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 cannillolite. 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, Na8, and (Na + K)8, are retained, but the primary divisions between the calcic, sodic-calcic, and alkali (renamed sodic) amphiboles have been adjusted to divisions at Na8 < 0.50 and Na8 > 1.50, instead of Na8 < 0.67 and Na8 > 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 Na8. 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 Pnma 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 AB2V4C4T8O2(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;
LEAKE ET AL.: AMPHIBOLE NOMENCLATURE

NaNa₂(kM₂)Si₇Al₂₂(OH)₂

Nyboite

Fetric-nyboite NaNa₂(L₂M₃)Si₆Al₂₂(OH)₂

NaNa₂(L₅M₉)Si₅Al₃O₂₂(OH)₂

Eckermannite

l4agnesio-arfvedsonite

A trca₂lssiso₂₂(oH)₂

Tremolite

1.00 (Na+K)₀ 8.00 Si 100 (Na+K)₀

2.00 Na₅ 500 Si

3.00 Na₀ 1.50 Na₀

0.00 (!"!a+K)o 500 Al

Na(NaCa)L₂l₄SisAl₃O₂₂(OH)₂

Magnesiosadanagaite

trCa₂(L₅₄₃)Si₇AlO₂₂(OH)₂

L₄agnesiohornblende

trCa₂(L₃N₄)Si₆Al₂O₂₂(oH)₂

Tschermakite

5.00 Si 0.00 (Na+K)₀ 0.00 Na⁰

trCa₂(L₂N₄₃)Si₅Al₃O₂₂(OH)₂

$g$

\[ \text{OH} = \text{OH, O, F, Cl} \]

\[ \text{M} = \text{Al}^{+6}, \text{Fe}^{+3} \]

\[ \text{L} = \text{Mg, Fe}^{+2}, \text{Mn} \]

 throughout this report, superscripted arabic numerals refer to ionic charge (oxidation state), e.g., Fe²⁺, superscripted roman numerals to coordination number, e.g., VIAl, 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,Cl).

2. If the H₂O plus halogen content is uncertain, the formula should be calculated on the basis of 23(O) with 2(OH,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, Fe⁷⁺ 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$^{2+}$, 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$_2$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 a composition is near Mg/(Mg + Fe$^{2+}$) : 0.50 or Fe$^{3+}$/Fe$^{3+}$ + $^{3+}$Al : 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 (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 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., (Si + Al + Cr + Ti + Zr + Li + Fe + Mg + Mn) = 13, and if for the magnesium-iron-manganese-lithium amphiboles the sum of (Si + Al + Cr + Ti + Zr + Li + Fe + Mg + Mn + Ca) = 15 is used, then only the Ti : 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$_2$O$^+$ contents that lead to more than (OH) 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 (Ca + Na)$_B < 1.00$ and the sum of L-type ions (Mg,Fe,Mn,Li)$_B$ is $\geq 1.00$, the amphibole is a member of the magnesium-iron-manganese-lithium group.

(2) Where (Ca + Na)$_B \geq 1.00$ and Na$_B < 0.50$, then the amphibole is a member of the calcic group. Usually, but not in every case, Ca$_B > 1.50$.

(3) Where (Ca + 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 Na$_B \geq 1.50$, then the amphibole is a member of the sodic group, previously referred to as alkali 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 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 = $^{2+}$Al, $^{3+}$Al = (Na,K)$_B$, Ca$_B$ = Na$_B$, Li = L$^2$+, Mn$_C$ = L$^2$+, (Ti, Zr) = L$_C$, O = (OH,F,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 Mg = Fe$^{2+}$, $^{3+}$Al = Fe$^{3+}$ and OH = 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 \(Na\)\(_a\), \((Na + K)\)\(_a\), and \(Si\), as shown in Figure 1, but the subdivision into the sodic-calcic group is now at \(Na\)\(_a\) = 0.50 (instead of \(Na\)\(_a\) = 0.67) and \(Na\)\(_a\) = 1.50 (instead of \(Na\)\(_a\) = 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 \(Na\)\(_a\), \((Na + K)\)\(_a\), and \(Si\) box into equal volumes, as in IMA 78. The committee considered at length various proposals for the use of axes other than the three chosen, including four components, but eventually agreed, by a significant majority, that the IMA 78 axes be retained despite their inability to represent \(R\)\(^{2+}\) and \(R\)\(^{3+}\) (i.e., usually \(L-\) and \(M\)-type ions) separately in the \(C\) group. The importance of the difference between \(R\)\(^{2+}\) and \(R\)\(^{3+}\) in the \(C\) group has, however, been 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 \(2R\)\(^{3+}\) 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., potassic 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 unhynphenated name is awkward and a hyphen assists in deciphering the name” (Nickel and Mandarino 1987) e.g., ferric-nyboite. 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 to alumino-ferrohornblende, chloro-ferro-actinolite, and fluoro-ferro-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 1. Prefixes in addition 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>(^{#}Al &gt; 1.00)</td>
<td>Calcic and sodic-calcic only</td>
</tr>
<tr>
<td>Chloro</td>
<td>Cl &gt; 1.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Chromo</td>
<td>Cr &gt; 1.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Ferri</td>
<td>Fe(^{3+}) &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>Mangano</td>
<td>Mn(^{3+}) = 1.00-2.99</td>
<td>All groups except kozulite and unnegaredite</td>
</tr>
<tr>
<td>Permangano</td>
<td>Mn(^{3+}) = 3.00-4.99</td>
<td>All groups except kozulite</td>
</tr>
<tr>
<td>Magnani</td>
<td>Mn(^{3+}) &gt; 1.00</td>
<td>All groups except kornite and unnegaredite</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>Titanos</td>
<td>Ti &gt; 0.50</td>
<td>All groups except kaersulite</td>
</tr>
<tr>
<td>Zinco</td>
<td>Zn &gt; 1.00</td>
<td>All groups</td>
</tr>
</tbody>
</table>

Note: The prefixes in the figures are ferro (Fe\(^{3+}\) > Mg) and magnesio (Fe\(^{2+}\) < Mg) and in Figure 5a only ferric-nyboite with \(^{\#}Al < Fe^{3+}\) (not ferricyboite, which is not clear).
### Table 2. Modifiers and their suggested ranges

<table>
<thead>
<tr>
<th>Modifier</th>
<th>Meaning*</th>
<th>Applicable to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barian</td>
<td>Bar &gt; 0.10</td>
<td>All groups</td>
</tr>
<tr>
<td>Borian</td>
<td>B &gt; 0.10</td>
<td>All groups</td>
</tr>
<tr>
<td>Calcian</td>
<td>Ca &gt; 0.50</td>
<td>Mg-Fe-Mn-Li group</td>
</tr>
<tr>
<td>Chlorian</td>
<td>0.25 &lt; Cl &lt; 0.99</td>
<td>All groups</td>
</tr>
<tr>
<td>Chromian</td>
<td>0.25 &lt; Cr &lt; 0.99</td>
<td>All groups</td>
</tr>
<tr>
<td>Ferrian</td>
<td>0.75 &lt; Fe&lt;sup&gt;3+&lt;/sup&gt; &lt; 0.99</td>
<td>All groups except sodic</td>
</tr>
<tr>
<td>Fluorian</td>
<td>0.25 &lt; F &lt; 0.99</td>
<td>All groups</td>
</tr>
<tr>
<td>Hydroxylian</td>
<td>OH &gt; 3.00</td>
<td>All groups</td>
</tr>
<tr>
<td>Lithian</td>
<td>Li &gt; 0.25</td>
<td>All groups</td>
</tr>
<tr>
<td>Manganian</td>
<td>0.25 &lt; Mn&lt;sup&gt;2+&lt;/sup&gt; &lt; 0.99</td>
<td>All groups, but excludes those species defined by Mn&lt;sup&gt;2+&lt;/sup&gt; abundance</td>
</tr>
<tr>
<td>Nickelian</td>
<td>Ni &gt; 0.10</td>
<td>All groups, but excludes those species defined by Mn&lt;sup&gt;2+&lt;/sup&gt; abundance</td>
</tr>
<tr>
<td>Oxygenian</td>
<td>(OH + F + Cl) &lt; 1.00</td>
<td>All groups, except for ungaretii</td>
</tr>
<tr>
<td>Potassian</td>
<td>K &lt; 0.49</td>
<td>All groups</td>
</tr>
<tr>
<td>Plumbian</td>
<td>Pb &gt; 0.10</td>
<td>Mg-Fe-Mn-Li group only</td>
</tr>
<tr>
<td>Strontian</td>
<td>Sr &gt; 0.49</td>
<td>All groups</td>
</tr>
<tr>
<td>Titanian</td>
<td>Ti &gt; 0.49</td>
<td>All groups</td>
</tr>
<tr>
<td>Zincian</td>
<td>Zn &lt; 0.25</td>
<td>All groups</td>
</tr>
<tr>
<td>Zirconian</td>
<td>Zr &gt; 0.10</td>
<td>All groups</td>
</tr>
</tbody>
</table>

* 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)<sub>0</sub> < 1.00 and (Mg, Fe, Mn, Li)<sub>0</sub> ≥ 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<sup>2+</sup>) = 0.50, the reduction of adjectives, and the abolition of tirodite and dannemorite.

**Orthorhombic forms**

**Anthophyllite series.** Na<sub>4</sub>L<sub>1</sub>(Mg, Fe<sup>2+</sup>, Mn, ...), ... Al, (Si<sub>4</sub> ... Al ... O<sub>12</sub>(OH,F,Cl))<sub>2</sub>, 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 Pnmb structure may be prefixed proto without a hyphen.

**End-members:**
- Anthophyllite: [Mg, Al, Si, O<sub>4</sub>(OH)]<sub>2</sub>
- Ferro-anthophyllite: [Fe<sup>2+</sup>Al, Si<sub>4</sub>O<sub>12</sub>(OH)]<sub>2</sub>
- Sodic-ferro-anthophyllite: [NaMg, Al, Si<sub>4</sub>O<sub>12</sub>(OH)]<sub>2</sub>

**Limits for the use of end-member names:**
- Anthophyllite: Mg/(Mg + Fe<sup>2+</sup>) ≤ 0.50
- Ferro-anthophyllite: Mg/(Mg + Fe<sup>2+</sup>) > 0.50
- Sodic-ferro-anthophyllite: Mg/(Mg + Fe<sup>2+</sup>) ≥ 0.50; Na ≥ 0.50

**Gedrite series.** Na<sub>4</sub>L<sub>1</sub>(Mg, Fe<sup>2+</sup>, Mn, ...), ... Al, (Si<sub>4</sub> ... Al ... O<sub>12</sub>(OH,F,Cl)), where x + y + z ≥ 1.00 so that Si < 7.00, this being the distinction from anthophyllite. Li < 1.00.

**End-members:**
- Gedrite: [Mg, Al, Si, O<sub>4</sub>(OH)]<sub>2</sub>
- Ferrogedrite: [Fe<sup>2+</sup>Al, Si, O<sub>4</sub>(OH)]<sub>2</sub>
- Sodicgedrite: [NaMg, Al, Si, O<sub>4</sub>(OH)]<sub>2</sub>
- Sodic-ferrogedrite: [NaFe<sup>2+</sup>Al, Si, O<sub>4</sub>(OH)]<sub>2</sub>

**Limits for the use of end-member names:**
- Gedrite: Mg/(Mg + Fe<sup>2+</sup>) ≥ 0.50
- Ferrogedrite: Mg/(Mg + Fe<sup>2+</sup>) < 0.50
- Sodicgedrite: Mg/(Mg + Fe<sup>2+</sup>) ≥ 0.50; Na ≥ 0.50
- Sodic-ferrogedrite: Mg/(Mg + Fe<sup>2+</sup>) < 0.50; Na ≥ 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)₅Al₃Si₅AlO₁₂(OH,F,Cl) will justify a new name.

**Holmquistite series.** [Li(Mg,Fe<sup>2+</sup>),(Fe³⁺,Al),Si₈O₂₂(OH,F,Cl)], Li ≥ 1.00 is critical.

**End-members:**
- Holmquistite: [Li,Mg,Al,Si, O<sub>22</sub>(OH)]<sub>2</sub>
- Ferroholmquistite: [Li,Fe<sup>3+</sup>Al, Si, O<sub>22</sub>(OH)]<sub>2</sub>

**Limits for the use of end-member names:**
- Holmquistite: Mg/(Mg + Fe<sup>3+</sup>) ≥ 0.50
- Ferroholmquistite: Mg/(Mg + Fe<sup>3+</sup>) < 0.50

**Monoclinic forms of the Mg-Fe-Mn-Li amphiboles**

**Cummingtonite-Grunerite series.** (Mg, Fe<sup>2+</sup>, Mn, Li),Si<sub>2</sub>O₄(OH), 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: [Mg, Si, O, O<sub>4</sub>(OH)]<sub>2</sub>
- Grunerite: [Fe<sup>3+</sup>Si, O, O<sub>4</sub>(OH)]<sub>2</sub>
- Manganocummingtonite: [Mn,Mg, Si, O, O<sub>4</sub>(OH)]<sub>2</sub>
- Permanganogrunerite: [Mn,Fe<sup>3+</sup>Si, O, O<sub>4</sub>(OH)]<sub>2</sub>
Manganogrunerite: MnFe<sup>3+</sup>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>2</sub>

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

- Cummingitine: Mg(Mg + Fe<sup>2+</sup>) > 0.50
- Grunerite: Mg(Mg + Fe<sup>2+</sup>) < 0.50
- Manganogrunerite: Mg(Mg + Fe<sup>2+</sup>) > 0.50; 1.00 < Mn < 3.00
- Permanganogrunerite: Mg(Mg + Fe<sup>2+</sup>) < 0.50; 3.00 < Mn < 5.00
- Manganogrunerite: Mg(Mg + Fe<sup>2+</sup>) < 0.50; 1.00 < Mn < 3.00

It should be noted that the names given extend down to 7.00 Si. If a mineral with less than Si = 7.00 is discovered, then it will justify a new name based on the endmember MgAlSiAlO(OH).5

**Clinoholmquistite series:** (Li, (Mg,Fe<sup>2+</sup>,Mn), (Fe<sup>3+</sup>Al),SiO<sub>5</sub>(OH,FeCl), Li ≥ 1.00.

**End-members:**

- Clinoholmquistite: (Li,Mg,Al)SiO<sub>5</sub>(OH)
- Clinofenoholmquistite: (LigFe<sup>2+</sup>Al,)SiO<sub>5</sub>(OH),
- Ferri-clinoholmquistite: (Li, Fe<sup>3+</sup>Al)SiO<sub>5</sub>(OH),
- Ferri-clinoferroholmquistite: (Li,Fe<sup>3+</sup>Fer<sup>3+</sup>)SiO<sub>5</sub>(OH),

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

- Clinoholmquistite: Mg/(Mg + Fe<sup>2+</sup>) = 0.50
- Clinoferroholmquistite: Mg/(Mg + Fe<sup>2+</sup>) < 0.50
- Ferri-clinoholmquistite: Fe<sup>3+</sup> > 1; Mg/(Mg + Fe<sup>2+</sup>) ≥ 0.50
- Ferri-clinoferroholmquistite: Fe<sup>3+</sup> > 1; Mg/(Mg + Fe<sup>2+</sup>) < 0.50

**Calcic amphiboles**

The group is defined as monoclinic amphiboles in which (Ca + Na)<sub>9</sub> = 1.00 and Na<sub>12</sub> is between 0.50 and 1.50; usually Ca<sub>9</sub> ≥ 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 tschermakite 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: CaMgSiO<sub>5</sub>(OH),
- Ferro-actinolite: CaFe<sup>3+</sup>SiO<sub>5</sub>(OH),
- Edinette: NaCaMgSiAlO<sub>5</sub>(OH),
- Ferro-edenite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Pargasite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Ferropargasite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Magneisohastingsite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Hastingsite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Tschermakite: CaMgAlSiO<sub>5</sub>(OH),
- Ferro-fermerskimate: CaFe<sup>3+</sup>MgFe<sup>3+</sup>SiO<sub>5</sub>(OH),
- Magnesiohastingsite: NaCaMgFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Sadanagaite: NaCaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Cudolhornblende: CaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Kaersutite: NaCaFe<sup>3+</sup>TiSiO<sub>5</sub>(OH),
- Cannilolote: CaMgSiAlO<sub>5</sub>(OH),

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

- These are summarized in Figure 3 with respect to Si, (Na + K)<sub>9</sub>, Mg/(Mg + Fe<sup>2+</sup>), and Ti. The prefixes ferri and alumino are only used when Fe<sup>3+</sup> > 1.00 and tAl > 1.00 (Table 1). For kaersutite and ferrokaersutite, Ti > 0.50; any lesser Ti content may optionally be indicated as in Table 2. Cannilolote requires Ca<sub>9</sub> ≥ 0.50.

**Sodic-calcic amphiboles**

This group is defined to include monoclinic amphiboles in which (Ca + Na)<sub>9</sub> = 1.00 and 0.50 < Na<sub>12</sub> < 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: NaCaNaMgSiAlO<sub>5</sub>(OH),
- Ferriorichterite: NaCaNaFe<sup>3+</sup>SiAlO<sub>5</sub>(OH),
- Winchite: NaCaMg(AlFe<sup>3+</sup>)SiO<sub>5</sub>(OH),
- Ferrowinchite: NaCaFe<sup>3+</sup>(AlFe<sup>3+</sup>)SiO<sub>5</sub>(OH),
Diagram Parameters:
\[(Na + K)A > 0.50; (Ca + NaB) > 1.00; 0.50 < NaB < 1.50\]

Sodic amphiboles

This group is defined to include monoclinic amphiboles in which \(Na_B \geq 1.50\). The detailed classification is shown in Figures 5a and 5b. Apart from revision of the boundary at \(Na_B \geq 1.50\), instead of \(Na_B \geq 1.34\), and the abolition of crosite so that the 50% division is followed, the principal changes are the introduction of nybőite with Si close to 7, as approved in 1981 (Ungaretti et al. 1981), ferricybőite (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: \(Na(Na,Mg,Al)_{5}SiO_{10}(OH)_2\)
- Ferroglaucophane: \(Na(Na,Mg,Fe^3)_{5}SiO_{10}(OH)_2\)
- Magnesioriebeckite: \(Na(Mg,Fe^3)_{5}SiO_{10}(OH)_2\)
- Riebeckite: \(Na(Na,Fe^3)_{5}SiO_{10}(OH)_2\)
- Eckermannite: \(NaNa(Mg,Al)_{5}SiO_{10}(OH)_2\)
- Ferro-eckermannite: \(NaNa(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Magnesio-arfvedsonite: \(NaNa(Mg,Fe^3)_{5}SiO_{10}(OH)_2\)
- Arfvedsonite: \(NaNa(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Kozulite: \(NaNa_{2}(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Nybőite: \(NaNa_{2}(Mg,Al)_{5}SiO_{10}(OH)_2\)
- Ferronyböite: \(NaNa_{2}(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Ferricybőite: \(NaNa_{2}(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Leakeite: \(NaNa_{2}(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Ferroleakeite: \(NaNa_{2}(Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Kornite: \(NaNa_{2}(Mg,Fe^3,Al)_{5}SiO_{10}(OH)_2\)
- Ungarettiite: \(NaNa_{2}(Mg,Fe^3,Al)_{5}SiO_{10}(OH)_2\)

Limits for the use of end-member names:
These are summarized in Figure 5 with respect to Si, \((Na + K)A\), and Mg/(Mg + Fe^2+) parameters. Kozulite requires \(Mn^2+ > (Fe^{2+} + Fe^{3+} + Mg + \nu Al)\) with \(\nu Al \leq 0.5\); ungarettiite has both \(Mn^2+ \) and \(Mn^3+ > (Fe^{2+} + Mg + Fe^{3+} + \nu Al)\) with \(Li < 0.5\) and \(OH + F + Cl < 1.00\); leakeite and kornite require Mg/(Mg + Fe^2+) \(\geq 0.50\), Li \(\leq 0.50\) with Fe^3+ > Mn^3+ in leakeite and Fe^3+ < Mn^3+ in kornite. Ferricybőite means Fe^3+ \(\geq \nu Al\) and should be clearly distinguished from ferri (meaning Fe^3+ > 1.00) because neither alumino (meaning \(\nu Al > 1.00\)) 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 = soderite
- Magnesio-holmquistite = holmquistite
- Magnesio-cummingtonite = cummingtonite
- Tremolitic hornblende = magnesiohornblende
- Magnesio-clinoholmquistite = clinoholmquistite
- Crossite = glaucophane or ferroglaucophane or magnesioriebeckite or riebeckite

**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 crosite so that the 50% division is followed, the principal changes are the introduction of nybőite with Si close to 7, as approved in 1981 (Ungaretti et al. 1981), ferricybőite (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).
Diagram Parameters: $Na_B \geq 1.50; (Mg + Fe^{2+} + Mn^{2+}) > 2.5$;
$Li < 0.5; (Mg or Fe^{2+}) > Mn^{2+}$

(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.

**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 = ferrotsermakite
Edentic hornblende = edenite
Ferro-edenitic hornblende = ferro-edenite
Pargasitic hornblende = pargasite
Ferrooan pargasitic hornblende = pargasite or ferropargasite
Ferroan pargasite = ferropargasite
Ferroan pargasite = ferropargasite or ferropargasite
Silicic edenite = edenite
Silicic ferro-edenite = ferro-edenite
Magnesio-hastingsitic hornblende = magnesiohastingsite
Magnesio hastingsitic hornblende = magnesiohastingsite or hastingsite
Hastingsitic hornblende = hastingsite or hastingsite
Magnesio hastingsitic hornblende = 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: \(a = 9.884 \text{ Å}, b = 18.145 \text{ Å}, c = 5.294 \text{ Å}, \beta = 104.7^\circ\).

(PDF 25-157 on specimen from Sobotin, Czech Republic).


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 Kong'sberg.

X-ray data: \(a = 18.5 \text{ Å}, b = 17.9 \text{ Å}, c = 5.28 \text{ Å}\). (PDF 9-455 on specimen from Georgia, U.S.A.).


Arfvedsonite
Named for J.A. Arfvedson.

Type locality: Kangerdluarsuk, Greenland.

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

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

Barroisite
Origin of name not found.
Type locality: Not traced.

Cannilloite
Named for Elio Cannillo of Pavia, Italy.
Type locality: Pargas, Finland.

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. B 109.10°. (PDF 25-498 on specimen from Siberia, Russia).

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).

Eckermannite
Named for H. von Eckermann.
Type locality: Norra Kärre, Sweden.
X-ray data: a 9.7652 Å, b 17.892 Å, c 5.284 Å. B 103.16°. (PDF 20-386 on synthetic material).

Edenite
Named for locality.
Type locality: Eden (Edenville), New York, U.S.A.

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.).

Glaucophane
Named from the Greek glaukos, bluish green and phainesthai, to appear.
Type locality: Syra, Cyclades, Greece.
X-ray data: a 9.595 Å, b 17.798 Å, c 5.307 Å. β 103.66°. (PDF 20-453 on specimen from Sebastopol Quadrangle, California, U.S.A. See also PDF 15-58 and 20-616).

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).

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. B 105.058°. (PDF 20-278 on specimen from Dashkesan, Transcaucasia, Russia. Also PDF 20-469).

Holmquistite
Named for PJ. 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).

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.

Kaersutite
Named from locality.
Type locality: Kaersut, Umanaksfjord, Greenland.
X-ray data: $a = 9.83 \, \text{Å}, \ b = 17.89 \, \text{Å}, \ c = 5.30 \, \text{Å}, \ \beta = 105.18^\circ$.
(PDF 17-478 on specimen from Boulder Dam, Arizona, U.S.A.).

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: $a = 9.94(1) \, \text{Å}, \ b = 17.80(2) \, \text{Å}, \ c = 5.30(2) \, \text{Å}, \ \beta = 105.52^\circ$.

Kozulite
Named for S. Kozu
Type locality: Tanohata mine, Iwate Prefecture, Japan.
X-ray data: $a = 9.991 \, \text{Å}, \ b = 18.11 \, \text{Å}, \ c = 5.30 \, \text{Å}, \ \beta = 104.6^\circ$.
(PDF 25-850)

Leakeite
Named for B.E. Leake.
Type locality: Kajlidongri manganese mine, Jhabua district, Madhya Pradesh, India.
X-ray data: $a = 9.822 \, \text{Å}, \ b = 17.836 \, \text{Å}, \ c = 5.286 \, \text{Å}, \ \beta = 104.37^\circ$.

Nyböte
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 for locality.
Type locality: Pargas, Finland.
X-ray data: $a = 9.870 \, \text{Å}, \ b = 18.006 \, \text{Å}, \ c = 5.300 \, \text{Å}, \ \beta = 105.43^\circ$.
(PDF 23-1406 and PDF 41-1430 on synthetic material).

Richterite
Named for T. Richter.
Type locality: L. Ängban, Värmland, Sweden.
X-ray data: $a = 9.907 \, \text{Å}, \ b = 17.979 \, \text{Å}, \ c = 5.269 \, \text{Å}, \ \beta = 104.25^\circ$.
(PDF 25-808 on synthetic material; see also PDF 31-1284 for calcian and 25-675 and 31-1082 for potassian).

Riebeckite
Named for E. Riebeck.
Type locality: Island of Socotra, Indian Ocean.
X-ray data: $a = 9.769 \, \text{Å}, \ b = 18.048 \, \text{Å}, \ c = 5.335 \, \text{Å}, \ \beta = 103.59^\circ$.
(PDF 19-1061 on specimen from Doubrutschia, Romania).

Sadanaigaite
Named for R. Sadanaga.
Type locality: Yuge and Myojin Islands, Japan.
X-ray data: $a = 9.922 \, \text{Å}, \ b = 18.03 \, \text{Å}, \ c = 5.352 \, \text{Å}, \ \beta = 105.30^\circ$.

Taramite
Named for type locality.
Type locality: Walitarama, Mariupol, Ukraine.
X-ray data: $a = 9.952 \, \text{Å}, \ b = 18.101 \, \text{Å}, \ c = 5.322 \, \text{Å}, \ \beta = 105.45^\circ$.
(PDF 20-734 on specimen of potassian taramite from Mbozi complex, Tanzania).

Tremolite
Named for locality.
Type locality: Val Tremola, St. Gotthard, Switzerland.
X-ray data: $a = 9.84 \, \text{Å}, \ b = 18.02 \, \text{Å}, \ c = 5.27 \, \text{Å}, \ \beta = 104.95^\circ$.
(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-
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 recalibration 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 Deere 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.

**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.

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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).

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 ≤ 8, ΣCa ≤ 15, or ΣK ≤ 16 (Appen. 2 Fig. 1). Violations of the other three criteria, ΣAl ≥ 8, ΣMn ≥ 13, and ΣNa ≥ 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 sites'). These analyses should not be used for empirical ferric estimates.

Minimum and maximum estimates

For many amphibole analyses, none of the criteria Si ≤ 8, ΣCa ≤ 15, and ΣK ≤ 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 ≤ 8, ΣCa ≤ 15, and ΣK ≤ 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, ΣCa = 15.030, and ΣK = 15.065, then the ΣSi limit is exceeded by 0.005 and the ΣCa limit by 0.030. Because ΣSi is in greatest excess, the minimum ferric estimate is obtained by recalculating the formula so that ΣCa = 15.000 (15 eNK estimate, Appen. 2 Fig. 1).

The maximum ferric estimates are obtained from the stoichiometric limits ΣAl ≥ 8, ΣMn ≥ 13, and ΣNa ≥ 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 ΣAl = 9.105, ΣMn = 13.099, and ΣNa = 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 ΣNa = 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 Fe_{2}O_{3}); 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 ΣCa ≤ 15 (here ΣCa = 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

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'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

<table>
<thead>
<tr>
<th>Analysis (wt%)</th>
<th>All ferrous</th>
<th>13 eNK</th>
<th>15 eCNK</th>
<th>All ferrous</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>39.38</td>
<td>5.000</td>
<td>5.000</td>
<td>5.714</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.70</td>
<td>2.246</td>
<td>2.246</td>
<td>2.296</td>
</tr>
<tr>
<td>FeO</td>
<td>23.54</td>
<td>8.000</td>
<td>8.000</td>
<td>8.000</td>
</tr>
<tr>
<td>MgO</td>
<td>4.40</td>
<td>1.051</td>
<td>1.051</td>
<td>1.051</td>
</tr>
<tr>
<td>CaO</td>
<td>11.03</td>
<td>1.139</td>
<td>1.139</td>
<td>1.140</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.37</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Total 97.42

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.

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)

<table>
<thead>
<tr>
<th></th>
<th>1 wt%</th>
<th>Molecular proportions wt% = mol wt</th>
<th>2</th>
<th>Atomic proportions (cations) col. 2 x cations in oxide</th>
<th>3</th>
<th>Atomic proportions (O atoms) col. 2 x oxygens in oxide</th>
<th>4</th>
<th>Anions on the basis of 23 O atoms col. 4 × 8.45012</th>
<th>5</th>
<th>Cations on the basis of 23 O atoms col. 3 × 8.45012</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>51.63</td>
<td>0.85928</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.00</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>7.39</td>
<td>0.07248</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.00</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>7.55</td>
<td>0.10509</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
<td>0.00240</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>18.09</td>
<td>0.44884</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>12.32</td>
<td>0.21969</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.61</td>
<td>0.00984</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>0.00</td>
<td>0.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>1.7994</td>
<td>2.72185</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Factor for the recalculation of atomic proportions to 23 O basis: 23 / 2.72185 = 8.45012

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

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 × (Si + Ti + Al + Cr) + Fe³⁺ = 10, which describes the desired resulting stoichiometry and (2) Fe³⁺ = (23 - 23 × N) × 2, which gives the Fe³⁺ for this normalization. The solution is N = 36/(46 - Si - Ti - Al - 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 10⁵Fe³⁺) is 0.977, which is less than the value 0.983 of the 13 eCNK factor; therefore the 10⁵Fe³⁺ 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 10⁵Fe³⁺ correction discussed in the preceding paragraph will probably not be
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 with known maximum ferric formulae for restricted types of amphibole. For example, R. Schumacher (1991) derived a normalization scheme that yields formulae intermediate to maximum and minimum ferric content 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 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 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 FeO, 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

<table>
<thead>
<tr>
<th>Limit</th>
<th>Calculation method</th>
<th>Calculation</th>
<th>Normalization factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) the eight tetrahedral (T) sites:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(i) Place all Si here; if Si < 8 fill the remaining sites with Al.
(ii) If Si + 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 $\Sigma(Mg...Mn) < 5$, 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 $\Sigma(Mg...Ca) < 2$, 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 the all the normalization factors (8Si, 16CAT, and 15 eNK) are greater than all the normalization factors (8 SiAl, 15 eK, 10Fe$^{3+}$, 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 (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 ÷ 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 × 2 = 14.4802; for AlO$_{1.5}$, 1.2214 × 1.5 = 1.8321; for MgO, 3.7818 × 1 = 3.7818; for NaO$_{1.5}$, 0.1659 × 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 $(23 - 22.9331) \times 2 = 0.133$.

(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 gives 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 ÷ 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) ÷ 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.

REFERENCES CITED


