

# Nomenclature of Amphiboles: Report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on New Minerals and Mineral Names

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### Abstract

The International Mineralogical Association's approved amphibole nomenclature has been revised in order to simplify it, make it more consistent with divisions generally at 50%, define prefixes and modifiers more precisely and include new amphibole species discovered and named since 1978, when the previous scheme was approved. The same reference axes form the basis of the new scheme and most names are little changed but compound species names like tremolitic hornblende (now magnesiohornblende) are abolished and also crossite (now glaucophane or ferroglaucophane or magnesioriebeckite or riebeckite), tirodite (now manganocummingtonite) and dannemorite (now manganogrunerite). The 50% rule has been broken only to retain tremolite and actinolite as in the 1978 scheme so the sodic calcic amphibole range has therefore been expanded. Alkali amphiboles are now sodic amphiboles. The use of hyphens is defined. New amphibole names approved since 1978 include nyböite, leakeite, kornite, ungarettiite, sadanagaite and cannilloite. All abandoned names are listed. The formulae and source of the amphibole end member names are listed and procedures outlined to calculate  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  when not determined by analysis.

KEYWORDS: amphibole nomenclature, crossite, dannemorite, tirodite.

### Introduction

THIS report was produced in response to a motion at the IMA 1986 meeting in Stanford, California asking the CNMMN to produce a more simplified amphibole nomenclature than that currently approved which dates from 1978. The 1978 nomenclature (IMA 78) took over 13 years to formulate; a quicker response was attempted this time.

To ensure a fresh look at the nomenclature scheme the Chairman of the Amphibole Subcommittee, Prof. B.E. Leake, with the agreement of the CNMMN

officials, completely reconstituted the committee so that (1) representation was more international; (2) more than 80% of the voting members of the committee were not members of the committee which produced the 1978 report; in addition, none of the CNMMN officials was on the 1978 committee; (3) three members were retained from the 1978 committee to ensure that there was some continuity and collective memory of the main problems that had been dealt with previously; (4) representation included the principal proposer to the CNMMN of an improved nomenclature scheme; (5) representation was across the various fields concerned with amphibole nomenclature from crystal-chemists,

\* Indicates a non-voting official of the CNMMN.

metamorphic and igneous petrologists to computer experts and ordinary broad-based petrologists. There were 18 voting members when the major framework of the revised scheme was approved.

The committee circulated over 1000 pages over nine years, and considered in detail all proposals made to it. Views were expressed that because the amphibole system is so complicated, adequate representation cannot be made with two- and three-dimensional diagrams whereas four variables can represent the system adequately. However, the committee, by a very large majority, wanted to retain conventional nomenclature diagrams because they are easier for most scientists to use. The committee considered a range of different naming schemes, but none was judged overall to be sufficiently better to justify abandoning the main basis of IMA 78 which has been widely accepted and is capable of simplification to provide an improved scheme. It must be remembered that over 95% of all amphibole analyses are currently obtained by electron microprobe with no structural information, no knowledge of the oxidation states of Fe, Ti and Mn, the H<sub>2</sub>O content or how the site populations are derived. What follows is a *nomenclature* scheme, not one to determine at which position the ions really are located. All numbers are atoms per formula unit.

The proposed scheme involves reducing the number of subdivisions, especially in the calcic amphiboles, making the divisions generally follow the 50% rule (whereas IMA 78 uses divisions at 90%, 70%, 66%, 50%, 33%, 30% and 10%), and making the use of adjectival modifiers (additional to prefixes which are part of the basic names) optional. The new scheme has over 20 fewer names than IMA 78 and involves the abolition of only a few commonly used names such as crossite. End member formulae defined and approved in IMA 78 are generally retained although the ranges to which they apply have often been changed.

The principal reference axes of IMA 78, namely Si, Na<sub>B</sub> and (Na+K)<sub>A</sub> (see below), are retained, but the primary divisions between the calcic, sodic-calcic and alkali (renamed sodic) amphiboles have been adjusted to divisions at Na<sub>B</sub> < 0.50 and Na<sub>B</sub> ≥ 1.50, instead of Na<sub>B</sub> < 0.67 and Na<sub>B</sub> ≥ 1.34. Previously, the amphibole 'box' was divided into three equal volumes with respect to Na<sub>B</sub>. The new scheme enlarges the sodic-calcic amphiboles at the expense of the calcic and sodic amphiboles (Fig. 1) in order to make the divisions at 50% positions.

As with the 1978 scheme, the problem of what to do with analyses in which only the total iron is known (and not its division into FeO and Fe<sub>2</sub>O<sub>3</sub>) has been left to individual judgement although a recommended procedure is given. This means that again an analysis may yield different names depending upon the

procedure used to estimate Fe<sup>3+</sup> and Fe<sup>2+</sup>. It clearly would be advantageous *for naming purposes* if the recommended procedure were followed even if other procedures were used for other purposes.

General works dealing with the amphiboles include Deer *et al.* (1963, 1997), Ernst (1968), Chukhrov (1981), Veblen (1981), Veblen & Ribbe (1982), Anthony *et al.* (1995) and Hawthorne (1983) from which adequate general background summaries can be obtained. Appendix 1 lists the derivations of amphibole end member names.

### General classification of the amphiboles

As with the IMA 78 scheme, the proposed nomenclature is based on chemistry and crystal symmetry; when it is necessary to distinguish different polytypes or polymorphs, this may be done by adding the space group symbol as suffix. Anthophyllites with *Pnmm* symmetry (as distinct from the more usual *Pnma* symmetry) may be prefixed proto.

The classification is based on the chemical contents of the standard amphibole formula AB<sub>2</sub>C<sub>5</sub><sup>VI</sup>T<sub>8</sub><sup>IV</sup>O<sub>22</sub>(OH)<sub>2</sub>. It is to be noted, however, that possession of this formula does not define an amphibole. An amphibole must have a structure based on a double silicate chain: a biopyribole consisting of equal numbers of pyroxene chains and triple chains would have this formula but would not be an amphibole.

The components of the formula conventionally described as A, B, C, T and 'OH' correspond to the following crystallographic sites:

A	1 site formula unit;
B	2 M4 sites per formula unit;
C	a composite of 5 sites made up of 2 M1, 2 M2 and 1 M3 sites per formula unit;
T	8 sites, in two sets of 4 which need not be distinguished in this document;
'OH'	2 sites per formula unit.

The ions considered NORMALLY to occupy these sites are in the following categories:

□ (empty site) and K	at A only
Na	at A or B
Ca	at B only
L type ions: Mg, Fe <sup>2+</sup> , Mn <sup>2+</sup> , Li and rarer ions of similar size such as Zn, Ni, Co	at C or B
M type ions: Al	at C or T
Fe <sup>3+</sup> and more rarely Mn <sup>3+</sup> , Cr <sup>3+</sup>	at C only
High valency ions: Ti <sup>4+</sup>	at C or T
Zr <sup>4+</sup>	at C only
Si	at T only
Anions, OH, F, Cl, O	at 'OH'

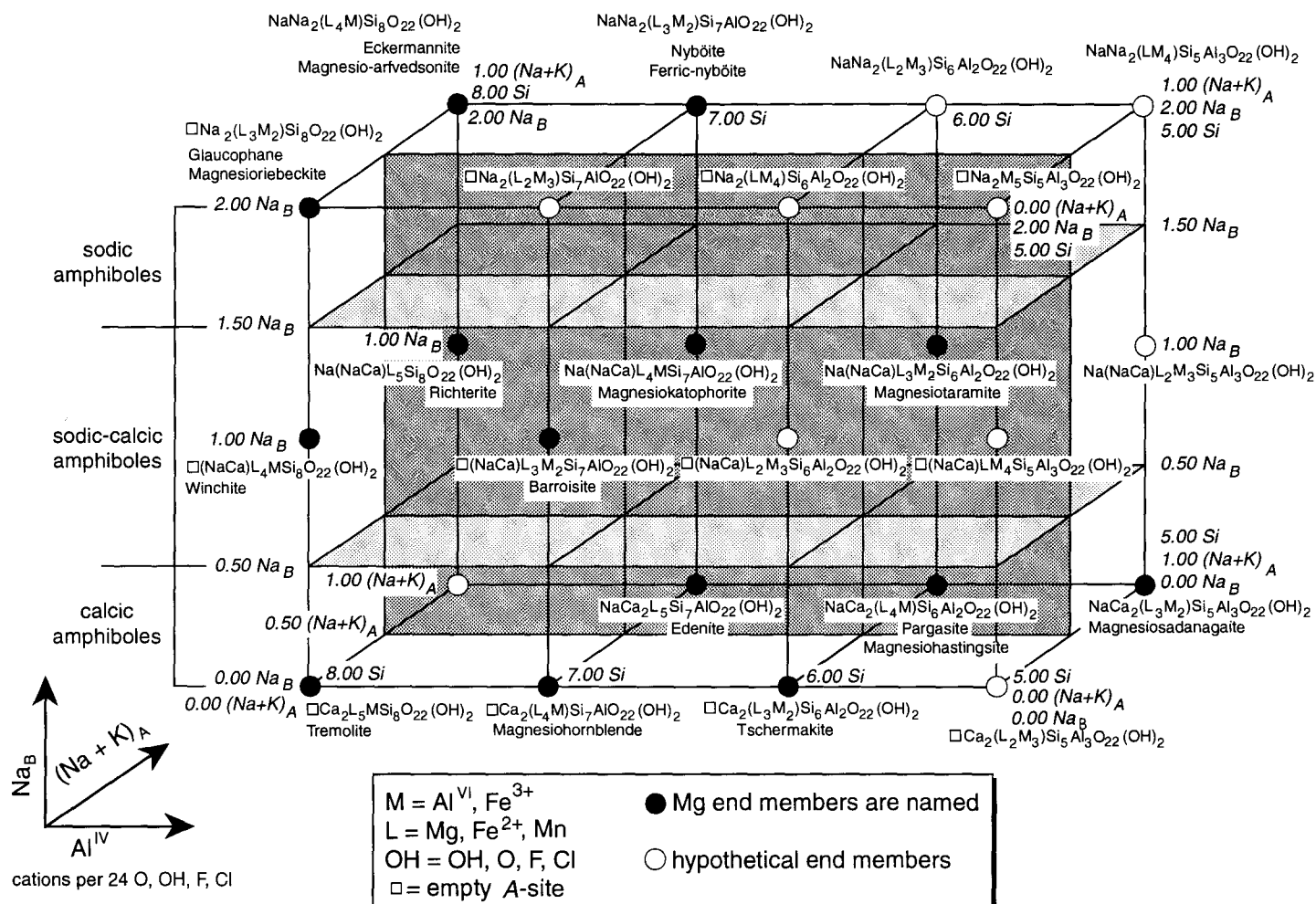


FIG. 1. General classification of the amphiboles excluding the Mg-Fe-Mn-Li amphiboles.

M type ions normally occupy M2 sites and so are normally limited to 2 of the 5 C sites. Exceptions may occur to the above 'normal' behaviour but are ignored for the present purposes of nomenclature.

Throughout this report superscript arabic numerals refer to ionic charge (oxidation state) eg.  $\text{Fe}^{2+}$ ; superscript roman numerals to coordination numbers e.g.  $\text{Al}^{\text{VI}}$ ; and subscript numerals to numbers of atoms e.g.  $\text{Ca}_2$ .

To take account of these facts it is recommended that the standard amphibole formula be calculated as follows, though it must be clearly appreciated that this is an arithmetic convention that assigns ions to convenient and reasonable site occupancies. These cannot be confirmed without direct structural evidence.

- (1) If  $\text{H}_2\text{O}$  and halogen contents are well established, the formula should be calculated to  $24(\text{O}, \text{OH}, \text{F}, \text{Cl})$ .
- (2) If the  $\text{H}_2\text{O}$  plus halogen content is uncertain, the formula should be calculated to the basis of  $23(\text{O})$  with  $2(\text{OH}, \text{F}, \text{Cl})$  assumed, unless this leads to an impossibility of satisfying any of the following criteria, in which case an appropriate change in the assumed number of  $(\text{OH} + \text{F} + \text{Cl})$  should be made.
- (3) Sum T to 8.00 using Si, then Al, then Ti. For the sake of simplicity of nomenclature  $\text{Fe}^{3+}$  is not allocated to T. The normal maximum substitution for Si is 2, but this can be exceeded.
- (4) Sum C to 5.00 using excess Al and Ti from (3) and then successively Zr,  $\text{Cr}^{3+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Mn}^{3+}$ , Mg,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$ , any other  $\text{L}^{2+}$  type ions, and then Li.
- (5) Sum B to 2.00 using excess Mg,  $\text{Fe}^{2+}$ ,  $\text{Mn}^{2+}$  and Li from (4), then Ca, then Na.
- (6) Excess Na from (5) is assigned to A, then all K. Total A should be between 0.00 and 1.00.

The most common uncertainty results from lack of analyses for  $\text{H}_2\text{O}$ ,  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$ . The procedure adopted to divide the Fe into  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  can influence the resulting name, especially if an analysis is near to  $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 0.50$  or  $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Al}^{\text{VI}}) = 0.50$ , i.e. the same analysis may give two or more names depending upon the allocation of the Fe. The committee was almost unanimous in not wanting to specify one compulsory procedure for allocating  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  but in *recommending* that a common procedure be used *for naming purposes*. Rock and Leake (1984) showed that, based on processing over 500 amphibole analyses, the IMA-favoured procedure of adjusting the sum of the  $(\text{Si} + \text{Al} + \text{Cr} + \text{Ti} + \text{Fe} + \text{Mg} + \text{Mn})$  to 13 by varying the  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  appropriately gave  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  values reasonably close to the true determined values

in 80% of the analyses studied, excluding kaersutites, for the calcic, sodic-calcic and sodic amphiboles. If this sum is adjusted to include Li and Zr i.e.  $(\text{Si} + \text{Al} + \text{Cr} + \text{Ti} + \text{Zr} + \text{Li} + \text{Fe} + \text{Mg} + \text{Mn}) = 13$  and for the Mg-Fe-Mn-Li amphiboles the sum of  $(\text{Si} + \text{Al} + \text{Cr} + \text{Ti} + \text{Zr} + \text{Li} + \text{Fe} + \text{Mg} + \text{Mn} + \text{Ca}) = 15$  is used, then only the  $\text{Ti} \geq 0.50$  amphiboles need special treatment, although it is recognised that Mn-rich amphiboles pose problems with the variable valency state of both the Fe and Mn and that, as shown by Hawthorne (1983, pp. 183–5), both in theory and practice, any calculation of  $\text{Fe}^{3+}$  and  $\text{Fe}^{2+}$  values is subject to considerable uncertainty. A full discussion of the problem and a recommended procedure, both by Dr J.C. Schumacher, are given as an appendix. Some analyses have  $\text{H}_2\text{O} +$  contents that lead to more than  $(\text{OH})_2$  in the formula, but the structure contains only 2 sites for independent  $\text{OH}^-$  ions and the structural role of the extra H ions is uncertain.

The amphiboles are classified primarily into 4 groups depending on the occupancy of the B sites. These 4 principal amphibole groups are slightly redefined as compared with IMA 78 and are:

- (1) When  $(\text{Ca} + \text{Na})_{\text{B}} < 1.00$  and L type ions  $(\text{Mg}, \text{Fe}, \text{Mn}, \text{Li})_{\text{B}} \geq 1.00$ , then the amphibole is a member of the *magnesium-iron-manganese-lithium group*.
- (2) When  $(\text{Ca} + \text{Na})_{\text{B}} \geq 1.00$  and  $\text{Na}_{\text{B}} < 0.50$ , then the amphibole is a member of the *calcic group*. Usually, but not always,  $\text{Ca}_{\text{B}} > 1.50$ .
- (3) When  $(\text{Ca} + \text{Na})_{\text{B}} \geq 1.00$  and  $\text{Na}_{\text{B}} 0.50$  to 1.50, then the amphibole is a member of the *sodic-calcic group*.
- (4) When  $\text{Na}_{\text{B}} \geq 1.50$ , then the amphibole is a member of the *sodic group*, previously alkali amphiboles. The new name is more precise, as Na is the critical element, not any other alkali element such as K or Li.

Within each of these groups an analysis can then be named by reference to the appropriate two-dimensional diagram (Figs 2–5). These are subdivided with respect to Si and  $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$  or  $\text{Mg}/(\text{Mg} + \text{Mn}^{2+})$ , with *prefixes* to indicate major substitutions and *optional modifiers* to specify less important substitutions

Within the groups, the amphiboles are divided into individually named species distinguished from one another on the basis of the heterovalent substitutions:  $\text{Si} = \text{Al}^{\text{IV}}$ ,  $\square = (\text{Na}, \text{K})_{\text{A}}$ ,  $\text{Ca}_{\text{B}} = \text{Na}_{\text{B}}$ ,  $\text{Li} = \text{L}^2$ ,  $\text{M}_{\text{C}} = \text{L}_{\text{C}}^2$ ,  $(\text{Ti}, \text{Zr}) = \text{L}_{\text{C}}$ ,  $\text{O} = (\text{OH}, \text{F}, \text{Cl})$ . These substitutions necessarily occur in pairs or multiplets to maintain neutrality. The species defined on this basis are shown in Fig. 1 and along the horizontal axes of Figs 2–5. Different species defined in this way correspond to different distributions of charge over

the A, B, C, T, and 'OH' sites. Discovery of amphiboles with new or quantitatively extended distributions of charge over these sites would merit the introduction of new species names.

Within the species there occur homovalent substitutions, most commonly  $Mg = Fe^{2+}$ ,  $Al^{VI} = Fe^{3+}$  and  $OH = F$ . The end members of these substitution ranges are distinguished by the use of prefixes, one or other end member usually having a traditional name without a prefix. These substitutions usually correspond to independent binary systems X–Y: the name of the X end member applies in the range  $1.00 > X/(X+Y) > 0.50$  and the name of the Y end member to  $1.00 > Y/(X+Y) > 0.50$ . For the boundaries of substitution ranges in ternary systems see Nickel (1992).

*The discovery of amphiboles with new or exotic homovalent substitutions never requires a new species name. They can always be named by use of an appropriate prefix. In future one root or trivial name ONLY should be approved for each charge arrangement in each amphibole group and all species defined by homovalent substitutions should be designated by the relevant prefix. New species defined by heterovalent substitutions (including major oxygen replacement of (OH, F, Cl) and major entry of high (>3) charged cations into A, B or C) result in new root, or trivial names.*

The principal reference axes chosen for the calcic, sodic-calcic and sodic amphiboles are as in IMA 78 namely  $Na_B$ ,  $(Na+K)_A$ , and Si as shown in Fig. 1, but the subdivision into the sodic-calcic group is now at  $Na_B$  0.50 (instead of 0.67) and  $Na_B$  1.50 (instead of 1.34). This increases the volume, and therefore the number of analyses, assigned to the sodic-calcic

amphiboles at the expense of the calcic and sodic amphibole groups but is a logical consequence of applying the 50% rule for all divisions rather than dividing the  $Na_B$ ,  $(Na+K)_A$  and Si box into equal volumes as in IMA 78. The committee considered at length various proposals for the use of axes other than the three chosen, including four components, but eventually agreed, by a significant majority, that the IMA 78 axes be retained, despite their inability to represent  $R^{2+}$  and  $R^{3+}$  (i.e. usually L and M type ions) separately in the C group. The importance of the difference between  $R^{2+}$  and  $R^{3+}$  in the C group has however been recognised rather more formally than previously by the way in which  $Fe^{3+}$ ,  $Al^{3+}$ ,  $Cr^{3+}$  or  $Mn^{3+}$  abundance has been defined with prefixes, not modifiers, when they occupy 50% or more of the normal maximum of  $2R_C^{3+}$  as shown in Table 1.

Following Nickel and Mandarino (1988), prefixes are an essential part of a mineral name (e.g. ferroglaucophane and ferro-actinolite), whereas modifiers indicate a compositional variant, and may be omitted (e.g. potassian pargasite). Modifiers generally represent subsidiary substitutions whereas prefixes denote major substitutions. In order to reduce the number of hyphens used, a single prefix is generally joined directly to the root name without a hyphen (e.g. ferrohornblende) unless two vowels would then adjoin (e.g. ferro-actinolite) or "an unhyphenated name is awkward and a hyphen assists in deciphering the name" (Nickel and Mandarino, 1988) e.g. ferric-nyböite. For all amphibole names involving multiple prefixes, a hyphen shall be inserted between the prefixes but not between the last prefix and the root name, unless two vowels would be juxtaposed or the name would be difficult to decipher or awkward. Thus

TABLE 1. Prefixes additional to those in the figures

Prefix	Meaning	Applicable to
Alumino	$Al^{VI} > 1.00$	Calcic & sodic-calcic only
Chloro	Cl $> 1.00$	All groups
Chromio	Cr $> 1.00$	All groups
Ferri	$Fe^{3+} > 1.00$	All groups except sodic
Fluoro	F $> 1.00$	All groups
Mangano	$Mn^{2+} = 1.00-2.99$	All groups except kozulite & ungarrettiite
Permangano	$Mn^{2+} = 3.00-4.99$	All groups except kozulite
Mangani	$Mn^{3+} > 1.00$	All groups except kornite & ungarrettiite
Potassic	K $> 0.50$	All groups
Sodic	Na $> 0.50$	Mg-Fe-Mn-Li only
Titano	Ti $> 0.50$	All groups except kaersutite
Zinco	Zn $> 1.00$	All groups

The prefixes in the figures are ferro ( $Fe^{2+} > Mg$ ) and magnesio ( $Fe^{2+} < Mg$ ) and in Fig. 5a only ferric-nyböite with  $Al^{VI} < Fe^{3+}$  (not ferricnyböite which is not clear).

alumino-ferrohornblende, chloro-ferro-actinolite and fluoro-ferri-cannilloite. Most (>90%) names will lack any hyphens and less than 5% will have more than one prefix.

In general, excluding juxtaposed vowels, the prefixes (Table 1), which have o, i or ic endings, are either attached directly to the root name (without a space or hyphen) or to a following prefix with a hyphen. All these characters distinguish them from modifiers.

All the modifiers (Table 2) have 'ian' or 'oan' endings to indicate moderate substitutions as listed by Nickel & Mandarino (1988). Modifiers are not accompanied by hyphens and are invariably followed by a space and then the remainder of the name. The excluded applications follow from the fact that these groups will usually have substantial contents of these elements as part of the parameters which define them. The use of modifiers is optional and strictly qualitative (i.e. they can be used in other senses than in Table 2 but use as in Table 2 is strongly recommended).

*Naming of amphiboles in thin section and hand specimen*

For amphiboles of which the general nature only is known, for instance from optical properties without a chemical analysis, it is not generally possible to

allocate a precise name. The nearest assigned amphibole name should then be made into an adjective followed by the word amphibole. Thus anthophyllitic amphibole, tremolitic amphibole, pargasitic amphibole, glaucophanic amphibole and richteritic amphibole. The familiar word hornblende can still be used where appropriate for calcic amphiboles in both hand specimen and thin section, because hornblende is never used without an adjective in the precise classification, so no confusion should arise between colloquial use and precise use.

As in IMA 78, asbestiform amphiboles should be named according to their precise mineral name in this report, followed by the suffix -asbestos: e.g. anthophyllite-asbestos, tremolite-asbestos. Where the nature of the mineral is uncertain or unknown, asbestos alone or amphibole-asbestos may be appropriate. If the approximate nature of the mineral only is known the above recommendations should be followed but the word amphibole replaced by asbestos e.g. anthophyllitic asbestos, tremolitic asbestos.

**Mg-Fe-Mn-Li amphiboles**

The group is defined as possessing  $(Ca+Na)_B < 1.00$  and  $(Mg,Fe,Mn,Li)_B \geq 1.00$  in the standard formula;

TABLE 2. Modifiers and their suggested ranges

Modifier	Meaning	Applicable to
Barian	Ba > 0.10	All groups
Borian	B > 0.10	All groups
Calcian	Ca > 0.50	Mg-Fe-Mn-Li
Chlorian	Cl = 0.25-0.99	All groups
Chromian	Cr = 0.25-0.99	All groups
Ferrian	Fe <sup>3+</sup> = 0.75-0.99	All groups except sodic
Fluorian	F = 0.25-0.99	All groups
Hydroxylian	OH > 3.00	All groups
Lithian	Li > 0.25	All groups but excludes those defined by Li abundance (e.g. holmquistite)
Manganoan	Mn <sup>2+</sup> = 0.25-0.99	All groups but excludes those defined by Mn <sup>2+</sup> abundance
Manganian	Mn <sup>3+</sup> or Mn <sup>4+</sup> = 0.25-0.99	Ditto, Mn <sup>3+</sup> abundance (e.g. kornite)
Nickeloan	Ni > 0.10	All groups
Oxygenian	(OH+F+Cl) < 1.00	All groups except ungarrettiite
Potassian	K = 0.25-0.49	All groups
Plumbian	Pb > 0.10	All groups
Sodian	Na = 0.25-0.49	Mg-Fe-Mn-Li only
Strontian	Sr > 0.10	All groups
Titanian	Ti = 0.25-0.49	All groups
Vanadian	V > 0.10	All groups
Zincian	Zn > 0.10-0.99	All groups
Zirconian	Zr > 0.10	All groups

## Mg-Fe-Mn-Li amphiboles

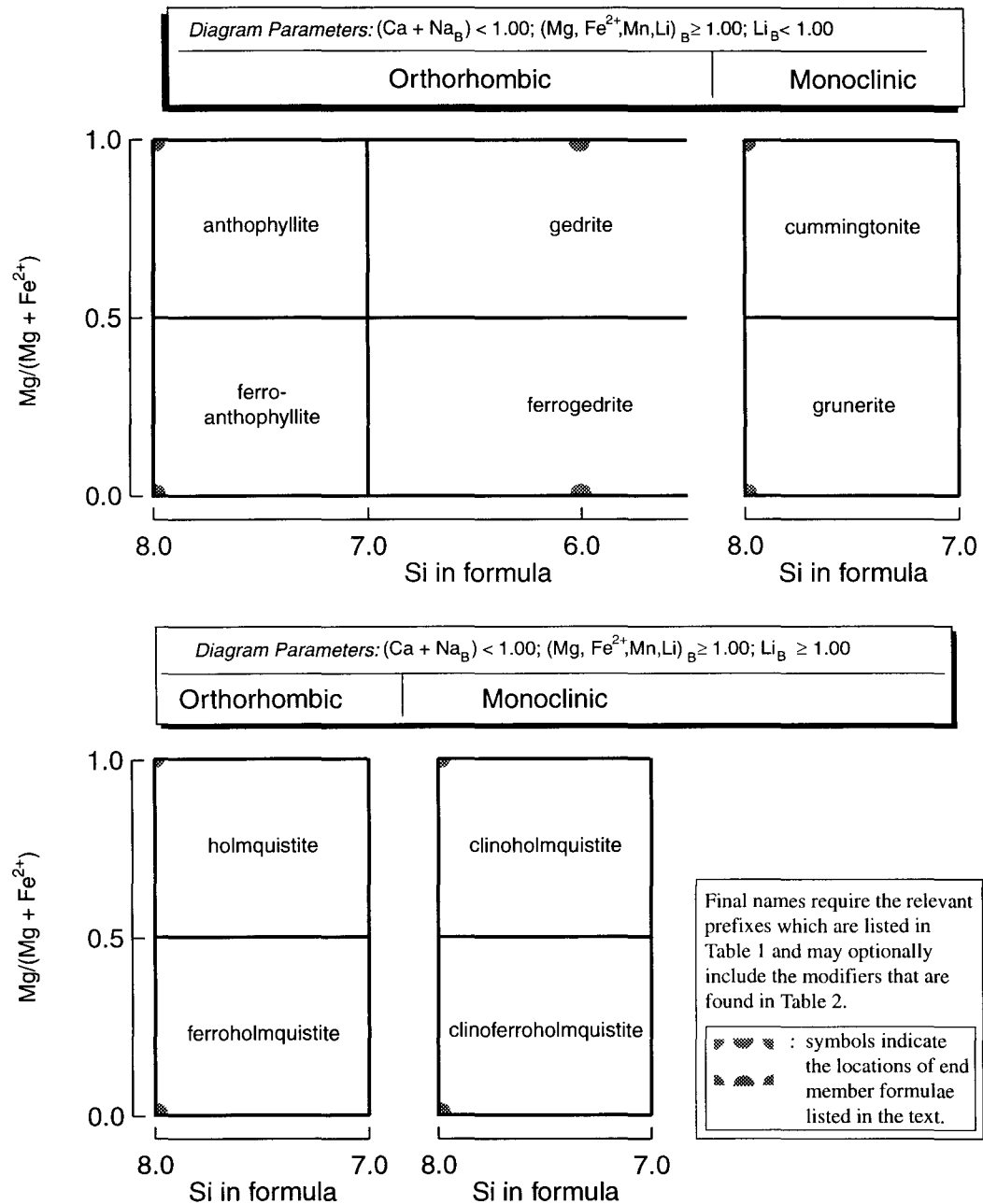


FIG. 2. Classification of the Mg-Fe-Mn-Li amphiboles.



the detailed classification is shown in Fig. 2. The main changes from IMA 78 are the adoption of divisions at  $Mg/(Mg+Fe^{2+}) = 0.50$ , the reduction of adjectives and the abolition of tirodite and dannemorite.

#### Orthorhombic forms

##### (1) Anthophyllite series.

$Na_xLi_z(Mg,Fe^{2+},Mn)_{7-y-z}Al_y(Si_{8-x-y+z}Al_{x+y-z})O_{22}(OH,F,Cl)_2$  where  $Si > 7.00$  (otherwise the mineral is gedrite) and  $Li < 1.00$  (otherwise the mineral is holmquistite). Most anthophyllites have the *Pnma* structure; those with the *Pnmm* structure may be prefixed proto without a hyphen.

##### End members

Anthophyllite	$\square Mg_7Si_8O_{22}(OH)_2$
Ferro-anthophyllite	$\square Fe_7^{2+}Si_8O_{22}(OH)_2$
Sodicanthophyllite	$NaMg_7Si_7AlO_{22}(OH)_2$
Sodic-ferro-anthophyllite	$NaFe_7^{2+}Si_7AlO_{22}(OH)_2$

##### Limits for the use of end member names

Anthophyllite	$Mg/(Mg+Fe^{2+}) \geq 0.50$
Ferro-anthophyllite	$Mg/(Mg+Fe^{2+}) < 0.50$
Sodicanthophyllite	$Mg/(Mg+Fe^{2+}) \geq 0.50; Na \geq 0.50$
Sodic-ferro-anthophyllite	$Mg/(Mg+Fe^{2+}) < 0.50; Na \geq 0.50$

##### (2) Gedrite series

$Na_xLi_z(Mg,Fe^{2+},Mn)_{7-y-z}Al_y(Si_{8-x-y+z}Al_{x+y-z})O_{22}(OH,F,Cl)_2$  where  $x + y - z \geq 1.00$  so that  $Si \geq 7.00$  this being the distinction from anthophyllite.  $Li < 1.00$ .

##### End members

Gedrite	$\square Mg_5Al_2Si_6Al_2O_{22}(OH)_2$
Ferrogedrite	$\square Fe_5^{2+}Al_2Si_6Al_2O_{22}(OH)_2$
Sodicgedrite	$NaMg_6AlSi_6Al_2O_{22}(OH)_2$
Sodic-ferrogedrite	$NaFe_6^{2+}AlSi_6Al_2O_{22}(OH)_2$

##### Limits for the use of end member names

Gedrite	$Mg/(Mg+Fe^{2+}) \geq 0.50$
Ferrogedrite	$Mg/(Mg+Fe^{2+}) < 0.50$
Sodicgedrite	$Mg/(Mg+Fe^{2+}) \geq 0.50; Na \geq 0.50$
Sodic-ferrogedrite	$Mg/(Mg+Fe^{2+}) < 0.50; Na \geq 0.50$

It should be noted that gedrite and ferrogedrite, with or without sodic-prefixes, extend down to at least  $Si \ 5.50$ . Discovery of homogeneous  $Na(Fe,Mg)_5Al_2Si_5Al_3O_{22}(OH)_2$  will justify a new name.

##### (3) Holmquistite series

$\square (Li_2(Mg,Fe^{2+})_3(Fe^{3+},Al)_2)Si_8O_{22}(OH,F,Cl)_2$ .  $Li \geq 1.00$  is critical.

##### End members

Holmquistite	$\square (Li_2Mg_3Al_2)Si_8O_{22}(OH)_2$
Ferroholmquistite	$\square (Li_2Fe_3^{2+}Al_2)Si_8O_{22}(OH)_2$

##### Limits for the use of end member names

Holmquistite	$Mg/(Mg+Fe^{2+}) \geq 0.50$
Ferroholmquistite	$Mg/(Mg+Fe^{2+}) < 0.50$

#### Monoclinic forms

##### (1) Cummingtonite-Grunerite series

$\square (Mg,Fe^{2+},Mn,Li)_7Si_8O_{22}(OH)_2$ .  $Li < 1.00$ . Most members of this series have space group *C2/m*; those with *P2/m* may optionally have this symbol suffixed at the end of the name.

##### End members

Cummingtonite	$\square Mg_7Si_8O_{22}(OH)_2$
Grunerite	$\square Fe_7^{2+}Si_8O_{22}(OH)_2$
Manganocummingtonite	$\square Mn_2Mg_5Si_8O_{22}(OH)_2$
Permanganogrunerite	$\square Mn_4Fe_3^{2+}Si_8O_{22}(OH)_2$
Manganogrunerite	$\square Mn_2Fe_5^{2+}Si_8O_{22}(OH)_2$

##### Limits for the use of end member names

Cummingtonite	$Mg/(Mg+Fe^{2+}) \geq 0.50$
Grunerite	$Mg/(Mg+Fe^{2+}) < 0.50$
Manganocummingtonite	$Mg/(Mg+Fe^{2+}) \geq 0.50; 1.00 < Mn < 3.00$
Permanganogrunerite	$Mg/(Mg+Fe^{2+}) < 0.50; 3.00 < Mn < 5.00$
Manganogrunerite	$Mg/(Mg+Fe^{2+}) < 0.50; 1.00 < Mn < 3.00$

It should be noted that the names given extend down to 7.00 Si. If a mineral with less than Si 7.00 is discovered, then it will justify a new name based on the end member  $Mg_5Al_2Si_6Al_2O_{22}(OH)_2$ .

##### (2) Clinoholmquistite series

$\square (Li_2(Mg,Fe^{2+},Mn)_3(Fe^{3+},Al)_2)Si_8O_{22}(OH,F,Cl)_2$ .  $Li \geq 1.00$

##### End members

Clinoholmquistite	$\square (Li_2Mg_3Al_2)Si_8O_{22}(OH)_2$
Clinoferroholmquistite	$\square (Li_2Fe_3^{2+}Al_2)Si_8O_{22}(OH)_2$
Ferri-clinoholmquistite	$\square (Li_2Mg_3Fe_2^{3+})Si_8O_{22}(OH)_2$
Ferri-clinoferroholmquistite	$\square (Li_2Fe_3^{2+}Fe_2^{3+})Si_8O_{22}(OH)_2$

##### Limits for the use of end member names

Clinoholmquistite	$Mg/(Mg+Fe^{2+}) \geq 0.50$
Clinoferroholmquistite	$Mg/(Mg+Fe^{2+}) < 0.50$
Ferri-clinoholmquistite	$Fe^{3+} > 1; Mg/(Mg+Fe^{2+}) \geq 0.50$
Ferri-clinoferroholmquistite	$Fe^{3+} > 1; Mg/(Mg+Fe^{2+}) < 0.50$

### Calcic amphiboles

The group is defined as monoclinic amphiboles in which  $(Ca + Na)_B \geq 1.00$  and  $Na_B = 0.50$  to  $1.50$ ; usually  $Ca_B \geq 1.50$ . The detailed classification is shown in Fig. 3. The number of subdivisions used in IMA 78 has been more than halved; silicic edenite and compound names like tschermakitic hornblende have been abolished, sadanagaite, which was approved in 1984 (Shimazaki *et al.*), and cannilloite

(Hawthorne *et al.*, 1996), have been added, and the boundaries of the group have been revised. Hornblende is retained as a general or colloquial term for coloured calcic amphiboles without confusion with the precise range shown in Fig. 3 because hornblende is always pre-fixed with an adjective in the precise nomenclature. Because of the strong desire especially, but not solely by metamorphic petrologists, to retain the distinction of green actinolite from colourless tremolite, the subdivisions

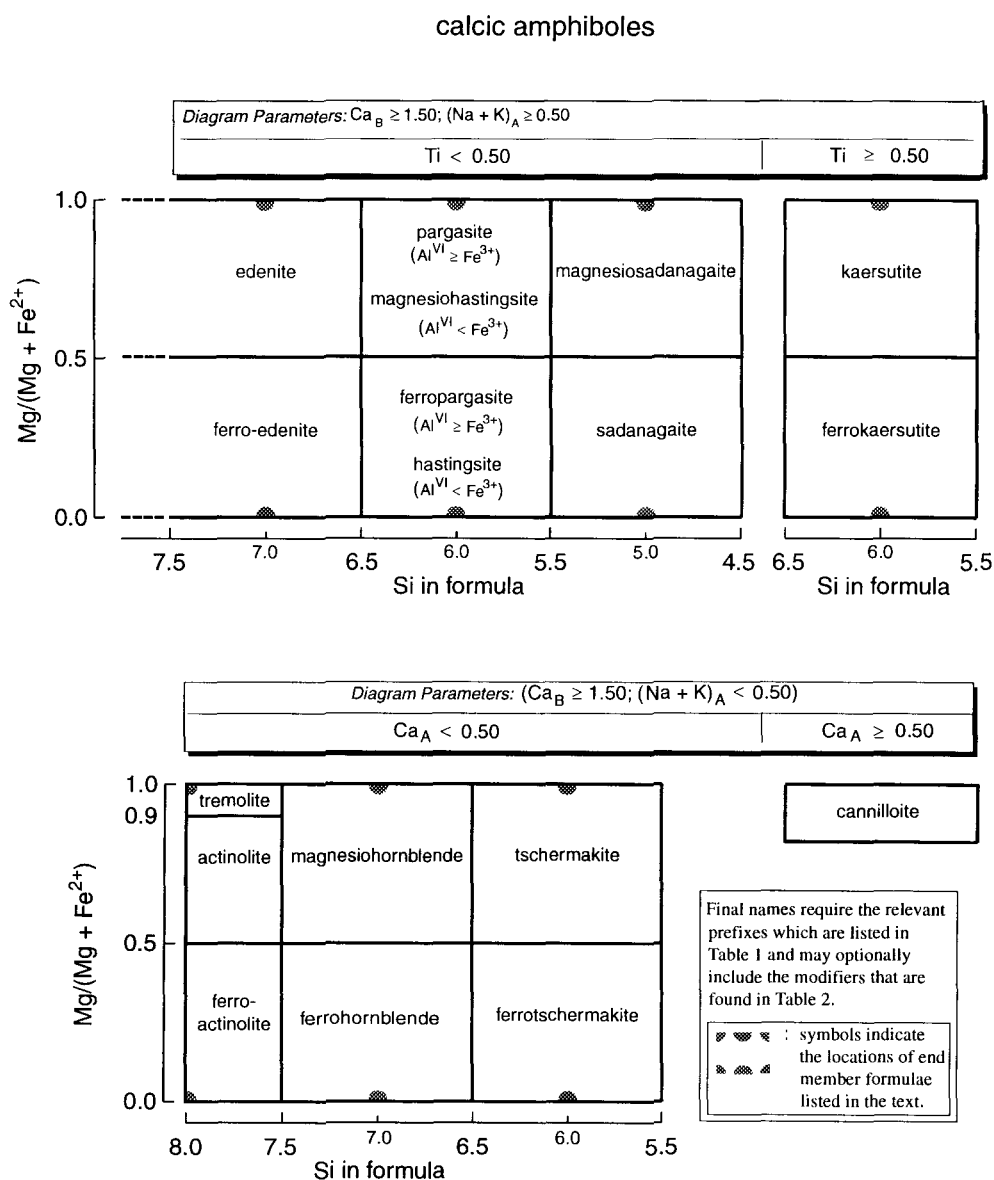


FIG. 3. Classification of the calcic amphiboles.

tremolite, actinolite, ferro-actinolite of IMA 78 are retained as shown in Fig. 3.

#### End members

Tremolite	$\square \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferro-actinolite	$\square \text{Ca}_2\text{Fe}_5^{2+}\text{Si}_8\text{O}_{22}(\text{OH})_2$
Edenite	$\text{NaCa}_2\text{Mg}_5\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferro-edenite	$\text{NaCa}_2\text{Fe}_5^{2+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Pargasite	$\text{NaCa}_2(\text{Mg}_4\text{Al})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferropargasite	$\text{NaCa}_2(\text{Fe}_4^{2+}\text{Al})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Magnesiosthastingsite	$\text{NaCa}_2(\text{Mg}_4\text{Fe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Hastingsite	$\text{NaCa}_2(\text{Fe}_4^{2+}\text{Fe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Tschemmakite	$\square \text{Ca}_2(\text{Mg}_3\text{AlFe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferrotschemmakite	$\square \text{Ca}_2(\text{Fe}_3^{2+}\text{AlFe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Aluminotschemmakite	$\square \text{Ca}_2(\text{Mg}_3\text{Al}_2)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Alumino-ferrotschemmakite	$\square \text{Ca}_2(\text{Fe}_3^{2+}\text{Al}_2)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferritschemmakite	$\square \text{Ca}_2(\text{Mg}_3\text{Fe}_2^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferri-ferrotschemmakite	$\square \text{Ca}_2(\text{Fe}_3^{2+}\text{Fe}_2^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Magnesiostadanagaite	$\text{NaCa}_2(\text{Mg}_3(\text{Fe}^{3+}, \text{Al})_2)\text{Si}_5\text{Al}_3\text{O}_{22}(\text{OH})_2$
Sadanagaite	$\text{NaCa}_2(\text{Fe}_3^{2+}(\text{Fe}^{3+}, \text{Al})_2)\text{Si}_5\text{Al}_3\text{O}_{22}(\text{OH})_2$
Magnesiosthornblende	$\square \text{Ca}_2(\text{Mg}_4(\text{Al}, \text{Fe}^{3+}))\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferrohornblende	$\square \text{Ca}_2(\text{Fe}_4^{2+}(\text{Al}, \text{Fe}^{3+}))\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Kaersutite	$\text{NaCa}_2(\text{Mg}_4\text{Ti})\text{Si}_6\text{Al}_2\text{O}_{23}(\text{OH})$
Ferrokaersutite	$\text{NaCa}_2(\text{Fe}_4^{2+}\text{Ti})\text{Si}_6\text{Al}_2\text{O}_{23}(\text{OH})$
Cannilloite	$\text{CaCa}_2(\text{Mg}_4\text{Al})\text{Si}_5\text{Al}_3\text{O}_{22}(\text{OH})_2$

#### Limits for the use of the end member names

These are summarised in Fig. 3 with respect to Si,  $(\text{Na}+\text{K})_{\text{A}}$ ,  $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$  and Ti. The prefixes ferri and alumino are used only when  $\text{Fe}^{3+} > 1.00$  and  $\text{Al}^{\text{VI}} > 1.00$  (Table 1). For kaersutite and ferrokaersutite,  $\text{Ti} \geq 0.50$ ; any lesser Ti content may optionally be indicated as in Table 2. Cannilloite requires  $\text{Ca}_{\text{A}} \geq 0.50$ .

#### Sodic-calcic amphiboles

This group is defined as monoclinic amphiboles in which  $(\text{Ca}+\text{Na})_{\text{B}} \geq 1.00$  and  $0.50 < \text{Na}_{\text{B}} < 1.50$ . The detailed classification is shown in Fig. 4. There are no significant changes from IMA 78 except for the 50% expansion of the volume occupied in Fig. 1 by the group. Because of the concentration of analyses relatively near to the end member compositions, the increase in the number of analyses in this group compared with the number classified in IMA 78 is quite small (much less than 50%). Nevertheless a

number of previously classified calcic and alkali amphiboles now become sodic-calcic amphiboles.

#### End members

Richterite	$\text{Na}(\text{CaNa})\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferrichterite	$\text{Na}(\text{CaNa})\text{Fe}_5^{2+}\text{Si}_8\text{O}_{22}(\text{OH})_2$
Winchite	$\square (\text{CaNa})\text{Mg}_4(\text{AlFe}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferrowinchite	$\square (\text{CaNa})\text{Fe}_4^{2+}(\text{AlFe}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Barroisite	$\square (\text{CaNa})\text{Mg}_3\text{AlFe}^{3+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferrobarroisite	$\square (\text{CaNa})\text{Fe}_3^{2+}\text{AlFe}^{3+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Aluminobarroisite	$\square (\text{CaNa})\text{Mg}_3\text{Al}_2\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Alumino-ferrobarroisite	$\square (\text{CaNa})\text{Fe}_3^{2+}\text{Al}_2\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferri-barroisite	$\square (\text{CaNa})\text{Mg}_3\text{Fe}_2^{3+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferri-ferrobarroisite	$\square (\text{CaNa})\text{Fe}_3^{2+}\text{Fe}_2^{3+}\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Magnesiokatophorite	$\text{Na}(\text{CaNa})\text{Mg}_4(\text{AlFe}^{3+})\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Katophorite	$\text{Na}(\text{CaNa})\text{Fe}_4^{2+}(\text{AlFe}^{3+})\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Magnesiotaramite	$\text{Na}(\text{CaNa})\text{Mg}_3\text{AlFe}^{3+}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Taramite	$\text{Na}(\text{CaNa})\text{Fe}_3^{2+}\text{AlFe}^{3+}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Alumino-magnesiotaramite	$\text{Na}(\text{CaNa})\text{Mg}_3\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Aluminotaramite	$\text{Na}(\text{CaNa})\text{Fe}_3^{2+}\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferri-magnesiotaramite	$\text{Na}(\text{CaNa})\text{Mg}_3\text{Fe}_3^{3+}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferritaramite	$\text{Na}(\text{CaNa})\text{Fe}_3^{2+}\text{Fe}_3^{3+}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$

#### Limits for the use of end member names

These are summarised in Fig. 4 with respect to Si,  $(\text{Na}+\text{K})_{\text{A}}$  and  $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ . Alumino and ferri are again restricted to  $\text{Al}^{\text{VI}} > 1.00$  and  $\text{Fe}^{3+} > 1.00$  being 50% of the normal maximum of  $2\text{R}_{\text{C}}^{3+}$  places.

#### Sodic amphiboles

This group is defined as monoclinic amphiboles in which  $\text{Na}_{\text{B}} \geq 1.50$ . The detailed classification is shown in Fig. 5. Apart from revision of the boundary  $\text{Na}_{\text{B}} \geq 1.50$  instead of  $\text{Na}_{\text{B}} \geq 1.34$ , and the abolition of crossite so that the 50% division is followed, the principal changes are the introduction of nyböite with Si close to 7, as approved in 1981 (Ungaretti *et al.*), ferric-nyböite (instead of previously abandoned anophorite), leakeite (Hawthorne *et al.*, 1992), ferroleakeite (Hawthorne *et al.*, 1996), kornite (Armbruster *et al.*, 1993), and ungarettiite (Hawthorne *et al.*, 1995).

#### End members

Glaucophane	$\square \text{Na}_2(\text{Mg}_3\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferroglaucophane	$\square \text{Na}_2(\text{Fe}_3^{2+}\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$

Magnesioriebeckite	$\square\text{Na}_2(\text{Mg}_3\text{Fe}_3^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$	Leakeite	$\text{NaNa}_2(\text{Mg}_2\text{Fe}_3^{3+}\text{Li})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Riebeckite	$\square\text{Na}_2(\text{Fe}_3^{2+}\text{Fe}_2^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$	Ferroleakeite	$\text{NaNa}_2(\text{Fe}_3^{2+}\text{Fe}_3^{3+}\text{Li})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Eckermannite	$\text{NaNa}_2(\text{Mg}_4\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$	Kornite	$(\text{Na},\text{K})\text{Na}_2(\text{Mg}_2\text{Mn}_2^{3+}\text{Li})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferro-eckermannite	$\text{NaNa}_2(\text{Fe}_4^{2+}\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$	Ungarettiite	$\text{NaNa}_2(\text{Mn}_2^{2+}\text{Mn}_3^{3+})\text{Si}_8\text{O}_{22}\text{O}_2$
Magnesio-arfvedsonite	$\text{NaNa}_2(\text{Mg}_4\text{Fe}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$		
Arfvedsonite	$\text{NaNa}_2(\text{Fe}_4^{2+}\text{Fe}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$		
Kozulite	$\text{NaNa}_2(\text{Mn}_4^{2+}(\text{Fe}^{3+},\text{Al}))\text{Si}_8\text{O}_{22}(\text{OH})_2$		
Nyböite	$\text{NaNa}_2(\text{Mg}_3\text{Al}_2)\text{Si}_7\text{AlO}_{22}(\text{OH})_2$		
Ferronyböite	$\text{NaNa}_2(\text{Fe}_3^{2+}\text{Al}_2)\text{Si}_7\text{AlO}_{22}(\text{OH})_2$		
Ferric-nyböite	$\text{NaNa}_2(\text{Mg}_3\text{Fe}_3^{3+})\text{Si}_7\text{AlO}_{22}(\text{OH})_2$		
Ferric-ferronyböite	$\text{NaNa}_2(\text{Fe}_3^{2+}\text{Fe}_2^{3+})\text{Si}_7\text{AlO}_{22}(\text{OH})_2$		

#### Limits for the use of end member names

These are summarised in Fig. 5 with respect to Si,  $(\text{Na}+\text{K})_A$  and  $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ , Li and Mn parameters. Kozulite requires  $\text{Mn}^{2+} > \text{Fe}^{2+} + \text{Fe}^{3+} + \text{Mg} + \text{Al}^{\text{VI}}$  with  $\text{Al}^{\text{VI}}$  or  $\text{Fe}^{3+} > \text{Mn}^{3+}$ ,  $\text{Li} < 0.5$ ; ungarettiite has both  $\text{Mn}^{2+}$  and  $\text{Mn}^{3+} > \text{Fe}^{2+} + \text{Mg} + \text{Fe}^{3+} + \text{Al}^{\text{VI}}$  with  $\text{Li} < 0.5$  and  $(\text{OH}+\text{F}+\text{Cl}) < 1.00$ ; leakeite and kornite require  $\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) \geq 0.50$ ,  $\text{Li} \geq 0.50$  with  $\text{Fe}^{3+} > \text{Mn}^{3+}$

### sodic-calcic amphiboles

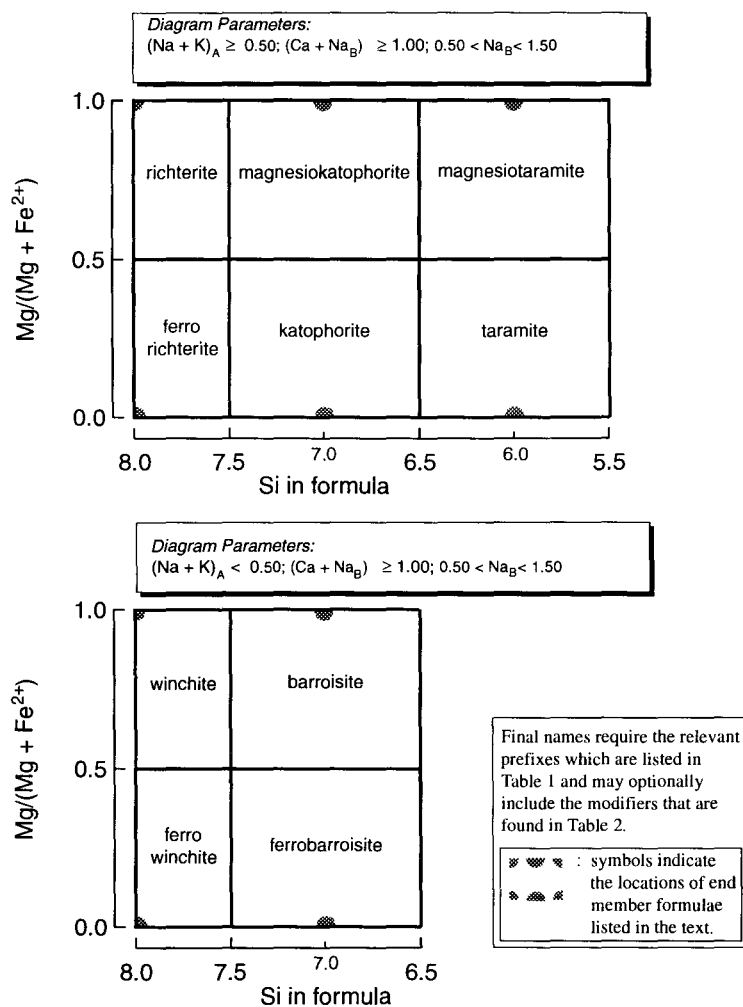
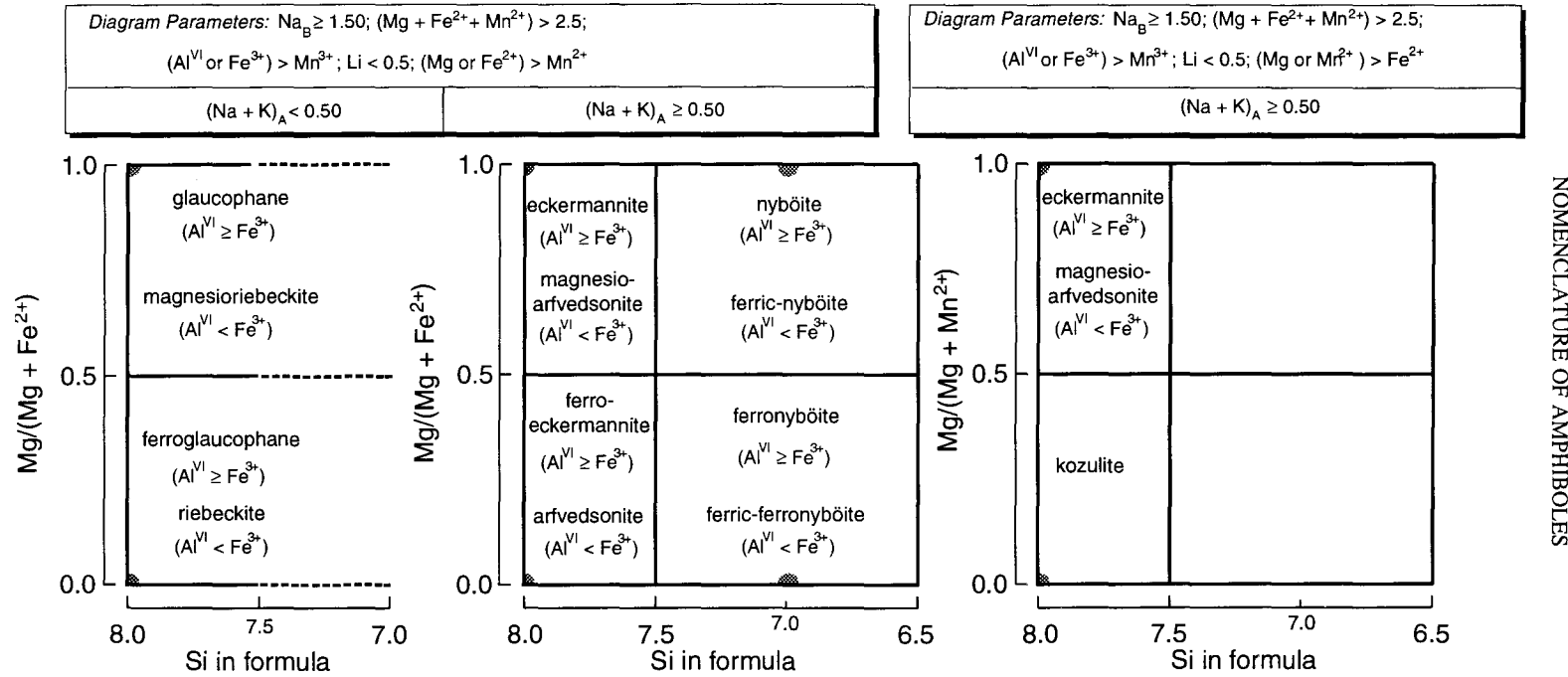


FIG. 4. Classification of the sodic-calcic amphiboles.

sodic amphiboles



NOMENCLATURE OF AMPHIBOLES

FIG. 5a. Classification of the sodic amphiboles with  $(Mg+Fe^{2+}+Mn^{2+}) > 2.5$ .

sodic amphiboles

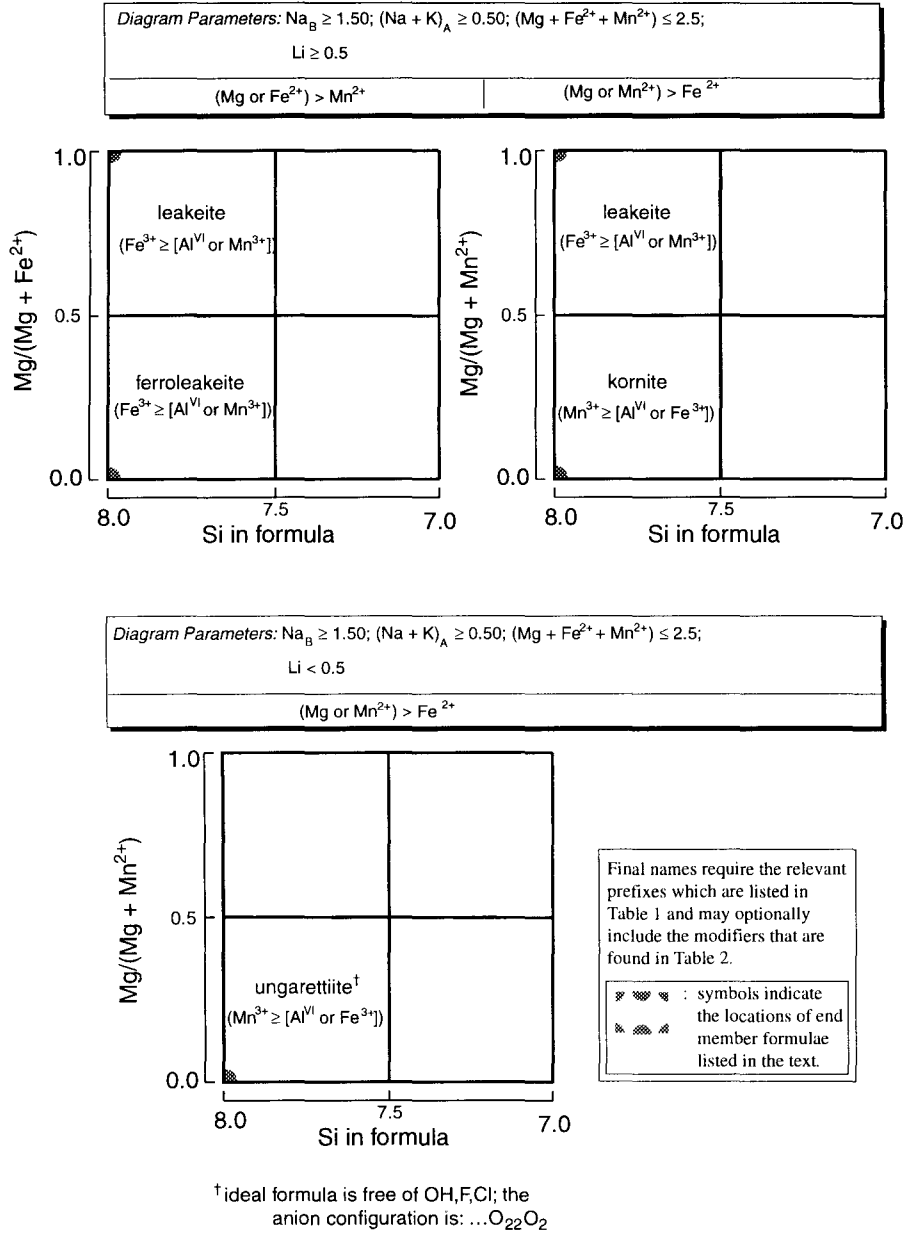


Fig. 5b. Classification of the sodic amphiboles with  $(Mg+Fe^{2+}+Mn^{2+}) \leq 2.5$ .

in leakeite and  $Fe^{3+} < Mn^{3+}$  in kornite. Ferric-nyböite means  $Fe^{3+} \geq Al^{VI}$  and should be clearly distinguished from ferri (meaning  $Fe^{3+} > 1.00$ ) because neither alumino (meaning  $Al^{VI} > 1.00$ ) nor ferri are used in the sodic amphiboles.

**Amphibole names recommended for extinction**

The following amphibole names used in IMA 78 are recommended to be formally abandoned. IMA 78 lists 193 abandoned names.

Magnesio-anthophyllite	= anthophyllite
Sodium-anthophyllite	= sodicanthophyllite
Magnesio-gedrite	= gedrite
Sodium gedrite	= sodicgedrite
Magnesio-holmquistite	= holmquistite
Magnesio-cummingtonite	= cummingtonite
Tirodite	= mangano-cummingtonite
Dannemorite	= manganogrunerite
Magnesio-clinolholmquistite	= clinoholmquistite
Crossite	= glaucophane or ferroglaucophane or magnesioriebeckite or riebeckite
Tremolitic hornblende	= magnesiohornblende
Actinolitic hornblende	= magnesiohornblende
Ferro-actinolitic hornblende	= ferrohornblende
Tschermakitic hornblende	= tschermakite
Ferro-tschermakitic hornblende	= ferrotschermakite
Edenitic hornblende	= edenite
Ferro-edenitic hornblende	= ferro-edenite
Pargasitic hornblende	= pargasite
Ferroan pargasitic hornblende	= pargasite or ferropargasite
Ferro-pargasitic hornblende	= ferropargasite
Ferroan pargasite	= pargasite or ferropargasite
Silicic edenite	= edenite
Silicic ferro-edenite	= ferro-edenite
Magnesio-hastingsitic hornblende	= magnesiohastingsite
Magnesian hastingsitic hornblende	= magnesiohastingsite or hastingsite
Hastingsitic hornblende	= hastingsite
Magnesian hastingsite	= magnesiohastingsite or hastingsite

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[Manuscript received 22 November 1996]

## APPENDIX 1

### Amphibole end-members

**Actinolite.** Named from the Greek *aktin* a ray and *lithos* a stone, alluding to the radiating habit.

**Type locality:** None

**X-ray data:**  $a$  9.884 Å,  $b$  18.145 Å,  $c$  5.294 Å.  $\beta$  104.7°.

(PDF 25-157 on specimen from Sobotin, Czech Republic)  
**References:** R. Kirwan (1794. *Elements of Mineralogy*, 1: 167) (actynolite); modified by J.D. Dana (1837. *Syst. Min.* 1st ed., 309).

**Anthophyllite.** Named from *anthophyllum* 'clove' referring to its characteristic brown colour.

**Type locality:** Described by Schumacher (1801, p. 96) as from the Kongsberg area, Norway, the exact locality being kept secret, but later (Möller, 1825) as from the Kjennerudvann Lake near Kongsberg.

**X-ray data:**  $a$  18.5 Å,  $b$  17.9 Å,  $c$  5.28 Å.

(PDF 9-455 on specimen from Georgia, USA)

**References:** N.B. Möller (1825, *Magazin for Naturvedenskaberne*. Christiania. 6: 174-). C.F. Schumacher (1801. *Versuch Verzeich. Danisch-Nordisch Staat, einfach Min.* 96 and 165).

**Arfvedsonite.** Named for J.A. Arfvedson.

**Type locality:** Kangerdluarsuk, Greenland

**X-ray data:**  $a$  9.94 Å,  $b$  18.17 Å,  $c$  5.34 Å.  $\beta$  104.40°.

(PDF 14-633 on specimen from Nunarsuatsiak, Greenland)

**References:** H.J. Brooke (1823. *Ann. Phil.* **21**: (2nd ser., vol. 5), 381) (arfvedsonite); amended by T. Thomson (1836. *Outlines of Mineralogy, Geology, and Mineral Analysis*, **1**: 483).

**Barroisite.** Origin of name not found.

**Type locality:** Not traced.

**References:** G. Murgoci (1922. *C.R. Acad. Sci. Paris*, **175A**: 373 and 426). Now defined by B.E. Leake (1978. *Min. Mag.* **42**: 544).

**Cannilloite.** Named for Elio Cannillo of Pavia, Italy.

**Type locality:** Pargas, Finland.

**X-ray data:** (Fluor-cannilloite)  $a$  9.826 Å,  $b$  17.907 Å,  $c$  5.301 Å.  $\beta$  105.41°.

**Reference:** F.C. Hawthorne, R. Oberti, L. Ungaretti and J.D. Grice (1996. *Am. Min.* **81**: 995).

**Clinoholmquistite.** Named as a monoclinic polymorph of holmquistite.

**Type locality:** Golzy, Sayany Mountain, Siberia, Russia.

**X-ray data:**  $a$  9.80 Å,  $b$  17.83 Å,  $c$  5.30 Å.  $\beta$  109.10°.

(PDF 25-498 on specimen from Siberia, Russia)

**References:** I.V. Ginzburg (1965. *Trudy Min. Muz. Akad. Nauk. SSSR*, **16**: 73). In B.E. Leake (1978. *Min. Mag.* **42**: 540) defined in a series with magnesio-clinoholmquistite and ferro-clinoholmquistite.

**Cumingtonite.** Named for locality.

**Type locality:** Cumington, Ma., USA.

**X-ray data:**  $a$  9.534 Å,  $b$  18.231 Å,  $c$  5.3235 Å.  $\beta$  101.97°.

(PDF 31-636 on specimen from Wabush iron formation, Labrador, Canada)

**References:** C. Dewey (1824. *Amer. J. Sci.* ser. 1, **8**: 58). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 549).

**Eckermannite.** Named for H. von Eckermann.

**Type locality:** Norra Kärr, Sweden.

**X-ray data:**  $a$  9.7652 Å,  $b$  17.892 Å,  $c$  5.284 Å.  $\beta$  103.168°.

(PDF 20-386 on synthetic material)

**References:** O.J. Adamson (1942. *Geol. För. Stockh.* **64**: 329; *ibid.* 1944. **66**: 194). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 546).

**Edenite.** Named for locality.

**Type locality:** Eden (Edenville), New York, USA.

**X-ray data:**  $a$  9.837 Å,  $b$  17.954 Å,  $c$  5.307 Å.  $\beta$  105.18°.

(PDF 23-1405 on specimen from Franklin Furnace, New Jersey, USA)

**References:** Not analysed in original description. Two analyses of toptype material by C.F. Rammelsberg (1858. *Ann. Phys. Chem. (Pogg)*, **103**: 441) and G.W. Hawes (1878. *Amer. J. Sci. Ser. 3*, **16**: 397) differ considerably, and neither falls within edenite range of Leake (1978. *Min. Mag.* **42**: 542). Current definition proposed by N. Sundius (1946. *Årsbok Sver. Geol. Unders.* **40**: no. 4). Nearest analysis to end-member may be that of Leake (1971. *Min. Mag.* **38**: 405).

**Gedrite.** Named from locality.

**Type locality:** Héas Valley, near Gèdres, France.

**X-ray data:**  $a$  18.594 Å,  $b$  17.890 Å,  $c$  5.304 Å.

(PDF 13-506 on specimen from Grafton, Oxford County, Maine, USA.)

**References:** A. Dufrenoy (1836. *Ann. Mines*, ser. 3, **10**: 582). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 539).

**Glaucophane.** Named from the Greek *glaukos*, bluish green and *phainesthai*, to appear.

**Type locality:** Syra, Cyclades, Greece.

**X-ray data:**  $a$  9.595 Å,  $b$  17.798 Å,  $c$  5.307 Å.  $\beta$  103.66°.

(PDF 20-453 on specimen from Sebastopol Quadrangle, California, USA. See also PDF 15-58 and 20-616).



**Reference:** J.F.L. Hausman (1845. *Gel. Kön. Ges. Wiss. Göttingen* p. 125) (Glaukophan).

**Grunerite.** Named for E.L. Gruner.

**Type locality:** Collobrières, Var, France.

**X-ray data:**  $a$  9.57 Å,  $b$  18.22 Å,  $c$  5.33 Å.

(PDF 17-745 on specimen from White Lake, Labrador, Canada)

**References:** Described by E.L. Gruner (1847. *C.R. Acad. Sci. Paris*, **24**: 794) but named by A. Kenngott (1853. *Mohs'sche Min. Syst.* 69). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 549).

**Hastingsite.** Named for locality.

**Type locality:** Hastings County, Ontario, Canada.

**X-ray data:**  $a$  9.907 Å,  $b$  18.023 Å,  $c$  5.278 Å.  $\beta$  105.058°. (PDF 20-378 on specimen from Dashkesan, Transcaucasia, Russia. Also PDF 20-469)

**References:** F.D. Adams and B.J. Harrington (1896. *Amer. J. Sci.* 4th ser., **1**: 212; 1896. *Canad. Rec. Sci.* **7**: 81). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 553).

**Holmquistite.** Named for P.J. Holmquist.

**Type locality:** Utö, Stockholm, Sweden.

**X-ray data:**  $a$  18.30 Å,  $b$  17.69 Å,  $c$  5.30 Å.

(PDF 13-401 on specimen from Barrante, Quebec, Canada) **References:** A. Osann (1913. *Sitz. Heidelberg Akad. Wiss., Abt. A, Abh.* 23). Dimorphous with clinoholmquistite. Defined by B.E. Leake (1978. *Min. Mag.* **42**: 549).

**Hornblende.** The name is from the German mining term *horn*, horn, and *blenden*, to dazzle.

**Reference:** Use of the term hornblende and relationship to other calcic amphiboles discussed by Deer *et al.* (1963. *Rock-forming minerals. 2. Chain silicates.* 265. Longmans, London). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 551).

**Kaersutite.** Named from locality.

**Type locality:** Kaersut, Umanakfjord, Greenland.

**X-ray data:**  $a$  9.83 Å,  $b$  17.89 Å,  $c$  5.30 Å.  $\beta$  105.18°.

(PDF 17-478 on specimen from Boulder Dam, Arizona, USA).

**References:** J. Lorenzen (1884. *Medd. Grönland* **7**: 27). Defined and given species status by B.E. Leake (1978. *Min. Mag.* **42**: 551).

**Katophorite.** Named from the Greek *kataphora* a rushing down, in reference to its volcanic origin.

**Type locality:** Christiana District (now Oslo), Norway.

**References:** W.C. Brögger (1894. *Die Eruptivgest. Kristianiagebietes, Skr. Vid.-Selsk I, Math.-natur.* Kl. **4**: 27). Frequently termed catophorite, and other variants, but accepted IMA spelling is katophorite. Defined by B.E. Leake (1978. *Min. Mag.* **42**: 544).

**Kornite.** Named for H. Korn.

**Type locality:** Wessels Mine, Kalahari Manganese Fields, South Africa.

**X-ray data:**  $a$  9.94(1) Å,  $b$  17.80(2) Å,  $c$  5.302(4) Å.  $\beta$  105.52°.

**Reference:** T. Armbruster, R. Oberhänsli, V. Bermanec and R. Dixon (1993. *Schweiz. Mineral. Petrogr. Mitt.* **73**: 349).

**Kozulite.** Named for S. Kozu

**Type locality:** Tanohata mine, Iwate Prefecture, Japan.

**X-ray data:**  $a$  9.991 Å,  $b$  18.11 Å,  $c$  5.30 Å.  $\beta$  104.6°. (PDF 25-850)

**References:** M. Nambu, K. Tanida and T. Kitamura (1969. *J. Japan Assoc. Min. Petr. Econ. Geol.* **62**: 311). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 557).

**Leakeite.** Named for B.E. Leake.

**Type locality:** Kajlidongri manganese mine, Jhabua district, Madhya Pradesh, India.

**X-ray data:**  $a$  9.822 Å,  $b$  17.836 Å,  $c$  5.286 Å.  $\beta$  104.37°.

**Reference:** F.C. Hawthorne, R. Oberti, L. Ungaretti and J.D. Grice (1992. *Am. Min.* **77**: 1112).

**Nyböite.** Named from locality.

**Type locality:** Nybö, Nordfjord, Norway.

**X-ray data:** In Ungaretti *et al.* (1981) X-ray data given for many specimens and a single 'type' specimen not distinguished.

**Reference:** L. Ungaretti, D.C. Smith and G. Rossi (1981. *Bull. Min.* **104**: 400).

**Pargasite.** Named from locality.

**Type locality:** Pargas, Finland.

**X-ray data:**  $a$  9.870 Å,  $b$  18.006 Å,  $c$  5.300 Å.  $\beta$  105.43°. (PDF 23-1406 and PDF 41-1430 on synthetic material)

**References:** F. von Steinheil (1814 in *Tasch. Min.* (1815) Jahrg. 9, Abt 1, 309). The name was widely used for green hornblende but was redefined by N. Sundius (1946. *Arsb. Sver. geol. Undersök.* **40**: 18) and B.E. Leake (1978. *Min. Mag.* **42**: 550 and 552).

**Richterite.** Named for T. Richter.

**Type locality:** Långban, Värmland, Sweden.

**X-ray data:**  $a$  9.907 Å,  $b$  17.979 Å,  $c$  5.269 Å.  $\beta$  104.25°. (PDF 25-808 on synthetic material; see also PDF 31-1284 for calcian and 25-675 and 31-1082 for potassian)

**References:** An imperfect description by A. Breithaupt (1865. *Bergmann Huttenmann. Zeit.* **24**: 364) was shown by H. Sjögren (1895. *Bull. Geol. Inst. Univ. Upsala*, **2**: 71) to be an amphibole. Defined by B.E. Leake (1978. *Min. Mag.* **42**: 544).

**Riebeckite.** Named for E. Riebeck.

**Type locality:** Island of Socotra, Indian Ocean.

**X-ray data:**  $a$  9.769 Å,  $b$  18.048 Å,  $c$  5.335 Å.  $\beta$  103.59°. (PDF 19-1061 on specimen from Doubrutscha, Romania).

**References:** A. Sauer (1888. *Zeit. deut. geol. Ges.* **40**: 138). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 546).

**Sadanagaite.** Named for R. Sadanaga.

**Type locality:** Yuge and Myojin Islands, Japan.

**X-ray data:**  $a$  9.922 Å,  $b$  18.03 Å,  $c$  5.352 Å.  $\beta$  105.30°.

**Reference:** H. Shimazaki, M. Bunno and T. Ozawa (1984. *Amer. Min.* **89**: 465).

**Taramite.** Named from type locality.

**Type locality:** Walitarama, Mariupol, Ukraine.

**X-ray data:**  $a$  9.952 Å,  $b$  18.101 Å,  $c$  5.322 Å.  $\beta$  105.45°. (PDF 20-734 on specimen of potassian taramite from Mbozi complex, Tanzania)

**References:** J. Morozewicz (1923. *Spraw. Polsk. Inst. Geol.*

(*Bull. Serv. Geol. Pologne*), **2**: 6). Redefined by Leake (1978. *Min. Mag.* **42**: 544).

**Tremolite.** Named from locality.

**Type locality:** Val Tremola, St Gotthard, Switzerland.

**X-ray data:** *a* 9.84 Å, *b* 18.02 Å, *c* 5.27 Å.  $\beta$  104.95°.

(PDF 13-437 on specimen from San Gotardo, Switzerland and PDF 31-1285 on synthetic material)

**References:** E. Pini (1796. in H.-B. Saussure, 1923.

*Voyages dans les Alpes*, 4: sect). Defined by B.E. Leake (1978. *Min. Mag.* **42**: 542)

**Tschemakite.** Named for G. Tschermak. Originally described as a hypothetical 'Tschermak molecule'.

**References** A.N. Winchell (1945. *Amer. Min.* **30**: 29).

Defined by B.E. Leake (1978. *Min. Mag.* **42**: 550 and 552).

**Ungarettiite.** Named for L. Ungaretti.

**Type locality:** Hoskins mine, near Grenfell, New South Wales, Australia.

**X-ray data:** *a* 9.89(2) Å, *b* 18.04(3) Å, *c* 5.29(1) Å.  $\beta$  104.6(2)°.

**Reference:** F.C. Hawthorne, R. Oberti, E. Cannillo, N. Sardone and A. Zanetti (1995. *Amer. Min.* **80**: 165).

**Winchite.** Named for H.J. Winch, who found the amphibole.

**Type locality:** Kajlidongri, Jhabua State, India.

**X-ray data:** *a* 9.834 Å, *b* 18.062 Å, *c* 5.300 Å.  $\beta$  104.4°.  
(PDF 20-1390)

**References:** L.L. Fermor (1906. *Trans. Mining Geol. Inst. India*, **1**: 79) naming the amphibole described in 1904 (*Rec. Geol. Surv. India*, **31**: 236). Topotype material found by B.E. Leake, C.M. Farrow, F. Chao and V.K. Nayak (1986. *Min. Mag.* **50**: 174) proved to be very similar in composition to that originally found by Fermor (1909. *Mem. Geol. Surv. India*, **37**: 149).

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## APPENDIX 2

# The estimation of ferric iron in electron microprobe analysis of amphiboles

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### Introduction

Most users of the amphibole nomenclature will want to classify amphibole compositions that have been determined with the electron microprobe, which cannot distinguish among the valence states of elements. This is unfortunate because it is clear that most amphiboles contain at least some ferric iron — see compilations of Leake (1968) and Robinson *et al.* (1982), for example. Consequently, the typical user of the amphibole nomenclature will need to estimate empirically ferric contents of amphiboles.

Empirical estimates of ferric iron are not just poor approximations that suffice in the absence of analytical determinations of ferric-ferrous ratios.

Empirical estimates yield exactly the same results as analytical determinations of ferric iron, if (1) the analysis is complete (total Fe plus all other elements), (2) the analytical determinations are accurate and (3) the mineral stoichiometry (ideal anion and cation sums) is known. In the case of amphiboles, condition (3) cannot be uniquely determined because the *A*-site occupancy varies. However, knowledge of amphibole stoichiometry and element distribution can be used to estimate a range of permissible structural formulae and ferric contents.

The most welcome circumstances will be where the difference between the limiting structural formulae are trivial, and the entire range plots within the same classification field. However, there will also be cases

where the range of stoichiometrically allowable formulae is broad and span two or more fields in the classification. Some users of the amphibole nomenclature may consider this a less than satisfactory solution, but, until it is possible to determine ferric contents routinely with the same ease and convenience of electron microprobe analyses, empirical estimates are probably the best alternative.

The procedure of estimating ferric iron will require at least one recalculation of the all-ferrous analysis to a different cation sum. Consequently, familiarity with calculation of mineral formulae is highly recommended for a fuller understanding of the ferric estimation procedure. Thorough discussions of the calculation of mineral formulae can be found in the appendices of Deer *et al.*, (1966, 1992). The topic of ferric estimates in amphiboles has been discussed by Stout (1972), Robinson *et al.* (1982, p. 3–12), Droop (1987), Jacobson (1989), J. Schumacher (1991) and Holland and Blundy (1994). An example of the recalculation of an electron microprobe analysis and the procedure for estimating minimum and maximum ferric contents are given at the end.

#### Empirical ferric iron estimates for amphiboles

*The basic formula.* Present knowledge of amphibole crystal chemistry suggests that many amphiboles contain essentially ideal stoichiometric proportions of 2 (OH) and 22 O. These anions can be rearranged to give the anhydrous formula basis 23 O (+ H<sub>2</sub>O), and calculation of the anhydrous formulae on this basis is the first basic assumption necessary to estimate ferric Fe. The ideal cation sums in amphibole formulae are not fixed and can vary between 15 and 16 cations per 23 O (anhydrous). Consequently, it is not possible to arrive at a unique ferric estimation based on stoichiometry, as can be done for minerals with fixed ratios of cations to anions (e.g. pyroxenes or the ilmenite-hematite series). Nevertheless, based on our present understanding of permissible and usual site occupancies, limits can be placed on the maximum and minimum values of ferric contents, and these limits yield a range of acceptable mineral formulae.

*Critical examination of electron microprobe analyses.* The suitability of an electron microprobe analysis of an amphibole for a ferric estimation requires the evaluation of the all-ferrous, anhydrous formula that is calculated on a 23 oxygen basis. The site assignments can be used to evaluate the analyses, and these are given in Fig. 1. From the site assignment data, it is possible to define the important stoichiometric limits (cation subtotals) for the amphiboles (Column 3, Figure 1). Acceptable amphibole formulae will satisfy all six of these criteria. Exceeding one or more of these stoichiometric

limits indicates that there are problems with the structural formula, and the identity of the unfulfilled condition will suggest the cause.

For minerals that bear ferric iron, the all-ferrous structural formulae will have cation sums that are too high (for discussion see J. Schumacher, 1991 and refs. therein). In amphiboles, this can result in violation of at least one of the criteria  $\text{Si} \leq 8$ ,  $\Sigma\text{Ca} \leq 15$  or  $\Sigma\text{K} \leq 16$  (Fig. 1). Violations of the other three criteria,  $\Sigma\text{Al} \geq 8$ ,  $\Sigma\text{Mn} \geq 13$  and  $\Sigma\text{Na} \geq 15$  (Fig. 1), **cannot** be due to failure to account for ferric iron and usually indicate an analytical problem (too few cations at some of the sites<sup>1</sup>) These analyses should not be used for empirical ferric estimates.

*Minimum and maximum estimates.* For many amphibole analyses, none of the criteria  $\text{Si} \leq 8$ ,  $\Sigma\text{Ca} \leq 15$  and  $\Sigma\text{K} \leq 16$  will be exceeded by the all-ferrous formula, the minimum ferric estimate is the all-ferrous formula (i.e.  $\text{Fe}^{3+} = 0.000$  and the site occupancies of all-ferrous formula are all allowable). If one or more of the three criteria  $\text{Si} \leq 8$ ,  $\Sigma\text{Ca} \leq 15$  and  $\Sigma\text{K} \leq 16$  are exceeded, ferric Fe may be present, and a minimum ferric estimate can be made that will yield a formula with acceptable stoichiometry. The condition that is most greatly exceeded determines the basis for the recalculation. For example, if  $\text{Si} = 8.005$ ,  $\Sigma\text{Ca} = 15.030$  and  $\Sigma\text{K} = 15.065$ , then the  $\Sigma\text{Si}$  limit is exceeded by 0.005 and the  $\Sigma\text{Ca}$  by 0.030. Since  $\Sigma\text{Ca}$  is in greatest excess, the minimum ferric estimate is obtained by recalculating the formula so that  $\Sigma\text{Ca} = 15.000$  (15eNK estimate, Fig. 1).

The maximum ferric estimates are obtained from the stoichiometric limits  $\Sigma\text{Al} \geq 8$ ,  $\Sigma\text{Mn} \geq 13$  and  $\Sigma\text{Na} \geq 15$  (Fig. 1). The condition that is nearest to the minimum value of one of these sums gives the maximum ferric estimate. For example, if  $\Sigma\text{Al} = 9.105$ ,  $\Sigma\text{Mn} = 13.099$  and  $\Sigma\text{Na} = 15.088$ , then  $\Sigma\text{Al}$  is exceeded by 1.105,  $\Sigma\text{Mn}$  by 0.099 and  $\Sigma\text{Na}$  by 0.088. The  $\Sigma\text{Na}$  is nearest the minimum value, and recalculating the formula so that  $\Sigma\text{Na} = 15.000$  (15eK estimate, Fig. 1) will give the maximum ferric formula.

*Recalculation of the formulae.* The recalculation procedure is described step-by-step at the end of this discussion, but some general aspects are discussed here. Table 1 lists a hypothetical amphibole analysis (wt.%) and four formulae that are based on 23 oxygens. Formulae were calculated for the two chemical limits (all iron as FeO or Fe<sub>2</sub>O<sub>3</sub>); the other two are the stoichiometric limits (see Fig. 1) which

<sup>1</sup> Exceptions do exist: potassium titanian richterite (Oberti *et al.*, 1992) has Ti at the tetrahedral sites and cannoillite which has 1 Ca at the A and 2 Ca at the B (M4) positions. These exceptions are rare.

Summary of site assignments and stoichiometric constraints					
Site and Occupancy	Cation*	Stoichiometric Limit	Correction Minimum	Maximum	
T-site	Si	Si $\leq 8$	8Si	8SiAl	
	Al	$\Sigma \text{Al} \geq 8$			
	Ti				
C-site	Cr				
	Fe <sup>3+</sup>				
	Mg				
	Ni				
	Zn				
	Fe <sup>2+</sup>				
B-site	Mn	$\Sigma \text{Mn} \geq 13$		13eCNK	
	Ca	$\Sigma \text{Ca} \leq 15$	15eNK		
	Na	$\Sigma \text{Na} \geq 15$		15eK	
A-site	K	$\Sigma \text{K} \leq 16$	16CAT		
	□				

\* cations arranged according to increasing ionic radius (smallest, Si to largest K)

$\Sigma$  = cation subtotal (e. g.  $\Sigma \text{Mn}$  = sum of all cations from Si through Mn in the list)

□ = vacancy at the A-site

FIG. 1. Summary of ideal site assignments, limits of various cation subtotals and the type of correction (minimum or maximum) that can be obtained by calculating the formulae to these stoichiometric limits (after J. Schumacher, 1991). Abbreviations of normalizations: 8Si = normalized such that total Si = 8; 8SiAl = normalized such that total Si + Al = 8; 13eCNK = normalized such that total the sum of the cations Si through Mn (ie, all cations exclusive of Ca, Na, K) = 13; 15eNK = normalized such that total the sum of the cations Si through Ca (ie, all cations exclusive of Na, K) = 15; 16CAT = normalized such that total the sum of all cations = 16 (see also Robinson *et al.* 1982, pp. 6–12).

give the minimum (15eNK) and maximum (13eCNK) ferric estimates. All of the stoichiometric limits except  $\Sigma \text{Ca} \leq 15$  (here  $\Sigma \text{Ca} = 15.029$ ) are met by the all-ferrous formula, which means that the minimum ferric formula is given by with the 15eNK estimate (Table 1).

Since  $\Sigma \text{Mn}$  is nearest the lowest allowable sum, the maximum ferric estimate values, and the ferric formula is obtained by recalculating as before, but, in this case, the normalization must insure that  $\Sigma \text{Mn} = 13.000$  (here the normalization factor is:  $13 \div 13.201 = 0.9848$ ). The minimum values for  $\Sigma \text{Al}$ ,

TABLE 1. A hypothetical amphibole analysis. The structural formulae that are based on the chemical and stoichiometric limits. The *ferrous* formula assumes total Fe as FeO, the *ferric* formula assumes total Fe as Fe<sub>2</sub>O<sub>3</sub>. The 13eCNK and 15eNK formulae are based on stoichiometric limits. See text for discussion.

Analysis (wt %)		Formulae				
		All Ferrous	15eNK	13eCNK	All Ferric	
SiO <sub>2</sub>	39.38	Si	6.093	6.081	6.000	5.714
Al <sub>2</sub> O <sub>3</sub>	16.70	Al	1.907	1.919	2.000	2.286
FeO	23.54	Σ	8.000	8.000	8.000	8.000
MgO	4.40					
CaO	11.03	Al	1.139	1.122	1.000	0.571
Na <sub>2</sub> O	2.37	Fe <sup>3+</sup>	0.000	0.088	0.700	2.857
		Mg	1.015	1.014	1.000	0.952
Total	97.42	Fe <sup>2+</sup>	2.845	2.777	2.300	0.000
		Σ	5.000	5.000	5.000	4.380
		Fe <sup>2+</sup>	0.201	0.176	0.000	0.000
		Ca	1.799	1.824	1.800	1.714
		Na	0.000	0.000	0.200	0.286
		Σ	2.000	2.000	2.000	2.000
		Ca	0.029	0.000	0.000	0.000
		Na	0.711	0.709	0.500	0.381
		Sum	15.740	15.709	15.500	14.761

ΣMn and ΣNa are, respectively, 8.000, 13.000 and 15.000 and the actual values are 9.139, 13.201 and 15.740.

These formulae for the minimum and maximum ferric estimates can be calculated in either of two ways: (1) by normalizing all the cations of the all-ferrous formula that were calculated on a 23 oxygen basis such that ΣCa = 15.000 and ΣMn = 13.000 (i.e., cations of each element multiplied by  $15 \div \Sigma\text{Ca}$  or  $13 \div \Sigma\text{Mn}$ , here:  $15 \div 15.029 = 0.9981$  and  $13 \div 13.201 = 0.9848$ , respectively), or (2) by using the normalization factor to determine the new cation sum and then recalculating the entire formula on cation

bases that set ΣCa = 15.000 and ΣMn = 13.000. The second method requires more calculation, but J. Schumacher (1991) has shown that this method leads to fewer rounding errors than normalizing the cations in the 23 oxygen-based formula.

The formula obtained from either recalculation method will have less than 23 oxygens. The cations of ferric iron (Fe<sup>3+</sup>) are found by calculating the number of moles of FeO that must be converted to FeO<sub>1.5</sub> to bring the sum of the oxygens to 23 and equals  $(23 - \Sigma\text{Ox}) \times 2$ , where ΣOx is the sum of the oxygen in the normalized formula ( $\Sigma\text{Ox} = \Sigma\text{R}^{4+} \times 2 + \Sigma\text{R}^{3+} \times 1.5 + \Sigma\text{R}^{2+} + \Sigma\text{R}^{1+} \times 0.5$ , where ΣR = the

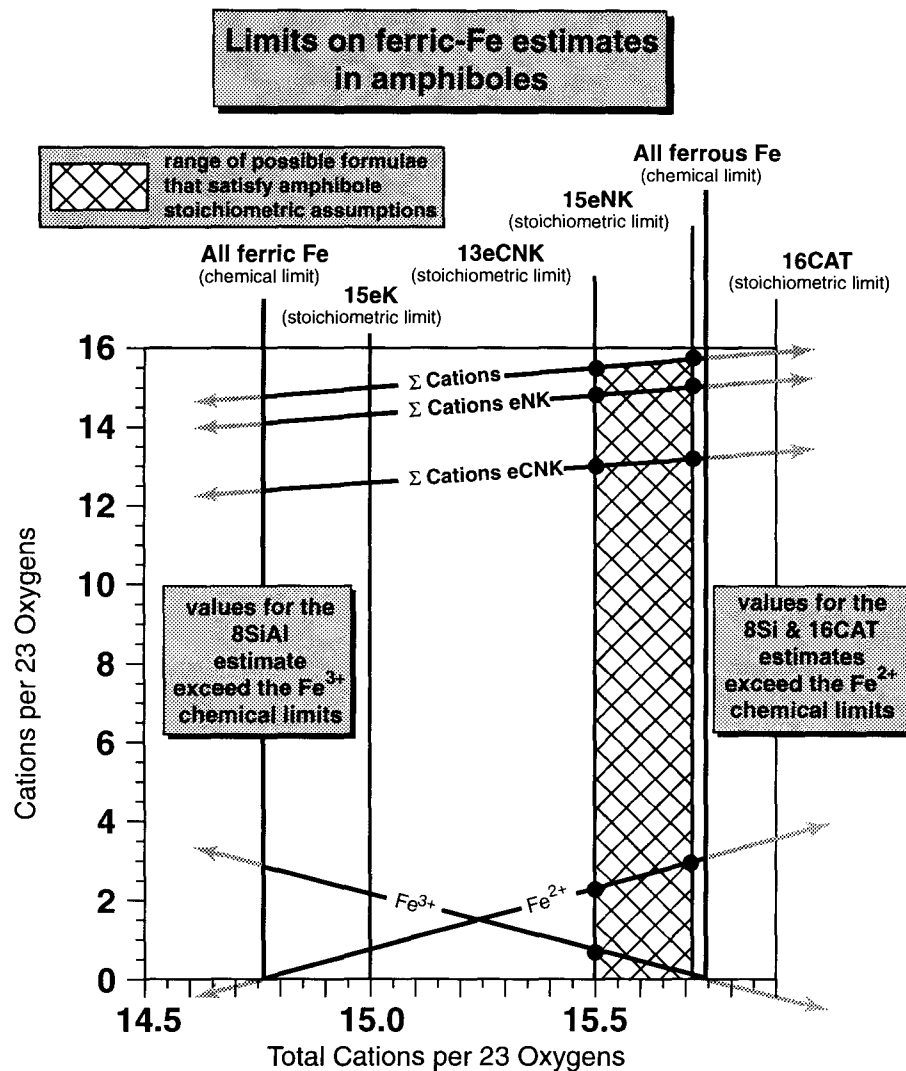


FIG. 2. Plot of various cation values and sums vs. total cations that illustrates the continuous variation of these values relative to chemical and stoichiometric limits. The stoichiometric limits are given in Fig. 1, and the values are based on the amphibole example in Table 1.

sums of cations with the same valence). The moles of FeO equal  $Fe_T - Fe^{3+}$  where  $Fe_T$  = total Fe in the normalized formula. Following any recalculation, it is good practice to recheck to see that all six stoichiometric limits are also satisfied by the new ferric formulae.

*Discussion of the recalculation results.* The variation in some cation values within the ranges of possible formulae (Table 1) that are defined by the chemical and stoichiometric limits are compared in

Fig. 2. In general, the range of possible formulae that are defined by the stoichiometric limits will be much narrower than the range obtained from the two chemical limits. A diagram like Fig. 1 could be constructed for every electron microprobe analysis, and, on such a diagram, the range of both the chemical and the appropriate set of stoichiometric limits could vary greatly from example to example. It can be inferred from Fig. 2 that the range of permissible amphibole formulae could be, and

commonly is, bounded by one of the chemical limits and one of the stoichiometric limits.

The relationships among cation sums that are illustrated in Fig. 2 shows that comparison of some of the possible normalization factors, which are obtained from the stoichiometric limits, can be used to (1) check the applicability of a specific ferric estimate and (2) determine limits, chemical or stoichiometric, give the minimum and maximum ferric estimates. To accomplish this, all the normalization factors for all stoichiometric constraints and the chemical limits must be compared (see Fig. 1). The normalization factors for the stoichiometric constraints are calculated from the all-ferrous formula using the data in Table 1 and are:

Minimum ferric estimate:

$$\begin{aligned} 8\text{Si} = 8/\text{Si} &= 8/6.093 = 1.313, & (1) \\ 16\text{CAT} = 16/\Sigma\text{K} &= 16/15.740 = 1.017, & (2) \\ \text{all Ferrous (no change)} &= 1.000, & (3) \\ 15\text{eNK} = 15/\Sigma\text{Ca} &= 15/15.029 = 0.998, & (4) \end{aligned}$$

Maximum ferric estimate:

$$\begin{aligned} 13\text{eCNK} = 13/\Sigma\text{Mn} &= 13/13.201 = 0.985, & (5) \\ 15\text{eK} = 15/\Sigma\text{Na} &= 15/15.740 = 0.953, & (6) \\ \text{all Ferric} &= 0.938, & (7) \\ 8\text{SiAl} = 8/\Sigma\text{Al} &= 8/9.139 = 0.875. & (8) \end{aligned}$$

For the normalizations that yield minimum estimates (1 to 4), the recalculation that requires the lowest normalization factor will be the minimum ferric estimate. For the normalizations that yield maximum estimates (5 to 8), the recalculation that requires the largest normalization factor will be the maximum ferric estimate. *All* normalizations that lie in between these values (in this example, 0.998 and 0.985) will give stoichiometrically acceptable formulae. If any of the normalization factors for the maximum estimate (5 to 8) are greater than any of those for the minimum estimate (1 to 4), then the analysis is not suitable for empirical ferric Fe estimations. Note that normalization factors greater than 1.000 or less than the normalization factor for the all ferric formula would yield impossible ferric estimates that lie outside of the chemical limits.

In addition to the stoichiometric constraints listed in Fig. 1, another constraint on maximum ferric Fe can be defined if the C site in the formulation of the amphibole nomenclature is further subdivided. The five C positions consist of 3 mica-like, two M1 octahedra and one M3 octahedron, and two pyroxene-like M2 octahedra. The cations Al, Fe<sup>3+</sup>, Ti and Cr<sup>3+</sup> are strongly partitioned into the M2 octahedra. Consequently, an additional maximum ferric estimate can be obtained by assuming all the tetrahedral and M2-octahedral sites are completely filled with cations of valences of 3+ and 4+. This

normalization factor (N) can be calculated by solving the two simultaneous equations for N: (1)  $N \times (\text{Si} + \text{Ti} + \text{Al} + \text{Cr}) + \text{Fe}^{3+} = 10$ , which describes desired resulting stoichiometry and (2)  $\text{Fe}^{3+} = (23 - 23 \times N) \times 2$ , which gives the ferric Fe for this normalization. The solution for N is:  $N = 36 / (46 - \text{Si} - \text{Ti} - \text{Al} - \text{Cr})$  where Si, Ti, Al and Cr are the amounts of these cations in the all ferrous formula. For the analysis in Table 1, this normalization factor (here abbreviated:  $10\Sigma\text{Fe}^{3+}$ ) is 0.977, which is less than the 0.983 value of the 13eCNK factor, so the  $10\Sigma\text{Fe}^{3+}$  normalization will not give the maximum ferric estimate in this case.

Most users of the nomenclature will want to report only a single mineral formula and name for each amphibole analysis; consequently, the overriding question is: which correction should be used? Unfortunately, there is no simple rule, and each group of similar analyses may require individual treatment — Robinson *et al.* (1982, p. 11) and J. Schumacher (1991, pp. 9–10) discuss some of these possibilities for Fe-Mg, calcic, sodic-calcic and sodic amphiboles in greater detail. The  $10\Sigma\text{Fe}^{3+}$  correction discussed in the preceding paragraph will not likely be important in Ca-amphiboles, but in sodic amphibole (e.g., riebeckites, glaucophanes) may commonly yield the maximum ferric estimate.

Choosing a single representative ferric formula out of the range possible formulae requires further justification or making additional assumptions. One solution is to use the mean value between maximum and minimum ferric contents (Spear and Kimball, 1984). Other solutions can be obtained for restricted types of amphibole. For example, R. Schumacher (1991) derived a normalization scheme that yields formulae intermediate to maximum and minimum ferric formulae for calcium-saturated, metamorphic hornblendes and is based on regression analysis of hornblende compositions for which ferric-ferrous determinations were known.

Generally, it will be desirable to determine the extent to which the minimum and maximum ferric estimations affect the classification of the amphibole in question by inspecting the formulae of both the maximum and minimum ferric estimates. If the entire range formulae give a wide spectrum of possible names, this should probably at least be mentioned where ever the amphibole is being described.

#### Deviations from the basic assumptions

*F and Cl substitutions.* Both F and Cl may substitute for (OH) in the amphibole structure, and these elements are not routinely determined at all electron microprobe facilities. Although it is highly recommended that these elements also be determined, their presence has no effect on the ferric

estimation procedure. Exchange of F or Cl for OH does not change the total number of negative charges (−46) in the anhydrous amphibole formula, so the proportions of cations required to give 46 positive charges will be independent of the proportions of OH, F or Cl that are present. The critical assumption is that exactly two anions [OH, F, Cl] are present for every 22 oxygens.

*Coupled substitutions involving anions.* The validity of a basic 23 oxygen anhydrous amphibole formula (i.e. exactly two OH+F+Cl) is an underlying assumption in the procedure to estimate ferric iron in amphiboles. Any variation in these values will have a tremendous affect the ferric iron estimation. The partial replacement of [OH+F+Cl] by O in the amphibole structure is an example of this kind of variation and has long been recognized. Amphiboles that are referred to in numerous mineralogy and optical mineralogy textbooks as 'basaltic hornblende' (Deer *et al.*, 1966), or the kaersutite end member of the IMA amphibole nomenclature can show this type of compositional variation (Dyar *et al.*, 1993).

Intuitively, one would expect analytical totals to be affected by variable O/OH; however, since these amphiboles tend to be richer in ferric Fe, the increase in the sum from the partial exchange of O for OH tends to be offset by treating the larger amounts of Fe<sub>2</sub>O<sub>3</sub> as FeO. Consequently, even in anhydrous amphiboles with significant ferric Fe, no compelling evidence of these substitutions will necessarily be seen in the analyses. Ferric estimation can still be carried out on analyses with variable O/OH, but an additional estimate of the H<sub>2</sub>O and halogen content will be an essential additional requirement.

### Conclusions

Amphiboles typically contain at least some and may contain significant amounts of ferric iron; however, the most common analytical method, the electron microprobe, cannot distinguish among valence states. The ferric contents of amphiboles can be estimated providing that all chemical analysis are complete and ideal stoichiometry (site occupancy) can be assumed. If these conditions hold, empirical estimates of ferric iron would have the comparable accuracy and precision as ferric-ferrous determination. For amphiboles, stoichiometry cannot be uniquely determined, but various crystal-chemical constraints allow a range of possible formulae that give the minimum and maximum ferric contents to be determined.

Selecting a single structural formula from the range of possibilities requires applying an additional constraint or making a further assumption, such as using the formula that gives minimum, maximum or

the mean ferric iron, or applying some petrologic constraint. In written descriptions, it will be important to report the analyses, which enables others to do their own recalculations, and a clear statement of the method and assumptions that were used to calculate the given structural formula.

The users of the IMA amphibole nomenclature ought to explore the formulae for the minimum and maximum ferric estimates. This defines the range of possible formulae and possible names. Since, some amphibole names carry special petrogenetic significance, care should be taken if the range of possible names is large.

### Worked example:

*Calculation of a mineral formula and a ferric estimate from an electron microprobe analysis of an amphibole*

As an example (Table 2), the analysis that appears in Deer *et al.* (1992, p. 678) was chosen. To simulate analysis by electron microprobe the ferric iron was recast as ferrous iron and the water analysis was ignored. The ferric estimate was made assuming 2 (OH) are present rather than the 2.146 suggested by the actual water determination. Any discrepancies in the final decimal places of the numbers that appear below and in Table 2 are due to rounding effects.

- (1) Divide each *wt. %* (column 1) by the molecular wt. of the oxide to yield the *molecular proportion* of each oxide (column 2). [e.g. for SiO<sub>2</sub>: 51.63 ÷ 60.085 = 0.85928]. Mol. wt. data from Robie *et al.*, 1978.
  - (2) Obtain *atomic proportions of the cations* (column 3) and *atomic proportions of the oxygens* (column 4) by multiplying each *molecular proportion* value by the number of cations and oxygens in the oxide. [e.g. for SiO<sub>2</sub>: 0.85928 × 1 = 0.85928 and 0.85928 × 2 = 1.71857]
- Note:** Assuming 2 (OH) groups are present, 1 oxygen is balanced by 2 H (i.e. H<sub>2</sub>O) so the cation charges are balanced by the remaining 23 oxygens which is the basis of the anhydrous amphibole formula (see text for discussion: it can be shown that, even if F and Cl have not been determined, as long as OH+F+Cl = 2 the 23 oxygen formula will give the correct mineral formula).
- (3) Obtain the *anions based on 23 oxygens* (column 5) by multiplying each value in column 4 by (23 ÷ the sum of column 4) [e.g. 23 ÷ 2.72185 = 8.45012; for SiO<sub>2</sub>: 1.71857 × 8.45012 = 14.52208]
  - (4) Obtain the *cations on the basis of 23 oxygens* (column 6) by multiplying each value in column 3 by 23 ÷ the sum of column 4 [e.g., for SiO<sub>2</sub>: 0.85928 × 8.45012 = 7.261]

**Note:** Column 6 is the all ferrous mineral formula for the amphibole. Assigning the cations to sites shows if any deviations from ideal stoichiometry can be explained by failure to account for ferric iron.

- (5) Ideal site assignments (column 7) are made from the cation values in column 6 — a general procedure is:



TABLE 2. A worked example of an amphibole analysis that appears in Deer *et al.* (1992, p. 678). See the end of the text for a step-by step discussion of this table

1	2	3	4	5	6	7	8	9	10	11	12	13		
wt%	Molecular Proportions	Atomic Proportions (cations)	Atomic Proportions (oxygens)	Anions on the basis of 23 oxygens	Cations on the basis of 23 oxygens	Ideal site assignments	Min. formula from col. 6	Cations Col. 6 × 0.99714	Col. 8 × oxygen per cation	Ideal site assignments	Formula (15eNK) minimum Fe <sup>3+</sup>	Formula (15eNK) maximum Fe <sup>3+</sup>	Formula Average of Min. and Max. Fe <sup>3+</sup>	Formula from DHZ
	wt% mol. wt.	col. 2 × cations in oxide	col. 2 × oxygens in oxide	col. 4 × 8.45012	col. 3 × 8.45012									
						Si	7.261			Si	7.240	7.161	7.201	7.196
						Al <sup>IV</sup>	0.739			Al <sup>IV</sup>	0.760	0.839	0.799	0.804
						sum T	8.000	Si	7.2401	14.4802	8.000	8.000	8.000	8.000
						Al <sup>VI</sup>	0.486	Al	1.2214	1.8321			0.416	0.410
						Fe <sup>3+</sup>	0.000	Ti	0.0000	0.0000			0.383	0.263
						Cr	0.000	Cr	0.0000	0.0000			0.000	0.000
						Mg	3.793	Mg	3.7818	3.7818			3.761	3.759
						Fe <sup>2+</sup>	0.721	Fe <sup>2+</sup>	0.8854	0.8854			0.440	0.618
						Mn	0.000	Mn	0.0202	0.0202			0.000	0.000
						sum C	5.000	Ca	1.8511	1.8511	5.000	5.000	5.000	5.000
						Mg	0.000	Na	0.1659	0.0829			0.000	0.000
						Fe <sup>2+</sup>	0.167	K	0.0000	0.0000			0.057	0.050
						Mn	0.020	sum	15.1659	22.9337			0.020	0.020
						Ca	1.856						1.841	1.840
						Na	0.000						0.082	0.090
						sum B	2.043				2.000	2.000	2.000	2.000
						Na	0.166						0.083	0.074
						K	0.000						0.000	0.000
						sum A	0.166				0.166	0.000	0.073	0.074
						Total	15.210				15.166	15.000	15.083	15.074

$$\Sigma Ca \text{ (col. 7)}$$

$$15 + 15.043 = 0.99714$$

$$(23 - 22.9337) \times 2 = 0.1325$$

$$0.885 - 0.133 = 0.753$$

Factor for the recalculation of atomic proportions to 23 O basis:  $23 \div 2.72185 = 8.45012$

- (a) *the 8 tetrahedral (T) sites:*
- place all Si here, if Si < 8 fill the remaining sites with Al.
  - if Si + total Al < 8, then place all Si + Al here
- (b) *the 5 octahedral (C) sites (M2, M1, M3)*
- place Al remaining from step (a), Ti, Fe<sup>3+</sup> (initially = 0), and Cr here. In the following order, place enough Mg, Fe<sup>2+</sup> and Mn to bring the total to 5.
  - if  $\Sigma(\text{Al}^{\text{VI}}\text{Mn}) < 5$ , then place all these elements here
- (c) *the 2 (B) sites (M4)*
- place any Mg, Fe<sup>2+</sup> or Mn and Ca remaining after step (b) here
  - if  $\Sigma(\text{MgCa})$  at  $B < 2$ , fill the remaining sites with Na to bring the total to 2
- (d) *the single large (A) site*
- place any remaining Na and K here
- (6) Evaluating the structural formula  
If any site has less than their ideal values ( $T=8.000$ ,  $C=5.000$ ,  $B=2.000$ ,  $A=0.000$  to  $1.000$ ), then a ferric estimate is either impossible or only possible with additional constraining information. This could also indicate an analytical problem.  
The suitability of the analysis for a ferric estimation and the normalizations that yield the maximum and minimum estimates of ferric iron can be determined by calculating the normalization factors for all the various stoichiometric and chemical limits. These are given in Table 3 and are obtained from columns 6 or 7 of Table 2.  
If the all the normalization factors (8Si, 16CAT and 15eNK) are greater than all the normalization factors (8SiAl, 15eK, 10 $\Sigma\text{Fe}^{3+}$  and 13eCNK), then a minimum and a maximum ferric estimation can be calculated; if not, then no estimation is possible.
- (7) Minimum ferric estimates  
The lowest normalization factor among the four choices, 8Si, 16CAT, 15eNK and all ferrous, determines the formula that yields the minimum ferric estimate. If the factors 8Si, 16CAT and 15eNK are all greater than 1.0000, then the all-ferrous formula (Fe<sup>3+</sup> = 0.000) is the lower limit. In this example, the 15eNK normalization factor is the lowest.  
To obtain the formula that gives the minimum ferric estimate (column 8), multiply the cations from column 6 by the 15eNK normalization factor 0.99714 ( $15 \div 15.043$ ).
- (8) Find the sum of oxygen (22.9337) in the normalized formula by multiplying each single cation value (column 8) by the number of balancing oxygens [e.g. for SiO<sub>2</sub>,  $7.2401 \times 2 = 14.4802$ ; for AlO<sub>1.5</sub>,  $1.2214 \times 1.5 = 1.8321$ ; for MgO,  $3.7818 \times 1 = 3.7818$ ; for NaO<sub>0.5</sub>,  $0.1659 \times 0.5 = 0.0829$ ]
- (9) Ferric Fe equals the amount of ferrous Fe that must be converted to bring the total oxygens up to 23. The amount is  $(23 - 22.9337) \times 2 = 0.133$ .
- (10) The new ferrous Fe value is the total Fe from column 8 minus the ferric Fe. [e.g.  $0.885 - 0.133 = 0.753$ ]
- (11) Recast the normalized cations as in step 5 (column 10). This should yield a formula with no violations of the ideal stoichiometry.
- Note:** Step 11 is a double check of the correctness of your calculations. It also is a check of whether correcting the initial stoichiometric violation will produce another [here, insufficient cations to fill *T* or *C* could result from the 15eNK normalization. Such analyses cannot be used for ferric Fe estimates (unfortunately, a lot of calculating is involved in determining this)].
- (12) Maximum ferric estimates  
The largest normalization factor among the four choices, 8SiAl, 15eK, 13eCNK and all ferric, determines the formula that yields the maximum ferric estimate. If the factors 8SiAl, 15eK and 13eCNK are all less than the all-ferric value, then the all-ferric formula would give the maximum Fe<sup>3+</sup>. In this example, the 15eK normalization factor is the largest and can be used to give the formula with maximum Fe<sup>3+</sup>.  
To obtain the formula that gives the maximum ferric estimate (column 11), repeat steps 7 through 10 for

TABLE 3. Normalization factors for all the various stoichiometric and chemical limits

Limit	Calculation method	Calculation	Normalization factor
<i>Calculations for minimum ferric estimates</i>			
8Si	8 ÷ Si	8 ÷ 7.261	1.1018
16CAT	16 ÷ $\Sigma\text{K}$	16 ÷ P15.210	1.0519
all ferrous	—	—	1.0000
15eNK	15 ÷ $\Sigma\text{Ca}$	15 ÷ P15.043	0.9971*
<i>Calculations for maximum ferric estimates</i>			
15eK	15 ÷ $\Sigma\text{Na}$	15 ÷ 15.210	0.9862*
13eCNK	13 ÷ $\Sigma\text{Mn}$	13 ÷ 13.187	0.9858
all ferric	23 ÷ [23 + (0.5 × Fe <sup>2+</sup> )]	23 ÷ 23.444	0.9811
10 $\Sigma\text{Fe}^{3+}$	36 ÷ (46 - Si - Al - Ti - Cr)	36 ÷ 37.5141	0.9596
8SiAl	8 ÷ $\Sigma\text{Al}$	8 ÷ 8.486	0.9427

\* Indicates normalizations that yield either the minimum or maximum ferric estimates

using the 15eK normalization factor  $0.98621 (15 \div 15.210)$ .

- (13) Average of the maximum and minimum ferric estimates  
To obtain the formula that gives the average of the maximum and minimum ferric estimates (columns 10 and 11), repeat steps 7 through 10 for using the average of the normalization factors that were obtained in steps 7 and 12. This normalization factor is  $0.99167 [(0.99714 + 0.98621) \div 2]$ .
- (14) The actual formula (column 12) given in Deer *et al.* (1992) lies approximately between the minimum (15eNK) in column 10 and maximum (15eK) in column 11, but is nearer to the minimum.

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