

*The calciferous and alkali amphiboles*By R. PHILLIPS and W. LAYTON<sup>1</sup>

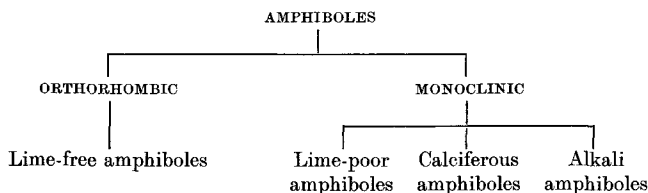
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*Summary.* An attempt is made to systematize the nomenclature of the calciferous and alkali amphiboles. The compositions of end-members can be plotted on a simple diagram, which can also be used to display the affinities of the naturally occurring minerals after deriving a basic atomic formula according to the rules given. The composition of an amphibole can in some cases be expressed quantitatively in terms of solid solution of two or three pure end-members.

SINCE the term 'amphibole' was first used by Haüy in 1801, the number of varietal names for members of this group has increased enormously. This multiplicity of names results in part from the wide range in composition that is possible in these minerals—the eight elements that together make up 98 % of the earth's crust are major constituents of the common amphiboles and other elements may occur in appreciable amounts.

As a preliminary to a revised nomenclature and classification, the authors have recognized the following major divisions within the amphibole group (Layton and Phillips, 1960):



In subdividing these major series it is desirable, as in other mineral groups, to employ the concept of solid solutions of pure end-member compositions. Unfortunately, owing to the complexities of composition in the amphibole group, a given chemical analysis may correspond more or less closely to more than one combination of the various named compositions in the literature. An added difficulty is that the same name has been used by different authors for amphiboles of different compositions. It is therefore desirable, when attempting to apply the

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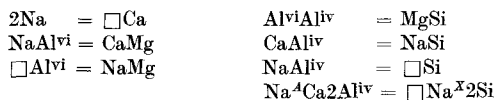
solid solution concept, to have a clear distinction between a name used to describe a pure theoretical end-member of exact composition and the same name used to describe a mineral of approximately the same composition. This can be done quite simply without adding to the already extensive series of varietal names by using a suffix  $\kappa$  to indicate a pure-end member composition.<sup>1</sup> Thus, the pure chemical compound  $\square\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ , where  $\square$  indicates a vacant lattice position, could be described as *tremolite- $\kappa$* , since the name tremolite is commonly accepted for this composition and minerals approximating to this composition.

It seems to be possible to describe the major observed compositional variations in the calciferous and alkali amphibole series using only nine end-member names of this type together with certain commonly used prefixes.

Taking tremolite- $\kappa$  as the starting-point, and bearing in mind the requirements of electrical neutrality, the available lattice positions and their coordination number, and the evidence from a large number of published chemical analyses of amphiboles, the apparent limits of various types of substitution can be worked out.

For simplicity, sodium and aluminium can be considered as typical of the various elements that may substitute in the *A*, *X* and *Y*, *Z* positions in the general formula  $\text{AX}_2\text{Y}_5\text{Z}_8\text{O}_{22}(\text{OH})_2$ . At this stage, substitutions involving cations with the same charge and closely similar ionic radii are regarded as trivial, e.g. the substitution of  $\text{Fe}^{2+}$  for  $\text{Mg}^{2+}$ .

With these conditions, the following substitutions in tremolite- $\kappa$  and compositions derived from it seem to be possible:



where superscript roman numerals indicate the coordination numbers of the aluminium atoms. It has also been assumed that the *Y* positions are normally fully occupied, so that substitutions leading to compositions such as  $\square\text{Ca}_2\text{Mg}_2\text{Al}_2\square\text{Si}_8\text{O}_{22}(\text{OH})_2$  are not considered, and that  $\text{Si}_6\text{Al}_2$  represents the maximum substitution of Al for Si in *Z*.

Thirteen compositions produced in this way can be shown as in fig. 1; the four compositions in the middle row can be produced by combining equal amounts of two other compositions, so there are nine

<sup>1</sup> From the Greek *καθαρός*, pure, free from admixture.

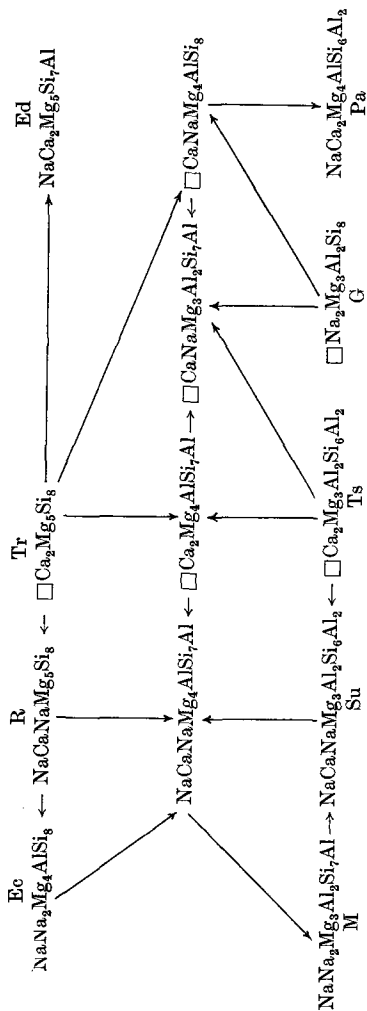


FIG. 1. The thirteen basic amphibole formulae obtained by substitutions in the basic tremolite formula. Only some of the possible substitutions are shown by lines. Three compositions in the middle row can be regarded as a combination of equal amounts of one of the compositions in the top row and one in the bottom row. The fourth is  $T_{50}G_{50}$ . The symbols appended to the other nine compositions are those used for the nine necessary end-members.

end-members whose relationship to named minerals can now be considered. Formulae have been written in such a way that the lattice position occupied by a given element is clearly demonstrated.

$\square\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ —already designated *tremolite- $\kappa$*  (abbreviated as *Tr*), since the name is well established for minerals approximating to this composition.

$\square\text{Ca}_2\text{Mg}_3\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$ —*Tschermakite- $\kappa$*  (*Ts*), the name proposed by Winchell (1945) for this composition and later used as a mineral name.

$\text{NaCa}_2\text{Mg}_5\text{Si}_7\text{AlO}_{22}(\text{OH})_2$ —*Edenite- $\kappa$*  (*Ed*). The material from Edenville, New York State, does not have this composition and Francis (1958) recommends that the name should be discarded. However, material of this composition has been synthesized by Boyd (1954) and given this name and the name is in fairly common use for this composition (Deer, Howie, and Zussman, 1963).

$\text{NaCa}_2\text{Mg}_4\text{AlSi}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$ —*Pargasite- $\kappa$*  (*Pa*). The name has been used in a different sense by some authors, but the original material from Pargas is close to this composition. Synthetic material of this composition is called pargasite by Boyd (1954).

$\text{NaCaNaMg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ —*Richterite- $\kappa$*  (*R*). The name is in fairly common use for an end-member of this composition.

$\square\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ —*Glaucophane- $\kappa$*  (*G*). In common use.

$\text{NaNa}_2\text{Mg}_4\text{AlSi}_8\text{O}_{22}(\text{OH})_2$ —*Eckermannite- $\kappa$*  (*Ec*). In common use.

$\text{NaCaNaMg}_3\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$ —This composition, together with the last of the nine end-members, has not previously been suggested as an end-member or named as a mineral. No minerals close to either composition are known to the authors, but several mineral analyses are equivalent to solid solution of these with other end-members. Since it is desirable for convenience of reference to have names for these rather complex compositions, the name *Sundiusite- $\kappa$*  (*Su*) will be used for this composition in recognition of the work of Dr. Nils Sundius on the amphibole minerals.

$\text{NaNa}_2\text{Mg}_3\text{Al}_2\text{Si}_7\text{AlO}_{22}(\text{OH})_2$ —*Miyashiroite- $\kappa$*  (*M*). The foregoing remarks apply to this composition, named in recognition of the work of Dr. Akiho Myashiro on the alkali amphiboles.

Smith (1959) has pointed out that a graphical representation is desirable to show the complex compositional variations in the amphibole

group and for this purpose he has suggested a three-dimensional diagram. The relationships between the nine pure end-members can however be shown on a simple plot of the number of sodium atoms in the formula against the number of aluminium atoms as shown in fig. 2. This diagram is a development of a two-axis diagram originally suggested by one of us (Layton, 1959).

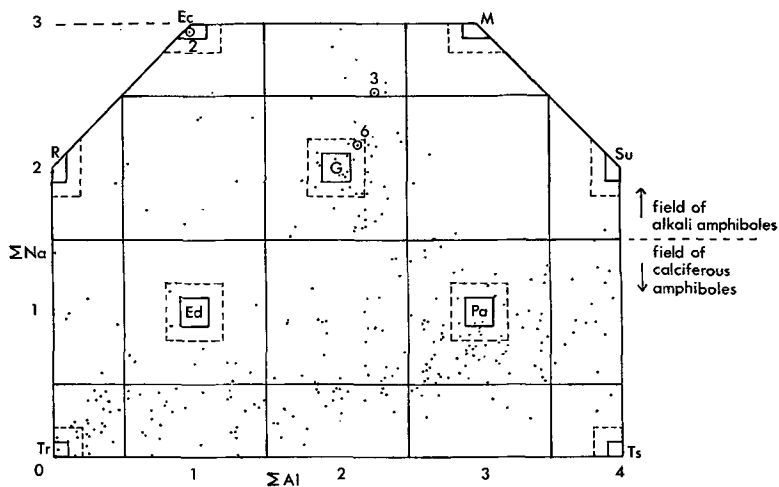


FIG. 2. The fields of the calciferous and alkali amphiboles, showing the nine end-members with their 10 %, 20 %, and 50 % solid solution fields (solid, pecked, and solid squares respectively), in a plot of total Na against total Al in the basic formula. The plotted points show the distribution of analyses from the literature on this basis (analyses from Hallimond, 1943; Winchell, 1945; Sundius, 1946; Miyashiro, 1957; and Layton, 1959).

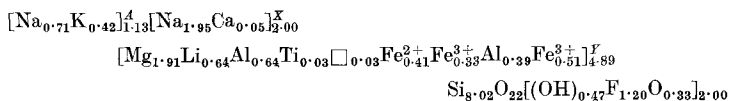
Phillips (1963) has suggested that the major divisions of the amphibole series are related to occupancy of the 'X' positions by ions of greater ionic radius than those normally present in 'Y'. In anthophyllites—the lime-free amphiboles—this is zero; in cummingtonites—the lime-poor amphiboles—there is only partial occupancy whilst in calciferous and alkali amphiboles there is full occupancy of the 'X' positions by such larger ions. Fig. 2 of this present paper suggests that there is no compositional break between the calciferous and alkali amphiboles, so an arbitrary division must be made. On fig. 2 this is shown at 1.5 sodium atoms per formula unit—calciferous amphiboles have up to 1.5 sodium plus potassium atoms per formula unit, alkali amphiboles having 1.5 to 3.0 sodium plus potassium atoms per formula unit.

Fig. 2 may also be used to show the major affinities of an actual mineral analysis if the atomic formula calculated in the normal way is converted into what may be called the *basic atomic formula*.

This is simply a formula derived by converting cations other than silicon into equivalent magnesium, sodium, or aluminium depending on their function in the lattice. The types of substitution that can be recognized have been discussed by Phillips (1963). The treatment of titanium does, however, require special mention. Its presence in the *Y* group represents either the substitution  $\text{Ti}^{4+} + \square = 2\text{Mg}^{2+}$  or  $\text{Ti}^Y + 2\text{Al}^Z = 2\text{Si}^Z$ .

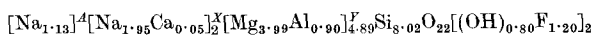
In the first case it is converted to equivalent magnesium in the basic formula by doubling the number of atoms. In the second case it is converted to equivalent aluminium in *Y* according to the scheme  $\text{Ti}^Y = 2\text{Al}^Y - \text{Mg}^Y$ . That is, a deduction must also be made from the magnesium figure.

An analysis of an eckermannite by Sundius (1946, p. 10, no. 1) is a suitable example to illustrate the method. The calculated atomic formula can be written:



Reasons for suspecting slight errors in this analysis have been given by Phillips (1963), but for the moment these may be neglected. Comparing the formula with that for tremolite- $\kappa$ , it is seen that the sodium in *X* represents the substitutions  $\square^A + \text{Ca}^X = \text{Na}^A + \text{Na}^X$  and  $\text{Ca}^X + \text{Mg}^Y = \text{Na}^X + \text{Al}^Y$ .

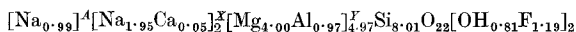
Potassium in *A* is fulfilling the same function as sodium, but the two combined are not enough to balance the sodium in *X*, so that trivalent ions in *Y* are required to complete the balance. The *Y* group has substitutions of the types:  $2\text{Mg}^{2+} = \text{Li}^+ + \text{Al}^{3+}$ ,  $2\text{Mg}^{2+} = \text{Ti}^{4+} + \square$ ,  $\text{Mg}^{2+} = \text{Fe}^{2+}$ , and  $\text{Fe}^{2+} + (\text{OH})^- = \text{Fe}^{3+} + \text{O}^{2-}$ . The last is the oxy-amphibole substitution discussed by Phillips (1963). All these substitutions are converted to equivalent magnesium. This leaves  $\text{Fe}_{0.51}^{3+}$ , which is converted to equivalent aluminium, as it is acting as aluminium in the substitution  $\text{Ca}^X + \text{Mg}^Y = \text{Na}^X + \text{Al}^Y$ . The basic atomic formula is therefore



which may be plotted as  $\text{Na} = 3.08$ ,  $\text{Al} = 0.90$  on the diagram, although

because of the errors previously referred to, it falls just outside the amphibole field. It is nevertheless very close to *Ec* on the diagram.

An adjusted formula for this amphibole, taking account of the most probable sources of error, can be derived as suggested by Phillips (1963) and when converted to a basic atomic formula this becomes



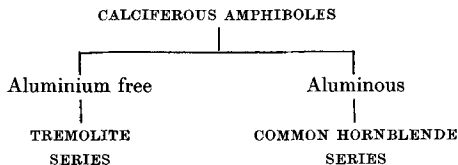
Without suggesting that this adjusted formula is necessarily any more correct than the original, it can be used to illustrate how a basic atomic formula plotting inside the amphibole field can be treated. The adjusted formula is plotted as point 2 at  $\text{Na} = 2.94$ ,  $\text{Al} = 0.97$ , on fig. 2. The smaller square around each named composition indicates a limit of 10 % solid solution of the nearest compositions with whole numbers of sodium and aluminium atoms. Since the above adjusted basic formula at point 2 falls within this square for *Ec*, we would call the basic formula eckermannite, without qualification. The next larger square represents a 20 % solid solution limit, and for compositions between 10 % and 20 % limits the description *sensu lato* may be used. The largest squares represent the 50 % solid solution limit, and for compositions between the 20 % and 50 % limits, the description *sensu extenso* may be used. Thus, on fig. 2, the point marked 6 is glaucophane *sensu lato* or *G-s.l.*, the point marked 3 is *Ec*<sub>50</sub>*M*<sub>50</sub> *s.e.*

The basic atomic formula combined with the sodium-aluminium diagram thus enables the major affinities of any calciferous or alkali amphibole to be displayed and a well-defined terminology is provided to cover the range of basic formula compositions (see fig. 2) without introducing new varietal names.

It is necessary to emphasize that the scheme as so far described ensures that a given basic formula will always receive the same name. Recent examples in the literature (Carmichael, 1963) show that without such a system even experienced workers may disagree on the name most appropriate for a certain composition. This simplification of nomenclature in a group having the wide compositional range of the amphiboles cannot be realized without some disadvantages. The basic formula takes no account of the  $\text{Mg}:\text{Fe}^{2+}$  substitution, which may be the variation of principal interest. Nevertheless, the basic formula does indicate major differences in geological environment, whilst  $\text{Mg}:\text{Fe}^{2+}$  variation is possible in all environments. A further disadvantage is that the same name will be obtained for compositions with the same amounts of sodium and aluminium, even though their distribution in

the lattice is not the same. At present this ambiguity will almost certainly be found unimportant for the non-specialist in comparison with the advantages of uniform description. For the specialist such an ambiguity is not to be tolerated, but it is at this level that a name is less important than the ability to express the composition quantitatively in percentages of end-members. An approach to this problem is described in later sections, which also illustrate how difficult it would be to apply any detailed but simple nomenclature to cover the complex combinations of end-members that may occur.

*Subdivision of the calciferous amphibole group.* For some purposes it may be useful to distinguish between calciferous amphiboles that are essentially free from aluminium and the remainder. We suggest that compositions giving basic formulae within the field of tremolite *sensu lato* should be referred to as the tremolite series, and that the remainder of the calciferous amphibole field could be regarded as the common hornblende series.



*Variation of chemical composition in the calciferous and alkali amphiboles.* As a demonstration of the range of chemical variation in these groups, some three hundred analyses from the literature have been plotted on fig. 2. No attempt has been made to check the accuracy of all the analyses, so that the diagram gives only an approximate representation of the true range in basic formulae. A small number of analyses giving aluminium greater than four were all checked. In all except three cases the analyses were obviously in error. The remaining three had appreciable amounts of ferric iron balancing the oxy-amphibole substitution and when allowance was made for this, they plotted within the diagram.

*Iron substitution.* The substitution of iron in the amphibole lattice requires the specification of iron-bearing equivalents of the nine magnesian end-members. This is complicated by the possibility of two types of iron substitution, ferrous iron for magnesium or ferric for aluminium in *Y* positions. This distinction cannot clearly be made with some of the end-member compositions that have been suggested by other authors. It may be that appreciable replacement of magnesium



by ferrous iron is automatically accompanied by replacement of aluminium by ferric iron, but until this is definitely established it is better to consider the two processes separately. The possibility of replacing three ferrous ions by two ferric plus a vacant lattice position is not considered.

We therefore recognize nine ferrous iron end-members formed by complete replacement of magnesium in the previously defined pure compositions and designated by the prefix 'ferro'. Thus, for example,  $\square\text{Ca}_2\text{Fe}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ —*ferrotremolite* (*fTr*; the abbreviated symbols previously used are prefixed by *f*). With the exception of the two new end-members and *ferro-eckermannite*, all the other names have been used in the same sense by previous authors.

It is not necessary for the purpose of this present paper to name the magnesian end-member compositions in which aluminium in *Y* is entirely replaced by ferric iron, although logically these merit the prefix 'ferri' and could be indicated in abbreviated form by the prefix *ff*. Unfortunately the prefix 'ferri' has also been used to describe oxyamphibole compositions, in which the ferric ion fulfils a different function. It is therefore best avoided until the relative importance of these two types of substitution has been more clearly evaluated.

Certain names are in fairly common use for amphiboles in which both magnesium and *Y*-position aluminium have been completely replaced by iron and it is useful to consider these here. We would use them in the following sense if necessary:

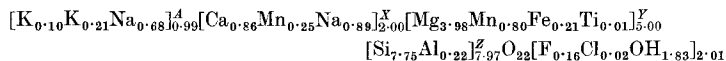
	Abbrev.	Related to
$\text{NaCa}_2\text{Fe}_4\text{Fe}^{3+}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$ — <i>Hastingsite-κ</i> . . . .	<i>Ha</i>	<i>fPa</i>
$\square\text{Na}_2\text{Fe}_3\text{Fe}_2^{3+}\text{Si}_6\text{O}_{22}(\text{OH})_2$ — <i>Riebeckite-κ</i> . . . .	<i>Re</i>	<i>fG</i>
$\text{NaCaNaFe}_4\text{Fe}^{3+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$ — <i>Catophorite-κ</i> <sup>1</sup> . . . .	<i>Ct</i>	<i>f(Ec<sub>50</sub>Pa<sub>50</sub>)</i>
$\text{NaNa}_2\text{Fe}_4\text{Fe}^{3+}\text{Si}_8\text{O}_{22}(\text{OH})_2$ — <i>Arfvedsonite-κ</i> . . . .	<i>Ar</i>	<i>fEc</i>

The magnesian iron-free equivalent of catophorite was not named as it can be expressed by *Ed<sub>50</sub>M<sub>50</sub>* or *Ec<sub>50</sub>Pa<sub>50</sub>* and its ferrous equivalent as in the table above. The term magnesiocatophorite suggested by Miyashiro (1957) would be one of our 'ferri' compositions, *ff(Ed<sub>50</sub>M<sub>50</sub>)* if the previous suggestion were accepted and magnesioriebeckite (Ernst, 1957; Miyashiro, 1957) and magnesioarfvedsonite (Andreev, 1957) would become *ffG* and *ffEc* respectively.

*Manganese substitution.* An analysis of a richterite by R. Blix quoted

<sup>1</sup> The spelling of catophorite varies; we have adopted L. J. Spencer's anglicized version of Brögger's Katoforit (Min. Mag., 1900, vol. 12, pp. 380, 385); Dana's Cataphorite is probably a misprint (Syst. Min., 6th edn, App. I).

by Sundius (1946, p. 8, Table 3, No. 1) gives an atomic formula calculated by Sundius that can be written:



in which  $\text{Ca}_{0.86}$  includes  $\text{Ba}_{0.02}$ .

There is too much manganese for it to be located solely in *Y*, so Sundius suggested that manganese partly occupied *X* positions, not only in this analysis, but in a number of other richterite analyses that he quotes. The present authors have also suggested that this is possible in the cummingtonites (Layton and Phillips, 1960). Examination of the remaining analyses in this table shows that the ratio  $\text{Mn}^X:\text{Mn}^Y$  is not constant, and that the major part of the manganese is apparently not necessarily in the *Y* group.

The solid solution of manganese can therefore only be adequately described in terms of end-members with manganese either only in the *X* position or only in the *Y* position. In the majority of amphibole analyses, manganese is only a minor constituent, so no problem arises. The basic atomic formula of an amphibole such as the one quoted above should be derived by converting manganese to equivalent magnesium or calcium. There is however an obvious need for further work on such minerals.

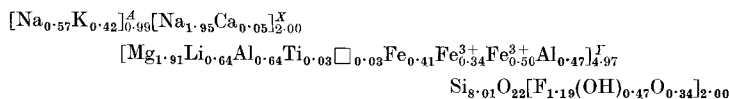
*Titanium substitution.* In many analyses of calciferous and alkali amphiboles titanium is of only minor importance. Two types of substitution are possible as discussed previously, but it is not usually necessary in either case to consider the pure titanium-bearing end-members of which only very small amounts would be required. There are nevertheless many amphiboles in which titanium is present in substantial amounts. The problems involved are somewhat complex and it is therefore proposed to discuss this subject in a separate paper.

*Potassium substitution.* The substitution of potassium for sodium has been regarded as trivial for the main purposes of this paper. However, in many published analyses, the amount of potassium may be much greater than that of sodium. It has been suggested (Phillips, 1963) that potassium enters '*A*' sites only, implying that analyses that require potassium to complete full occupancy of the '*X*' sites are suspect. This conclusion would have to be modified if it could be shown that these sites are not always fully occupied in the calciferous and alkali amphiboles as we have postulated.

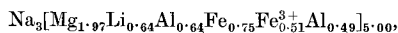
The relative amounts of sodium and potassium in an amphibole

would seem to have an important genetic significance. This is a field for further investigation which we hope to discuss at a later date.

Having plotted the basic formula, this gives an indication of which end-members must be combined to give the observed composition, as the following examples show. The adjusted formula for the Sundius eckermannite analysis referred to previously is:



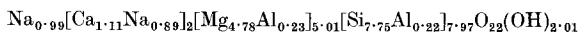
Ignoring the potassium substitution in *A*, the *A* and *X* groups together may be taken as sufficiently close to  $\text{Na}_3$  for all practical purposes. The formula can then be expressed fairly simply in terms of substituted *Ec* molecules, if the small amount of titanium is converted to equivalent magnesium and the ferric iron balancing the oxyamphibole substitution is regarded as ferrous iron. The lithium first of all requires 32%  $\text{Na}_3\text{Li}_2\text{Al}_2\text{Fe}^{3+}\text{Si}_8\text{O}_{22}(\text{OH})_2$  (*Un*), then the ferrous iron 18.75%  $\text{Na}_3\text{Fe}_4\text{Fe}^{3+}\text{Si}_8\text{O}_{22}(\text{OH})_2$  (*Ar*), and with the remainder 49.25%  $\text{Na}_3\text{Mg}_4\text{AlSi}_8\text{O}_{22}(\text{OH})_2$  (*Ec*) the final formula becomes



which is almost exactly the same as the formula required. The composition can then be stated as  $\text{Ec}_{49}\text{Ar}_{19}(\text{Un})_{32}$ , where (*Un*) indicates the unnamed lithium-substituted end-member, which is an important constituent of the mineral. This expression of the composition is more informative and likely to be of greater convenience in comparative studies. The final substitution to be considered is that of fluorine, which occupies more than half of the hydroxyl positions. An adequate name for this amphibole would seem to be *lithian fluor-eckermannite*.

If more than half of the hydroxyl positions are occupied by oxygen, the prefix oxy- should be used.

The richterite analysis quoted in the section on manganese substitution converts to a basic formula:



for which  $\text{Na} = 1.88$ ,  $\text{Al} = 0.45$  and from fig. 2 this is *R s.e.* Since the analysis plots within the triangle *R*, *Ed*, *G*, it is natural to try to express it in terms of a solid solution of these three end-members.

It should be remembered when doing this that two different compositions plot at each of the points marked *G*, *Ed*, and *Pa* on fig. 2, and in this case the composition  $\text{Ed}_{50}\text{M}_{50}$  corresponding to *G* is required. The analysis shows a very slight deficit in the *Z* group and an excess

in the *A* group compared with the theoretical requirements. Taking account of this, the composition  $R_{66}(Ed_{50}M_{50})_{23}Tr_{11}$  gives a fairly close approximation to the basic formula.

Leake (1962), in a paper considering the existence of natural amphiboles close to edenite, gives an analysis of an amphibole from Eganville, Ontario (No. 22, Table 2, p. 7). The corresponding basic formula plots as  $Na = 1.25$ ,  $Al = 1.66$ , in the field of  $(Ed_{50}Pa_{50})$  *s.e.* It is immediately obvious from fig. 2 that this composition is appreciably removed from that of edenite, and the nature of the discrepancy can be assessed rather more accurately than by simple inspection of the full formula.

From earlier comments it is obvious that a given atomic formula and the basic formula derived from it will not in general correspond with a unique combination of end-member formulae, although this may occur in special cases. Uniformity between users of the system can be achieved if a standard procedure, illustrated by the following example, is used:

Given a basic formula  $\square_{0.40}Na_{0.60}Ca_{0.95}Na_{1.05}Mg_{3.27}Al_{1.73}Si_{6.72}Al_{1.28}O_{22}(OH)_2$ , first check that occupancy of the various sites agrees with the amphibole formula and that  $Na^X + Al^Z = Na^A + Al^Y$ . Next, plot on fig. 2; in this case,  $\sum Na = 1.65$ ,  $\sum Al = 3.01$ , and the formula plots in the field of  $(G_{50}Su_{50})$  *s.e.* Now make a trial match, using the three nearest end-member compositions on the diagram; in case of ambiguity use compositions having smaller amounts of Na and Al substitution (for example, the above plot can be considered to lie in the triangle *M-Pa-Su* or in the triangle *G-Pa-Su*; by this rule the second combination is used; it is also obvious in this case that the first group cannot give a match since none of the members has vacancies in *A*). Note that *G* alone of the group *G-Pa-Su* has vacancies in *A*, and that 40% of *G* would be required; but the remaining 60% of *Pa+Su*, since both have  $Si_6Al_2$ , will only give 1.20  $Al^Z$ , less than is required. Therefore some of *G* must be replaced by a composition having vacancies in *A* and Al in *Z*; *Ts* is the only possibility, and 4% will supply the additional 0.08 Al required in *Z*. Finally, 33% *Su* is needed to provide the required amount of  $Na^X$ , leading to the desired combination:  $G_{36}Su_{33}Pa_{27}Ts_4$ .

These few examples illustrate principles that may be applied in the examination of all amphibole analyses. It is hoped that they will prove to be a more accurate means of comparing analyses than has previously been available, and so assist in the understanding of substitution problems in this complex mineral group.

*References*

- [ANDREEV (YU. K.)] Андреев (Ю. К.), 1957. [Труды Инст. Геол. Руд., Месторожд., Петрог., Мин., Геохим. (Trans. Inst. Geol. Ore-deposits, Petr., Min., Geochem.), vol. 10, p. 12]; abstr. in Зап. Всесоюз. Мин. Общ. (Mem. All-Union Min. Soc.), 1958, vol. 87, p. 486.
- BOYD (F. R.), 1954. Geophysical Laboratory Annual Report.
- CARMICHAEL (I. S. E.), 1963. Bull. Inst. Min. Met., vol. 72, no. 676, p. xii (book review).
- DEER (W. A.), HOWIE (R. A.), and ZUSSMAN (J.), 1963. Rock-forming minerals, vol. 2, Chain silicates. Longmans, London.
- ERNST (W. G.), 1957. Geophysical Laboratory Annual Report.
- FRANCIS (G. H.), 1958. Bull. Brit. Mus. (Nat. Hist.) Min., vol. 1, No. 5.
- HALLIMOND (A. F.), 1943. Amer. Min., vol. 28, p. 65.
- LAYTON (W.), 1959. Unpublished Ph.D. thesis, Durham.
- and PHILLIPS (R.), 1960. Min. Mag., vol. 32, p. 659.
- LEAKE (B. E.), 1962. Japan. Journ. Geol. Geogr., vol. 33, p. 1.
- MIYASHIRO (A.), 1957. Jour. Fac. Sci. Tokyo Univ., vol. 11, p. 57.
- PHILLIPS (R.), 1963. Min. Mag., vol. 33, p. 701.
- SMITH (J. V.), 1959. Amer. Min., vol. 44, p. 437.
- SUNDIUS (N.), 1946. Sveriges Geol. Undersökning, vol. 40, No. 480.
- WINCHELL (A. N.), 1945. Amer. Min., vol. 30, p. 27.

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*Editorial note:* Ernst (1957) used the names magnesian glaucophane ( $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ ) and magnesian riebeckite ( $\text{Na}_2\text{Mg}_3\text{Fe}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$ ); this is a dangerous misuse of Schaller's adjectival prefixes, which ought invariably to indicate a partial substitution by the element named, never a complete one.