor amphiboles namely the members of the tremolite-actinolite sub-series are never completely aluminium free but they may show as little as .02 atoms per unit cell (Winchell list No. 13 and Hallimond list No. 3). In general, however, amphiboles in the hornblende series show an average of about 2.00 atoms of aluminium in the structure.

The aluminous or common hornblendes show a wide range of percentage alumina content, ranging from the 7.00% limit to as much as 16-17%. It is useful to indicate, at this point, that the boundary between the aluminous and non-aluminous hornblendes drawn, for the purposes of this thesis at 7.00% alumina or about 0.7 atoms of aluminium per unit cell, is purely arbitrary. It will be shown later that this division is a convenient one and should not be taken as presupposing the existence of a break in the substitution of aluminium in the hornblende series as a whole. The position of aluminium in this latter context will be made clear in the discussion of the solid solution relationships in the hornblende series.

Silicon. The quantity of silicon is extremely variable in the calciferous amphibole series and ranges from 7.96 atoms in the non-aluminous types to about 5.9 atoms in the highly aluminous varieties. These figures taken from both the Winchell and the Hallimond lists show a difference of 2.06 atoms of silicon. This figure is very close to the theoretical limit of 2.0 atoms per formula unit for the replacement of silicon by aluminium. Fig.15 shows the relationship between the amounts of silicon and aluminium in the formula unit. It can be seen from this diagram that although in some cases there is a tendency to have a rather higher silicon content than would be expected from the amount of aluminium present, there is, in general, a marked trend towards the theoretical limits of 6.0 silicon atoms and 2.0 aluminium atoms per formula unit. The excess of aluminium atoms which appear to disturb the theoretical trend of Fig.15 are those which should be included in the 'Y' position in the structure.

It is interesting to note that in the Hallimond list there are only 11 analyses with silicon contents below 5.9 atoms per formula unit. If the Ti content was included in the 'Z' group, and the possibility of such inclusion of Ti"' in this position was indicated in Chapter 1, the value Si plus Ti would in every case exceed 6.00 atoms per formula unit. The theoretical number of 6.00 atoms of silicon would not be maintained. The peak in the silicon frequency diagram would suggest a rather higher value than 6.0 for the lowest number of silicon atoms per unit cell.

Ferrous Iron and Ferric Iron. In the non-aluminous hornblende series the maximum ferrous iron, so far determined, has been found in an actinolite (formerly wrongly named ferro-anthophyllite) from Tamarack Mine, Idaho (Shannon 1921). This mineral contains 30.5% FeO or 4.03 atoms Fe per formula unit. At the other end of the scale, the purest tremolite known appears to have been found at Edwards, N.Y. (Bygden 1933). This mineral contains no measurable ferrous iron.

Ferric iron is normally present in both tremolites and actinolites although it rarely exceeds 0.25 atoms per formula unit in amount. It is frequently present when ferrous iron is absent, a point which has been discussed in Chapter 3,b.

In the pargasite-hastingsite sub-series of the common hornblendes, high ferrous iron is not uncommon and may form as much as 26.0% of the total. In the other sub-series of the aluminous types ferrous iron rarely exceeds 1.5 atoms per formula unit.

The ferric iron content appears to follow the same general trends as the ferrous iron. It is usually moderately high in the hastingsite minerals, for example, a ferro-hastingsite from Hastings County, Ontario (Billings 1928) showed 12.62% Fe_2O_3 in its analysis or about 1.6 atoms per formula unit. This figure of 1.6 is only exceeded in two other cases, namely number 100 in the Winchell list and numbers 78 and 85 in the Hallimond list. Number 100 (Sabot

1914) is highly peculiar in that it is included in Winchell's list of common hornblendes and yet shows 1.87 atoms of Fe"' and only .03 atoms of Fe" in its structure. The 'H' content of number 100 is also very high and it is felt by the present writer that in view of these two conflicting results, there must either have been a considerable replacement of Fe" by Fe"' or that the analysis method was unreliable and a considerable portion of the Fe" content was determined as Fe"'. This latter appears to be the most reasonable solution in view of the high water content.

In the case of number 78 in the Hallimond list (Rice 1935) the (OH) and F contents were not given by the original author. The Fe"' and Fe" contents are 1.73 and 1.13 atoms per formula unit respectively and it would appear that there has been at least partial oxidation of the Fe". Similar arguments could be applied to number 85 (Rice 1935) but in this case the Fe" content 1.85 atoms is higher than the Fe"' (1.76) but again no (OH) values are available.

Fig. 16 shows the relationship between Fe" and Fe"' in the calciferous amphibole series. The dotted line shows roughly the limits of the fields. Numbers 78, 84 and 85 appear above the line but have unsatisfactory analyses. Number 166 (H.L.) is from an andesite and has very low (OH) values (.48 atoms). Number 144 (H.L.) also has only 0.51 atoms per unit cell. This mineral is classed as soretite but is probably a re-heated hornblende. Out of a total of 168 normal hornblendes only five examples appear above the dotted line in Fig. 16. This amounts to some 3% of the total.

Oxy-hornblendes may lay below the dotted line in Fig. 16 but in view of the foregoing paragraph any analysis which falls above the dotted line almost certainly represents an oxy-hornblende type.

Magnesium. In the tremolite-actinolite series the Mg atoms and the total number of the iron atoms show a simple relationship to each other. This relationship is even more marked when the small amounts of titanium and manganese are added to the total iron.

It is fortunate that the two near end members of the tremolite-actinolite series are available. At the tremolite end the maximum amount of MgO so far recorded is 25.01% or 5.07 atoms per formula unit. The mineral has a total Fe content of only .04 atoms. The most iron rich actinolite so far recorded (Shannon 1924) contains .66% MgO or .16 atoms per formula unit.

The 'Y' group in the aluminous sub-series, edenite-ferro-edenite, has the same value as the tremolite-actinolite series. The present author has yet to find a single natural edenite, the magnesian end member of the series, in which the Mg content approaches five atoms per formula unit. Number 43 in the Hallimond list contains 5.02 atoms of Mg per formula unit and is termed a pargasite. This mineral is clearly wrongly named. There are less than 0.5 atoms of aluminium in the 'Z' position and there are only 0.34 atoms in the vacant space. The mineral is clearly nearer to tremolite than edenite and is not a pargasite as labelled. No data concerning its optical properties are available. Number 99 in the Hallimond list contains 4.62 atoms of magnesium in its structure and seems to show the highest magnesium content of any of the known common hornblendes.

The original hastingsite from Dungannon, Ontario (Adams and Harrington 1896) shows the lowest magnesium content of the Hallimond list having only 0.34 atoms per formula unit. The lowest found from the literature by the present writer was in a ferro-hastingsite from Unsunjoki, Salmi area Finland (Sahama, 1947) and appears in the present writer's list as number 8. This mineral has only 0.26 atoms of magnesium in its structure.

Titanium. This element is not important in the normal hornblende series. It is rarely present in amounts greater than 0.5 atoms per formula unit. The present writer has a general impression from the various lists that titanium is more abundant in the oxy-hornblende series. Numbers 178 and 186 in the Hallimond list contain more than 1.00 atoms of titanium and tend to confirm this suggestion.

In terms of percentages the titania content ranges from 0% to about 4.00%, the latter being unusually high.

Manganese. This element is even less important in the normal series than titanium. Amounts of more than ¼ atom per unit cell are rare. Even the pink, so-called hexagonite from Edwards, New York (Bygden 1933) contained only 0.18

atoms or 1.54% MnO.

(OH),F, Group. The quantitative peculiarities of this group have already been discussed in Chapter 2,a. In the present lists, Hallimond and Winchell, 63% of the quoted analyses show no fluorine determinations and 25% of the analyses quoted show (OH,F) contents greater than 1.90 atoms per formula unit. About 6.5% pf the total show this group greater than 2.10 atoms per formula unit. The lowest recorded (OH) value appears to be .10 atoms per formula unit, with the lowest combined (OH,F) at 0.71 atoms in the structure.

4c The Physical Properties of the Hornblende Series.

1. The Optical Properties.

The optical data appertaining to parts of the hornblende series is probably more complete than that for any other section of the amphibole group. In order to obtain some logical sequence in the analysis of data each sub-series must be considered seperately. It must be remembered, however, that the solid solution relationships within this group are extensive and varied and whilst it is possible to define the broad extents and limits of the various member sub-series, the optical properties and indeed the other physical properties also are influenced by the inclusion of small amounts of ions not normally considered as part of the particular sub-series. For example, although the optical properties of *tremolite* and *actinolite* can be given, both of these minerals, in the natural state, contain quantities of aluminium. The inclusion of small amounts of this metal in the *tremolite-actinolite* structure must cause some dislocation in the trends of the physical properties of these minerals. In this section, where possible, the various physical properties are considered in relation to the purest members of the sub-series concerned.

The Tremolite Sub-series.

Probably the first major attempt to define seriously the optical limits of this sub-series was made by Winchell (1945). Prior to this it had been possible to make general inferences from the published data and some diagrams showing inferred optical limits were published Winchell (1924). Winchell's present estimates, however, were obtained from what amounts to a statistical presentation of collected tabulated data. The properties of the respective end-members of this sub-series were determined as follows.

	sign	2V	Ng	Ng-Np	Z∧C	G
Tremolite	-	88	1.628	.03	18	2.98
10 Actinolite	-	75	1.735	.025	12	3.40

The above data was used by Winchell (1945) in the construction of diagrams showing the variation of optical properties with chemical composition.

Sundius (1946) states that Winchell's estimated limits do not agree with determinations made by himself, Foslie and other writers. Regrettably, Sundius does not give any detail concerning published reference of this work. In general, however, it can be seen that the data selected by the present writer as being representative of the natural end-members of the tremolite series is not so very different from Winchell's estimates. This is particularly true in the case of tremolite.

	2V	Ng	Ng-Np	Z∧C	S.G.	Sign
Tremolite (Hexagonite)	79°20'	1.629	.025	15°	2.98	-re
10 Actinolite (Shannon 1924)	74°	1.685	.017	-	-	-re

It must be remembered that both of these minerals are slightly impure. Small percentages of aluminium are present in both cases, the tremolite is not completely iron free and the 10 actinolite is not completely magnesium free.

A synthetic tremolite, (Ann. Rep. Geophys. Lab. 1954-55) which is presumably, although not stated to be, aluminium and iron free, gave the following properties:-

	2V	Ng	Ng-Np	Z∧C	Sign
Tremolite (synthetic)	73°± 1°	1.625	.030	16°±2°	-re

It can be seen that apart from 2V and therefore Nm (in this case) there is some considerable similarity to Winchell's estimated properties. 2V in the synthetic tremolite is surprisingly low. The present writer wonders, and will consider the point later (Chapter 8), whether this is due to the fact that small amounts of aluminium and soda in the magnesium rich hornblendes tend to increase 2V. This would account for the optically positive nature of both edenite and pargasite. A synthetic fluor-tremolite (Comeforo + Kohn 1954) with composition $Na_{0.03}\ Ca_{1.91}\ Mg_{5.15}\ (Si_{7.98}\ O_{11})_2\ F_2$ gave the following optical properties:

Np	Nm	Ng	Z∧C	2Vm	Sign
1.581	1.593	1.602	21°	86½°	-

With reference to the optic sign the present writer has not so far been able to find any optically positive tremolites. The pure synthetic tremolite is certainly negative. Winchell's list No. 15 gives a mineral with only .37 atoms of aluminium in its structure and this mineral is recorded as being optically positive. A check of the quoted refractive indices for this mineral by the present writer's method (p. 99) shows that the given Np value is inaccurate and the mineral is in fact optically negative.

The Pargasite-Hastingsite Sub-series.

The optical limits for the end members of this sub-series have been estimated by Winchell (1945) and given as:-

	Sign	2V	Ng	Ng-Np	$Z \wedge c$	G
Pargasite	+	85	1.64	.02	28°	3.15
Hastingsite	-	35	1.74	.02	18	3.45

In the case of the pargasite end members it is possible to check the Winchell figures. Synthetic fluor edenite and fluor Boron edenite (Kohn + Comeforo 1955) have been made. These have the following compositions and optical properties:-

Fluor edenite $Na_{0.99}(Ca_{1.84}Na_{0.16})Mg_{4.79}Al_{0.18}Si_{7.12}Al_{0.88}O_{22}F_{2.15}$

Fluor Boron edenite $Na_{0.93}Ca_{1.87}Na_{0.13}Mg_{4.92}Si_{7.16}B_{0.92}O_{22}F_{2.0}$

	Ng	Nm	Np	$Z \wedge c$	2V	Sign
Fluor edenite	1.624	1.617	1.605	18	69°	-
Fluor Boron edenite	1.605	1.598	1.588	12	75°	-

A synthetic pargasite, of the same formula as natural materials was prepared at the Carnegie Institution (Ann. Rep. Geophys. Lab. 1954-54 -. 117) and gave the following values for the various optical properties.

	Sign	Ng	Np	Ng-Np	2V	ZnC
Pargasite	+	1.645	1.624	.021	74°±4°	21°±2°

No analysis of the pargasite was given (except the general formula) but it must be presumed that the material is reasonably pure and particularly iron free. It can be seen from the table that the data except for 2V and Z∧c do not differ appreciably from Winchell's estimated values. There are prebably several reasons why 2V should show this marked discrepancy from the theoretical values. The first is that many of the 2V values of Winchell were probably calculated from unreliable indices and a plot incorporating the values would be subject to considerable initial error. In the second place, the relationship between 2V and composition is complex and it seems unlikely that it could be represented by a simple straight line as in many of the Winchell diagrams. This point will be discussed in a later section. Thirdly, the natural members of the pargasite-hastingsite series are in solid solution with the other members of the hornblende series. This impure state of the natural pargasites would tend to cause displacement of the values for 2V and Z∧C.

In the case of the hastingsite the optical limits are not so easy to check. The present writer can appreciate that the limit for Ng may well be 1.74 because many natural hastingsites have recorded Ng values of 1.730 (see Fig. 11). It is not clear, however, how Winchell arrives at the figure of 35° for 2V. At least 2 examples in the writer's list, Numbers 5 and 8, have measured optic angles of less than 35°

namely 25° and 0° respectively. The original hastingsite (Adams and Harrington 1896) has at least as much iron in the structure as either of these two examples and should therefore match their 2V values. Number 5 (Billings 1928) is in fact chemically identical to the original materials.

With regard to the $Z \wedge c$ values this would appear to be rather high in Winchell's list, numbers 5, 6, 7 and 8 quote between 12° and 13° for the extinction angle in high iron hastingsites.

Edenite-Ferro-edenite Series.

End members of this series are very rare, in fact both the Winchell and Hallimond diagrams show that neither author was able to discover any described end members from the literature. The mineral described by Sundius (1946) as representative of the series (Van der Putte 1939) contains more than 1.52 atoms of Fe" in its structure and therefore occurs about half way in the series. The Carnegie Institute Report (1953-54 p. 110) states that edenite has been synthesized and that its optical properties were in accord with those of the corresponding natural amphiboles. The optical data is not given but presumably the report considers Winchell's figures to be accurate.

	Sign	2V	Ng	Ng-Np	$Z \wedge c$	S.G.
Edenite	+	50	1.63	.02	25	3.06
Ferro-edenite	-	20	1.73	.02	15	3.42

Tschermakite and Ferro-Tschermakite.

The optical limits of this series were estimated by Winchell (1945) and are quoted below.

	Sign	2V	Ng	Ng-Np	$Z \wedge C$	s.g.
Tschermakite	-	80°	1.657	.02	20	3.13
Ferro-Tschermakite	-	70°	1.750	.03	18	3.42

Natural tschermakites are very rare minerals. No pure end members of the series have been described. Some attempts have been made to synthesize the members of the series (Ann. Rep. Div. Geophys. Lab. 1953-54 p.110) but no pure material was made. The end members properties must remain highly suspect.

Optical Orientation and Pleochroism.

With regard to the optic orientation of the members of the hornblende series in all forms Y=b. Most of the forms are strongly pleochroic in shades of green, brown, yellow, or blue-green. The absorption in most cases is $X<Y<Z$ but there are exceptions. Three ferro-hastingsites (Buddington and Leonard 1953) numbers 2, 6, and 7 from the writer's list have absorption formulas $Y>Z>X$ in the case of No. 2 and $Y\geq Z\gg X$ in the case of numbers 6 and 7.

Many of the magnesian end members of the series are colourless and non-pleochroic. This is particularly so when the mineral is *completely* heavy ion free. With increasing iron content, the tremolite series shows pleochroism in a variety of shades of green, the general scheme being:

X very pale yellow or colourless
Y greenish yellow
Z pale to dark green with increasing iron content.

The natural pargasite minerals are usually strongly coloured with tints ranging from yellow to green and greenish blue. Number 19, writer's list (Rosenzweig and Watson 1954) shows the following pleochroic scheme. The green pargasite of Laitakari (Hallimond No. 50) is listed for comparison.

	X	Y	Z
19.	Yellow	Yellow-brown	Light brown
50.	Green-yellow	Pale green	Green-blue

The ferro-hastingsites shows extremely strong colouring usually in dark greens or greenish-blue. The pleochroic schemes of the three ferro-hastingsites listed above viz. 2, 6 and 7 illustrate this.

	X	Y	Z
2.	Green-yellow	Olive	Green
6.	Pale olive	Dark grey olive	Dark green blue tint
7.	Yellow-green	Very dark olive	Very dark green

No data on the edenites and ferro-edenites is available but members of the tschermakite series are represented by No. 38 (writer's list) which has the following pleochroic scheme.

X	Y	Z
Yellow	Green	Blue

2. Optical Relationships in the Hornblende Series.

The present writer wishes to consider the value of the experimental optical determinations carried out on material described in the literature. It has been generally appreciated that the Nm refractive index in amphiboles is difficult to measure satisfactorily because of the orientation of the cleavage flakes used in such determinations. The writer has noted, when checking measured 2V determinations against values calculated from the refractive indices, that there are many discrepancies. Measurement of 2V on the universal stage should allow attainable accuracies of ±1°. It must therefore be assumed, where discrepancies occur, that the calculated 2V is in error. This of course means that one or more of the refractive indices is at fault. The question is which is the refractive index most in error and can correction be applied?

The mathematical relationship between 2V and refractive index is widely used in its various forms. The author could not find, in the literature, any indication that the mathematical relationships which must exist between the various indices themselves could be made to serve a useful purpose. Birefringence data is usually given and is often referred to as diagnostic in mineral determinations. This appears to be the 'text-book' limit of this type of investigation. The present writer has accordingly made a few trial plots of possible relationships between the various refractive indices.

In the first case Fig. 17, the Ng index was plotted against the Nm index for a series of aluminous hornblendes. It has always been assumed, in the literature, that the Ng refractive index could be accurately measured in the hornblende series because of the orientation of cleavage flakes. Rosenzweig and Watson (1954) make this point clearly. If this is in fact so, then Fig. 17 shows that it is also possible to measure the Nm index accurately. All the points on the graph fall within the limits of possible experimental error in their distance from the mean line.

In the case of the tremolite series (Fig. 18) the points all fall on an exactly similar line of similar gradient. Points A and K lie some way off the mean line and it seems reasonable to assume that in these cases there has been some error of measurement. This supposition is supported by the fact that in case 'A' Ng-Np is only .015 when most of the members of the series show considerably higher birefringence values (Fig. 19).

In the case of the plots Ng against Np there is, apparently, an even greater spread of points. There is, however, a definite mathematical relationship between the two sets of indices. In the case of the common hornblendes the graph shows a slight curve (Fig. 20). A number of points can be seen to clearly depart from the general trend. The explanation of this appears to be fairly simple. Number 1 shows a calculated 2V of 46° against a measured 2V of 51°. In view of the accurate relationships shown in Fig. 17 between

Ng and Nm this discrepancy in the 2V determination can only be due to inaccuracies in the measurement of Np. Recalculation of Np from the measured 2V and the accurate indices places number 1 close to the mean line in Fig. 20. In minerals numbers 6 and 7 there are differences of 3° and 4 degrees respectively between 2V measured and 2V calculated. This again accounts for the displacement of these points from the mean line. Number 37 is a similar case with a difference of 3 degrees between measured and calculated 2V. Ng for number 51 is 1.700 and Nm is 1.693 Fig,17 shows that this is rather low. There is also some difference between $2V_m$ and 2Vc. The underlined numbers in the plots refer to examples from the Winchell list, all others are from the present writer's list. It was not possible to check numbers 58 and 56 (Winchell list) for measured 2V against calculated values but it is clear that these minerals do not fit too satisfactorily on any of the plots. They are therefore considered to have unreliable refractive index values.

The similar graphs for the tremolite series (Fig. 21) illustrate an identical state of affairs except that in this case the lines of the plots do not follow exactly the same trend but have more or less parallel trends. This difference in position of the trend lines between the common hornblendes and the tremolite series for the Ng to Np relationships can only have been caused by the entry of aluminium and sodium into the tremolite structure. An increase of these two elements in the structure clearly causes a depression of the

Np values. Clearly some of the so-called tremolites are nearer to the common hornblende line than to the tremolite line. An estimate of how much this displacement is mismeasurement of refractive indices can be obtained if the other graphs are inspected, for example 'A' is quite clearly misplaced in Fig. 21. One index is clearly therefore in error because in Fig. 18 the trend lines are identical for both the aluminous and non-aluminous hornblendes and 'A' is again displaced.

A further point in connection with minerals with low refractive indices is that in the hornblende series they tend to be colourless. It will be noted that the spread of points about the mean lines tends to be greater in these areas. It is suggested that the reason for this is that errors in measurement due to internal reflection tend to be greater in the colourless minerals than in the more intensely coloured higher refractive index hornblendes.

By way of summary, ~~it is~~ clear that if there is a mathematical relationship between 2V and the refractive indices there must be some sort of relationship between each index. If this is so, then with absolute measurement of refractive index all points should lie on the lines or curves suggested for them. The fact that they do so for relationships between Ng and Nm indicates that it is possible to measure these indices accurately. In other cases (Figs. 20, 21 and 22) it shows clearly that it is not always possible to measure Np accurately but that the graphs presented here allow an accurate prediction of this value to be made. Furthermore it is possible to use the graphs (Figs. 21, 20 and 22) to distinguish roughly between the members of the tremolite series and those of the common hornblende series. Fig. 19 showing the relationship of Ng to Ng-Np illustrates the salient points of this argument. One further point is that the trend lines for the tremolite series and the common hornblende tend to converge at about Ng and Nm equal to 1.680 (Fig. 22). This fact should be remembered when dealing with minerals in the 10 actinolite field.

The writer tested Ng and Nm relationships in the pyroxene series (Fig. 23) and found that they provided a relatively easy method of distinguishing between monoclinic and orthorhombic pyroxenes when the extinction angles were not available. When extinction data is available it provides a useful check on R.I determination.

For the sake of completion a nomogram (Fig. 23a) for the determination of 2V from the refractive indices has been included here. From this refractive index determinations can be readily cross-checked with calculated 2V determinations.

One of the major uses which the present writer has found for the various graphs given in this section has been to check and extend the limited information occasionally given for amphiboles from the literature. They have also been used as a check on the optical determinations of the writer's Ghana amphiboles.

3. Density.

The density limits of the hornblende series extend from 2.98 gm/c.c. in some tremolites to more than 3.433 gm/c.c. in some hastingsites. In general it is safe to say that minerals of this type showing density values of less than 3.05 gm/c.c. are almost certainly tremolite.

The limits of the tremolite series given by Winchell (1945) as 2.98 and 3.40 gm/c.c. appear to be satisfactory. In the same publication the lower limit for pargasite minerals is given as 3.10. This figure is not satisfactory and at least two examples from the writer's list show lower density values (14 and 16 Fig. 24). A better estimate would probably be in the region of 3.05 gm/c.c.. With regard to the iron rich or hastingsite end of the series the Winchell estimate of 3.450 gm/c.c. appears to be satisfactory.

The values given for edenite and tschermakite appear to be roughly in accord with those which could be predicted from Fig.10. It is proposed to discuss the significance of Figs. 24 and 10 in a later section. It is, however, noticeable that even in the tremolite portions of the graphs there is a considerable spread of points. This suggests the possibility of considerable experimental error in density measurement.

4 d. The Crystallography of the Hornblende Series.

1. Morphological Crystallography.

The morphological crystallography of the hornblende series is adequately dealt with in Dana 6th. Edition and the present writer has nothing to add to this information. The reader is referred to Chapter 3, d. 1. for the discussion on the relative sizes of the cleavage angle in the amphibole group. For the purposes of this thesis this is probably one of the most important inter-group diagnostic features because it enables the non-calciferous amphiboles to be distinguished from the calciferous varieties.

2. X-ray Crystallography.

The X-ray crystallography of the tremolite series has already been dealt with in some considerable detail (Chapter 2 a.). Some data on the cell dimensions of members of the tremolite series have been examined and examples of this data are listed here.

	a A°	b A°	c A°	
1.	9.78	17.8	5.26	Tremolite, Warren (1929-30)
2.	9.7	17.8	5.25	Actinolite, Warren (1929-30)
3.	-	18.00	5.38	Tremolite, Parsons (1931) Sov. N.Y.
4.	-	-	5.41	Tremolite, Parsons (1931) Sarahburg N.Y.
5.	9.8	17.9	5.27	Actinolite, Parsons (1931) (Unspecified).
6.	9.781	18.007	5.267	Fluor-tremolite (Kohn + Comeforo 1955)
7.	9.91	18.04	5.26	Grammatite tremolite, Johannson (1930)
8.	9.91	18.5	5.36	Actinolite, Gossner + Mussnug (1948)

In general, information on lattice constants for the tremolite series is extremely scanty, and quite clearly it is impossible to draw any conclusions concerning variations of composition with cell size in the tremolite series itself. It is noticeable however that the principal differences between the constants seem to be confined to the b and c dimensions although in the case of Johannson's grammatite (tremolite) from Kaveltorp the 'a' dimension is certainly one of the largest recorded in the literature. The composition of the mineral is not greatly different from that of tremolite from Sarahburg N.Y.

	Sarahburg	Kaveltorp
SiO_2	56.10	56.77
TiO_2	.10	
Al_2O_3	1.30	1.30
Fe_2O_3	.48	.67
FeO	1.01	1.77
MnO	.14	.54
MgO	24.94	23.31
CaO	13.06	12.54
Ng_2O	.84	.57
K_2O	.90	.023
H_2O	-	1.74
F	.83	.94
P_2O_3	trace	-
	100.28	100.45

The reasons why the cell dimensions should be so very different are difficult to see. The Sarahburg tremolite has more potash but this is a large ion and if anything, should increase the dimensions of the cell in this case. There is also more lime and more magnesia in this mineral. The only possible reason for the large cell size of the Kaveltorp mineral appears to be in the quantity of water and fluorine present. The (OH) and F ions are large radius $1.4A^{o}$-$1.5A^{o}$ and 1.33a respectively and may well cause swelling of the structure if present in full amount as they appear to be in the Kaveltorp tremolite.

In the case of the common hornblendes a few useful determinations of cell parameters are available from the literature but again the information is scanty.

a A^{o}	b A^{o}	c A^{o}	Name.
9.8	17.9	5.28	Hornblende unspecified (Warren 1930)
9.88	17.70	10.92	Pargasite, Pargas, Finland (Parsons 1931)
-	-	9.88	Monteagle Township, Ontario (Parsons 1931)
-	-	9.55	Edenite, Amity, New York. (Parsons 1931)
9.847	18.004	5.282	Fluor edenite, (Kohn + Comeforo 1955)
9.807	17.957	5.266	Boron edenite, (Kohn + Comeforo 1955)
9.89	17.94	5.32	Jakob + Brandenburger (1931) (Card Index 3.12, 1.44, 2.70)

The writer cannot find any comment in the literature concerning Greenwood and Parsons high figures for the 'c' dimension. In all other cases examined in the literature the 'c' axis remains essentially similar to the 'c' dimensions in the tremolite series namely 5.28 approximately.

There is a considerably greater amount of powder photograph data available for both the tremolite series and the common hornblende. This data will be discussed, in a later section, in relation to the composition of the various amphibole types.

CHAPTER 5.

THE MONOCLINIC AMPHIBOLES

The Non-Calciferous Amphibole Series.

General Formula: $Y_7 \quad Z_8 \quad O_{22} (OH, F)_2$

1. Introduction.

The non-calciferous series of the monoclinic amphibole group is known generally as the cummingtonite series. The question of the cummingtonite-anthophyllite relationship was the source of much mineralogical controversy in the early 1930s. The problem has been left in abeyance since then but it has not been solved.

Probably the earliest satisfactory work was by Kunitz (1930). He regarded the difference in symmetry between the anthophyllite series and the monoclinic cummingtonite series as of little importance and combined the two series in his study of their physical properties and composition. A comparative X-ray study of anthophyllite tremolite and cummingtonite was made by Johansson (1930). This showed that the difference in symmetry between the groups was a fundamental property of the space lattices and could not be ignored.

Winchell (1931) stated that he could see no good reason for disregarding the crystallographic differences and combining the two series. In 1938, however, primarily on the basis of two descriptions of high iron anthophyllites, by Orlov (1932) and Peacock (1928), Winchell decided that the anthophyllite series was continuous to about 90% of the iron end member. It was concluded from this that the anthophyllite and cummingtonite series illustrate a case of isodimorphism since the latter extends to about 60 numerical per cent of the magnesian end member and the anthophyllite series to about 90% of the iron end member. The alternate end members being the most common minerals in each series respectively.

It had been suggested by Winchell (1931) that the reason for the isodimorphism in the two series was that the magnesian end member was more stable in the orthorhombic phase whilst the ferrous end members was more stable in the monoclinic phase. A glance at the table (Table 2) from Rabbitt (1948) is sufficient to indicate the basis for this suggestion. Few if any anthophyllites are completely MgO free, the lowest recorded amount being 11.48% (No. 2). Number 41 has been shown to be very close to a magnesian end member for the anthophyllite series with 30.81% MgO.

Sundius (1933) stated that the two series are not dimorphous and demonstrated that a 6% to 9% molecular increase in alumina and Fe2O3 transforms the monoclinic into the orthorhombic amphibole. This is in general accordance with Collins (1942) results from Strathy.

If the anthophyllite and cummingtonite series are isodimorphous, there should exist a member of the cummingtonite series with a composition close to $Mg_7 Si_8 O_{22} (OH)_2$

and an anthophyllite with a composition close to $Fe_7\ Si_8\ O_{22}\ (OH)_2$. This is, of course, excluding aluminium, manganese and fluorine. The validity of the case presented by Winchell (1938) depends mainly on the accuracy of the determination of the so-called high iron anthophyllites (Orlov and Peacock). Rabbitt (1948) shows, by inference, that there is a strong possibility that both these minerals were in fact, cummingtonites. It has already been shown in the anthophyllite section that there are no bona fide high iron anthophyllites close enough to be rated as end members. It would thus appear on this evidence that the two series are not isodimorphous.

Eskola (1950) stated that the fields of the variation in the composition of the two series overlap at least within the range MgOmol. props./ MgO+FeO (mol. props.) equal to 0.60 and 0.69. Eskola indicates that this means there exist members of the two series with identical composition. It is also stated that in many cases where anthophyllite and cummingtonite occur in the same rock, as in many of the rocks of the Orijarvi region (Eskola 1914), the two types are of identical composition. Eskola cites only optical evidence in support of this and draws parallels from the dimorphism in clino-enstatite and enstatite,and clinozoisite and zoisite.

The present writer suggests that whilst there may be occasional 'accidents' of apparent chemical similarity, these are rare. The parallels drawn by Eskola (1950) do not strictly apply here. Rabbitt (1948) has shown that the anthophyllite series is characterised by the presence of considerable quantities of aluminium. This metal is rare in the cummingtonite series. On the other hand the latter series is often significantly rich in calcium and manganese and anthophyllites are not. The case for dimorphism, supported by the Muuruvesi mineral, Eskola (1950), seems to be somewhat exceptional. It should be noted that no X-ray evidence is given in support of the identification of this mineral. The optical evidence mentioned in support of other cases should be treated with due reserve. Rabbitt (1948) has shown how misleading this sort of evidence can be. The question of dimorphism will be considered later by the present writer.

5a Terminology.

The non-calciferous amphibole series is described in the literature by reference to three principal terms.

1. $Fe_7 Si_8 O_{22} (OH)_2$ Grunerite
2. $Fe_{3.5} Mg_{3.5} Si_8 O_{22} (OH)_2$ Cummingtonite
3. $Mg_7 Si_8 O_{22} (OH)_2$ Kupfferite.

The term 'grunerite' was originally given to a fibrous mineral approximating in composition to $FeSiO_3$ and occurring with magnetite and garnet at Collobriere, Department of Var, South of France. The original material was described by Gruner in 1847. The mineral was originally thought to be pyroxene but was later shown by Des Cloiszeaux and Lacroix to belong to the amphibole group. A similar material occurs in the iron deposits of the Lake Superior District (Lane and Sharpless 1891 and Richarz 1927).

The mineral was first named grunerite by Kenngott (1853). Grunerite is the correct term and the synonyms grünerite and gruenerite (Dana 6th. Ed.) should be discarded.

The chemical analysis of the orignal grunerite was somewhat inadequate (Table 11 analysis 1.) It is clear that the silicon content is essentially the same as the minerals from Pierrefitte (Warren 1931). The iron content is also clearly very high. If this original amphibole was correctly named then it is almost a pure iron end member.

The term kupfferite which describes the magnesian end member of the series was originally applied by Koksharov in honour of the Russian crystallographer Kupffer, to unanalyzed material from a graphite mine in the Turinsk Mountains near Baikal. Similar material was also found elsewhere in this part of Russia. It is interesting to note that Dana 6th. Ed. included this mineral in the anthophyllite series. Sundius (1931) states that the original Kupfferite of Koksharov was, in fact, a Ni-Cr actinolite.

From the present writer's point of view it is significant that so far (Carnegie Inst. 1954) it has proved impossible to synthesize a more magnesian-rich mineral of this series than Mg_{85} Fe_{15} but that if small amounts of magganese are included in the structure (Table 11 No. 21) it is possible to find, naturally occurring, minerals near the end member.

It has been shown that the term kupfferite which

Sundius (1931) showed to refer to a Ni/Cr actinolite is unsuitable and it is here suggested, that the term cummingtonite should be used as the end member term but also that it should cover minerals with the 'Y' group showing Mg_{20} Fe_{80}. The cummingtonite field can then be subdivided and the various sections described by the addition of a numerical prefix. Thus a mineral with the MgFe ratio of 70:30 would be known as 7cummingtonite. Minerals containing more than Fe_{80} should be known as grunerites.

The original cummingtonite was named by Dewey (1824). It was found by Porter at Cummington, Mass. U.S.A.. In colour, it was grey sometimes with a faint reddish tinge and yellow when weathered. The mineral which was originally recorded as epidote had a density of 3.42. No analysis was given for the original material in the early paper but Dana 6th. Ed. gives two analyses on material from Cummington.

SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Loss ign.	Total
51.09	0.95	32.07	1.50	10.29	tr.	0.75	tr.	3.04	99.69
50.74	0.89	33.14	1.77	10.31	tr.	0.54	tr	3.04	100.43

With regard to the various terms applied to manganese and zinc bearing cummingtonites namely danemorite, tirodite and zinkian danemorite, danemorite seems to have been coined by Kenngott in 1855 and refers to an iron manganese amphibole from Danemora, Sweden. The original material had the following composition and is somewhat unusual in having very low magnesia.

SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Total
48.89	1.46	38.21	8.46	2.92	0.73	100.67

The tirodites numbers 19 and 20, and 21, in the table are so named from the type locality, Tirodi, India. They are different from the danemorites in that they are manganese magnesium amphiboles. It will be shown later that there are good grounds for referring the non-calciferous amphibole series to a triangular (Fig. 26) diagram and that it is reasonable to maintain these terms danemorite and tirodite along with cummingtonite and grunerite. Zinkian danemorite merely refers to a zinc rich variety. This material could be quite well called zinc danemorite.

5b Chemistry of the Cummingtonite Series.

Apart from the Mg/Fe substitution, the prime cause of the variation in chemical composition in all other sub-series in the amphibole group, is the introduction of aluminium in to the crystal lattice either as a replacement for silicon or into the 'Y' group. In the non-calciferous amphiboles aluminium is not important. It is somewhat surprising to find that there should be considerable variation in the silica content of the members of the cummingtonite series.

Silicon.

A glance at the table of analyses taken from the literature shows that there is a remarkable variation in the percentage silica content in the members of the cummingtonite series. The lowest recorded is 43.9% in the original grunerite. The analysis was incomplete but is in reasonable agreement with the Pierrefitte grunerite which contained 46.42% silica. The highest weight percentage, on reliable material appears to be that recorded by Eskola (1950) No.15 in the table and contains 54.97% silica.

This variation in silica content does not seem to be related to the variation of any other single constituent. The variation of 10% is certainly well beyond experimental error. Certainly there is no correlation between the silica content and the alumina present. No. 12 which has 8.65% alumina contains 49.60% silica whilst No. 2 which has only 0.25% alumina contains only 42.46% silica. The variation in silica content is generally balanced by the 'Y' group. No. 2, for example, with 46.42% SiO_2 has approximately 8% more 'Y' group oxides than No. 15 which has 54.97% SiO_2.

Aluminium and Ferric Iron.

The percentage weight of aluminium in the cummingtonite series varies from approximately 0% to 8.65%. It should be noted that both the minerals showing high Al_2O_3 contents, numbers 11 and 12 are from the same locality and analysed by the same person (Collins 1942). Neither specimen has been confirmed by X-ray analysis and the present writer feels that these two minerals should be viewed with suspicion until confirmation is forthcoming.

It seems clear from the table that the variation in silica content is not related to the alumina content and if anything there is a simultaneous rise in silica and alumina contents. Alumina is definitely subordinate in the cummingtonite series and is definitely unusual in amounts greater than 4.00%. The series is generally sesqui-oxide poor. Ferric iron is present only in amounts of less then 3.00%. It is rare for the total percentage weight of sesqui-oxides to exceed 5.00%

Ferrous Iron.

The original grunerite, the iron end member, contained some 52.2% FeO. The figure, for an early analysis, is rather high but not exceptionally so. The Pierrefitte grunerite (Warren 1931) contained 42.60% FeO but also had 2.23% MnO and 3.12% MgO in its structure. The original grunerite with only 1.10% MgO was probably the nearest to the iron end member. Of the later material Kreutz (1908) analysed a further sample from La Malliere, near the original locality of Collobrieres, and showed that it had an iron content of 43.40% FeO. The mineral is No. 5 in Table 11 and it can be seen that small quantities of alumina and ferric iron are also present as well as 2.61% MgO.

No. 16 in the table is from Western Australia (Simpson 1928) - the material was referred to as a kupfferite in the original literature. This mineral was later shown by Winchell (and Cromer 1938) to be made up of about 90% anthophyllite and 10% other monoclinic mineral. Although Winchell uses this mineral and its deduced composition in his dissertation on the cummingtonite series, it would be better if further more reliable data were available.

The lowest ferrous iron recorded appears to be in the mineral from Muuruvesi, Finland, No. 15 in the table. This mineral was used by Eskola (1950) to support his claim that the cummingtonite series is isodimorphous. In the manganese bearing minerals FeO is often very low, this is so in the tirodite member. The so-called kupfferite from Edwards, New York shows only .06% FeO. This mineral contains nearly 3.00% MnO and can therefore not be regarded as an end member.

Magnesium.

The Muuruvesi mineral records the highest magnesia content of the manganese free cummingtonites with 22.11% MgO. The manganese bearing minerals certainly contain the highest recorded magnesia contents. The tirodite (No. 20 in the list) having 31.26% MgO in its structure.

Titanium.

Titanium is not important in the cummingtonite series and in all the examples examined by the present writer the amount of TiO_2 never exceeded 1.00% and was usually nearer 0.5%.

Manganese and Calcium.

Many writers have noted the presence of calcium and manganese in the cummingtonite molecule. In no case has the present writer found that the literature states that calcium should be regarded as an essential characteristic of the cummingtonite molecule. Other writers merely state that these elements are common but not necessarily essential. It issuggested here that the cummingtonite series is possibly intermediate between the calciferous amphibole group and the anthophyllite series, which is orthorhombic. Both manganese and calcium can exist in eight fold co-ordination in the cummingtonite series. This means that there are relics of the 'X' group present in the series and that this is the reason why it should remain monoclinic. The diagram illustrating the solid solution states of the tremolite series, the anthophyllite series and the cummingtonite series is probably four cornered (Fig. 27). The cummingtonite molecule could be formed,by replacement, from the hornblende series probably from the tremolite series. This point will be discussed in the section dealing with the X-ray crystallography of the series. It is important to note, in a general way, that alumina is not important in the cummingtonite series but that it is important in the anthophyllites.

It is suggested here (Fig. 27) that there are possibly two principal lines of substitution, firstly, possible substitution in the tremolite series to derive the cummingtonite molecule and secondly substitution in the aluminous hornblendes to derive the aluminous anthophyllite molecule. The presence or absence of aluminium is not important in determining the symmetry, if it was then there would be many members of the common hornblende series which should be orthorhombic. Tschermakite with very high alumina content is a case in point. On the other hand a glance at Fig. 2 in Chapter 2 shows that the calcium atom is a large atom and its removal from the structure would necessitate considerable re-arrangement of the lattice. The replacement of silicon by alumina or the replacement of iron/magnesium by aluminium requires little or no re-arrangement of the lattice due to the similar ionic radii of the elements concerned. This then is the explanation of the monoclinic nature of the cummingtonite series. Figs. 27a and 27b show the essential differences between the tremolite and the anthophyllite structures.

The manganese which occurs in quantity in many of the cummingtonite type minerals can occur in both the calcium or eight fold co-ordination or in six fold co-ordination as in the 'Y' group. It would appear from this that the function of the manganese atom is one of bridging. This explains why several of the anthophyllites described by Rabbitt (1948) contain small quantities of manganese and still retain their orthorhombic symmetry. It was shown that some of these anthophyllites could contain up to 2.77% MnO. This manganese would almost certainly be in the six fold co-ordination. Any greater quantity would probably cause some Mn to appear in the calcium position and the lattice would revert to the monoclinic form.

For the reasons described above it is not possible to show the separation of anthophyllites and cummingtonites graphically. It is clearly impossible from a straight forward chemical analysis to identify the co-ordination of the manganese and the calcium atoms. The only certain method for the identification of the two series is by X-ray analysis.

It is interesting to note that Eskola's (1950) cummingtonite from Muuruvesi can contain 3.26% of alkalis. The equivalent anthophyllite however contains negligible alkalis. This indicated that the two series are not isodimorphous and from the foregoing it is clear that the series do not have identical compositions, the cummingtonite types being characterised by a quantity of manganese or calcium in the eight co-ordination position. The anthophyllite series has been shown to contain less than 0.5% of calcium and less than 0.5% alkalis on average. Rabbitt suggests that these quantities appear to be definitely in the crystal structure. The present writer suggests that there is no place for these elements in the structure and that they represent impurity.

Some confirmation fo the present writer's suggestion is given by Eskola (1950). He states that it is mostly cummingtonite which appears in paragenesis with hornblende. On the basis of the theory suggested here anthophyllite would only form with hornblende if the rock was deficient in calcium or manganese to such an extent that none was available for the formation of cummingtonite.

Final, important confirmation of the writer's suggestion is available from the pyroxene series. The presence or absence of the calcium or manganese atom in the pyroxene structure determines the symmetry, thus all calcic pyroxenes are monoclinic. Clino-enstatite apparently only exists in a metastable form and is only stable at high temperatures, but it is interesting to note that in the case of pigeonite, a clino pyroxene with a low Ca content, under conditions of slow cooling there is inverson to orthopyroxene with ex-solution lamellae of almost pube diopside. This indicates that the orthorhombic pyroxene structure cannot tolerate atoms of the size of Ca. This is directly analogous to the amphibole case. Fig. 27c illustrates the enstatite structure. The essential similarity to that of anthophyllite Fig. 27b is easily appreciated. The orthorhombic pyroxenes have the greater cell size whilst the monoclinic varieties have a displaced interlocking structural system linked by calcium atoms. Earlier work stressed the similarity of the pyroxene structure to that of the amphiboles and it seems to be quite clear, therefore, that there must be certain limiting quantities of calcium and manganese beyond which the amphiboles cannot assume orthorhombic symmetry.

Finally it is suggested that the type formula for the cummingtonite series should be re-written to include the essential parts of the 'X' group. A possible formula is given below.

$$(\mathrm{Ca\ Mn})_{\substack{>0.\\<1}} \qquad (\mathrm{Mg\ Fe\ Mn})_{\substack{>6\\<7}} \qquad \mathrm{Si_8\ O_{22}\ (OH)_2}$$

It is necessary to point out with reference to the above fromula that the 'X' group in all cases will be greater then zero and the the 'Y' group will also in all cases be less than than 7.00. If this were not so then the group would assume orthorhombic form. Work is not sufficiently advanced at this stage to define the exact limits of these groups in the cummingtonite series.

Soda and Potash.

Soda is present in the cummingtonite series in amounts up to 1.50%. This is definitely allied to the lime and the r emarks made in the previous section apply here. Potash is also present in most members of this series but rarely exceeds 0.5%. The fact that the cummingtonite series may possibly have originated in some cases by substitution from the tremolite series would suggest an explanation why the overall amounts of alkalis tends to be small.

Water and Fluorine.

The literature shows that in many cases only the total water has been determined. The structural water is usually variable up to 2.5% but usually averages about 1.5%

Fluorine appears to have been almost totally ignored in the cummingtonite series. Only four determinations have been found by the present writer. The highest of these is No. 8 which has 0.57% fluorine in its structure.

5c The Physical Properties of the Cummingtonite Series.

1. Optical Properties.

The optic plane in the cummingtonite series is, as in all the other amphibole groups so far described, parallel to 010. The extinction angle is rather more variable than the data given by Winchell (1951) and ranges from 10° to 22°. The minerals of the series can be either positive or negative depending on the quantity of the magnesium atom present. The optical axial angle (2Vx) varies from as low as 50° in some of the manganese rich members of the series to about 139° in some manganese-magnesia rich types.

No synthetic end members of this series have been prepared but it is expected that the high manganese in some members of the series would affect the optic properties and in particular the refractive indices. Data, at the present time, is insufficient to determine precisely the refractive index limits. Winchell (1951) suggests the Ng limit should be rather more than 1.72 and a convenient lower limit would appear to be about 1.65. In the case of Nm a value of 1.73 has been recorded on the original grunerite. The lowest Nm value (1.639) is on the tirodite from Chickla, India.

The Np values range from 1.673 down to 1.629 and again the manganese bearing minerals have the lowest indices. Winchell (1938) records a cummingtonite with Np=1.626. This is a re-determination on the mineral from W. Australia (Simpson 1928).

The birefringence Ng-Np in the cummingtonite series varies from 0.019 to 0.056, the grunerite end members having the highest values. The manganese-magnesium minerals have a somewhat higher birefringence than the purer magnesium types. It is also noteworthy that numbers 19 and 20 in the list show values of 0.021 which are higher than the Collins (1942) Strathy minerals and yet have a much lower iron content.

Winchell (1951) has produced a four pole diagram in which the optical properties are related to the composition of the cummingtonite series including the manganese varieties. The data on which this diagram is based must have been extremely limited. Until further data is available this diagram should be treated with caution.

2. Density.

The density limits for this series are somewhat greater than for the amphibole groups previously described. The lowest value recorded in the table is 3.10. This excludes the suspect value of Simpson's kupfferite. The upper limit is fixed by the original grunerite which has a density of 3.713. This value is extremely high, much higher than number 4 in the list which has only 3.00% more MgO in its structure. It is important to note that if the density determination on the original grunerite is accurate then this is the highest recorded density of any member of the amphibole group.

5d The Crystallography of the Cummingtonite Series.

1. The Morphological Crystallography.

Crystals of the cummingtonite series are usually fibrous or lamellar with good (110) cleavages at 125°. The cleavage angle considerations are important and in all cases they are similar to anthophyllite usually between 54° and 55° in the acute angle. They are never greater than 55°. The relationship of the cleavage angle to the amphibole type was discussed in Chapter 3,d,1. It may be that the reason why the cleavage angle is smaller in the cummingtonite and anthophyllite series than in any other series is because both series are deficient in the large calcium ions. If this is, in fact, the case then the cummingtonite cleavage angle should be somewhat larger than that of anthophyllite but a good deal less than the other members of the amphibole group. This is so.

2. X-ray Crystallography.

In general the data on the cell constants in the cummingtonite series is scanty. Winchell (1951) gives the space group as C2/m and the lattice parameters for the end members as follows:-

	a. A°	b. A°	c. A°	
grunerite	9.7	17.8	5.25	
kupfferite	9.4	17.9	5.27	
Johan. (1933)	9.55	18.22	5.334	102 8'

It will be noted with reference to the discussion on isodimorphism that the 'a' dimension is only half that of the orthorhombic amphiboles. There is little re-arrangement of the basic structure of the amphibole molecule by the replacement of Ca by MgFe. The cell size changes slightly but the principal point is that the symmetry elements of the monoclinic and orthorhombic amphiboles are governed by the presence or absence of the Ca atom. The diagrams (Figs. 27a and 27b) show the anthophyllite and tremolite structures on both the same scale and both projections on (010). It can be seen that the extra planes of symmetry required by the orthorhombic anthophyllite minerals can only be obtained when the Ca atom is removed. It follows that if cummingtonite is without atoms in eight-fold co-ordination, the structure must perforce be that of an orthorhombic mineral.

The data given by Winchell for the mineral kupfferite was obtained by Warren (1930) on material first analysed by Allen and Clement (1908). The analysis is given as number 22 in the writer's list. The analysis shows that this mineral contains 2.77% MnO in its structure and is therefore not a pure magnesian end member.

Warren (1930) drew attention to the similarity between the monoclinic non-calciferous amphiboles and the tremolite series. This similarity was very marked in the rotation photographs. Warren discussed the replacement of Ca by Mg and points out that the eight oxygens about Ca are so arranged that on replacement of Ca by Mg, six oxygens can move closer to the Mg atom and form a nearly regular octahedron. The remaining two oxygens are each bound to the silicons and so have their valencé bonds already satisfied. The present writer would suggest that one of the chief reasons why the cummingtonite series shows rotation photographs similar to those of the tremolite series is because some of the large calcium atoms remain in the structure of the cummingtonite series and in view of the fact that the scattering power of Mg and Ca atoms is somewhat similar, the partial replacement of Ca atoms would not be noticeable.

In the case of the high iron members of the series, the grunerite rotation photograph was slightly different from that of tremolite. Warren concluded that this was partly due to the differences in scattering power of Fe and (Mg,Ca) but that the two structures were essentially similar.

CHAPTER 6.

THE MONOCLINIC AMPHIBOLES.

THE ALKALI AMPHIBOLES.

General Formula: $Na_{2-3}\ Ca_{0-1}\ Y_5\ Z_8\ O_{22}\ (OH)_2$

1. Introduction.

The general terminology of this groups was discussed in the calciferous amphibole chapter (Chapter 4,a) It was decided that this series should be termed the alkali amphibole series and that other terms, such as soda hornblende should be dropped.

It is clear that the alkali amphiboles are related to the hornblende series (and to the oxy-hornblendes) and that the substitution of Na for Ca, with certain other re-arrangements converts these series into the alkali amphibole series.

6 a. Terminology.

The early classification of this series given by Winchell (1951) was defined by four terms, glaucophane, riebeckite, arfvedsonite and eckermannite. Glaucophane was used as a collective term and covered three different minerals. The details of this original classification are given in Fig. 1. Clearly, there are many unsatisfactory features of this arrangement. The following is a resumé of the derivation and composition of the original minerals of the alkali amphibole classification. It is hoped that a consideration of these terms will reduce the terminology of the system and firmly establish the 'type' alkali amphiboles.

Glaucophane.

This term was first used by Hausman (1845). It was derived from the Greek and means 'to appear bluish green'. The term 'gastaldite' covers similar minerals but in the original form is more aluminous. 'Gastaldite' was first used by Struver (1875). The analyses of the original minerals glaucophane and gastaldite are given below.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
Isle of Syra (Glauc.)	56.49	12.23	-	10.91	0.50	7.80	2.40	9.34	tr.	99.63
Aosta (Gastaldaite.)	58.55	21.40	-	9.04	-	3.92	2.07	4.77	tr.	99.71

It can be seen that the original minerals of this group beth contain considerable quantities of FeO and rather smaller amounts of MgO. Fe_2O_3 is absent from both minerals. The term 'glaucophane' has been adopted in all the current classification of this section of the alkali amphiboles (Sundius 1946, Winchell 1951, Miyashiro 1957) as the magnesian end member of the glaucophane series. An inspection of the list of members of the series given by Miyashiro shows that nearly all his examples of natural glaucophane contain at least one atom of Fe''. Clearly the formula of natural glaucophane should read:-

$Na_2 Mg_2 Fe'' Al_2 Si_8 O_{22} (OH)_2$

The end member formulaa given by both Miyashiro and Sundius is:-

$Na_2 Mg_3 Al_2 Si_8 O_{22} (OH)_2$

Riebeckite.

In the Sundius and Miyashiro classifications, riebeckite is given as the ferrous iron end member of the glaucophane-riebeckite group. The original riebeckite was described by Sauer (1888) and came from the Island of Socotra in the Indian Ocean. The analysis of the orignal material is given below:-

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	FeO	MnO	CaO	Na_2O	K_2O	H_2O	F	Total
Original	50.01	-	28.30	-	0.34	9.87	0.63	1.32	8.79	0.72	-	-	99.98
Sundius	49.55	0.97	16.52	0.34	0.16	20.38	1.30	0.90	6.53	0.85	1.85	-	99.35
Sundius	51.79	0.68	14.51	1.28	0.10	21.43	1.15	1.28	6.16	1.10	1.30	.20	100.98

It is clear that this original mineral with its very high Fe_2O_3 and very low MgO, is very close to an iron end member of the series. It should be noted, at this point, that the theoretical end members of the glaucophane-riebeckite series really represent double end members, that is end members with respect to Al_2O_3 and Fe_2O_3 on the one hand and MgO, FeO on the other hand. The riebeckite of both Sundius (1946) and Miyashiro (1957) correspond with this analysis. The examples given by Sundius are given here as analyses 2 and 3. The Miyashiro examples are quoted in Table 13.

The end member formula can be written as follows:-

$Na_2 Fe_3'' Fe_2''' Si_8 O_{22} (OH)_2$

Arfvedsonite.

This mineral, from Greenland, was first described, and named, after the Swedish chemist Arfvedson, by Brooke (1823). The term was used to describe a mineral which was strongly pleochroic in the following colours:-

X	pale greenish yellow.
Y	Lavender.
Z	deep green blue.

The first recorded analysis is by Lorenzen (1882) and is given below:-

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O	Total
1.	43.85	4.45		3.80	33.43	0.45	0.81	4.65	8.15	1.06	0.15	100.80
2.	48.76	1.41	1.03	10.70	25.25	0.43	0.30	1.02	7.12	1.53	2.07	99.89

The mineral analysed occurred as black crystals with sodalite, eudialyte and feldspar. It is clear from the analyses given here that the original material was very close to an iron end member. The material from the original locality was re-analysed by Kunitz (1930) and is given above as analysis 2. The important features of the arfvedsonite composition are as follows:-

a. Moderately low alumina.
b. Presence of quantities of Fe"'.
c. Very low magnesia.
d. High soda.

There are two possible atomic formulae for this type mineral. The validity of each is discussed on page 145.

1. $Na_2\ CaO_{.5}\ Fe''_{3.5}\ Fe'''_{1.5}\ Si_{7.5}\ Al_{0.5}\ O_{22}\ (OH)_2$
2. $Na_3\ Fe''_4\ Fe'''\ Si_8\ O_{22}\ (OH)_2$

Eckermannite.

The original mineral was apparently described by Adamson (1942) and analysed by Mauzelius. The material was found to be richer in soda than any other known alkali amphibole. The analysis of the original mineral, given below, gave a type formula of :-

$$Na_4\ Mg_4\ AlFe'''\ Si_8\ O_{22}\ (OH)_2$$

The mineral was later purified and re-analysed by Bygden (Sundius 1946). On the basis of this new analysis, which showed quantities of lithium, the type formula was revised:

$$Na_3\ Mg_4\ (AlFe''')\ Si_8\ O_{22}\ (OH,F)_2$$

It can be seen that this formula is very similar to that of arfvedsonite, in formula 2 above,

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	ZnO	MgO
Mauzelius	56.45	0.39	5.47	9.47	1.90	0.52	0.67	9.43
Bygden	57.10	0.35	6.18	8.01	2.69	0.34	0.59	9.13

	CaO	Na_2O	Li_2O	K_2O	H_2O	F	Total
(cont.)	0.35	11.30	-	2.41	0.31	2.59	101.30
(cont.)	0.31	9.77	1.15	2.38	0.30	2.69	100.15

The claim by Miyashiro (1957) that eckermannite and the lithium glaucophane, holmquisite, are not alkali amphiboles because of their lithium content, does not appear to be fully justifiable. Li_2O is not usually estimated in amphibole analyses and it is therefore somewhat uncertain how many other members of the group are lithium bearing.

Soda-tremolite. $Na_2\ Ca\ (MgFe'')_5\ Si_8\ O_{22}\ (OH)_2$

This term was introduced by Berman and Larsen (1931) to describe a mineral which had the basic tremolite structure but contained a higher soda content than normal tremolites. Berman and Larsen do not give the complete analysis for this mineral but point out that it is not completely alumina-free and therefore tends towards the arfvedsonite composition.

The present writer considers that 'soda tremolite' is not a happy term and contains reference to the hornblende series. It will be shown later (Chapter 7) that tremolite is in almost complete solid solution with pargasite and may therefore approximate to the composition given by Berman and Larsen.

Richterite. $Na_2\ Ca\ (MnFe''Mg)_5\ Si_8\ O_{22}\ (OH)_2$

This term was coined by Breithaupt (1865). The character of the original mineral was apparently somewhat doubtful. A typical early analysis of the mineral from the type area Langban is given as analysis 1. Analysis 2 Blix and Sundius (1945) is on material from the same locality.

It will be noted that both these analyses show moderate MnO. Sundius points out that all the known minerals of the richterite type composition come from Fe-Mn deposits. This does not appear to be the case. Several soda tremolites or richterites which have the same structural formula are known to be manganese free or manganese poor (Larsen 1942).

Miyashiro (1957) describes this section by reference to the term soda tremolite. Richterite is retained to describe the manganese variety. The present writer suggests that there is, in this case, sufficient reason to re-arrange the original terminology. The term soda-tremolite should be dropped and the term richterite applied to minerals with this composition. Where appreciable quantities of manganese appear in the structure, the term manganese richterite should be applied.

	Cl.	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	FeO	MnO	CaO	Na_2O
1.	-	53.28	2.31	-	-	19.20	1.62	7.54	8.43	6.33
2.	0.04	53.80	1.37	0.10	1.89	18.45	-	8.69	5.43	5.63

(cont.)	K_2O	BaO	H_2O	F	Total
	0.06	-	0.71	-	100.08
	1.72	0.30	1.91	0.36	99.67

<u>Katophorite.</u>

The terminology, so far described, covers the classifications of the alkali amphiboles suggested by Sundius (1946) and Winchell (1951). It is also applicable to the terminology used by Berman and Larsen (1931). Miyashiro (1957) introduced a further sub-division into the system, namely the katophorite series. The end members of the series are given by Miyashiro as follows:-

Katophorite	$Na_2\ Ca\ Fe''_4\ Fe'''\ Si_7\ Al\ O_{22}\ (OH)_2$
Magnesio-katophorite	$Na_2\ Ca\ Mg_4\ Fe'''\ Si_7\ Al\ O_{22}\ (OH)_2$

The term 'katophorite' (katoforite, cataphorite) was first proposed by Broegger (1894) for an amphibole characterized by a deep reddish brown colour and a fairly large extinction angle. The mineral was originally described as a soda iron amphibole be tween barkevikite and arfvedsonite in its optical characters. The earliest analysis appears to have been given by Osann (1888) on material from Sao Miguel, Azores.

SiO_2	Al_2O_3	TiO_2	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O
45.53	4.10	-	9.35	23.72	2.96	2.46	4.89	6.07

(cont.)	K_2O	H_2O	F	Total
	0.88	-	-	99.96

It is seen that the above analysis is very similar to the No. 2 arfvedsonite analysis on page 132. Sundius (1946) regarded the katophorite minerals as being part of the riebeckite-arfvedsonite series. The magnesian end member of the series was designated as magnesio katophorite by Miyashiro (1957). This mineral is essentially the same as anophorite (Freudenburg 1910). It is intended to discuss the validity of the separate katophorite series in Chapter 7,f.

The Terminology of Minor Varieties.

Imerinite.

This name was given by Lacroix (1929) to a mineral from a contact metamorphosed limestone in Imerina, Madagascar. The composition was given as follows:-

SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	FeO	CaO	Na_2O	K_2O
57.73	2.72	0.41	4.72	20.60	4.70	2.73	7.42	1.82
7.58	.42.04	.04	.51	4.36	.55	.41	2.03	.32
8.00				4.91			2.76	

H_2O	F	Total.
0.85	0.92	100.62
.85	.92	
1.62		

The mineral was grouped by Sundius (1946) into the eckermannite series but was placed by Miyashiro in the soda-tremolite series. The structural formula, given above, shows that the mineral is more nearly soda-tremolite or richterite. Sundius, himself, indicates that the mineral shows departures from the theoretical ratios of the metal groups of the eckermannite series.

Tremolite-glaucophane.

An erroneous term for soda-tremolite or richterite. The term should be dropped.

Szechenyiite.

Described by Krenner (1900) from jadeite rock, Burma. The mineral is soda-tremolite or richterite and contains very slow sesqui-oxides. This term should be abolished.

Crocidolite.

Term derived from the Greek in allusion to the mineral's fibrous nature. Crocidolite was apparently known under a variety of names since 1811. Dana 6th. edition gives the composition near to that of riebeckite and observes that crocidolite is probably only a fibrous variety of this mineral. Currently the term appears to be in general use for the description of asbestiform varieties of alkali amphiboles. Crocidolite is an unnecessary term and should be dropped.

Osannite.

Both Sundius and Miyashiro place this mineral in the riebeckite group. An osannite from Portugal is used by Sundius (1946) to illustrate the composition of a typical riebeckite. The mineral was originally described by

Hlavatsch (1906) as Osannite. The term serves no useful purpose and should be abolished.

Crossite.

This term was proposed by Palache (1894) in honour of the American geologist Cross. The minerals covered by this term generally resemble glaucophane and riebeckite but have distinctive optical properties, which will be discussed later.

Crossite has been regarded, by some writers, as having a composition intermediate between glaucophane and riebeckite. Other writers, (as De Roever 1947), consider that crossite is identified as having an optic axial plane normal to (010) with b = Z.

The two definitions do not match. Miyashiro (1957) points out that optically defined crossite covers a fairly wide range of composition and could be included in the glaucophane series, or in the riebeckite or magnesio-riebeckite fields.

The present writer considers that although the range of chemical composition covdred by the term crossite is relatively wide, it is confined to a part of the galucophane series. It would be a pity to lose a term describing an amphibole of these unique optical properties.

Gastaldite.

This term has already been mentioned under the glaucophane heading. A mineral from the original locality was re-analysed by Zambonini (1906) and shown to be glaucophane. The term gastaldite should be dropped.

Ternovskite.

Introduced by Polovonkina (1924) to describe a mineral from Krivoi Rog, Ukraine. Ternovskite had 0.62 atoms of aluminium and 1.68 atoms of ferric iron. The magnesium content was almost twice the ferrous iron. The mineral was clearly of the riebeckite type. The term should be abandoned.

Heikolite.

Term proposed by Kinosaki (1935) and describes a mineral of the arfvedsonite type but with certain riebeckite characters. Amphiboles of this composition are included by Miyashiro (1957) in the arfvedsonite group.

Torendrikite.

Lacroix (1920) gave this term to an amphibole from the alkalic syentie at Torendrike in Madagascar. Miyashiro (1957) placed the mineral in the magnesio arfvedsonite series where it properly belongs.

Both Denaeyar (1924) and De Roever (1947) described the optical properties of so-called torendrikites. De Roever's amphibole was from the glaucophane schist group and showed a large departure of the absorption axes from the axes of the indicatrix, together with a relatively large extinction angle and low refractive indices. Miyashiro and Iwasaki (1957) described an amphibole with practically identical optics from the crystalline schists of Bizan. This mineral was certainly of magnesio-riebeckite composition.

Torendrikite clearly represents amphiboles of widely differing chemical composition. The term may have a small practical value but it is clearly useless in precise mineralogical description.

Taramite.

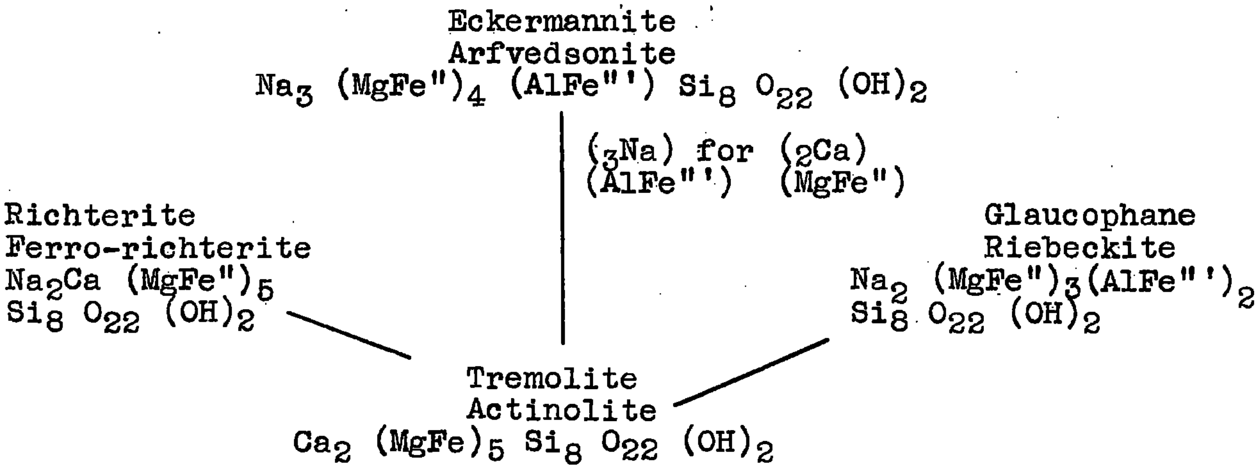
The fluor-taramites were described by Morozewicz (1925,30) from syenitic pegmatite of Mariupol in the Ukraine. Most of these minerals belong to the magnesio-arfvedsonite series and the rest to the magnesio-riebeckite series.

Barkevikite.

It is convenient at this point to give preliminary consideration to the mineral barkevikite which occurs at the Wohlerite locality near Barkevik on the Langesund fiord and elsewhere in Southern Norway. The colour is deep velvet-black with strong pleochroism in browns. Miyashiro (1957) excludes it from his consideration of the alkali amphiboles, stating that it belongs to the calciferous amphibole group. Sundius includes this mineral in the basaltic hornblendes because of its high Fe_2O_3 content and low (OH) content. Winchell (1945) ignores barkevikite but in Elements of Optical Mineralogy (3rd. edition 1946) barkevikite is placed in the basaltic hornblende section and called a variety of hornblende rich in ferrous iron and alkalis. In Hallimond's (1943) classic paper on the calciferous amphiboles, the barkevikites are firmly included in the calciferous amphibole series. It is proposed to leave the discussion of the classification of this mineral until the section dealing with the solid solution relationships in the amphibole group.

The Classification of the Alkali Amphiboles.

Having discussed the general terminology in the preceding paragraphs, it is now possible to illustrate the grouping of these terms into the classification systems. Although earlier work by Berman and Larsen (1931) and Berman (1937) was important and contributary, the first real step forward in the classification of the alkali amphiboles was made by Sundius (1946). The basis of his classification was as follows:-



Eckermannite
Arfvedsonite
$Na_3\ (MgFe'')_4\ (AlFe''')\ Si_8\ O_{22}\ (OH)_2$

$(_3Na)$ for $(_2Ca)$
(AlFe''') (MgFe'')

Richterite
Ferro-richterite
$Na_2Ca\ (MgFe'')_5$
$Si_8\ O_{22}\ (OH)_2$

Glaucophane
Riebeckite
$Na_2\ (MgFe'')_3(AlFe''')_2$
$Si_8\ O_{22}\ (OH)_2$

Tremolite
Actinolite
$Ca_2\ (MgFe)_5\ Si_8\ O_{22}\ (OH)_2$

This grouping was accepted in part by Miyashiro (1957). The riebeckite-glaucophane series was completely accepted and so was the richterite series renamed soda-tremolite. Eckermannite was shown to be somewhat unusual in having high lithium content. Miyashiro's proposal was to exclude this mineral but to include a magnesio-arfvedsonite. The arfvedsonite series was also to include, characteristically, 0.5 atoms of calcium in the 'X' position and 0.5 atoms of aluminium in the 'Z' position. Miyashiro introduced a further group, the katophorite group, this group was unique in that it contained one atom of calcium in the 'X' position and one atom of aluminium in the 'Z' position. The valency is maintained by the introduction of one atom of ferric iron into the 'Y' position.

In a general way the series of the Miyashiro classification are derived from two kinds of basic substitution:-

$$(\mathrm{NaK})\ R'' \longleftrightarrow R'''$$

$$(\mathrm{NaK})\ \mathrm{Al} \longleftrightarrow \mathrm{Si}$$

In the above R''' and R'' represent tri- and di-valent atoms, respectively, in six fold co-ordination. The first three groups of the Miyashiro classification, given below, being governed by the substitution $R'''\mathrm{Si} \leftrightarrow \mathrm{Ca}R''\mathrm{Al}$. This series is then called the riebeckite-arfvedsonite-katophorite series. Each series is then sub-divided on the basis of $\mathrm{Al} \leftrightarrow \mathrm{Fe}'''$ substitution in R''' and $\mathrm{Mg} \leftrightarrow \mathrm{Fe}''$ substitution in R''.

Riebeckite

$Na_2\ Fe''_3\ Fe'''_2\ Si_8\ O_{22}\ (OH)_2$

Riebeckite

$Na_2\ Mg_3\ Fe'''_2\ Si_8\ O_{22}\ (OH)_2$

Magnesio-Riebeckite

$Na_2\ Mg_3\ Al_2\ Si_8\ O_{22}\ (OH)_2$

Glaucophane

Arfvedsonite

$Na_2\ Ca_{0.5}\ Fe''_{3.5}\ Fe'''_{1.5}\ Si_{7.5}\ Al_{0.5}\ O_{22}\ (OH)_2$

Arfvedsonite

$Na_2\ Ca_{0.5}\ Mg_{3.5}\ Fe'''_{1.5}\ Si_{7.5}\ Al_{0.5}\ O_{22}\ (OH)_2$

Magnesio-Arfvedsonite

Katophorite

$Na_2\ Ca\ Fe''_4\ Fe'''\ Si_7\ Al\ O_{22}\ (OH)_2$

Katophorite

$Na_2\ Ca\ Mg_4\ Fe'''\ Si_7\ Al\ O_{22}\ (OH)_2$

Magnesio-Katophorite

Soda-tremolite $Na_2\ Ca\ Mg_5\ Si_8\ O_{22}\ (OH)_2$

Table 13 from Miyashiro (1957) shows the systematic sub-division of the alkali amphiboles on the basis of the R''' content. For these purposes R''' includes Fe'''+Ti +Al in six fold co-ordination and R'' includes Fe''+Mn+Mg.

Miyashiro points out that the end member of the arfvedsonite series contains no calcium but that in actual practice natural minerals of this series do in fact contain small quantities of calcium in their structures. This observation means that apart from the minor differences in terminology and the introduction of the katophorite group the two classifications are essentially similar.

The writer suggests that, in general, the classification, suggested by Miyashiro, is valid. The inclusion of the katophorite series is an important one because these are close to the calciferous amphiboles and it is useful to be able to distinguish chemically 'close' minerals by terminology. Fig. 37 also shows that katophorite has an end member status. The present writer feels that the Miyashiro arfvedsonite terminology is not valid because it is included between katophorite and glaucophane chemically and as such it is not an end member. The formula for arfvedsonite given by Sundius (1946) namely $Na_3\ Fe''_4\ Fe'''\ Si_8\ O_{22}\ (OH)_2$ would seem to be a more valid end member type. The present writer's diagram Fig. 37 shows this clearly. The point concerning the terminology of the soda tremolite series has also been made and this terminology should be revised in the Miyashiro classification.

6b The Chemistry of the Alkali Amphiboles.

Much of the chemistry of this group has already been discussed in the preceding sections. It was seen that, on a general basis, the alkali amphiboles are high in alkali and low in lime. content. In this series, also, the ferric iron content is much more important than in the claciferous amphibole s.

In previous sections the chemical analyses have always been recalculated, into the structural formula, on the basis of 24 (O,OH,F). In the Miyashiro lists given in Table 13 , it will be noted that the analyses were recalculated on the basis of O=2300, excluding the oxygen in H_2O. Miyashiro points out that this procedure is equivalent to the assumption of (OH, F) = 200 but was adopted because the water content of many of the analyses was unreliable.

Calcium.

In general the calcium content of the alkali amphiboles is less than 6.0% except in some katophorites and richterites. The lime content decreases regularly with increasing R"' content. The graph fig. 28 (from Miyashiro 1957) shows this relationship. It can also be seen that there is clear sub-division of the principal groups of alkali amphiboles on the basis of Ca/R"' content.

Sodium.

This element is the important member of the 'X' group in this series. It may be present in amounts of up to nearly 10.00% by weight of Na_2O as in eckermannite with 9.77% Na_2O. Eckermannite is, however, an unusual mineral and as a general rule amounts of Na_2O in the alkali amphiboles seldom exceed 7.00% by weight.

Potassium.

Most alkali amphiboles show quantities of potash in their structures. The Greenland arfvedsonite containing the highest recorded amount of 2.89% K_2O or 0.59 atoms of K. Usually the quantity is very much less than this and may in some cases be absent altogether.

Lithium.

Amphiboles containing this element in quantity have bee n excluded from the alkali amphibole series by Miyashiro (1957). If this reasoning were to be adopted as a general rule , amphiboles with, say, more than 1.00% TiO_2 should be grouped as seperate minerals. This is not normally done.

Eckermannites and holmquisites may have up to 1.12 atoms of lithium in their structures all of which is said to be contained in the 'X' position. It is pointed out that lithium has the same ionic radius as Mg, namely 0.78A° on this basis the 'Y' position is also a possible site.

Manganese.

This element is important in the richterite series and occurs in amounts of up to 8.65% MnO (mineral from Langban, Sweden. Sundius 1946) or 1.06 atoms of Mn per formula unit. Between one quarter to one half of the total

Mn content in the Swedish manganese richterites, enters the 'X' position.

Magnesium.

None of the natural alkali amphiboles is entirely without small quantities of magnesium. Probably the lowest amount was recorded by Palache & Warren (1911) in the riebeckite from Quincey, Mass.. This mineral contained only 0.10% MgO or .02 atoms of Mg per formula unit.

The highest recorded magnesia content was in a Swedish richterite (Sundius 1945). This mineral contained 23.67% MgO or 4.64 atoms Mg per formula unit.

Ferrous Iron.

Magnesium and ferrous iron are complementary in the Swedish richterites. Those showing the maximum MgO content contain no FeO. The maximum FeO content was recorded in an arfvedsonite from the Kola Peninsula. This contained more than 26.00% FeO or 3.53 atoms Fe" per formula unit.

Aluminium and Ferric Iron.

Table 13 shows that in the alkali amphiboles aluminium does not replace silicon to any great extent except in the katophor ite group and then only in amounts of up to 1.99 atoms per formula unit. In the glaucophane series replacement of silicon by aluminium rarely exceeds 0.35 atoms per formula unit whilst in the arfvedsonite series up to 0.62 agoms of aluminium enter the 'Z' position. All the richterites show some aluminium in this position and amounts of up to 0.65 atoms are known but are unusual.

In the case of the six co-ordinated aluminium, the amounts are usually very small, less than 0.2 atoms, in the cases of arfvedsonite, katophorite and richterite. Riebeckite shows similar low values for aluminium in this co-ordination but these increase to as much as 1.7 atoms per formula unit in the glaucophane field.

Ferric iron is complementary to six co-ordinated aluminium in the glaucophane series. Glaucophane itself has low ferric iron and high aluminium content. Riebeckite contains up to 2.33 atoms of ferric iron but very low aluminium. In all the natural examples of the richterite series, ferric iron is always less than 1.00 atoms per formula unit whilst the katophorite series usually contains about 1.00 atoms. This quantity increases to about 1.5 atoms in the arfvedsonite series.

In terms of weight percentages, the maximum alumina content occurs in glaucophane (gastaldite see section 6a) which has 21.4% Al_2O_3. This is exceptional and normal glaucophane analyses average 11% - 12% Al_2O_3.

The maximum Fe_2O_3 content recorded is about 17.00% in some riebeckites. The average for this series, is, however, less than this, usually about 14% -16%. Ferric iron is never entirely absent from the alkali amphiboles but some richterites show only small amounts, as little as 0.29%

has been recorded.

Silicon.

As already stated the amount of aluminium replacing silicon is nearly always less than 1.00 atoms, per formula unit, in the alkali amphiboles. This means that the variation in silica content is small. The katophorite group usually show the lowest silica values and average about 44.00% by weight. The richterite and glaucophane series have the highest silica content and amounts of up to 57.74 % by weight have been recorded from minerals of this type.

Fluorine.

The number of fluorine determinations on members of the alkali amphibole series is small. Fluorine is present in many examples in amounts of up to 1.00 atoms per formula unit. The fluor-taramites or magnesio-arfvedsonites all contain fluorine in amounts greater than 0.80 atoms per formula unit. Contrary to the original belief, this is not a characteristic of fluor-taramites because analyses of eckermannite and imerinite (richterite) often show rather more than 1.00 atoms of fluorine per formula unit.

Water.

The (OH) contents of the alkali amphiboles show the same wide range as the calciferous amphiboles. The highest recorded amount is 1.73 atoms per formula unit in a riebeckite (No. 9 Table 13). The (OH) content is normally less than this; about 1.00 atoms per formula unit being usual. This is not entirely due to the oxidation of ferrous iron to ferric iron because even the glaucophane, low in ferric iron, show low water content.

6c. The Physical Properties of the Alkali Amphiboles.

1. Optical Properties.

In the consideration of the calciferous amphiboles series it was stated that the optical properties of the series differed from those of the alkali amphiboles. This was one of the reasons why parallel terminology for the two series was abandoned by the present writer. It is important at this stage to summarise the differing optical characteristics of the two series.

In the first case Winchell (1946) shows that the majority of the alkali amphiboles, with the probable exception of glaucophane and some katophorites, have negative elongation. In the case of glaucophane, the extinction angle ($Z \wedge c$) is quoted as betwwen 4° and 6°. This is considerably lower than most calciferous amphiboles with the exception of the oxy-hornblendes. The katophorites which show positive elongation have extinction angles of between 30° to 60° and these are for the most part greater than the normal hornblende values.

It will also be shown, in this section, that the axial colours of the alkali amphiboles are generally more intense than those of the hornblende series. This is an unreliable diagnostic property but it is useful to note as a general guide.

Although synthetic alkali amphiboles have been made (Carnegie Inst. Rep. 1957-58) no optical data is available. In the following paragraphs the optical limits are quoted from the purest end member material available. The optical data for analysed minerals, taken from Miyashiro (1957) is given in Table 14.

The Glaucophane-Riebeckite Series.

In all pure glaucophanes the optical orientation in b = Y. The extinction angle $Z \wedge c$ is normally small but is usually greater than the maximum of six degrees given by Winchell (1946) and angles of up to 14° are known. The optic angle (2V) is very variable amongst the end members types of the glaucophanes proper and varies from 10° to 41° about X. The optic plane in all proper glaucophanes is paralle 1 to (010). These minerals were called by Miyashiro (1957) parallel-symmetric.

The refractive indices of glaucophanes together with the richteries⅞are amongst the lowest in the alkali amphiboles with Ng between 1.627 and 1.640. Np is between 1.606 and 1.619. The birefringences on the other hand, in both the glaucophanes and the richterites is high. This ranges from

0.019 to 0.020 in the glaucophanes.

With the increase of Fe" and Fe"' the optic angle in the glaucophane series approaches zero and the mineral becomes unaxial type, then with a further increase it becomes larger again in the plane normal to (010). Amphiboles having such optical orientation are termed 'crossites'. In such minerals b = Z and $Y \wedge c$ is small (2° to 15°). A number of authors, Tschopp (1923), Horikoshi (1936) and De Roever (1947), have described near uniaxial amphiboles on the boundary between crossite and glaucophane.

In the case of the optical properties of the riebeckite end member, the literature shows a variety of contradictions and confusions in the descriptions. This is probably the result of the very strong absorption shown by these minerals. In riebeckite itself b = Z and $X \wedge c$ is very small (0° - 5°). The minerals has been reported as either optically positive or optically negative. In one case (Miyashiro and Miyashiro 1956) riebeckite failed to show complete extinction in monochromatic light.

The optic angle 2Vx varies from about 50° to 112°. Ng-Np is usually very low and of the order of .003 to .008. The Ng refractive index is usually close to 1.700 with the values for Nm and Np very similar to this.

The axial colours of the glaucophane-riebeckite series vary considerably, thus:-

	X	Y	Z	
Glaucophane	Pale Yellow	Bluish Violet	Blue	$X<Z<Y$
Crossite	Pale Yellow	Blue	Violet	$X<Y<Z$

Riebeckite ($X_\wedge C$ small)	X Green-Blue	Y Brown-Yellow	Z Bluish-Grey	$Y<X<Z$
" " Winchell (1946)	Indigo Blue	Brown-Yellow	Dark Grey	$X>Y>Z$
" "	Deep Blue	Violet	Pale Green-Yellow	
" "	Smokey-Green	Yellow	Green to Black	
" "	Green-Blue	Clear Yellow	Blue-Violet	

The Arfvedsonite Series.

In this series, the iron end member, arfvedsonite, shows extinction angles which vary from $X_\wedge c$, 0° to 30°. The orientation is b = Z and the Ng values range between 1.68 and 1.71. Np varies between 1.67 and 1.70. The birefringence Ng-Np is very variable and ranges from .005 to .012. Most writers agree that the 2V is difficult to measure because of the strong absorption shown by this mineral.

Miyashiro (1957) states that the description of the pleochroism of arfvedsonite, in the literature, are confused. Winchell (1946) gives the following:-

X	Y	Z	$X>Y>Z$
Deep Blue-Green	Brown-Yellow	Bluish-Grey	
Berlin Blue	Violet	Greenish-Yellow	
Deep Green	Blue or Brown	Grey or Green-Brown	

Miyashiro points out that arvfedsonite resembles riebeckite in all its optical properties except the extinction angle $X_{\wedge}c$. As in the case of some riebeckite, many arfvedsonites do not show complete extinction, between crossed nicols, even in monochromatic light. This phenomenon was studied by Eskola and Sahlstein (1931), Iwao (1939), Shoda (1954), Sahama (1956) and Shoda (1956).

In the magnesio-arfvedsonites the orientation is b = Z. The extinction angle $X_{\wedge}c$ is large and varies between 18° and 50°. The birefringence Ng-Np is moderate for the alkali amphiboles and ranges from .010 to .020 with the values for Ng between 1.66 and 1.67. Np is from 1.65 to 1.66. The optic axial angle is very variable and ranges from 41° to 72°. The pleochroism is uncertain but the colours are generally similar to those of arfvedsonite.

The Katophorite Series.

As already indicated the katophorites can have either positive or negative elongation. In some katophorites b = X, $X_{\wedge}c$ is between 36° and 70° whereas in other members of the series b = Y and X c is 52° - 56°. At the boundary between the two cases b = Z and b = Y the mineral is uniaxial negative. In the katophorite series, in general, the optic angle 2Vx varies between 0° and 52°. The Np index ranges from 1.639 to 1.681. The upper limit of the Ng refractive index is not known. The values for the birefringence, given in the literature are very variable and range from .007 to .021.

In crystals with b = Z the pleochroic scheme is X=pale brown, Y=greenish brown and Z=deep purple reddish brown. Katophorites with b=Y show X=yellow, Y=deep brown and Z=greenish brown.

The Richterite Series.

For the most part the optical properties of this series are straight forward b = Y, Z c = 15° - 45°, 2Vx=66-87. The Np refractive index is between 1.60 and 1.65 with Ng up to 1.66. The birefringence Ng-Np is moderate to high ranging from .009 to .022. With regard to the axial colours, some richterites are colourless but others may show marked pleochroism from yellow to green or from green to blue.

2. Density.

The density data available for the alkali amphibole series is very scanty. The approximate values for the various type members are given in the table below:-

Riebeckite	3.44
Glaucophane	3.0 - 3.5
Arfvedsonite	3.33 - 3.45
Richterite	2.99 - 3.08

6d The Crystallography of the Alkali Amphiboles.

The various morphological crystallographic data are given in Dana 4th. and 6th. editions and it is thought to be unnecessary to reproduce it here. In general this data is not especially characteristic of the *alkali amphiboles*. With regard to the X-ray data, this is scanty in the extreme and the present author was not able to find any satisfactory X-ray powder data in the literature. Some data is given for synthetic fluor-richterite (Kohn and Comeforo 1955) but the synthetic fluor amphiboles show physical properties which are rather different from the natural minerals (Bowen and Schairer 1935) and the data from them is useless for present purposes.

Table 15 given here is from Sundius (1946) and sets out the crystallographic data of all types of amphiboles. It is clearly seen that there is little in this table to distinguish the alkali amphiboles from the calciferous types.

CHAPTER 7

SOLID SOLUTION RELATIONSHIPS AND GRAPHICAL PRESENTATION OF THE AMPHIBOLE GROUP.

1. Introduction.

Although Sundius (1946) stated that the data was insufficient to settle all the questions concerning the solid solution relationships in the amphibole group, several hundred analyses are available from the literature and the gaps in the various series of the group should at least be indicated. It is clear from the foregoing chapters, describing the chemistry of the group, that the major substitutions and therefore the major solid solution relationships are governed by three principal elements or element groups.

1. Sesqui-oxide substitution.
2. Fe" - Mg substitutions.
3. Lime-alkali relationships.

The consideration of the solid solution relationships can be divided into two principal groups, namely:

a. The relationships in the individual series.
b. Solid solution, in the amphibole group as a whole.

It is proposed to consider the relationships in the individual series first.

7 a Anthophyllite Series.

It has already been shown that the anthophyllite series is one of limited isomorphism. The series is a three component one involving, chiefly, magnesium, iron and aluminium. Ferrous iron replaces magnesium from about 5% to about 50% of complete replacement calculated on an atomic basis. Aluminium replaces silicon nearly up to 2 atoms and the same is true of its replacement of Mg and Fe". The formula $(Fe\ Mg)_5\ Al_2\ Si_6\ Al_2\ O_{22}\ (OH)_2$ is thus nearly fulfilled. Fig. 29 from Rabbitt (1948) shows the limits of the various substitutions. The alkalis and lime included in the diagram have very little effect. There is clearly absence of complete solid solution in the high Fe" high Al_2O_3 fields.

The present writer suggests that the solid solution relationships should be referred more properly, to a four component diagram with Fe_2O_3 seperated from the FeO and used as the fourth component. The reason for this is that the anthophyllites may contain up to 8.00% by weight of Fe_2O_3. Four component diagrams are complicated and it is suggested that when an anthophyllite shows more than 6.00% Fe_2O_3 on analysis it should be given the name ferric anthophyllite as distinct from Rabbitt's ferrian anthophyllite. The reasons for this change were discussed earlier in Chapter 4. Table 2 shows that high ferric iron members of this series contain relatively low alumina and that, therefore, there would not be any great complication in the fourth component.

Under the present writer's terminology Rabbitt's ferroan anthophyllites should be renamed ferrous anthophyllite and should be confined to the field indicated on the diagram.

7b Cummingtonite Series.

The chemical data available for this series are too few to draw any firm conclusions. It is clear that the series must be referred to a three component system containing manganese, iron, and magnesium. The critical amounts of calcium already mentioned in the cummingtonite section are interchangeable with the eight co-ordinated manganese. Aluminium appears in the system but is not of great importance and there is definitely an area of incomplete solution in the kupfferite field. All these relationships have been discussed in the Cummingtonite Chapter.

7c Calciferous Amphibole Series.

This series has been investigated as completely as possible by Hallimond (1943), Winchell (1945) and Sundius (1946). Hallimond showed that the calciferous amphiboles, including the oxy-hornblendes could be set out on the partial triangular diagram described in Chapter 4. It should be noted that this is really a two axis diagram and not a triangular diagram in the true sense of the word. The number of atoms in the vacant space is represented as one axis and the number of silicon atoms as the other. This diagram Fig. 12 shows that there is a non-continuous series between the tremolite and pargasite series. The present writer has shown, on a triangular diagram, Fig. 30, that continuous solid solution between the tremolite series and the common hornblendes exist only over a small range of compositions.

This question of this continuous series between tremolite and common hornblende is clearly a vexed one and has been examined by various writers who have reached opposing conclusions. Beskov (1929) decided that there were areas of considerable immiscibility between the two series. Kunitz (1930) showed that there were transition relationships between the two and Berman (1937) considered that there was little isomorphism between the tremolite series and the common hornblendes.

Sundius (1946) claimed that the evidence of the physical properties is inconsistent with the existence of transitional relationships. In other words that there cannot be a progressive enrichment of the tremolite series in sesqui-oxides. Sundius does agree however that the area of unmixing must be small. It is proposed to discuss in the next chapter the reasons given by Sundius for his suggestion but it can be seen, on a chemical basis, that there is some evidence for a small compositional break between the two series. This occurs only in the field of the highly magnesium rich members. There is, in fact, on the Hallimond diagram a slight discontinuity in the region of 7.25 atoms of silicon. This area is lightly shaded on Fig. 12. This amounts to a break of between 0.7 and 0.8 atoms and covers part of the Sundius gap which extends from 0.6 to 1.12 atoms of Al iv. In actual fact the gap shown by the Hallimond diagram should be almost non-existent in part of the field at any rate. Table 16 shows a list of minerals from the literature covering this gap. These show a range of Al^{iv} from 0.633 to 0.822 atoms. It should be remembered that the Hallimond diagram covers minerals which include high iron varieties as well as those rich in magnesium. Sundius in his discussion of this gap confines himself to the examples with between 90 to 100 parts of magnesium in the structure. A review of the literature shows that, even so, the gap is somewhat smaller than Sundius estimated. No. 1 in Table 16 is well within the allowed limits of magnesium content and yet contains .757 atoms of Al^{iv}. A further point is that Sundius shows that the change over to the sesqui-oxide rich minerals is accompanied by a change in optic sign from -ve to +ve. The example quoted here has a 2Vx of 84° and is therefore nearly positive. The gap has now been reduced to between 0.76 to 1.12 atoms Al^{iv}.

It is clear from the foregoing paragraph that there is continuous solution between the tremolite series and the common hornblende series in limited areas only and is mostly confined to fields of moderate iron and magnesium content.

Hallimond's diagram shows that minerals of edenite and tschermakite composition are extremely rare. Edenite can certainly be made synthetically and there are therefore grounds for suggesting that the blank areas of the diagram are not fields of immiscibility. The reason for the gaps would then appear to be that the natural conditions are such that they are unfavourable for the formation of natural edenites. Similar reasoning could be applied to the clear field in the tschermakite area although the area in which natural minerals do not occur is much smaller.

With regard to the coverage of the terminology, it would appear reasonable to limit the tremolite series to minerals containing up to .76 atoms of aluminium replacing silicon and up to 0.5 atoms of NaK in the vacant space. The tremolite field would thus be limited to negative minerals containing 90 to 100 parts of Mg. The edenite field would be composed of the area of apparent immiscibility from 6.6 to 1.0 atoms NaK in the vacant space and also bounded by silicon atoms from 6.8 to 7.4. The other area of immiscibility, the tschermakite field should extend from NaK equal to 0 to 0.5 atoms and silicon equal to 6.0 to 7.3 atoms. The pargasite type minerals are very abundant and form a useful collective group and would satisfactorily be included in the remaining part of the diagram. Fig. 31 shows the limits of the various end members with respect to silicon and NaK in the vacant space.

The relationships between the Fe" and Mg substitutions in the hornblende series are shown very clearly on the Winchell (1945) partial prism diagram Fig. 32. The various series represented tend to be almost completely filled out to the iron end member only in the case of minerals of the theoretical pargasite-hastingsite composition. There are areas of considerable immiscibility, with respect to the iron members, in the actinolite, edenite and tschermakite fields although in the latter case natural tschermakites tend to be rather more iron than magnesia rich. The writer's diagram Fig. 30 shows that there is a considerable field of immiscibility between 10 actinolite and hastingsite.

7d The Alkali Amphiboles.

The diagrams of Miyashiro (1957) Figs. 28, 33, show no noticeable discontinuities or gaps between the various subsidiary members of the alkali amphiboles. The small gap between the soda-tremolite group and the katophorites may only be due to lack of data. A consideration of the sesquioxides and ferrous iron shows the presence of a number of discontinuities in the sub-groups of the alkali amphiboles. The Miyashiro diagrams Fig. 34 for the glaucophane series show that it can be subdivided into five groups on the basis of Fe"/R" plotted against Fe"'/R"' all calculated in atomic proportions. The nature of R" and R"' has already been explained in Chapter 6. Fig. 34 shows that there are two areas, delineated by the two ratios, in which glaucophane minerals do not occur. These are marked by shading. Natural minerals of the ferro-glaucophane and sub-glaucophane types are rare.

In the cases of the other members of the alkaline group, the data is insufficient to form any major conclusions but Fig. 35 from Miyashiro (1957) show the boundaries of their occurrence with respect to the ferrous and ferric iron ratios mentioned above.

Miscibility Relationships in the Amphibole Group as a Whole.

In Table 15 the physical data for the various members of the amphibole group were given. This shows that only in the case of the anthophyllite series was there any marked discontinuity of those properties. Sundius (1946) suggests that the β angle relationships indicate a possible continuous series between the calciferous and alkaline series thus:-

106° 02'	Tremolite Series
105° 45'	Common Hornblendes
103°-104°	Alkali Amphiboles

There are exceptions to this, for example Osannite (riebeckite) shows a β angle of 107° 34'.

Sundius (1946) in his classification of the hornblendes plotted the compositions of the alkali amphiboles and the hornblendes on a triangular diagram (Fig. 36) with co-ordinates Ca, NaK and AlFe"' all in atomic proportions. Sundius' assumption that the number of silicon atoms remains theoretically similar in all alkali amphiboles is incorrect (see katophorite previous chapter). Sundius also points out that the diagram also displays the calciferous amphiboles adequately but that the greatest short-coming is the excess of Fe"' in many analyses and for this reason many of the members of the eckermannite-arfvedsonite series mix with the glaucophane riebeckites. Another difficulty, the present writer sees is the relationship between tremolite edenite and *richterite*. The composition of at least one *richterite* appears to be very close to that of edenite and the close relationship between tremolite and *richterite* is not clearly brought out in the diagram. Sundius suggests that if due regard is made to the Fe''' content, the majority of the *richterites* would then align themselves in their proper place along the base line of the diagram. The broken line in the diagram indicates the area of unmixing in the hornblende series.

In the discussion Sundius states that the amphiboles corresponding to the outermost points of the alkaline group, i.e. those nearest the calciferous group, always behave optically as alkali amphiboles and similarly all the calciferous amphiboles close to the alkaline types behave as calciferous types. It is claimed that these facts support the suggestion of an area of unmixing between the two types.

7f Graphical Presentation.

The present writer suggests that the Sundius diagram is unnecessarily complicated and does not take into account the other members of the amphibole group, the anthophyllites and the cummingtonites. It is suggested here that a triaangular diagram is not required but that the position of all the major types of amphibole can be plotted on a simple two-axis diagram, Fig. 37. This diagram fits in with the theories out-lined in previous chapters, concerning the formation of the cummingtonite/anthophyllite series. It also allows for possible substitution in the calciferous amphiboles to form the alkali types. The position of the katophorite series is shown and because this is close to the calciferous amphibole series but with somewhat characteristic optical properties, it is felt reasonable to maintain this term in the alkali amphibole group. The oxy-hornblendes are also clearly defined.

One major difficulty of many of the graphical presentations of the amphibole group is the question of the difference between the theoretical value for the number of calcium atoms in the 'X' position in the calciferous amphiboles, namely 2.00 atoms and the actual value, which although is nearly 2.00 in most cases, often requires a proportion of sodium to make it up to the theoretical limit. In the writer's diagram all this should be accepted as the calcium content.

The problem in Sundius' diagram of the ferric iron is not so important in Fig. 37 because the various groups are clearly seperated and the iron rich types can be represented in the third dimension which should be graduated from 0 to 7.00 atoms Fe".

A cross check to see if there is any continuous relationship between the soda rich and calcium rich amphiboles is given in Fig. 38. It is noticeable that there is only one case where there is any mixing of the two groups.

The analysis of this so-called richterite is given by Sundius (1946, No. 9, Page 9) and from this it is clearly seen that the mineral is tremolite in composition. The amount of Mn is certainly high, but the present writer knows of no provision in any of the classifications which would preclude the presence of the Mn in tremolite.

	Si	Al	Fe"'	Fe	Mg	Mn	Ca	Na	K	H	F
Atom. Props.	7.78	0.04	0.50	-	4.32	0.82	1.68	0.08	.62	1.28	-

It is unfortuante that the optics of the mineral are not available for cross checking but in the absence of complete data it would be unwise to accept this analysis as evidence of solid solution between the two series. The other points close to the boundary of 1.5 atoms would be excluded from further consideration because of their high sesqui-oxide content.

With regard to Fig. 37 which shows the relative positions of all the amphiboles, it is clearly seen that the anthophyllites are more closely related to the calciferous amphiboles by substitution than from the alkali amphiboles. The reason for this is that the total number of sesqui-oxides in the sesqui-oxide rich anthophyllites is greater than in the alkali amphiboles. Thus aluminium anthophyllite would be derived from tschermakite and there would be no intermediate cummingtonites. Reference to the crystal structure shows that the change-over would be sharp and that there would be no solid solution series between the two groups.

7g Summary.

In all groups of amphiboles there are compositional fields in which natural amphiboles do not occur. These fields have been particularly noted in the anthophyllite and hornblende series. With regard to the solid solution relationships between the groups there is some evidence of partial chemical continuity between the richterites. and the tremolites. There is also some appearance of continuity between tremolite and cummingtonite. Numbers 14 and 17 in the Hallimond list Table 9 have only 1.57 and 1.54 atoms of calcium respectively. The presence of manganese in eight fold co-ordination could well be the bridge between the tremolite series and the cummingtonites. In view of the lattice changes required to form the orthorhombic anthophyllites there can be no unbroken solid solution series between this series and hornblende-cummingtonite. There is, however, the possibility of miscibility, at high temperatures similar to the pyroxene relationships.

The diagram Fig. 37 shows clearly the position of the barkevikites and the oxy-hornblendes. The former are clearly members of the oxy-hornblende series. Unfortunately it does not distinguish between the various types of oxy-hornblende although those with the lowest sesqui-oxides will tend to be ferri-tremolite and ferri-edenite. There is some indication that oxy-hornblendes may be in solid solution series with the hornblende series. Many hornblende analyses show water contents lower than 2 atoms; this may notbe altogether due to errors in analysis but may show a trend towards oxyhornblende type.

CHAPTER 8

THE CORRELATION OF PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION IN THE AMPHIBOLES GROUP

1. Introduction.

It is clearly impossible to analyse every amphibole which is encountered in day-to-day petrology. Some system has to be devised whereby an idea of the chemical constitution and therefore the position in the classification of any amphibole, could be determined by easily measureable physical properties.

The difficulties of the earlier workers were obvious. There was for example no satisfactory definition of the structure of the amphibole molecule. The chemical analyses of the times were largely incomplete and inaccurate. For the sake of a complete record some of the views of these earlier workers will be given.

It is proposed to divide this section into two major parts. The first part will deal with the methods of establishing, by physical properties, the particular group to which an unknown amphibole may belong. The second part will review the methods of estimating chemical composition from physical data within each amphibole group.

8a Method of Identifying Class of Amphiboles.

The amphiboles, as already shown, can be divided into two major groups on the basis of crystallography, namely the orthorhombic and monoclinic types. At first sight this would appear to provide an immediate method of distinction between the two types. All orthorhombic minerals show straight extinction and all the monoclinic minerals should show oblique extinction. The added complication of straight extinction, almost uniaxial, alkali amphiboles (Chapter 6c) is not important at this juncture.

In practice, in certain sections, many monoclinic minerals show straight or near straight extinction. This feature has resulted in many classic cases of false identification of members of the orthorhombic anthophyllite series. Three principal published instances of this are:

1. Amosite (Peacock 1928) Correctly Tremolite.
2. Ferro-anthophyllite (Shannon 1921) Correctly Actinolite.
3. Manganese anthophyllite (Slavik and Vesely 1927) Correctly Cummingtonite.

A number of other examples are given in Rabbitt (1948) but these given above are sufficient to show that anthophyllite can be very easily mistaken for cummingtonite or tremolite, both of which are monoclinic.

The other physical properties, which were discussed in the appropriate sections, show that these cover the same ranges in this respect for both the monoclinic and orthorhombic minerals. It was also seen that although the term anthophyllite means 'clove', all members of this series are not brown in colour, a number are colourless whilst others are pleochroic in yellows, greens and browns.

It has been shown in Chapter 3d,1, that the cleavage angle of anthophyllite is smaller than that of the other monoclinic minerals with the exception of cummingtonite. This property is apparently only of importance when the orientation of the section is known and when the cleavage angle can be measured with considerable accuracy.

It is clear therefore that the identification of minerals of the anthophyllite series as distinct from the monoclinic types, by optical methods, is in some cases very difficult and uncertain. This is particularly so in the cases of the more fibrous types.

8a 1 X-Ray Methods.

The unit cell of anthophyllite was shown by Warren and Modell (1930) to contain twice as many molecules as the monoclinic cell. This leads to doubling along the 'a' parameter, thus in anthophyllite 'a' equals approximately 18.5Å as compared to 9.8Å in the monoclinic amphiboles. The β angle which is obtuse in monoclinic amphiboles is of course 90° in anthophyllites.

Rotation photographs are more difficult and time consuming to take than the simple powder photograph. From the measurements of the cell dimensions it would be expected that there would be differences in the position of the respective characteristic powder photo lines. This is, in fact the case, and the powder photo therefore presents the best method of distinguishing between ortho and clino amphiboles.

Anthophyllite	Rabbitt (1948)	Tremolite	Edwards N.Y.
d.	I	d.	I
3.030	10	3.142	10
3.235	9	2.705	9
2.531	8	2.522	8

Tremolite	(Layton)	Cummingtonite	Johansson 1930
d.	I	d.	I
3.12	str^1	2.754	10
2.70	str^2	1.406	9
2.534	str^3	2.187	8

8a 2 The Cummingtonite Series.

It was shown above that only by X-ray determination can anthophyllite be distinguished from cummingtonite with any surety. With regard to the distinction between this series and the hornblende series, the difference in the powder patterns have been noted above.

In the case of the optical properties, many of the published cummingtonite optical properties fit very closely to the Winchell (1951) prism face diagrams for the hornblende series. The Mount Humbolt grunerite, for example, number 4 in Table 11 fits closely to 60% ferro-tremolite and 10% edenite. The major difference the present writer is able to find appears to be in the axial colours. The grunerites tend to be either pale or colourless whilst the hornblendes of that composition would almost certainly be moderately strongly coloured.

A better fit on the same Winchell diagram is a pale brown-violet cummingtonite from Strathy, number 11 in Table 11. It is thus possible to misidentify cummingtonite using Winchell diagrams.

The birefringence of the cummingtonite series particularly at the grunerite end of the scale, is very high. Fig. 39 shows plot of Ng against Nm. The solid line on the same graph is the position of the Ng against Nm line for the common hornblende series. From a consideration of the equivalent line for the cummingtonite series it is easy to see that the grunerite members can be readily identified. At the magnesium end the lines for the two series converge and it is here that the likelihood of misidentification could occur.

Probably the best method of distinguishing cummingtonites from members of the hornblende series, where both series have essentially similar optical properties, is by the axial colours. Most of the natural pargasites and edenites are moderately coloured and all of the pale coloured minerals of the tremolite series which could be mistaken for pale coloured cummingtonites are negative. Such cummingtonites would be positive in this field. Although the above provides a possible method of identification, it is very unreliable and should not be used where alternative methods are available.

8a 3 The Alkali Amphiboles.

In the previous pages, it has been shown that it is relatively difficult to be sure of the group identity of any of the calciferous amphiboles by the use of normal optical properties. It is possible however to classify an amphibole by X-ray powder photography. By this means anthophyllite, cummingtonite and hornblende can all be distinguished from one another.

The alkali amphiboles have extremely variable optical properties owing to the variable positions of the indicatrix. By the use of the writer's diagrams it is relatively easy to distinguish the cummingtonites from all the alkali amphiboles. In Fig. 39 it can be seen that the Ng against Nm line for the cummingtonite series is well clear of the corresponding line for the alkali amphiboles.

Reference to the equivalent diagram for the hornblende series shows that the Ng onto Nm line for hornblendes cuts the cummingtonite line in the low refractive index end and it also cuts the alkali amphibole line at the high refractive index end.

It will be remembered that most hornblendes with high refractive indices, mostly the hastingsites, show extinction angles of between 15 and 20 degrees or at any rate greater than 15°. All the representatives of the alkali amphiboles, in the region where the two lines meet (numbers 42, 2, 36, 4 and 37 from Table 14) all have $Z \wedge c$ extinction angles greater than 75°. Thus by a consideration of Fig. 39 and by reference to the relevent extinction angle, the alkali amphiboles can be distinguished from the hornblende series.

An examination of Fig. 40 showing the plot of the birefringence against Ng shows clearly that a distinction between tremolite and the alkali amphiboles is readily possible. It is also fortunate that the Ng against Nm line is displaced from the hornblende line in Fig. 39, because the richterites have apparently very similar optical properties and orientation to tremolite. Even the axial colours, , colourless, yellows and greens and green to blue resemble tremolite.

8b Prediction of Composition from Physical Properties within each Amphibole Group.

Probably the earliest attempt to correlate optical properties and composition was made by Tschermak (1871). He appreciated that the iron-content had a large effect on the optical characteristics and showed that in the tremolite series the optic angle decreased with increasing iron content.

The extinction angle $Z \wedge c$ was probably the easiest optical property to measure. It is therefore not surprising that much of the early work, on the correlation of chemical composition and optics was done with reference to this property. Wiik (1883, 1886), Broegger (1894) and Murgoci (1906) all made observations of the effects of the various chemical components of the amphiboles on the extinction angle. Wiik noted that in certain hornblendes, from Finland, the extinction angle $Z \wedge c$ increased with increasing alumina content. Curves were constructed to illustrate this feature. Later work has shown that such alteration of the extinction angle by alumina is not a universal property of the amphiboles. Broegger, in similar work, observed a concomitant increase in the extinction angle with the increase of ferrous iron and alkalis. This work of Broegger's has been proved by the present writer to be partially correct. Riebeckite for example has high ferrous iron and high soda; its extinction angle on $Z \wedge c$ is large.

Murgoci, in a rather more comprhensive study of the glaucophane amphiboles, regarded Fe_2O_3 or $Fe_2Si_3O_9$ as the most influential chemical constituent on the optical properties, not only in the glaucophane series but in the amphibole group in general. He suggested that 2V, the position of the axial plane and even the extinction angle were related to the amount of Fe_2O_3 in the structure.

In a general examination of the whole amphibole group, however, Murgoci found that the extinction angle was related neither to the percentage of Fe_2O_3 nor to the percentage of Al_2O_3 but to the proportion of their molecular co-efficients of combination in the amphibole structure. This latter observation is interesting because 19 years later in 1925 Porter showed that in experimental mixtures of ammonium and rubidium magnesium chromate the variation in optical properties, the refractive index in this case, was

was proportional to the molecular percentage rather than to the percentage weights. From his investigations Murgoci concluded, that, with the increase of the molecular ratio $Fe_2O_3 : Al_2O_3$ there was a corresponding increase in extinction angle. The present writer finds that this is the case in the glaucophane-riebeckite series where the extinction angle varies from 4° to 6° in glaucophane up to 85° in riebeckite as the composition changes from aluminium rich to ferric iron rich. With the increase of Fe_2O_3 there is also a decrease in the optic axial angle. An inspection of the examples of the glaucophane riebeckite series in Tables, 14, 13, shows that this is also the case.

Murgoci concluded that alkali amphiboles of this type with Fe''' : Al equal to 1 : 3 were uniaxial and that with more ferric iron the optic plans became normal to (010). These conclusions were found to be substantially correct by Miyashiro in his analysis of the alkali amphibole group.

Murgoici's final conclusions of importance here, was that an increase of ferrous iron at the expense of magnesia, had little effect on the optical properties. This latter observation has been shown to be untrue both by previous writers and the present author.

Kreutz (1908) after detailed studies of many kinds of amphibole, concluded that, the optical and chemical properties could only be correlated in limited parts of the amphibole group. He also found that the same oxides produced different reactions in different parts of the group. This has also been found by the present writer and it will be shown later that the same oxides in different co-ordination produce different optical effects. On the basis of his work, Kreutz decided that the chemical components of the amphiboles could not exist as simple oxides but rather as complicated molecules. In the tremolite series it was noted that there was no corresponding increase in birefringence with increasing FeO content as there should be if the FeO was present as the grunerite molecule. In the case of pargasite, Kreutz suggested that the molecule $Ca\ Mg_2\ Al_2\ Si_3\ O_{12}$ was present and that an increase in the tenor of this molecule caused an increase in the extinction angle $Z \wedge c$ and in the optic angle about 'X' but a distinct decrease in birefringence.

8b. 1. Physico-Chemical Aspects.

Most of the work on the correlation of physical properties with chemical composition done by mineralogists, has been of an empirical nature. The chemists have however approached the problem from a different direction (See Partington 1953). The first attempt by a chemist appears to have been made by Herschel (1830) who used the Newton Laplace formula:

$$(n^2-1)/d = \frac{4k}{c^2} = r \text{ (constant)}$$

c = velocity of light in a vacuum, n = RI d = density,
k = constant.

The basis of the formula $(n^2-1)/d = k$ was derived empirically by Newton (1931 Ed. 270) who showed that the 'r' value was the same for a number of compounds. Herschel obtained the values of $(n^2-1)/d$ for a number of atoms and multiplied them by their atomic weights. These values he called the intrinsic refractive powers of the atoms.

Berthelot (1856) also used the Newton-Laplace formulae. He found that the product of the constant (r) and the equivalent weight showed equal differences for equal differences of CH_2 in analogous organic compounds.

Several variations of the Newton-Laplace formula have been produced. One of the most useful is the refractivity formula deduced independently by Lorenz in Copenhagen (1869) and Lorenz in Leyden (1879), thus:

$$(n^2-1)/\ (n^2+2)d = \text{constant} = (r)$$

Most of the work by chemists with reference to the above formulae has been done on the homologous series of organic compounds on which consistent results have been obtained.

The Lorenz-Lorenz equation modified to include the molecular weight, to give the molecular refractivity, can be used to predict the refractive indices of simple compounds (Bragg 1924), thus:

$(n^2-1)/(n^2+2).\ \frac{M}{D} = \frac{4}{3}\pi\ \text{No}\ \alpha m = \text{Rm}$ (Molecular refractivity) No = Avogadro's Number, m = mean polarizability.

If the molecules each consist of 'a' atoms each having a polarizeability 'α_1' and 'b' atoms each having a polarizeability 'α_2'. The molecular polarizeability is assumed to be an additive function of the atomic polarizeability. The Lorenz-Lorenz equation thus becomes:

$$(n^2-1)/(n^2+1) \; . \; \frac{M}{D} = R_1 \; + b \; R_2$$

Where R1 and R2 are the atomic refractivities or refraction equivalents of the constituent atoms.

As already indicated the above equation holds with a very fair degree of accuracy (1%) for liquid organic compounds containing only carbon, hydrogen and oxygen, or the halogens provided that certain complications associated with the double bond are absent. It is not intended to enter into a discussion into the methods of calculating and measuring refraction equivalents but it has been shown that in many elements these vary considerably for different states of combination. In the case of nitrogen for example, 30 values are required to cover all states of combination.

It is proposed here to show the method of estimation of the refractive indices of a simple compound, calcite, from the Lorenz-Lorenz equation. Certain estimated values for the refraction equivalents of the constituent atoms have to be assumed. (It is not proposed to consider, here, the method of determining these values. Full details are given in Partington 1953) These are:

$Ca^{++} = 1.99$, $O = 3.30$, $C =$ nil

The calcium value is from Wasastjerna (1920). Fajans and Joos later gave 1.33 for calcium. The other values were based on considerations of Wasastjerna's values for molecules and ions containing three oxygen atoms joined to a small central atom e.g. Al_2O_3, SO_3, NO_3 and CO_3 from which it appeared that the refraction was almost entirely due to oxygen. The contribution of carbon is therefore very small and was neglected, in the present calculation.

There are three oxygen atoms to every calcium and the contribution by the calcium to the refractivity of the whole will therefore be very small, thus:

$$\frac{1.99}{(1.99 + 3) \times 3.30} = 0.167$$

Bragg (1924), in fact, assumed that calcite behaved virtually as an isotropic medium with the greater refractivity attributed to the carbonate ions. It was important to introduce factors to equate the positions of the oxygen atoms with respect to the O and E vibration directions. Full details of the calculations are given by Bragg (1924) and from these details and the refractive equivalents of the atoms, Bragg calculated the principal refractive indices by substitution in the Lorenz-Lorenz equation.

$$\frac{(n_E^2-1)}{(n_E^2-1)} = \frac{D}{m} \quad (R_{ca}) + \quad 0.815 + 3(Ro)$$

$$= \frac{1}{36.13} \quad 1.99 + \quad 0.815 \times 3 \times 3.30)$$

$\underline{E = 1.468}$ (observed value 1.486)

Similarly:-

$$\frac{(n^2_w-1)}{(n_w^2+2)} = \frac{1}{36.13} \quad 1.99 + \quad (1.17 \times 3 \times 3.30)$$

$\underline{w = 1.676}$ (observed value 1.658).

It is clear that there is a wide disagreement between the measured refractive index and the values calculated by Bragg. If this is the case in a relatively simple substance, such as calcite, then accurate prediction of the refractive indices of the amphiboles is most unlikely. It was thought that values could be worked out for tremolite and used for calculation for the rest of the hornblende isomorphous series. This proved to be impossible.

8b 2 The Empirical Approach.

The empirical approach to the correlation of optical properties with chemical composition consists merely of plotting on a graph one physical property against the content of certain single atoms or combinations of atoms. Refinements of this method consist of simultaneous consideration of all the physical properties with respect to one or more chemical constituents.

Probably the earliest, serious, systematic attempt to correlate chemistry and optics in the amphibole group was made by Ford (1914). He plotted the mean refractive index against the percentages of the constituent oxides of a series of calciferous amphiboles already analysed by Penfield and Stanley (1907). The mean refractive index

(Ng+Nm+Np/3) was used as the abscissa whilst the weight percentages of the different oxides were used as the ordinates. Ford's graphs are reproduced in Figs. 41, 42.

The graphs show that it is silica, total iron, lime and magnesia, which follow closely, in their varying percentages, the variation in the mean index. Ford also confirmed from these graphs, that it was the total iron content which has the greatest effect on the mean refractive index. In graph number eight, the CaO content shows a remarkable correlation with the mean refractive index. The alkalis Na_2O and K_2O increase with increasing refractive index whilst the CaO decreases.

Ford and many other writers have indicated that the introduction of notable quantities of titania and fluorine into the amphibole lattice produce marked changes of optical character. Whilst this is so to some extent in the case of fluorine (see Chapter 4c), it is not so in the case of titania as the present writer's plot Fig. 43, shows.

Owing to the limited data available some of Ford's conclusions were inaccurate. For example, the apparently very satisfactory plots of total Fe ($FeO + Fe_2O_3$) against the mean index, for the combined tremolite and common hornblende series, led him to suppose that these were correct. In the test cases which did not fit the graphs, Ford presumed that the test hornblendes were unusual types. Two of the pargasites tested did not fit and in 1920 Laitakari showed that Ford's diagrams especially those for alumina and silica gave ambiguous results for his Finnish pargasites.

The present writer has considered a large number of analysed amphiboles from the literature and has shown that there is a fairly good agreement between the Ng refractive index and the total iron ($FeO + Fe_2O_3$) Fig. 44. It will be noted that the tremolite series is represented by crosses and that the majority of these crosses lay to the right hand side of the diagram and become more distant from the common hornblende trend as the tenor of iron increases. In view of the work by Porter (1924), which has already been described, the graphs were replotted using atomic proportions Fig. 45. It became clear that there were two seperate trends, one for the aluminous hornblendes and one for the tremolite series. Both Laitakari's and Ford's pargasites fit these graphs. In the present writer's graphs the Ng refractive index has been used because of the unreliable measurements found for many Np values (see Chapter 4c) and also because the relationship between the Nm index and the heavy atoms shows a distinct curve Fig. 46.

The differences in trend shown in Fig. 44 are thought to help confirm the presence of the solid solution gap between the *common hornblendes* and the *tremolite series*. Furthermore if the inaccuracies of estimation of both the iron content and the refractive indices could be taken into account, the present writer feels that there would be remarkable correlation between the Ng index and the total iron content. This would be particularly the case if the other heavy atoms Mn and Ti were added to the total Fe.

Three crosses in Fig. 45 which appear to be well inside the common hornblende field, have been shown to be incorrectly placed owing to inaccurate refractive index determinations. This point has been discussed in Chapter 4c.

One would expect that the good correlation shown between the heavy ions and the Ng index would be reflected in the correlation of magnesia with the refractive index. This is in fact the case. There is again, however, a spread of points between the tremolite series and the common hornblendes. This difference between the two series is probably most marked in the seperate plots of silica, Fig. 47, and alumina against the refractive index.

There is fairly good correlation between the silica content and the refractive index in the common hornblende series but when the hornblendes are considered as a whole there is, as would be expected, a very considerable spread in the lower refractive index region. Obviously it is impossible to expect a single trend from plots of Al_2O_3 against refractive index for both types of hornblende because many tremolites with low, or no alumina have similar refractive indices to aluminium hornblendes.

In the next stage of the investigation, Ford examined the possibility of predicting chemical change from the changing extinction angle. For this purpose he used 16 analyses, 8 of tremolite and 8 of common hornblende all of which for his purposes were classed as common hornblende. By arranging the 16 analyses in order of decreasing extinction angle he noted that they could be divided into two distinct groups, which covered the same range of variation of extinction angle, but which were quite distinct chemically. The first group showed extinction angles ranging from 20° to 8° with percentages of silica varying from 58% to 51%. The second group showed a range of extinction angle from 33° to 9° with silica percentages from 44% to 36%. Thus it was found possible to have two different hornblendes with the same extinction angle.

In his study of the tremolite series, Ford noted that the decrease in the extinction angle was concomitant with a decrease in silica, magnesia and lime and an increase in the percentages of FeO, Fe_2O_3, Al_2O_3 and alkalis. The variations in composition were by no means regular and the relationship between the composition and the extinction angle was not clear. As with the refractive index the total Fe content did seem to bear a closer relationship, to the extinction angle, than the other components. With reference to the common hornblende series, Ford was unable to show any reasonable correlation between the percentages of the various constituent oxides and the extinction angle. He was able to record that as the amount of iron increased, there was a general decrease in extinction angle but the relationship was not systematic and was of little practical value. The graphs illustrating Ford's work on the extinction angle are shown in Fig. 48.

The present writer found that correlation of chemical composition and the extinction angle was almost impossible in the hornblende series. In a general way it is observed that there are considerable differences between the extinction angle of the alkali amphiboles and the hornblendes and it must be that the presence of high soda and high sesqui-oxides could account for this. In general in the statistical examination, (see Appendix 1), the best correlation with the extinction angle is with the alkali content. The various Winchell diagrams which purport to illustrate chemical correlation with this property are by no means conclusive and care should be taken not to accept them at their face value.

No attempt was made by Ford to use the specific gravity data which were available from the work of Penfield and Stanley (1907). It is clear from the current work of the present writer that the specific gravity of an amphibole increases with increases of refractive index (Fig. 25). There is, therefore, a relationship between density and composition and as might be expected this is marked in the cases of the heavy ions Fe, Ti and Mn. Fig. 24 which illustrates this relationship shows a considerable spread of points presumably due as much to the inaccuracies in density measurement as well as to the analytical errors.

Recent work by other writers on the lines indicated by Ford has been extremely limited, although the method is simple. Rabbitt (1948) Produces two diagrams in an attempt to effect simple correlation in the anthophyllite series. The first (Fig. 49) shows a plot of FeO + MnO + Fe_2O_3 + TiO_2 against Ng refractive index and the second (Fig. 50) shows the same elements of composition against density. Notwithstanding the amount of latitude allowed by experimental error, neither of these plots show very satisfactory correlation between composition and physical properties. It is noteworthy, however, that the Montana specimens, high in alumina, fall significantly above the line and those low in alumina 17, 29 and 30 fall close to the line.

Pantin (1956) demonstrated that in the hornblendes from the Ben Vrackie epidiorites the Nm refractive index increased sympathetically with increasing percentages of FeO + Fe_2O_3. This point has already been demonstrated by Ford (1914) using the mean refractive index. Similar good results were obtained by plotting 2V against Fe_2O_3 and the Nm index against the ratio FeO + Fe_2O_3/MgO + Al_2O_3 in molecular proportions. The correlations achieved by Pantin are quite remarkable and the present writer has found that Pantin's graphs could only be made to work, with such efficiency, over a very limited range of amphibole composition. It should be borne in mind that Pantin's amphiboles bear a definite genetical relationship to one another and would therefore tend to show closer physical and chemical relationships.

Variations of the simple empirical approach have been made by various writers. Most of these depend on the use of a number of elements of composition in the form of a ratio. This was done by Foslie (1945), Rosenzweig and Watson (1954), Billings (1928) and Buddington and Leonard (1953). The graphs produced by the first two mentioned writers are of little practical value unless the analysis of the amphibole is known and even then there appears to be little practical point to them. The chemical constitution cannot be predicted from such ratios. On the other hand if the chemistry is known it is possible to predict the physical properties with greater accuracy from a ratio than from a simple single oxide graph of the Ford type. It is important to remember in this respect that the physical properties are more easily measured than the chemical composition. The ratios derived by Billings and Buddington and Leonard were used for a somewhat different purpose, namely to subdivide the pargasite series and as such they have some point.

It is proposed here to describe the ratios adopted by Rosenzweig and Watson (1954) in which 2V, refractive index and specific gravity were all plotted against the ratio Mg + Al(6)/Y expressed as atomic proportions and where Al(6) is the amount of aluminium in the 'Y' group (or in other words in six-fold co-ordination) and 'Y' is the sum total of the 'Y' group.

The graphs in Fig. 51 show the relationships of the physical properties of eight hornblendes from Pennsylvania and Delaware to the proportions of the ratio given above.

It can be seen that even in the limited range of these hornblendes the correlation is not 100% effective and in general merely shows that with the increase of the heavy ions there is a concomitant increase in refractive index and density with a corresponding decrease in 2V.

The hornblendes of the Glen Tilt complex (Deer 1938) have been plotted on the Rosenzweig and Watson diagrams to emphasize the fact that the graphs are of limited value only. For all practical correlation purposes, over the hornblende range, they should be disregarded.

In 1924 Winchell introduced a method of plotting the molecular percentages of end-members against the various physical properties. This work set a fashion which was later developed and extended by Winchell himself (1931, 1938, 1945), Sundius (1933), Orlov (1932) and Kunitz (1930). At the present time the graphs published in Winchell (1951) are the only guide to the determination of the composition from the physical properties for many members of the amphibole group. The tendency is to accept these graphs as being the ultimate method for this type of determination and to accept the results which they give as being highly accurate. The present writer has already shown that it is quite possible to wrongly identify, using optical properties, cummingtonites on the hornblende graphs. The following paragraphs will describe the Winchell (1951) method of determination of chemical composition from the physical properties and to discuss the accuracies and inaccuracies of the method.

Anthophyllite.

Winchell (1931) in his consideration of the anthophyllite series showed that an estimate of the composition of an anthophyllite from the optical properties could be made from a plot which combined the molecular percentages of the two end members $Mg_7Si_8O_{22}(OH)_2$ and the corresponding iron end member $Fe_7Si_8O_{22}(OH)_2$. Winchell's (1931) system was originally worked out from seven analyses. The number was incr eased in 1938 to eleven and to at least 25 in 1951. It is significant to note that as the number of analyses increases, the correlation of optics with chemical composition becomes less reliable. In Fig. 52 it is very difficult to see on what basis the Nz and Nx lines have been drawn; they certainly do not appear to correspond with the plotted points.

Fig. 52 makes no allowance for the alumina content of anthophyllite. It has already been shown that alumina may be present in the anthophyllite structure in amounts of up to 24% and this must be taken into account in any correlation of the type described here. In the Winchell (1951) diagram Fig. 53, the present writer finds it difficult to see how this graph can be made to work. For example, an anthophyllite with Ng equal to 1.66 amy have according to the graph, any amount of the FeAl molecule up to 100%. In other words it is impossible to fix the composition of an anthophyllite from this graph. It is difficult to draw any further conclusions from the Winchell diagrams other than to say that with an increase in iron there is an increase in density and specific gravity.

The present writer considers that the only possible method of estimation of the composition of an anthophyllite from the physical properties is by the statistical method of multiple regression. The details of this type of estimation will be discussed later (see Chapter 8 d.)

Cummingtonite Series.

It has already been shown in Chapter 5 that the cummingtonite series must be referred to a triangular diagram. Although the present writer considers that the 'X' group must be represented in this series, this does not seriously affect the plots using the previous formula $Y_7Z_8O_{22}(OH)_2$ as the seperate poles of the triangle for the purposes of determining composition from the physical characteristics.

The minerals of the cummingtonite series are somewhat more simple in composition that the other members of the amphibole group. They lack the complications in the physical properties produced by the introduction of sesquioxides into the structure. It would be expected therefore, that the plots of physical properties against composition would be simple. In the case of the non-manganese varieties this is so. Fig. 54.

Bowen and Schairer (1935) investigated synthetically the fluorine bearing non-manganese minerals of the series. Good agreement was shown between the optical properties of these minerals and those of the hydroxy types (see Figs. 55, 54).

It can be seen that the general effect of the replacement of the (OH) group by F is a parallel increase or emphasis in the optical properties except in the birefringence which is slightly weaker in the fluorine bearing minerals.

The differences in the form of the 2V curve in Figs. 55 are easily explained. The Bowen and Schairer diagram shows 2Vz and Winchell shows 2Vx.

To determine an unknown member of the cummingtonite series it is essential to use the graph showing the manganese pole. It would appear from this that Fig. 54 has only a very limited use and that all determinations should be made on Fig. 56 from Winchell (1951). This latter diagram does not give a highly satisfactory representation of the composition from the optical properties as the plotting of the optical properties of the manganese amphiboles in Table 12 show. Fig. 56 appears to have been constructed from two points only in the Manganese field.

The Hornblende Series.

Winchell's study of the hornblende series follows the same general pattern as that for the two series described in the foregoing. In the case of the minerals of the tremolite series Winchell (1931) states that the analyses indicate that minerals of this series usually contain a moderate tenor, 20 to 30 mol. per cent of other amphibole molecules including edenite and cummingtonite. He suggested that ranges in composition determined from the optical properties were due to this cause. Fig. 57 from Winchell (1931) illustrates this and it is claimed that the position of number 18 on the Np line is due to the presence of 15 mol. percent of the glaucophane molecule.

The next step in the process was clearly to examine the introduction of soda and aluminium into the tremolite molecule. Winchell (1931) concluded that the substitution Al/Na for Si changed the refractive index but had the greatest effect on the 2V which it changed from approximately 75° to more than 120° about X thus changing the optic sign. Winchell (1934) Fig. 58 gives the relationship between the optical properties and the composition for the tremolite pargasite series. It should be noted however that the pargasite end member given by Winchell in this case is in fact edenite. The various trend lines are plotted on the basis of only six analyses.

Winchell (1931) shows a square diagram for determination of composition in the tremolite and pargasite series. The positions of the various values of the refractive indices are plotted. The graph is not reproduced here but it has no value from the point of view of estimating composition from physical properties.

The diagrams of Winchell (1951) are merely developments of these early graphs and it is difficult to determine, in many of these just how the positions of the lines representing the various physical properties were drawn from the position of the points plotted. This is particularly so in the case of the (1951) tremolite-actinolite diagram Fig. 59, which shows many tremolite extinction angles lower than the predicted value for 60 mol. per cent actinolite. Similar ambiguities can be seen in the line representing the birefringence Ng-Np.

The next major development of importance was the appearance of the partial prism, described in Chapter 4a. On this diagram more than 100 analyses of calciferous amphiboles were plotted. Winchell (1945) made it clear that the partial prism made no allowance for the replacements by various minor constituents for example.

It was found in current work that these minor constituents do affect the physical properties in some measure. For example, there is an appreciable difference between the properties of the cummingtonites and the manganese cummingtonites. It has already been shown that the replacement of (OH) by F produces noteworthy differences in physical properties. Some compromise must be effected and that made by Winchell seems to be the most reasonable.

The optical properties of all the calciferous amphiboles used in the construction of the original partial prism were recorded. The projection of these physical properties with respect to the prism is shown in Fig. 60. The prism faces are reproduced by Winchell on the plane of the paper and are used for determination purposes. Fig. 61.

The prism faces probably show very satisfactory agreement between composition and physical properties for minerals whose compositions locate them on the various prism faces. Some discrepancy is bound to arise when attempts are made to predict composition from prism faces when the minerals are in fact located in the body of the prism.

The present writer has found that at least two cases in his list Table 8 Nos. 3 and 33 common hornblendes, could have been identified as members of the tremolite series on the basis of the prism faces diagrams. Winchell did point out that the partial prism would not correspond with the facts in every case; indeed it would rarely correspond with all the data. Rosenzweig and Watson (1954) plotted eight hornblendes on the Winchell diagram and showed that the Ng index was generally lower than the predicted value but that the other properties were in good agreement.

Fundamentally it is considered by the present writer that Winchell's graphical attempt to correlate physical and chemical properties on the basis of the partial prism is really a simplified graphical presentation of statistical analysis by multiple regression. The mathematical process has been worked out by the present writer for both the common hornblendes and the tremolite series and it is to be discussed later in this chapter.

It has been made clear in nearly all the previous discussion that the iron content of an amphibole has the greatest effect on the physical properties, the other atoms tending to serve as diluents of greater or lesser effectiveness. Thus in the natural tremolites which have very low iron content the series remains optically negative but if a quantity of aluminium and soda is introduced into the structure, the minerals become optically positive as in the case of edenite and pargasite. The reason for this is that the amount of iron which increases the refractive index and reduces 2Vx is reduced by the proportion of Al/Na in the unit cell. It is for this reason that the present writer would expect the magnesium end member of the tschermakite series to be positive. Although the presence of Al (4) increases with increasing refractive index (Fig. 62) the introduction of Al(6) into the 'Y' group has no effect on the refractive indices (Fig. 63) but it does reduce the possible proportion of iron/magnesia in the 'Y' group and causes the low iron aluminous minerals to become optically positive.

It is clear from Winchell's table of end members for the partial prism that the physical properties of the hornblende series are much affected by the presence or absence of sesqui-oxides. Work by the present writer (Fig. 45) has shown the differences between common hornblendes and tremolites with respect to Mg/Fe. Part of the discrepancy could be attributed to the increased amounts of alkalis in the latter series. It seems, however, that the introduction of aluminium has a far more important affect on the physical properties.

A method of study of the effects of the sesqui-oxides was suggested by Sundius (1946). A two axial diagram, Fig. 64, was used. The points in it were divided up into different groups with different amounts of Alii, that is, the different amounts of aluminium replacing silicon. Seperate diagrams were then constructed for the seperate groups, choosing, as axes, certain optical properties and the ratios of selected elements. The diagram, which did not include the basaltic hornblendes, was based on 127 examples from Winchell, Hallimond, Foslie and Kulling.

For the study of the optical properties the points were divided into three groups with boundaries at AlII=0.6 and 1.4. In order to test the greater amounts of sesqui-oxides in the Y group (Al I+Fe"') only the analyses to the left of the broken line were used in the construction of the curves. These analyses were marked with points, whereas the sesqui-oxide rich ones to the right of the line were marked with crosses. A similar distinction to the left of the line connecting pargasite with tremolite was not necessary as the content of AlI+Fe"' is only small in members of the actinolite-tremolite series. The properties of pure edenite, therefore, were not accessible. The properties tested by means of this diagram were the Ng refractive index and the axial angle. The horizontal axis of the constructed diagrams was the ratio Fe"+Fe"'+Mn+Ti : Mg. These being the elements known to affect most strongly the optical properties mentioned.

As regards the Ng index Sundius suggested that it was obvious from Fig. 65 that the increasing introduction of Al into the SiO_2 chains caused an increase in the value of the index. This does not seem to be altogehter true, the high refractive index appears to be as dependent on 'Y' group as on AlII. In the Sundius graphs AlII is the amount of aluminium replacing silicon in the 'Z' group. The points are somewhat scattered along the curves and it should be noted that the scatter is greatest in group three. It is suggested here that this is probably due to the effects of alkalis which are concomitantly introduced into the tremolite frame work with the introduction of sesqui-oxides. Sundius indicated that some small uncertainty could not be avoided when drawing the curves but that the material available left no doubt about the relatively higher position of the curves in the diagram when passing from groups one to groups two and three. On the other hand it was claimed that there was no regular difference in distribution of the points and crosses in relation to the individual curves. Thus the introduction of Al into the 'Y' group as a compensation for Mg does not seem to exert any noteworthy influence on the Ng index of refraction.

Sundius next investigated the extent to which the positions of the curves in the diagram could be influenced by varying the content of Fe"' and Ti. Both of these components were stated to be strong agents in raising the refraction power. With reference to Fe"' Sundius found it necessary to allow for its greater refractive power as compared with Fe" and, when using the calculated number of atom numbers in the construction of Fig. 66 he gives double weighting to Fe"'.

Current work shows that whilst the inclusion of Fe"' and Ti with Fe" gives a better relationship with the Ng index, the effect of Fe''' and Ti, individually, on the refractive indices is not marked. Fig. 43 demonstrates this point quite clearly. It shows that although there is a very slight tendency to an increase of the index with increasing Fe''' and Ti neither component should be individually regarded as having a major effect on the refractive indices.

In an analysis of the graphs Figs. 65, 64, Sundius pointed out that it was unlikely that the differences in found at the Mg extreme side of the diagrams should be due to different amounts of Fe''' and Ti, because the amounts of these components would be small at this point. He suggested, therefore that the differences in refractive index of tremolite Mg extreme common hornblende and pargasite may be due to the exchange of part of the Si for Al.

Sundius himself, has drawn attention to the fact that the change from tremolite to hornblende is not just a simple matter of the introduction of aluminium into the SiO_2 chains of the tremolite molecule. There is also, as Warren (1929) has shown, a simultaneous introduction of Na and K into the vacant spaces except in the case of tschermakite. Ford (1914) showed, and current work confirms, that an increase in the amount of Na, K in the amphibole molecule also produces a rise in refractive index. On the other hand an increase in the value of the Ca component tends to reduce the value of the indices (Fig. 67). Sundius has made no allowances for these points in his discussion of the introduction of sesqui-oxides into the tremolite molecule. Thus whilst it is agreed that the introduction of aluminium into the SiO_2 chains causes an increase in the refractive indices it should be borne in mind that this increase is probably not wholly due to the Al component. There is a certain amount of inconsistency in these statements. Al/Na amphiboles edenite and pargasite are optically positive, the effect of aluminium and soda must be to increase the refraction index of Np which reduces the birefringence and causes the minerals of this type to become optically positive.

It is clear that if Fe''' and Ti should have any influence on the position of the curves it would be restricted to the more iron rich parts of them. It would become apparent in the generally higher position of analyses with the larger amounts of these two elements. The relations shown in Fig. 66 do not tally with this as is demonstrated by the irregular distribution of the points and crosses. The former referring to the analyses situated above the curves in Fig. 66 and the latter to those on or beneath the curves. The foregoing statement is by Sundius and he interpreted this to indicate that the Fe''' was fairly well compensated when calculated twice and that the Ti component, which was claimed to be the more strongly active, was present in subordinate amounts, thereby exerting no perceptible influence on the position of the points and crosses.

Sundius, therefore, suggested that the relatively higher position of curves 2 and 3 was also, in the more iron rich parts of the diagram, chiefly due to the higher amounts of AlII in groups two and three. The explanation suggested by current work is that the relatively higher position of the curves is due to AlII and Na, K and that Fe"' and Ti have themselves, individually, no direct effect on increasing the value of the refractive index (see Fig. 43).

It has been shown earlier that Tschermak indicated that the iron content of an amphibole had a large effect on the optical characteristics and that in particular in the tremolite-actinolite series the optic angle decreases with increasing iron content. Later work by Winchell usually included references and graphs illustrating the variation of 2V with composition. Billings (1928) showed that an increase of the FeO/MgO ratio in the hastingsite series caused an increase of the value of the refractive indices and specific gravity with a concomitant decrease in 2V. Later Pantin (1956) showed that in certain circumstances 2V decreases with increasing Fe_2O_3.

In his investigation of the behaviour of the axial angle Sundius, plotted the values of 2V against the horizontal component Mg:Fe"+Fe"'+Mn+Ti. The plot as in Fig. 10 Sundius (1946) was made for the three groups of AlII substitutions. The diagram, Fig. 68, shows analyses with high contents of Fe"'+AlI marked as crosses and those with low amounts marked with points. Both types are irregularly distributed and this was interpreted to mean that the presence of varying amounts of tschermakite with high 'Y' group sesqui-oxides did not seem to influence the size of the optic angle greatly.

It was suggested that the distribution of points invited the construction of an 'S' shaped curve for groups II and III and that it would be reasonable to expect similar 2V relationships in these groups in view of their similar refractive index curves. The diagram, Fig. 69, Sundius stated, showed clearly that a sudden change in 2V occurred in the interval between the tremolite-actinolite series and the common hornblendes.

Sundius also indicated that in the pargasite-hastingsite series there was a marked decrease in 2V, extending from about 125° in pargasite to about 10° in hastingsite. It was alos shown that as far as the information was avsilable, the relationships were similar in the other hornblendes. In strong contrast to these 2Vx is little altered in the tremolite-actinolite series ranging from about 83° in tremolite to about 74° in actinolite.

By a consideration of the Mg extreme members of the calciferous amphiboles, Sundius was able to construct diagrams with AlII as one axis and the respective optical property as the other. Fig. 69 has been constructed from the Mg side of Figs. 68 and shows quite clearly that there is a break in the series between 0.6 and 1.2 AlII. This break is most marked for 2V but is also evident in the refractive index graph. This point has already been discussed in Chapter 7c.

Sundius concluded that in view of the optical discontinuities between the various components of the hornblende series and the tremolite-actinolite series, it would seem justifiable, to regard the latter series as a seperate group as compared with the more sesqui-oxide rich hornblende series. It has been shown that the boundary between the two groups lies somewhere between AlII=0.6 and AlII=1.2, where the general diagrams have a zone with few or no points. The present writer has shown in Chapter 7 that this gap can be reduced somewhat.

The Alkali Amphiboles.

It has been shown in Chapter 6a that the Winchell (1951) conception of the classification of the alkali amphiboles is untenable. This being so it is not possible to use the various graphs produced by him to identify the members of the group. Sundius (1946) gives no indication, beyond a brief description of the optical properties of the end members, as to how the individual members of the group should be identified.

The graphs reproduced here from Miyashiro (1957) Figs. 70, 71 are helpful when the sub-class of the amphibole in question is known. Fig. 70 is also helpful when it is known definitely that glaucophane is not represented. This is unsatisfactory for present purposes. An examination of the table of optical properties of alkali amphiboles in Table 14 shows that riebeckite has a very low birefringence (Ng-Np) and a very high Ng refractive index. No. 39 in the table, an arfvedsonite shows almost identical optical properties and it would be impossible to distinguish between these two minerals on the data given here.

The present writer finds that the two most important physical properties for identification of series type in the alkali amphiboles are birefringence and extinction angle. Fig. 72 shows the results of a simultaneous consideration of these two properties. It will be noted that there is a certain amount of over-lap in the field of the katophorite and richterite series. These two minerals can be distinguished by their refractive indices thus, richterites <1.659 and katophorites >1.660. The orientation should always be considered and it would be found that in richterites b = Y always. In the case of similarity between arfvedsonite and riebeckite the axial colours may help in some cases but chemical analysis is the only sure means of establishing identity although riebeckite has a somewhat lower birefringence (Ng-Np).

8 d. Statistical Correlation of Physical Properties with Composition.

The graphical attempts at correlation by Ford, Winchell, Rabbitt, and others, described earlier in this chapter, deal with simple correlation with only two varieties. This relationship may be expressed mathematically so:-

$$y = ax + b \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where 'a' is the parameter expressing slope of the line and 'b' is the parameter which indicates at what value the straight line cuts the 'y' axis. The relationship expressed above can be used to indicate the typical correlations described earlier, thus:-

$$(Fe) = a(Ng) + b \ldots\ldots\ldots\ldots (2)$$

In the case of most of the physical properties, over the range examined, there is certainly definite linear correlation with the iron component and probably with most of the others as well. If the correlation is in fact represented by a curve this is so flat that the portion, which is of interest here , is satisfactorily represented by a straight line.

The correlation of Fe_2O_3 with the axial angle appears to be definitely represented by a curve although again, in most cases straight lines could be drawn which would give reasonable correlation. For the above reasons the possibility of curvilinear correlation has not been considered in this thesis.

It has been shown in the various graphs that the plots of the physical properties against composition show a linear trend but with a spread of points. For the present purposes the statistical best line must be drawn through these points and this is done by the method of least squares. Such a line indicates the position in which the points would lie were it not for some other disturbing factors. It is not intended, here, to discuss the method of calculation of least squares for the simple linear regression plots.

The above is, briefly, the procedure for one chemical component to be correlated mathematically with one physical property. It is possible by combining the physical properties of the mineral to estimate from each simultaneously the corresponding quantity of the required chemical component.

The increase from two to three variates adds a number of complications to the simple linear regression expressions developed in equation (2). Perhaps the most striking is the necessity for three dimensions in which to depict the variates graphically (see Winchell prism 1945). Solid geometry is required instead of plane and if for example Fe partly depends on Ng and Np for its value, three mutually perpendicular axes are demanded for graphical presentation. Ng is measured along one, Np is laid out parallel to the second and Fe rises from the plane Ng.Np parallel to the third axis. The points in space fixed by the triplets of the three values (Ng, Np, Fe) determine a regression plane whose equation is:-

$$Fe = b + b_{Fe_{1.2}}(Ng) + b_{Fe_{2.1}} (Np) \ldots\ldots\ldots\ldots \quad (3)$$

$b_{Fe_{1.2}}$ and $b_{Fe_{2.1}}$ being partial regression co-efficients. This is the case with only three variates.

It was shown in the case of simple linear regression, that the method of least squares was invoked to ensure that the line for equation (2) is the best line for the regression of Fe on Ng.

In the case of more than two variates, in the present instance with three, there will be the added complication of three correlation co-efficients (estimates of mutual relationships between measurements). To combine these into the two regression co-efficients the method of least squares used in the simple case, is again invoked. The regression plane, replacing the regression line of the simple case, is designed to pass amongst the points so that the sum of the squares of the vertical distances shall be a minimum.

The application of the principle of least squares in the case of a three variate system leads to a pair of simultaneous normal equations. Full details of the method of calculation of the multiple regression equations is given in Snedecor 1946, 13, p. 340-399. This book has been used as the basis for all the present writer's statistical determination.

The description given in Snedecor covers multiple regression with three and four variates. Increasing the number of variates involves no new principle but does lead to complications in the solution of the larger numbers of simultaneous equations.

Equations derived from the solution of the simultaneous equations mentioned above can only be used to estimate the total Fe content. If it is desired to predict the optical characters given enough chemical data, then it is necessary to derive a further set of regression equations.

The first attempt to use multiple regression equations of the type described for correlation in the amphibole group appears to have been made by Hey (1956). The principal difficulty experienced by Hey was the collection of an adequate amount of data which was complete in every respect. His available optical data consisted of 38 sets of data on analysed specimens from Rabbitt (1948), Pirani (1952 and 1953) and G.H. Francis (1955). In many cases the sets were not complete and in view of the fact that ten sets of data were all determined by one worker (Rabbitt) and were of decidedly superior accuracy, these alone were used to derive the regression equations. The X-ray data consisted of ten sets of cell dimensions for the Rabbitt group of analysed specimens. The variations of the a and c dimensions were within the accuracy of the measurements but there was a significant variation in the b dimensions.

Clearly the first step in any statistical analysis of the type suggested here should be the selection of suitable parameters or numerical characteristics of the populations. Hey (1956) selected (Ti+Fe'''), (Ca+Na+K), (Fe''+Mn), Mg, Si and Al as suitable paramteters of composition. By assuming that the replacements Ti Fe Ca (Na K) and O (OH,F) can be set against one another and balanced out within the probable accuracy of chemical analysis, Hey reduced the number of independent parameters to five. For a reason not given Hey disregarded Al as an independent parameter, leaving for correlation with the optical and physical data the following:-

Si, (Ti+Fe'''), (Fe''+Mn), Mg, and (Ca+Na+K)

All the chemical data being expressed in atoms per 24 (O,OH,F).

For the determination of the chemical composition from the physical properties, the birefringence values (Ng-Nm) and (Ng-Np) were used with density and the refractive index. Equations were derived to solve for Si, Al, Mg and Fe.

The anthophyllite data selected by Hey was reduced in the standard manner for the preparation of multiple regression simultaneous equations, which were then solved by the method of matrices. The solutions to the equations were then used to derive regression equations. Adjustments were made to remove the non-significant terms, and the final version of the equations is given below:

$$Ng = 1.7249 - .0130\,Si + .0140\,(Ti + Fe^{\prime\prime\prime} + Fe^{\prime\prime} + Mn) \pm .0012$$

$$Nm = 1.7275 - .0142\,Si + .024\,(Ti + Fe^{\prime\prime\prime}) + .011\,(Fe^{\prime\prime}+Mn) \pm .0015$$

$$Np = 1.6951 - .0117\,Si + .04\,(Ti + Fe^{\prime\prime\prime}) + .0133(Fe^{\prime\prime}+Mn) \pm .0025$$

$$b\mathring{A} = 16.44 + 0.28\,Si - .13\,Mg + .0.40\,(Ca + Na + K) \pm .04$$

$$Si = 165\,(Ng-Nm) - 102\,(Ng-Np) - 30\,Ng - 313D + 60.13 \pm 0.5$$

$$Al = -346\,(Ng-Nm) + 229\,(Ng-Np) + 29Ng + 10.8\,D - 81.70 \pm 1.0$$

$$Mg = -33\,(Ng-Nm) + 37\,(Ng-Np) - 61Ng + 0.2\,D + 103.87 \pm 0.5$$

$$Fe^{\prime\prime} = 103\ \ Ng-Nm - 10\,(Ng-Np) - 50Ng + 18.3\,D + 24.59 \pm 0.4$$

The equations given above show a fairly satisfactory relationship between the calculated and experimental data for the selected anthophyllites. The Glen Urquhart gedrite (Francis 1955), however, shows calculated indices greater than those determined experimentally. Hey points out that the regression equations neglect the variation in total oxygen atoms per unit cell and by calculating the approximate additional terms for the extra oxygen, it is indicated that this interstitial oxygen of the Glen Urquhart gedrite could considerably lower the refractive indices. Francis and Hey (1956) point out that the gedrite, which was tested on the regression equations was impure. The interpretation, of the low refractive indices as suggested above must therefore be held in abeyance until the gedrite is re-investigated.

In general terms, various substitutions in the regression equations show the effects on the individual physical properties of replacement in the anthophyllite molecule, for example, the b-axis of pure magnesio-anthophyllite as calculated from the regression equation is 17.77 A and it is lowered by 0.15Å for each MgSi per quarter unit cell replaced by Al_2. It is raised by 0.13Å by the substitution of Al_2 for Mg_3 per quarter unit cell of Mg replaced. The substitution of Ca, Na or K for Mg appears to increase b markedly.

With reference to the optical characteristics the replacement of Mg by Fe leads to an increase in all three refractive indices but with hardly any change in Ng-Np but with a moderate increase in Ng-Nm hence a decrease in 2V for one Fe'' replacing Mg per 24 (O,OH,F) the increase is 0.014 for Ng, 0.011 for Nm, 0.013 for Np. Hey noted that the replacement of MgSi by Al in gedrites leads to an unexpectedly large effect; Al_2 replacing MgSi increases Np by 0.012 Nm by 0.014, Ng by 0.013, Ng-Nm and 2 V are increased but Ng-Nm is decreased. The replacement of Al by Fe or Ti causes a marked increase in refractive index whilst the replacement of Mg by Ca or Na appeared to have little effect.

The present writer obtained from the literature 20 analyses of the tremolite series and 40 of the *common hornblende* series. All these analyses were recalculated on the basis of 24 (O,OH,F) and the resultant data reduced in the manner appropriate for inclusion in the multiple regression equations.

Expressions were derived for the regression of the following chemical parameters on the physical properties, $(\mathrm{Fe''}+\mathrm{Fe'''}+\mathrm{Mn}+\mathrm{Ti}) = (\mathrm{Fe})$, Mg, Si, $((\mathrm{Fe})+\mathrm{Al})$, $(\mathrm{Mg}+\mathrm{Ca}+\mathrm{Na}+\mathrm{K}) = (\mathrm{Mg})$ and (Na+K). The physical properties chosen were Ng, Np, density, $\sin Z_{\wedge}c$ and sin. 2V. The sines of the angular measurements were chosen in order to keep the data in a manageable form. This work was done early in the research programme and it has since been found that these physical parameters were perhaps not the best which might have been chosen. In view of the writer's more recent work on the refractive index relationships the writer would now have included the birefringence values. It is intended to recalculate all the current regression equations using a complete list of amphibole analyses at present being compiled by Dr. Leake at Bristol University. The present equations should therefore be regarded as provisional.

In the first instance the regression equations for the two series were worked out separately for each chemical parameter. In the second case the tremolite series was combined with the common hornblendes so that one set of equations covering the two series was derived for each chemical parameter.

In some cases, the iron chemical parameter was included with the physical properties. This was so in the estimation of Fe+Al, Mg and Si. In these cases the number of simultaneous equations to be solved increased by one from five to six. All these equations were then solved on the Pegasus Electronic Computer and the present writer is indebted to Mr. J. Tuson for initial help in the preparation of the tremolite series tapes and the use of the computer.

In an examination of the simultaneous equations derived from the reduction of the data it quickly became apparent that certain terms were of greater significance than others. If we examine the calculation for the hornblende series for (Fe) on to physical properties (Appendix 2 No. 1) the simultaneous equations show that the co-efficients for Np, Ng, D and (Fe) are of the order of 0.9 on the other hand if the co-efficients for 2V, $Z \wedge c$ and (Fe) are examined it is found that these are very small in the case of $Z \wedge c$ and of the order of .66 in the case of 2V. This all means that the refractive indices and density correlate better with the iron content than do 2V and $Z \wedge c$ in that order. The values of $Z \wedge c$ are so low that they could quite well be ignored in these calculations. It was for similar reasons that the calculation of Na+K and (Mg) were abandoned in the hornblende and common hornblende series.

It is not proposed to give details, in every case of the working and arithmetic necessary to compute the simultaneous equations or to calculate the regression equations and correlation co-efficients. All the primary data is given in Appendix 1 and all the derived statistical data are given in Appendix 2. Together in this appendix is a complete computation of the % (Fe) for common hornblendes. The scheme follows exactly that described in Snedecor (1946) for the simple case. It will also be noted that some equations apparently give three answers. This is due to the fact that three batches of six by six equations can be solved simultaneously on the computer.

Having derived a method of estimating the quantity of a series of chemical components of a mineral from the physical properties, it is of some considerable interest to find out how accurately this method can do this. In the first case it is clear that when the predicted value is the same as the actual value then the correlation is 100% between the two or that the correlation co-efficient is 1.00. With increasing differences between actual and predicted values, this co-efficient becomes progressively smaller. Appendix 2 shows that in the majority of cases the multiple correlation co-efficients for the various calculations is usually greater than 0.91 which is, from the tables of the significance of 'r', highly significant. The regression plane only gives the best estimate of the value of the chemical parameter in question and it is possible to estimate the degree of uncertainty in this estimate by calculating a quantity known as the 'standard error of estimate'. This has been done in Appendix 2. In about 95% of the cases the actual values will lie within plus or minus two standard errors of the estimated values given by the regression equation (Moroney 1956); and almost without exception actual values will be found to depart from the estimated value by not more than three standard errors. These limits have been indicated in Appendix 2.

Summary.

Estimates of the principal chemical components of the anthophyllite series can be made from the equations developed by Hey (1956) for the anthophyllite series.

The present writer found the presentation of the statistical aspects of Hey's paper somewhat complicated and a simplified although adequate version has been adopted for the preliminary equations derived by him for the member series of the hornblendes. The most significant physical proper ties in all correlations have been found to be the refractive indices and density. Significant results for (Fe), Al Si and Mg have been achieved and other chemical parameters can be predicted from the graphs given earlier, using these calculated quantities as a basis.

No attempt has been made in this section to show the effect of inaccuracies of determination of physical properties and chemical composition. Such a discussion would involve somewhat complicated statistical arguments beyond the scope of the present work.

8 e Estimation of Composition from X-ray Analysis.

It has been shown in the earlier chapters that in general the single crystal data are too few to allow a satisfactory estimation of composition to be made from the unit cell parameters. A certain amount of statistical work has been done by Hey (1956) on the estimation of the 'b' lattice parameter from the chemical composition for members of the anthophyllite series. The equation derived for this estimation is as follows:-

$$b\,\text{Å} = 16.44 + 0.28\,\text{Si} - 0.13\text{Mg} + 0.40\,(\text{Ca} + \text{Na} + \text{K})$$

Although the above equation may be useful in some instances, the present writer feels that it is the wrong way round and that it is more important to be able to estimate chemical constitution from easily measured physical properties.

It was decided by the present writer that the powder photograph method offered the greatest possibilities because the changes in position of the characteristic lines in the powder photograph may well be brought about by the substitution of larger atoms for smaller ones. Trial and error tests were done to see which line showed the greatest correlation with alumina content. This oxide was chosen because aluminium replaces the smaller silicon atom and therefore high alumina content should indicate larger lattice size. The line selected was a strong to medium one of 'd' spacing 1.5?? and which has an index of $20\bar{2}$ (matched from synthetic fluor-edenite, Kohn and Comeforo 1955) Some precedence had already been established in investigations on other minerals, Kourimsky (1955) on pyroxenes and Smith (1956), Goodyear and Duffin (1954) and others on the feldspars.

The present writer decided to approach the problem in the simplest manner and simply plot the percentage weight of the various oxides in several analysed and X-rayed amphiboles against the measurements of the $20\bar{2}$ line. The examples used in the construction of Figs. 73, 74, 75 and 76 were six from Dr. Bernard Leake of Bristol University, eight from Ghana analysed by the present writer, one from Sierra Leone (Dunham and Others 1958), one brown basaltic hornblende from the Durham departmental collection and one from the A.S.T.M. index Card, Number 2771. This latter shows exceptionally high alkali content and may be somewhat impure.

Powder photographs of the Ghana and Leake amphiboles were originally taken by the writer but owing to a defective X-ray tube these were unsuitable. The photographs (by the method of Straumanis) were finally taken by British Chrome and Chemicals Ltd., Eaglescliffe and the writer is indebted to them for 14 excellent powder photographs. These were measured and the 'd' spacings calculated by the present writer. This data is given in Appendix 3 together with the chemical analyses of the amphiboles used in the construction of Figs. 73, 74, 75, 76.

Table 17 in Appendix 3 shows that many of Dr. Leake's analyses show low CaO values. The present writer is not sure whether this is due to analytical technique or, if in fact, the minerals have low Ca contents. The other oxides fit the writer's graphs within the limit of reasonable experimental error.

Most of the amphiboles in the A. S. T. M. card index are useless for the present purposes since the 'd' spacings are only given to two decimal places. The major differences seem to be in the third decimal place. Allowing for measuring errors these differences appear to be quite significant.

It is interesting to note that although the calcium atom is a large one no significant variation could be found in the position of the $20\bar{2}$ line with respect to CaO. Furthermore when the total quantity of oxides in the 'X' position was plotted against the position of the $20\bar{2}$ line there was again no significant variation.

Some of the amphiboles supplied by Dr. Leake show low 'Y' group values, this is reflected in the positions of the examples with reference to the FeO and MgO lines. Similarly a number of the Ghana minerals show high 'Y' group values and the points plotted on the graphs are in a correspondingly higher position. Unfortunately no high iron actinolite member was available, so the writer has not been able to show where this would be placed with reference to the MgO and FeO plots. This is an obvious case where a low 'd' reading may give an erroneous iron and magnesia estimation. The same would apply with hastingsite and pargasites.

It has been suggested that the replacement of silicon by aluminium is responsible for the increased 'd' values for the $20\bar{2}$ line. It is also suggested that the filling of the vacant spaces is an important contributary factor although in Chapter 2 Fig. 5 it was shown that there was no direct relationship between the amount of aluminium in the silicon position and the Na+K in the vacant spaces.

The remarkable fit of alumina in Fig. 73 is almost certainly coincidental and is probably due to a cancellation of errors since both Dr. Leake and the present writer determined this oxide directly. It may also be due to the fact that Al^{iv} causes the swelling of the lattice because Al^{iv} is a larger atom than Si. It is significant to note that although the brown hornblende shows 4.00% greater alumina than would be expected it shows about 3.5% less silica than would be estimated from the graphs. Fig. 76 showing a plot of the silicon atomic propertions against 'd' spacing is not satisfactory. This is probably due to inaccuracies in the estimation of other constituents, water for example if wrongly determined could have a considerable effect on the atomic proportions of the other constituents.

With reference to the slopes of the lines it is interesting to note that these follow the same pattern as the plots of the refractive indices against composition namely negative slopes for silica and magnesia and positive slopes for FeO and alkalis. The closer fit of these plots to the mean lines is probably due to the greater accuracy of measurement of the 'd' spacing than the estimation of the refractive index.

The present writer has plotted data for a synthetic fluor-amphibole on the graph Fig. 73, this shows higher Al_2O_3

values than the equivalent hydroxy type. If a parallel is drawn with optical properties it is found that in the fluor-amphiboles there is a somewhat marked change in physical properties. Fig. 55 in Chapter 8 demonstrates this.

It is realised that the number of samples for the construction of these graphs is small and the variation of composition is not as extensive as would be wished but they do at least give an indication that some sort of correlation between the powder photograph and chemical constitution is possible. There is also a possibility of correlation of X-ray spacing by the use of the new diffractometer for better recording.

8 f Infra-red Absorption Spectra of Hornblendes.

All the analysed hornblendes from Ghana and from Dr. Leake were submitted for infra red spectrometry on the Grubb Parsons grating spectrometer. The present writer had read Launer's work (1952) in which an example of hornblende had been examined. In Launer's Fig. 9 showing the infra red absorption maxima for a series of hornblendes, tremolite, actinolite and presumably common hornblende some differences are shown in the absorption maxima particularly between hornblende and tremolite in the wave length band of 10 to 11 microns.

The 14 analysed amphiboles examined by the present writer cover a wide range of alumina content but owing to a broad band in that part of the spectrum in which some peaks did occur no concrete information could be obtained.

There is a great deal of similarity between the actinolite and common hornblende patterns in Launer's paper so presumably the effect of aluminium substitution must be small and the differences between the tremolite and actinolite patterns would then be accountable to the differences in magnesia iron content.

In the case of the water content of the amphiboles certain necessities of technique make the interpretation of the type of bonding difficult. The suggestion is that standards should be set up with pure tremolite and possibly synthetic pargasite and from them some correlation may be possible.

Summary of Recommendations for the Identification of Amphiboles.

MEASURE MAXIMUM EXTINCTION ANGLE.

1. Extinction Angle $Z \wedge C$ is 0°.

Mineral may be either monoclinic or orthorhombic. X-ray analysis is the only sure method of identification.

If the mineral is orthorhombic then substitute physical data in Hey's multiple regression equations to determine composition.

2. Extinction Angle $Z \wedge C$ is 1° to 9°.

Amphibole is : Oxy-hornblende, Alkali Amphibole, Cummingtonite Series.

3. Extinction Angle $Z \wedge C$ is 9° to 30°.

Amphibole is : Tremolite Series, Common Hornblende Series, Cummingtonite Series, Alkali Amphibole or Oxy-hornblende.

4. Extinction Angle $Z \wedge C$ is 50°-89°.

Amphibole is : Alkali Amphibole.

MEASURE REFRACTIVE INDICES.

PLOT ON FIG. 39.

1. Plotted at Cummingtonite-Hornblende intersection.

    1. Pale coloured - Cummingtonites or Tremolites.
    2. Moderately strongly coloured - Common Hornblendes.

(N. B. Tremolites -ve optic sign and lower Ng than cummingtonite optically +ve at this point).

2. Plotted at Alkali Amphibole-Hornblende intersection.

    All alkali amphiboles at this point have $Z \wedge C > 60^\circ$

    All hornblendes at this point have $Z \wedge C \ll 60^\circ$

The Oxy-hornblendes: In this case diagnosis is complicated by solid solution relationships with the hornblende series. Normal diagnosis $Ng\text{-}Np > .060$ $Z \wedge C < 10^\circ$.

The Tremolite Series:

Distinguish from Alkali Amphiboles by Fig. 40.

Distinguish from Common Hornblendes by Figs. 19 and 22.

Hornblende Series:

$Ng < 1.650$ and optically +ve amphibole is pargasite, edenite or tschermakite. The two latter are very rare in this compositional field, the amphibole is therefore almost certainly pargasite.

Ng 1.650 mineral is optically -ve and probably hastingsite type (see Fig. 11). There is 1 chance in 50 that it may have tschermakite composition and about 1 in 200 that it will be edenite or actinolite. This could be checked to some extent by the Winchell diagram Fig. 61 or by the regression equations in Appendix 2.

Chemical Composition in Hornblende Series:-

1. Winchell partial prism.
2. Substitution in partial regression equations Appendix 2.
3. X-ray powder photograph methods Figs. 73, 74, 75, 76.
4. Graphically by two axis graphs, Figs. 45, 47, 62, 67.

N.B. Fig. 45 is sufficient to locate mineral in correct position in the tremolite series.

The Alkali Amphiboles:-

Distinction in the group by Fig. 72.

Further sub-divisions by Miyashiro 1957 Fig. 3.

Cummingtonite Series: At present data insufficient for complete identification but high refractive index is grunerite end member.

N.B. All experimental optical data can be cross-checked by Figs. 20, 21, 22 and 39.

PART 2

THE GEOLOGY OF THE WINNEBA DISTRICT

OF GHANA

CHAPTER 9

INTRODUCTION

This report describes the geology of the 1:62,500 quarter degree sheet No. 32 (Map 1) which extends from 0° 45'W to 0° 30'W and from 5° 30'N to 5° 15'N. The area mapped extends from Apam along the coast almost to Senya Beraku and from Winneba to Mile 13 on the Winneba-Swedru road.

Winneba, the principal town in the district, is a small port and is linked by first class motor roads to Accra in the east and Saltpond in the west (Fig. 77). The name Winneba is locally supposed to have been derived from the name Weighing Bar, a place where the gold was weighed before export. Currently, however, the town has lost most of its former importance as a commercial centre.

Field work in the area was started in February 1956 and continued until March 1957. For the most part the mapping was on the scale 1:62,500 but in the Mankwadzi area around the Mukuba lagoon and in the coastal section the mapping was plotted directly on aerial photographs with a scale of about 5 inches:1 mile. Compass and tape traverses were necessary on the Winneba plain and here mapping was carried out on the scale of 4 inches to 1 mile. All information was eventually replotted on the 1:62,500 topographical survey sheet No. 32. Aerial photographs were used whenever possible and were found to be particularly useful for ascertaining the boundaries of the Togo quartzites, the Winneba granite and the geology of coastal section generally. All bearings are measured in degrees east of north and corrected for magnetic variation. The spellings of place names are those shown on the survey sheet No. 32.

The purpose of the work was to produce a geological map of the region, and to determine the relationships between the various granite types. Small quantities of minerals of economic value had been found by previous workers and in view of this an appreciation of the mineral resources was also required. In previous years a number of mining companies had operated in the area, interested chiefly in gold, tin and molybdenite; all the sections in which these companies worked were carefully re-examined and as a result it was decided not to continue the present examintion by further sub-surface exploration.

9 a Physical Features and Vegetation.

The district is trisected by three principal rivers, the Brusheng in the west which flows into the Apabaka Lagoon near Apam, the Pratu situated centrally and flowing into the Muni Lagoon near Winneba, and in the east by the Ayensu river which flows into and forms the Oyibi Lagoon. This latter is the largest river in the district and maintains a steady flow at all seasons thus providing the supply for the Winneba town water works.

For the most part the major rivers flow almost down the dip of the foliation of the underlying rocks; for this reason it is often difficult to correlate topographical directions with the linear geology. A series of dissected ridges formed by the Upper Birrimian are however vaguely discernible; these vary in strike from 20° to practically east-west, thereby following the foliation trends.

The topographic reflections of the various rock types found in the district are reasonably characteristic and have been classified as follows:-

1. The Winneba granite hills with scrub vegetation and large blocky tors of granite are clearly exposed. The granite forms a low range of hills striking 10° and generally discordant with other topographic features.
2. The Yenku range is probably the most marked physical feature containing the highest point in the district namely Yenku which is 764 feet O.D. The ridge forms the back-bone of the Upper Birrimian, its northern end being sharply truncated by a small fault trending to 30°.
3. The Ejisimanku-Apam coastal range which may be taken to include the Osi hills is part of a series of ridges of which Ejisimanku and the Apam Rest House hills form the highest points. For the most part these hills trend slightly north of east.
4. The Adzintam banded quartz schists form a well defined ridge which is eventually partially cut-off in the north by the Odominadzi granites. The

ridge is arcuate and swings from 10° in the north to about 130° in the south. The southern extension of the ridge is considerably lower and less marked in outline.

5. Just north of the Awomiro-Nsuaem road and west of the Awomiro-Old Agwakrom path, a highly characteristic series of connected conical hills are easily found. These represent the outcrop of the Awuku quartz schists and extend to the middle south-west part of the district where they run into the granite to the north of Ogwan.
6. East of the town of Nyakwadzi the actinolite schist series forms a number of low dome-shaped hills.
7. The Winneba plain forms a low lying stretch of country between the Winneba granite hills and the Muni River. The underlying rocks are nearly always coarse amphibolites although several small patches of gneiss have been found. Low hills reaching a height of 50 feet O.D. occur in this plain and these also for the most part are composed of coarse amphibolite with pegmatite.
8. At the base of the Upper Birrimian (Lower Birrimian in age?- exists a more or less continuous band of mica schists. Topographically these form rounded lateritized ridges which are usually strongly dissected.
9. The topography of the older granites and gneisses

is reasonably characteristic; sharp edges and ridges are rare, the topography is rounded and sugar loaf hill types like Obusumnyiye are common.

10. The Togo Series forms a distinct low crowned hill in the south-east corner of the district near Senya Beraku. The northern edge of the Series is clearly defined by a well-marked scarp face.

11. Four principal lagoons occur in the district. The Muni lagoon, probably the largest, lies just west of Winneba town.

In general the district can be divided up into three areas of more or less characteristic vegetation:-

(a) A coastal area of grassland comprising the Winneba plain.
(b) A central zone of stunted secondary bush.
(c) A northern semi-forest area.

Stunted bushes cover many of the hills in the coastal area, and it is noticeable that in that many cases clumps of bushes in the grassland can be seen, on aerial photographs, to be strung out along the foliations of the underlying rocks. So constant was this feature found to be that in one instance, in the Mankwadzi area, it was possible to indicate the contacts between two sets of rocks by reference to the distribution and alignment of small clumps of bushes.

I. Communications and Accessibility.

In general the whole area is reasonably accessible by road or footpath and only in one instance, on the north-west side at the Yenku range, was difficulty of access experienced. Over the north-west of the district generally the communications are poor; all former roads except Dahun-Achiasi and Manso-Brofoyedru do not now exist. The villages of Saraha, Amanfo and Amankesim are no longer flourishing and the small hamlet of Adansi has disappeared altogether.

The Awomiro-Onyadzi road is now only a foot-path and Asiebu, the only remaining village, is moving to a site on the Winneba-Saltpond road. Etchifekwa of the map has now become Budukwa and has moved ½ mile to the north-west. A new road has been cleared from Potsin to the Accra-Winneba road and the Kwekrom-Odommadzi road is impassable south of the main road.

The road from Kwekrom via Ewurukwa and Dabeyin is no longer passable and the former village is now derelict. A new road from Kwekrom to Ojobi has been constructed. This has a good surface and is straight. The Kwekrom-Senya Beraku and Jahadzi-Nsuechiri roads are impassable except by lorries and the Nsuechiri-Winneba road is impassable because of a broken bridge over the Ayensu river.

The net effect of the construction of tarred highways in the district has been to depopulate the bush areas. Medium-sized villages apparently find it uneconomic to exist far away from arterial roads. The larger towns, Potsin, Ojobi and Kwekrom, which are route centres, continue to grow and are generally only limited in growth by availability of water supplies.

CHAPTER 10

GENERAL GEOLOGY AND CLASSIFICATION

The rocks of the area, comparable with those of the same type in other parts of Ghana, may be classified as follows from older to younger in ascending succession.

	Tertiary to Recent	Lagoonal deposits, alluvium, gravels, salt beds, beach and raised beach sands, laterites, boulder beds, bedded and laminated sands, clay of uncertain age.
	Togo Series	Quartzites, purple + white facies, breccias, sericite phyllite near base.
	UNCONFORMITY	
	(?) Tarkwaian	Mumford quartz schists.
Pre-Cambrian.	Acid Intrusives	Aplites and pegmatites, quartz reefs, series of granites including the Winneba granite. Graphic granite, aplites (?), veins quartz, migmatites and the western gneiss.
	Post Birrimian-Igneous Activity	
	Basic Intrusives	Dykes now amphibolite, Epidiorite dykes Tarkwaian(?)
	Upper Birrimian	Metamorphosed porphyritic and vesicular lavas, quartz biotite and hornblende schists; hornblende schists, coarse amphibolites, actinolite schists, quartz schists. Gondites, manganiferous phyllite, epidosites and granulites.
Archaean	Lower Birrimian	Mica schists finely laminated.
	(?) Dahomeyan	Garnetiferous biotite gneiss with large feldspar and quartz lenses.

10 a The Dahomeyan.

In this area this series is represented by a small exposure, only a few yards in width, at the extreme western end of the Togo quartzite exposures on the beach near Senya Beraku. The contact between the Togo quartzites and the gneiss is somewhat obscure although the respective exposures are only two yards apart. Trenching across the contact has shown a thin band of talc occurs approximately at the junction. It is interesting to note that a few yards to the east a conspicuous over-fold exists in the quartzite (Plate 1). Further evidence is not available but the general field relations seem to indicate that the small wedge of gneiss in the quartzite has been in-thrust.

In general the rock is a finely foliated biotite gneiss with conspicuous lenses of quartz and feldspar; some pink garnet also occurs. Quartz veins about one inch thick are present and are strongly sheared; they show slight contortions in places. There is some jointing at 130° having a northerly hade of 45° with other vertical joints at 50°. The strike of the gneiss is 120° dipping south-westerly at 40° thereby conforming reasonably well with the strike of the adjacent Togo quartzites.

Similar rocks have been found to the east of Senya Beraku near Fetteh. These rocks which have been termed the Dawa Series by McCallien appear to be somewhat more garnetiferous. Some similarity to the Dahomeyan gneiss is apparently also recognized.

10 b The Birrimian System.

The rocks of this system occupy somewhat more than one-third of the total area mapped. They are in the shape of a reversed "S" and form a raft on the later gneisses. Numerous windows in the Birrimian allow portions of these gneisses to be examined. In the south the Birrimian strip is more than seven and a half miles wide across the foliation whilst to the north it is very much narrower being only four miles wide and gradually thinning out northwards.

The system is reasonably well exposed over the whole area, the best sections being found in river beds, road cuttings and on the various hill-sides. The Yenku range for example provides an almost continuous section from the bottom of the hills to the top. It has already been shown that the topographic reflections of the rocks of this system are very variable ranging from the relatively high ridges of Yenku to flat plains at Winneba. The exposures are sufficient to follow some untis short distances along the strike but a detailed overall sub-division of the system on the map is not possible; however, some sub-division into petrographic provinces has been done (Fig. 78). This is partly for convenience in description and partly because the various rock types are relatively clearly seen.

In the northern section the dip of the foliation is about 45° except where locally disturbed by granite and gneiss contacts when it may be as low as 30°. Although in general the dip of the foliation is easterly, some westerly dips are found in the eastern areas close to the migmatite gneiss. Micro-isoclinal folding has been found in several places, notably in a cutting by the Mpata junction on the new Accra road. Here north striking actinolitic hornblende schists show injections of granitic material and the dips vary from 45°-90° east and west. These schists are however unconnected with the main mass of the Birrimian and form only small relics in the gneiss. Another exposure of this type is also seen about 30 yards west of the Winneba roundabout along the new Mankesim road. Here a thin strip of green actinolite schist shows intense micro-folding. However over the whole area the dip of the foliations of the Birrimian rocks remains commonly easterly and south-easterly increasing from 45° in the north to almost vertical in the south.

The strike of the foliation in the northern section is almost due north swinging in the mid-northern section to 10°-20° and in the mid-southern section to 40°, finally swinging in the south-west to almost eastward. Locally gneiss stocks and the various granite intrusions disturb the general trends; for example the hornblende schists of the Osi hills strike east-west having been pushed from a 10°-20° direction by the Winneba granites and the eastern type granites and gneisses. The Tachem gneiss stock also causes a purely local disturbance of strike.

The gneiss apparently underlies the Birrimian at shallow depth and many stocks and pinnacles push through the system over most of the Winneba district. The gneiss is probably at maximum depth somewhere in the region of the Yenku Range where the gneiss roof is certainly at a minimum depth of 1,000 feet and probably much more.

10 c The Lower Birrimian - The Mica Schists.

This series, which is widely exposed on the adjacent 1:62,500 sheet No. 31, is developed to a relatively minor extent in the area covered by the Winneba sheet. In the neighbourhood of Akwapim village it is only a few yards thick but thickens both in a northerly and southerly direction, the strike and dip being concordant with the overlying characteristic Upper Birrimian greenstones. In the northern and central sections the dip is 45° but in common with the rest of the Birrimian of this district it increases to 80°-85° in the south-west section.

The mica schists are clearly exposed in three distinct sections, namely - in the Brusheng river near Lome, in a small stream near the village of Akwapim, and well exposed in a road cutting where the Winneba-Swedru road crosses a low lateritized ridge at mile 11. Between these exposures the schists are represented by broad lateritized ridges which are apparently continuous between exposures. Some small patches of similar mica schists have been found in the granite near Dahum; these however appear to belong to a different horizon of the same series.

The schists in outcrop show a certain amount of colour banding and often contain quartz veins, pegmatites and greenstones. In general they are composed of small biotite mica flakes, angular quartz grains and are strongly schistose. Staurolite is absent from the schists. When wet, for example in stream beds, the unlateritized schists show somewhat specular mica. Lateritization of the schists is however common and characteristic.

These schists are unlike any rock found in the characteristically Upper Birrimian sequence which forms the other component of this strip. The mica schists are well exposed in sheet 31, the adjacent western sheet, and on litho-logical grounds it seems reasonable to group the series within the Lower Birrimian, and although there are no structural grounds in the Winneba district for division into an upper and Lower Birrimian Series, the mica schist horizon has a lithology out of character with the rest of the Upper Birrimian and certainly occurs low down in the series and makes a convenient horizon to mark the sub-division.

10 d The Upper Birrimian.

Directly above the mica schists and sometimes intruded into them occur a series of extrusive and hypabyssal rocks here called greenstones for convenience, and inter-bedded with quartz schists; Some thin hornstones, epidosites, manganiferous phyllites and gondites also occur. Pyritization, silicification, sericitization and carbonation are relatively common.

The greenstones are generally hard rocks, forming such high ground as the Yenku range, the Ejisimanku and Apam hills and the smaller hills near Osi. The rocks are usually massive but often exhibit schistosity. They may be rich in chlorite and often contain feldspar as basic as andesine. Zoisite-epidote, magnetite, ilmenite and leucoxene are all very common. Remnants of original porphyritic and directional textures are usual and vesicular types are frequent.

To a greater or lesser degree the whole series has been subjected to regional metamorphism. In small areas principally around the Winneba granite and round the peripheries of the gneissic masses some thermal effects have been noted.

The Upper Birrimian of this district is transgressed by large numbers of mineralized minor intrusions of pegmatites, aplites and quartz reefs. Pneumatolitic effects in the greenstones are common and particularly noticeable is the introduction of tourmaline found in many localities.

Minor intrusions, mostly in the form of dykes and possibly small sills, are present. These were, prior to metamorphism, probably largely gabbro, monomineralic ultrabasic rocks and dolerites, all of which are now epidiorites, coarse amphibolites and the like. A zone of coarse amphibolites and recrystallized feldspar amphibolites is sufficiently well developed around the western and northern sides of the Winneba granite to merit separate description.

The strip of Birrimian of this map sheet can be divided into three distinct bands separated by two more or less continuous bands of quartz schists. A third series of banded quartz schist or gneiss appears on the eastern boundary of the Upper Birrimian and parts of this band are definitely Upper Birrimian in character. It is proposed to discuss this series separately. In view of the foregoing, therefore, it is convenient to make the following sub-divisions:

1.. North-western greenstone series.
2. Ayensuadzi-Brusheng quartz schists.
3. Mumford quartz schists.
4. Central greenstone series.
5. Central quartz schist.
6. The eastern greenstone series.
7. Zone of coarse amphibolites.
8. Quartz schist or gneiss series of uncertain age.

CHAPTER 11

DESCRIPTIVE GEOLOGY

11 a The North-Western Greenstone Series.

Generally this series is poorly exposed. A few outcrops are seen in the low hills to the west of Abasa village but the best section is exposed in a stream near the village of Akwapim.

The horizon is also seen at the head of the Pratu River and is well exposed down-stream as far as the contact with the Ayensuadzi-Brusheng quartz scists.

At the base, in contact with and amongst the mica schists, the series consists of fine grained bluish somewhat contorted actinolite schists. The contortions are local and are probably due to minor quartz reefs and pegmatite intrusions. In places the rock is well jointed giving a shale-like appearance to the outcrops. Higher in the series the dip flattens from 80° to 50° and some infaulted fine grained amphibolites appear.

The section is well represented by specimens LY820 and LY822. Both are actinolite schists and occur within a half mile of the biotite gneiss contact in the Akwapim river.

In thin section LY820 is composed of an arrangement of par allel and sub-parallel fibrous and occasionally slightly bent actinolite laths. The mineral is quite markedly pleochroic in pale yellow to dark green, and fine longitudinal cleavage with well defined transverse cracks is distinct. The extinction angle $Z \wedge c$ is 15°. A small quantity of red-yellow slightly pleochroic alteration product is associated with the actinolite and is clearly seen on some of the more ragged grains. The groundmass is fine grained and consists mainly of allotriomorphic quartz, oligoclase and andesine feldspar. Some lozenge-shaped untwinned feldspar is present and much of the quartz shows strain shadows. Small granules of magnetite and ilmenite with a little leucoxene occur throughout the section. A thin quartz vein is also present.

Specimen LY822 is essentially different in structure. The actinolite laths are only a fraction of the size of those in LY820 and markedly parallel. Magnetite and ilmenite grains are similarly in strong parallel orientation. Occasionally larger plates of green-greenish blue amphibole slightly disturb the monotony of the texture. Streaks and lenses composed of mosaics of completely allotriomorphic quartz grains occur and probably represent later silicification. LY822 is close to a strongly sheared zone which may account for the marked parallelism exhibited by the actinolite grains.

The Pratu River section, where the eastern continuation of the sub-division is exposed, consists of vesicular lavas with some remaining original texture, some even grained hornblende schists and a few thin actinolite schists. Feldspar and quartz amphibolites appear throughout the section and in one instance a garnetiferous schist containing small pink garnets is clearly exposed in contact with a coarse monomineralic amphibolite. Occasional aplites, some composite with quartz, and one epidiorite dyke conformable with the general strike are exposed.

The greenstones in this series show strong jointing trending due north and occasionally they may be shattered. The strike is reasonably constant at 350° and the dip is commonly 70° to 80° easterly.

Specimen LY832 is typical of the coarse feldspar amphibolites of this section. Relic structures clearly indicate a vesicular lava parentage. In thin section the rock is composed of clots of pale green to bluish-green hornblende with possibly some actinolitic hornblende. The grains are generally in the form of laths, basal sections and small acicular grains. The edges of the clots are normally ragged and many individual acicular amphiboles grains are found in the vesicles. The latter are now filled with aggregates of andesine feldspar laths all somewhat saussuritized. Ilmenite occurs in large grains but is rare.

The typical hard flinty greenstone of the section is characteristically a metamorphosed basic lava. Microscopically it consists of greenish blue amphibole (X - pale yellow, Y - dark green, Z - bluish green) and is usually prismatic in form but may be fibrous and often also appears as ragged laths with inclusions. There is a slight tendency for sub-parallel arrangements to occur. Quartz and feldspar occur in the groundmass, the former usually as small allotriomorphic grains and the latter normally untwinned and myrmekitic. Large polysynthetically twinned feldspars are usually andesine. Magnetite and ilmenite are abundant.

The hornblende schists of which specimen LY830 is representative, are very compact rocks in which the amphibole is the same as that in the metamorphosed vesicula lava of the series. It usually occurs in sub-parallel laths but some basal sections are present. The groundmass is microgranular and consists of allotriomorphic grains of amphibole, quartz and a little feldspar. Magnetite and ilmenite are present inl large skeletal grains.

The tremolite schist of the section are petrologically uninteresting, consisting only of a mass of somewhat subparallel tremolite fibres and a little epidote; some ilmenite and limonite after pyrite are common.

11 b Ayensuadzi-Brusheng Quartz Schists.

The Ayensuadzi-Brusheng quartz schists form a well-marked horizon stretching from the Ayensu River at Ayensuadzi along the north-western face of the Yenku block and finally dying out against the granite and gneiss just west of the Brusheng River about 1 mile south of where it crosses the Otaw-Lome foot-path.

Other quartz schists have been found between Mumford and Apam and there is no field evidence to indicate that these are similar in age to the Ayensuadzi-Brusheng schists. Certainly no pebble beds have been found in the main horizon but some indications in the form of pebble-holes (?) have been seen east of Mumford and there are extensive conglomerates further west. For the most part the Mumford schists as represented on Sheet 32 are strongly foliated sericite-rich, current-bedded quartz schists.

In general the strike and dip of the Ayensuadzi-Brusheng quartz schists are completely conformable with those of the rest of the Upper Birrimian and although the lithology changes somewhat from silvery white schists in the Awuku hills to black hard flinty schists in the Yenku block, the continuity of strike, the distribution and the petrological evidence all indicate that they are part of the same horizon and that the lithological differences are lateral variations of the same horizon.

The age of the quartz schists appears to be somewhat doubtful. The evidence insofar as the Ayensuadzi-Brusheng schists are concerned seems to favour the inclusion of these schists within the Birrimian. The following evidence together with the conformable attitudes of strike and dip appears to justify this. If the Mumford quartz schists are in fact a continuation of this horizon then they are also Birrimian in age.

The quartz schist is cut by greenstones and amphibolites in the Awuku hills and in the Ayensu river; the black quartz schist north of the Obaw-Lome path to the west of the Yenku block is similarly affected.

The Tachem granite which is clearly post-Birrimian causes strike displacements in the Birrimian greenstone and such displacements are represented in the quartz schist by bulges.

The schists between Awuku and Ntefro(Ayensuadzi) are well marked by a series of low conical hills stretching from Aboni on the Winneba-Swedru road to Ayensuadzi on the Ayensu River. These include the two large conical hills of Ntefro and Awuku. The schists are a pale silver grey colour which apparently weathers to a pinkish white. Small translucent needles of sillimanite can sometimes be distinguished in hand specimen; foliation is usually marked and epidotization is common, particularly around Ntefro.

LY83, a typical specimen, is composed of quartz, sillimanite and some muscovite; much of the quartz is embedded in areas of elongated clusters of sillimanite grains. Strain shadows and inclusions are seen. Pyrite and some epidote occur. Occasionally the clusters of sillimanite are smaller and quartz may be much more abundant, often as elongated grains. In specimen LY99 the quartz is even more clearly discernible and the sillimanite tends to be collected in brown fibrous clusters showing cruciform extinction.

The sillimanite in these rocks usually occurs as ragged pale yellow-brown clusters of small prisms. Many clusters show cruciform extinction and quartz grains are common "inclusions". Sillimanite also occurs as individual prisms scattered throughout the sections and it would appear that this mineral in the Awuku-Ayensuadzi schists has been formed from biotite by contact metamorphism of schists petrologically similar to the Aboni-Brusheng schists. The proximity of the Tachem granite makes this suggestion feasible particularly when it is noted that the same sillimanite phenomenon occurs in the central quartz schists which are cut by the Tachem granite. If this suggestion of contact metamorphism by the granites is correct and if it can be shown that the granites are pre-Tarkwaian then it follows that this quartz schist is Birrimian in age.

The Aboni-Brusheng schist which is the continuation of the Awuku section is a characteristically fine grained, black, often silicified quartz-biotite schist noticeably lacking in sillimanite. It may or may not show marked foliation. In thin section (LY790) it consists of a mosaic of semi-rounded quartz grains some of which show shadowy extinction. Abundant biotite appears in the form of randomly orientated shreds. Muscovite often occurs in broad irregular shreds enclosing rounded quartz grains. Ilmenite is quite common. One specimen (LY791) taken from the Pratu River at the contact with the greenstone shows marked parallel arrangement of shreds and strings of small biotite laths. A little muscovite is present and silicification is shown by small quartz veins.

The quartz schists are well exposed to the west of the Yenku block and appear as a banded series with strong vertical joints at 120° and 20°. The rock is markedly pyritous and some intruded amphibolites occur. A number of quartz veins and much interstitial siliceous material was observed. Some shattering trending to 10° occurs and there is some brecciation. In thin section the structure is mylonitic with elongated parallel quartz grains showing shadowy extinction; shreds of chlorite with magnetite ilmenite and pyrite are present. Brown, strongly pleochroic biotite plates and flecks are seen developed as a later stage thermal metamorphic effect caused by local intrusions of rock which is now amphibolite. Dusty calcite is abundant in streaks and rounded grains frequently disturbing the structure in which over-folding and small thrust planes are features. Evidence of late silicification is indicated by thin quartz veins.

An exposure of these schists near the granite is seen in the Brusheng river and at this point they contain small pink garnets and have lost all trace of the cataclastic structures described previously.

11 c The Mumford Quartz Schists.

The designation Mumford quartz schists, in this instance, refers only to those rocks exposed in the extreme south-west corner of the area. The evidence for their relationship to the schists already described occurs in the adjoining 1:62,500 sheet 31.

In general the Mumford quartz schists are grey buff coloured somewhat equi-granular sericite schists. False-bedding is indicated by streaks of ilmenite and magnetite. In parts the schist became coarse and pebbly. The rock is well jointed and sheared and strikes generally at 50° and has a south-esterly dip of 80°-85°.

A brief examination of the conglomerates to the west of these exposures showed that the contact between the quartz schist and conglomerate is relatively sharp and that the latter occurs in pockets with a somewhat irregular distribution. Foliation and shearing are continuous from quartz schist to conglomerate without interruption.

Generally the schist are rather coarser than the Ayensuadzi-Brusheng type. In thin section the texture is seen to be quite granular and the quartz grains are all completely allotriomorphic; many contain inclusions, most show evidence of shearing and practically all grains exhibit shadowy extinction. The grains vary considerably in size, a feature which is not common in the Ayensuadzi schists. Muscovite occurs as thin tabular grains haveing a somewhat random orientation, but may in places show sub-parallel arrangements. Sericite is present as a feldspar alteration product. Ilmenite occurs in reasonable quantities, the grains appearing in irregular clusters which may be skeletal in all cases. The ilmenite is usually more or less altered to leucoxene and a little epidote is present. Biotite which is the common mineral in the Ayensuadzi schists is absent. Ilmenite is also more abundant here than elsewhere.

11 d The Central Greenstone Series.

This series forma a strip of Upper Birrimian greenstones stretching from the Krobon River in the north to the Simbrofo-Ogwan road in the south and appears to contain a representative of almost every rock type found in the Upper

Birrimian of this district. The general geology shows that the rocks of the Yenku block which form the back-bone of the Central greenstones extend north and southwards. The Yenku block seems to be largely monolithic whilst to the north and south the rocks are a selection of Upper Birrimian greenstone types.

In the northern section, represented by the rocks exposed from Awomiro to the Krobon River, the series is principally actinolitic. The rocks are pale or dark green soft schists mostly without strong parallel alignment of grains. They form low-lying rounded outcrops and hills. Elsewhere along the Awomiro-Nsuaem road and east of the Awomiro-Ayakwadzi road outcrops of actinolite schists show a dog tooth form which is highly characteristic of the exposures of similar schists in the eastern greenstone series.

A good section is seen along the footpath from Nsuaem to Abakwa, and in the Ayensu river at Nsuaem the green schists are cut by veinlets of fine grained feldspar amphibolite. The section shows a somewhat variable strike owing to local granitic intrusions. Some fine grained bluish-green pyritous schists similar to those found in the Yenku block appear along the Awomiro-Tachem road and a few medium grained feldspar amphibolites are exposed near the Central Quartz Schists. Hornblende schists often containing small pink garnets are quite common.

In thin section the actinolite schists of the series are composed of a plexus of actinolite-tremolite needles.

Abundant chlorite and some cloudy calcite is present. Some epidote and a few grains of rutile also occur. Iron staining is very common. The epidote-feldspar-hornblende schists of the locality contain thin laths of green-blue green pleochroic amphibole which shows marked parallel arrangement. Small granular epidote is abundant, and with feldspar and some quartz occurs interstitially. In the higher grades of metamorphism the hornblende schists of this series contain small pink garnets and epidote is rare.

The Pratu River probably provides the most continuous section across the central greenstone series extending from the Ayensuadzi-Brusheng Quartz Schists to the Central Quartz Schists with very few gaps in the succession. The rocks are principally actinolitic but also include feldspar amphibolites, a few hornblende schists, some Yenku type actinolite schists and a number of late intrusives which are now epidiorites and coarse amphibolites. In parts the actinolites and hornblende schist develop mica and pneumatolytic effects are sometimes indicated by the introduction of tourmaline into the pale green schists.

The actinolite schists are often quite coarse grained and are composed of radiating sheaves of actinolite visible even in hand specimen. In thin section they show ragged laths of pale green actinolite in completely random orientation; some magnetite is present and may occasionally be skeletal. The texture is quite coarse. The hornblende schists, best illustrated by LY789, are probably more properly termed plagioclase amphibolites and are composed of pale green amphibole and feldspar approaching andesine in composition. A little epidote is present. The occurrence of grains of diopside pyroxene indicate an increasing grade of metamorphism in the sequence.

A thin hornfels occurs in the section and is found 0.85 miles downstream from the Asiebu-Awomiro footpath. In hand specimen the rock is black, fine grained and somewhat sheared. In thin section it is composed of an irregular quartz mosaic which is proabably partly due to later silicification. Dark brown biotite occurs as clots and streaks in apparent complete optical continuity throughout the section. The clots are seen to be made up of biotite grains probably formed from amphibole. Feldspar is present in saussuritized laths and sometimes shows a little twinning. Abundant pyrite, some muscovite and a little carbonate are also present.

The Yenku block is the principal topographic feature of the central greenstone series and consists of a range of hills about 2¼ miles in length, the highest point being 764 feet above sea level. The range is almost entirely composed of very fine grained compact actinolite schists. In situ the rocks are quite unlike those from the Awomiro and Akwapim districts previously described. The Yenku schists are pale greenish or bluish grey, extremely fine grained and flinty and generally show well marked pyritous streaks. They usually exhibit marked north striking vertical jointing.

Typically, in thin section, the schists consist of masses of fibrous slightly bluish green actinolitic amphibole and occasionally a small quantity of tremolite is present. Usually the amphibole occurs as thin fibrous laths sometimes markedly bent. Interstitially quartz and a little untwinned albite occurs. Irregular grains of occasionally skeletal ilmenite appear together with infrequent epidote. Some specimens show marked pyroclastic structures having matrices of short stubbly prisms of actinolite with irregular orientation. Ilmenite is abundant and appears in irregular clots which may be skeletal in parts. Large "pebbles" composed of masses of small actinolite needles occur; usually these fragments have a markde rim. Small quartz veins and patches of quartz are common in the mesostasis.

The southern portion of the central greenstone series is seen in two principal sections, firstly along the footpath from Otaw to Lome, and secondly in a well exposed section in the Brusheng River downstream from the Otaw-Lome footpath. A few exposures of hornblende-schist and some vesicular greenstones also occur along the Simbrofo-Ogwan road. These serve to mark the central greenstone series along the boundary of sheet 32.

The exposures along the Otaw-Lome footpath are rather poor and considerable lateritization occurs in parts, further obscuring the contact between the central greenstone series and the Ayensuadzi-Brusheng schists. The section is principally one of coarse amphibolites of intrusive origin with vesicular and porphyritic lavas. Actinolite schists are subordinate and some hornblende schists, possibly of pyroclastic origin, also appear.

The petrography of the vesicular and porphyritic greenstones is quite characteristic for this locality. Typically they consist of hornblende which is strongly pleochroic from straw yellow through dark green to bluish green and appears generally as stubbly laths with inclusions of quartz and epidote. The feldspars are usually completely allotriomorphic, saussuritized, with epidote and/or zoisite very abundant; small inclusions of quartz in the feldspar are also common. Some small grains of feldspar where distinguishable are andesine-oligoclase. Interstitially a mosaic of quartz and albite exists. Ilmenite is usual. Later silicification probably accounts for some of the abundant quartz present in these rocks.

Occasionally some porphyritic lavas show a superimposed thermal metamorphism. This was found to be almost always local and due to the presence of post-Birrimian intrusives or intrusives of late Birrimian age. In these cases all the amphibole has been converted into flakes of dark brown biotite. Magnetite and ilmenite are rare. The porphyritic crystals are saussuritized feldspar characteristically full of inclusions of epidote and quartz. Abundant calcite and epidote occur throughout the sections.

In the Brusheng River the section is more complete and consists of a series of amphibolites some of which were originally porphyritic or vesicular lavas. Occasional actinolite schists are present together with coarse amphibolites which appear to belong to the epidiorite group. The actinolite schists show marked foliation usually in a 25° direction, the dips are southerly and are usually about 80° to 85° in common with the rest of the Birrimian in this section.

Petrologically the section differs little from those previously described. The actinolite schists are rather softer than those at Yenku but on the whole they are very similar except in so far as the schists of the Brusheng section show a rather stronger development of feldspar.

11 e The Central Quartz Schists.

The central quartz schists extend at intervals from the Ayensu River near Nsuaem as far as the point where the Winneba-Mankessim road cuts the old Apam motor road. The horizon is generally not well exposed, except in river sections, and normally forms features of only moderate relief. It has not been found east of the Ayensu river, probably having been cut off by the granite which is found just north-east of Nsuaem. The principal exposures of the schists are to be found around the Tachem granite, in the Pratu River, along the foot hills of the south-west side of the Yenku block and again in the hills near Mprumen village on the old Apam motor road.

The rock is generally massive in character with little marked foliation, but where measurable the strikes and dips have been found to be essentially conformable with those of the rest of the Upper Birrimian of the district. In the field the rocks of this series are often difficult to distinguish from the highly siliceous and sheared aplites of the Apam and Mankwadzi type. The lithology of the schists, like that of the Ayensuadzi-Brusheng series, is somewhat variable and apparently governed by the granite masses of Tachem and Simbrofo.

North of the Tachem granite, towards the Awomiro-Nsuaem road, the schists are extremely fine grained and black in colour; they show little foliation but are often strongly silicified. Small quartz veinlets are generally distinguishable even in hand specimen. In appearance the central quartz schists at this point are very similar to the grey-black quartz schists of the Ayensuadzi-Brusheng series. In thin section however the characteristics are somewhat different. The matrix consists of a granular mosaic of semi-hexagonal quartz grains, usually with a few inclusions but showing no sign of strain, cordierite is present also. Scattered throughout the sections are buff coloured clusters of sillimanite needles similar to those described in the section dealing with the Ayensuadzi-Brusheng series. The central quartz schists at this point outcrop not more than one quarter mile from the Tachem granite and as would be expected the development of sillimanite is marked.

South of the Tachem granite hill the quartz schists show rather differ ent field characteristics. The schists are grey-white in colour with individual quartz grains clearly recognizable in hand specimen. The rocks have a granular appearance in which the sillimanite shows as rounded spots.

In thin section the matrix is composed of the usual mosaic of quartz grains but the sillimanite is clearly seen to be collected in patches which are generally quite large, diameters of the order of 1/16 inch being not uncommon. The structure and composition of the spots is not clear; they appear to be in a half-way stage of formation from biotite and they may show rims with small needles of sillimanite attached to the peripheries. In thin sections of the spotted quartz schists the cruciform extinction of the sillimanite aggregates is absent.

The southerly continuation of the central quartz schists is found in the Pratu River 1.2 miles downstream from the old Ogwakrom-Asiebu footpath. The schists are strongly jointed in a more or less north-south direction and some secondary quartz appears along the joint planes. At the base of the section the schists are spotted and similar in lithology to those previously described except that the spots are characteristically biotite rather than sillimanite. Higher in the section biotite and muscovite are present and are clearly distinguishable in hand specimen. In thin section the biotite is abundant and occurs as small clots of dark brown flakes which become gradually disseminated throughout the rocks. Some chlorite and a little saussuritized feldspar are present. Some of the feldspar may have been introduced by a number of veins which cut the rocks.

South-westerly, along the strike the central quartz schists are exposed several times in the south-eastern foot hills of the Yenku block. The characteristics of the schists in these areas are essentially similar but tend to be rather finer grained than the schist in the more northerly exposures. The matrix of the rocks is microgranular rather than granular and the biotite usually appears as small disseminated dark brown flakes.

The final exposures of the central quartz schists is found just outside the village of Mprumen on the old Onyadzi-Ajumako road. The hill feature in which the schist occurs is probably the highest and most marked topographic feature of the whole horizon. In outcrop the rock is moderately fine grained and grey in colour, with small pink garnets usually clearly distinguishable. Microscopically it is coarser than the schists near Yenku and the matrix is clearly a granular mosaic of quartz some grains showing shadowy extinction. A little untwinned feldspar containing inclusions appears as grains several times larger than the quartz of the mesostasis. Biotite is abundant, dark brown, and tends to collect in clusters; occasionally some sub-parallel arrangement is discernible. Small idiomorphic unzoned pink garnets occur.

11 f <u>The Eastern Greenstone Series.</u>

The eastern greenstone series covers the largest area of all the sub-divisions of the Upper Birrimian. It extends from the Muni lagoon to Apam and northwards as far as the Abakwa granite. It is bounded on the western side by the broken strip of the central quartz schists and on the eastern side the boundary is composed of the amphibolite series in the south and the banded quartz schists in the north. The strike of the series is markedly affected by the various granite stocks and intrusions. The strongest effect is produced by the tongues of granite and gneiss pushing easterly and westerly into the series along the Accra-Saltpond road. Some local minor displacements of strike and dip occur in the neighbourhoods of the Tachem granite and the small granite knob north-east of Nsuaem. Exposures of Birrimian in the extreme northern section are rare and it is thought by the author that the granite exists here at very shallow depth.

In the southern section the division contains the largest number of minor acid intrusions found in the district. Furthermore the characteristic green dioritic or gabbroic bodies are more abundant and more clearly exposed here than elsewhere. The general bend of strike from Mankwadzi to Apam and the concentration of minor intrusives with attendant mineralization in this locality suggests the existence of another granite mass, or possibly an extension of the Winneba granite, on the seaward side of Mankwadzi and Apam.

The rocks of the series vary considerably in character from north to south. In the northern section they are predominantly actinolitic with relatively few amphibolites, whilst at Mampong a hard black fine grained pyritous hornblende schist appears and extends south-westerly into the quartz and feldspar amphibolites of the Osi hills. Southwards from the Osi hills the series is predominantly composed of feldspar amphibolites with interbanded sediments; some actinolite schists are also present and they are most marked around Okeseo and the village of Adanka near the Brusheng river. The south-western or Apam section is similar to the Mankwadzi series and contains a number of garnet hornfels and greywackes. Hornblende schists of rather obscure parentage appear amongst the pillow lavas at Apam and elsewhere.

Basically the actinolite schists of the northern part of the series are the same as those described in the section dealing with the central greenstone series. In the eastern series the schists show a rather stronger development and extend, sontinuously and clearly defined, from the Krobon River to at leas t mile 6 on the Winneba-Swedru road and as far as the northern side of the Osi hills. South-west of this latter point they become less well defined. In the field t they form low rounded hills and outcrops have a characteristic dog tooth form. The schists are dark olive green to pale green and are requently iron stained; individual actinolite needles are generally visible to hand specimen. In and around Monastery hill to the north-east of mile 6 Winneba-Swedru road, and along the Nyakwadzi-Mampong road amphibolite dykes are well exposed and just west of Tachem village and north of Adzintam near the Chindrua river some feldspathic amphibolites rich in epidote occur. These appear to have been originally vesicular lavas.

South and south-west of Mampong, the eastern greenstone series shows a marked development of porphyritic and vesicular lavas which are intercalated with ash, epidosite and more highly siliceous bands. Occasionally, for example on the coast near Mankwadzi and on the north-eastern slopes of Ejisimanku, fine tuffs or sediments which are now garnetiferous biotite schists appear. These have been traced northwards as far as the point where the Pratu River cuts the Winneba-Saltpond road. The whole series has been cut by many minor acid and basic intrusions which have been responsible for local metamorphic and pneumatolytic effects.

The area designated as the Osi hills locality extends from Mampong to the Accra-Mankessim road. The rocks here show a marked swing in strike from 20° at Mampong to 60° to 80° in the Osi hills proper. There is also a general increase in dip from 45° near Mampong to 70° in the Osi hills. The strike returns to a 10°-20° trend where the greenstone series cuts the new Accra-Mankessim road.

It has already been mentioned that the green actinolitic schist series which is characteristic of the northern areas is subordinate in the Osi hills. When they do occur the schists are composed of sub-parallel laths and fibres of very pale green slightly pleochroic actinolite. Ziosite epidote is common and carbonates of reasonable size are clearly distinguishable. Pyrite is plentiful.

The Osi hills themselves are a marked topographic feature reaching a height of about 150 feet above the surrounding plain. The summits of the hills are composed of a a hornblende quartz schist which can be traced from the Mampong district. The schist in the Osi hills strikes somewhat irregularly as the result of the intrusion of a large composite aplite and pegmatite body. At the top of the most westerly hill, lenticles and patches of aplite can be seen as stringers in the hornblende schist and tourmalinization is common.

In the hand specimen the schist is fine grained and black in colour; usually it is strongly foliated with streaks of pyrite along the planes. In thin section the rock is more properly termed an amphibolite, the matrix consisting of a granoblastic mosaic of allotriomorphic quartz and a little untwinned albitic feldspar. The amphibole occurs as short, stubby, rounded laths and plates showing a tendency towards sub-parallel arrangement. The pleochroism is usually green to a somewhat bluish green. The centres of some of the amphibole grains are cloudy and small hypidiomorphic magnetite grains are found associated with this feature. Larger grains of magnetite and ilmenite have a more random distribution.

The origin of this type of rock is somewhat obscure; the granular texture of the groundmass together with the appearance of rounded semi-orientated amphiboles and the similarity of composition to the closely associated porphyritic and vesicular lavas suggests that its parentage was probably tuffaceous. In such a case one would tend to expect larger fragments to occur within the matrix but this does not seem to be the case here. The contact between these rocks and vesicular lavas appears to be sharp and it should be appreciated that these lavas are generally of submarine origin. In view of this there is some support for the supposition that bodies such as this hornblende schist are formed from locally derived tuff.

The black, very fine grained hornblende schist from the Osi hills is not characteristic of what the writer normally regards as Birrimian tuff. The latter are, currently hornblende schists, granular is hand specimen, and with the quartz and feldspar grains clearly visible and somewhat frosted. No textural directional features are noticeable but in thin section the texture is not as markedly granular as would be expected from inspection of the hand specimen. The amphibole present is characteristically similar to that of the vesicular and porphyritic lavas. The feldspar is usually saussuritized andesine but some untwinned albite is also common. There is some tendency for the feldspars to be clear of inclusions. Those which remain are usually found in the centre of the grains.

In the case of tuffs derived from basic lavas, the net result of regional metamorphism of a grade in which structural deformation is not marked, is to form rocks characteristically not unlike some of the feldspar amphibolites which were without doubt vesicular and porphyritic basic lavas. It may be that in the case of tuffs some of the clastic features remain after low grade metamorphism, in which instance the distinction between tuffs and lavas is relatively simple, but tuffs because of their clastic state weather more easily and consequently are more willing subjects for metamorphism and tend to loose their clastic features more easily. Here unless the field relations show characteristic tuff formation it is preferable to refer to them as hornblende schists which they currently are, appreciating at the same time that this refers to a present state which may include types of non-tuffaceous origin.

The vesicular and porphyritic lavas of the Osi hills are clearly recognizable in the field. They are usually well jointed and sometimes show a little foliation. Veining and pyritization are common features. Some of the greenstones having an extrusive origin may not show vesicles or porphyritic crystals in which case they are classed as hornblende schists (see previous section).

In thin section the vesicular lavas consist of laths of pleochroic hornblende sometimes closely packed and almost always of identical composition throughout the Osi hills. The pleochroism varies from pale yellow to blue-green. There is an occasional tendency for some directional structure to show. Interstitially quartz, feldspar which is probably albite, epidote and zoisite occur. Metallic ores are absent. The vesicles show a well-marked rounded form and appear to be in two stages of metamorphism. In one case they are composed of a fine mosaic of zoisite, albite and quartz with occasional small flakes of amphibole included. At low magnification vesicles of this type show an overall shadowy twinning. In the second case the vesicles are almost wholly untwinned feldspar crowded with small inclusions. Occasionally small moderately well formed andesine grains appear and these also contain many inclusions.

The amphibole of the porphyritic lavas has a similar composition to that of the vesicular types. A slight difference is that in the former the colouring appears to be rather more intense particularly in the green component. The texture of the matrix of the porphyritic lava is somewhat granoblastic although it does show remnants of trachytic texture. Quartz and albitic feldspar occur interstitially. Pyrite is abundant appearing around the peripheries of the felsic grains in the matrix. Porphyritic pyroxene grains are now completely replaced by masses of amphibole laths. The feldspar porphyries are granular masses of albitic feldspar and quartz. At low magnifications the porphyries which show hypidiomorphic outlines are packed with inclusions. Ilmenite and epidote - zoisite are quite common but a noticeable feature of both vesicular and porphyritic lavas in the Osi hills series is the absence of carbonates.

Intercalated with the lavas of the Osi hills section are the remnants of original calcareous grits which have since become granulites and epidosites. These rocks are only poorly exposed and of very small extent. Generally they show little or no original or superimposed structure.

The granulite from the old Pomadi Brofeyedru-Mpata motor road shows the typically granoblastic mosaic of quartz and feldspar with small flakes of greenish amphibole scattered throughout the section; grains of granular zoisite appear to be of the clino variety. Metallic ores and carbonates are absent.

The epidosites found on the south-west slopes of the Osi hills are uninteresting in thin section and consist merely of a granular mass of epidote and quartz. The epidote is not strongly coloured and no iron ores are seen.

11 f 1 The Mankwadzi Locality.

This locality is defined as the area lying between the Saltpond-Accra road and the sea, and bounded to the east and west respectively by the Muni lagoon and the Onyadzi-Abrekum road. The area is itself principally composed of amphibolites and hornblende schists with the best sections exposed along the coast from Munianu village to the western Abrekum lagoon, and in the Mukuba lagoon to the west of the village of Mankwadzi. Adequate supporting sections are found along the Abrekum-Mankwadzi road and also along the telegraph lines from Apam to Biwadzi.

The strike of the foliation in the district is normally to 30°-40° dipping at 85°-90° to the south-east. There is a sharp turn in strike near the Abrkum lagoon where it swings to 50°-60°. The rocks are normally strongly jointed but faulting and shearing are not common. It should be noted however that shattering occurs along the quartz and aplite dykes.

The best section is the coastal section which extends from Mankwadzi to the eastern Abrekum lagoon and the sequence is repeated with slight variations in the Mukuba lagoon and along the Mankwadzi road. On the coast the section commences with a series of highly shattered minor acid intrusions which will be discussed in a separate section. The hosts of these intrusions are actinolitic hornblende schist composed of bent fibrous laths of amphibole with carbonates, albite and quartz occurring interstitially. Ilmenite and chlorite are common. In many respects these rocks are similar to the actinolitic facies of the northern section of the eastern greenstone series.

At the western end of the Mankwadzi beach a few yards east of a rocky promontory and forming the promontory itself, a banded series of schsists appears. They show rubbly irregular surface characteristics and are strongly foliated. In the field these banded schists are cut by and intercalated with lavas which are now feldspar amphibolites, some of which show remnants of pillow structures; in one place the coarse biotite feldspar amphibolite may be of gabbroic or ultrabasic origin. In a small sandy cove between the Mankwadzi beach and the eastern Abrekum lagoon the schists reach their maximum development and are strongly garnetiferous.

Petrologically the schists consist of alternating bands of biotite and hornblende feldspar quartz schists. Tourmalinization is common in the vicinity of the minor acid intrusions and pyrite and arsenopyrite appear to be scattered throughout. In hand specimen the biotite shows as a somewhat sparkling bronze mineral, characteristic of the schists and greenstones of the locality.

In thin section a variety of interesting mineral associations are seen. The hornblende-rich sections show a granoblastic mosaic composed of quartz and andesine feldspar, some of which may show inclusions. The amphibole is a strongly pleochroic hornblende with absorption scheme Z - sea green, Y - dark olive green, X - pale yellow. It appears in ragged prisms, and more rarely in basal sections, both forms showing some sieve structure. Small flakes of sub-parallel brown biotite appear throughout the section but are considerably more abundant in the hornblende-poor parts. Some zoisite and a little calcite are seen but iron ores are absent.

In other parts the schists consist of an uneven granular mosaic of more or less untwinned feldspar and quartz. The feldspar is commonly crowded with inclusions. Hornblende appears as dark green laths filled with small iron grains and in some places has disappeared entirely leaving a mass of former inclusions. The amphibole in this section is clearly subordinate in amount to the brown biotite whcih occurs characteristically as basal plates. Occasionally the biotite flakes are seen in clusters in very close association with hornblende.

In a thin section from a band in which amphibole was absent the biotite again occurs principally as basal flakes although some thin prismatic grains are absent. There is some tendency for parallel alignment and the brown biotite is rather more disseminated than in previous sections. The feldspars of the granoblastic matrix are slightly cloudy with inclusions and untwinned. Zoisite is fairly abundant and sulphide ores occur but magnetite and ilmenite are absent.

In the hornblende-rich sections where biotite is entirely absent the blue green amphibole is arranged in strongly parallel orientation. The matrix is a granular mosaic of quartz and untwinned feldspars and iron ores are abundant. It will be noted that when amphibole is present to the exclusion of biotite iron minerals occur in these schists. On the other hand when biotite is present these minerals are characteristically absent.

The hornblende-biotite schists are intercalated with a series of feldspar amphibolites in which actinolite rocks occasionally appear. The section referred to extends from the schists at the western end of the Mankwadzi beach as far as the garnetiferous schists which occur in the sandy cove between the Mankwadzi and Abrekum lagoons. They are found to have, where measurable, the same strike and dip of foliation as the banded schists and are cut by aplites and mineralized veins. Occasionally they contain small strings of arsenopyrite along the foliation.

In hand specimen the bronzy biotite of some of the amphibolites is clearly seen without the use of a lens. In thin section the rock is composed of rather large ragged laths of pale coloured pleochroic amphibole with an absorption scheme Z - green with slight bluish tinge, Y - definite green, X - pale yellow green. The laths have a noticeable parallel arrangement and frequently include grains of feldspar and quartz; clusters of amphibole grains are not uncommon. The biotite present occurs in small strongly pleochroic pale brown to almost colourless flakes. The intimate textural relationship which it shows with the pale green amphibole almost certainly indicates that the biotite is appearing at the expense of the hornblende. Iron ores are absent, a feature which may well account for the restricted development of the biotite. The felsic material is subordinate in amount and occurs interstitially. It consists of somewhat granular untwinned altered feldspar and a little quartz.

Both the hornblende-biotite banded schists and the biotite-amphibolite have been traced in a continuous band inland from the coastal section to the most northerly hill of the Ejisi-Manku range and have also been seen in the Mukuba lagoon and on the Mankwadzi road. The banded schists described on the coast are microscopically identical with those inland. The biotite amphibolite on the other hand becomes much coarser away from the coast. A specimen taken from the flanks of the most northerly hill of the Ejisimanku range shows large rather more strongly coloured hornblende with abundant magnetite along the cleavage planes and in the centres of the grains. The brown strongly pleochroic biotite is plentiful and is obviously developing from the amphibole. Large masses of arsenopyrite and pyrite appear throughout. The matrix is considerably coarser and the feldspars, for the most part still untwinned, are clear of inclusions. Quartz is not very abundant.

The coastal section continues with an exposure 600 yards long of banded garnetiferous mica and hornblende schists which weather easily and form a sandy cove. When fresh they are grey coloured and some bands contain small pink sheared garnets. When weathered the schists are brown coloured and glisten with mica. The garnets are usually well formed and stand proud of the weathered surfaces. The strike and dip of the foliation of these rocks is essentially the same as that of the other rocks of the sequence but the general swinging of the strike towards Apam is beginning to show in the structure of this part of the coast.

Petrologically, except for the abundance of garnet in some bands, these schists seem to be similar to those found at the western end of the Mankwadzi beach. They are tourmalinized in parts and cut by pegmatites and aplites some of which are composite with quartz and show arsenopyrite.

The section finishes at Mosul point at the extreme western end of the sandy cove. Here the schist is hornblende rich but still garnetiferous. A few yards west a molybdenum-bearing tourmalinized quartz reef cuts the Birrimian and further west the biotite-bearing amphibolite, already described, appears. Continuing westwards as far as the eastern Abrekum lagoon fine grained strongly jointed actinolite schists and feldspar amphibolites predominate. Tourmalinization, some sulphide mineralization and the occasional appearance of bronze biotite are features of this section of the coast and, as usual, highly sheared aplites are common.

The Mankwadzi coastal section continues in the Abrekum lagoon, and although the exposures along the coast between the eastern Abrekum lagoon andAbrekum villages are very scarce, abundant outcrops are found a quarter of a mile inland. The reason for this seems to be that pivoting somewhere in the region of the eastern Abrekum lagoon has occurred the strike taking a sharp bend between this lagoon and Abrekum village where the foliation of the Birrimian runs almost parallel to the coast. In point of fact along the shore between the two Abrekum lagoons only one exposure, in a small stream mouth, was found.

In the eastern Abrekum lagoon the strike of the foliation is to 40° and the series consists of rubbly shattered actinolitic schists which were probably of pyroclastic origin. In thin section these are composed of large aggregates of actinolite needles and occasional individual hypidiomorphic hornblende grains. The whole series is cut by quartz veining.

The Onyadzi-Abrekum road which marks the western boundary of the Mankwadzi locality shows a good general section of the Upper Birrimian Series. It consists of greenstones of basaltic origin and a few hornblende schists of somewhat uncertain origin. Intrusive epidiorite and amphibolites are quite common. Aplites, pegmatites and quartz reefs are abundant but are subordinate to those in the district around the Mukuba lagoon. Tourmalinization of the Birrimian from these intrusions is again a usual feature.

The area is reasonably low lying but on approaching the coast a series of low ridges trending to about 60° are crossed by the Abrekum road. In the first part of the section up to about 1.3 miles from Onyadzi the rocks are strongly weathered and appear in the characteristic washed out green colour showing clearly yellowish-white feldspar grains and veining. Commonly jointing in a north-south and east-west direction is quite marked and occasionally some shearing is seen.

0.5 mile from Onyadzi along the Abrekum road a typical greenstone of basaltic origin occurs. This rock is probably the most characteristic of this type found in the district. In hand specimen the rock is not markedly vesicular or porphyritic although some large feldspars are distinguishable. In thin section it shows numerous laths of very basic andesine or acid labradorite; usually these show dome birefringent alteration products. A small vesicle filled with altered feldspar some of which is evidently more acid than andesine occurs. The amphibole present is the typical pleochroic pale yellow green-green-bluish green Upper Birrimian hornblende. It occurs usually in clots of laths and plates, often showing a somewhat opitic relationship to the feldspar. The texture in general is rather coarse for rocks of extrusive origin but this may be attributable to subsequent metamorphism. In this rock iron ores and quartz are completely absent.

1.15 miles from Onyadzi along the Abrekum road the feldspar amphibolites appear, occasionally forming ridges or parts of ridges. Usually in the field they are not exceptionally coarse but the individual grains are clearly identifiable and occasionally small pink garnets may be seen. The amphibolites in this locality contain an amphibole of rather more intense colouring than is common in the district. The rocks have suffered a certain amount of structural deformation during metamorphism, a feature which is illustrated by a number of bent amphibole grains. The appearance of the small pink garnets suggests an increasing grade of metamorphism. Epidote or zoisite is still extremely abundant with some feldspar probably albite. Quartz is present interstitially and in veins. Information regarding the origin of this type of zoisite amphibolite is scanty but its texture seems to indicate that its inclusion in an epidiorite group would not be unreasonable.

The highest ground in the Mankwadzi locality occurs to the north and east of Mankwadzi village and although in this ar ea the coastal section is very poor a good overall section for the district can be obtained using supporting exposures from the Ejisimanku range. It is in this locality where the only manganiferous phyllite and gondite in the area of sheet 32 is found. In general however the section is very similar to the rest of the Upper Birrimian Series in the Mankwadzi locality. Hornblende schist, amphibolites and bronze-biotite feldspar amphibolites all appear, and just south and weat of the village of Biwadzi the garnetiferous mica schists again occur. The whole series is cut by the usual minor intrusions and it is interesting to note that here they strike at a slightly different angle from the foliation of the Birrimian rocks. The marked shattering of the aplites and quartz veins which is common elsewhere in the Mankwadzi locality is again a feature here.

The Ejisimanku range is, broadly speaking, a double row of hills. Immediately inland from the coast a low range of conical hills is connected to the principal range by a col. The most westerly conical hill which is about 600 yards east of Mankwadzi village is wholly composed of a manganiferous horizon. Six pits sited at various points on the hill produced manganiferous phyllitic rocks and also samples similar in composition to gondites. In places the manganese bearing quartz veins which have a general strike of 210° traverses the country rock. They are characteristically black greasy rocks with rubbly surfaces when outcropping.

The extent of the manganiferous horizon is extremely limited. It appears only in the hill to the east of Mankwadzi and has not been traced along the strike. No sign of the rock was found along the north of face of the Ejisimanku range.

The rocks appear to have been original Birrimian sediments which contained quantities of manganese oxide in their composition (Kitson and Junner, 1927). By progressive stages of metamorphism the manganese oxide has become the manganese garnet spessartite. Some rock specimens now show marked foliation and colour banding but others may show no structure and appear in hand specimen as a homogeneous grey siliceous rock. In thin section this latter is composed of large numbers of colourless,more or less hypidiomorphic, minute spessartite garnets. Under high power magnification the rock has a characteristic frog-spawn texture produced by the spessartite. Generally the centres of the individual grains show a cloud of black opque inclusions and commonly they may show under crossed nicols white colours due to internal reflection. A number of clusters of garnets show brown staining and appear rather anisotropic. Curved, colourless, tremolitic amphibole grains showing inclusions of spessartite are common. Some grains of a colourless mineral which is probably rhodonite occur and show grey and yellow polarization colours and have a markedly lower relief than garnet. A small amount of quartz, having almost always undulatory extinction is present. Clots of ilmenite as well as pyrite and some epidote occur as accessory minerals.

Other thin sections show a mosaic of spessartite and shadowy quartz. In many cases the garnets are completely broken down and have become clouds of small manganese oxide grains. The mosaic of quartz and garnet also, in general, appears to have been dusted with this mineral. Occasional irregularly shaped patches of black opaque manganese oxide, which do not seem to be related to the garnets, also appear. A quantity of brown stained somewhat fibrous colourless amphibole is seen in clusters of laths. Microscopically the rock is composed of quartz rich bands and melanocratic garnetiferous bands.

It seems clear from the thin sections that these rocks are metamorphosed sediments which probably originally consisted of argillaceous matter, free silica and varying proportions of manganese oxide and a little alkali. Kitson and

Junner (1927) state that if after the formation of spessartite there were an excess of MnO and SiO_2 manganese oxide and quartz or possibly some braunite and rhodonite would form. The presence of tremolite in the sections just described is no complication to this suggestion of original sedimentary parentage. If the original sediments were somewhat calcareous, the formation of tremolite and possibly some epidote would not be unexpected under the condistions of metamorphism normally found in this section of the Birrimian Series.

The section along the beach commences at 0.4 mile east of Mankwadzi village where two shattered quartz reefs are seen striking due north. At 0.58 mile bands of coarse amphibolite appear and these contain a little feldspar but usually the distinctive feature is the large grains of amphibole which weather out on the surface. Some thin quartz veins usually not more than half inch wide are reasonably common and generally run to 100°. A similar set trending 210° are frequently found to displace the first. Some vertical joints striking to 200° appear.

At 0.6 mile from Mankwadzi village the rock is somewhat fine grained, the large amphibole crystals are absent from the weathered surfaces, and parts of the outcrop have a decidedly schistose appearance being rather finer grained than is common in this locality. The jointing and veining characteristics however remain the same. Small amounts of pyrite are present and in parts the quartz veins show inclusions of country rock.

In thin section the rock at 0.6 mile shows sheaves of pale grren to light blue pleochroic amphibole often showing some parallel orientation; chlorite is also reasonably common. The feldspars are completely sericitized and often include small grains of zoisite which also appears in hypidiomorphic grains which may occasionally be of the same order of size as some of the amphibole grains. Biotite is present and is seen developing from hornblende as the characteristic bronze flakes. Carbonate is very abundant and some skeletal pyrite appears. Quartz is absent except in veins.

Slightly east of the exposure just described the rocks become definitely schistose and are clearly seen striking at 210° and dipping to the south-east at 85°. This hornblende schist has been traced inland as far as a small rock promontory on the south-east corner of the Ejisimanku range. It is found again in the 50 feet high hill west of the Muni lagoon. A similar rock is exposed in the amphibolite zone north of the Apam telephone lines at mile 2 on the Winneba-Swedru road. At this point however the hornblende schist is intercalated with the coarse amphibolites and therefore its correlation with rocks elsewhere is difficult. It will be noted that correlation of the coastal exposure with that in the small hill west of the Muni lagoon indicates a marked swing in the strike of the foliation in this locality. This swing in strike is also reflected in the directions of the minor intrusions.

In hand specimen the hornblende schist is a compact and very heavy rock showing marked parallel alignment of the minerals. Both the amphibole and the feldspars are clearly distinguishable. Microscopically the rock is composed of the typical green to bluish green pleochroic amphibole of the Winneba Birrimian. In this rock the hornblende laths are rather ragged and show reasonably strong parallelism; sieve structure is present but infrequent. Feldspars are not particularly abundant but when they occur they are completely saussuritized being composed of aggregates of untwinned albitic feldspar, minute granules of greenish epidote and sericite. Some feldspar grains appear extremely dusty. A number of granular epidote grains with a magnetite core also appear but this structure is unusual. The section is cut by a quartz vein in which the individual grains have an elongated character and show marked strain extinction. Many of these quartz grains exhibit regularly arranged inclusions.

The Ejisimanku hill known locally as Manku is the highest point of the coastal range and rises to a height of 595 feet above sea level. The hill itself is composed of a feldspar amphibolite, somewhat mineralized on the northern side, and is capped by pebbly laterite. As is usual in this district, aplites, similar in appearance to those of the west Mankwadzi beach, are common. The exposures on this hill serve in some measure to complete the eastern coastal series and fill the gap between the manganiferous horizon and the amphibolite and hornblende schists just described.

The amphibole of the feldspar amphibolites found in Ejisimanku is more intensely coloured than is normal in the

Birrimian of this locality. It is pleochroic from pale yellow green, through a darker green in basal sections to a deep greenish blue. Rotation structures in the amphibole are common and in one instance an almost circular hornblende lath was observed. The feldspars are highly altered and it is impossible to identify the original variety. Limonite after pyrite, occasional magnetite and some epidote appear but quartz is rare.

11 f 2 The Apam Locality.

The area designated as the Apam locality is bounded to the east by the Abrekum road, to the north by the southern contact of the Onyadzi-Mprumen granite, by the sea to the south and by the faulted junction of the Mumford quartz schists to the south-west. The rocks of this section are clearly a natural continuation of the eastern greenstone series of t he Mankwadzi and Osi hills localities and are cut discordantly by a suite of aplites which are markedly similar to the Mankwadzi type. A few well marked basic and ultrabasic intrusives appear and where these are recognizable in dyke form they are generally orientated more or less along the strike of the foliation of the Birrimian rocks.

Around Apam the marked swing, in strike, the beginnings of which can be observed in the Mankwadzi locality, is intensified. This is particularly noticeable in the neighbourhood of Adanka village where the strike of the foliation is only a few degrees north of east. At Apam itself similar orientation can be seen but north of the small village of Mamfam the strike returns to 50°.

Over most of this locality the Birrimian rocks are moderately well exposed. As would be expected the best section is along the coast from near the Apabaka lagoon as far west as the boundary of the map sheet. There are no exposures along the coast between the western Abrekum lagoon and the mouth of the Apabaka lagoon. This feature is probably accounted for by the fact that at this point the foliation of the Birrimian is parallel to the coastline.

The coastal section therefore starts with the small outcrops seen in the western Abrekum lagoon. The exposures are in two parts and occur about 100 yards upstream from the mouth of the lagoon. In hand specimen the rocks consist of an equigranular hornblende quartz feldspar rock which glistens slightly. Silicification is clearly visible and indicated by a number of thin quartz veins. In thin section the rock shows a granoblastic mosaic of andesine feldspar, some quartz showing shadowy extinction and a little untwinned zoned feldspar. A common feature is the occurrence of small grains of sericite along the cleavage planes in the feldspars. A little epidote is also associated with the matrix. The amphibole occurs in randomly orientated elongated laths occasionally showing sieve structure, and appears to be the typical blue green hornblende of the Birrimian of the Winneba district. Magnetite is abundant in small grains which are sometimes skeletal. The rock is a meta basalt and somewhat similar to the rock described by Hirst and Junner (1946).

Just west of the mouth of the Apabaka lagoon a hard grey schist appears. Small flakes of bronze biotite and pyrite are clearly recognizable in hand specimen. The rock is well jointed at 210° and 240° and shows well developed east-west vertical foliation. These rocks were termed metamorphosed phyllite and greywacke by earlier workers.

Microscopically the rock is quite fine grained and shows a moderately well marked schistose structure. It is composed of clusters and flakes of dark reddish brown biotite set in an inequigranular groundmass of allotriomorphic quartz and feldspar. The latter which is usually andesine and albite often contains small blebs of quartz as well as minute grains of other minerals. The section is dusty with a black powdery mineral which is characteristically seen along the foliation planes. Small shreds of muscovite occur amongst the dust. It is thought that the dusty material may be manganese oxide and in support of this suggestion one spessartite garnet has been found. Silvery arsenopyrite is abundant, and the section is cut by a thin aplite vein.

It is uncertain what relationship this metamorphosed greywackes bears to the garnetiferous biotite hornfels which occurs on the east side of the sandy cove south-west of the triangulation point on the Apam Rest House hills. Mineralogically this rock consists of a granular mosaic of quartz with possibly a little untwinned feldspar. The bronze biotite occurs in small dark brown basal flakes which show parallel orientation and also curved edges towards the quartz of the matrix. The garnet present is pale pink and completely allotriomorphic. A large number of minute epidote grains occur, and calcite, muscovite and metallic minerals are generally absent.

It can be seen from the foregoing that in the composition this rock is unlike the metamorphosed greywacke described previously. It does however show some general relationship to the biotite schists from the rocky promontory along the west beach at Mankwadzi.

At a point 1.8 miles along the coast west of the Apabaka lagoon and just east of the first exposures of the Mumford quartz schists, a siliceous flinty grey pyritous rock was found. This shows in hand specimen an abundance of biotite and pyrite. The outcrop bears a strong resemblance to the metamorphosed greywacke. It is well jointed in a northerly direction. Vertical foliation in a 70° direction is quite clear and microscopically the rock shows many marked similarities to the metamorphosed greywacke previously described. It contains a rather smaller amount of somewhat paler coloured brown biotite. The black (?) manganese oxide dust which was abundant in the greywacke is also present but again in smaller amount. The matrix is markedly similar being made up of an inequigranular mosaic of quartz, andesine and albite feldspar which as before contains bleb-like inclusions of quartz. Strings of pyrite, some calcite and epidote all appear in varying quantities.

It is clear that in some way the two metamorphosed greywackes may be correlated. Evidence from the general orientation of the strike indicates that they may be the same horizon although the exposures are certainly discontinuous. It is interesting to note that the band has not been found in the Mankwadzi locality, unless it is part of the gondite horizon.

Westwards from the greywacke at the Apabaka lagoon the section continues with one exposure of very coarse amphibolite, which exhibits plates of amphibole up to half-inch in size. A little feldspar is present in this rock which is well jointed and evidently of intrusive gabbroic origin. The host rocks are seen to be hornblende schists some of which show remnants of vesicular texture. Similar rocks were identified on the top of the hill around the Police Post. In general these partly vesicular rocks are strongly jointed and very broken up, a feature which is particularly noticeable in definite bands. Joints at 210°, 220° and 280° are common. The surfaces of the exposures are usually rubbly and scoriacious and some pillow structures have been noted. The direction of foliation is usually about 80° to 90° and generally either vertical or with a very high southerly dip. The close jointing is also seen at 0.18 mile west of the Apam pier where the main jointing is at 110° and subsidiary jointing at 350°. One exposure of epidiorite was recorded by earlier workers but was not seen by the author.

Half a mile westwards along the coast from the pier the hornblende schists maintain their almost east-west foliation strike but the dip flattens from almost vertical to as low as 30° in some cases; this is probably the result of the intrusion of the later aplites. A little actinolitic amphibolite was found close to the contact with the garnetiferous biotite hornfels already described. The succession here continues with the typical basaltic greenstone already described from other localities. A gap 0.35 mile wide with no exposures forms a slightly arcuate sandy bay which is terminated by the second exposure of the greywacke and Mumford quartz schists. A diorite reported by earlier workers and seen in the town at Apam does not appear on the beach and from general descriptions it would seem that this rock is contemporaneous with the Birrimian lavas and not with the later suite of epidiorite dykes.

The Apam coastal section occurs practically parallel to the strike of the Birrimian Series and consequently shows a somewhat monotonous section of metamorphosed basic lavas with intercalated greywacke and garnetiferous biotite hornfels, though a traverse from the Winneba-Saltpond road at Oboko to Apam along the trace of the disused Simbrofo-Apam road cuts almost at right-angles across the strike of the foliation in the Apam locality. Some information was also gained by traverses along the present Apam road from Ankamu junction (1:62,500 sheet 31) and traverses north of Mamfam village also resulted.

The Birrimian section along the old Apam road shows a series of typical greenstones together with a number of other rock types rarely seen in the series in the district. In parts the rocks are tourmalinized, a feature which is particularly noticeable in a low conical hill a quarter of a mile south-west of a point 0.7 mile from Oboko. At this point the greenstone at mile 0.7 is a fine grained compact actinolite schist with large areas composed of several broad laths of disorientated actinolitic amphiboles. These clusters are usually surrounded by a clearly recognizable fine grained actinolitic rim. In hand specimen these clusters of amphibole grains are clearly recognizable as small knots of black amphibole which are apparently quite out of character with the rest of the rock. This feature has been described in a rock from the central greenstone series where it was considered that the rim was indicative of foreign material of a different or slightly different composition from the main body of the rock and that the indications were that the rock was therefore probably tuffaceous in origin.

The section continues along the old Apam road to 1.1 miles from the new Mankessim-Winneba road. At this point a greenish schist appears in a small north west-south east ridge. The ridge is deceptive and does not lie along the strike of the foliation of the green schist which strikes to 50° and dips south-west at 40°. The rock is almost entirely composed of actinolitic amphibole but contains an appreciable quantity of pale green chlorite which is readily recognizable in hand specimen as a green flaky mica-like mineral. In parts the schist shows marked tourmalinization. Towards the crest of the ridge the rock is much harder and flakes of chloritic material are not seen. In appearance the rock is not unlike the Yenku schists.

The old Apam road joins the Apam-Ankamu road slightly less than three miles from Apam and near the village of Nsawam; here actinolite schist are exposed. These are composed almost wholly of randomly orientated actinolite-tremolite fibres with patches of semi-skeletal magnetite generally showing intimate textural relationship with the actinolite. The remainder of the section is largely composed of the common vesicular greenstone showing close jointing and intercalated with a few thin hornstones. In the stream bed almost due north of Nsawam some well-jointed medium grained amphibolite is closely associated with a vesicular greenstone but it is impossible to say whether or not this rock is of intrusive origin or a metamorphosed rather solid core of the vesicular lava.

At the extreme northern end of the Apabaka lagoon just south of the well-marked meander of the Brusheng river, a rather coarse strongly shattered hornblende schist occurs. In thin section the rock shows pronounced parallel orientation of the rather intensely coloured, strongly pleochroic, blue-green amphibole; occasionally the laths are slightly bent. Zoisite and epidote are both rather common and set in a matrix composed of a mosaic of quartz and some untwinned albite. Magnetite is frequent in small allotriomorphic grains. Thin quartz veining occurs with most grains showing shadowy strain extinction.

From the Apam lagoon the ridges which are clearly visible on the west side of the Onyadzi-Abrekum road continue to the west side of the Apabaka lagoon and apparently show only slight lateral displacement. However, aerial photographs show that the ridges on the eastern side of the lagoon are sharply truncated and that there is a well defined break. The strike of the inferred fault is concordant with the major direction of faulting in the Birrimian of this locality.

The Ankamu-Apam road and the Nsawam-Mamfam road provide a good section terminated by the faulted scarp of the Mumford quartz schists. In the field the section produces no surprises. The rocks form ridges parallel to the strike of the foliation and for the most part they are essentially similar to those found elsewhere in the Eastern Greenstone Series. Actinolite schists are common and are often found intruded by epidiorite dykes as well as by gabbroic or ultrabasic intrusive bodies now amphibolites. Vesicular lavas showing the characteristic amphibole are very common. Hornblende schists which are probably of basaltic origin are fairly common and where they appear they are usually fine grained and often show evidence of later silicification and pyritization.

In places the ridges are crossed by transverse ridges striking between 10° and 20°. These represent aplites of the same suite as those found on the coast. Occasionally the greenstone ridges are dissected and slightly displaced. Although no direct field evidence is available a small fault system my be safely inferred.

CHAPTER 12.

THE ZONE OF COARSE AMPHIBOLITES.

The Upper Birrimian Series so far described has been a greenstone series composed of basic lavas, some intrusive rocks, tuffs and the like. All these have been subjected to regional metamorphism to a degree which has not been great enough to destroy the major original texutures in most cases. Around the Winneba granite periphery and the southern portion of the eastern gneiss there appears a well-developed zone of very coarse almost monomineralic amphibolites and very fresh feldspar amphibolites. The extent of this zone is marked on the map accompanying this report by a dotted line but in actual fact the zone grades off gradually westerly and north westerly into the greenstone of the Birrimian Series.

At least four individual patches of granite and one granitic nose extending from the east appear in the amphibolite zone. It should be noted also that the zone is in contact with the Winneba granite along the whoqle of its western boundary. All but one of the granite patches appear to be biotite be aring showing abundant ghosts which in the field are composed of very dark brown, almost black biotite. The exception is hornblendic, the origin of which may be due to admixture of granitic material with greenstones; this will be the subject of discussion later in the report. The contact between the Winneba granite and the coarse amphibolite zone can be seen just east and west of the Winneba-Swedru road between miles 1 and 2. The junction is a very sharp one and there is only a little pink feldspar veining in the amphi-

-bolite. Where the contact with the small gneiss-stocks has been observed the contact rocks appear to be coarse hornblende and biotite schists whilst the gneisses appear to be very much more rich in biotite than is normal.

Some clarification of the terms amphibolite and hornblendite as used in this chapter is probably necessary. The collective term for the very coarse rocks of this zone is amphibolite and where actinolite is the principal mineral then the name actinolite amphibolite is used. When hornblende is recognized as the major component then the term hornblendite is used. In the cases where felsic minerals are recognizable in reasonable amounts in hand specimen the terms feldspar or quartz amphibolite, as the case may be, are applied.

The field relations of many of these amphibolites clearly shows the intrusive origin of the original rocks. They appear characteristically to assume dyke or possibly tilted sill form, orientated more or less parallel to the direction of foliation in the granite bodies. This dyke formation is clearly seen over the whole zone. It is however appreciated that although many rocks in this zone show this type of formation all occurrences cannot be explained in this way, many exposures being irregular or even circular in form.

The amphibolites of the zone are generally very well jointed and occasionally show a little foliation. They may include small thin veins of quartz and feldspar, a feature which is particularly noticeable in a hornblendite exposed ¾ mile south-east of the Winneba roundabout. Here the hornblendite shows large hornblende grains up to three quarters of an inch in length clearly exposed on the weathered surfaces.

Shearing is not very common but has been particularly noted 1¼ miles due south of the village of Mpata.

The whole zone is cut by large pegmatite, aplite and quartz intrusions, the strike of which are concordant with the strike of the outcrops of the coarse amphibolites. Where the contact with the Winneba granite is approached all linear bodies strike parallel to this contact.

West of the Winneba-Swedru road, between mile 1 and mile 3, the coarse amphibolites are associated with clear feldspar and quartz amphibolites and with coarse somewhat garnetiferous hornblende schists. It is interesting to note that neither of these rock types are found east of the Winneba-Swedru road.

In thin section the feldspar amphibolites are composed of abundant rather ragged laths of very pale green pleochroic amphibole which is quite unlike the normal green to bluish green pleochroic hornblende commonly found in the Upper Birrimian metamorphosed lavas. The cores of the amphibole grains are usually filled with a cloud of birefringent minerals some of which can be identified as epidote and zoisite. A little pyroxene is beginning to appear in rims round the edges of the more ragged grains. Pale green chlorite still remains. The matrix of the rock is composed of untwinned albite feldspar generally in completely allotriomorphic grains which only rarely show some sericitization. Metallic ore minerals are not abundant.

In another specimen taken from a low hill between the two arms of the Muni lagoon the effects of admixture with acid material can be observed. The amphibole occurs in larger although still ragged grains which show colours considerably more intense than in the previous section; indeed occasionally the slight bluish tinge of the metabasalt hornblende is visible. As before most grains contain clouds of birefringent inclusions. A reasonable quantity of irregular grains of colourless pyroxene appears and these grains are only rarely observed in close association with the amphibole. Untwinned tabular feldspars, often as large as the amphibole grains, are quite common. They generally show inclusions of blebs of quartz and some saussuritisation. Quartz and untwinned feldspar is commonly intergrown to some extent. Microcline is fairly abundant but in the more granular grains the feldspar is andesine. Zoisite and apatite are the common accessary minerals.

The normal feldspar amphibolite (unaffected by acidic material) shows a composition and texture very similar to the rock described above except that in this instance rims and patches of brown flaky biotite are seen developing round the amphibole grains.

In the coarse amphibolite zone two types of amphibolite are recognizable in hand specimen. One type shows large black plates of hornblende which may be as much as 1 inch across. The second type contains a rather feathery amphibole and has been given the field description of actinolite amphibolite. By definition neither of these varieties contain felsic minerals in large enough quantities to be readily identifiable in hand specimen. The actinolite amphibolites are the most abundant and practically all the rocks in the zone east of the Winneba-Swedru road, with one or two exceptions, are of this type.

In the field the actinolite amphibolite is not always in dyke form. This is well seen ½ mile due west of a point 2½ miles from Winneba along the Winneba-Swedru road. Here the actinolite amphibolite is bluish green in colour and forms a low dome-shaped hill about one hundred yards in diameter and almost completely circular in plan. This type of amphibolite shows in most outcrops a characteristic onion weathering and is generally well-jointed.

Mineralogically the actinolite amphibolites show little variation from locality to locality and a specimen taken from ½ mile east of mile 2 on the Winneba-Swedru road may well be taken as representative. In thin section it shows large laths of fibrous tremolite in the centres of which are found nets of magnetite sometimes completely obscuring the core of the host mineral. Reasonably strongly pleochroic actinolite occurs and is also associated with magnetite but to a much lesser extent. In places both magnetite and ilmenite develop into large grains which may ophitically enclose the amphiboles. Chlorite and the yellowish-brown alteration product usually associated with actinolitic rocks of the

Upper Birrimian of this district are quite common. Deformational structures in the form of rotated and twisted amphibole grains appear.

At 0.8 mile from Pomadi Brofoyedru along the footpath to Mampong the actinolite amphibolites develop locally a highly micaceous facies. The general mineralogy of the rock is similar to that just described except that flakes and stringers of pale coloured mica bear an intimate textural relationship to the chlorite and amphibole.

The hornblendites appear in the zone only to the east of the Winneba road between miles 1 and 3; elsewhere they are rare. In these rocks the hornblende occurs in two principal sizes: in large allotriomorphic plates and prisms and in similar form but smaller grains in the matrix. All grains are strongly pleochroic, X - very pale yellow, Y - brilliant pea green, Z - bluish green. The extinction angle $Z \wedge c$ is 25°. The larger amphibole grains commonly show inclusions of epidote, apatite, sphene and feldspar. The groundmass of the rock in this instance consists of irregular fresh mosaics of oligoclase, microcline and albite feldspar with some quartz, sphene, apatite and a uniaxial titaniferous mineral. These fresh grains undoubtedly represent admixture with granitic material. The presence of the apatite would appear to be more or less conclusive in this respect. The feldspars of theoriginal rock occur in large completely sericitized masses in which some original structure can occasionally be seen.

In other sections from the same locality but which do not contain acid material very little difference in texture is observed except that the granular mosaic of the acid material is absent.

It is convenient at this point to discuss the relationship of the hornblendites of the zone to the actinolite amphibolites and to the hornblendites found in the Birrimian outside the coarse amphibolite zone. Field work has shown that the hornblendites are not confined to the coarse amphibolite zone but that they exist over the whole of the Upper Birrimian of the district. It is appreciated that some hornblendites occur in the gneisses but these are thought to owe their origin to a somewhat different set of circumstances which will be discussed later. It has been possible in most cases to show that the hornblendites of the Birrimian occur principally if not solely in dyke form. This feature is clearly seen in the Pratu River section, in the Monastery hill, in the Yenku range, on the Mampong and Saltpond roads and in many other places. Whilst the hornblendites have a somewhat universal distribution in the Birrimian of the district, the actinolite amphibolites are confined to the coarse amphibolite zone and are rarely found elsewhere.

CHAPTER 13.

QUARTZ SCHISTS OR GNEISS SERIES OF UNCERTAIN AGE.

This series exists in an arcuate strip extending from south-east of Ojinjinadzi to the Adzintam hills where it bifurcates forming athin series on the easter and western sides of the Odominadzi granite. Looking slightly north of west from the Potsin junction on the Accra road the series forms a marked range of hills with several somewhat rounded peaks. In the southern section between the Accra road and Ojinjinadzi the rocks are partly lateritized and show only a low rounded topography which blends with that shown by the gneisses.

The series forms an arc concordant with the strike of, and forming in part the western boundary of the Eastern migmatites. In the northern section the dip of the foliation and banding is south-easterly at 45° increasing to 85° in the mid-north section whilst the dip of the foliation of the migmatites is 60° north-westerly. In the sections along the Accra road the direction of dip can be seen to be reversed and is now concordant with that of the gneisses. This attitude persists up to the point where the series is obscured by the superficial deposits of the eastern arm of the Oyibi lagoon.

The twisting of the quartz schist together with its bifurcation round the Odominadzi granite seems to indicate that the rock is certainly of pre-gneiss origin. This supposition is further supported by the fact that the Winneba granite, which is later than the migmatites, has caused a bending in the strikes of the foliation thereby being responsible for the arcuate outcrop.

In the northern section the rock is conformable in dip and strike with the main Birrimian series with which it is in contact on the western side. The strike and dip undergo reversal only from a point where the intrusive effect of the Winneba granite is beginning to be felt, and here gneiss also occurs at both the eastern and western contacts of the quartz schist.

It would thus seem reasonable to place the strip of quartz schists within the Birrimian on structural grounds.

It is suggested later in Chapter 19 that the banded quartz schist series represents a limb of the isoclinally folded Birrimian quartz schists. Petrologically this is quite feasible as the banded quartz schists include stringers of hornblende schist, a feature which is also quite common in the Ayensuadzi-Brusheng schists. Naturally having suffered lit-par-lit injection and severe metamorphism the quartz schists would recrystallize and contorted coarse quartz bands would therefore not be unexpected.

The major bands of the hornblende schist are easily accounted for as being part of the feldspar amphibolite facies which is found on both sides of the Birrimian quartz schists in the same way as the hornblende schist is found on both sides of the banded quartz schist. The composition of the hornblende schists remains essentially the same as the feldspar amphibolites except for the added material which would be expected from close contact with a granite and granitized mass. In view of the foregoing it seems reasonable to place the eastern limit of the Winneba Birrimian Series, in the northern section at any rate, on the east side of the banded quartz schist series.

The best section of the banded quartz schist series is seen in a borrow pit north of the Accra road eight miles from Winneba. Here a considerable development of hornblende schist is seen on both eastern and western sides of the quartz schist. Both facies have suffered lit-par-lit injection and pegmatites are very common. The hornblende schist without quartz bands continues to appear at intervals further east along the Accra road.

13 b. Post-Birrimian Basic Dykes.

Two principal types of dykes cut the Birrimian Series. One is the coarse almost monomineralic hornblendite type already described and for which there are good reasons for assuming them to be contemporaneous with the Birrimian. The second suite of dykes which are doleritic or epidioritic in character are certainly post-Birrimian but there is hardly sufficient evidence to show whether or not they are post-gneiss. The dolerite suite is certainly found in the Winneba granite and in the migmatites. They do not however appear to be highly metamorphosed and are probably therefore later intrusions into the gneiss.

The doleritic dykes are generally more or less concordant with the structural trends of the Birrimian of the district but they appear to be fresher than their hosts and indeed show fine grained selvedges when in contact with them, furthermore they have not been seen being cut by the minor acid intrusions which are commonly found in the Birrimian.

In the field the dykes form low-lying rather bouldery outcrops usually moderately well-jointed. In hand specimen the rock is fresh and medium grained with pyroxene, hornblende and greenish feldspar clearly distinguishable. The rocks are generally markedly pyritous.

In general it is obvious from the thin sections that the dykes have only undergone a very low grade of metamorphism. Their textures are distinctly ophitic; abundant pale brownish pyroxene encloses slightly sericitized idiomorphic laths of basic andesine-labradorite feldspar. The pyroxene is occasionally altered to uralite (and later chlorite) which appears as a somehwat bright green mineral either psuedomorphing the pyroxene grains or showing as rims. The amphibole also appears along cracks and cleavages in the feldspar. A quantity of ilmenite is developed and generally ophitically encloses both pyroxene and feldspar. Sections taken from widely separated outcrops show little diversity in composition. For example sections taken from the upper Pratu river appear to be essentially the same as those from the coast near Abrekum. The only difference which is occasionally seen is in the alteration of the feldspar and the quantity of uralite present. It is clear from the examination of a number of sections that uralite increases in amount simultaneously with increasing alteration of the feldspars.

CHAPTER 14.

THE ACID INTRUSIVES.

A little under two-thirds of the total area consists of post-Birrimian granite. In this section the term granite is collective and is used to cover all the varieties which are to be found in the principal granitic localities.

The granites are to be found in seven main areas of which the two most distinctive are the eastern migmatite area and the Winneba granite. Hornblende granites are somewhat rare and have only been found in two places where there is evidence that their origin is due to the admixture of biotite granite material with the Birrimian greenstones. In the cases of the granites in the other regions it is very difficult to make any field distinction between them. The western gneiss certainly forms part of a large granite mass which contains pendants of Lower Birrimian and there is some evidence which shows that the mass is at least partly of migmatitic origin. Undoubtedly the eastern and western gneisses are connected to the north of Sheet 32 but a detailed examination of this locality was not carried out.

The seven principal granite localities are as follows:-

1. Winneba granite.
2. Eastern migmatite granite and gneiss.
3. Granite windows in coarse amphibolite west of the Winneba granite.
4. Abakwa-Odominadzi granite.
5. Tachem-Nsuaem granites.
6. Mprumen-Onyadzi granite.

7. Manso-Dahum-Amankesim granite.

14 a. The Winneba Granite.

The term Winneba granite as used by previous authors does not appear to have been a very precise one. It apprently referred to almost any of the granites or gneiss in the Winneba area, provided that they had the same general composition. In this description the designation Winneba granite refers to the elongated granitic mass which is seen forming tors, devoid of vegetation, on the eastern side of the Winneba-Swedru road, and on the western side of the Hahadzi-Nsuechiri road. The map shows that the area of the Winneba granite forms a well marked sharply defined topographic feature which also stands out very clearly on aerial photographs making it possible to map the boundary of this granite with some accuracy. Furthermore, apart from a slight veining of the coarse amphibolites with which it is in contact on the western side, the junction between the Winneba granite and the surrounding rocks is a sharp one.

The coastal section is the best and provides almost continuous exposures from a few yards east of the Winneba Club bathing pool as far as the Oyibi lagoon. The granite which is a porphyroblastic microcline-biotite adamellite, is cut by grey and pink biotite granite and by later pink pegmatites. Fine grained aplitic granite and aplites may be either earlier or later than the pink pegmatites. When they occur earlier they are usually markedly displaced by them, a feature clearly seen 0.7 mile along the coast east of the Elder Dempster offices.

The western and northern margins of the granite are relatively fine grained and non-porphyroblastic. In parts the eastern margin shows similar characteristics but microcline porphyroblasts may occur. This is seen particularly on the western side of the mouth of the Oyibi lagoon where there is an occurrence of banded and foliated biotite-rich gneiss with vein-like bodies of porphyritic granite. Certainly however, the more central portions of the mass are coarser and may show marked flow banding.

Apart from linearly arranged biotite-rich ghosts there are larger inclusions of hornblende schists often contorted, finely schistose and cut by irregular feldspar veining. At a point 0.96 mile along the coast east of the Elder Dempster offices a small inclusion of contorted biotite gneiss appears. In this locality the strike of the foliation is about 150° with a high easterly dip usually about 85°. Strong east-west shattering is also a marked feature. In this locality also two patches of green doleritic dyke were found. The most distinctive being 1.18 miles east of the Elder Dempster offices. It is impossible to say with any certainty whether or not this body was of intrusive or inclusive origin, except that the epidiorite is not highly metamorphosed and is therefore probably post-gneiss.

Typically the coarse porphyroblastic Winneba granite is grey in colour and medium to coarse grained in hand specimen. In thin section it shows abundant microcline in two modes, firstly in large tabular porphyroblastic crystals, and secondly in rather rounded allotriomorphic grains in the matrix. Occasionally the large microcline grains show flask shaped perthitic strings of plagioclase. These larger microcline grains often include small rounded completely sericitized feldspar grains. Myrmekitic structures are common in untwinned feldspar and are occasionally found in twinned oligoclase. They are rare or absent in both occurrences of microcline. Perthitic structures are also absent from the smaller microcline grains of the matrix. Many of the smaller grains of untwinned and twinned feldspars (excluding microcline) show sericitization with which epidote is sometimes associated although this mineral commonly occurs in rather larger grains in some cases showing corse of allanite. Apatite, sphene, and rare magnetite are also occasionally seen as accessory minerals.

Oligoclase feldspar is probably slightly more abundant in the matrix than other feldspars and a little orthoclase is occasionally seen. Quartz is present in large allotriomorphic masses and also in small grains, generally all showing strain extinction and appearing to be somewhat fractured or crushed. Biotite is present in strongly pleochroic dark brown to yellow brown laths. Pleochroic haloes are sometimes distinct. Occasionally a little chlorite after biotite is present.

The mineralogy of the rocks of the margins of the

Winneba granite is essentially the same as the coarse rocks of the interior except that the porphyroblastic crystals of microcline are absent. The texture is of course much finer at the margins. Myrmekitic, perthitic and similar structures are rare or absent.

14 b. The Eastern Migmatites and Gneiss.

The migmatite covers the whole of the eastern portion of the sheet. It is divided into two parts by the banded quartz schists alreadly described. To the west of the schists the gneiss extends as a nose along the Accra-Saltpond road from near the Ayensu river to about one mile west of the Winneba roundabout. Along the northern and part of the southern boundary the gneiss is in contact with the amphibolite zone previously described. Where the contact is well exposed in road cuttings granitization and local refusion are common features. Elsewhere west of the quartz schist the migmatite zone is in contact with the Winneba granite but for the most part the actual contact is obscured by the superficial deposits of the Oyibi lagoon.

East of the quartz schists the migmatites and gneisses pass under neath the Togo quartzites which occur in the south-east corner of the sheet. The junction between the quartzites and the gneisses is largely obscured by the superficial lagoonal deposits and the cemented boulder and pebble beds which exist round the northern and western fringes of the Togo quartzites. The gneiss-quartzite junction is probably more clearly seen along the Ojobi-Senya Beraku road and south of the southern arm of the Kwekrom-Bowobere road. It should however be noted that extensive trenching and pitting in these localities failed to establish the contact proper.

It has been reported that the eastern gneiss reappears on the southern side of the Togo quartzites, that is, in the coastal section east of Senya Beraku. Kitson (1928) states that at low tide on a calm dry day near crumpled indurated quartzites, fragments of arkose and purple quartzite can be seen to rest on decayed biotite gneiss.

To the north of the Accra road the eastern migmatites are seen in contact with the banded quartz schists which have been shown to be Birrimian in age. It however is appreciated that in the Odominadzi-Buruata district this horizon is patchy in distribution and it is likely that some contact occurs between the migmatites and the Abakwa-Odominadzi granites; this however was not seen in the field.

In view of the geographical distribution of the eastern migmatite it is convenient to describe the body in two sections, (a) the portion between the quartz schist and the coarse amphibolite zone and (b) that part to the east of the schists which forms the major portion of the gneiss.

In (a) ptygmatic folding and the characteristic features of the migmatite proper are more rare. The major portion is composed of an even grained granite occasionally cut by thin quartz veins usually about 1 inch wide. The porphyroblastic crystals of microcline common in the Winneba granite are absent here and the rock commonly shows a marked foliation to 10° with westerly dips of about 85°.

In thin section the major difference between this granitic gneiss and the Winneba granite proper is textural. In the main the texture of the latter is uneven and signs of crushing sometimes appear whilst the gneiss shows an even granular texture in which most of the grains are completely allotriomorphic. Myrmekitic structures which are very common in the Winneba granite occur in this rock but they are not marked. Muscovite and biotite are about equally abundant but so far no muscovite has been found in the Winneba granite. In the gneiss slight saussuritization of the oligoclase feldspars is common. Some untwinned feldspar occurs and is occasionally seen inter-grown with quartz. Microcline and microperthite are usual. Quartz is present and shows cracking and strain extinction. Epidote is present as an accessory mineral.

The best exposures of this gneiss are seen in the first large road cutting east of the Winneba roundabout. Good exposures are also seen both north and south of the road at least as far as the Ayensu river.

Where the gneiss is found in contact with the Birrimian, granitization, refusion and other features commonly associated with marginal zones of gneissic masses are seen. These are particularly noticeable in the neighbourhood of the Winneba roundabout and in the small cutting west of the point where the Mpatah village joins the Accra-Winneba road. In these areas granitic hornblende phases are frequent.

South of the Accra-Winneba road the granitic gneiss just described passes into banded highly foliated gneiss, exposures of which are seen at the Winneba water-works pump house, near Jahadzi and along the Jahadzi-Winneba road. The gneiss in these localities is distinctly similar to the migmatites proper on the eastern side of the banded quartz schists and quite unlike the granite gneiss described in the foregoing paragraphs. It would seem reasonable to assume that the granite-gneiss represents a rather later intrusion or possibly a fully mobilized portion of the eastern gneiss. The boundary between the two is not seen but the graphic granite intrusions which are abundant in the migmatite gneiss are not found in the rather uniform granite body. From this it would seem that the latter is somewhat later than the banded gneisses and possibly of the same order of age as the Winneba granite.

East of the quartz schists the migmatite zone is fully developed and shows a number of features of a granitized zone, more than one stage in the processes being clearly recognizable. In general, the gneissic mass is arcuate with a foliation strike varying from 120° in the neighbourhood of Attachera to 40°-50°- in the Dabeyin locality. The dip is usually westerly ranging in magnitude from about 40° in the extreme west to 60-70° in the eastern part of the area. Owing to local contortions and folds a large number of measurements of foliation were necessary to obtain the general structure. Jointing is very marked in certain areas and considerable numbers of minor acid intrusions are present in the form of graphic granites, pegmatites and aplites. Coarse amphibolites, usually hornblendites, occur but not abundantly and one small doleritic dyke was found. In many localities epidote is abundant.

The gneiss shows a characteristic rounded topographic form with outcrops which are generally low lying and devoid Of sharp edges and tors. Occasionally outcrops may be blocky but this is exceptional. Usually the rounded ridges are well covered with red or pale grey-buff soil. In road cuttings the depth of weathering is sometimes as much as 20 feet but this is very variable.

The migmatite is well exposed over the whole area but the best sections are along the Accra road, the two roads from Kwekrom to Ojobi and along the Jahadzi-Kwekrom road. The gneiss is not exposed along the coastal section. The Accra road section is probably the most complete but unfortunately in many of the cuttings the rocks are highly weathered.

Along the Accra road the section commences about 1 mile from the Ayensu bridge after passing through a complicated lit-par-lit injection zone with the banded quartz schists. Finely and coarsely banded gneiss appear in the section but nearest to the quartz schists and gneiss is nearly always fine grained. This is well seen along the old Potsin-Ochreku r oad where the gneiss shows small clots of biotite arranged parallel with the foliation planes and is quite characteristic in hand specimen. Elsewhere in the district, particularly along the Kwekrom-Ojobi roads, the gneiss is very coarsely banded and pegmatite granite is not unusual. There appears to be, however, little appreciable difference in mineralogy between the two types.

In thin section the finely banded gneisses show an almost equigranular texture. Quartz showing strain extinction is often elongated parallel to the biotite and hornblende grains. Under low power magnification the banding noted in hand specimen is faintly seen. Generally the texture shows some interlocking of quartz and feldspar. Intimate intergrowth texture are not usually common although some myrmekitic structures do appear. The feldspar is usually oligoclase with some untwinned feldspar and a little microcline; alteration of these feldspars is not extensive. In some sections a rather bright green hornblende may be present; in others it may be absent but in all sections a dark brown biotite appears. Epidote, apatite and sphene appear commonly as accessory minerals.

One mile from Kwekrom along the old Ojobi road the gneiss is rather coarsely banded, the essential mineralogy however remaining practically the same as before except that the Na/Ca feldpar may tend to be slightly more basic. The textures are rather inequigranular and a little saussuritization occurs. The feldspars appear larger and more idiomorphic than in the finely banded gneiss. An examination of some of the banded gneisses indicates that the leucocratic portions show considerably more intergrowth textures, with microcline usually the more dominant feldspar. In this locality small brown red garnets appear in the gneiss. 0.2 mile from Dabeyin village a somewhat pegmatitic granite phase shows a mineralogy and texture similar to the Winneba granite. Microcline is abundant, the feldspars are generally rather large and the general texture is uneven. Perthitic inter-growths are common and some myrmekitic structures appear. Most of the quartz grains are moderately large and show strain extinction. Biotite is present in the usual form. Epidote and secondary muscovite also occur.

In several areas hornblende-rich gneisses are to be found. These are usually strongly banded and have a rather sporadic distribution. They are seen along the Accra road at mile 9, near Akramang, on the new road from Ojobi to Kwekrom and many other places. Generally the extent of the hornblende gneisses is so small that it is not possible to map them separately and the exposures usually prove to be small patches in a host of biotite gneiss. The patches are generally strongly foliated and much veined by feldspar frequently containing microscopic crystals and pockets of epidote.

In thin section the hornblende gneisses are seen as rather granular mosaics of hornblende, feldspar, and quartz. Most of the grains have a rather rounded outline and quartz and feldspar enclosed by hornblende is not uncommon. The amphibole is pleochroic in pale yellow, through green, to blue-green, the pleochroism being rather more intense than the common Birrimian amphibole but similar to amphiboles occasionally found in the rather more strongly metamorphosed hornblende schists of the series. The feldspars are oligoclase but rather more basic than is usual in the biotite gneiss. A little microcline showing myrmekitic structures occurs but is not abundant.

The limited extent of the hornblende gneiss and the fact that it is generally out of character with the main mass of the eastern migmatite zone and somewhat similar to parts of the Birrimian Series indicates that these rocks are probably limbs of Birrimian isoclinal folds which although having suffered lit-par-lit injection have not been fully granitized.

14 c. Granites in the Zone of Coarse Amphibolites.

At least four individual patches of granite appear in the coarse amphibolite zone and occur for the most part to the north and north-east of the Muni lagoon. The exposures are only a few yards in width but it is evident that the main mass of the granite is at shallow depth in this locality. The granites are largely biotitic types but two exposures do show quantities of hornblende.

The principal outcrop of hornblende gneiss is found on the old Apam-Winneba road about 1 mile west of the junction with the Swedru-Winneba road. The rock forms an elongated low lying outcrop about thirty-five yards wide and two hundred and fifty yards long, striking about 150°. No noticeable foliation is seen but numbers of biotite/hornblende ghosts occur; some of these are of the order of 8 to 9 inches in length and may be somewhat elongated in a 60° direction. The rock is characterized by numbers of quartz veins forming hard ridges standing proud of the surface. The trend of the main veins is to 200° and they slightly displace the subsidiary veins trending to 290°.

In thin section the rock has a peculiar texture being completely inequigranular. The largest grains are quartz occurring in clusters and knots, mostly showing strain extinction. Some of this quartz is probably secondary. Several of the larger feldspar grains have centres of microcline, but the edges show a deep rim of untwinned feldspar with myrmekitic structure. Other larger feldspars frequently show no twinning but are strongly saussuritized, epidote appearing commonly in quite large grains. The matrix is composed of rather rounded grains of basic oligoclase with a good deal of untwinned feldspar and some quartz; microcline is present but rather rare. Both biotite and hornblende occur and are intimately associated. The amphibole is the pleochroic pale yellow to dark bluish green variety and often occurs in quite large grains. In some cases dark brown biotite and the hornblende form different parts of the same crystal. Inview of the foregoing it would seem reasonable to assume that this rock has been formed by the admixture of granitic material with Birrimian feldspar amphibolites. Indeed some of the texture shown is quite similar to that in the vesicular lava types. The amphibole has some appearance of being made over into biotite and there appears to have been some recrystallization or addition to the felsic constituents.

Half a mile south-east of the hornblende granite a rather larger patch of foliated biotite granite is exposed.

In parts this is a fine to medium grained slightly foliated biotite granite with no marked alterations or inclusions. In other parts of the rock becomes highly biotite-rich with abundant biotite ghosts and showing strong veining. Thin sections from this locality show abundant basal sections of green biotite together with a little prismatic brown biotite. A little pale green to bluish green pleochroic amphibole occurs but is rare. The feldspar are mostly untwinned and show considerable alteration. Epidote is very abundant.

In general it would appear that the granites and gneisses in the coarse amphibolite zone were originally material similar to the eastern migmatites which had become mixed with a larger quantity of Birrimian than it was capable of fully digesting. This situation would obtain on the fringes of the migmatite zone. The net result of this partial digestion of Birrimian by granitizing media has been the production of a rock in which the amphibole is in some measure retained and in which the original textures are occasionally preserved. The feldspars however tend to be rather more acid than in the Birrimian and rather more basic than in the biotite gneisses proper. As would be expected rocks of this type are very variable in composition over short distances on the ground.

14 d. The Odominadzi Granite.

This granite forms a more or less semi-circular mass extending from west of Etchitikwa southwards to a point close to the Adzintam range of hills. It continues through Odominadzi to Buruata thus completing the semi-circle. Along the whole of its boundary the granite was observed or inferred to be in contact with the banded quartz schists or hornblende schists of the eastern quartz schist series. The principal contacts or near contacts were observed west of Etchifikwa, in the Chindrua river, in Odominadzi village and again on the road between Amuanda and Akramang on the 1:62,500 sheet 56.

Where observed the Odominadzi granite showed none of the features of the eastern migmatite zone. It tends to be mostly rather fine grained although parts are pegmatitic. It is normally more or less foliated. Occasionally exposures of hornblendite appear but these are rare.

14 e. The Abakwa Granite.

This granite is represented by an outcrop in Abakwa village and along the footpath from Abakwa to Odominadzi. In hand specimen and thin section it is quite unlike any other granite found in the Winneba district. It is seen to be very biotite-rich, largely unfoliated and somewhat blocky in outcrop. Biotite-rich ghosts are present and show some elongation in a 20° direction.

In thin section the rock shows abundant finely twinned large hypidiomorphic zoned feldspar grains. The cores of the grains appear to have been oligoclase-andesine prior to albitization. A small amount of myrmekitic structure is present principally around the peripheries of some of the grains, but it is not abundant. Quartz is subordinate and many grains show strain extinction. Slightly bent feldspar and biotite crystals are not uncommon. Biotite is plentiful and is the dark brown variety commonly found in the gneisses. Muscovite is present but scarce. Some slight alteration of the feldspars is common and epidote is abundant.

14 f. The Tachem, Nsuaem Granites.

The Tachem granite forms a somewhat elongated patch of high ground in the centre of a triangle formed by villages of Awomiro, Tachem and Nsuaem. One mile north-east of the Tachem granite the Nsuaem granite appears in a small conical hill over-looking the village of Nsuaem. No connection on the ground between the two granites was observed.

In the field the rocks do not appear to be similar. The Tachem granite is medium to fine grained and shows a general likeness to the gneiss north of the Winneba granite. The Nsuaem granite on the other hand is coarser, the ferromagnesian minerals are collected into clots, parts are quite pegmatitic and the granite in general was observed to be strongly pyritous.

Microscopically the two granites are not dissimilar; both show completely inequigranular textures and micro-porphyroblastic crystal development. In the Tachem granite the porphyroblasts are oligoclase with rims of microcline. The oligoclase is normally markedly saussuritized. The matrix consisting of an uneven mass of quartz, oligoclase and albite. Sericite and epidote are both abundant. Pale yellowish-green corroded biotite occurs infrequently and shows marked pleochroic haloes with zircon centres.

The Nsuaem granite contains rather more abundant microcline and some of the micro-porphyroblasts are almost wholly composed of this feldspar. Large grains of saussuritized oligoclase are equi-abundant with the microcline and are set in an uneven groundmass of allotriomorphic microcline, oligoclase, quartz and some albite. All the feldspar grains except microcline show signs of alteration and sericite is very common. Yellowish green biotite occurs in rather feathery grains grouped in irregular masses. Epidote is present but not abundant.

4 g. The Onyadzi-Mprumen Granite.

The granite in this locality is very poorly exposed and appears principally along the line of the Winneba-Mankesim road, where it is generally seen only in road cuttings and culverts from just east of the Onyadzi junction to the western limits of the map sheet. There is considerable general evidence to show that the rocks here are the same as the Manso-Dahum-Amankesim granite and a connection in the field has been established on the adjacent sheet.

The section along the road is somewhat difficult to resolve and is complicated by numerous Birrimian xenoliths and roof pendants. The granite itself is highly weathered and has become a soft yellowish-brown pudding-like mass in which yellowish-brown biotite is generally distinct. The granite is cut by the usual series of aplites and quartz veins.

14 h. The Manso-Dahum-Amankesim Granites and Gneiss.

The north-western boundary of the raft of Birrimian rocks is in contact with a series of granites and gneisses which extends from north of Asamkrom, on the Winneba-Swedru road, as far south as Ogwan on the Simbrofo-Lome road. The mass of granite and gneiss which covers the whole of the north-western corner of the sheet is part of a large granitic area which exists to the north and west of the sheet. The granites contain numerous xenoliths and roof pendants which are particularly well marked in the south-west of the area.

Granitic exposures in the locality are relatively scarce particulalry in the southern and western sections where there exists a relatively thick covering of lateritic clays. Many of the exposures show the pegmatitic nature of the gneiss; in fact the only exposures seen on many traverses throughout the area of this material. In many cases the pegmatite is thought not to occur in the characteristic dyke-like intrusions but rather as irregular phases in the gneiss. Muscovite is extremely abundant in all pegmatites in the north-western gneisses and sizeable books showing plates up to 2½ inches in diameter are common.

The best exposures in the most northerly portion are found along the Winneba-Swedru road between Asamkrom and Brofeyedru. In the Tachemang, Manso and Adansi-Asamkrom ocalities the gneiss is again very well exposed in rather large blocky outcrops on the crests of ridges and low hills. The gneisses are generally massive in character and occasionally unfoliated. In the Brofeyedru district and between Manso and Akwapim they show a good deal of banding, the darker bands being biotite-rich. This feature is also seen to the south-east of Dahum where it was observed that the gneiss is similar in appearance to that near the old Potsin road junction on the Accra-Winneba road. Indeed microscopically the two rocks are almost identical, the only difference being the appearance of slightly more microcline in the Dahum rock.

Between Adansi and Asamkrom the gneiss is markedly different in appearance being a uniformly even textured grey, pyritous biotite granite which may or may not show foliation. Microscopically it shows distinctive features unlike those seen in the gneisses near Dahum. The texture is quite uneven and irregular, microcline is rare and the dominant feldspar appears to have been oligoclase which has been albitized and is now untwinned and zoned. Quartz appears both interstitially and as veins and usually shows strain extinction. Biotite occurs in brown and slightly greenish brown ragged flakes often associated with epidote and sphene.

In a small stream just north of the village of Akwapim the gneiss is exposed on the west side of the path and the mica schists on the east side. In this locality the gneiss is considerably more biotite-rich than is common, the biotite being as unusual reddish brown colour which does not mask the polarization colours. Sphene and epidote are associated as before with the biotite. Quartz is present in veins and interstitially and frequently shows strain extinction. Some microcline and oligoclase feldspar occurs but much of the feldspar is strongly zoned untwinned albite. The texture is again inequigranular and the majority of the grains are allotriomorphic.

Probably the best example of zoned feldspar gneiss was noted 0.9 mile from Simbrofo and 150 yards west of the Simbrofo-Ogwang road. The rock is almost on the Birrimian gneiss contact but in this case the Birrimian rocks are greenstones rather than Lower Birrimian mica schists. In thin section the gneiss shows relatively large untwinned, completely saussuritized, strongly zoned feldspars. A little twinned oligoclase is also present and some microcline appears as rims round zoned untwinned grains. Occasionally simple Carlsbad twinning is seen. Biotite again appears in aggregates of small flakes and larger ragged grains. It is commonly greenish-brown and is again associated with sphene and epidote. Quartz is present but only as small interstitial grains.

There are general similarities of texture and mineralogy be tween the Adansi gneiss and those described from Akwapim and the Ogwang road. All show inequigranular texture, contain zoned feldspars and have a rather higher biotite content than is normal. They are quite different from the gneisses which occur about 1 mile south-east of Dahum and 1 mile north-west of Amankesim. The latter are hot albitized, the feldspars are unzoned and the texture is equigranular. It would thus appear that this alteration of the feldspars is primarily in this instance a marginal feature of the north-western gneiss.

CHAPTER 15.

MINOR ACID INTRUSIVES.

Minor acid intrusives which vary in width from a few inches to several yards can be found over the whole of the area and in all types of rocks except the Togo quartzites. Occasionally some varieties are exclusively found in certain areas, for example, the graphic granites seen in the Eastern migmatite gneiss are not found elsewhere. Similarly the sheared and shattered aplites which are well exposed on the Mankwadzi and Apam beaches are not found in the Winneba granite. These exclusive occurrences of certain minor intrusives provide a possible indication of the relative ages of the host rocks.

15 a. The Aplites.

At least two varieties of aplite have been recognized within the sheet. One is the highly flinty, sheared, Mankwadzi-Apam variety and the other is a late stage aplitic granite found only in the Winneba granite. It is thought that the aplites in the Eastern migmatite area are of the same age as the Mankwadzi-Apam suite but the evidence for this is scanty and based only on general lithology.

The Mankwadzi-Apam aplites when seen in the coastal section are usually discordant intrusives and this feature is particularly well seen along the beach section between Apam and Mumford where the strike of the dykes is 30° and the strike of the foliation of the Upper Birrimian is 70°. These aplites, which are almost wholly composed of a granular mosaic of quartz grains with possibly a little untwinned feldspar and some flecks of brown biotite, may occasionally show some foliation structures not related to the regional foliation. Inland, particularly in the Yenku range occurrences of these aplites are difficult to distinguish from quartz schists and the only reliable guide is microscopic identification.

Along the contact of the Winneba granite with the coarse amphibolites, the minor intrusions are orientated parallel or sub-parallel to the boundary but do not cut it. It is thought that some of the fine grained saccharoidal rock of this suite may be the same as the Mankwadzi aplites but alterated by the later Winneba granite. To summarise the rather scanty information concerning the age of the Mankwadzi-Apam aplites, it would appear that they are later than the imposition of the regional foliation and the eastern migmatite granites and gneisses and that they are earlier or perhaps contemporaneous with the mineralization (they contain arsenopyrite) and certainly earlier than the Winneba granite.

Aplite bodies found further north, in the neighbourhood of Tachem, Nsuaem and the Osi hills bear no marked field similarities to the Mankwadzi-Apam types and they do in general appear to follow the Birrimian foliation trends; it is however appreciated that this may only be a coincidence. They do not show the strong shattering and shearing characteristic of the coastal aplites and there is not sufficient general evidence available to indicate the relationship of these bodies to the coastal aplites.

15 b. The Pegmatites.

This type of minor intrusion is recognized in three major phases, i.e.

(a) White pegmatites with abundant pale greenish mica.

(b) White pegmatites, quartz and feldspar with practically no mica.

(c) Pink pegmatites with or without mica.

The pegmatites with a pale slightly greenish white mica are largely but not exclusively confined to the Birrimian. They are rarely found in the eastern migmatite gneisses and the Winneba granite but they are quite common in the north-western granites and gneiss. On the other hand the pegmatites without mica are only occasionally found in the Birrimian but they are abundant in the eastern migmatites and gneisses and they also occur in the Winneba granite. The pink pegmatites which are abundant in the Winneba granite are sometimes seen in the eastern gneiss but do not occur in the Birrimian except as pink veins developed locally at the contact with the Winneba granite. Two types of garnets appear in all pegmatites; one is a well formed small rose pink variety while the other usually occurs in large dark brown masses rarely showing any crystal form. This latter variety may contain up to 19 per cent MnO and is most abundant in the mica pegmatites which occur between the Muni lagoon and the Winneba granite.

The age relations of the three types of pegmatite appear to be relatively clear cut. The white oligoclase-bearing mica pegmatites appear to have been the earliest. In general they are intruded along the foliation directions in the Birrimian, a notable exception being the cassiterite-bearing pegmatite at Mankwadzi which is markedly transgressive and contains microcline. The pegmatites become sacchariodal near the contact of the Winneba granite and coarse amphibolites, and in this locality they run parallel and sub-parallel to the granite boundary but do not cut it. The mica-poor pegmatites are found principally in the eastern migmatite gneiss and occasionally in the Winneba granite and Birrimian and these are considered by the author to have been the next phase. The final phase appears to have been the microcline-bearing pink pegmatites which are found cutting most other minor intrusions except possibly the very latest aplites of the Winneba granite and these appear in some cases to have been more or less contemporaneous with the pegmatites.

15 c. The Graphic Granites.

The graphic granites have a rather peculiar distribution being solely confined to the eastern migmatite gneiss. They are extremely well exposed along the Accra-Winneba road, particularly between Bonporo and Mankokwa. The intrusions very from a few inches to several yards in width and may be concordant with the foliation but more usually they are transgressive. Occasionally the graphic granites show included flakes of brown biotite picked up from the country rock. Also in many instances they are cut by quartz veins and pink pegmatite.

The feldspar of the graphic granite is microcline which is cut by thin veinlets of plagioclase more or less regularly arranged at 70° to the edges of the microcline-quartz contact.

15 d. The Quartz Veins and Reefs.

Quartz veins and reefs appear throughout the gneisses and Birrimian and are undoubtedly of a variety of ages; some are definitely connected with silicification during Birrimian times whilst others are major quartz reefs principally connected with the mineralization of the southern portion of the map sheet area. Many show no apparent connection with either of these phenomena.

The quartz intrusions vary from a few millimetres to several yards in size and are generally much shattered and strongly jointed. In a reef one and a half miles east of Onyadzi along the Winneba road a large quartz crystal is seen (Plate 2). In general the reefs show no particular respect for the foliation directions of the host rocks. Broadly however, except in the notable instances at the east end of the Mankwadzi sandy cove, the major quartz reefs do tred to follow the general Birrimian trends, being concordant in some places and transgressive in others. The minor veins on the other hand appear to have random orientation.

Usually the larger reefs and occasionally some of the smaller ones contain amounts of tourmaline which in some cases may appear as schorl rock bands on either or both sides of the quartz vein. A good example of this is found in the molybdenite-bearing quartz reef 1.4 miles west of Mankwadzi where the molybdenite appears in a 6 inch thick quartz schorl band at the base of the rather flat-lying quartz reef. In such cases it is very difficult to say whether the quartz reef or the tourmalinization was the earliest or whether or not they were in fact contemporaneous. In some instances there is very little tourmaline in the quartz reefs and a considerable amount in the country rock and this would appear to indicate that such quartz veining is later. In other places, for example on the west bank of the Mukuba lagoon and south-west of mile 6 on the Winneba-Swedru road, tourmaline crystals appear in the quartz reefs themselves. Crystals up to 6 inches in length have been found in several localities. As a general rule the greenstones in the immediate vicinity of both types of quartz tourmaline association show extensive boron metamorphism.

In many cases aplites and quartz veins form single composite dykes usually with aplitic sides and quartz centres. This feature is clearly illustrated in the centre of the sandy cove between Mankwadzi andABrekum. In the Winneba granite similar composite veins of pink and white feldspar are also not uncommon. However it is not usual to find composite associations in the large pegmatite dykes of the Mankwadzi-Winneba localities.

CHAPTER 16.

MINERALIZATION.

An inspection of Map 2 shows that although the minor acid intrusions appear throughout the sheet they are numerous in the Winneba-Mankwadzi localities and it is in this area where primarily the strongest mineralization has taken place. It would therefore appear that the occurrence of minerals in pegmatites, aplites and quartz veins is confined to those intrusions which are earlier than the Winneba granite. (Chapter 15).

In general beyond a radius of two miles from Mankwadzi most of the pegmatites, aplites and quartz reefs are barren except perhaps for tourmaline. In the vicinity of Mankwadzi village the most abundant minerals are undoubtedly tourmaline and mispickel (arsenopyrite). The latter occurs abundantly in all minor acid intrusions in the district and is particularly abundant in the aplites at the top of the northern-most hill of the Ejisimanku range. In other occurrences particularly in the greenstones of the Mankwadzi coastal section, the mineral appears in rather yellowish barrel-shaped crystals which when broken open reveal silvery white interiors. Arsenopyrite in fact is found abundantly throughout the coastal section.

At a point 0.6 mile upstream from the mouth of the Mukuba lagoon a well marked ridge cuts the feeder stream and half way up the south-western slope of this ridge the arsenopyrite occurs in blocky masses. The ridge is primarily composed of a bronze-biotite rich amphibolite with pegmatite and showing signs of extensive mineralization. It was from this locality that Kitson (1925) obtained platinum in amounts up to eight grains per ton. Small quantities of nickel and copper were also found.

Detrital and alluvial cassiterite has been found at several points in the Mankwadzi locality and during the mid 1930s attempts were made to work the alluvial cassiterite deposits of the Mukuba lagoon. It was found that the gravels worked averaged about 25 feet in width and about 1½ feet thick and consisted primarily of unsorted greenstone, epidiorite and quartz pebbles, some of the latter being rich in tourmaline. The cassiterite was heavily concentrated in patches in the gravel in some cases averaging 3 to 4 lb. per cubic yard and several individual lumps up to 3 lb. in weight were reported. The bedrocks were hornblende schists and (?) epidiorite penetrated by veins of pegmatite and mineralized aplite; cassiterite, arsenopyrite and tourmaline were recorded from some of the pegmatites and aplites.

The workings in the 1930s were confined to the head of the Mukuba lagoon; however the creek which flows into the lagoon from the N.N.W. had been proved to contain cassiterite for more than a mile upstream but for the most part there is very little gravel in this stream except in the lower part of its course.

In addition to cassiterite the concentrates were reported to contain varying amounts of ilmenite, columbite, tantalite, staurolite, garnet, zircon, schorl, hornblende and possibly some rutile. During the examination by the author very little cassiterite was found in the concentrates from the lagoon but some was found in the grey-white pegmatite at the western end of Mankwadzi beach, just east of the rocky promontory. A further half per cent by weight was also recorded in the black radio-active sands in the cove east of Mosul point.

Gold has been found over most of the sheet but is usually most abundant in the Mankwadzi-Apam locality. It has been previously reported in pegmatites and aplites in this area and also as an alluvial mineral from rivers and lagoons. This was confirmed during present work and some was also found in beach sands. Values were not sufficiently high to be of economic interest.

The mineral assemblage found in the Mankwadzi-Abrekum locality is characteristic of the pheumatolytic type of mineralization; silicification, tourmalinization and partial greisenization are all present. Garnets are produced in abundance in the hornblende mica schists and biotite is developed in the amphibolites.

No known mineralization has been directly related to the Winneba granite and it has been shown in Chapter 15 that the Mankwadzi suite of minor intrusives is earlier than the emplacement of this granite. It would thus appear that the granitic body responsible for the mineralization of the Mankwadzi locality is older than the Winneba granite although possibly younger than the eastern migmatite gneiss.

CHAPTER 17.

THE TOGO SERIES.

The Togo series, in this locality, consists of a succession of even grained purple or buff coloured quartzites. In places where thrusting and faulting has been observed a sericite phyllite appears at the base. Broadly the quartzites form a semi-circular patch of high ground in the south-eastern corner of the sheet, the northern and north-western limits forming a well marked scarp whilst on the seaward side cliffs, coves and potential sea stacks are all clearly defined features. The series extends from sea-level to at least 350 feet O.D. However, it is not possible to estimate the true thickness owing to the large amount of faulting and folding which has taken place.

The best exposures are seen in the coastal cliffs where the quartzites show a great variety of structural features; jointing, normal faults, thrust faults, disharmonic folding, false bedding and shearing are all common. In one locality a few yards east of the thrust wedge of (?) Dahomeyan a recumbent fold exists. In general however along the coast the dip of the series is to the south-east usually about 35°-45° but along the northern scarp face the dips appear to be somewhat shallower; here dips of 15°-35° are more common and the strike broadly follows the scarp edge. On the west side of the small stream which enters the sea in the south-east corner of the area the direction of dip is to the south-west usually at 30°-40°. A considerable amount of brecciation and shattering is found in this stream for some distance inland and it would seem likely that faulting along the river valley has caused this change in strike direction.

It has been noticed that the purple facies are more commonly associated with the traces of botryoidal iron minerals which appear in the series in this locality. Microscopic examination show that both varieties contain detrital microcline and occasionally other feldspars. The quartz grains for the most part are rounded and shattered and occasionally elongated with practically all grains showing strain extinctions.

CHAPTER 18.

GEOLOGICAL HISTORY.

18 a. Introduction.

The oldest rocks of the area are gneisses which may be Dahomeyan in age but since these are only represented by a small inthrust wedge it is not proposed to discuss them here. Apart from these, the oldest major series represented here is the Birrimian which is generally considered to be Pre-Cambrian in age. In this district it has been possible on general lithological grounds to split the Birrimian into two sub-divisions namely Upper and Lower, the latter being represented by a strip of mica schist along the north-western granite contact. The Upper Birrimian, as already described, consists of metamorphosed sediments:- gondites and various types of schist, quartz schists, lavas now meta-basalts and feldspar amphibolites, and occasional intrusive bodies such as sills and dykes which are now also feldspar amphibolites and hornblendites. The rocks of both sub-divisions have been isoclinally folded along north-easterly axes.

Following the Upper Birrimian volcanic phase the major granite and migmatitic granite masses were emplaced probably largely by granitization of pre-existing Birrimian rocks. Later, rather more minor granitic intrusions, for example the Winneba granite and the Odominadzi granite, served to displace both the strikes of the Birrimian and the earlier gneisses. Earlier and in part concomitant with the emplacement of the later granites, the minor acid intrusive phases and mineralization occurred.

Probably after the emplacement of the gneiss the sericite quartz schists of the Mumford locality were formed. These are lithologically quite unlike the Birrimian quartz schists and structurally they do not wholly appear to tie in with the Birrimian pattern. A suite of relatively fresh metamorphosed epidiorite dykes also appear; these may well be related to Tarkwaian igneous activity. Following the Tarkwaian diastrophism conditions appeared to settle down and no further igneous activity took place in the district. The Togo quartzites were laid down and contain no intrusive bodies which could be related to any subsequent activity. In post-Togo Series times considerable faulting, folding and thrusting took place and most of the lines of fracture throughout the area are orientated in a north-westerly direction.

The broad outline of the geological history of the area may be thus summarised;

1. Manganiferous, argillaceous and siliceous sediments. Extrusive and hypabyssal rocks of the Birrimian greenstone series.
2. Subsequent metamorphism of the Birrimian with concomitant emplacement of early orogenic biotite gneisses by intrusion and granitization; some minor acid intrusions and mineralization.
3. Emplacement of late orogenic granites and gneisses with minor acid intrusives.

4. Deposition of (?) Tarkwaian sediments - Mumford quartzites.
5. Post-Tarkwaian orogeny represented by intrusion of epidiorite dykes.
6. Deposition of Togo quartzite.
7. Post-Togo; thrusting, faulting and folding.
8. Deposition of Tertiary to Recent sediments; laterite caps on hill tops, salt-beds, raised beach deposits and the Senya Beraku Boulder Beds. Some faulting may be Tertiary in age but there is no direct evidence of this.

18 b. The Birrimian-Granite Relationship.

The original Birrimian sediments were undoubtedly of aluminous, semi-calcareous magnesian types, quantities of manganese appear in some of them and when metamorphosed they produced gondites with actinolitic amphiboles, epidosites and granulites. The origin of the two central bands of quartz schist is somewhat uncertain; no bedding or false bedding has been detected in them and in the field they are generally black and fine grained. One suggestion is that they may have originally been rhyolites. However a consideration of the petrology of the regional metamorphism does not appear to support this suggestion.

Probably during the deposition of the sediments or very shortly afterwards the Upper Birrimian extrusive and hypabyssal igneous activity commenced. The presence of pillow lavas indicates that a number of the lavas of this phase were extruded under water. The feldspars in many of these lavas have undergone extensive albitization, examples of which can be found in all the greenstone series sub-divisions described earlier.

Concomitant with the extrusion of the lavas a number of hypabyssal bodies were emplaced. These usually appear to have had a doleritic or gabbroic composition. Certainly some of these were emplaced after the volcanic phase and in many places, particularly east of the Winneba road roundabout, there is clear evidence of the later intrusive nature of these rocks.

Much of the silicification and pyritization in the Birrimian rocks is thought to be Birrimian in age and not later. Many of the minor quartz veins in the metamorphosed lavas show shearing and strain structures which would tend to indicate that they were already in place when the regional metamorphism took place. Furthermore in the case of the pyritization, pyrite is not a very common mineral in either the early orogenic or the late orogenic granites, and also it is rarely associated with the Mankwadzi mineralization.

18 c. The Age of the Granites and Metamorphism of the Birrimian Series.

It has already been shown in earlier sections that the structures of the Birrimian rocks have been displaced by the emplacement of the granites. The rocks themselves have also been altered to a greater or lesser extent by the post-Birrimian orogeny. Undoubtedly the earliest of the granites and gneisses was the eastern migmatite with its possible extension in the north-western gneiss.

Indirect and direct evidence exists in support of the foregoing statement. The graphic granite dykes which are abundant in the eastern gneiss are found nowhere else in the area and thus they are probably associated with granitic bodies later than the eastern migmatite. The indirect evidence appertains to the relative ages of the Winneba granite and the eastern gneiss. The former appears to be an intrusive body; its contacts with the surrounding rocks are sharp; it seems to have pushed aside the Birrimian with its earlier minor intrusives and possibly partly accounts for the structure of the eastern gneiss. The Winneba granite body appears on the map as a somewhat discordant structural feature. It becomes finer grained at its periphery and although ghosts are to be found, it shows none of the characteristic granitization features of the eastern gneiss. The late stage minor intrusions connected with the Winneba granite are pink pegmatites and feldspar veins, which are seen to be later than the attendant minor intrusives of any other granite body in the district.

In the case of the other granites at Abakwa, Nsuaem, Tachem, Mpata-Winneba roundabout and Odominadzi, they appear to belong to a similar age or phase as the Winneba granite. They appear to be of an intrusive nature and none of the typical features of a granitized zone have been found in them, nor have any graphic granites been observed. Their contacts with the surrounding rocks are sharp and cause minor structural displacements in them and although some contact metamorphic effects have been noted, for example the development of sillimanite and cordierite in the central quartz schists, the effects are not extensive.

A little direct evidence concerning the age of the Odominadzi granite is available. It appears to have displaced and split the banded quartz schists in the northern section and if it is considered that these schists are Birrimian in age and also conformable with the eastern gneiss then the Odominadzi granite is certainly of post-migmatite age.

The Birrimian-gneiss contact of the north-western gneiss shows evidence of alkali metasomatism and the granitic rocks along the contact appear to be quite different, in thin section, from those far removed from the contact zone. In others, principally the Abakwa, Tachem and Nsuaem granites, considerable alteration and zoning of the feldspars was noted. Indeed the albitization with concurrent porphyroblastic microcline development was marked. The porphyroblasts in the Winneba granite are also undoubtedly due to this phase of metasomatism.

In view of the extensive albitization and alteration of the feldspars in the granites and gneisses marginal to the main gneissic mass it would appear not unreasonable to assume that the formation of the spilitic rocks of the Birrimian was not wholly due to their extrusion as spilitic lavas but was due rather to the later stage albitization of normal basaltic rocks.

Petrologically the Upper Birrimian of the district can be divided into four principal rock facies. In the north and northern-central sections medium to fine grain actinolite schists predominate. In the south-west the rocks are principally composed of feldspar amphibolite containing the typically blue green amphibole of the Birrimian and developed largely from vesicular lavas and hypabyssal intrusives and have become similar in part to those types which comprise Harker's (1932) epidiorite group. In the extreme south the hornblende of the rocks changes slightly to a more intensely coloured variety and a garnet biotite hornblende facies is developed. In the south around the periphery of the Winneba granite a zone of coarse actinolite amphibolite is developed. This rock is not found in such a major development anywhere else in the district. In the sketch map Fig. 78 showing the possible distribution of the various facies of metamorphosed Upper Birrimian rocks it can be clearly seen that the zones are quite regular in form and the nature of the superimposed isoclinal folding is clearly seen.

The question of the original nature of the actinolite schists is a difficult one to answer; currently they seem to represent a phase of the green schist facies. No false or normal bedding has been found in them but occasionally the schists tend to be broadly colour banded.

An inspection of the analyses of the rocks analysed by the present writer shows that for the most part they have compositions which could well be correlated with those of average basic extrusive rocks. Several analyses of which are included in Table 18 given here for comparison. It can be seen that numbers LY 550, LY 20 and LY 484 are generally lower in alumina than the average basalt. These are the hornblendite types from the zone of coarse amphibolites and were probably basic gabbroic dykes or tilted sills.

The most marked difference in composition is between LY 109, LY 485 and LY 987 and the other rocks of the Birrimian Series. These rocks are in fact the actinolite schists (LY 109) and the actinolite amphibolites (LY 485 and LY 987) it can be seen from the table that there is very little difference between the coarse amphibolite and the schists.

It is very clear that these rocks have different compositions from the average basalt (Table 19), principally they have low alumina and iron content but high magnesia and lime. This points to a siliceous dolomitic limestone as the original rock. A further piece of evidence is that Hallimond's diagram Fig. 79 shows clearly that tremolite-series amphiboles are usually derived from rocks of near limestone composition. Notwithstanding the differences in composition, the present writer is unable to see why if these actinolite schists do represent an extrusive rock they should produce on metamorphism a rock so completely different both mineralogically and texturally form the other basaltic rocks with which they are in close association. Furthermore, as the grade of metamorphism increases in the Mankwadzi area, actinolite schists are preserved amongst the amphibolites and schists of the biotite garnet facies. It would therefore be more reasonable to assume that the actinolite schists were not originally basic lavas, but rather that they represent a somewhat siliceous magnesia-iron rich sedimentary horizon. The change in petrography between the various facies would then be easily explained; for example it is more reasonable to assume that the coarse actinolite amphibolites are developed from actinolite schist than from feldspar (hornblende) amphibolites, particularly since the latter have been shown to become hornblendites under the same conditions. If the actinolites are in fact of sedimentary origin then the occurrence of actinolite schists in the biotite-garnet zone is easier to imagine.

Whilst many of the feldspar amphibolites have been identified as having been originally basic lavas, in some cases where original textures are absent there is considerable difficulty in distinguishing between rocks which may have been originally intrusive or extrusive, although as a general rule the former are coarser grained.

Where the grade of metamorphism increases, for example in the Mankwadzi locality, the feldspar amphibolites show this increase by the development of biotite whilst the sedimentary or tuffaceous rocks generally produce both biotite and garnet. The actinolitic facies however tend to become much coarser in texture and the felsic minerals decrease in quantity. This is clearly seen in the neighbourhood of Okeseo and Onyadzi whilst around the Winneba granite periphery the coarse actinolite amphibolites are fully developed.

It can be seen from Map 1 that the gneisses and granites appear at shallow depths beneath this coarse amphibolite zone. The emergence of small granite knobs is clear evidence of this. The inference is that the net metamorphic effect on the original rocks of this zone would be the same as the effect on a large xenolith. Normally the hornblendites found in small irregular masses in the granites and gneisses are not thought to have the same origin as the hornblendite dykes commonly found in the Birrimian. The dykes are considered to have been originally gabbroic or even ultrabasic in composition whereas the xenoliths in the granites and gneiss were probably originally greenstone.

In this case, around the Winneba granite periphery the actinolite amphibolite xenolith was probably developed from an actinolitic schist.

18 d. The Relationship between the Gneiss and the Togo Series.

The quartzite of the Togo series are thought to rest on the contorted gneisses of the eastern migmatite series. The quartzites do not contain any of the minor intrusives common to the gneiss and the Birrimian, and certainly in this locality no granitic veining is found in them. The contact between the quartzite and granite was not observed but it was clear from a general examination that it is a sharp one.

It is appreciated that considerable faulting took place in post-Togo times and that many of these faults are thrusts. The quartzites are seen to be quite strongly folded and at least one conspicuous recumbent fold exists. Thus, whilst there is evidence of thrusting on a minor scale there is no major evidence to indicate that the junction between the quartzites and gneiss is a tectonic one. There is however evidence to the east of Senya Beraku indicating that the junction in that locality at least is probably a depositional unconformity.

18 e. Tertiary and Recent Geology.

Here there is no evidence of the existence of any formation between the Togo quartzites and the Tertiary to Recent deposits. Towards the end of the period of faulting the whole area was subjected to erosion and pedeplanation. This was followed in late-Tertiary times by the up-lift of the land or the lowering of the sea level with the attendant formation of the successive levels of raised beaches.

Along the coast from the eastern to the western boundary of the sheet and particularly in the south eastern corner, marine terraces and wave cut benches are marked at 5 feet to 20 feet and 30 feet to 40 feet above sea level. Occasionally, for example around the Muni lagoon, low hills capped with laterite and 50 feet high probably represent residuals of a plane of marine erosion.

The low hills along the coast from the Muni lagoon to Apam possibly represent the residuals of the 150-250 feet O.D. erosional platform. The tops of the higher hills, Ejimanku and Yenku are at present at elevations of 593 feet

O.D. and 764 feet O.D. respectively. These hills have generally well rounded outlines and it may be that they represent higher and older eroded land surfaces.

18 e 1. The Lagoonal Deposits.

Three major and three minor lagoons occur in the Winneba district and for the most part they contain dark grey clays with occasional sands. The smaller Mukuba lagoon at Mankwadzi contains alluvial gravels at its northern end.

The lagoons are all separated from the sea by well developed sand bars which can be particularly well seen at the mouths of the major lagoons. At the mouth of the Muni lagoon for example, the sand bar is many yards wide, more than 1½ miles long, and able to accommodate fishing villages and a motor road. All lagoons except the Oyibi lagoon, which is fed by the permanently flowing Ayensu river, are closed by the sand bars during the dry season.

18 e 2. The Boulder and Pebble Beds.

Around the western and north-western edges of the Togo quartzite scarp a cemented boulder and pebble bed exists. The horizon, which is at least 40 to 50 feet thick and probably much more, is composed of rounded Togoquartzite pebbles and has been observed in direct contact with the underlying quartzites. Previous investigations suggested that the partially consolidated finely laminated sands found along the coast near the village of Ndadetaw underlay the boulder beds

(Kitson 1928). Present work shows that these laminated sands are either more recent than the boulder beds or that they are quite impersistent and erratic in distribution.

The deposit has often been compared with the Amissian rocks at Saltpond and whilst it is clear that there are some lithological similarities the shape of the occurrence of the boulder beds would appear to make the deposit more intimately related to the present form of the Togo quartzites than to the independent deposit of the Saltpond Amissian. Also, whilst it is apparent that the Saltpond Amissian is faulted and that fossil evidence indicates that its inclusion in the Jurassic would not be unreasonable, faulting affecting the beds in the Senya Beraku district has not been observed and so far no fossils have been found. It would thus appear that the Senya Beraku horizon is a more local formation and probably younger than the Saltpond Amissian.

CHAPTER 19.

STRUCTURE.

The structure of the Birrimian and post-Birrimian gneisses has been generally referred to in the various previous sections. Faulting has not been discussed but the general trends of the foliation in both Birrimian and gneiss have been indicated and are clearly shown on the structural map. (Map 3).

At first glance it would appear that the direction of trends in the eastern migmatite are illustrative of thrust faulting, particularly when they are compared with the foliation trends of the Birrimian in the southern portion of the strip. The banded quartz schists or gneiss appear to be largely discordant but on close inspection this is found not to be so. They are concordant with the Birrimian in the northern section and concordant with the gneiss in the southern section. It is necessary at this juncture to refer to the map of the distribution of the Birrimian facies (Fig. 78) where it is clearly seen that the structure of the Birrimian Series is one of pitching isoclinal folding. The two quartz schist bands would appear to be part of the same horizon, that is, different limbs of the same isoclinal fold (Fig. 79). A third limb has been subjected to lit-par-lit injection and now forms the banded quartz schists. The horizon, as already described, is a composite one composed of hornblende schists as well as quartz schist. In the gneissic area it is not possible to make any further sub-divisions. It seems clear that this composite body represents the quartz schist horizon of the Birrimian and parts of the actinolite and hornblende facies. The divergence to the south-east and south-west of the two parts of the Birrimian Series can thus be directly attributable to the intrusion of the relatively large masses of the later orogenic granites, particulalry the Winneba granite. It seems probable from this that the Winneba granite was intruded whilst the rocks of the eastern migmatite gneiss were in a plastic or semi-plastic state.

If the banded quartz schist represented a thrust mass one would have expected to find remains of the series on top of such hills as Obusomnyinye and Bonproro which are for the most part topographically higher than the banded quartz schist horizon. Furthermore the absence of mylonites, although not conclusive, is further evidence against the thrust hypothesis.

The axis of the isoclinal folding is orientated in a north-east south-westerly direction and it would appear that the principal directions of force were from the south-east and presumably the intrusion of the Winneba granite also accounts in part for the orientation of the fold axes.

19 a. Faulting.

It can be seen from Map 1 that the principal direction of faulting is west of north. It is not possible to assign a definite age to the faulting except to say that it is post-Togo and pre-Recent.

The faulting is most clearly marked in the Togo quartzites, both normal faulting and thrust faulting occurring. It seems clear that the rocks overlying the beach to the west of Senya Beraku are near the base of the Togo quartzites because normal faults and thrust faults cause the basal fine grained phyllite to be exposed. It is thought that the majority of the faults have only a small throw otherwise the underlying eastern migmatite series would possible be exposed.

The faulting in the Winneba granite seen along the coast is only minor, for the most part having displacements of only one to two feet. The northern block of the Winneba granite has however been displaced by a 300° trending fault with down-throw to the south-west. The lateral displacement caused by this fault is just under half a mile. Similarly the north-eastern end of the Yenku block is somewhat truncated by an inferred fault which would trend about 335°. Again the down-throw side is to the west and the displacement just over a quarter of a mile. There is probably some faulting in the neighbourhood of Akwapim; here much shattering is seen and the greenstone is considerably thicker in this locality. It is also possible that many of the valleys in the Yenku block, which strike in the same direction as the regional trend of the faults, represent fault-lines or at least shatter belts.

The Abrekum fault is inferred by the sharpness of the ends of the ridges north of Abrekum and the slight displacement of those features on each side of the Apabaka lagoon. Abundant shattering is found in the vicinity of Abrekum village.

The faulting in the Mumford quartz schist is clearly seen along the coast. The large fault with the regional trend is clearly marked by a faulted scarp of quartz schist with a brecciated greenstone at its base.

Over the whole of the area considerable shattering has been observed. The Mankwadzi aplites for example are strongly broken up. A good deal of the shattering is undoubtedly associated with faulting, but it is very difficult to identify faulting in the Birrimian greenstones series particularly in localities remote from the coast. The Birrimian facies distribution map (Fig. 78) would seem to indicate that there has been no faulting of greater throw than half mile otherwise the limbs of the isoclinal folds would have suffered rather more major displacements.

19 b. Joints.

The structural map (Map 3) shows that the major joint pattern for the Birrimian Series and the eastern migmatite gneiss is broadly the same. The Winneba granite shows a slightly different arrangement which would appear to be additional evidence that the Winneba granite is later than the eastern gneiss. The joint pattern of the Togo quartzites is also slightly different from the main Birrimian gneiss pattern but this is not unexpected.

CHAPTER 20.

ECONOMIC GEOLOGY

20 a. Minerals.

In previous years the district has been energetically prospected by various mining companies and officers of the Geological Survey and although an attempt was made by a private company to work the alluvial tin in the Mukuba lagoon near Mankwadzi the efforts met with little success and eventually all commercial prospecting in the district ceased. During the present investigation the author re-examined all old workings and prospects but nothing was found which would justify the re-openig of the district to more detailed and expensive prospecting (Fig. 80).

Tin. Cassiterite has been found in small pegmatites along the coast and in the gravels at the northern end of the Mukuba lagoon. The indications are that the mineral is sparsely distributed in the pegmatites and has been concentrated in the lagoonal gravels.

Gold. Small amounts of gold have been found in most places in the district. Old prospect at Ogwakrom (Junner 1938-39) and Onyadzi were re-examined and were found to be barren or of no commercial value.

Gold is found in sands, gravels and minor acid intrusions between Mankwadzi and Apam. In every locality values are so low that further investigation is not justified particularly in the light of the earlier prospecting.

Platinum. Small quantities of platinum were found in the Mankwadzi locality by Kitson in 1925. The amount found was very small, only six grains per ton by assay.

Molybdenite. During the current investigation the reported molybdenite occurrence in the schorl rock associated with the quartz reef of Mosul point, Mankwadzi, was re-examined. The reef was prospected by the African Manganese Company in 1942 and abandoned.

Columbite and Tantalite. Very small quantities of columbite and tantalite were found in 1938-39 (Junner) associated with the alluvial cassiterite in Mukuba lagoon near Mankwadzi.

Radioactive Minerals. Many of the graphic granites and smoky quartz veins found along the Accra-Winneba road show radioactive "highs". The best results are however obtained from the black sands which are found at various points along the coast between the Oyibi lagoon and Apam. The sands between Mankwadzi and Abrekum are particularly interesting although detailed prospecting showed them to be too limited to be of economic value. Fig. 81 gives the details of trenching in these sands.

A mineralogical examination by the Atomic Energy Division of the Geological survey of Great Britain proved the presence of the following minerals in the concentrate.

		Wt. per cent
Radioactive Minerals	Monazite	2.5
	Xenotime	tr.
	Zircon	9.0
	Cassiterite	0.5
	Rutile	4.0
	Garnet	10.5
	Ilmenite	60.0
	Magnetite	3.0
	Staurolite	8.0
	Calcite	1.0
	Chiastolite	tr.

The radioactivity of the concentr ate was proved to be almost entirely due to monazite whichassayed about 6.5 per cent ThO_2.

Wolfram and Scheelite. Both these minerals have been recorded from the gravels in Mukuba lagoon (Kitson 1930) The occurrence is of no economic value.

Silver. Silver was found in dykes associated with gold and arsenopyrite (Kitson and Wyllie 1913-14) The quantity by assay is very small.

Arsenic. Arsenkc occurs as arsenopyrite and appears widely in the Makwadzi locality. The occurrence is not of commercial importance.

Manganese. The principal occurrence of manganiferous rocks is in a small hill about ½ mile east of the Mukuba lagoon. The rock is principally gondite and on analysis showed only 11 per cent MnO_2.

20 b. Engineering Geology.

During the construction of the Winneba-Mankesim road quantities of non-plastic gravel were required for the base course of the road. In the absence of suitable alluvial gravels, it was found possible to use the mechanical weathering products of the Winneba granite and the eastern migmatite gneiss.

Occasionally concentrations of quartz pebbles and boulders were used for base course material. The principal localities where this was found were on the north side of the Winneba roundabout and near the village of Mpata. Generally however the quartz reefs and quartz boulders are worked only by local contractors to provide aggregate for concrete.

The granite in the district has only been quarried on a small scale. However the reason for this was probably that the location is inconvenient. Outside the limits of the sheet the same granites and gneisses have been quarried on a commercial scale at Obutu and Gomoa Assin. The products of these quarries were originally used largely for the road surfacing materials on the Winneba-Mankesim road.

At some points along the coast, notably near the Winneba Club bathing pool, the beach sands are excavated in considerable quantities and used locally as fine aggregate in concrete work.

In the Senya Beraku district where the Ojobi-Senya Beraku road crosses the Togo quartzites scarp the red gravelly cap of the quartzites provide a suitable material for maintaining laterite roads.

20 c. Brick and Pottery Clays.

Most villages have readily available clayey deposits which can be used for sun-baked bricks and the swish type of construction. The villages of Otaw and Enyadzi also carry on a thriving local industry in pots and clay vessels. The largest deposits of clay are certainly in the major lagoons but as far as it is known their suitability for use in ceramics has not been determined.

20 d. Water Supply.

At present only the town of Winneba is supplied by pipe-borne water from the Ayensu River. Recently however a survey was carried out by the Ghana Government to examine the possibilities of providing pipe-borne water for practically the whole of the Winneba-Swedru district. The source of the supply was again to be the Ayensu River near Swedru.

0 d 1. Water Supply in Areas of Birrimian Rocks.

The soils derived from the weathering of Upper Birrimian rocks are generally clayey and impervious. The underlying greenstones are also practically impervious except when strongly foliated, faulted or jointed. In view of the foregoing, surface water is more important than well water in are as underlain by Birrimian rocks. This is clearly seen at Mankwadzi, Otaw, Abrekum, Apam and many other places where ponds have been constructed to provide local supplies. In many villages also, tanks have been constructed to conserve rain water.

Many of the smaller villages obtain water from rivers for example the Pratu, the Brusheng and the Bumbi Rivers which although seasonal in flow retain water in sizeable pools for most of the year. Naturally in the eastern Birrimian locality the water supply problem is not serious because most villages are situated within easy reach of the Ayensu River.

20 d 2. Water Supply in Areas of Granitic Rocks.

In the areas underlain by granitic rocks the situation is quite different; this particularly applies in the eastern gneiss area and parts of the north-western granite area. In these localities the bed rock is covered by granitic sands and angular gravels which may or may not have clayey and lateritic layers. The fresh rock in these localities is usually impervious except where structural features allow percolation. Mostly the wells are sunk to solid rock through the pervious superficials, the bed rock acting as a sump for the water which seeps in laterally through weep holes in the concrete lining.

The wells are usually sited in low ground where the superficial cover is thicker and where probably the intake area is larger. It is felt that many of the sources tapped by these are of the reservoir type and liable to become exhausted during the dry seasons. Other wells sited in major valleys probably yield a steady supply at all seasons.

PART 3

FACTORS GOVERNING THE OCCURRENCE OF AMPHIBOLES IN AMPHIBOLITES.

CHAPTER 21.

EXPERIMENTAL TECHNIQUES USED ON THE GHANA ROCKS AND MINERALS.

Introduction.

In Part 2 of this thesis a description of the geology of the Winneba District of Ghana was given and a number of characteristic rock and mineral types were described. A selection of these rocks belonging to the Birrimian series have been analysed by the present writer. Their selection was based on two principal factors, namely:

1. Importance as a 'type' rock in the Birrimian Series.
2. Presence of characteristic amphiboles of the 'type' rock.

It was decided that as a general rule it was more important and useful to analyse 'type' rocks and 'type' amphiboles than to pick on the unusual and rare varieties which may occur.

21 a Procedure.

Ten rocks were selected on the above basis for investigation. Each rock selected was then ground to pass 90 mesh B.S. sieve and after a thorough mixing each batch was divided into two parts one for complete analysis and the other for the mineral separation process.

The method of separation of the amphibole was simple. It was found that material coarser than 100 mesh contained too many composite grains but that material finer than 150 mesh was difficult to handle and tended to clog in the magnetic separator and in the heavy liquids. Accordingly the sample for separation was further crushed and the batch between 100 and 150 mesh retained. The resultant powder from this crushing in an agate mortar was then washed to remove the dust and finally dried by washing in alcohol and warming slightly. Dust free samples are easier to handle in the separator and are more effectively separated in heavy liquids. Removal of water by washing in alcohol lessens the danger of oxidation of the ferrous iron.

After the above operations were complete, the sample, dry and free from dust, was rather bulky, containing quantities of feldspar, epidote and other minerals. Initial separation was carried out on the Cooke Isodynamic Separator using a side slope of 15° and a forward slope of 20°. This setting was found to be very satisfactory in the initial stages. The following standard procedure was used for the whole operation.

1. Highly magnetic material was separated by hand magnet.
2. The material was then passed through the separator at a low intensity field of 0.1 ampere. This removed material such as limonite, pyrite and some magnetite in inclusions.
3. The next step was to reduce the bulk of the sample by the removal of feldspar and quartz. This was done by passing it through the separator at 1.2 amp. reducing after several passes to 1.0 amp. intensity.

4. The field intensity of the separator was then returned to 0.4 amp. and several passes were made at this value to remove the ilmenite and hornblende-ilmenite grains.
5. The field strength was gradually increased up to 0.9 amp. and the fraction between 0.7 and 0.9 amps. was retained in all cases as containing by inspection the cleanest amphibole fraction.
6. The samples were then subjected to separation at various field intensities between 0.7 and 0.9 amps. Purity checks were made by the binocular microscope.
7. Final passes in the separator were made with a side slope of 25° and a forward slope of 40°. These settings appeared to give a sharper separation over a smaller range of field intensity.

The samples containing micas and diopside were found to be separated from these constituents cleanly although some composite feldspar and hornblende grains were left. These were removed by bromoform separation. Finally a certain amount of hand picking was done to remove epidote which had not been cleanly separated.

One of the major difficulties experienced was in the removal of ilmenite and magnetite from the cores of some of the amphibole grains. Fine crushing is not completely the answer to this problem for the reasons already given. In one case LY 534 the TiO_2 value is certainly much too high and this is clearly shown up in the re-calculation of the analysis into atomic proportions on the basis of 24 (O,OH,F). Re-calculation on this basis has been used for all the Ghana amphiboles so that they can satisfactorily be compared with other amphiboles from the literature.

21 b. Chemical Analysis.

The present writer, not an experienced analyst, was faced with an analytical programme of ten rocks and ten minerals. By normal classical procedure the analysis of these twenty samples would be a lengthy procedure. A scheme for the rapid analysis of rocks had been worked out by Shapiro and Brannock (1956) and had been tested to some length by Mercy (1955). This would evidently be very suitable for the rock analyses.

Most analysts apparently regard the rapid methods with some suspicion. The present writer finds this difficult to understand, particularly if proper control is maintained by the use of analysed standards. Furthermore there is the question of the value of and the reason for the chemical analyses. The present writer required the rock analyses to compare with those of other metabasalts and sediments analysed by many different chemists and in view of Fairbairn's (1951) work it would appear that accuracy would be of little advantage and the small inaccuracies of the rapid method would make very little difference to the interpretation.

In the case of the mineral analyses it is clear that the maximum accuracy possible should be attained. After considering the work of Mercy (1955) the present writer feels that the rapid methods by an unskilled operator, such as himself, are at least as goodas, if not better, than the classical methods for mineral analysis. It is important to note in this respect that the minerals analysed by the present writer correlate very satisfactorily with the physical properties and X-ray data. This can be well seen in Chapter 8.

The whole question of the accuracy and precision of the rapid methods of silicate analysis by the Shapiro and Brannock process as compared with the more classical methods has been investigated by E.L.P. Mercy (1955). To measure the accuracy of the rapid methods, Mercy analysed W1 and G1, the American diabase and granite standards (Fairbairn et al. 1951) and six dilutions of W1 in G1. The most probable values for the standards were taken to be the concensus of means given in U.S.G.S. Bulletin 980 Tables 19 and 20, and modified to include the revised figures for SiO_2 and Al_2O_3 (Fairbairn 1953). The analyses of the dilutions numbers 1 to 6 were calculated from these consensus means. The results of these calculations are given in Table 20. In this table column 'C' is important and shows the percentage difference between the classical and rapid methods for each oxide determined. Mercy gives the following summary, which has been abbreviated by the present writer, for the analyses within the range of composition for the two standard rocks.

SiO_2. The method is highly accurate. Single determinations show an average error of only ± 0.6% of the amount present. Maximum error is + 1.0% and -1.1% of the amount present.

TiO_2. Small error, about 3% of the amount present. The method is accurate.

Al_2O_3. Moderately accurate, average error ± 2.0% of the amount present with maximum deviations of +2.8% and -4.3%.

Total Fe. Accurate results, deviation only -1.7% of the amount present. With concentrations of 3.0% or less average deviation is only ±0.7% of the amount present.

FeO. Accurate results, deviations being only ±2.4% of the amount present. It should also be noted that the histogram for FeO in U.S.G.S. Bull. 980 shows an extraordinary wide variation for FeO for the diabase W1, in which case the consensus figure may be biassed.

Fe_2O_3. The error for this oxide amounts to 6.0% of the amount present. Reference to Table 20 of U.S.G.S. Bull. 980 shows that the arithmetic and consensus means for G1 and W1 differ by about 10% and 20% respectively. In view of this the accuracy of the determination of Fe_2O_3 by rapid methods is reasonable.

MnO. Accuracy is poor, but this is also the case in the classical methods (Bulletin 980).

MgO. Average error of ±2.0% of the amount present. The accuracy is very reasonable according to Mercy.

CaO. Error of ± 3.0% of the amount present. The accuracy is considered to be reasonable.

Na_2O and K_2O. Owing to the inaccuracies in the classical methods of determination comparison in this case is difficult. It would seem that the figures for the consensus means of the classical methods are somewhat low. The flame photometric method should be accurate to ±3.5% of the amount present.

H_2O. The accuracy of the method of water determination is poor.

Totals. The average deviation of the totals is only ±0.4%. This is very satisfactory indeed. The conclusion is that there are no strongly biassed errors in any of the methods.

Having discussed the accuracy of the rapid methods, Mercy (1955) then considered the precision with which such methods could be worked. 'Precision' he defines as the concordance of a series of measurements of the same quantity. In order to measure this, two rocks, one dioritic and one granitic were each analysed six times by rapid methods. It was found that SiO_2, total Fe, FeO, MgO, CaO, Na_2O and K_2O were all precise, whereas determinations of TiO_2, Fe_2O_3 and MnO were only moderately precise. As expected the determination of H_2O lacks precision.

Table 21 shows the comparison of the precision of the determinations of the data for standards G1 and W1. Bearing in mind the differences in method of analysis and the number of analysts, it is reasonable to conclude that the rapid methods give results comparable to those given by the conventional methods of analysis and in the cases of MgO, CaO, Na_2O P_2O_5 and total FeO the results are decidedly superior.

The analyses of the 20 Ghana rocks and minerals were carried out at the same time as 14 analyses of the rocks from the Connemara District of Ireland. All this work was carried out by the present writer in conjunction with Mr. J. Cobbing. The analytical procedure was the same as that laid down by Shapiro and Brannock (U.S.G.S. Bull. 1036-C 1956), although, in some cases, certain modifications were suggested by Mr. R.P. Hollingworth. These were adopted and are recorded as follows.

Solution 'A'. Fusion carried out using 13 pellets of NaOH, giving about the same quantity of NaOH as 15c.c., of S. and B. solution, instead of solution. This reduces the tendency to splash.

Silica. Only 1 ml. of tartaric acid was used instead of 4 ml. This allows the silico molybdate to remain more stable.

Solution 'B'. Lime. 10 ml. aliquots of solution 'B' were diluted to 100 ml.

2. Add 0.3 ml. of sodium potassium tartrate solution.
3. Add 0.1 ml. of murexide indicator solution.
4. Add NaOH until alkaline. Test with litmus.
5. Titrate with 1gm/litre E.D.T.A. solution, using a microburette in a spectrophotometer set at a wave length of 590μ

The reason for the revised lime determination was because the standard apparatus used by Shapiro and Brannock was not available. The scale was thus reduced by the above procedure by a factor of 5 thereby allowing the spectrophotometer to be used.

In all cases the analyses were run with checks by parallel analyses of an analysed sample of feldspar and an analysed sample of the Cleveland dyke. The analyses were done in duplicate and it was found that those of the Connemara rocks agreed very well with the published data for other similar rocks from the same locality. Also one analysis of a Nigerian Granite for Mr. Oyawoye carried out by the present writer and Mr. Cobbing agreed very well with an analysis, by classical methods, of the same sample by the Geological Survey of Nigeria.

A review of the results shows that the CaO contents by the rapid methods tended to be slightly higher and the MgO contents slightly lower than would be expected from standard analyses. In spite of any of these inaccuracies a significant feature of all the mineral analyses is that all of them can be satisfactorily re-calculated into atomic proportions. Mineral No. 542 on later inspection was found to be slightly impure containing small amounts of feldspar adhering to the small amphibole grains. The H_2O values in all cases are probably inaccurate being determined by the Penfield Method. Owing to the lack of suitable apparatus the fluorine content could not be determined.

21 c. Determination of the Physical Properties.

1. Refractive Index.

The refractive indices of all Ghana minerals were determined, with reference to sodium light, by immersion in liquids of known refractive index. All measured refractive indices were checked against the writer's graphs for refractive index determinations and found to be in good agreement. The accuracy of the determinations is ±0.0025.

2. Optic Angle.

The optic angle was measured in sodium light on the universal stage to an accuracy of ± 2 degrees. 2V was also calculated from the refractive indices and good agreement with the measured values was obtained in most cases. It was found that a refractive index error of ±0.002 could cause an error in the calculation of the optic angle of up to ± 7 degrees.

3. Specific Gravity.

Attempts were made to measure the specific gravity of single grains of amphibole by use of the torsion balance. For the most part this was unsuccessful. In view of this all measurements of this physical property were made by the pyknometer method. Boiled, distilled water to which a trace of Teepol had been added were used in all determinations. The specific gravity results obtained are quoted at 20°C.

All the data from the above measurements as well as that from the chemical analysis is recorded in Table 17 along with details of the optical orientation, the extinction angle, and the pleochroism.

In all cases the physical and chemical data for the Ghana amphiboles conforms with the graphs illustrating the correlation of physical and chemical properties which are given in this thesis. The single exception is the mineral LY 534 which shows exceptionally high alumina due to impurity.

CHAPTER 22.

FACTORS GOVERNING THE OCCURRENCE OF AMPHIBOLES.

Amphiboles occur principally in igneous and metamorphic rocks. In the latter Teall (1885) demonstrated the formation of hornblende from pyroxene in a metamorphosed dolerite dyke from Scourie Bay N.W. Scotland. The original dolerite contained andesine feldspar, augite, titaniferous magnetite, apatite and some secondary products including hornblende and chlorite. The analysis of the dolerite is given in (1) below.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MnO
(1)	47.45	1.47	14.83	2.47	14.71	8.87	-
(2)	49.78	2.22	13.13	4.35	11.71	8.92	0.27

	MgO	K_2O	Na_2O	H_2O	CO_2	Total
(1) cont.	5.00	0.99	2.97	1.00	0.36	100.12
(2) cont.	5.40	1.05	2.39	1.14	0.10	100.46

It is clear from Teall's original description that the rock was moderately coarse with the augite grains up to 1mm. in length and the feldspar grains twice this size. The typical analysis of the hornblende schist which is seen to shade into dolerite with almost imperceptible gradations (Teall) is given above as analysis (2). This is clearly closely similar to the original dolerite except that in the schist the silica is rather higher and so is the ferric iron. On the other hand the ferrous iron is somewhat lower. Teall suggests that the change from augite to hornblende goes with the conversion of Fe" to Fe"' this ould effect the liberation of silica which is often seen enclosed in the hornblende plates.

The hornblende schist is foliated and frequently banded showing individual grains considerably smaller than those in the original dolerite. The amphibole (hornblende) showed a definite pleochroism X - pale greenish yellow, Y - dark greenish yellow and Z - deep rich green. A quantity of sphene was also identified as associated with the titaniferous magnetite.

The relations of augite to hornblende in connection with crystalline schists are discussed by Irving (1883 and '84) and Williams (1884). The latter points out that augite appears to be the stable form at high temperatures and hornblende at low temperatures but that pressures clearly play a large part. It is of interest here to give a brief indication of the early literature on the conversion of pyroxenes to hornblendes.

Giekie: in "Nature Review" mentions Prof. Jukes suggestion that many areas of hornblende rocks may be due to "metamorphosis" of basic lavas and tuffs.

Darwin: in "Geological Observations" calls attention to the gradual passage from hornblende slate to greenstone.

Allport: in Q. J. G. S. (1876) greenstones which may be described as hornblende schists which may in their turn be metamorphosed igneous rocks such as dolerites or gabbros.

Phillips (1876) and Bonney (1883) also describe similar changes. The latter describing the Lizard district refers to a transition from hornblende schists to rocks resembling diorites. Similar work has been done on the continent by Lehman who described the passage of gabbro into schistose amphibolite and also by Runard Lasaulx and others who suggested that the amphibolite schists of the Ardennes have been produced by the mechanical metamorphism of diorite.

The above work was all done in the period pre-1890 and is now of historical interest only. It is important to note that this early work mostly deduced from field evidence, has confirmation in the structural form of pyroxene and amphibole-minerals. Warren (1929) showed that whole blocks of the tremolite and diopside structures were similar and that if the diopside structure in Fig. 4 was sheared along the plane R'R' so that the lower part is displaced by an amount a/2 + c/2 a structure which is essentially that of tremolite is produced. A further point of similarity is that appreciable aluminium sometimes occurs in high pressure pyroxenes (Rothstein 1957) and this is a common feature of high pressure amphiboles.

In the above it has been shown that pyroxenes convert easily into amphiboles on metamorphism. It now remains to discuss the factors which affect this transformation and the types of amphibole which can be produced. The hornblende series of the calciferous amphiboles are the most abundant of the amphibole family and it is proposed to discuss these types first and then the lime-poor and lime-free varieties and finally the alkali types are briefly mentioned.

22 a The Hornblende Series.

It has been shown earlier in Chapter 7 Fig. 30 that there are fields in the hornblende system in which few or no hornblendes occur. These are principally in the tschermakite and edenite fields. In the case of the former the Carnegie Institute (1953-54) showed that at extreme pressure (800°c and 10,000 bars) amphiboles could be made whose composition extended at least half way between tremolite and tschermakite. Highly aluminous amphiboles of this type do not appear to have a stability field as low pressures. The aluminous phase obtained by crystallizing a glass of tschermakitic composition, hydrothermally above about 500°C, is anorthite. It is interesting to note that the co-ordination of the aluminium in anorthite is four fold and in tschermakite it is partially four and partially six fold. The suggestion by Wickmann (1943) and Thompson (1947) that six fold co-ordination in aluminium is a condition of high pressures would thus appear to be substantiated experimentally. This point will be discussed later.

With regard to edenite, although minerals of this composition appear to be easily synthesized (800°C and 400-1000 bars pressure) they are not common in the natural rocks. The present writer suggests that the reason for this is that in the natural rocks alumina and soda are generally present in quantities which would allow the formation of pargasite or near pargasite minerals in preference to the Al/Na poor pure edenites. Where the alumina content is low there is also a tendency for the soda content to be low and tremolites or near tremolites are formed.

In the case of tremolite it has not been possible to grow this mineral at less than 400 bars pressure. Below 500 bars metastable assemblages such as quartz and cristobalite together and a single pyroxene solid solution make their appearance. The reaction which is reversible is as follows (Carnegie Inst. Rep. 1954-55):-

$$\text{Tremolite} \rightleftharpoons 3\ \text{Enstatite} + 2\ \text{Diopsite} + \text{quartz} + \text{vapour.}$$

Experiments at 1000 bars and 900°C show a poor yield of tremolite. This is much improved when the pressure is increased up to 2000 bars.

Fig. 82 from the Carnegie Institute report shows the break down curve for synthetic tremolite. It was found also that natural tremolite agrees with this very well. At pressures below 1000 bars they will not break down until the temperature is raised some 40° to 50°C above this curve.

It is apparent from the foregoing that tremolite will be stable to high metamorphic grades, even under low pressures, in assemblages of minerals with which it will not react. The disappearance of tremolite at low metamorphic grades during progressive metamorphism is due to its reaction with other phases, usually carbonates. The temperature at which such reactions take place will be a function of the $P.CO_2$ as well as the $P.O_2$.

The question of fluorine in the hornblende series is an important one and should be discussed here. The Carnegie Institute Report (1953-54) states that the fluor amphiboles can be readily crystallized by heating charges in sealed platinum tubes at temperatures of little over 1000°C. Tremolite, edenite, pargasite, and tschermakite have all been made in this manner. The effect of the substitution of fluorine for the hydroxyl group is generally to increase, markedly, the stability range of the amphibole. This point is very important and will be considered in relation to the natural minerals. Presumably owing to the ease of formation of the synthetic fluor amphiboles the presence of high fluorine in natural rocks would tend to facilitate the formation of amphiboles and possibly render them stable over much greater ranges of temperature and pressure.

The Carnegie Institute Geophysical Laboratory found that pargasite was much easier to synthesize than tremolite. The composition of pargasite was found to fall into a six component system and the break-down relations are correspondingly more complex.

Pargasite Aluminous Diopside + Nepheline +
forsterite + anorthite + spinel + water.

In the above equation the dominant break down products are underlined. The addition of soda and alumina to tremolite to form pargasite increases the stability range of the amphibole. For example, at 1000 bars water vapour pressure tremolite is stable up to 933°C but at the same pressure pargasite is stable up to 1050°C. The high temperatures of these amphibole break down reactions are in accordance with the occurrence of these types of amphibole as phenocrysts in lavas and their persistence to a high grade of regional metamorphism. The higher stability of pargasite relative to that of tremolite would apparently reflect the tendency of natural amphiboles to take up soda and alumina on increasing grade of metamorphism.

The whole question of the stability of pargasite at varying temperature and water pressure was investigated and reported in the Carnegie Institute Report (1955-56). The diagram from this report is reproduced here Fig. 84, and consists of three phase boundaries which intersect at the invariant point 'd'. The compositions of the various phases are marked and it can be seen that the stable phase assemblage is bounded by the phase boundaries 'A' and 'B'. The invariant point is situated at 1025°C and 800 bars H_2O. At greater pressures pargasite heated at constant pressure, melts incongruously to aluminous diopside, forsterite, spinel, liquid and vapour. The Carnegie Institute found that the stability field of pargasite extends to higher temperatures than any other investigated hydrous silicate except the magnesian mica phlogopite. At 1000 bars (H_2O) the stability limit of pargasite is intersected at 1045°C. Yoder and Eugster (1955) found that under the same conditions of pressure the stability limit of phlogopite extended to the same temperature.

It was concluded from the above experimental data that the mineral assemblages augite - hypersthene - plagioclase and hypersthene plus potash feldspar, which are the anhydrous chemical equivalents of hornblende and quartz and biotite and quartz make their appearance in the granulite facies at roughly the same metamorphic grade.

In the case of the natural rocks the diagram Fig. 84 reflects the relationships amongst certain mineral facies in igneous and metamorphic rocks. Common hornblendes are often found as phenocrysts in lavas as well as in plutonic rocks. The Carnegie Institute Report (1955-56) states that the physical conditions under which the hornblende bearing magmatic rocks were formed are such that if these conditions were to be projected on to the T-PH_2O plane the fields comprising the amphibolite facies and the magmatic facies must directly adjoin one another. The report goes on to say that there are metamorphic rocks whose bulk compositions are such that they could contain hornblende but which are in fact made up of anhydrous phases. These rocks are usually grouped in the pyroxene hornfels or pyroxene granulite facies. It is stated that on the T-PH_2O projection these two pyroxene facies must lie in a position intermediate between the amphibolite and the magmatic facies.

In Fig. 84 the stability field of the pargasite corresponds to the amphibolite facies. In the region above the boundaries 'B' and 'C' a liquid phase is stable and this is the region which corresponds to the magmatic facies. The two fields are in contact along the curve 'C' along which pargasite is stable in association with the melt thereby reflecting the occurrence of hornblendes as phenocrysts in lavas.

In the T-PH_2O field bounded by the curves 'A' and 'B' neither the amphibole nor the melt can exist as the stable phase. This region corresponds to the two pyroxene fields mentioned above. Thus the pyroxene facies represents conditions of low vapour pressure and in the system illustrated here the vapour pressure must be less than that of the invariant point (800 bars) for the sub-solidus pyroxene to be stable at all.

It is clear from Fig. 84 that the presence of excess silica in the reactions would considerably affect the amphibole boundary curve. The Carnegie Institute found (1955-56) that if an amount of silica in excess of that required to saturate all the break down products is added to the pargasite composition the phase assemblage above 1000 bars at 900°C becomes diopside - enstatite - labradorite and quartz and the phase below 900°C changes from pargasite to near tremolite. Pargasite thus appears to have no stability field in the presence of excess silica.

The Carnegie Institute investigated this point in connection with the natural rocks and found that all the analysed natural magnesian pargasites come from under saturated rocks and furthermore a number of magnesian calciferous amphiboles from high grade regional metamorphic assemblages, which included plagioclase and quartz, were checked and found to be near tremolite in composition. In the case of the iron rich members of the pargasite-hastingsite series it is found that they are typically present in pegmatites and granites in association with quartz (confirmed by the present writer see Figs. 88 and 89) this would suggest that the Fe/Mg ratio in a silica saturated rock may well control the amount of soda and alumina an amphibole growing in such a rock could absorb.

In the foregoing paragraphs the experimental data for the conditions of occurrence of the calciferous amphiboles has been analysed and good reasons have been given for the scarcity of the members of the edenite and tschermakite series. The relationship of tremolite to pargasite has been examined in some detail. It is clear from the experimental work that tremolite can exist at relatively high metamorphic grades given the appropriate conditions. The presence of absence of excess silica is also demonstrated to be a controlling factor in the formation of pargasite during increasing metamorphism. It is proposed to deal more briefly in the following paragraphs with the lime-poor and lime-free amphiboles.

22 b. The Lime-Poor and Lime-Free Amphiboles.

An investigation of both these types of amphibole was carried out simultaneously by the Carnegie Institute (1954-55) The examination was done at a pressure of 1000 bars (H_2O). The components appear to have been in all cases lime free and both cummingtonite and anthophyllite were claimed to have been synthesized during the experiments. No X-ray data were given in support of these claims. The synthesis was found to be easier in the more iron rich portion of the field and it is here that the most fibrous of the anthophyllites were produced. It was in these experiments that it was found that a cummingtonite more magnesian than $Mg_{85}Fe_{15}$ could not be produced. This point has already been discussed in Chapter 5. It is important to note that cummingtonite could only be synthesized at temperatures above 800°C and close to the break down interval. Orthorhombic amphiboles were produced in the same composition range but at lower temperatures.

The present writer suggests that there is here a close parallel to the enstatite - clinoenstatite series in which the clinoenstatite is only stable at high temperatures and that the clino-amphibole synthesized at temperatures above 800°C is in fact clino-anthophyllite and not cummingtonite which the present writer has shown must have calcium in its structure. Below 800°C the stable phase is ortho-anthophyllite in the same way as the low temperature pyroxene is ortho-enstatite.

All the experimental work on the amphiboles of this type produced these minerals in association with hypersthene, which in all cases was richer in iron than the associated amphiboles. It was also found impossible to produce amphiboles richer in iron than Mg50 Fe50. Bulk compositions richer in iron than this yielded in all cases amphiboles of the above composition together with fayalite and quartz. This same relation persists into the hypersthene field where hypersthene fayalite and quartz are produced.

The Carnegie Institute Report describes a peculiar state of affairs. The most abundant natural phase of the cummingtonite series is grunerite or near grunerite which cannot be synthesized in the manner described. The present writer would draw attention at this point to the findings of Rabbitt who showed that there existed a field of imniscibility at the iron end of the anthophyllite series. The results of this experiment would clearly be in agreement with these findings. The mineral synthesized is clearly a clino-anthophyllite and not a cummingtonite.

The report points out that the magnesian amphibole end member is meta-stable in the T-PH_2O range in which it was synthesized. The more iron rich minerals are rather more stable. It has also proved impossible to crystallize amphiboles from hypersthene and quartz. It is clear from the foregoing that the presentation of this system in the manner suggested by the Carnegie Institute does not represent the true state of affairs existing in the natural rocks. The present writer would suggest that a small quantity of calcium be added to the batches in just sufficient amount to prevent the formation of tremolite but enough to cause the lime-poor cummingtonite to form along with the anthophyllite phase and so represent conditions similar to the Montana rocks of Rabbitt.

22 c. The Alkali Amphiboles.

As far as the present writer can ascertain the only experimental work on these amphiboles has been done with reference to the glaucophane-riebeckite series. Fig. 85 from the Carnegie Institute Report (1957-58) illustrates the results of the experimental work on this series. The invariant point where all phases co-exist is found at 867°C and 1500 bars pressure. It is clear from the diagram that glaucophane synthesized under the conditions shown here is not entirely a high pressure mineral. It is intended to discuss this point more fully in the next chapter.

CHAPTER 23.

THE NATURAL OCCURRENCE OF AMPHIBOLES.

In the previous chapter some of the early work on the conversion of pyroxene into amphibole and some of the more recent experimental work on the physical and chemical conditions required to produce the various types of amphibole, were discussed. It is proposed in the current chapter to show how this experimental work can be related to the natural environments of the amphibole group of minerals. Although the writer's principal interest in this section is the calciferous amphibole series and in particular the hornblende series, which is to be discussed in relation to the rocks and minerals of the Birrimian series of the Winneba District of Ghana; it is intended to discuss briefly the natural occurrence of the other major amphibole series. These will be dealt with first.

In this chapter the use and limitations of the term 'amphibolite' are discussed. The way in which this term is used in the description of the Ghana rocks is defined.

23 a The Alkali Amphiboles.

The occurrence and paragenesis of the alkali amphiboles was discussed at some length by Miyashiro (1957). In the first instance, some attempt was made to show the relationship between chemical composition and occurrence by means of the two axis diagram Fig. 33 in which Si and R"' (in atomic proportions) are plotted against one another. This graph shows a rough division of the alkali amphiboles into igneous and metamorphic types.

Broadly all the riebeckite, glaucophane and richterite minerals are metamorphic but there are a number of exceptions.

A further diagram from Miyashiro Fig. 86 shows the relationship of R" and R"' to the occurrence of these amphiboles. It can be seen that it is also possible, on this basis, to distinguish between the igneous and metamorphic alkali amphiboles. In view of the remarks in the previous chapter concerning the occurrence of glaucophane in high pressure rocks and the experimental conditions which govern the appearance of this mineral, these sub-divisions of Miyashiro may not be as clearly defined as might first appear.

Miyashiro points out that as the value of CaR"Al increases the temperature of the formation of the minerals of the series become higher. This is clearly shown in Fig. 86 where the igneous field represents the highest temperature zone. The katophorites from volcanic rocks are the typical representatives of this zone. Miyashiro regards this graph as a useful temperature indicator in the petrology of the alkali amphibole bearing rocks.

In the case of riebeckite, laboratory experiments at the Carnegie Institute (1957-58) indicate that its stability limit at 2,000 bars pressure lies between 600° and 700°C and that the break down products are fayalite, magnetite, quartz and acmite. Miyashiro states that it has been claimed that riebeckite occurs in quartz bearing alkalic rocks whilst arfvedsonite occurs in nepheline bearing ones and that the degree of silica saturation is the factor which determines which of the two amphiboles will be formed. This does not appear to be altogether the case, riebeckite can form in nepheline bearing rocks (Nos. 6 and 9 in Table 13) when the temperature is low. There is also the classic case of arfvedsonite occurring in the Greenland soda granites. The experimental evidence does seem to indicate that a saturated environment is more likely to produce riebeckite rather than arfvedsonite.

In general riebeckite occurs in alkalic igneous rocks, granites and syenites, as well as in crystalline schists and metamorphosed iron-stones. The metamorphic riebeckites usually appear to have a larger R"' value than the igneous ones. Magnesio-riebeckite on the other hand is rare in igneous rocks but is common in crystalline schists and other metamorphosed rocks. In the case of glaucophane all the minerals of this type recorded in Miyashiro's (1957) paper occur only in crystalline schists and associated rocks. Dr. Emeleus of Durham University has drawn my attention to the occurrence of glaucophane in a nepheline syenite from south-west Greenland. The appearance of glaucophane in such an environment is uncommon but that it is clearly possible is indicated by the experimental conditions described in the previous chapter. In general, however, glaucophane is regarded as a high pressure mineral and the reasons for this are as follows.

1. Glaucophane schists are more dense than parent sediments lavas and typical metamorphic rocks.
2. Many glaucophane schists are chemically equivalent

to green schists and amphibolites.

3. Glaucophane schists are developed on a regional scale in some areas.

4. Jadeite, experimentally demonstrated to be a high pressure mineral has been found in certain glaucophane schists. In other cases glaucophane schists have developed in areas adjacent to serpentinites.

With reference to the conditions of formation for members of the glaucophane-riebeckite series, it is found that riebeckite and magnesio-riebeckite have a large excess of alkalis over the alkali/alumina ratio of the alkali feldspars. This would indicate that their formation would be promoted under conditions of excess alkali present in the parent rocks. The two principal cases of this would be alkali metasomatism or the alkali igneous rocks and their metamorphic derivatives. In so far as the chemical considerations are fulfilled riebeckite and magnesio-riebeckite probably form under both high and low pressures and generally at low temperatures.

In the case of glaucophane no excess alkali is required for its formation and the necessary alkalis can readily be supplied from albite. Broadly, Miyashiro (1957) stated that under very high pressure and low temperatures any members of the riebeckite glaucophane group may form, its composition depending on that of the host rock. At lower pressures and/or higher temperatures the possible compositions become riebeckite or magnesio-riebeckite only.

The occurrence of the arfvedsonite series is restricted only to the alkaline igneous rocks commonly in the nepheline syenites but more rarely in syenites and the quartz bearing rocks. Magnesio-arfvedsonite has a similar mode of occurrence to its iron rich counterparts.

The katophorite series is the most decidedly igneous amphibole of the whole group. It occurs in theralite, shonkinite and trachyte and is frequently associated with sanidine.

The occurrence of richterite appears to be somewhat variable. It usually occurs in metamorphosed limestone and jadeite rock. Examples have also been found in hydrothermally altered rocks associated with alkaline igneous rocks.

23 b. The Anthophyllite Series.

All the anthophyllite minerals recorded by Rabbitt (1948) occur either in the pre-Cambrian or the paleozoic. The present writer has not fully examined the mode of occurrence of this amphibole but Rabbitt's table shows that the general association of the anthophyllite minerals is with garnet, cordierite and staurolite in amphibolite and gneiss. Occasionally anthophyllite occurs with cummingtonite and hornblende although at Mysore (India) it is found with cordierite and hypersthene.

The anthophyllites in some cases appear to be associated with serpentines and talc. They are also found in close association with dunites. It is significant that few of the orthorhombic amphiboles found in such connections have high alumina contents. This point is to be discussed more fully later in this chapter.

23 c. The Cummingtonite Series.

It will be shown in the following section that the appearance of cummingtonite indicates increasing grade of metamorphism. In some of Rabbitt's Montana specimens this mineral is found in association with anthophyllite and staurolite. The association cummingtonite and hornblende is more usual and more interesting from the mineralogical point of view. It is interesting to find that the cummingtonite from Muruuvesi, Finland is intergrown with hornblende. This is of considerable significance when considered in relation to the discussion in Chapter 5.

The experimental work on the cummingtonite and anthophyllite series, discussed here, cannot be used for reasons outlined in the previous chapter. There clearly remains a considerable field for further investigation into the paragenesis of these two minerals.

23 d. The Hornblende Series.

The hornblende minerals are one of the most common constituents of metamorphic rocks. Under favourable conditions they may be stable from the green schist facies to the lower part of the granulite facies. Wiseman (1934) noted that there were distinct differences in the characters of the amphiboles of the garnet grade and those of the chlorite and biotite grades of metamorphism in the Grampian Highlands. The refractive indices of the majority of the amphiboles from the garnet zone are in general higher than those from the biotite and chlorite zones. The total Al as well as the aluminium replacing silicon and the Fe content is greater. This is in good agreement with the experimental data given in the previous chapter.

Wiseman also described a colour change in the hornblendes with advancing grade of metamorphism, thus:

Pale green → Blue green → Green
Chlorite-biotite zone   Garnet zone   Sillimanite zone

Eskola, Barth and Correns (1939) suggested that the change of actinolite to common hornblende takes place in the epidote amphibolite facies. This change was to be used as a sort of geological thermometer. The present writer suggests that in view of the experimental evidence given in the previous chapter, the presence or absence of quartz should be specified because in silica saturated rocks, tremolite minerals are more stable than the pargasite phase. The present writer will show that in the Ghana amphiboles actinolite amphibolites are stable well into the amphibolite facies.

Shido (1958) in his discussion of the plutonic and metamorphic rocks of Nakoso and Iritono, Japan, divides the metamorphic area into four zones representing progressive metamorphism in response to rising temperature. These zones are as follows:

A. Characterised by actinolite in basic rocks and the commonest type of basic rock is epidote chlorite actinolite schist.

B. Characterised by blue green hornblende. The commonest types of basic rocks are epidote blue green hornblende schist and blue green hornblende schist.

C. Distinguished from zone B by the presence of brown hornblende and from zone D by the absence of ortho-pyroxene. The commonest types of basic rocks are brown hornblende schist and clino pyroxene brown hornblende schist.

D. Characterised by the presence of ortho pyroxene. The commonest types of basic rocks are ortho and clino pyroxene and brown hornblende schist and a similar schist but with the presence of cummingtonite.

Shido claims that the 'Z' axial colour of the hornblendes changes, very sensitively, with the increasing grade of metamorphism. He shows the changes in colour for the zones indicated above as follows:

Zone A.	—— 50/50 ⟶	Zone B ⟶	Zone C
Actinolites Z colourless Pale green	Pale green | blue green boundary	Common hbde. Z=bluish green to greenish blue	Common hbdes. Z=green or brown. Brown= highest grade clino-pyroxene.

↙

Zone D

Appearance of O-pyroxene cummingtonite.
Z=brown in hornblende.

The present writer can find few differences in the chemical analyses of the amphiboles from zone 'C' and 'B'

(Tables 22 and 23). In general the amphiboles of zone 'C' have rather higher titania and alkali content than those of zone 'B'. No reason for the differences in colour of the amphiboles in the two zones was given by Shido but the present writer suggests that the change in colour must be related to the titania content which is generally higher in zone 'C'. There are however other factors which would appear to have some effect. Analysis No. 10 contains 1.7% TiO_2 and is the third highest quoted for the two zones and yet the mineral is coloured blue green and is in the lowest grade. The 'Y' axial colours do seem to show the influence of high TiO_2 and in the case of No. 10 'Y' is yellow brownish green. Fe_2O_3 is generally somewhat higher in the blue green amphiboles of zone 'B' and the combination of TiO_2, Fe_2O_3 and the FeO/MgO ratio has been found by the present writer to settle the relationship of colours to composition in this particular case. This is demonstrated by Fig. 87. From the foregoing it would appear that the increasing grade of metamorphism shows a concomitant increase of FeO and TiO_2 and that the proportion of Fe_2O_3 tends to become somewhat smaller.

This suggested increase of the FeO content with increasing metamorphism is to some extent supported by Figs. 88, 89 drawn by the present writer. This increase in the iron content also takes place at the same time as a change in state of the amphibole from the tremolite types to the hastingsite types. Figs. 88, 89 demonstrate that this is clearly independant of the quartz content of the original rock. The hastingsite minerals do occur in silica saturated rocks although pargasites are rare in such environments (the normal amphibole is tremolitic). It would appear that the Fe/Mg ratio exerts a controlling influence on the amount of aluminium and sodium an amphibole can absorb in the presence of excess silica.

In the case of the Na and K contents of amphiboles under increasing metamorphic grade Shido (1958) attempts to show by a diagram Fig. 90 that the alkali content increases with increasing grade. The present writer considers that this diagram does not give conclusive proof of this. In fact amphiboles numbers 10, 9, 5, and 2 have very nearly the same alkali content but are found to be spread over practically the whole range of the metamorphic zones. Although Shido concludes that hornblendes in rocks free from quartz would have larger alkali contents than hornblendes in quartz bearing rocks of the same grade, he seems to have missed the point indicated by the experimental work described in the previous chapter which shows that near actinolite members in amphibolites containing free quartz could well exist in zone 'B' or even possibly in the lower part of zone 'C'.

The present writer would point out here that this story is not complete and that even under conditions of advancing metamorphism Na ions will not enter the structure unless the valency balance of the structure is maintained by the introduction of aluminium. In the presence of free quartz this clearly does not take place.

In support of his suggestion of increasing alkali content with increasing metamorphism, Shido re-allocates the

the various atomic proportions calculated from the amphibole analyses to a series of special end members. These end members are given in Table 24 and are derived by assuming that when the 'Y' group is greater than 5.0 the balance is included in the eight co-ordinated position with Ca and/or Na. It is also suggested that when Ca is in excess of 2.0 atoms then some Ca must be present in the vacant space. It is claimed that the entrance of Ca into the vacant space is balanced by the replacement of silicon to maintain electrical neutrality.

The present writer is not sure whether these premises are valid. In the first place there is evidence that when MgFe enter the calcium position there is a slight re-arrangement and the calcium positions become 6 co-ordinated and the anthophyllite not the cummingtonite structure is formed (This thesis Chapters 1 and 5). The present writer realizes that this may not be necessarily so at high temperatures. Further no known amphiboles have compositions in the 'X' group of Ca_3 on the other hand Na_3 is in fact an end member. It is appreciated that minerals such as katophorite contain both Na and Ca in the 'X' position but even in this case the Na is probably largely in the vacant space and the Ca in the proper position in the monoclinic lattice and will gradually be replaced by Na. Thus we have the position where monovalent elements can enter the vacant space or the Ca position but it is very rare for the divalent Ca to enter the monovalent position. Hallimond's table (Table 9) shows that amphiboles even approaching the calcium edenite composition of Table 24 are extremely rare.

When the atomic proportions are allocated to these Shido molecules much depends on the order in which this is done. Shido makes the allocations in the order given in Table 24 - the selected order is sympathetic to Shido's system of grading the metamorphic zones. The calculated molecules are given in Table 25. It can be seen that the soda tremolite molecule is more abundant in zone 'C' than in zone 'B' and it is for this reason that Shido considers that there is an increase in Na and K with increasing metamorphism.

In discussing the appearance of cummingtonite Shido stated that this may happen more readily in hornblendes associated with quartz than in those not associated with free silica. The equations given here were worked out with reference to the tschermakite 'molecule' content and that the appearance of this molecule which decreases in quantity with increasing grade is in harmony with the crystallo-chemical considerations in which the aluminium changes from 6 co-oridnation in tschermakite to 4 co-ordination in feldspar.

$7\ Ca_2\ Mg_3\ Al_2\ Si_6\ Al_2\ O_{22}\ (OH)_2$
Tschermakite
$+ 10SiO_2 \rightleftarrows 14\ Ca\ Al_2\ Si_2\ O_8$
Anorthite
$+ 3Mg_7\ Si_8\ O_{22}\ (OH)_2 + 4H_2O$
Cummingtonite

$Ca_2\ Mg_3\ Al_2\ Si_6\ Al_2\ O_{22}\ (OH)_2$
Tschermakite
$+ SiO_2 \rightleftarrows 3Mg\ SiO_3 + Ca\ Al_2\ Si_2\ O_8 + H_2O$
Orthopyroxene
Anorthite.

Harry (1950) showed statistically from Hallimond's (1943) tables that the highest temperature hornblendes were richest in 4 co-ordinated aluminium. Shido on the basis of 10 analyses claims that this is not so and that the contents of Al(4) have no systematic relationship to the grade of metamorphism and further that the average Al(4) value of zone 'C' is lower than that of zone 'B'. An inspection of Table 23 shows that they are in fact very close together.

The present writer suggests that because the two sets of zone analyses are very similar and that the pleochroic colours of zone 'C' have touches of green and yellow and that those of zone 'B' have touches of brown (No. 9) the metamorphic index of the two grades must be very similar or very close to one another. The colour distinction test would therefore appear to be a critical one. It seems clear that the incoming of biotite and the two forms of pyroxene are also essential critical index minerals.

At this point it is necessary to discuss the miscibility gap between the common hornblendes and the tremolite series. In Chapter 7 it has been shown that there are good reasons for the assumption of a miscibility gap between the pure tremolites and the pure pargasites but there is miscibility in the higher iron ranges between the two series. It now remains to consider the significance of these relationships from the point of view of amphibole paragenesis. The point is an important one because the amphiboles of the low grade meta-volcanics generally lie on the tremolite-pargasite join.

Shido (1958) found that in the central Abukuma region the change from actinolites of zone 'A' to the hornblendes of zone 'B' was abrupt. The reasons for this conclusion were given as follows:

1. The boundary between the actinolite core and the hornblende periphery in zoned crystals appeared to be sharp in all cases, with increasing grade the core becomes smaller and finally disappears without losing the sharpness of the boundary.

2. That the Ng index of the co-existing blue green hornblendes from the transitional part of the zones between 'A' and 'B' are in definite relationship with the Ng index of actinolite. It is claimed that this indicates that the two amphiboles were probably in equilibrium with each other at these metamorphic grades.

This evidence is supported to some extent by Compton (1958) who stated that the conversion of actinolite to hornblende takes place abruptly in the outer zone of the Bidwell Bar (California) metamorphic aureole. Turner (1948) states that amphiboles of the Otago (New Zealand) region support the concept of gradual conversion of actinolite to hornblende during progressive metamorphism. The amphiboles studied by Wiseman (1934) provide additional evidence and show a progressive increase in Al in the 'Z' position as the metamorphic grade increases. Further evidence is from the classical area of the southern Highlands of Scotland (Barrow 1912) and Tilley 1925), where composition changes from green schist actinolite to the two hornblendes of the epidote amphibolite of the garnet zone are distinct. Compton points out that these garnet zone amphiboles are not much more aluminous than Hutton's chlorite 4 sub-zone amphiboles and that they are less aluminous than the hornblendes of the typical epidote free amphiboles of comparable areas. It is suggested by Compton that these garnet zone hornblendes fit exactly into the serial change from green schist through epidote amphibolite to amphibolite conditions, thus further supporting the view that the reactions of actinolite to hornblende are continuous.

In the above discussion there are two conflicting views. Firstly Shido with the non-continuous actinolite-hornblende reaction and secondly Compton with the postulation of a continuous reaction between the two series in some cases. Compton suggests that the two states may be brought about by the different reaction rates and differences in dehydration.

The present writer suggests, after a consideration of the literature that a non-continuous reaction series must exist in cases where the members of the two series have more than 90% Mg in the 'Y' position. This would be in line with the findings in Chapter 7. With increasing temperature amphiboles will take up iron into their structure. There are many examples of this particularly in the hastingsite pargasite series. It has also been demonstrated by the present writer, Fig. 30, that there is a more or less continuous solid solution series from iron-poor actinolite to common hornblende particularly in the magnesio-hastingsite part of the field. Thus it would be expected that if there is iron available the tremolite minerals will take up iron on increasing metamorphism and under the appropriate conditions set out in Chapter 22 will convert continuously to pargasite or magnesio-hastingsite. Some evidence for this suggestion is available, the actinolites from the Start District of Devon (Tilley 1938) contain a considerable amount of iron and occasionally show a distinct blue green element in the 'Z' absorption colour.

23 e <u>The Paragenesis of the Birrimian Amphiboles of Ghana.</u>

It was clear from the field work that many of the Birrimian amphibolites were originally porphyritic or vesicular lavas and tuffs now metamorphosed to the garnet grade. Intercalated with the lavas, and of uncertain origin are the fine to coarse grained actinolite schists. The present writer has plotted on Fig. 91 the positions and 'Z' axial colours of the various amphiboles recorded from the area mapped and described in Section 2. It can be seen that the region of dark blue green amphiboles is a wedge-shaped area near the core of an antiform which also includes the Winneba gr anite and the pneumatolytic mineralization of the Mankwadzi area.

Some of the details of the metamorphism of the Winneba District have already been discussed in Section 2, 12. In Section 2 definitions of the terms amphibolite and hornblendeite as used in the field decription were given. The definitions fit very broadly with the classification of the amphibolites given by Loewinson-Lessing (1905). There are however small notable differences and these are listed as follows:

1. The collective term for a dominantly hornblendic meta-

morphic rock is amphibolite. When the rock is monomineralic, or almost so, the terms hornblendite or actinolite amphibolite, as the case may be, are used.

2. When quartz is present in the rock the term quartz amphibolite is used.
3. When feldspar is present the term feldspar amphibolite is used but if quartz and feldspar are present together both terms are used in the description. The reasons for this are clear from the previous paragraphs of this chapter.
4. Where the structure is schistose or gneissose this is referred to in the description but the term amphibolite is maintained until the degree of schistosity is thoroughly visible in hand specimen without the use of a lens. This type of rock is then called an amphibole schist with exactly the same qualifying terminology as in the case of the amphibolite.

The rocks of the Birrimian series of the Winneba District belong largely to the epidote amphibolite facies with some green schist facies in some localities and in the south and south-east the amphibolite facies is reached. A significant feature is the presence of the tremolite schists and amphibolites from the lowest (schists) to the highest (amphibolite) grades of metamorphism.

In general, the classification of Shido (1958) is well illustrated in the Winneba District. Fig. 91 shows diagrammatically the increasing colour of the amphiboles from the north rowards the Mankwadzi district in the south. Pyroxene appears to enter the rocks in a somewhat patchy fashion but this is probably due to the presence of the granitic body at shallow depth in the area around Winneba town. The change in colour of the amphiboles of the Winneba District is given by the following scheme:

<u>North and N.W.</u>

Pale tremolite-actinolite
Schists LY 109
Actinolitic hornblende
blue green from meta-
basalts
Mixed colours in the
same rock

Tremolites rimmed
→
by hornblendes in
Yenku block

<u>South and S.E.</u>

Coarse actinolite
tremolite amphibo-
lite + schists.
Vesicular lavas LY 542
Dark blue green
amphibole

↙

<u>Extreme South and South-East</u>

Coarse actinolite amphibolite with
mica and clino-pyroxene LY 486
(Ghana slide) amphiboles meta,
basalts and dolerites all amphiboles
dark blue in colour LY 313, 308

A summary of the positions of the important amphiboles and their 'Z' axial colours is given at the end of this Chapter.

It can be seen that there are some differences from the basic classification of Shido. The first and most striking is the persistence of tremolite and actinolite into the highest grades. This mineral can be seen changing directly into pyroxene in the actinolite amphibolites. This is in agreement with the experimental findings that tremolite-actinolite can persist to the highest grades particularly when minerals with which it would react are absent. Quartz is usually present in these rocks and according to the experimental evidence this would inhibit the formation of the aluminous amphiboles. The principal effect on the actinolite schist of increasing grade of metamorphism is the change in texture from a fine schist to a coarse almost monomineralic amphibolite.

The second difference from the Shido scheme is that in the Winneba District there appears to be two distinct varieties of blue green 'Z' absorption colours. In the lowest grades, the paler blue green amphibole may exist in rocks intercalated with pale to colourless tremolite schists. Indeed in some cases particularly in the Pratu river section the two amphibole colours may exist in the same rock. A similar instance is found in LY 485 an actinolite amphibolite where in one case the iron has been absorbed by the tremolite to form actinolite and in the other it forms nets in the centres of the colourless grains.

In the south and south-east of the district the blue green colour is replacd by a dark blue green colour which then becomes more decidedly green with the incoming of biotite and clino-pyroxene. The brown hornblende of the highest grades of Shido is not seen in the Winneba District.

The significance of the presence or absence of free silica as quartz is well demonstrated in the Winneba District LY 308 and LY 313 both contain amphiboles of pargasitic composition, quartz does not appear in either of these rocks. In other cases the amphiboles still assume deep bluish green tints but their compositions are near that of actinolite. No. 20 is a good example of this case.

1. Summary of the Occurrence of Amphiboles in the Winneba District.

North-Western Greenstone Series: Akwapim River.	Pale coloured actinolite in schists and pale actinolite with greenish blue hornblende in amphibolite. Two colours in the same rock.
Pratu River:	Amphibole occurrence similar to Akwapim River.
Central Greenstone Series: North.	Pale green actinolite-tremolite schists + calcite present. No iron ores present. (LY 109) Epidote-Feldspar quartz amphibolites show blue green hornblende.
Pratu River:	Pale green feldspar and quartz amphibolite pyroxene present due to local thermal effects.
Yenku:	Actinolite schist pale colours, fibres usually bent quartz present, clots of actinolite show deeper coloured rims. Metabasalts hornblende bluish green with quartz epidote and ilmenite.
Brusheng River:	Local development of biotite from hornblende abundant post-Birrimian intrusives.

Eastern Greenstone Series:

Osi Hills: Slightly pleochroic actinolite in schists but subordinate to hornblende schist - blue green hornblende with quartz magnetite + ilmenite (LY 534) Iron ores absent from meta-vesicular lavas but present in porphyritic lavas which have darker blue amphibole (LY 542).

Mankwadzi Locality: Coarse biotite feldspar amphibolite on coast. Quartz present hornblende deeply pleochroic dark green iron ores absent where biotite present.
Eastwards from Mankwadzi similar rock but no quartz present, biotite occurs. Amphibole darker coloured blue greens. (LY 308)

Ejisimanku: Hornblende Schist no quartz some magnetite (LY 313) amphiboles twisted.

Apam: Rimmed amphiboles, dark coloured near Apabaka lagoon quartz present.

Coarse Amphibolite Zone: Mile 1 to mile 3 Swedru road feldspar amphibolite pale green hornblende cores filled with epidote pyroxene on rims. Iron ores not abundant (LY 484 Ghana slide).

Near Muni Lagoon: Somewhat darker blue green colours in amphiboles, brown biotite occasionally pyroxene and quartz present. (LY 486)

Actinolite-amphibolite:- large feathery fibrous tremolite with nets of magnetite in core. Strongly pleochroic actinolite also present but not associated with iron ores. Amphiboles twisted and rotated chlorite present also quartz (LY 485)

Pomadi Brofeyedru: Tremolite schists with phlogopite.

Hornblendites: East of Winneba road show strongly pleochroic amphibole, quartz and epidote present (LY 20 LY 550)

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