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 nyboite, 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,

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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 H2O 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, NaB 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 NaB < 0.50 and NaB ≥ 1.50, instead of NaB < 0.67 and NaB > 1.34. Previously, the amphibole 'box' was divided into three equal volumes with respect to NaB. 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 Fe2O3) 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 Fe3+ and Fe2+. 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 Pmn 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 AB2C~IT[VO22(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: 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
- L type ions: Mg, Fe2+, Mn2+, Li and rarer ions of similar size such as Zn, Ni, Co at C or B
- M type ions: A1 at C or T
- Fe3+ and more rarely Mn3+, Cr3+ at C or T
- High valency ions: Ti4+, Zr4+ at C or T
- Si at T only
- Anions, OH, F, Cl, O at 'OH'

Si, NaB 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 NaB < 0.50 and NaB ≥ 1.50, instead of NaB < 0.67 and NaB > 1.34. Previously, the amphibole 'box' was divided into three equal volumes with respect to NaB. 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 Fe2O3) 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
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) e.g. Fe$^{2+}$; superscript roman numerals to coordination numbers e.g. Al$^{V}$; and subscript numerals to numbers of atoms e.g. 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 H$_2$O and halogen contents are well established, the formula should be calculated to 24(O,H,F,Cl).

2. If the H$_2$O plus halogen content is uncertain, the formula should be calculated to the basis of 23(O) with 2(O,H,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 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, 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 0.00 and 1.00.

The most common uncertainty results from lack of analyses for H$_2$O, 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 an analysis is near to Mg/(Mg+Fe$^{2+}$) = 0.50 or Fe$^{3+}$/(Fe$^{3+}$+Al$^{V}$) = 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 Fe$^{3+}$ and 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 (Si+Al)+Cr+Ti+Fe+Mg+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 analyses studied, excluding kaersutites, for the calcic, sodic-calcic and sodic amphiboles. If this sum is adjusted to include Li and Zr i.e. (Si+Al+Cr+Ti+Zr+Li+Fe+Mg+Mn)+13 and for the Mg-Fe-Mn-Li amphiboles the sum of (Si+Al+Cr+Ti+Zr+Li+Fe+Mg+Mn+Ca) = 15 is used, then only the Ti $\geq$0.50 amphiboles need special treatment, although it is recognised that Mn-rich amphiboles pose problems with the variable valency state of both the Fe and Mn and that, as shown by Hawthorne (1983, pp. 183-5), both in theory and practice, any calculation of Fe$^{3+}$ and 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 H$_2$O+ contents that lead to more than (OH)$_2$ in the formula, but the structure contains only 2 sites for independent 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 (Ca+Na)$_B$ < 1.00 and L type ions (Mg,Fe,Mn,Li)$_B$ $\approx$ 1.00, then the amphibole is a member of the magnesium-iron-manganese-lithium group.

2. When (Ca+Na)$_B$ $\approx$ 1.00 and Na$_B$ < 0.50, then the amphibole is a member of the calcic group. Usually, but not always, Ca$_B$ > 1.50.

3. When (Ca+Na)$_B$ $\approx$ 1.00 and Na$_B$ 0.50 to 1.50, then the amphibole is a member of the sodic-calcic group.

4. When Na$_B$ $\approx$ 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 Mg/(Mg+Fe$^{2+}$) or Mg/(Mg+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: Si = Al$^{IV}$, $\square$ = (Na,K)$_A$, Ca$_B$ = Na$_B$, Li = L$^2$, Mg = L$^2$, (Ti,Zr) = L$^2$, O = (OH,F,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 = Fe²⁺, Al⁴⁺ = Fe³⁺ 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_a 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 R²⁺ and R³⁺ (i.e. usually L and M type ions) separately in the C group. The importance of the difference between R²⁺ and R³⁺ in the C group has however been recognised rather more formally than previously by the way in which Fe³⁺, Al³⁺, Cr⁵⁺ or Mn⁴⁺ abundance has been defined with prefixes, not modifiers, when they occupy 50% or more of the normal maximum of 2R²⁺ 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. ferricyböite. 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**

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Meaning</th>
<th>Applicable to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumino</td>
<td>Al⁴⁺ &gt; 1.00</td>
<td>Calcic &amp; sodic-calcic only</td>
</tr>
<tr>
<td>Chloro</td>
<td>Cl &gt; 1.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Chromio</td>
<td>Cr &gt; 1.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Ferri</td>
<td>Fe³⁺ &gt; 1.00</td>
<td>All groups except sodic</td>
</tr>
<tr>
<td>Fluoro</td>
<td>F &gt; 1.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Manganio</td>
<td>Mn²⁺ = 1.00–2.99</td>
<td>All groups except kozulite &amp; ungarettite</td>
</tr>
<tr>
<td>Permanganio</td>
<td>Mn²⁺ = 3.00–4.99</td>
<td>All groups except kozulite</td>
</tr>
<tr>
<td>Mangani</td>
<td>Mn³⁺ &gt; 1.00</td>
<td>All groups except kornite &amp; ungarettite</td>
</tr>
<tr>
<td>Potassic</td>
<td>K &gt; 0.50</td>
<td>All groups</td>
</tr>
<tr>
<td>Sodic</td>
<td>Na &gt; 0.50</td>
<td>Mg-Fe-Mn-Li only</td>
</tr>
<tr>
<td>Titanio</td>
<td>Ti &gt; 0.50</td>
<td>All groups except kaersutite</td>
</tr>
<tr>
<td>Zincio</td>
<td>Zn &gt; 1.00</td>
<td>All groups</td>
</tr>
</tbody>
</table>

The prefixes in the figures are ferro (Fe²⁺>Mg) and magnesio (Fe²⁺<Mg) and in Fig. 5a only ferricyböite with Al⁴⁺<Fe³⁺ (not ferricyböite 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)\textsubscript{B} < 1.00 and (Mg,Fe,Mn,LI)\textsubscript{B} ≥ 1.00 in the standard formula;

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Meaning</th>
<th>Applicable to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barian</td>
<td>Ba</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Borian</td>
<td>B</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Calcian</td>
<td>Ca</td>
<td>&gt; 0.50</td>
</tr>
<tr>
<td>Chlorian</td>
<td>Cl</td>
<td>= 0.25–0.99</td>
</tr>
<tr>
<td>Chromian</td>
<td>Cr</td>
<td>= 0.25–0.99</td>
</tr>
<tr>
<td>Ferrrian</td>
<td>Fe\textsuperscript{3+}</td>
<td>= 0.75–0.99</td>
</tr>
<tr>
<td>Fluorian</td>
<td>F</td>
<td>= 0.25–0.99</td>
</tr>
<tr>
<td>Hydroxylian</td>
<td>OH</td>
<td>&gt; 3.00</td>
</tr>
<tr>
<td>Lithian</td>
<td>Li</td>
<td>&gt; 0.25</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn\textsuperscript{2+}</td>
<td>= 0.25–0.99</td>
</tr>
<tr>
<td>Manganian</td>
<td>Mn\textsuperscript{3+} or Mn\textsuperscript{4+}</td>
<td>= 0.25–0.99</td>
</tr>
<tr>
<td>Nickelooan</td>
<td>Ni</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Oxygenian</td>
<td>(OH+F+Cl)</td>
<td>&lt; 1.00</td>
</tr>
<tr>
<td>Potassian</td>
<td>K</td>
<td>= 0.25–0.49</td>
</tr>
<tr>
<td>Plumbian</td>
<td>Pb</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Sodian</td>
<td>Na</td>
<td>= 0.25–0.49</td>
</tr>
<tr>
<td>Strontian</td>
<td>Sr</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Titanian</td>
<td>Ti</td>
<td>= 0.25–0.49</td>
</tr>
<tr>
<td>Vanadian</td>
<td>V</td>
<td>&gt; 0.10</td>
</tr>
<tr>
<td>Zincian</td>
<td>Zn</td>
<td>&gt; 0.10–0.99</td>
</tr>
<tr>
<td>Zirconian</td>
<td>Zr</td>
<td>&gt; 0.10</td>
</tr>
</tbody>
</table>
Mg-Fe-Mn-Li amphiboles

**Diagram Parameters:** (Ca + Na) < 1.00; (Mg, Fe, Mn, Li) > 1.00; Li < 1.00

<table>
<thead>
<tr>
<th>Orthorhombic</th>
<th>Monoclinic</th>
</tr>
</thead>
<tbody>
<tr>
<td>anthophyllite</td>
<td>gedrite</td>
</tr>
<tr>
<td>ferro-anthophyllite</td>
<td>ferrogedrite</td>
</tr>
<tr>
<td>cummingtonite</td>
<td>grunerite</td>
</tr>
</tbody>
</table>

**Diagram Parameters:** (Ca + Na) < 1.00; (Mg, Fe$^{2+}$, Mn, Li) ≥ 1.00; Li ≥ 1.00

<table>
<thead>
<tr>
<th>Orthorhombic</th>
<th>Monoclinic</th>
</tr>
</thead>
<tbody>
<tr>
<td>holmquistite</td>
<td>clinoholmquistite</td>
</tr>
<tr>
<td>ferroholmquistite</td>
<td>clinoferroholmquistite</td>
</tr>
</tbody>
</table>

Final names require the relevant prefixes which are listed in Table 1 and may optionally include the modifiers that are found in Table 2.

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 \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) = 0.50 \), the reduction of adjectives and the abolition of tirodite and dannemorite.

**Orthorhombic forms**

(1) **Anthophyllite series.**

\[
\text{Na}_{2}\text{Li}_{3}\text{(Mg,Fe}^{2+},\text{Mn})_{7-y-x}\text{Al}_{x}\text{(Si}_{7-x-y+z}\text{Al}_{x+y-z})\text{O}_{22} \quad \text{(OH,F,Cl)}_{2} \text{ where } \text{Si} > 7.00 \text{ (otherwise the mineral is gedrite) and Li} < 1.00 \text{ (otherwise the mineral is holmquistite). Most anthophyllites have the } \text{Pnma} \text{ structure; those with the } \text{Pnmn} \text{ structure may be prefixed proto without a hyphen.}
\]

**End members**

- Anthophyllite: \( \text{Mg}_{7}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Ferro-anthophyllite: \( \text{Fe}^{2+}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Sodicanthophyllite: \( \text{NaMg}_{7}\text{Si}_{8}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)
- Sodic-ferro-anthophyllite: \( \text{NaFe}^{2+}\text{Si}_{8}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)

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

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

(2) **Gedrite series**

\[
\text{Na}_{x}\text{Li}_{y}\text{(Mg,Fe}^{2+},\text{Mn})_{7-y-x}\text{Al}_{x}\text{(Si}_{7-x-y+z}\text{Al}_{x+y-z})\text{O}_{22} \quad \text{(OH,F,Cl)}_{2} \text{ where } x + y - z > 1.00 \text{ so that } \text{Si} > 7.00 \text{ this being the distinction from anthophyllite. Li} < 1.00.
\]

**End members**

- Gedrite: \( \text{Mg}_{5}\text{Al}_{2}\text{Si}_{6}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)
- Ferrogedrite: \( \text{Fe}^{2+}\text{Al}_{2}\text{Si}_{6}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)
- Sodigedrite: \( \text{NaMg}_{5}\text{Al}_{2}\text{Si}_{6}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)
- Sodic-ferrogedrite: \( \text{NaFe}^{2+}\text{Al}_{2}\text{Si}_{6}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \)

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

- Gedrite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) > 0.50 \)
- Ferrogedrite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) < 0.50 \)
- Sodigedrite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) > 0.50; \text{Na} > 0.50 \)
- Sodic-ferrogedrite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) < 0.50; \text{Na} > 0.50 \)

(3) **Holmquistite series**

\[
\square\text{(Li}_{2}\text{Mg}_{3}\text{Al}_{2})\text{Si}_{8}\text{O}_{22}(\text{OH,F,CI})_{2} \text{ Li} \geq 1.00 \text{ is critical.}
\]

**End members**

- Holmquistite: \( \square\text{(Li}_{2}\text{Mg}_{3}\text{Al}_{2})\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Ferroholmquistite: \( \square\text{(Li}_{2}\text{Fe}^{3+}\text{Al}_{2})\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)

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

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

**Monoclinic forms**

(1) **Cummingtonite-Grunerite series**

\[
\square\text{(Mg,Fe}^{2+},\text{Mn,Li})_{3}\text{(Fe}^{3+}\text{,Al})_{2}\text{Si}_{8}\text{O}_{22}(\text{OH,F,Cl})_{2} \text{ Li} < 1.00 \text{. Most members of this series have space group C2/m; those with P2/m may optionally have this symbol suffixed at the end of the name.}
\]

**End members**

- Cummingtonite: \( \square\text{Mg}_{7}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Grunerite: \( \square\text{Fe}^{2+}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Manganocummingtonite: \( \square\text{Mn}_{3}\text{Mg}_{5}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Permanganogrunerite: \( \square\text{Mn}_{3}\text{Fe}^{2+}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Manganogrunerite: \( \square\text{Mn}_{3}\text{Fe}^{2+}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)

**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: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) > 0.50; \text{Mn} > 3.00 \)
- Permanganogrunerite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) < 0.50; \text{Mn} > 3.00 \)
- Manganogrunerite: \( \text{Mg}/(\text{Mg}+\text{Fe}^{2+}) > 0.50; \text{Mn} > 3.00 \)

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 \( \text{Mg}_{5}\text{Al}_{2}\text{Si}_{6}\text{Al}_{2}\text{O}_{22}(\text{OH})_{2} \).

(2) **Clinoholmquistite series**

\[
\square\text{(Li}_{2}\text{Mg,Fe}^{2+},\text{Mn})_{3}\text{(Fe}^{3+}\text{,Al})_{2}\text{Si}_{8}\text{O}_{22}(\text{OH,F,Cl})_{2} \text{ Li} \geq 1.00
\]

**End members**

- Clinoholmquistite: \( \square\text{Li}_{2}\text{Mg}_{3}\text{Al}_{2}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Clinoferroholmquistite: \( \square\text{Li}_{2}\text{Fe}^{3+}\text{Al}_{2}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Ferri-clinoholmquistite: \( \square\text{Li}_{2}\text{Fe}_{3}\text{Al}_{2}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)
- Ferri-clinoferroholmquistite: \( \square\text{Li}_{2}\text{Fe}_{3}\text{Al}_{2}\text{Si}_{8}\text{O}_{22}(\text{OH})_{2} \)

**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 \(\text{Na}_B = 0.50\) to 1.50; usually \(\text{Ca}_B \geq 1.50\). 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

![Diagram of Calcic Amphiboles](image-url)

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

**End members**

<table>
<thead>
<tr>
<th>Tremolite</th>
<th>Na$_2$Mg$_3$Si$<em>4$O$</em>{10}$(OH)$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferro-actinolite</td>
<td>Na$_2$Fe$_3^+$(Si$<em>6$O$</em>{18}$)(OH)$_2$</td>
</tr>
<tr>
<td>Edenite</td>
<td>Na$_2$CaMg$_3$Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Ferro-edenite</td>
<td>Na$_2$CaFe$_3^+$(Si$<em>6$O$</em>{18}$)(OH)$_2$</td>
</tr>
<tr>
<td>Pargasite</td>
<td>Na$<em>2$Ca(Fe$</em>{2+}$Al$_{6+}$)Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Ferropargasite</td>
<td>Na$<em>2$(Fe$</em>{2+}$Al$_{6+}$)Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Magnesiomagnesiohastingsite</td>
<td>Na$_2$Ca$_2$(Mg$<em>4$Fe$</em>{2+}$)Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
</tbody>
</table>

**End members**

<table>
<thead>
<tr>
<th>Na$_2$Fe$_3^+$(Si$<em>6$O$</em>{18}$)(OH)$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_2$CaMg$_3$Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Na$_2$CaFe$_3^+$(Si$<em>6$O$</em>{18}$)(OH)$_2$</td>
</tr>
<tr>
<td>Na$<em>2$Ca(Fe$</em>{2+}$Al$_{6+}$)Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Na$<em>2$(Fe$</em>{2+}$Al$_{6+}$)Si$_6$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
</tbody>
</table>

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

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

**Sodic-calcic amphiboles**

This group is defined as monoclinic amphiboles in which (Ca+Na)$_B$ ≥ 1.00 and 0.50 < Na$_B$ < 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**

<table>
<thead>
<tr>
<th>Richterite</th>
<th>Na$_2$(CaNa)Mg$_3$Si$<em>4$O$</em>{10}$(OH)$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferronrichterite</td>
<td>Na$_2$(CaNa)Fe$_3^+$(Si$<em>6$O$</em>{18}$)(OH)$_2$</td>
</tr>
<tr>
<td>Winchite</td>
<td>Na$_2$(CaNa)Mg$<em>4$Fe$</em>{2+}$Si$<em>6$O$</em>{18}$(OH)$_2$</td>
</tr>
<tr>
<td>Ferrowinchite</td>
<td>Na$_2$(CaNa)Fe$_3^+$(AlFe$^{3+}$)Si$<em>6$O$</em>{18}$(OH)$_2$</td>
</tr>
<tr>
<td>Barroisite</td>
<td>Na$_2$(CaNa)Mg$<em>3$AlFe$</em>{2+}$Si$_7$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Ferrobartoisite</td>
<td>Na$_2$(CaNa)Fe$_3^+$(AlFe$^{3+}$)Si$_7$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Aluminobarroisite</td>
<td>Na$_2$(CaNa)Mg$_3$Al$_2$Si$_7$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
<tr>
<td>Aluminoferrobarroisite</td>
<td>Na$_2$(CaNa)Fe$_2+$(AlFe$^{3+}$)Si$_7$Al$<em>2$O$</em>{22}$(OH)$_2$</td>
</tr>
</tbody>
</table>

**Sodic amphiboles**

This group is defined as monoclinic amphiboles in which Na$_B$ ≥ 1.50. The detailed classification is shown in Fig. 5. Apart from revision of the boundary Na$_B$ ≥ 1.50 instead of Na$_B$ ≥ 1.34, and the abolition of crossite so that the 50% division is followed, the principal changes are the introduction of nybOite with Si close to 7, as approved in 1981 (Ungaretti et al.), ferric-nybOite (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**

<table>
<thead>
<tr>
<th>Glaucoephane</th>
<th>Na$_2$(Mg$_3$Al$_2$)Si$<em>4$O$</em>{10}$(OH)$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferroglaucoephane</td>
<td>Na$<em>2$(Fe$</em>{2+}$Al$_{6+}$)Si$<em>6$O$</em>{18}$(OH)$_2$</td>
</tr>
</tbody>
</table>
Magnesio-ribeckite $\text{Na}_2(\text{Mg}_{3\text{Fe}^{3+}})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Riebeckite $\text{Na}_2(\text{Fe}^{3+}\text{Fe}^{2+})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Eckermannite $\text{Na}_2(\text{Mg},\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Ferro-eckermannite $\text{Na}_2(\text{Fe}^{3+}\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Magnesio-arfvedsonite $\text{Na}_2(\text{Mg}_{2\text{Fe}^{2+}})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Arfvedsonite $\text{Na}_2(\text{Fe}^{3+}\text{Fe}^{2+})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Kozulite $\text{NaNa}_2(\text{Mn}^{2+}\text{Fe}^{2+}\text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Nyböte $\text{NaNa}_2(\text{Mg},\text{Al})_2\text{Si}_7\text{AlO}_{22}(\text{OH})_2$

Ferronyböte $\text{Na}_2(\text{Fe}^{3+}\text{Al})_2\text{Si}_7\text{AlO}_{22}(\text{OH})_2$

Ferric-nyböte $\text{Na}_2(\text{Mg},\text{Fe}^{2+})_3\text{Si}_7\text{AlO}_{22}(\text{OH})_2$

Ferric-ferronyböte $\text{Na}_2(\text{Fe}^{3+}\text{Fe}^{3+})_3\text{Si}_7\text{AlO}_{22}(\text{OH})_2$

Leakite $\text{NaNa}_2(\text{Mg}^{2+}\text{Fe}^{2+}\text{Li})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Ferroleakite $\text{NaNa}_2(\text{Fe}^{3+}\text{Fe}^{2+}\text{Li})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Kornite $\text{(Na,K)}\text{Na}_2(\text{Mg},\text{Mn})\text{Si}_8\text{O}_{22}(\text{OH})_2$

Ungarettii $\text{NaNa}_2(\text{Mn}^{2+},\text{Mn}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$

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

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

---

**sodic-calcic amphiboles**

**Diagram Parameters:**

(\(\text{Na} + \text{K}\))$_A$ \(\geq 0.50\); (\(\text{Ca} + \text{Na}_B\)) \(\geq 1.00\); 0.50 < \(\text{Na}_B$ < 1.50

---

**Diagram Parameters:**

(\(\text{Na} + \text{K}\))$_A$ < 0.50; (\(\text{Ca} + \text{Na}_B\)) \(\geq 1.00\); 0.50 < \(\text{Na}_B$ < 1.50

---

**Fig. 4. Classification of the sodic-calcic amphiboles.**
sodic amphiboles

Diagram Parameters: \( Na_g \geq 1.50; (Mg + Fe^{2+} + Mn^{2+}) > 2.5; \)
\((Al^{VI} \text{ or } Fe^{3+}) > Mn^{3+}; Li < 0.5; (Mg or Fe^{2+}) > Mn^{2+} \)

\[ (Na + K)_A < 0.50 \]

\[ (Na + K)_A \geq 0.50 \]

**Fig. 5a.** Classification of the sodic amphiboles with \((Mg + Fe^{2+} + Mn^{2+}) > 2.5.\)
Diagram Parameters: \( \text{Na}_s \geq 1.50; (\text{Na} + \text{K})_A \geq 0.50; (\text{Mg} + \text{Fe}^{2+} + \text{Mn}^{2+}) \leq 2.5; \)
\( \text{Li} \geq 0.5 \)
\( (\text{Mg or Fe}^{2+}) > \text{Mn}^{2+} \)
\( (\text{Mg or Mn}^{2+}) > \text{Fe}^{3+} \)

in leakeite and \( \text{Fe}^{3+} < \text{Mn}^{3+} \) in kornite. Ferric-nybôite means \( \text{Fe}^{3+} \geq \text{Al}^{VI} \) and should be clearly distinguished from ferri (meaning \( \text{Fe}^{3+} > 1.00 \)) because neither aluminio (meaning \( \text{Al}^{VI} > 1.00 \)) 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.
NOMENCLATURE OF AMPHIBOLES

Magnesio-anthophyllite = anthophyllite
Sodium-anthophyllite = sodicanthophyllite
Magnesio-gedrite = gedrite
Sodium gedrite = sodicgedrite
Magnesio-holmquistite = holmquistite
Magnesio-cummingtonite = cummingtonite
Tirodite = mangano-cummingtonite
Dannemorite = manganogrunerite
Magnesio-clinoholmquistite = clinoholmquistite
Crossite = glaucochlore or ferroglaucophane or magnesioriebeckite or riebeckite
Tremolitic hornblende = magnesiohornblende
Actinolitic hornblende = magnesiohornblende
Ferro-actinolitic hornblende = ferrohornblende
Tschermainitic hornblende = tschermainite
Ferro-tschermainitic hornblende = ferrotschermainite
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

References


Nauka, Moscow. 397 pp.
Hawthorne, F.C., Oberti, R., Ungaretti, L. and Grice, J.D. (1992) Leakeite, NaNa_{2}(Mg_{2}Fe^{2+}Li)Si_{8}O_{22}(OH)_{2}, a new alkali amphibole from the Kajilondri manganite mine, Jhabua district, Madhya Pradesh, India. Amer. Mineral., 77, 1112–5.
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:* $a = 9.884 \, \text{Å}, \ b = 18.145 \, \text{Å}, \ c = 5.294 \, \text{Å}, \ \beta = 104.7^\circ$.


**Anthophyllite.** Named from anthropyllum '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:* $a = 18.5 \, \text{Å}, \ b = 17.9 \, \text{Å}, \ c = 5.28 \, \text{Å}$.


**Arvedsonite.** Named for J.A. Arvedson.

*Type locality:* Kangerdluarsuk, Greenland

*X-ray data:* $a = 9.94 \, \text{Å}, \ b = 18.17 \, \text{Å}, \ c = 5.34 \, \text{Å}, \ \beta = 104.40^\circ$.


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

*Type locality:* Not traced.


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

*Type locality:* Pargas, Finland.

*X-ray data:* (Fluor-cannilloite) $a = 9.826 \, \text{Å}, \ b = 17.907 \, \text{Å}, \ c = 5.301 \, \text{Å}, \ \beta = 105.41^\circ$.


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

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

*X-ray data:* $a = 9.80 \, \text{Å}, \ b = 17.83 \, \text{Å}, \ c = 5.30 \, \text{Å}, \ \beta = 109.10^\circ$.


**Cummingtonite.** Named for locality.

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

*X-ray data:* $a = 9.534 \, \text{Å}, \ b = 18.231 \, \text{Å}, \ c = 5.3235 \, \text{Å}, \ \beta = 101.97^\circ$.


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

*Type locality:* Norra Kärr, Sweden.

*X-ray data:* $a = 9.7652 \, \text{Å}, \ b = 17.892 \, \text{Å}, \ c = 5.284 \, \text{Å}, \ \beta = 103.168^\circ$.


**Edenite.** Named for locality.

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

*X-ray data:* $a = 9.837 \, \text{Å}, \ b = 17.954 \, \text{Å}, \ c = 5.307 \, \text{Å}, \ \beta = 105.18^\circ$.


**Gedrite.** Named from locality.

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

*X-ray data:* $a = 18.594 \, \text{Å}, \ b = 17.907 \, \text{Å}, \ c = 5.304 \, \text{Å}$.


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

*Type locality:* Syra, Cyclades, Greece.

*X-ray data:* $a = 9.595 \, \text{Å}, \ b = 17.978 \, \text{Å}, \ c = 5.307 \, \text{Å}, \ \beta = 103.66^\circ$.

Hastingsite. Named for locality.
Type locality: Hastings County, Ontario, Canada.
X-ray data: a 18.30 Å, b 17.69 Å, c 5.30 Å.
(PDF 13-401 on specimen from Barrantes, Quebec, Canada)

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 Barrantes, Quebec, Canada)

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

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, USA).

Katophorite. Named from the Greek kataphora a rushing down, in reference to its volcanic origin.
Type locality: Christiana District (now Oslo), Norway.

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°.

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)

Type locality: Kajidongri 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°.

Nyböite. Named from locality.
Type locality: Nybø, Nordfjord, Norway.
X-ray data: In Ungaretti et al. (1981) X-ray data given for many specimens and a single 'type' specimen not distinguished.

Pargasite. Named from 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)

Type locality: Långbod, 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)

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 Doubrutschia, Romania)

Sadanagaite. Named for R. Sadanaga.
Type locality: Yuge and Myojin Islands, Japan.
X-ray data: a 9.922 Å, b 18.003 Å, c 5.352 Å. β 105.30°.

Taramite. Named from type locality.
Type locality: Wadi Tarama, Maripol, 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...
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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. β 104.95°. (PDF 13-437 on specimen from San Gotardo, Switzerland and PDF 31-1285 on synthetic material)

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

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)°.

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)

General references

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 (+ 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 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 stoicho-

1 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**

<table>
<thead>
<tr>
<th>Site and Occupancy</th>
<th>Cation*</th>
<th>Stoichiometric Limit</th>
<th>Correction</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-site</td>
<td>Si</td>
<td>Si ≤ 8</td>
<td>8Si</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Al</td>
<td>ΣAl ≥ 8</td>
<td></td>
<td></td>
<td>8SiAl</td>
</tr>
<tr>
<td></td>
<td>Ti</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-site</td>
<td>Cr</td>
<td>ΣMn ≥ 13</td>
<td>13eCNK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>ΣCa ≤ 15</td>
<td>15eNK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-site</td>
<td>Mn</td>
<td>ΣMn ≥ 13</td>
<td>13eCNK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>ΣCa ≤ 15</td>
<td>15eNK</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Na</td>
<td>ΣNa ≥ 15</td>
<td>15eK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-site</td>
<td>K</td>
<td>ΣK ≤ 16</td>
<td>16CAT</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Σ = cation subtotal (e.g., ΣMn = 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 ΣCa ≤ 15 (here ΣCa = 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 ΣMn 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 ΣMn = 13.000 (here the normalization factor is: 13 ÷ 13.201 = 0.9848). The minimum values for ΣAl,
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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 Fe₂O₃. The 13eCNK and 15eNK formulae are based on stoichiometric limits. See text for discussion.

<table>
<thead>
<tr>
<th>Analysis (wt %)</th>
<th>Formulae</th>
<th>All</th>
<th>Ferrous</th>
<th>15eNK</th>
<th>13eCNK</th>
<th>All</th>
<th>Ferric</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>Si</td>
<td>39.38</td>
<td>6.093</td>
<td>6.081</td>
<td>6.000</td>
<td>5.714</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>Al</td>
<td>16.70</td>
<td>1.907</td>
<td>1.919</td>
<td>2.000</td>
<td>2.286</td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>Σ</td>
<td>23.54</td>
<td>8.000</td>
<td>8.000</td>
<td>8.000</td>
<td>8.000</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td></td>
<td>4.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td></td>
<td>11.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td></td>
<td>2.37</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>97.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 ÷ ΣCa or 13 ÷ ΣMn, here: 15 ÷ 15.029 = 0.9981 and 13 ÷ 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 (Fe³⁺) are found by calculating the number of moles of FeO that must be converted to FeO₁.₅ to bring the sum of the oxygens to 23 and equals (23 − ΣOx) × 2, where ΣOx is the sum of the oxygen in the normalized formula (ΣOx = ΣR⁴⁺ × 2 + ΣR⁺ × 1.5 + ΣR²⁺ + ΣR¹⁺ × 0.5, where ΣR = the
sums of cations with the same valence). The moles of FeO equal $F_{\text{TOT}} - F_{\text{Fe}^2+}$ where $F_{\text{TOT}} = \text{total Fe}$ 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
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:**

\[
\begin{align*}
8\text{Si} &= 8/\text{Si} = 8/6.093 = 1.313, \\
16\text{CAT} &= 16/\Sigma\text{K} = 16/15.740 = 1.017, \\
\text{all Ferrous (no change)} &= 1.000, \\
15\text{eNK} &= 15/\Sigma\text{Ca} = 15/15.029 = 0.998,
\end{align*}
\]

**Maximum ferric estimate:**

\[
\begin{align*}
13\text{eCNK} &= 13/\Sigma\text{Mn} = 13/13.201 = 0.985, \\
15\text{eK} &= 15/\Sigma\text{Na} = 15/15.740 = 0.953, \\
\text{all Ferric} &= 0.938, \\
8\text{SiAl} &= 8/\Sigma\text{Al} = 8/9.139 = 0.875.
\end{align*}
\]

For the normalizations that yield minimum estimates (1 to 4), the recalculaion that requires the lowest normalization factor will be the minimum ferric estimate. For the normalizations that yield maximum estimates (5 to 8), the recalculataion 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\(^{3+}\), Ti and Cr\(^{3+}\) 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) \(N \times (\text{Si} + \text{Ti} + \text{Al} + \text{Cr}) + 2\text{Fe}^{3+} = 10\), which describes desired resulting stoichiometry and (2) \(\text{Fe}^{3+} = 23 \times (N) \times 2\), 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 Fe₂O₃ 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 H₂O 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 SiO₂: 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 SiO₂: 0.85928 x 1 = 0.85928 and 0.85928 x 2 = 1.71857]
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 SiO₂: 1.71857 x 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 SiO₂: 0.85928 x 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>
<thead>
<tr>
<th>Cation</th>
<th>Fe²⁺</th>
<th>Fe³⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td></td>
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</tr>
<tr>
<td>Fe</td>
<td></td>
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</tr>
<tr>
<td>K</td>
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<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>Molecular Proportions</td>
<td>Atomic Proportions (cations)</td>
<td>Atomic Proportions (oxygen)</td>
<td>Anions on the basis of 23 oxygen</td>
<td>Cations on the basis of 23 oxygen</td>
<td>Ideal site assignments</td>
<td>Min. formula from col. 6</td>
<td>Cations</td>
<td>Col. 6 X</td>
<td>Col. 8 X</td>
<td>Ideal site assignments</td>
<td>Formula (15:57)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>col. 2 X</td>
<td>col. 2 X</td>
<td>col. 4 X</td>
<td>col. 3 X</td>
<td></td>
<td></td>
<td></td>
<td>oxygen per cation</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>51.63</td>
<td>0.65928</td>
<td>0.85928</td>
<td>1.71857</td>
<td>14.52208</td>
<td>7.261</td>
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<td>0.00000</td>
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<td>0.00000</td>
<td>0.739</td>
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<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>7.39</td>
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<td>1.2214</td>
<td>1.8321</td>
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<td>22.9337</td>
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<td>2.72185</td>
<td>23.9683</td>
<td>0.00000</td>
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<td>Factor for the recalculation of atomic proportions to 23 O basis: 23 x 2.72185 = 8.45012</td>
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</table>

For example, the calculation for the sum of Al<sup>3+</sup> in column 7 is:

\[
\text{sum } \text{Al}^{3+} = 8.000 \times \text{Si} + 0.486 \times \text{Al} + 1.2214 \times \text{Cr} + 1.8321 \times \text{Mg} + 0.8854 \times \text{Fe}^{3+} + 0.8854 \times \text{Mn} = 7.240
\]
(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\(^{3+}\) (initially = 0), and Cr here. In the following order, place enough Mg, Fe\(^{2+}\) and Mn to bring the total to 5.
- if Σ(AiV1Mn) < 5, then place all these elements here
(c) the 2 (B) sites (M4)
- place any Mg, Fe\(^{2+}\) or Mn and Ca remaining after step (b) here
- if Σ(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

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 estimation 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, 15eNK and all ferrous) are all greater than 1.0000, then the all-ferrous formula (Fe\(^{3+} = 0.000\)) 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 ÷ 15.043).

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\(_2\), 7.2401 ÷ 2 = 14.4802; for AlO\(_{1.5}\), 1.2214 ÷ 1.5 = 1.8321; for MgO, 3.7818 ÷ 1 = 3.7818; for NaO\(_{0.5}\), 0.1659 ÷ 0.5 = 0.8029]

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) × 2 = 0.133.
The new ferrous Fe value is the total Fe from column 8 minus the ferric Fe. [e.g. 0.885 - 0.133 = 0.752]
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)].

Maximum ferric estimates
The largest normalization factor among the four choices, 8SiAl, 15eK, 13eCNK and all ferric, determines the 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\(^{3+}\). In this example, the 15eK 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 for

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

<table>
<thead>
<tr>
<th>Limit</th>
<th>Calculation method</th>
<th>Calculation</th>
<th>Normalization factor</th>
</tr>
</thead>
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<tr>
<td><strong>Calculations for minimum ferric estimates</strong></td>
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<tr>
<td>8Si</td>
<td>8+Si</td>
<td>8+7.261</td>
<td>1.1018</td>
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<td>16CAT</td>
<td>16+ΣEk</td>
<td>16÷P15.210</td>
<td>1.0519</td>
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<tr>
<td>all ferrous</td>
<td>-</td>
<td>-</td>
<td>1.0000</td>
</tr>
<tr>
<td>15eNK</td>
<td>15+ΣCa</td>
<td>15÷P15.043</td>
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<tr>
<td><strong>Calculations for maximum ferric estimates</strong></td>
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<tr>
<td>15eK</td>
<td>15+ΣNa</td>
<td>15÷15.210</td>
<td>0.9862*</td>
</tr>
<tr>
<td>13eCNK</td>
<td>13+ΣMn</td>
<td>13÷13.187</td>
<td>0.9858</td>
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<tr>
<td>all ferric</td>
<td>23+[(23 + (0.5 × Fe(^{2+}))]</td>
<td>23÷23.444</td>
<td>0.9811</td>
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<tr>
<td>10ΣFe(^{3+})</td>
<td>36÷(46-Si-Al-Ti-Cr)</td>
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<tr>
<td>8SiAl</td>
<td>8+ΣAl</td>
<td>8÷8.486</td>
<td>0.9427</td>
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</table>

* Indicates normalizations that yield either the minimum or maximum ferric estimates
using the 15eK normalization factor 0.98621 (15 ÷ 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) ÷ 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.

References


