

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 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, as are 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; 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 Fe³⁺ and Fe²⁺ where not determined by analysis.

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INTRODUCTION

This report was produced in response to a motion at the IMA 1986 meeting in Stanford, California, asking the Commission on New Minerals and Mineral Names (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, 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 that 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 scheme of nomenclature; and (5) representation was sought across the various fields concerned with amphibole nomenclature, from crystal chemists, 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 schemes of nomenclature, 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, Mn, the H₂O content, or how the site populations are derived. What follows is a scheme of *nomenclature*, not one to determine at which position the ions really are located.

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 that 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 commonly been changed. Information on the etymology, the type locality, and the unit-cell parameters of thirty end-members is provided in Appendix 1.

The principal reference axes of IMA 78, namely Si, Na_B, and (Na + K)_A (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_B < 0.50 and Na_B ≥ 1.50, instead of Na_B < 0.67 and Na_B ≥ 1.34. (Here, and elsewhere in this report, concentrations are expressed in atoms per formula unit of the standard formula of an amphibole given below.) Previously, the amphibole "box" was divided into three equal volumes with respect to Na_B. The new scheme enlarges the sodic-calcic amphiboles at the expense of the calcic and sodic amphiboles (Fig. 1) 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 Fe is known (and not its division into FeO and Fe₂O₃) has been left to individual judgement, although a recommended procedure is given. This means that again an analysis may yield different names depending on the procedure used to estimate Fe³⁺ and Fe²⁺. It clearly would be advantageous, for purposes of naming an amphibole, 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 and Ribbe (1982), and Anthony et al. (1995), from which adequate general background summaries can be obtained.

GENERAL CLASSIFICATION OF THE AMPHIBOLES

As with the IMA 78 scheme, the proposed nomenclature is based on chemistry and crystal symmetry; where it is necessary to distinguish different polytypes or polymorphs, this may be done by adding the space group symbol as suffix. Anthophyllite 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 AB₂^{VI}C₅^{IV}T₈O₂₂(OH)₂. 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 one site per formula unit;
- B two M4 sites per formula unit;

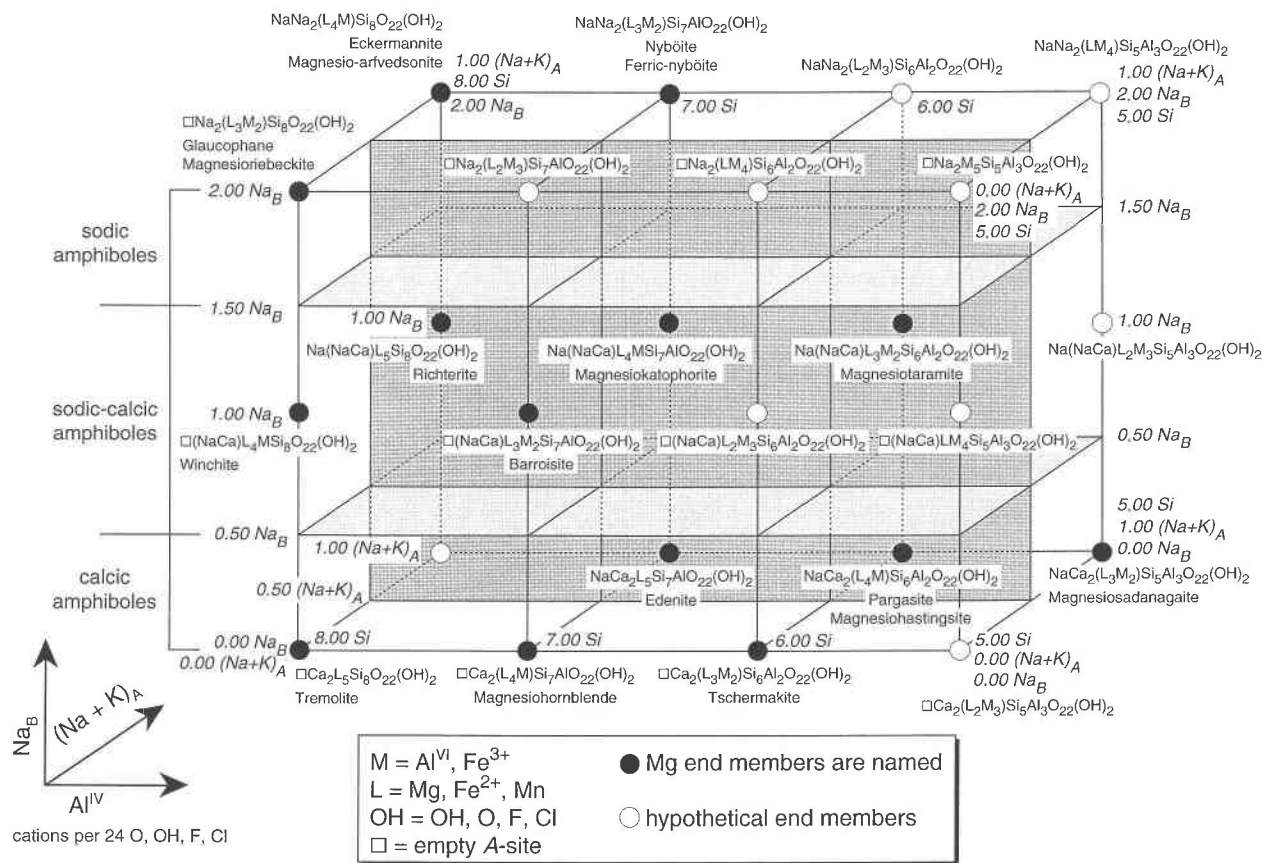


FIGURE 1. General classification of the amphiboles, excluding the Mg-Fe-Mn-Li amphiboles.

- C a composite of five sites made up of two M1, two M2, and one M3 sites per formula unit;
 T eight sites, in two sets of four, which need not be distinguished in this document;
 OH two 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 ²⁺ , Mn ²⁺ ,
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 ³⁺ and more rarely Mn ³⁺ , Cr ³⁺ | at C only |
| High-valency ions: Ti ⁴⁺ | at C or T |
| Zr ⁴⁺ | at C only |
| Si | at T only |
| Anions, OH, F, Cl, O | at "OH" |

M-type ions normally occupy M2 sites and so are normally limited to two of the five C sites. Exceptions may occur to the above "normal" behavior but are ignored for the present purposes of nomenclature.

Throughout this report, superscripted arabic numerals refer to ionic charge (oxidation state), e.g., Fe²⁺, superscripted roman numerals to coordination number, e.g., ^{VI}Al, and subscripted numerals to numbers of atoms, e.g., Ca₂.

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 H₂O and halogen contents are well established, the formula should be calculated to 24(O,OH,F,Cl).
- (2) If the H₂O plus halogen content is uncertain, the formula should be calculated on the basis of 23(O) with 2(OH,F,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 (OH + F + Cl) should be made.
- (3) Sum T to 8.00 using Si, then Al, then Ti. For the sake of simplicity of nomenclature, Fe³⁺ 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, Cr^{3+} , Fe^{3+} , Mn^{3+} , Mg, Fe^{2+} , Mn^{2+} , any other L^{2+} -type ions, and then Li.

- (5) Sum B to 2.00 using excess Mg, Fe^{2+} , 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 and 1.00.

The most common uncertainty results from lack of analyses for H_2O , Fe^{3+} , and Fe^{2+} . The procedure adopted to divide the Fe into Fe^{3+} and Fe^{2+} can influence the resulting name, especially if a composition is near $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 0.50$ or $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{VIAl}) = 0.50$, i.e., the same bulk composition may give rise to two or more names depending on the allocation of the Fe. The committee was almost unanimous in not wanting to specify one compulsory procedure for allocating Fe^{3+} and Fe^{2+} , but in recommending that a common procedure be used for purposes of naming the amphibole. Rock and Leake (1984) showed that, on the basis of processing over 500 amphibole analyses, the IMA-favored procedure of adjusting the sum ($\text{Si} + \text{Al} + \text{Cr} + \text{Ti} + \text{Fe} + \text{Mg} + \text{Mn}$) to 13, by varying the Fe^{3+} and Fe^{2+} appropriately, gave Fe^{3+} and Fe^{2+} values reasonably close to the true determined values in 80% of the compositions studied, excluding those of kaersutite, 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 if for the magnesium-iron-manganese-lithium 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 recognized that Mn-rich amphiboles pose problems with the variable valence state of both the Fe and Mn and that, as shown by Hawthorne (1983, p. 183–185), both in theory and practice, any calculation of Fe^{3+} and Fe^{2+} values is subject to considerable uncertainty. A full discussion of the problem and a recommended procedure, both by J.C. Schumacher, are given in Appendix 2. Some analyses have given H_2O^+ contents that lead to more than $(\text{OH})_2$ in the formula, but the structure contains only two sites for independent OH^- ions, and the structural role of the extra H ions is uncertain.

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

- (1) Where $(\text{Ca} + \text{Na})_B < 1.00$ and the sum of L-type ions $(\text{Mg}, \text{Fe}, \text{Mn}, \text{Li})_B \geq 1.00$, then the amphibole is a member of the *magnesium-iron-manganese-lithium group*.
- (2) Where $(\text{Ca} + \text{Na})_B \geq 1.00$ and $\text{Na}_B < 0.50$, then the amphibole is a member of the *calcic group*. Usually, but not in every case, $\text{Ca}_B > 1.50$.
- (3) Where $(\text{Ca} + \text{Na})_B \geq 1.00$ and Na_B is in the range 0.50–1.50, then the amphibole is a member of the *sodic-calcic group*.
- (4) Where $\text{Na}_B \geq 1.50$, then the amphibole is a member of the *sodic group*, previously referred to as alkali

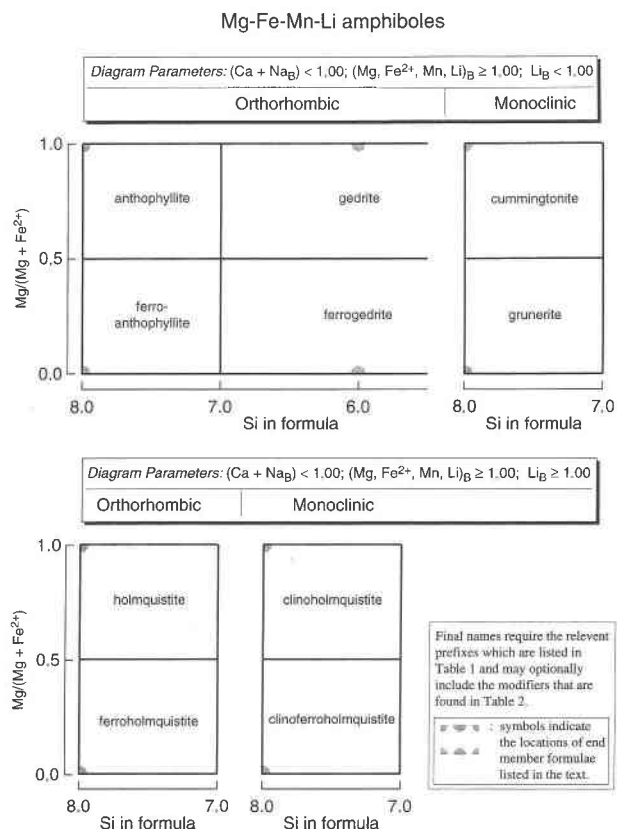


FIGURE 2. Classification of the Mg-Fe-Mn-Li amphiboles.

amphiboles. The new name is more precise, since Na is the critical element, not any other alkali element such as K or Li.

Within each of these groups a composition 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: $\text{Si} = \text{VIAl}$, $\square = (\text{Na}, \text{K})_A$, $\text{Ca}_B = \text{Na}_B$, $\text{Li} = \text{L}^{2+}$, $\text{M}_C = \text{L}_C^{2+}$, $(\text{Ti}, \text{Zr}) = \text{L}_C$, $\text{O} = (\text{OH}, \text{F}, \text{Cl})$. These substitutions necessarily occur in pairs or multiplets to maintain neutrality. The species defined on this basis are shown in Figure 1 and along the horizontal axes of Figures 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 $\text{Mg} = \text{Fe}^{2+}$, $\text{VIAl} = \text{Fe}^{3+}$ and $\text{OH} = \text{F}$. The end-members of these ranges of substitution 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 over 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 replacement of (OH, F, Cl) by O, and major entry of high-charge (>3+) 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 , $(\text{Na} + \text{K})_A$, and Si, as shown in Figure 1, but the subdivision into the sodic-calcic group is now at $\text{Na}_B = 0.50$ (instead of $\text{Na}_B = 0.67$) and $\text{Na}_B = 1.50$ (instead of $\text{Na}_B = 1.34$). This increases the volume, and therefore the number of compositions, 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 , $(\text{Na} + \text{K})_A$, 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 recognized rather more formally than previously by the way in which the abundance of Fe^{3+} , Al^{3+} , Cr^{3+} , or Mn^{3+} 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 (1987), prefixes are an essential part of a mineral name (e.g., ferroglauco-phane 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. 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 1987) 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. This convention gives rise

TABLE 1. Prefixes in addition to those in the figures

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

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

to 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 modifiers (Table 2) have *ian* or *oan* endings to indicate moderate substitutions as listed by Nickel and Mandarino (1987). Modifiers are not accompanied by a hyphen 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 that 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).

The 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, e.g., 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 a ferro or magnesio prefix in the precise classification, such that confusion should not arise between colloquial use and precise use.

As in IMA 78, asbestiform amphiboles should be named according to their precise mineral name, as listed in this report, followed by the suffix-asbestos: e.g., anthophyllite-asbestos, tremolite-asbestos. Where the nature

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 group
Chlorian	0.25 < Cl < 0.99	All groups
Chromian	0.25 < Cr < 0.99	All groups
Ferrian	0.75 < Fe ³⁺ < 0.99	All groups except sodic
Fluorian	0.25 < F < 0.99	All groups
Hydroxylan	OH > 3.00	All groups
Lithian	Li > 0.25	All groups, but excludes those species defined by Li abundance (e.g., holmquistite)
Manganooan	0.25 < Mn ²⁺ < 0.99	All groups, but excludes those species defined by Mn ²⁺ abundance
Manganian	0.25 < Mn ³⁺ or Mn ⁴⁺ < 0.99	All groups, but excludes those species defined by the abundance of Mn ³⁺ (e.g., komite)
Nickeloan	Ni > 0.10	All groups
Oxygenian	(OH + F + Cl) < 1.00	All groups, except for ungarrettite
Potassian	0.25 < K < 0.49	All groups
Plumbian	Pb > 0.10	All groups
Sodian	0.25 < Na < 0.49	Mg-Fe-Mn-Li group only
Strontian	Sr > 0.10	All groups
Titanian	0.25 < Ti < 0.49	All groups
Vanadian	V > 0.10	All groups
Zincian	0.10 < Zn < 0.99	All groups
Zirconian	Zr > 0.10	All groups

* Concentrations are expressed in atoms per formula unit.

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 with 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; the detailed classification is shown in Figure 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

Anthophyllite series. $Na_x Li_z (Mg, Fe^{2+}, Mn)_{7-y-z} Al_y (Si_{8-x-y+z} Al_{x+y-z}) O_{22} (OH, F, Cl)_2$ 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	$\square Mg_7 Si_8 O_{22} (OH)_2$
Ferro-anthophyllite	$\square Fe_7^{2+} Si_8 O_{22} (OH)_2$
Sodicanthophyllite	$NaMg_6 Si_7 AlO_{22} (OH)_2$
Sodic-ferro-anthophyllite	$NaFe_6^{2+} Si_7 AlO_{22} (OH)_2$

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	$Mg/(Mg + Fe^{2+}) < 0.50; Na \geq 0.50$
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Gedrite series. $Na_x Li_z (Mg, Fe^{2+}, Mn)_{7-y-z} Al_y (Si_{8-x-y+z} Al_{x+y-z}) O_{22} (OH, F, Cl)_2$ where $(x + y - z) \geq 1.00$ so that

$Si < 7.00$, this being the distinction from anthophyllite. $Li < 1.00$.

End-members:

Gedrite	$\square Mg_6 Al_2 Si_6 Al_2 O_{22} (OH)_2$
Ferrogedrite	$\square Fe_6^{2+} Al_2 Si_6 Al_2 O_{22} (OH)_2$
Sodicgedrite	$NaMg_6 AlSi_6 Al_2 O_{22} (OH)_2$
Sodic-ferrogedrite	$NaFe_6^{2+} AlSi_6 Al_2 O_{22} (OH)_2$

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 $Na(Fe, Mg)_5 Al_2 Si_5 Al_3 O_{22} (OH)_2$ will justify a new name.

Holmquistite series. $\square (Li_2 (Mg, Fe^{2+})_3 (Fe^{3+}, Al)_2) Si_8 O_{22} (OH, F, Cl)_2$ $Li \geq 1.00$ is critical.

End-members:

Holmquistite	$\square (Li_2 Mg_7 Al_3 Si_8 O_{22} (OH)_2)$
Ferroholmquistite	$\square (Li_2 Fe_7^{2+} Al_3 Si_8 O_{22} (OH)_2)$

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 of the Mg-Fe-Mn-Li amphiboles

Cummingtonite-Grunerite series. $\square (Mg, Fe^{2+}, Mn, Li)_7 Si_8 O_{22} (OH)_2$. $Li < 1.00$. Most members of this series have space group *C2/m*; those with *P2/m* may optionally have this symbol as a suffix at the end of the name.

End-members:

Cummingtonite	$\square Mg_7 Si_8 O_{22} (OH)_2$
Grunerite	$\square Fe_7^{2+} Si_8 O_{22} (OH)_2$
Manganocummingtonite	$\square Mn_7 Mg_6 Si_8 O_{22} (OH)_2$
Permanganogrunerite	$\square Mn_7 Fe_6^{2+} Si_8 O_{22} (OH)_2$

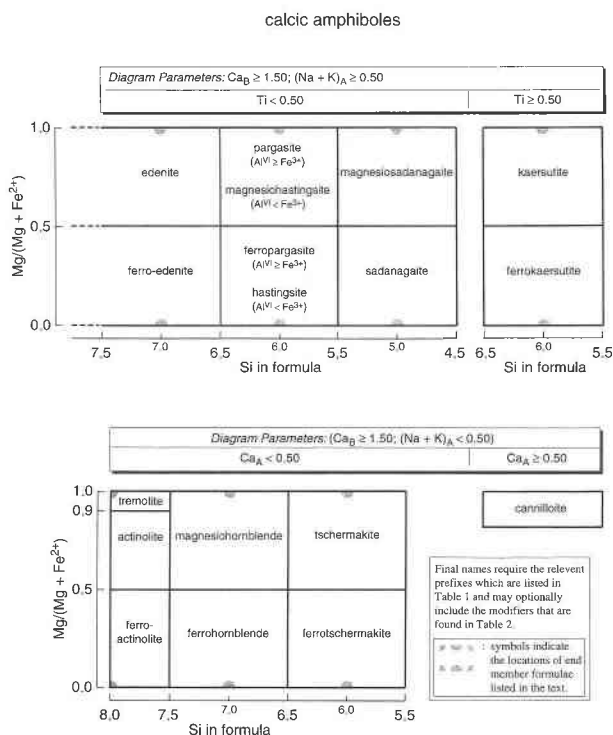


FIGURE 3. Classification of the calcic amphiboles.

Manganogrunerite $\square \text{Mn}_2\text{Fe}_2^+\text{Si}_8\text{O}_{22}(\text{OH})_2$

Limits for the use of end-member names:

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

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 $\text{Mg}_2\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$.

Clinoholmquistite series: $\square(\text{Li}_2 (\text{Mg}, \text{Fe}^{2+}, \text{Mn})_2 (\text{Fe}^{3+} \text{Al})_2)_2 \text{Si}_8\text{O}_{22}(\text{OH}, \text{F}, \text{Cl})_2$, $\text{Li} \geq 1.00$.

End-members

Clinoholmquistite	$\square(\text{Li}_2\text{Mg}_3\text{Al}_2)_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
Clinoferroholmquistite	$\square(\text{Li}_2\text{Fe}_3^+\text{Al}_2)_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferri-clinoholmquistite	$\square(\text{Li}_2\text{Mg}_2\text{Fe}_3^+)\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferri-clinoferroholmquistite	$\square(\text{Li}_2\text{Fe}_2^+\text{Fe}_3^+)\text{Si}_8\text{O}_{22}(\text{OH})_2$

Limits for the use of end-member names:

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

Calcic amphiboles

The group is defined as monoclinic amphiboles in which $(\text{Ca} + \text{Na})_B \geq 1.00$ and Na_B is between 0.50 and 1.50; usually $\text{Ca}_B \geq 1.50$. The detailed classification is shown in Figure 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 (Shimazaki et al. 1984) and cannilloite (Hawthorne et al. 1996b), have been added, and the boundaries of the group have been revised. Hornblende is retained as a general or colloquial term for colored calcic amphiboles without confusion with respect to the precise range shown in Figure 3, because hornblende is always prefixed with an adjective in the precise nomenclature. Because of the strong desire especially, but not solely, expressed by metamorphic petrologists to retain the distinction of green actinolite from colorless tremolite, the subdivisions tremolite, actinolite, and ferroactinolite of IMA 78 are retained, as shown in Figure 3.

End-members:

Tremolite	$\square \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferro-actinolite	$\square \text{Ca}_2\text{Fe}_3^+\text{Si}_6\text{O}_{22}(\text{OH})_2$
Edenite	$\text{NaCa}_2\text{Mg}_5\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Ferro-edenite	$\text{NaCa}_2\text{Fe}_3^+\text{Si}_7\text{AlO}_{22}(\text{OH})_2$
Pargasite	$\text{NaCa}_2(\text{Mg}_4\text{Al})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferropargasite	$\text{NaCa}_2(\text{Fe}_2^+\text{Al})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Magnesiohastingsite	$\text{NaCa}_2(\text{Mg}_4\text{Fe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Hastingsite	$\text{NaCa}_2(\text{Fe}_2^+\text{Fe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Tschermakite	$\square \text{Ca}_2(\text{Mg}_3\text{AlFe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferrotschermakite	$\square \text{Ca}_2(\text{Fe}_2^+\text{AlFe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Aluminotschermakite	$\square \text{Ca}_2(\text{Mg}_3\text{Al}_2)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Alumino-ferrotschermakite	$\square \text{Ca}_2(\text{Fe}_2^+\text{Al}_2)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferritschermakite	$\square \text{Ca}_2(\text{Mg}_3\text{Fe}_2^+)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Ferri-ferrotschermakite	$\square \text{Ca}_2(\text{Fe}_2^+\text{Fe}_2^+)\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$
Magnesiosadanagaite	$\text{NaCa}_2[\text{Mg}_3(\text{Fe}^{3+}, \text{Al})_2]\text{Si}_5\text{Al}_2\text{O}_{22}(\text{OH})_2$
Sadanagaite	$\text{NaCa}_2[\text{Fe}^{2+}, (\text{Fe}^{3+}, \text{Al})_2]\text{Si}_5\text{Al}_2\text{O}_{22}(\text{OH})_2$
Magnesiohornblende	$\square \text{Ca}_2[\text{Mg}_4(\text{Al}, \text{Fe}^{3+})]\text{Si}_5\text{AlO}_{22}(\text{OH})_2$
Ferrohornblende	$\square \text{Ca}_2[\text{Fe}^{2+}, (\text{Al}, \text{Fe}^{3+})]\text{Si}_5\text{AlO}_{22}(\text{OH})_2$
Kaersutite	$\text{NaCa}_2(\text{Mg}_2\text{Ti})\text{Si}_6\text{Al}_2\text{O}_{23}(\text{OH})$
Ferrokaersutite	$\text{NaCa}_2(\text{Fe}_2^+\text{Ti})\text{Si}_6\text{Al}_2\text{O}_{23}(\text{OH})$
Cannilloite	$\text{CaCa}_2(\text{Mg}_4\text{Al})\text{Si}_5\text{Al}_2\text{O}_{22}(\text{OH})_2$

Limits for the use of the end-member names:

These are summarized in Figure 3 with respect to Si, $(\text{Na} + \text{K})_A$, $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$, and Ti. The prefixes ferri and alumino are only used when $\text{Fe}^{3+} > 1.00$ and ${}^{\text{VI}}\text{Al} > 1.00$ (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 $\text{Ca}_A \geq 0.50$.

Sodic-calcic amphiboles

This group is defined to include monoclinic amphiboles in which $(\text{Ca} + \text{Na})_B \geq 1.00$ and $0.50 < \text{Na}_B < 1.50$. The detailed classification is shown in Figure 4. There are no significant changes from IMA 78 except for the 50% expansion of the volume occupied by the group in Figure 1. Because of the concentration of compositions relatively near the end-members, 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	$\text{Na}(\text{CaNa})\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Ferrorichterite	$\text{Na}(\text{CaNa})\text{Fe}_3^+\text{Si}_6\text{O}_{22}(\text{OH})_2$
Winchite	$\square(\text{CaNa})\text{Mg}_4(\text{Al}, \text{Fe}^{3+})\text{Si}_6\text{O}_{22}(\text{OH})_2$
Ferrowinchite	$\square(\text{CaNa})\text{Fe}_2^+(\text{Al}, \text{Fe}^{3+})\text{Si}_6\text{O}_{22}(\text{OH})_2$

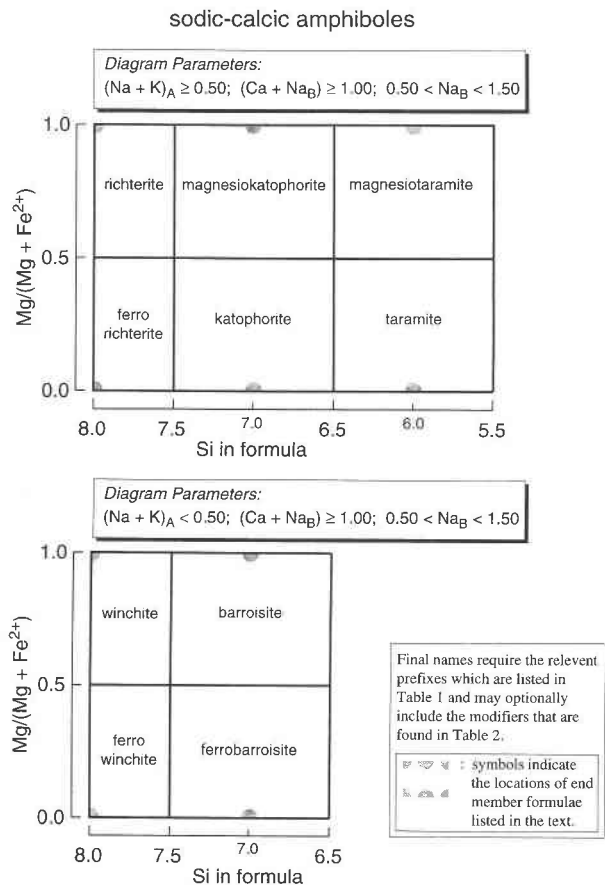


FIGURE 4. Classification of the sodic-calcic amphiboles.

Barroisite	\square (CaNa)Mg ₃ Al Fe ³⁺ Si ₇ AlO ₂₂ (OH) ₂
Ferrobarrisite	\square (CaNa)Fe ₃ ⁺ Al Fe ³⁺ Si ₇ AlO ₂₂ (OH) ₂
Aluminobarroisite	\square (CaNa)Mg ₃ Al ₂ Si ₇ AlO ₂₂ (OH) ₂
Alumino-ferrobarrisite	\square (CaNa)Fe ₃ ⁺ Al ₂ Si ₇ AlO ₂₂ (OH) ₂
Ferribarroisite	\square (CaNa)Mg ₃ Fe ₃ ⁺ Si ₇ AlO ₂₂ (OH) ₂
Ferri-ferrobarrisite	\square (Ca Na)Fe ₃ ⁺ Fe ₃ ⁺ Si ₇ AlO ₂₂ (OH) ₂
Magnesiokatophorite	Na(CaNa)Mg ₄ (Al,Fe ³⁺)Si ₇ AlO ₂₂ (OH) ₂
Katophorite	Na(CaNa)Fe ₂ ⁺ (Al,Fe ³⁺)Si ₇ AlO ₂₂ (OH) ₂
Magnesiotaramite	Na(CaNa)Mg ₃ Al Fe ³⁺ Si ₆ Al ₂ O ₂₂ (OH) ₂
Taramite	Na(CaNa)Fe ₃ ⁺ Al Fe ³⁺ Si ₆ Al ₂ O ₂₂ (OH) ₂
Alumino- magnesiotaramite	Na(CaNa)Mg ₃ Al ₂ Si ₆ Al ₂ O ₂₂ (OH) ₂
Aluminotaramite	Na(CaNa)Fe ₃ ⁺ Al ₂ Si ₆ Al ₂ O ₂₂ (OH) ₂
Ferri-magnesiotaramite	Na(CaNa)Mg ₃ Fe ₃ ⁺ Si ₆ Al ₂ O ₂₂ (OH) ₂
Ferritaramite	Na(CaNa)Fe ₃ ⁺ Fe ₃ ⁺ Si ₆ Al ₂ O ₂₂ (OH) ₂

Limits for the use of end-member names:

These are summarized in Figure 4 with respect to Si, (Na + K)_A, and Mg/(Mg + Fe²⁺). Alumino and ferri are again restricted to ^{VI}Al > 1.00 and Fe³⁺ > 1.00 being 50% of the normal maximum of 2R³⁺ sites.

Sodic amphiboles

This group is defined to include monoclinic amphiboles in which Na_B ≥ 1.50. The detailed classification is shown in Figures 5a and 5b. Apart from revision of the boundary at Na_B ≥ 1.50, instead of Na_B ≥ 1.34, and the abolition of crossite so that the 50% division is followed, the prin-

cipal changes are the introduction of nyböite with Si close to 7, as approved in 1981 (Ungaretti et al. 1981), ferric-nyböite (instead of the previously abandoned anophorite), leakeite (Hawthorne et al. 1992), ferroleakeite (Hawthorne et al. 1996a), kornite (Armbruster et al. 1993), and ungarettiite (Hawthorne et al. 1995).

End-members:

Glaucophane	\square Na ₂ (Mg,Al ₂)Si ₈ O ₂₂ (OH) ₂
Ferroglaucophane	\square Na ₂ (Fe ₂ ⁺ Al ₂)Si ₈ O ₂₂ (OH) ₂
Magnesioriebeckite	\square Na ₂ (Mg,Fe ³⁺)Si ₈ O ₂₂ (OH) ₂
Riebeckite	\square Na ₂ (Fe ³⁺ Fe ³⁺)Si ₈ O ₂₂ (OH) ₂
Eckermannite	NaNa ₂ (Mg ₄ Al)Si ₈ O ₂₂ (OH) ₂
Ferro-eckermannite	NaNa ₂ (Fe ₄ ⁺ Al)Si ₈ O ₂₂ (OH) ₂
Magnesio-arfvedsonite	NaNa ₂ (Mg ₄ Fe ³⁺)Si ₈ O ₂₂ (OH) ₂
Arfvedsonite	NaNa ₂ (Fe ₄ ⁺ Fe ³⁺)Si ₈ O ₂₂ (OH) ₂
Kozulite	NaNa ₂ Mn ₂ ⁺ (Fe ³⁺ ,Al)Si ₈ O ₂₂ (OH) ₂
Nyböite	NaNa ₂ (Mg ₃ Al ₂)Si ₇ AlO ₂₂ (OH) ₂
Ferromnyböite	NaNa ₂ (Fe ₃ ⁺ Al ₂)Si ₇ AlO ₂₂ (OH) ₂
Ferric-nyböite	NaNa ₂ (Mg ₃ Fe ₃ ⁺)Si ₇ AlO ₂₂ (OH) ₂
Ferric-ferromnyböite	NaNa ₂ (Fe ₃ ⁺ Fe ₃ ⁺)Si ₇ AlO ₂₂ (OH) ₂
Leakeite	NaNa ₂ (Mg ₂ Fe ₃ ⁺ Li)Si ₈ O ₂₂ (OH) ₂
Ferroleakeite	NaNa ₂ (Fe ₂ ⁺ Fe ₂ ⁺ Li)Si ₈ O ₂₂ (OH) ₂
Kornite	(Na,K)Na ₂ (Mg ₂ Mn ₂ ⁺ Li)Si ₈ O ₂₂ (OH) ₂
Ungarettiite	NaNa ₂ (Mn ₂ ⁺ Mn ₃ ⁺)Si ₈ O ₂₂ O ₂

Limits for the use of end-member names:

These are summarized in Figure 5 with respect to Si, (Na + K)_A and Mg/(Mg + Fe²⁺), Li, and Mn parameters. Kozulite requires Mn²⁺ > (Fe²⁺ + Fe³⁺ + Mg + ^{VI}Al) with ^{VI}Al or Fe³⁺ > Mn³⁺, Li < 0.5; ungarettiite has both Mn²⁺ and Mn³⁺ > (Fe²⁺ + Mg + Fe³⁺ + ^{VI}Al) with Li < 0.5 and (OH + F + Cl) < 1.00; leakeite and kornite require Mg/(Mg + Fe²⁺) ≥ 0.50, Li ≥ 0.50 with Fe³⁺ > Mn³⁺ in leakeite and Fe³⁺ < Mn³⁺ in kornite. Ferric-nyböite means Fe³⁺ ≥ ^{VI}Al and should be clearly distinguished from ferri (meaning Fe³⁺ > 1.00) because neither alumino (meaning ^{VI}Al > 1.00) nor ferri are used in the sodic amphiboles.

AMPHIBOLE NAMES RECOMMENDED TO BE FORMALLY ABANDONED

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	=	manganocummingtonite
Dannemorite	=	manganogrunerite
Magnesio- clinoholmquistite	=	clinoholmquistite
Crossite	=	glaucophane or ferroglaucophane or magnesioriebeckite or riebeckite
Tremolitic hornblende	=	magnesiohornblende

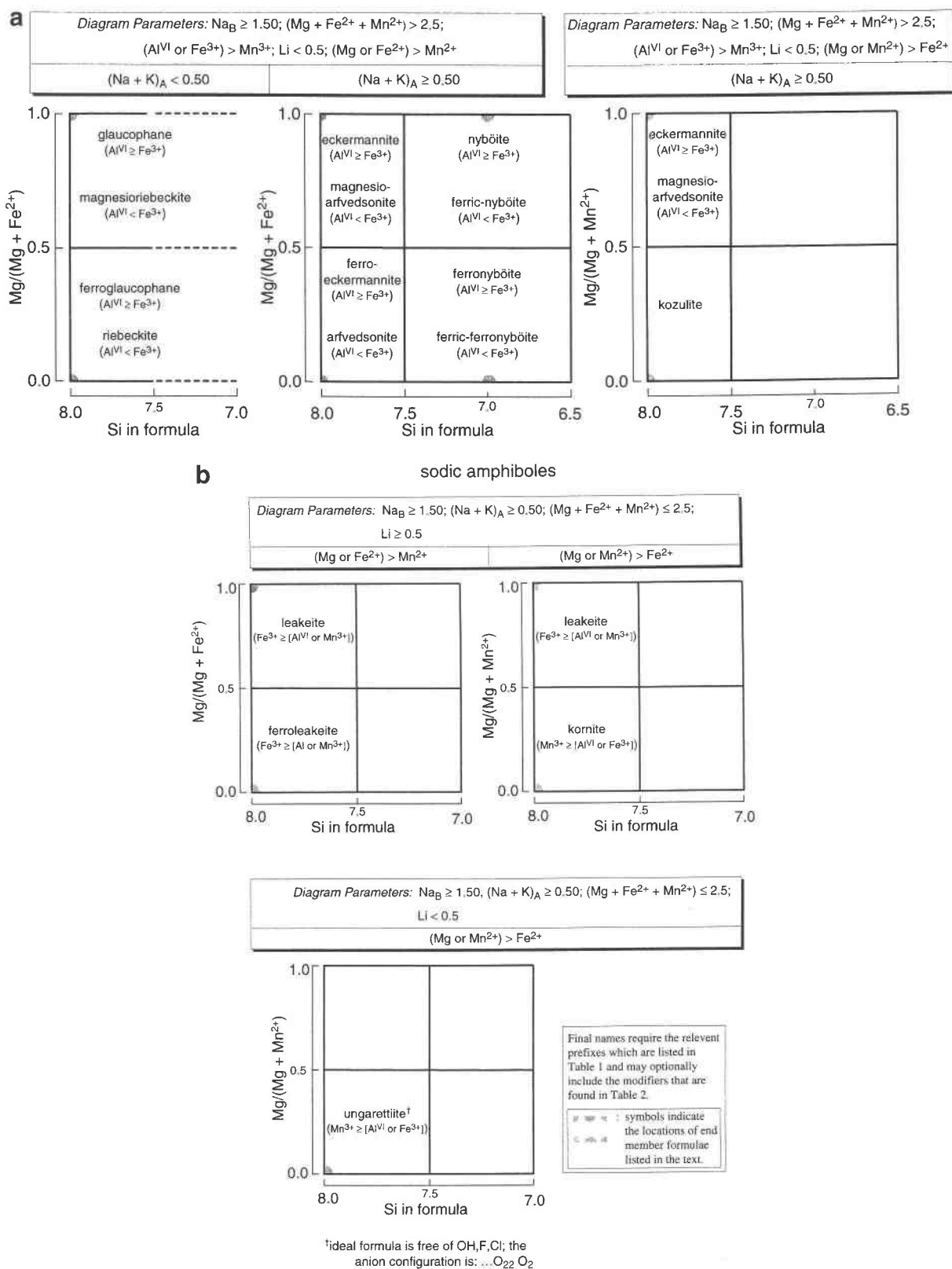


FIGURE 5. (a) Classification of the sodic amphiboles with $(Mg + Fe^{2+} + Mn^{2+}) > 2.5$ apfu. (b) Classification of the sodic amphiboles with $(Mg + Fe^{2+} + Mn^{2+}) \leq 2.5$ apfu.

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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APPENDIX 1.

Information concerning the etymology, the type locality, and the unit-cell parameters of thirty amphibole end-members

Actinolite

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, β 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. Systematic Mineralogy (1st ed.), 309].

Anthophyllite

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

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, U.S.A.).

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. β 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. β 105.41°.

Reference: F.C. Hawthorne, R. Oberti, L. Ungaretti and J.D. Grice (1996. Am. Mineral. 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. β 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.

Cummingtonite

Named for locality.

Type locality: Cummington, Massachusetts, U.S.A.

X-ray data: *a* 9.534 Å, *b* 18.231 Å, *c* 5.3235 Å. β 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. β 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, U.S.A.

X-ray data: *a* 9.837 Å, *b* 17.954 Å, *c* 5.307 Å. β 105.18°. (PDF 23-1405 on specimen from Franklin Furnace, New Jersey, U.S.A.).

References: Not analyzed 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, U.S.A.).

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

Glaucofanite

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. β 103.66°. (PDF 20-453 on specimen from Sebastopol Quadrangle, California, U.S.A. See also PDF 15-58 and 20-616).

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

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. β 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. Can. 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, Umanaksfjord, Greenland.

X-ray data: a 9.83 Å, b 17.89 Å, c 5.30 Å. β 105.18°. (PDF 17-478 on specimen from Boulder Dam, Arizona, U.S.A.).

References: J. Lorenzen (1884. *Medd. Grønland* 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. β 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. β 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. β 104.37°.

Reference: F.C. Hawthorne, R. Oberti, L. Ungaretti, and J.D. Grice (1992. *Am. Mineral.* 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 for locality.

Type locality: Pargas, Finland.

X-ray data: a 9.870 Å, b 18.006 Å, c 5.300 Å. β 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: L. Ängban, Värmland, Sweden.

X-ray data: a 9.907 Å, b 17.979 Å, c 5.269 Å. β 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. β 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. β 105.30°.

Reference: H. Shimazaki, M. Bunno, and T. Ozawa (1984. *Am. Mineral.* 69: 465).

Taramite

Named for type locality.

Type locality: Walitarama, Mariupol, Ukraine.

X-ray data: a 9.952 Å, b 18.101 Å, c 5.322 Å. β 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 for locality.

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

X-ray data: a 9.84 Å, b 18.02 Å, c 5.27 Å. β 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. *Voy-*

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

Tschermakite

Named for G. Tschermak. Originally described as a hypothetical "Tschermak molecule."

References A.N. Winchell (1945. *Am. Mineral.* 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. β 104.6(2)°.

Reference: F.C. Hawthorne, R. Oberti, E. Cannillo, N. Sardone, and A. Zanetti (1995. *Am. Mineral.* 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. β 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*

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 examples. 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 those 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 spans 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 requires 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 atoms. These anions can be rearranged to give the anhydrous formula basis 23 O (+ H₂O), 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 max-

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Summary of site assignments and stoichiometric constraints				
Site and Occupancy	Cation*	Stoichiometric Limit	Estimation:	
			Minimum	Maximum
T-site	Si	Si ≤ 8	8Si	8SiAl
	Al	ΣAl ≥ 8		
	Ti			
C-site	Cr			
	Fe ³⁺			
	Mg			
	Ni			
	Zn			
B-site	Fe ²⁺			
	Mn	ΣMn ≥ 13	15eNK	13eCNK
	Ca	ΣCa ≤ 15		
	Na	ΣNa ≥ 15		
K	ΣK ≤ 16	16CAT		
A-site	□			

* cations arranged according to increasing ionic radius (smallest, Si to largest, K)
 Σ = cation total or subtotal (e. g. ΣMn = sum of all cations from Si through Mn in the list)
 □ = vacancy at the A-site

APPENDIX 2: FIGURE 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; 13 eCNK = normalized such that total the sum of the cations Si through Mn (i.e., all cations exclusive of Ca, Na, K) = 13; 15 eNK = normalized such that total the sum of the cations Si through Ca (i.e., all cations exclusive of Na and K) = 15; 16CAT = normalized such that total the sum of all cations = 16 (see also Robinson et al. 1982, p. 6–12).

imum 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 O atom basis. The site assignments can be used to evaluate the analyses, and these are given in Appendix 2 Figure 1. From the site assignment data, it is possible to define the important stoichiometric limits (cation subtotals) for the amphiboles (column 3, Appen. 2 Fig. 1). Acceptable amphibole formulae satisfy all six of these criteria. Exceeding one or more of these stoichiometric limits indicates that problems exist with the structural formula, and the identity of the unfulfilled condition suggests the cause.

For minerals that bear ferric iron, the all-ferrous structural formulae have cation sums that are too high (for further discussion see J. Schumacher 1991, and references

therein). In amphiboles, this can result in violation of at least one of the criteria $Si \leq 8$, $\Sigma Ca \leq 15$, or $\Sigma K \leq 16$ (Appen. 2 Fig. 1). Violations of the other three criteria, $\Sigma Al \geq 8$, $\Sigma Mn \geq 13$, and $\Sigma Na \geq 15$ (Appen. 2 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 sites¹). These analyses should not be used for empirical ferric estimates.

Minimum and maximum estimates

For many amphibole analyses, none of the criteria $Si \leq 8$, $\Sigma Ca \leq 15$, and $\Sigma K \leq 16$ will be exceeded by the all-ferrous formula; the minimum ferric estimate is the all-ferrous formula (i.e., $Fe^{3+} = 0$ and the site occupancies of the all-ferrous formula are all allowable). If one or more of the three criteria $Si \leq 8$, $\Sigma Ca \leq 15$, and $\Sigma K \leq 16$ are exceeded, Fe^{3+} may be present, and a minimum ferric estimate can be made that yields a formula with acceptable stoichiometry. The condition that is exceeded by the greatest amount determines the basis for the recalculation. For example, if $Si = 8.005$, $\Sigma Ca = 15.030$, and $\Sigma K = 15.065$, then the ΣSi limit is exceeded by 0.005 and the ΣCa limit by 0.030. Because ΣCa is in greatest excess, the minimum ferric estimate is obtained by recalculating the formula so that $\Sigma Ca = 15.000$ (15 eNK estimate, Appen. 2 Fig. 1).

The maximum ferric estimates are obtained from the stoichiometric limits $\Sigma Al \geq 8$, $\Sigma Mn \geq 13$, and $\Sigma Na \geq 15$ (Appen. 2 Fig. 1). The condition that is nearest to the minimum value of one of these sums gives the maximum ferric estimate. For example, if $\Sigma Al = 9.105$, $\Sigma Mn = 13.099$, and $\Sigma Na = 15.088$, then ΣAl is exceeded by 1.105, ΣMn by 0.099, and ΣNa by 0.088. The ΣNa is nearest the minimum value, and recalculating the formula so that $\Sigma Na = 15.000$ (15 eK estimate, Appen. 2 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. Appendix 2 Table 1 lists a hypothetical amphibole analysis (in weight percent) and four formulae that are based on 23 O atoms. Formulae were calculated for the two chemical limits (all Fe as FeO or Fe₂O₃); the other two are the stoichiometric limits (see Appen. 2 Fig. 1), which give the minimum (15 eNK) and maximum (13 eCNK) ferric estimates. All of the stoichiometric limits except $\Sigma Ca \leq 15$ (here $\Sigma Ca = 15.029$) are met by the all-ferrous formula, which means that the minimum ferric formula is given by the 15 eNK estimate (Appendix 2 Table 1).

Because ΣMn (13.201) is nearest the lowest allowable sum, the maximum ferric estimate values, and the ferric formula is obtained by recalculating as before, but, in this

¹ Exceptions do exist: Potassium titanian richterite (Oberti et al. 1992) has Ti at tetrahedral sites, and cannilloite has one Ca at the B (M4) position. These exceptions are rare.

APPENDIX 2: TABLE 1. A hypothetical amphibole analysis and the structural formulae that are based on the chemical and stoichiometric limits

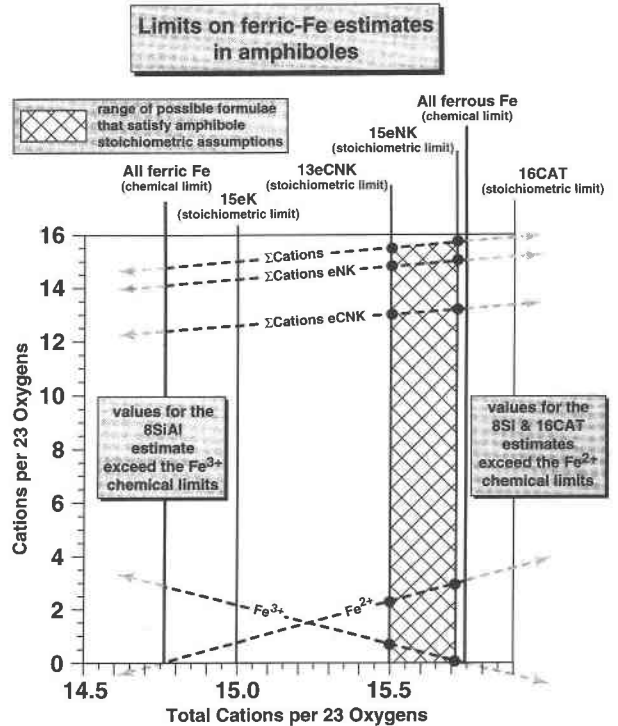
Analysis (wt%)		Formulae			
		All ferrous	15 eNK	13 eCNK	All ferric
SiO ₂	Si	6.093	6.081	6.000	5.714
Al ₂ O ₃	Al	1.907	1.919	2.000	2.286
FeO	Σ	8.000	8.000	8.000	8.000
MgO					
CaO	Al	1.139	1.122	1.000	0.571
Na ₂ O	Fe ³⁺	0.000	0.088	0.700	2.857
	Mg	1.015	1.014	1.000	0.952
	Fe ²⁺	2.845	2.777	2.300	0.000
	Σ	5.000	5.000	5.000	4.380
	Fe ²⁺	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

Note: The ferrous formula assumes total Fe as FeO, the ferric formula assumes total Fe as Fe₂O₃, the 13 eCNK and 15 eNK formulae are based on stoichiometric limits. See text for discussion.

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 ΣAl , 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 O atom basis such that $\Sigma\text{Ca} = 15.000$ and $\Sigma\text{Mn} = 13.000$ (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 $\Sigma\text{Ca} = 15.000$ and $\Sigma\text{Mn} = 13.000$. 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 O atom-based formula.

The formula obtained from either recalculation method has less than 23 O atoms. The number of Fe³⁺ cations is found by calculating the number of moles of FeO that must be converted to FeO_{1.5} to bring the sum of the O atoms to 23 and equals $(23 - \Sigma\text{Ox}) \times 2$, where ΣOx is the sum of the O atoms 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 sums of cations with the same valence). The moles of FeO equal $\text{Fe}_T - \text{Fe}^{3+}$, where Fe_T = total Fe in the normalized formula. Following any recalculation, it is good practice to recheck that all six stoichiometric limits are also satisfied by the new ferric formula.



APPENDIX 2: FIGURE 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 Appendix 2 Figure 1, and the values are based on the amphibole example in Appendix 2 Table 1.

Discussion of the recalculation results

The variation in some cation values within the ranges of possible formulae (Appendix 2 Table 1) that are defined by the chemical and stoichiometric limits are compared in Appendix 2 Figure 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 Appendix 2 Figure 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 can be considered. These will vary greatly from example to example. It can be inferred from Appendix 2 Figure 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 Appendix 2 Figure 2 show 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 estimate of the proportion of ferric iron, and (2) determine limits, chemical or stoichiometric, that give the minimum and maximum estimates of the proportion of ferric iron. To accomplish this, all the normalization factors for all stoichiometric con-

APPENDIX 2: TABLE 2. A worked example of an amphibole analysis that appears in Deer et al. (1992, p. 678)

	1	2	3	4	5	6
	wt%	Molecular proportions wt% ÷ mol. wt.	Atomic proportions (cations) col. 2 × cations in oxide	Atomic proportions (O atoms) col. 2 × oxygens in oxide	Anions on the basis of 23 O atoms col. 4 × 8.450 12	Cations on the basis of 23 O atoms col. 3 × 8.450 12
SiO ₂	51.63	0.859 28	0.859 28	1.718 57	14.522 08	7.261
TiO ₂	0.00	0.000 00	0.000 00	0.000 00	0.000 00	0.000
Al ₂ O ₃	7.39	0.072 48	0.144 96	0.217 44	1.837 36	1.225
Cr ₂ O ₃	0.00	0.000 00	0.000 00	0.000 00	0.000 00	0.000
FeO	7.55	0.105 09	0.105 09	0.105 09	0.887 99	0.888
MnO	0.17	0.002 40	0.002 40	0.002 40	0.020 25	0.020
MgO	18.09	0.448 84	0.448 84	0.448 84	3.792 74	3.793
CaO	12.32	0.219 69	0.219 69	0.219 69	1.856 41	1.856
Na ₂ O	0.61	0.009 84	0.019 68	0.009 84	0.083 17	0.166
K ₂ O	0.00	0.000 00	0.000 00	0.000 00	0.000 00	0.000
Sum			1.799 94	2.721 85	23.000 0	15.210

Factor for the recalculation of atomic proportions
to 23 O basis: $23 \div 2.721\ 85 = 8.450\ 12$

Notes: See the end of the text for a step-by-step discussion of this table. Molecular weights are from Robie et al. (1978).

straints and the chemical limits must be compared (see Appen. 2 Fig. 1). The normalization factors for the stoichiometric constraints are calculated from the all-ferrous formula using the data in Appendix 2 Table 1 and are:

Minimum ferric estimate:

$$8\text{Si} = 8/\text{Si} = 8/6.093 = 1.313, \quad (1)$$

$$16\text{CAT} = 16/\Sigma\text{K} = 16/15.740 = 1.017, \quad (2)$$

$$\text{all ferrous (no change)} = 1.000, \quad (3)$$

$$15\text{eNK} = 15/\Sigma\text{Ca} = 15/15.029 = 0.998, \quad (4)$$

Maximum ferric estimate:

$$13\text{eCNK} = 13/\Sigma\text{Mn} = 13/13.201 = 0.985, \quad (5)$$

$$15\text{eK} = 15/\Sigma\text{Na} = 15/15.740 = 0.953, \quad (6)$$

$$\text{all ferric} = 0.938, \quad (7)$$

$$8\text{SiAl} = 8/\Sigma\text{Al} = 8/9.139 = 0.875. \quad (8)$$

For the normalizations that yield minimum estimates (1–4), the recalculation that requires the lowest normalization factor will be the minimum ferric estimate. For the normalizations that yield maximum estimates (5–8), the recalculation that requires the largest normalization factor will be the maximum ferric estimate. All normalizations that lie 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 (5–8) are greater than any of those for the minimum estimate (1–4), then the analysis is not suitable for empirical ferric 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 the chemical limits.

In addition to the stoichiometric constraints listed in Appendix 2 Figure 1, another constraint on maximum Fe³⁺ can be defined if the C site in the formulation of the amphibole nomenclature is further subdivided. The five C positions consist of three mica-like octahedra (two M1 and one M3) and two pyroxene-like M2 octahedra. The cations Al, Fe³⁺, Ti, and Cr³⁺ 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 the desired resulting stoichiometry and (2) $\text{Fe}^{3+} = (23 - 23 \times N) \times 2$, which gives the Fe³⁺ for this normalization. The solution 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 Appendix 2 Table 1, this normalization factor (here abbreviated $10\Sigma\text{Fe}^{3+}$) is 0.977, which is less than the value 0.983 of the 13 eCNK factor; therefore the $10\Sigma\text{Fe}^{3+}$ normalization does 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, p. 9–10) discuss some of these possibilities for Mg-Fe-Mn-Li, calcic, sodic-calcic, and sodic amphiboles in greater detail. The $10\Sigma\text{Fe}^{3+}$ correction discussed in the preceding paragraph will probably not be

APPENDIX 2: TABLE 2.—Extended

Ideal site assignments	7 Min. formula from col. 6	Cations	8 Col. 6 × 0.997 14	9 Col. 8 × oxygen per cation	Ideal site assignments	10 Formula (15 eNK) minimum Fe ³⁺	11 Formula (15 eK) maximum Fe ³⁺	12 Formula ave. of min. and max. Fe ³⁺	13 Formula from DHZ
Si	7.261				Si	7.240	7.161	7.201	7.196
Al ^{IV}	0.739				Al ^{IV}	0.760	0.839	0.799	0.804
Sum T	8.000	Si	7.2401	14.4802	Sum T	8.000	8.000	8.000	8.000
Al ^{VI}	0.486	Al	1.2214	1.8321	Al ^{VI}	0.462	0.369	0.416	0.410
Fe ³⁺	0.000	Ti	0.0000	0.0000	Fe ³⁺	0.133	0.634	0.383	0.263
Cr	0.000	Cr	0.0000	0.0000	Cr	0.000	0.000	0.000	0.000
Mg	3.793	Mg	3.7818	3.7818	Mg	3.782	3.740	3.761	3.759
Fe ²⁺	0.721	Fe ²⁺	0.8854	0.8854	Fe ²⁺	0.624	0.242	0.440	0.618
Mn	0.000	Mn	0.0202	0.0202	Mn	0.000	0.015	0.000	0.000
Sum C	5.000	Ca	1.8511	1.8511	Sum C	5.000	5.000	5.000	5.000
Mg	0.000	Na	0.1659	0.0829	Mg	0.000	0.000	0.000	0.000
Fe ²⁺	0.167	K	0.0000	0.0000	Fe ²⁺	0.129	0.000	0.057	0.050
Mn	0.020	Sum	15.1659	22.9337	Mn	0.020	0.005	0.020	0.020
Ca	1.856				Ca	1.851	1.831	1.841	1.840
Na	0.000				Na	0.000	0.164	0.082	0.090
Sum B	2.043				Sum B	2.000	2.000	2.000	2.000
Na	0.166				Na	0.166	0.000	0.083	0.074
K	0.000				K	0.000	0.000	0.000	0.000
Sum A	0.166				Sum A	0.166	0.000	0.073	0.074
Total	15.210				Total	15.166	15.000	15.083	15.074

ΣCa (col. 7)
 $15 \div 15.043 = 0.99714$
 $(23 - 22.9337) \times 2 = 0.1325$
 $0.885 - 0.133 = 0.753$

important in calcic amphiboles, but in sodic amphiboles (e.g., riebeckite, glaucophane) this correction may commonly yield the maximum ferric estimate.

Choosing a single representative ferric formula from the range of possible formulae requires further justification or 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 Ca-saturated, metamorphic hornblende and is based on regression analysis of hornblende compositions for which ferric-ferrous determinations were known.

Generally, it is 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 of formulae gives a wide spectrum of possible names, this should probably be mentioned wherever the amphibole is 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 are independent of the pro-

portions of OH, F, or Cl that are present. The critical assumption is that exactly two anions (OH, F, Cl) are present for every 22 O atoms.

Coupled substitutions involving anions

The validity of a basic 23 O atom anhydrous amphibole formula [i.e., exactly two (OH + F + Cl)] is an underlying assumption in the procedure to estimate Fe³⁺ in amphiboles. Any variation in these values will have a tremendous effect on the Fe³⁺ 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 (see also 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 Fe³⁺, the increase in the sum from the partial exchange of O for OH tends to be offset by treating the larger amounts of Fe₂O₃ as FeO. Consequently, even in anhydrous amphiboles with significant Fe³⁺, 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 H₂O and halogen contents is an essential additional requirement.

WORKED EXAMPLE: CALCULATION OF A MINERAL FORMULA AND A FERRIC ESTIMATE FROM AN ELECTRON MICROPROBE ANALYSIS OF AN AMPHIBOLE

The analysis that appears in Deer et al. (1992, p. 678) was chosen as an example (Appendix 2 Table 2). To sim-

APPENDIX 2: TABLE 3. Calculation of normalization factors

Limit	Calculation method	Calculation	Normal-ization factor
Calculations for minimum ferric estimates			
8Si	$8 \div \text{Si}$	$8 \div 7.261$	1.1018
16CAT	$16 \div \Sigma K$	$16 \div 15.210$	1.0519
All ferrous	—	—	1.0000
15 eNK	$15 \div \Sigma \text{Ca}$	$15 \div 15.043$	0.9971*
Calculations for maximum ferric estimates			
15 eK	$15 \div \Sigma \text{Na}$	$15 \div 15.210$	0.9862*
13 eCNK	$13 \div \Sigma \text{Mn}$	$13 \div 13.187$	0.9858
All ferric	$23 \div [23 + (0.5 \times \text{Fe}^{2+})]$	$23 \div 23.444$	0.9811
$10\Sigma\text{Fe}^{3+}$	$36 \div (46 - \text{Si} - \text{Al} - \text{Ti} - \text{Cr})$	$36 \div 37.5141$	0.9596
8SiAl	$8 \div \Sigma \text{Al}$	$8 \div 8.486$	0.9427

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

ulate analysis by electron microprobe the Fe^{3+} was recast as Fe^{2+} and the H_2O analysis was ignored. The ferric estimate was made assuming 2(OH) are present rather than the 2.146 suggested by the actual H_2O determination. Any discrepancies in the final decimal places of the numbers that appear below and in Appendix 2 Table 2 are due to rounding effects. Molecular weights are from Robie et al. (1978).

- (1) Divide each wt% value (column 1) by the molecular weight of the oxide to yield the *molecular proportion* of each oxide (column 2). [e.g., for SiO_2 : $51.63 \div 60.085 = 0.85928$]
 - (2) Obtain *atomic proportions of the cations* (column 3) and *atomic proportions of the O atoms* (column 4) by multiplying each *molecular proportion* value by the number of cations and O atoms in the oxide. [e.g., for SiO_2 : $0.85928 \times 1 = 0.85928$ and $0.85928 \times 2 = 1.71857$]
- Note:* Assuming 2 (OH) groups are present, 1 O atom is balanced by 2 H (i.e., H_2O) so the cation charges are balanced by the remaining 23 O atoms that are 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 $\text{OH} + \text{F} + \text{Cl} = 2$, the 23 O atoms formula gives the correct mineral formula).
- (3) Obtain the *anions based on 23 O atoms* (column 5) by multiplying each value in column 4 by (23 \div the sum of column 4) [e.g., $23 \div 2.72185 = 8.45012$; for SiO_2 : $0.85928 \times 8.45012 = 14.52208$]
 - (4) Obtain the *cations on the basis of 23O atoms* (column 6) by multiplying each value in column 3 by (23 \div the sum of column 4) [e.g., for SiO_2 : $0.85928 \times 8.45012 = 7.261$]

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:

- (a) *the eight tetrahedral (T) sites:*
 - (i) Place all Si here; if $\text{Si} < 8$ fill the remaining sites with Al.
 - (ii) If $\text{Si} + \text{total Al} < 8$, then place all Si + Al here.
 - (b) *The five octahedral (C) sites (M2, M1, M3)*
 - (i) Place Al remaining from step (a), Ti, Fe^{3+} (initially = 0), and Cr here. In the following order, place enough Mg, Fe^{2+} , and Mn here to bring the total to 5.
 - (ii) If $\Sigma(\text{Al} \dots \text{Mn}) < 5$, then place all these elements here.
 - (c) *The 2 (B) sites (M4):*
 - (i) Place any Mg, Fe^{2+} , or Mn and Ca remaining after step (b) here.
 - (ii) If $\Sigma(\text{Mg} \dots \text{Ca}) \text{ at } B < 2$, fill the remaining sites with Na to bring the total to 2.
 - (d) *The single large (A) site:*
 - (i) Place any remaining Na and K here.
- (6) *Evaluating the structural formula*
 If any site has less than its ideal value ($T = 8, C = 5, B = 2, A = 0-1$), 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 Appendix 2 Table 3 and are obtained from columns 6 or 7.
 If all the normalization factors (8Si, 16CAT, and 15 eNK) are greater than all the normalization factors (8 SiAl, 15 eK, $10\Sigma\text{Fe}^{3+}$, and 13 eCNK), 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 ($\text{Fe}^{3+} = 0$) is the lower limit. In this example, the 15 eNK 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 15 eNK normalization factor, 0.99714 ($15 \div 15.043$).
- (8) Find the sum of O atoms (22.9337) in the normalized formula by multiplying each single cation value (column 8) by the number of balancing O atoms [e.g., for SiO_2 , $7.2401 \times 2 = 14.4802$; for $\text{AlO}_{1.5}$, $1.2214 \times 1.5 = 1.8321$; for MgO , $3.7818 \times 1 = 3.7818$; for $\text{NaO}_{0.5}$, $0.1659 \times 0.5 = 0.0829$].
 - (9) *Ferric Fe* equals the amount of ferrous Fe that must

be converted to bring the total O atoms 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 double checks the correctness of your calculations. It also is a check of whether correcting the initial stoichiometric violation will produce another violation [Here, insufficient cations to fill T or C could result from the 15 eNK normalization. Such analyses cannot be used for ferric Fe estimates (unfortunately, much of calculation is involved in determining this)].

- (12) *Maximum ferric estimates*

The largest normalization factor among the four choices, 8SiAl, 15 eK, 13 eCNK, and all ferric, determines the formula that yields the maximum ferric estimate. If the factors 8SiAl, 15 eK, and 13 eCNK are all less than the all-ferric value, then the all-ferric formula would give the maximum Fe^{3+} . In this example, the 15 eK normalization factor is the largest and can be used to give the formula with maximum Fe^{3+} .

To obtain the formula that gives the maximum ferric estimate (column 11), repeat steps 7 through 10 using the 15 eK 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 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 (15

eNK) in column 10 and maximum (15 eK) in column 11, but is nearer to the minimum.

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