THE CHEMISTRY, OPTICS, AND GENESIS OF THE ALKALI-AMPHIBOLES

By

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Abstract

The alkali-amphiboles are divided into the groups of riebeckite-glaucophane, of arfvedsonite, of katophorite and of soda-tremolite on the basis of the degrees of the (Na, K) $R'' \longleftrightarrow R'''$ and (Na, K)$Al \longleftrightarrow Si$ substitutions, where R''' and R'' represent trivalent and divalent atoms in 6-coordination respectively (Fig. 1). The first three groups are in serial relation, being governed by the substitution $R'''Si \longleftrightarrow CaR''Al$. This series is called the riebeckite-arfvedsonite-katophorite series.

Each group is subdivided on the basis of the $A \longleftrightarrow Fe'''$ substitution in R''' and the $Mg \longleftrightarrow Fe''$ substitution in R''. The idealized formulas of main subdivisions are as follows:

Riebeckite-glaucophane group	
Riebeckite	$Na_2Fe_3''Fe_2'''Si_8O_{22}(OH)_2$
Magnesioriebeckite	$Na_2Mg_3Fe_2'''Si_8O_{22}(OH)_2$
Glaucophane proper	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
Arfvedsonite group	
Arfvedsonite	$Na_2Ca_{0.5}Fe_{3.5}''Fe_{1.5}'''Si_{7.5}Al_{0.5}O_{22}(OH)_2$
Magnesioarfvedsonite	$Na_2Ca_{0.5}Mg_{3.5}Fe_{1.5}'''Si_{7.5}Al_{0.5}O_{22}(OH)_2$
Katophorite group	
Katophorite	$Na_2CaFe_4''Fe'''Si_7AlO_{22}(OH)_2$
Magnesiokatophorite	$Na_2CaMg_4Fe'''Si_7AlO_{22}(OH)_2$
Soda-tremolite group	
Soda-tremolite	$Na_2CaMg_5Si_8O_{22}(OH)_2$

The relations of the chemical compositions to the optical properties and to the modes of occurrence are examined in detail. In the riebeckite-arfvedsonite-katophorite series, the formation temperature increases generally with the increase of $CaR''Al$. The alkali-amphiboles are a fairly good temperature indicator. It is interesting that the high pressure member (glaucophane) is high in 6-coordinated Al, whereas the high temperature member (katophorite group) is high in 4-coordiated Al.

I. Introduction

In this paper I intend to give a critical compilation and review of the existing data on the chemical compositions, substitution relations, optical properties and modes of occurrence of the alkali-amphiboles. The main purpose of this study is to have a better grasp of their petrological properties in relation to the problems of glaucophane-schists and alkalic igneous rocks.

The most remarkable progress in the systematic treatment of amphibole in recent years was made by Hallimond (1943). He deviced a useful method of graphical representation of the composition relations of the calciferous amphiboles, and thereby opened up a new way in the study of amphibole in general. Then, Sundius (1946) made another important contribution in the systematic study of calciferous as well as alkali amphiboles. I am greatly indebted to these works.

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The alkali-amphiboles are generally high in alkali and low in Ca content. Their CaO contents by weight are lower than 6% except in some katophorites and soda-tremolites. Amphiboles higher in Ca and generally lower in alkali content, such as barkevikite and hastingsite, are not treated in this paper, because they belong to the family of calciferous amphiboles and not to that of alkali-amphiboles. The CaO content of the calciferous amphiboles are usually higher than 9%.

In this paper, the boundaries between subdivisions of the alkali-amphiboles are determined on the principle that they should conform, as far as possible, with the general current usage of the names for the subdivions, and also with differences in their modes of occurrence. It is important from petrological point of view to take the modes of occurrence into consideration.

Unfortunately the identification of alkali-amphiboles and the description of their optical properties in the literature are erroneous in many cases. Therefore the literature should be examined with great care. The chemical analyses that can not be reconciled with the structural formula derived from the X-ray studies are mostly rejected in the present study.

Eckermannite (ADAMSON, 1944; SUNDIUS, 1945b) and holmquistite (OSANN, 1913; SUNDIUS, 1947) are not treated in this paper, because they are very different from the other alkali-amphiboles in their richness in Li. The Li must have some effects on the optical properties as well as on the stability.

II. Graphical Representation of the Main Substitutions

The X-ray studies of WARREN (1929, 1930) have established the chemical formula of tremolite as $Ca_2Mg_5Si_8O_{22}(OH)_2$, and have shown that the formulas of the other amphiboles can be derived by isomorphous substitutions from the tremolite formula. The Ca atoms of tremolite may be replaced by Na and K. The Mg atoms may be replaced by Mn, Fe″, Al and Fe‴. The Si atoms may be replaced partly by Al. At most one more (Na, K) atom can enter the vacant space of the structure. Thus we come to the general formula of the alkali-amphiboles as follows:

$$(Na, K, Ca)_{2-3}(R'', R''')_5(Si, Al)_8O_{22}(OH)_2$$

The (Na, K, Ca) atoms are in 8- and 12-coordinated positions, (R″, R‴) atoms are in 6-coordinated ones and the (Si, Al) atoms are in 4-coordinated ones.

The substitutions of $R'' \leftrightarrow R'''$ and of $Si \leftrightarrow Al$ are between atoms of different valencies. Then some additional substitutions must accompany them in order to maintain electrical neutrality. If we neglect the sustitution among Na, K and Ca, the electrical neutrality is maintained by intoducing (Na, K) atoms into the vacant spaces. Thus, the compositional variation of the alkali-amphiboles may be represented mainly by the following two kinds of substitution: $(Na, K)\ R'' \leftrightarrow R'''$ and $(Na, K)\ Al \leftrightarrow Si$. The sustitution $R''Si \leftrightarrow R'''Al$ may be regarded as a combination of these two.

Indeed, the Ca and K contents of the alkali-amphiboles are generally low in comparison to the Na content, and so we can neglect the substitution among Na, K and Ca as a first approximation. Consequently the main compositional variation of the alkali-amphiboles can be graphically shown by a rectangular diagram having the degrees of the above two subtitutions as coordinates. Such a diagram is shown in Fig. 1, in which the abscissa represents the amount of R‴ and the ordinate represents that of Si. Special attention should be paid to the fact that symbols R‴ and R″ in this paper do not represent all the amounts of trivalent and divalent atoms respectively but represent only the trivalent and divalent atoms which are in 6-coordinated positions.

If the Ca content is zero, only the area having $Na_2R''_3R'''_2Si_8O_{22}(OH)_2$, $Na_3R''_4R'''Si_8O_{22}(OH)_2$, $Na_3R''_2R'''_3Si_6Al_2O_{22}(OH)_2$, and $Na_2R''_2R'''_3Si_7AlO_{22}(OH)_2$ at its four corners is in harmony with the condition that $Na+K=2-3$. This area is indicated by broken lines in Fig. 1. However, actually the Ca content is not always negligible, and we will see that points fall not only on the area but also widely to the left.

III. Four Groups in the Alkali-Amphiboles

A number of reliable chemical analyses of the alkali-amphiboles were collected from the literature. The H_2O content in many of these analyses is not reliable. Moreover, H_2O_+ and H_2O_- are not always separated from each other. Then, all the analyses were calcualated into the chemical formula on the basis of $O=2300$, excluding the oxygen in H_2O. This procedure is equivalent to the assumption of $(OH, F)=200$. (The basis of $O=2300$ was adopted instead of $O=23.00$, only because it simplifies the printing of the table concerned by avoiding decimal points.) The results of the calculation are shown in Table 1. The optical properties of the analysed amphiboles, so far as given in the original descriptions, are shown in Table 2. The analysis numbers are common to both tables.

In Table 1, the Al is divided into those in 4-coordination (Al^{IV}) and in 6-coordination (Al^{VI}), and the water content is shown as H_2O in molecular ratio on the same basis. When H_2O_+ and H_2O_- are distinguished in the analysis, only the H_2O_+ is taken into calculation, and the result is indicated by figures with sign+ before. (For example, see "+100" in No. 1.) When H_2O_+ and H_2O_- are not distinguished, the figures concerned indicate the total H_2O. (For example, see "97" in No. 6.) The bar— means that the component concerned was not determined.

The amphiboles of Table 1 are plotted in Fig. 1, which have R''' and Si as the coordinates. Since symbols R''' and R'' in this paper represent the trivalent and divalent atoms respectively in 6-coordination, $R'''+R''$ should be equal to 500 in the idealized compositions, and is either equal or close to 500 in the reliable actual compositions. The Ti atoms in 6-coordination are included in the R''' group for the sake of convenience, though they are probably tetravalent. (This procedure will be permissible as the Ti content is usually small.)

The actual procedure of calculating R''' and R'' is as follows: Si is smaller than 800 in most cases, and so Al is allotted so that $Si+Al=800$. These Si and Al atoms represent the cations forming (Si, Al)$-$O tetrahedra. Rarely the Si and Al atoms are too small in amount to fulfill the condition $Si+Al=800$. In such cases Ti is added to fulfill the condition $Si+Al+Ti=800$. When the total amount of Si, Al and Ti joined is still smaller than 800, the want is left as it is. The remaining Al and Ti are regarded as being situated in 6-coordinated positions, together with Fe''', Fe'', Mn, and Mg. Then R''' and R'' are calculated from them as $R'''=Al+Ti+Fe'''$ and $R''=Fe''+Mn+Mg$. In a few cases Si is slightly over 800, and all the Si atoms are treated as forming Si$-$O tetrahedra.

Some part of Mn may be present in 8-coordinated positions, together with Ca, K and Na. But this possibility is disregarded for the present. This disregard will not cause any serious error, as the Mn content is usually very small.

In Fig. 1, we can notice a close relationship between the chemical compositions and modes of occurrence of the alkali-amphiboles. The amphiboles from igneous

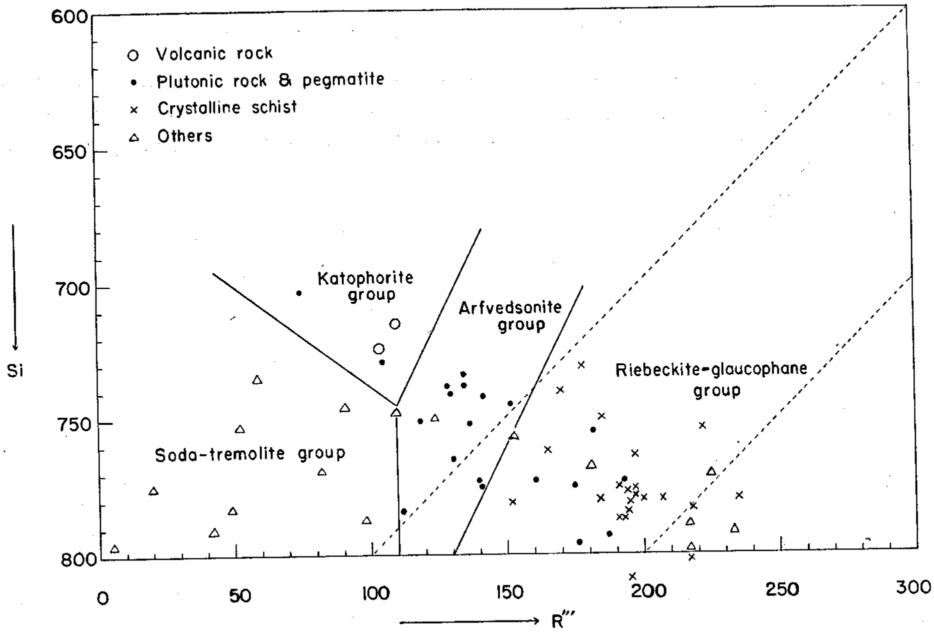

Fig. 1. The (Na, K) $R'' \longleftrightarrow R'''$ and (Na, K) $Al \longleftrightarrow Si$ substitutions in the alkali-amphiboles. The symbols represent the host rocks. "Others" represented by triangles include metamorphosed ironstone and limestone and hydrothermal products.

rocks fall on the upper central part of the composition field, while those from crystalline schists and other metamorphic rocks fall on the lower part at the right and left ends of the compostition field. In some intermediate parts, amphiboles from both igneous rocks and crystalline schists appear intermingled.

As shown in Fig. 1, the alkali-amphiboles are divided into four groups: riebeckite-glaucophane, arfvedsonite, katophorite and soda-tremolite groups. Each boundary between the fields of these groups is a straight line passing through two points as follows:

Between the fields of the riebeckite-glaucophane and arfvedsonite groups: ($R'''=130$, $Si=800$) and ($R'''=180$, $Si=700$).

Between the fields of the arfvedsonite and katophorite groups: ($R'''=110$, $Si=745$) and ($R'''=140$, $Si=685$).

Between the fields of the katophorite and soda-tremolite groups: ($R'''=110$, $Si=745$) and ($R'''=50$, $Si=700$).

Between the fields of the arfvedsonite and soda-tremolite groups: ($R'''=110$, $Si=745$) and ($R'''=110$, $Si=800$).

These boundaries are in harmony with the current usage of the names of the four groups.

Each group will be subdivided later according to the Fe'''/R''' and Fe''/R'' ratios. Table 1 shows mineral names that are given systematically to the subdivisions in this paper. The definitions of these names will be explaind later. In many cases these names agree to those given in the original descriptions. When they differ, the systematic names adopted in this paper are followed by the names of the original descriptions in brackets.

IV. Ca Contents and Group Formulas

The Ca contents of the alkali-amphiboles excluding soda-tremolite are shown in Fig. 2. It is clear that the Ca content increases rather regularly with the decrease of R'''. Thus, the Ca contents are usually small in the riebeckite-glaucophane group, but are larger in the arfvedsonite and katophorite groups. The idealized compositions of arfvedsonite and katophorite should have Ca contents of about 50 and 100 respectively.

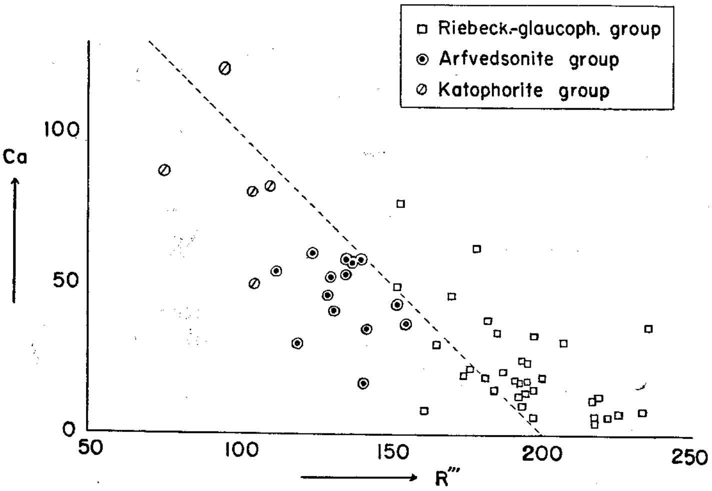

Fig. 2. The Ca contents of alkali amphiboles (excluding soda-tremolite).

Thus, from Figs. 1 and 2, we obtain the idealized formulas which follow:

Riebeckite-glaucophane group	$Na_2R_3''R_2'''Si_8O_{22}(OH)_2$
Arfvedsonite group	$Na_2Ca_{0.5}R_{3.5}''R_{1.5}'''Si_{7.5}Al_{0.5}O_{22}(OH)_2$
Katophrite group	$Na_2CaR_4''R'''Si_7AlO_{22}(OH)_2$

The compositional variation between the three groups is expressed by the substitution $R'''Si \leftarrow\rightarrow CaR''Al$. Then the riebeckite-glaucophane, arfvedsonite, and katophorite groups are in serial relation.

The formula of the riebeckite-glaucophane group given above is practically the same as those given by KUNITZ (1930) and SUNDIUS (1946), whereas that of the arfvedsonite group is different. The formulas of arfvedsonite given in most, if not all, of the literature are wrong. Only the above formula enables us to correlate the compositions with their optical properties and modes of occurrence.

The soda-tremolite group has the following idealized formula;

$$Na_2CaR''_5Si_8O_{22}(OH)_2$$

This formula can be derived from the tremolite formula $Ca_2Mg_5Si_8O_{22}(OH)_2$ by the substitution $Ca \leftarrow\rightarrow Na_2$.

V. Riebeckite-Glaucophane Group

1. General statement

Fig. 3 shows the $\mathrm{Fe}'''/\mathrm{R}'''$ and $\mathrm{Fe}''/\mathrm{R}''$ ratios of amphiboles of the riebeckite-glaucophane group.

$\mathrm{Fe}'''/\mathrm{R}'''=\mathrm{Fe}'''/(\mathrm{Al}+\mathrm{Ti}+\mathrm{Fe}''')$ in 6-coordination.

$\mathrm{Fe}''/\mathrm{R}''=\mathrm{Fe}''/(\mathrm{Mg}+\mathrm{Mn}+\mathrm{Fe}'')$ in 6-coordination.

As the Ti and Mn contents are usually very small, these ratios represent practically the degrees of the $\mathrm{Al}\longleftrightarrow\mathrm{Fe}'''$ substitution in R''' and the $\mathrm{Mg}\longleftrightarrow\mathrm{Fe}''$ substitution in R'' respectively.

The amphiboles with $\mathrm{Fe}'''/\mathrm{R}'''$ ratios lower than 0.7 occur characteristically in the so-called glaucophane-schist group of metamorphic rocks, whereas those with $\mathrm{Fe}'''/\mathrm{R}'''$ ratios higher than 0.7 occur not only in such rocks but also in other metamorphic as well as alkalic igneous rocks. Then, it is in harmony with petrographical custom and convenience to call the amphiboles with the $\mathrm{Fe}'''/\mathrm{R}'''$ ratios lower than 0.7 "*glaucophane*" or "*glaucophane in a broad sense*".

As shown in Fig. 3B, the members rich in Al and Mg ($\mathrm{Fe}'''/\mathrm{R}'''<0.3$, $\mathrm{Fe}''/\mathrm{R}''<0.5$) will be called *glaucophane proper*, and their ferrous analogues will be

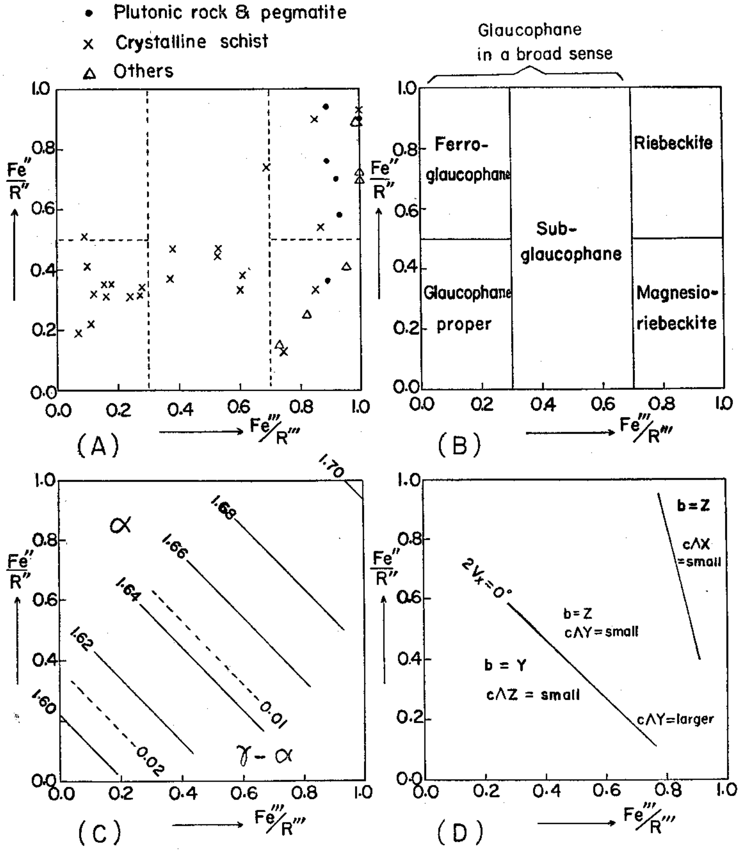

Fig. 3. The $\mathrm{Fe}'''/\mathrm{R}'''$ and $\mathrm{Fe}''/\mathrm{R}''$ ratios in amphiboles of the riebeckite-glaucophane group. (A) compositions, (B) nomenclature, (C) refractive indices, (D) optic orientation.

called *ferroglaucophane.* The members with intermediate values of Fe'''/R''' ratio (0.3-0.7) will be called *subglaucophane.*

The members rich in Fe''' and Fe'' ($Fe'''/R''' > 0.7$, $Fe''/R'' > 0.5$) will be called *riebeckite*, whereas their magnesium analogues will be called *magnesioriebeckite.*

The idealized formulas of these members are as follows:

Riebeckite	$Na_2Fe_3''Fe_2'''Si_8O_{22}(OH)_2$
Magnesioriebeckite	$Na_2Mg_3Fe_2'''Si_8O_{22}(OH)_2$
Subglaucophane	$Na_2Mg_{1.5}Fe_{1.5}''AlFe'''Si_8O_{22}(OH)_2$
Glaucophane proper	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
Ferroglaucophane	$Na_2Fe_3''Al_2Si_8O_{22}(OH)_2$

Kunitz (1930) has claimed that there is a continuous series of solid solution between glaucophane and tremolite-actinolite. However, this statement is not justified as was already discussed by Sundius (1946, p. 11). (What was called tremolite-glaucophane by Polovinkina (1924) is actually a soda-tremolite.)

2. Optical properties

C and D of Fig. 3 show the relation between the chemical compositions and optical properties in this group. The refractive indices increase from the corner of glaucophane proper to that of riebeckite, that is, with the increase of Fe''' and Fe''. So far as the refractive indices are concerned, the riebeckite-glaucophane group may be regarded as a pseudo-binary system corresponding to the diagonal from glaucophane proper to riebeckite, as is shown in Fig. 4. As regards the other optical properties such as optical orientation, such a treatment may not be justified.

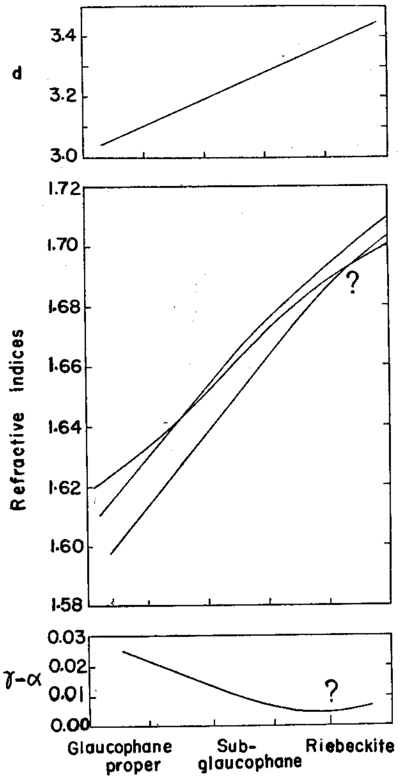

Fig. 4. Refractive indices and density in the pseudo-binary series of glaucophane proper, subglaucophane and riebeckite.

In glaucophane near the MgAl corner of the diagram Fig. 3D, $b = Y$, $c \wedge Z = $ small (4°-15°) and $2V_X = $ medium (ca. 50°) to small. The optic axial plane is parallel to (010). Hence such glaucophane may be called *parallel-symmetric* one. With the increase of Fe''' and Fe'', the optical angle becomes smaller down to zero. With further increase of Fe''' and Fe'', it becomes larger again in the optic axial plane normal to (010). Thus, $b = Z$ and $c \wedge Y = $ small (2°-15°). Amphiboles having such an optical orientation (i. e. normal-symmetric glaucophanes) have been usually called *crossite.* (This name will be discussed later.) Tschopp (1923), Horikosi (1936) and de Roever (1947) have observed practically uniaxial amphiboles on the boundary between parallel-symmetric glaucophane and crossite.*

In riebeckite near the $\mathrm{Fe''Fe'''}$ corner of the diagram, $b=\mathrm{Z}$ and $c\wedge\mathrm{X}=$small (0°-5°) The literature shows confusions and contradictions in the optical description of riebeckite, mainly as a result of very strong absorption. Some riebeckites were reported to be optically positive and others optically negative. Some riebeckites do not show complete extinction between crossed nicols even with monochromatic light (e. g. MIYASHIRO and MIYASHIRO, 1956).

The optical properties of the transitional minerals between crossite and riebeckite with $c\wedge\mathrm{X}=$small are not clear. Fig. 4 shows a possible (if not probable) interpretation for the transitional state that the mineral becomes uniaxial positive on the boundary.

The pleochroism is as follows. In parallel-symmetric glaucophane, X=pale yellow, Y=bluish violet, and Z=blue with $\mathrm{X}<\mathrm{Z}<\mathrm{Y}$. In crossite, X=pale yollow, Y=blue, and Z=violet with $\mathrm{X}<\mathrm{Y}<\mathrm{Z}$. In riebeckite with $c\wedge\mathrm{X}=$small, X=greenish blue, Y=light brownish yellow, and Z=dark bluish grey with $\mathrm{Y}<\mathrm{X}\leqq\mathrm{Z}$, according to VENDL (1924).

In the members of the group near the diagonal from glaucophane proper to riebeckite, the extinction angle is smaller than 15°, as mentioned above. However, in magnesioriebeckites, near the $\mathrm{MgFe'''}$ corner of the diagram, the extinction angle is much larger. Thus, for example, $b=\mathrm{Y}$ and $c\wedge\mathrm{Z}=$ about 30°-35° in some magnesioriebeckites with very low $\mathrm{Fe''/R''}$ ratios, and $b=\mathrm{Z}$ and $c\wedge\mathrm{Y}=$ about 28° in others. The optical angle about X is small (0°-50°). The most remarkable feature of such magnesioriebeckites is that two of the principal axes of the absorption ellipsoid show a large departure from the axes of the indicatrix. One of the absorption axes is parallel to b, another is parctically parallel to c and the remaining is practically normal to both b and c.**

Amphiboles having such optical properties were called *torendrikite* by certain writers. (Some of torendrikites belong to magnesioriebeckite and others to magnesioarfvedsonite in composition. This name will be discussed in the next chapter.)

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* The descriptions of the axial dispersion of glaucophanes in the literature show marked contradictions to one another. According to recent observations of Shohei BANNO (personal communication), parallel-symmetric glaucophanes with optic angles larger than 30° show weak axial dispersion of $\rho<v$, but parallel-symmetric glaucophanes with optic angles smaller than 30° show too weak axial dispersion to be determined. Probably the axial dispersion of parallel-symmetric glaucophane becomes zero when the optic angle is about 10°. Normal-symmetric glaucophanes (crossites) with optic angles larger than 10° show strong axial dispersion of $\rho\ll v$.

** The following optical properties were observed in a magnesioriebeckite from a crystalline schist of Bizan in Sikoku (MIYASHIRO and IWASAKI, 1957), though the mineral is not included in Table 1, because it was analyzed after the completion of the table. $b=\mathrm{Z}$; $c\wedge\mathrm{Y}=28°$ for yellow light, 31° for green and 35° for blue; 2V over X=43° for yellow light and 51° for green. $\alpha=1.660$ and $\gamma=1.670$ for yellow light. Owing to very strong dispersion, the (010) section does not show extinction for white light, but shows complete extinction for monochromatic light. The pleochroism is as follows: parallel to b=purple, practically parallel to c=blue, and practically normal to both b and c=very pale yellow (nearly colorless). Absorption: parallel to $b=$ parallel to $c>$ normal to both b and c. Its composition is as follows: Si=780, Al(IV)=20, Al(VI)=55, Ti=3, $\mathrm{Fe'''}$=136, $\mathrm{Fe''}$=41, Mn=15, Mg=250, Ca=29, Na=152, K=7, $\mathrm{H_2O}=+92$ and F=n. d., all on the anhydrous basis of O=2300. Its host-rock is a garnet-aegirine-amphibole-muscovite-quartz-schist from Bizan in the city of Tokusima, Sikoku, and belongs to the Sanbagawa schists.

3. Modes of occurrence

Riebeckite occurs in alkalic igneous rocks as well as in crystalline schists and metamorphosed ironstones. The alkalic igneous rocks concerned include granites, quartz-syenites, syenites and nepheline-syenites. However, metamorphic riebeckites have generally larger R''' values than igneous ones, as shown later (Fig. 7). SUZUKI (1939) described a riebeckitic amphibole (called crocidolite) with unusually high refractive indices (β=about 1.71; $c \wedge X=0°-2°$) from a low-grade schist of Hokkaido. Probably it is also a typical riebeckite with a very high R''' value.

Magnesioriebeckite occurs rarely in alkalic igneous rocks, but more commonly in crystalline schists and other metamorphosed rocks.

Subglaucophane and glaucophane proper occur only in crystalline schists and associated rocks. Ferroglaucophane with relatively low Fe''/R'' ratios occurs in crystalline schists, but that with relatively high Fe''/R'' ratios has not been found in any rocks.

4. Conditions of formation

Riebeckite and magnesioriebeckite have a large excess of alkalies over the alkalies/alumina ratio of alkali-feldspars. Then, their formation should be promoted by richness in alkalies, especially by the presence of excess alkalies in the rocks. However, most rocks in the earth's crust have no excess of alkalies. The excess of alkalies can be present generally only in two cases: (1) in alkalic igneous rocks and their metamorphic derivatives, and (2) in rocks whose compositions were markedly modified by alkali-metasomatism (or metamorphic differentiation). Therefore the occurrence of riebeckite and magnesioriebeckite is very limited. So far as such chemical conditions are fulfilled, riebeckite and magnesioriebeckite probably form under both high and low pressures, at generally low temperatures.

On the other hand, Fe'''-free glaucophane does not require any excess of alkalies for its formation. This fact will be understood from the following examples of chemical equations:

$$\underset{\text{glaucophane}}{2H_2Na_2Mg_3Al_2Si_8O_{24}}+2H_2O=\underset{\text{albite}}{4NaAlSi_3O_8}+\underset{\text{antigorite molecule (in chlorite)}}{H_8Mg_6Si_4O_{18}}$$

$$\underset{\text{glaucophane}}{5H_2Na_2Mg_3Al_2Si_8O_{24}}+\underset{\text{lawsonite}}{2CaAl_2Si_2O_8\cdot 2H_2O}$$

$$=\underset{\text{albite}}{10NaAlSi_3O_8}+\underset{\text{chlorite}}{2H_8Mg_5Al_2Si_3O_{18}}+\underset{\text{tremolite}}{H_2Ca_2Mg_5Si_8O_{24}}$$

The alkalies of Fe'''-free glaucophane can be supplied from albite. Therefore the chemical condition for the formation of Fe'''-free glaucophane can be fulfilled generally easily. Thus, Fe'''-free glaucophane should form easily only if some physical conditions are fulfilled. The glaucophane-bearing sides of the above equations have smaller solid volumes than the other sides, and we may safely consider that the essential factor of physical condition for the formation of Fe'''-free glaucophane is high solid pressures combined with low temperatures, as is discussed in another paper (MIYASHIRO and BANNO, 1958).

Glaucophane proper and ferroglaucophane, being poor in Fe''', would resemble the Fe'''-free glaucophane in the condition of formation. As subglaucophane is intermediate in chemical composition between Fe'''-free glaucophane on the one hand and riebeckite and magnesioriebeckite on the other, its formation must be effectively controlled by both physical conditions (high pressure and low temperature) and chemical ones (including the presence of excess alkalies).

The composition and stability of the members of the riebeckite-glaucophane group may be schematically represented by the diagram of Fig. 5. Under very high pressure and low temperature, any member of the riebeckite-glaucophane group may form, its composition depending upon that of the host-rock. At lower pressure and /or higher temperature, the possible composition field of the amphibole becomes smaller, and glaucophane proper and ferroglaucophane become unstable. At still lower pressure and/or higher temperature, the possible composition field becomes confined to the area of riebeckite and magnesioriebeckite

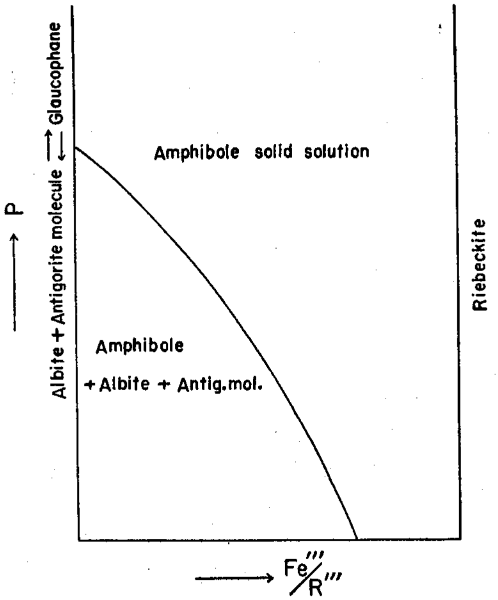

Fig. 5. The composition and stability in regard to solid pressure of the amphiboles of the riebeckite-glaucophane group.

The problem treated in this section has been discussed in greater detail in another paper (MIYASHIRO and BANNO, 1958).

5. Names and varieties

Riebeckite was first recognized to be a member of the amphiboles by SAUER in 1885 and was named in honor of Emil RIEBECK. *Glaucophane* was first described and named by HAUSMANN in 1845 from the island of Syra in the Cyclades without knowing that it belongs to the amphiboles. The name came from the blue color in Greek (HINTZE, 1897).

Some writers restricted the use of the name glaucophane only to the parallel-symmetric variety. However, such a nomenclature would lead to an unfortunate confusion.

The name *crossite* was proposed by PALACHE (1894) in honor of the geologist W. CROSS for an amphibole that generally resemble glaucophane and riebeckite but was considered to have distinctive optical properties. He stated that the optic axial plane of the crossite was parallel to (010) with b=Y, and the X axis is near to c. However, this statement was erroneous. SWITZER (1951) reexamined the original specimen of PALACHE, and noticed that actually the crossite has the optic axial plane perpendicular to (010) with $b=Z$ and $c\wedge Y=2°$.

Some writers regarded crossite as having been defined by the composition which is intermediate between those of glaucophane proper and of riebeckite (e. g., HOLGATE, 1951). Other writers considered that crossite is an alkali-amphibole with the optic axial plane normal to (010) with $b=Z$ and $c\wedge Y=$small (e. g., DE ROEVER, 1947). These two definitions, chemical and optical, do not agree to each other. (For example, some minerals having intermediate compositions show $b=Y$.) Probably the optical definition has been adopted more generally. I believe that such an optically defined name is covenient for us in petrographical works. Such optically defined crossite belongs in chemical composition to subglaucophane in most cases, and to riebeckite and magnesioriebeckite in rare cases.

Osannite (HLAWATSCH, 1906) is a variety of riebeckite.

Ternovskite (POLOVINKINA, 1924) belongs to magnesioriebeckite.

Crocidolite is fibrous amphibole or asbestos, having riebeckite or magnesioriebeckite composition. Usually it occurs in ironstones, probably slightly metamorphosed at very low temperatures after deposition.

The name *gastaldite* was proposed for a glaucophane-like amphibole from St. Marcel by STRUEVER in 1875 (refer to MILCH, 1907). The original analysis shows an unusually high R''' value ($R'''=300$). A later analysis of a similar mineral from the same locality by ZAMBONINI (1906) gave an ordinary composition of glaucophane proper. It seems that the original analysis was wrong.

Torendrikite (LACROIX, 1920) will be discussed in the next chapter.

VI. Arfvedsonite Group

1. General statement

Fig. 6A shows the Fe'''/R''' and Fe''/R'' ratios of amphiboles of the arfvedsonite group. The Fe'''/R''' ratios are larger than 0.7 in these amphiboles with only one exception.

The main substitution in this group is Mg←→Fe. The Fe''-rich membere ($Fe''/R''>0.5$) are called *arfvedsonite*. The Mg-rich members ($Fe''/R''<0.5$) will be called *magnesioarfvedsonite*.

The idealized formulas of these members are as follows:

Arfvedsonite	$Na_2Ca_{0.5}Fe_{3.5}''Fe_{1.5}'''Si_{7.5}Al_{0.5}O_{22}(OH)_2$
Magnesioarfvedsonite	$Na_2Ca_{0.5}Mg_{3.5}Fe_{1.5}'''Si_{7.5}Al_{0.5}O_{22}(OH)_2$

2. Optical properties

In arfvedsonite, $b=Z$, $c\wedge X=$small to medium (0°–30°), $\alpha=1.67-1.70$, $\gamma=1.68-1.71$ and $\gamma-\alpha=0.005-0.012$ The determination of optical angle and orientation is very difficult owing to strong absorption. The literature shows confusions in the description of pleochroism.

One of the principal axes of the absorption ellipsoid is parallel to *b*, and hence is parallel to Z, but the others show a departure from the axes of the indicatrix, as in the case of magnesioriebeckite. This fact was described in detail by SHODA (1956) on a variety of arfvedsonite (called heikolite). According to him, one of the absorption axes is parctically parallel to *c*, and the remaining is practically parallel to both *b* and *c*. The pleochroism is as follows: parallel to $b=$deep yellowish green; practically parallel to $c=$deep bluish green; and practically normal to both *b* and $c=$yellowish brown. Parallel to $c>$ parallel to $b>$ normal to both *b* and *c*.

Arfvedsonite resembles riebeckite in optical properties except the extinction angle ($c\wedge X$). At least some arfvedsonites do not show complete extinction between crossed nicols even with monochromatic light. The phenomenon was studied in detail by several investigators such as ESKOLA and SAHLSTEIN (1931b), IWAO (1939), SHODA (1954), SAHAMA (1956) and SHODA (1956).

In magnesioarfvedsonite, $b=Z$, $c\wedge X=$large (18°–50°) with very strong dispersion, $\alpha=1.65-1.66$, $\gamma=1.66-1.67$, and $\gamma-\alpha=0.01-0.02$. The principal axes of the absorption ellipsoid in magnesioarfvedsonite also show a large departure from those of indicatrix. This feature was described by several writers. DENAEYER (1924) gives the pleochroism of a variety of the mineral (called torendrikite) as follows: parallel to $b=$greyish violet; practically parallel to $c=$bluish green; and practically normal to both b and $c=$light greenish yellow. Parallel to $b>$ parallel to $c>$ normal to both b and c.

Probably, in magnesioarfvedsonites with very low Fe''/R'' ratios, $b=Y$ and the extinction angle is very large.

3. Modes of occurrence

Arfvedsonite occurs only in alkalic igneous rocks—commonly in nepheline-syenites and rarely in syenites and quartz-bearing rocks.

Magnesioarfvedsonite occurs in alkalic igneous rocks, including syenitic and nepheline-syenitic rocks. LARSEN (1942) described a magnesioarfvedsonite from a hydrothermal product associated with alkalic igneous rocks of Iron Hill, Colorado, under the unfortunate name glaucophane.

4. Names and Varieties

Arfvedsonite was first described by BROOKE in 1823 from Greenland and was named in honor of the Swedish chemist J. A. ARFVEDSON (HINTZE, 1897).

Heikolite (KINOSAKI, 1935) is a variety of arfvedsonite with a composition near the boundary to riebeckite.

The name *torendrikite* was proposed by LACROIX (1920) for an amphibole from alkalic syenite in Madagascar. The amphibole belongs to magnesioarfvedsonite in composition. Later, DENAEYER (1924), DE ROEVER (1947), etc. called optically resembling amphiboles torendrikite without chemical analysis. The diagnostic features of these amphiboles were a large departure of the absorption axes from the axes of the indicatrix, together with relatively large extinction angle and low refractive indices.

The amphibole of DE ROEVER was from a metamorphic rock of the glaucophane-schist group. MIYASHIRO and IWASAKI (1957) described an amphibole, whose optical properties are practically identical to those of the DE ROEVER's, from a crystalline schist of Bizan. It belongs to magnesioriebeckite in composition. Thus, it is reasonable to consider that the name torendrikite represents a series of alkali-amphibole characterized by certain optical properties, as mentioned above, and that in chemical composition torendrikite ranges from magnesioarfvedsonite to magnesioriebeckite.

MOROZEWICZ (1925, 1930) described a series of alkali-amphiboles from syenitic pegmatites of Mariupol in Ukraine under the name *fluotaramite*. Most of the fluotaramites belong to magnesioarfvedsonite and the remaining belong to magnesioriebeckite.

VII. Katophorite Group

1. General statement

The name katophorite was proposed by BROEGGER (1894) for an amphibole characterized by deep reddish brown color and a fairly large extinction angle. The oldest chemical analysis of such an amphibole had been made by OSANN (1888) before. Some writers spelled the name *katoforite*, *kataphorite*, and *cataphorite*.

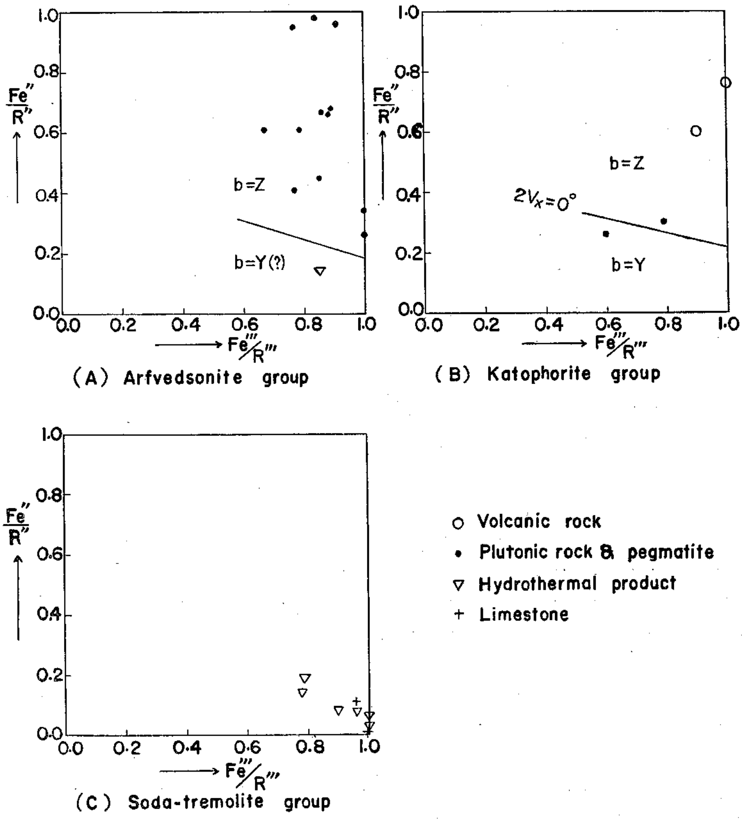

Fig. 6. The Fe'''/R''' and Fe''/R'' ratios in amphiboles of the arfvedsonite, katophorite, and soda-tremolite groups.

Fig. 6B shows the Fe'''/R''' and Fe''/R'' ratios of amphiboles of the katophorite group. The Fe'''/R''' ratios are large in these amphiboles, similarly as in the arfvedsonite group.

The main substitution in this group is Mg←→Fe''. The Fe''-rich members ($Fe''/R''>0.5$) will be called simply *katophorite* and the Mg-rich members ($Fe''/R''<0.5$) will be called *magnesiokatophorite*.

The idealized formulas of these members are as follows:

Katophorite	$Na_2CaFe''_4Fe'''Si_7AlO_{22}(OH)_2$
Magnesiokatophorite	$Na_2CaMg_4Fe'''Si_7AlO_{22}(OH)_2$

2. Optical properties

In katophorites and some magnesiokatophorites, $b=Z$ and $c\wedge X=36°-70°$, with

$\rho > \upsilon$, whereas in other magnesiokatophorites b=Y and $c \wedge X = 52°–56°$ ($c \wedge Z = 34°–38°$) with $\rho < \upsilon$. At the boundary between the two cases where b=Z and b=Y, the mineral is to be uniaxial negative. The optical angle over X is usually small (0°–52°) in this group.

The α index ranges from 1.639 to 1.681, and the birefringence ($\gamma - \alpha$) ranges from 0.007 to 0.021 in the literature.

In crystals with b=Z, X=pale brown, Y=greenish brown, and Z=deep purple-reddish brown, whereas in crystals with b=Y, X=yellow, Y=deep brown, and Z=greenish brown.

3. Modes of occurrence

Katophorite occurs in alkalic igneous rocks, including theralite, shonkinite, trachyte and sanidinite inclusions in trachyte. These rocks belong to either volcanic or associated plutonic masses. Katophorite is associated with sanidine in most cases.

I have repeatedly stated that the crystallization temperature of alkalic igneous rocks differs in different complexes (MIYASHIRO, 1951; MIYASHIRO and MIYASHIRO, 1956). Katophorite appears to be confined to the higher-temperature group of alkalic rocks.

4. Variety

The name *anophorite* (FREUDENBERG, 1910) was proposed for a magnesiokatophorite in shonkinite of Katzenbuckel in Odenwald, Germany.*

VIII. Riebeckite-Arfvedsonite-Katophorite Series

We have seen that the riebeckite-glaucophane, arfvedsonite, and katophorite groups are in serial relation. The compositional differences between the groups are governed by the substitution R'''Si←→CaR''Al. This series will be called the *riebeckite-arfvedsonite-katophorite series* in this paper.

It is interesting that with the increase of CaR''Al the formation temperature of the minerals of this series tends to become higher. This relation is clearly shown in Fig. 7. The fields of igneous and metamorphic amphiboles are separated nearly perfectly from each other in this figure. The igneous field represents higher temperature than the metamorphic one. Thus, probably the formation temperature generally increases from the lower right part to the upper left. Then it is significant that katophorites from volcanic rocks, probably having crystallized at the highest temperatures among the alkali-amphiboles, fall on the upper left end of the whole composition field. The kind of alkali-amphiboles formed should be a useful temperature indicator in petrology.

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* According to FREUDENBERG (1910), the Katzenbuckel "anophorite" (No. 51 in Tables 1-2) has the following properties: the extinction angle=20°–27°, the optic plane normal to (010), 2E=44°20′, and $\rho > \upsilon$. In order to make the optic orientation clearer, I examined "anophorite" in the Katzenbuckel shonkinite, composed of augite ($c \wedge Z = 45°$) with an aegirine rim ($c \wedge X = 0°$), nepheline, sanidine (2V=10°), olivine, anophorite, apatite and opaque minerals. The anophorite has the following properties: $c \wedge Y = 30°$ for yellow light and 28° for green light, b=Z with the optic plane normal to (010), 2V over X=52° for yellow light and 40° for green light, $\rho > \upsilon$, and $\alpha = 1.650$, $\beta = 1.662$, and $\gamma = 1.664$ for yellow light. The absorption axes coincide with the optic elasticity axes, with X=light brown, Y=yellowish brown with greenish tinge, Z=purple-reddish brown and Z>Y>X. This observation has been taken into consideration in Table 2.

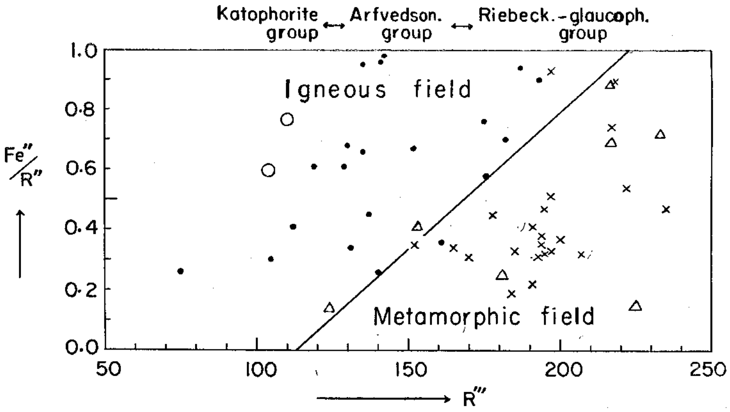

Fig. 7. The relation between the compositions and modes of occurrence of amphiboles of the riebeckite-arfvedsonite-katophorite series. Glaucophane is included. The open circles represent amphiboles of volcanic rocks, the points those of plutonic rocks and pegmatites, the crosses those of crystalline schists, and the triangles those of ironstones and others.

Certain writers claimed that riebeckite occurs in quartz-bearing alkalic rocks, while arfvedsonite occurs in nepheline-bearing ones, and that the degree of saturation with silica is the factor to determine which of the two is formed. However, this statement is not justified. Riebeckite can form in nepheline-bearing rocks as seen in Nos. 6 and 9 of Table 1, when the formation temperature is low.

In the arfvedsonite and katophorite groups the Fe'''/R''' ratio is high, whereas the riebeckite-glaucophane group includes not only members with high Fe'''/R''' values (riebeckite and magnesioriebeckite) but also those with low Fe'''/R''' values (glaucophane). Consequently, if we remove glaucophane from the riebeckite-arfvedsonite-katophorite series, the compositional variations of the remaining members will be expressed mainly in terms of the following two substitutions: R'''Si←→Ca R''Al and Mg←→Fe. Then the relation between their chemical compositions and optical properties can be represented in a rectangular diagram showing the two substitutions as coordinates. A tentative example of such diagrams is shown in Fig. 8. This diagram is very incomplete, because reliable optical data are too little.

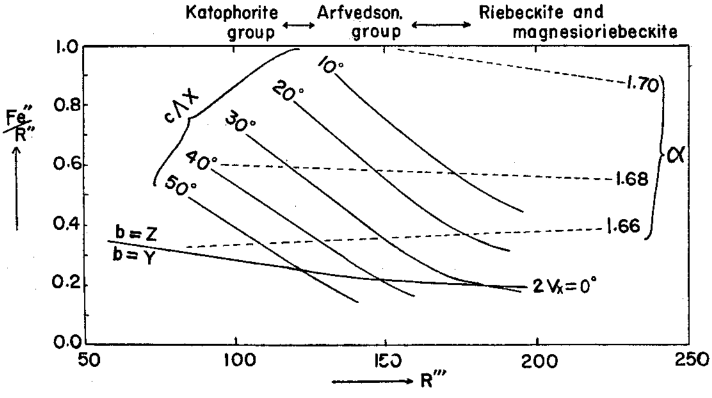

Fig. 8. The approximate relation between the compositions and optical properties of amphiboles of the riebeckite-arfvedsonite-katophorite series, excluding glaucophane.

Moreover, some members of this series may have suffered secondary change in optical properties owing to exsolution after formation of the crystals, as was discussed by ESKOLA and SAHLSTEIN (1931b) and SAHAMA (1956).

IX. Soda-Tremolite Group

1. General statement

In some soda-tremolites, the R''' content is too small to give a definite reliable value of Fe'''/R'''. As shown in Fig. 6C, the Fe'''/R''' ratio is large, so far as determined, and the Fe''/R'' ratio is very small.

Probably there exist a continuous series of solid solution between soda-tremolite and tremolite (SUNDIUS, 1946), and also between soda-tremolite and magnesioarfvedsonite.

Figs. 1 and 2 show that soda-tremolite is in serial relation with some of magnesioarfvedsonite and magnesioriebeckite. However, no further comment will be given of this series, because the series is of rather small petrological importance.

2. Optical properties

The optical properties of members of the soda-tremolite group are as follows: b=Y, $c \wedge Z=15°–45°$, $2V_x=66°–87°$, $\alpha=1.60–1.65$, $\gamma=1.62–1.66$, $\gamma-\alpha=0.009–0.022$. Some soda-tremolites are colorless and others show marked pleochroism from yellow to green, or from green to blue.

3. Modes of occurrence

Soda-tremolite occurs in metamorphosed limestone and jadeite-rock. It was found also in hydrothermally altered rocks associated with alkalic igneous rocks.

4. Names and Varieties

Imerinite (LACROIX, 1921) belongs to soda-tremolite.

Richterite is also a variety of soda-tremolite, usually rich in Mn. It occurs in metamorphosed limestone of Långban in Sweden and so on.

Szechenyiite (KRENNER, 1900) is a soda-tremolite with a small R''' value from a jadeite-rock of Burma.

Soda-tremolite was regarded erroneously as being closely related to glaucophane, and hence was called *tremolite-glaucophane* or so by certin writers. Such names should be rejected.

X. Colors and Formation Temperatures of the Amphiboles

In the whole family of amphibole, brown members are formed at higher temperatures than green and blue ones having resembling chemical compositions. Among the alkali-amphiboles, only katophorite is brown. It corresponds to the fact that katophorite is formed generally at higher temperatures than any other members of the alkali-amphiboles. Brown common hornblende occurs in gabbro, whereas green one occurs in diorite and granite. In metamorphic rocks, brownish common hornblende occurs at higher grades than blue-green one (WISEMAN, 1934: MIYASHIRO, 1953). Barkevikite (brown) occurs in rocks which may be considered to have crystallized generally at higher temperatures than hastingsite (blue-green). Moreover, the marginal changes of katophorite to arfvedsonite (BROEGGER, 1894), of brown hornblende to greenish one, and of barkevikite to hastingsite in igneous rocks with falling temperature are known to take place.

The cause of this color variation is not clear. One might attribute it to some chemical differences. Indeed, some of the brown members are richer, for example, in Ti than the corresponding blue-green ones. However, there are many exceptions for such chemical differences. The color variation may be due to some slight structural difference in response to temperature difference.

XI. Aluminum in 4- and 6-Coordinations

Wickman (1943) and Thompson (1947) claimed that Al in 4-coordination tends to form at high temperatures, whereas Al in 6-coordination tends to form at high pressures. This rule holds splendidly in the alkali-amphiboles. Fig. 9 shows the amounts of Al in 4- and 6-coordiantions in the members of the alkali-amphiboles.

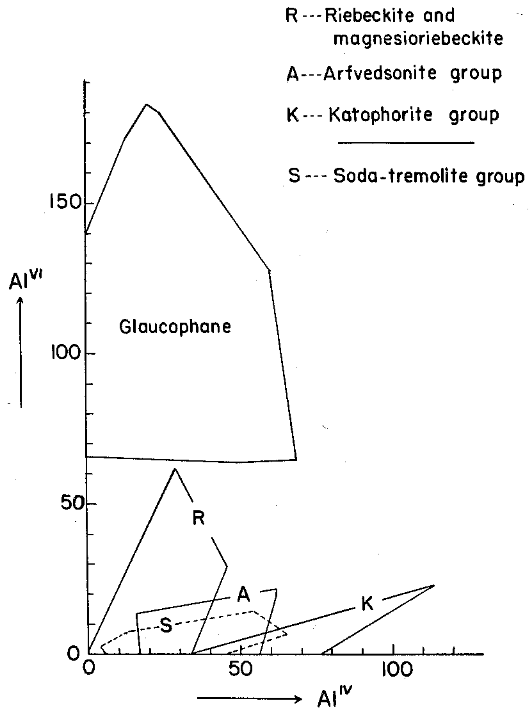

Fig. 9. The amounts of Al in 4- and 6-coordinations in the members of the alkali-amphiboles.

Glaucophane, being formed at high pressures, is very high in 6-coordinated Al. In the other members of the riebeckite-arfvedsonite-katophorite series, 6-coordinated Al decreases and 4-coordinated Al increases in the order from riebeckite and magnesioriebeckite through the arfvedsonite group to the katophorite group. This compositional variation corresponds to the order of decreaseing pressure and increasing temperature in their formation.

In albite and nepheline, Al is in 4-coordination, whereas in glaucophane and jadeite, Al is in 6-coordination. Then the formation of glaucophane and jadeite from albite, nepheline, and/or some mafic minerals is accompanied by an increase in the coordination number of Al. However, that glaucophane and jadeite are stable at higher pressures, is a result of the fact that their density is higher than the bulk

Table 1. Analyses of Alkali-Amphiboles Calculated

No.	Name and occurrence	Locality	Author
1	Riebeckite (crocid.) from ironstone	Hamersley Range, Australia	Simpson
2	Riebeckite from schist	Mill Creek, Calif.	Switzer
3	Riebeckite from schist	Vallone delle Miniere, Piemont	Grill
4	Riebeckite (crocid.) from ironstone	Kliphuis, S. Africa	Peacock
5	Riebeckite (crocid.) from ironstone	Hamersley Range, Australia	Simpson
6	Riebeckite (osannite) from metamor. neph. gneiss	Cevadaes, Portugal	Hlawatsch
7	Riebeckite from quartz-syenite-pegmatite	Fukushin-zan, Korea	Miyashiro, 1956
8	Riebeckite from granite-pegmatite	Quincy, Mass.	Palache & Warren
9	Riebeckite from neph.-syenite (?)	Mariupol, Ukraine	Ainberg
10	Riebeckite from quartz-syenite	Fukushin-zan, Korea	Miyashiro, 1956
11	Riebeckite from syenite-pegmatite	Alter Pedroso, Portugal	Vendl
12	Magnesioriebeckite (crocid.) from limestone	S. Australia	Jack
13	Magnesioriebeckite (ternovskite) from schist (?)	Krivoi Rog, Ukraine	Polovinkina
14	Magnesioriebeckite (crocid.) from metasediment	Cochabamba, Bolivia	Ahlfeld
15	Magnesioriebeckite (fluotaram.) from syenite-pegmatite	Mariupol, Ukraine	Morozewicz
16	Magnesioriebeckite (riebeck.-cross.) from metamor. rock	Glen Lui, Scotland	McLachlan
17	Subglaucophane (glaucoph.) from gneiss	Alpe de Sevreu, Switz.	Woyno
18	Subglaucophane (riebeck.) assoc. with schist	Saint-Véran, Hautes-Alpes	Routhier
19	Subglaucophane (crossite) from schist	Vodno, Jugoslavia	Nikitin & Klemen
20	Subglaucophane (crossite) from schist	Berkeley, Calif.	Kunitz
21	Subglaucophane (crossite) from schist	Berkeley, Calif.	Switzer
22	Subglaucophane (glaucoph.) from schist	Lavintzie, Switzerland	Grubenmann
23	Subglaucophane (crossite) from schist	Anglesey, Wales	Holgate
24	Ferroglaucophane (glaucoph.) from schist	Cykladen, Greece	Kunitz
25	Glaucophane proper from prasinite	Rocca Bianca, Piemont	Zambonini
26	Glaucophane proper from schist	Horokanai Pass, Hokkaido	Suzuki
27	Glaucophane proper from schist	Syra, Greece	Washington
28	Glaucophane proper from schist	Champ de Praz, Piemont	Kunitz
29	Glaucophane proper from schist	Smyrna, Turkey	Kuninz
30	Glaucophane proper (gastaldite) assoc. with schist	St. Marcel, Piemont	Zambonini
31	Glaucophane proper from schist	Zermatt, Switzerland	Kunitz
32	Glaucophane proper from schist	San Pablo, Calif.	Blasdale
33	Glaucophane proper from schist	San Pablo, Calif.	Blasdale
34	Glaucophane proper from schist	Mt. Saleve, Switzerland	Kunitz

to Atomic Ratios for O=2300 (Excluding H_2O)

No.	Si	Al^{IV}	Al^{VI}	Ti	Fe'''	Fe''	Mn	Mg	Ca	Na	K	H_2O	F	R'''	Fe'''/R'''	F''/R''
1	792	1	0	0	233	189	0	74	8	181	6	+100	—	233	1.00	0.72
2	754	46	29	1	192	165	63	79	6	144	6	+44	0	222	0.87	0.54
3	783	17	32	0	186	218	3	23	13	230	22	+60	—	218	0.85	0.89
4	798	2	2	—	215	249	—	31	3	181	1	+132	—	217	0.99	0.89
5	789	4	0	0	217	194	0	89	6	177	5	+135	—	217	1.00	0.69
6	779	18	0	4	196	268	17	4	15	199	17	97	—	197	1.00	0.93
7	773	9	0	11	193	279	7	25	13	197	11	+105	22	193	1.00	0.90
8	793	7	5	15	167	274	15	2	21	181	22	+66	10	187	0.89	0.94
9	755	14	0	46	167	222	7	86	38	130	15	+173	—	182	0.92	0.70
10	796	4	7	5	164	188	19	115	22	145	41	+102	14	176	0.93	0.58
11	775	25	11	8	156	240	29	48	21	197	19	+105	22	175	0.89	0.76
12	771	29	61	—	164	41	0	234	7	176	13	+111	—	225	0.73	0.15
13	764	36	26	3	168	99	—	198	33	166	13	89	—	197	0.85	0.33
14	768	32	33	0	148	87	3	256	19	151	8	34	—	181	0.82	0.25
15	773	27	3	15	143	110	69	130	8	239	57	+67	116	161	0.89	0.36
16	757	34	0	16	146	136	2	191	77	142	14	+120	9	153	0.95	0.41
17	780	20	81	29	125	109	3	118	36	141	13	+78	—	235	0.53	0.47
18	802	0	66	1	150	208	2	70	12	150	8	+84	—	217	0.69	0.74
19	780	20	122	4	74	110	1	183	19	188	2	+57	—	200	0.37	0.37
20	781	19	120	—	75	141	4	154	24	175	7	+93	—	195	0.38	0.47
21	777	23	72	3	119	119	2	193	24	162	2	+96	1	194	0.61	0.38
22	750	50	64	10	111	100	—	199	34	198	20	+21	—	185	0.60	0.33
23	731	69	65	18	95	131	2	160	62	198	11	+57	—	178	0.53	0.45
24	776	24	180	—	17	160	—	153	6	182	15	94	—	197	0.09	0.51
25	780	20	182	—	25	93	0	195	31	157	6	+125	—	207	0.12	0.32
26	809	0	139	3	53	92	1	190	18	162	10	+65	—	195	0.27	0.32
27	784	16	161	—	33	110	1	199	14	179	7	+16	—	194	0.17	0.35
28	787	13	163	—	30	95	—	215	10	182	11	103	—	193	0.16	0.31
29	787	13	171	—	20	126	—	184	18	173	11	89	—	191	0.10	0.41
30	775	25	170	—	21	71	—	254	18	167	0	111	—	191	0.11	0.22
31	780	20	172	—	12	61	—	262	15	183	12	102	—	184	0.07	0.19
32	740	60	128	2	40	108	0	239	46	168	0	+121	—	170	0.24	0.31
33	762	38	114	4	47	115	5	215	30	205	3	+83	—	165	0.28	0.34
34	781	19	127	—	25	123	—	231	49	149	10	85	—	152	0.16	0.35

Table 1 (Continued)

No.	Name and occurrence	Locality	Author
35	Arfvedsonite	Hackmannschlucht	KUNITZ
36	Arfvedsonite (heikolite) from granite pegmatite	Fukushin-zan, Korea	MIYASHIRO, 1956
37	Arfvedsonite from neph.-syenite	Kangerdluarsuk, Greenland	SAHAMA
38	Arfvedsonite from neph.-syenite	Kangerdluarsuk, Greenland	KUNITZ
39	Arfvedsonite from pegmatite	Urma-varaka, Kola Penin.	KUPLETSKIJ
40	Arfvedsonite from pegmatite	Kakasnjujakok, Kola Penin.	KUNITZ
41	Arfvedsonite from neph.-syenite	Loparsky Pass, Kola Penin.	KUNITZ
42	Arfvedsonite (riebeck.-arfved.) from neph.-syenite	Kiihtelysvaara, Finland	ESKOLA & SAHLSTEIN
43	Arfvedsonite from neph.-syenite	Los-Archipel, W. Africa	KUNITZ
44	Magnesioarfvedsonite (torendrikite) from syenite	Ambatofinandrahana, Madagascar	LACROIX, 1920
45	Magnesioarfvedsonite (fluotaramite) from syenite pegm.	Mariupol, Ukraine	MOROZEWICZ
46	Magnesioarfvedsonite (fluotaramite) from syenite pegm.	Mariupol, Ukraine	AINBERG
47	Magnesioarfvedsonite from hydrothermal rock	Iron Hill, Colorado	LARSEN
48	Magnesioarfvedsonite (fluotaramite) from syenite pegm.	Mariupol, Ukraine	MOROZEWICZ
49	Katophorite from sanidinite inclusion in trachyte	Sao Miguel, Azores	OSANN, 1888
50	Katophorite from trachyte	Fuente Vaca	KUNITZ
51	Magnesiokatophorite (anophorite) from shonkinite	Katzenbuckel, Odenwald	FREUDENBERG
52	Magnesiokatophorite (Katophorite)	Chibinpachk, Kola Penin.	KUNITZ
53	Magnesiokatophorite from theralite	Crazy Mts., Montana	WOLFF
54	Soda-tremolite from metamorphic rock (?)	Krivoi Rog, Ukraine	POLOVINKINA
55	Soda-tremolite (asbestos) from lead deposit	Camp Albion, Colorado	WAHLSTROM
56	Soda-tremolite from hydrothermal rock	Iron Hill, Colorado	LARSEN
57	Soda-tremolite from hydrothermal rock	Iron Hill, Colorado	LARSEN
58	Soda-tremolite from hydrothermal rock	Iron Hill, Colorado	LARSEN
59	Soda-tremolite (imerinite) from limestone	Ambatoharina, Madagascar	LACROIX, 1921
60	Soda-tremolite from hydrothermal rock	Iron Hill, Colorado	LARSEN
61	Soda-tremolite from hydrothermal rock	Iron Hill, Colorado	LARSEN
62	Soda-tremolite (richterite) from limestone	Långban, Sweden	SUNDIUS, 1945
63	Soda-tremolite (richterite) from limestone	Långban, Sweden	SUNDIUS, 1945

Note. In the original descriptions, amphibole No. 53 was erroneously called "hastingsite", and amphiboles Nos. 47 and 54 were unfortunately called "soda-tremolite-glaucophane" and "tremolite-glaucophane" respectively. The optical properties of amphibole No. 44 were re-examined by WINCHELL (1925).

Table 1 (Continued)

No.	Si	Al^{IV}	Al^{VI}	Ti	Fe'''	Fe''	Mn	Mg	Ca	Na	K	H_2O	F	R'''	Fe'''/R'''	Fe''/R''
35	737	52	0	25	141	212	16	110	37	207	17	100	—	155	0.91	0.63
36	745	55	9	13	130	246	13	106	43	143	28	+148	—	152	0.86	0.67
37	742	58	17	6	119	343	0	6	35	203	59	+66	—	142	0.84	0.98
38	775	25	1	12	128	339	6	7	17	219	31	110	—	141	0.91	0.96
39	738	62	21	10	104	353	10	10	53	163	34	60	—	135	0.77	0.95
40	734	56	0	26	119	234	18	100	58	191	24	86	—	135	0.88	0.66
41	741	50	0	24	115	241	10	103	52	211	21	98	—	130	0.89	0.68
42	738	62	19	23	87	210	6	126	46	240	35	55	—	129	0.67	0.61
43	751	49	1	24	94	232	11	134	30	232	17	104	—	119	0.79	0.61
44	773	17	0	5	140	97	—	273	58	145	17	6	5	140	1.00	0.26
45	752	48	13	7	117	157	5	185	57	179	41	+82	83	137	0.85	0.45
46	765	25	0	10	131	131	7	242	41	156	35	+104	80	131	1.00	0.34
47	750	50	5	14	105	50	2	317	60	192	9	+59	35	124	0.85	0.14
48	784	16	13	13	86	147	8	207	54	196	39	+72	97	112	0.77	0.41
49	715	76	0	—	110	311	39	57	82	185	18	—	—	110	1.00	0.76
50	724	67	0	19	94	233	19	135	80	187	19	79	—	104	0.90	0.60
51	729	34	0	59	83	112	4	253	50	225	34	74	—	105	0.79	0.30
52	686	114	23	11	61	105	15	288	121	126	33	91	—	95	0.64	0.26
53	703	97	16	14	45	115	2	319	87	169	41	+71	—	75	0.60	0.26
54	748	52	11	12	87	0	—	366	115	144	5	69	—	110	0.79	0.00
55	787	13	7	3	88	31	—	361	40	218	32	40	—	98	0.90	0.08
56	746	54	14	5	72	77	4	331	69	203	14	+76	19	91	0.79	0.19
57	769	31	3	0	79	35	6	374	50	214	38	+29	96	82	0.96	0.08
58	735	65	7	6	46	62	3	380	101	151	39	+7	—	59	0.78	0.14
59	753	45	0	4	50	55	—	430	41	202	32	40	41	52	0.96	0.11
60	783	12	0	3	49	10	1	451	91	138	32	+40	57	49	1.00	0.02
61	791	5	0	3	42	29	7	429	77	148	54	+113	0	42	1.00	0.06
62	775	23	0	1	20	0	106	396	84	157	32	92	16	20	indef.	0.00
63	796	4	2	0	3	0	28	486	133	84	11	110	16	5	indef.	0.00

Table 2. Optical Properties of Analyzed Alkali-Amphiboles

No.	α	β	γ	γ−α	2V over X	Disp.	Optic	Orient.
2	1.680	1.683	1.685	0.005	50°		b=Z,	c∧Y=5°
3		1.692						c∧X=4°
4	1.698	1.699	1.706	0.008			b=Z,	c∧X=0°
6		1.693						
7	1.701	1.711						
8		1.695					b=Z,	c∧X=4-5°
9	1.688		1.691	0.003	112°	ρ<υ	b=Z,	c∧Y=1°
10		1.686						
11		1.6934					b=Z,	c∧X=2°
13	1.655	1.664	1.668	0.013	42°		b=Y,	c∧Z=27-35°
16	1.668		1.680	0.012	50°		b=Z,	c∧X=14°
19		1.645		0.011	12-65°		b=Z,	c∧Y=8°
20	1.640		1.652	0.012			b=Y,	c∧Z=3°
21	1.659	1.663	1.666	0.007	50°	ρ>υ	b=Z,	c∧Y=2°
23	1.649	1.656	1.657	0.008	17°		b=Y,	c∧Z=11°
24	1.622		1.640	0.018			b=Y,	c∧Z=5-6°
26		1.660			10-15°	ρ>υ	b=Y,	c∧Z=8-14°
28	1.615		1.634	0.019	41°		b=Y,	c∧Z=6-8°
29	1.618		1.637	0.019			b=Y,	c∧Z=4°
31	1.606		1.627	0.021			b=Y,	c∧Z=8°
34	1.619		1.640	0.021				c∧Z=6°
35	1.690	1.695					b=Z,	c∧X=27°
36	1.680	1.687	1.691	0.011			b=Z	
37	1.696	1.700	1.705	0.009			b=Z,	c∧X=0°
38	1.695	1.698			large		b=Z,	c∧X=8°
39	1.695		1.700	0.005			b=Z,	c∧X=7°
40	1.688	1.693					b=Z,	c∧X=30°
41	1.687	1.693					b=Z,	c∧X=28°
42	1.670	1.680	1.682	0.012	small		b=Z,	c∧X=20-25°
43	1.683	1.687					b=Z,	c∧X=15°
44		1.665					b=Z,	c∧Y=ca. 40°
46	1.655		1.664	0.009	41°	ρ>υ	b=Z,	c∧X=18-30°
47	1.651	1.661	1.670	0.019	(72°)	(ρ>υ)		c∧Z=57°
50	1.681	1.688					b=Z,	c∧X=36°
51					ca. 25°	ρ>υ	b=Z,	c∧X=63-70°
52	1.655		1.662	0.007	(small)		b=Y,	c∧X=56°
53	1.639	1.658	1.660	0.021	38°	ρ<υ	b=Y,	c∧X=52°

Table 2 (Continued)

No.	α	β	γ	$\gamma-\alpha$	2V over X	Disp.	Optic	Orient.
54	1.621		1.640	0.019	76–80°			$c\wedge Z=15^{\circ}$
55	1.633	1.639	1.642	0.009				$c\wedge Z=44^{\circ}$
56	1.650	1.657	1.659	0.009	(64°)			$c\wedge Z=35^{\circ}$
57	1.623	1.633	1.641	0.018	(87°)	$(\rho>\upsilon)$		$c\wedge Z=40^{\circ}$
58	1.628	1.638	1.644	0.016	(82°)	$(\rho>\upsilon)$		$c\wedge Z=24^{\circ}$
59							$b=Y$,	$c\wedge Z=45^{\circ}$
60	1.612	1.623	1.627	0.015				$c\wedge Z=20^{\circ}$
61	1.606	1.616	1.623	0.017				$c\wedge Z=24^{\circ}$
62	1.622	1.635	1.641	0.019	66°		$b=Y$,	$c\wedge Z=19^{\circ}$
63	1.605		1.627	0.022			$b=Y$,	$c\wedge Z=17^{\circ}$

Note. The analysis numbers are common to Tables 1 and 2. In amphiboles Nos. 47, 52, 56, 57 and 58, it is not clear whether the value of their optical angle was measured over X or over Z. The accompanying axial dispersion was observed probably over the acute bisectrix, which is either X or Z. These values of optical angle and accompanying axial dispersion are shown in brackets. In the remaining amphiboles, the optical angle and axial dispersion are shown in regard to X.

Table 3. Representative Examples of Chemical Analyses of Alkali-Amphiboles

No.	8	37	49	27	60
SiO_2	51.79	44.61	45.53	57.67	56.74
Al_2O_3	0.68	4.02	4.10	11.07	0.71
TiO_2	1.28	0.48	—	—	0.28
Fe_2O_3	14.51	9.92	9.35	3.20	4.71
FeO	21.43	25.79	23.72	9.68	0.87
MnO	1.15	0.00	2.96	0.06	0.07
MgO	0.10	0.25	2.46	9.85	21.95
CaO	1.28	2.06	4.89	0.95	6.15
Na_2O	6.16	6.58	6.07	6.80	5.15
K_2O	1.10	2.89	0.88	0.42	1.80
H_2O_+	1.30	1.24	—	0.36	0.87
H_2O_-	0.10	0.00	—	0.12	0.00
F	0.20	—	—	—	1.30
	101.08	99.84	99.96	100.18	100.91
O=F	0.09				0.54
	100.99				100.37

No. 8 : Riebeckite from Quincy, Mass. By PALACHE and WARREN (1911).
No. 37 : Arfvedsonite from Kangerdluarsuk, Greenland. By SAHAMA (1956).
No. 49 : Katophorite from Sao Miguel, Azores. By OSANN (1888).
No. 27 : Glaucophane proper from Syra, Greece. By WASHINGTON (1901).
No. 60 : Soda-tremolite from Iron Hill, Colorado. Contains also SrO 0.02, NiO 0.23, Cr_2O_3 0.06. By LARSEN (1942).

density of the isochemical assemblages containing albite and/or nepheline. It follows that the stability of 6-coordinated Al at higher pressures is based on that 6-coordinated Al makes more closely packed structures possible in silicates than 4-coordinated one in most cases at least.

Therefore, if the increase of the coordination number is accompanied by decrease in density, the crystals with a higher coordination become stable at lower pressures. A good example for this relation is found in andalusite, having 5-coordinated Al, and sillimanite, having 4-coordinated Al, both together with 6-coordinated Al. Andalusite is stable on the lower-pressure side of the andalusite-sillimanite stability boundary as pointed out by MIYASHIRO (1949) and THOMPSON (1955). (Kyanite, stable at higher pressures than the two, has 6-coordinated Al only.)

Crystals stable at higher pressures have generally a smaller entropy, and hence are stable at lower temperatures (THOMPSON, 1955, p. 70).

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XIII. Alphabetical List of the Names of the Subdivisions in the Alkali-Amphiboles

V ....Riebeckite-glaucophane group.
VI ....Arfvedsonite group.
VII ....Katophorite group.
IX ....Soda-tremolite group.

Anophorite (VII)
Arfvedsonite (VI)
Cataphorite (VII)
Crocidolite (V)
Crossite (V)
Ferroglaucophane (V)
Fluotaramite (VI and V)
Gastaldite (V)
Glaucophane (V)
Glaucophane proper (V)
Heikolite (VI)
Imerinite (IX)
Kataphorite (VII)
Katoforite (VII)
Katophorite (VII)
Magnesioarfvedsonite (VI)
Magnesiokatophorite (VII)
Magnesioriebeckite (V)
Osannite (V)
Richterite (IX)
Riebeckite (V)
Soda-tremolite (IX)
Subglaucophane (V)
Szechenyiite (IX)
Ternovskite (V)
Torendrikite (VI and V)

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