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ON THE CLASSIFICATION OF AMPHIBOLES

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ABSTRACT

Major issues involved in the classification of the amphiboles are examined: (1) the role of (OH), Li and Fe^{3+}, (2) the formal definition of a root name, (3) irreducible charge-arrangements and distinct species, (4) the use of prefixes, (5) the principal chemical variables used in a classification procedure, and (6) the use of the dominant-constituent principle. The current IMA-approved classification scheme is based on the *A*, *B* and *T* groups of cations in the amphibole formula: $AB_2C_5T_8O_{22}W_2$. We argue here that classification should be based on the *A*, *B* and *C* groups of cations as (i) it is in these groups of cations that the maximum variation in chemical composition occurs, and (ii) as a result of (i), the scheme is more in accord with the IMA-sanctioned dominant-constituent principle, which governs the recognition (and approval) of distinct mineral species. Two new classifications are presented here; one is based on the *A*, *B* and *C* groups of cations, and another on the dominant-constituent principle. These two schemes were produced to illustrate (i) the problems inherent in the classification of a group of minerals as complicated as the amphiboles, and (ii) the sometimes disparate needs of crystallographer, mineralogist, petrologist and geochemist. Scheme 1 conserves current formulae and names as much as possible, whereas scheme 2 minimizes the number of formulae and names as much as possible. The differences between the current classification and the two schemes presented here are discussed, and we highlight the problems associated with each scheme.

Keywords: amphibole group, classification.

SOMMAIRE

Nous passons en revue les aspects importants d'une classification des amphiboles: (1) le rôle de (OH), Li et Fe^{3+}, (2) la définition formelle d'un nom "racine", (3) les arrangements irréductibles des charges et le concept des espèces distinctes, (4) l'utilisation de préfixes, (5) les variables chimiques importantes utilisées dans la procédure de classification, (6) l'utilisation du principe de la composante dominante. Le schéma de classification accepté présentement par l'Association Internationale de Minéralogie (IMA) repose sur une considération des occupants cationiques des sites *A*, *B* et *T* d'une amphibole, $AB_2C_5T_8O_{22}W_2$. Nous proposons plutôt de fonder le schéma de classification sur les occupants des sites *A*, *B* et *C*, parce que c'est parmi ces groupes de cations que se trouve la plus grande variabilité en composition chimique. De plus, cette pratique donnerait un schéma plus en accord avec le principe de la composante dominante, qui régit la distinction et l'acceptation des espèces minérales distinctes. Nous présentons deux nouvelles classifications; une de celles-ci est fondée sur les occupants cationiques des sites *A*, *B* et *C*, et une autre est fondée sur le principe de la composante dominante. Ces deux schémas ont été préparés afin d'illustrer (i) les problèmes intrinsèques d'une classification d'une groupe de minéraux aussi compliqués que les amphiboles, et (ii) les besoins assez disparates des cristallographes, minéralogistes, pétrologues et géochimistes. Le schéma 1 conserve les formules et les noms

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courants autant que possible, et le schéma 2 minimise le nombre de formules et de noms autant que possible. Nous discutons des différences entre la classification acceptée présentement et les deux schémas que nous proposons, de sorte que les problèmes soulevés par chaque schéma sont mis en évidence.

(Traduit par la Rédaction)

Mots-clés: groupe des amphiboles, classification.

INTRODUCTION

The production of a satisfactory classification of the amphiboles seems to be a process with a long gestation period. The first IMA (International Mineralogical Association) classification scheme was published almost thirty years ago (Leake 1978). A new approach was initiated in 1986, and culminated in the scheme of Leake *et al.* (1997), but subsequent discoveries of novel compositions of amphiboles (*e.g.*, Oberti *et al.* 2000, 2003, 2004, Caballero *et al.* 2002) forced revision of this scheme (Leake *et al.* 2004). In 2005, Ernst Burke, Chair of the IMA CNMMN (Commission on New Minerals and Mineral Names) approached the authors to re-examine the issue of amphibole classification and to publish a discussion paper with a view to eventually reconsider the classification of the amphiboles. We emphasize here that this paper is *not* a final new scheme of classification and does not carry the *imprimatur* of the IMA; it is a discussion of the problems associated with various aspects of amphibole classification; in it, we examine some alternative schemes of classification that differ from the currently approved scheme. Furthermore, this paper only deals with the chemical classification of amphiboles; *it does not deal with the classification of amphiboles in the field or under the petrographic microscope*; the classification of amphiboles in these cases is a separate issue, although one that has been addressed in the previous classifications of amphiboles (Leake 1978, Leake *et al.* 1997).

There have been many criticisms of the previous classifications. If anyone has ideas that differ from those expressed here, or have criticisms or comments on any of the ideas expressed here, we encourage them to write a proposal or discussion paper to ensure that the widest opinion is solicited prior to any official reconsideration of amphibole classification.

VARIATION IN THE CHEMICAL COMPOSITION OF AMPHIBOLES

The chemical composition and variability of the amphiboles may be expressed by the general formula $A\ B_2\ C_5\ T_8\ O_{22}\ W_2$, where A = □, Na, K, Ca, Pb^{2+}; B = Li, Na, Mg, Fe^{2+}, Mn^{2+}, Ca; C = Li, Mg, Fe^{2+}, Mn^{2+}, Zn, Co, Ni, Al, Fe^{3+}, Cr^{3+}, Mn^{3+}, V^{3+}, Ti^{4+}, Zr; T = Si, Al, Ti^{4+}; W = (OH), F, Cl, O. The allocation of cations to the various groups was described by Leake *et al.* (2004); the correspondence of the *A, B, C, T* and *W* groups to the basic amphibole structure is described in Appendix I.

THE ROLES OF FE, (OH) AND LI

The complete analysis of amphiboles is a difficult experimental issue. Prior to the development of the electron microprobe, amphiboles were analyzed for all major and minor constituents as a matter of course, and compilations such as that of Leake (1968) are invaluable sources of complete results of chemical analysis. The advent of the electron microprobe completely changed the situation with regard to mineral analysis. It became relatively easy to make numerous chemical analyses at a very fine scale, which made available chemical data on finely zoned materials. However, this step forward came at a cost: the concentration of some elements (*e.g.*, H, Li) cannot be so established, and valence state is not accessible. For many minerals, these limitations are not relevant; for amphiboles, they are major disadvantages. Recent work has shown that (1) Li is a much more common constituent in amphiboles than had hitherto been realized (Hawthorne *et al.* 1994, Oberti *et al.* 2003), and (2) H, as (OH), can be a variable component in amphiboles unassociated with the process of oxidation–dehydroxylation (Hawthorne *et al.* 1998). Moreover, the role of Fe in amphiboles is very strongly a function of its valence state. Lack of knowledge of these constituents results in formulae that generally must be regarded as only semiquantitative. Of course, if Li and Fe^{3+} are not present and (OH + F) = 2 *apfu*, the resulting formula can be accurate. However, such a situation is uncommon [few amphiboles have Li = Fe^{3+} = 0 and (OH + F) = 2 *apfu*], resulting in formulae with significant systematic error.

Previous classifications obscured this issue by not incorporating *C*-group cations into the classification procedure, and thus the problem is not visually apparent in the classification diagrams. However, the problem is still present in that the formulae are still inaccurate, and the lack of H, Li and Fe^{3+} seriously distorts the amounts of other constituents, particularly those that are distributed over two different groups (*e.g.*, ${}^{T}Al$ and ${}^{C}Al$, ${}^{B}Na$ and ${}^{A}Na$). There are methods available to establish the amount of these components, and amphibole analysts should be acquiring or using these on a routine basis. For "small-laboratory" instrumentation, SIMS (Secondary-Ion Mass Spectrometry) can microbeam-analyze amphiboles for H and Li (using the appropriate methodology and standards), LA–ICP–MS (Laser-Ablation – Inductively Coupled Plasma – Mass Spectrometry) can microbeam-analyze materials for Li, single-crystal refinement of the structure can characterize the levels of Li, Fe^{2+} and Fe^{3+} at a scale of ≥ 30 μm, and with structure-based equations, one can estimate the amount of H; with EELS (Electron Energy-Loss Spectroscopy), one can measure Fe^{3+} / (Fe^{2+} + Fe^{3+}) at a scale of ≥ 1 μm, and with milli-Mössbauer spectroscopy one can measure Fe^{3+} / (Fe^{2+} + Fe^{3+}) at a scale of ≥ 50 μm. For "big-laboratory" instrumentation, usually involving a synchrotron light-source, one can characterize Li, Fe^{2+} and Fe^{3+} at a scale of ≥ 2 μm by single-crystal refinement of the structure, and with milli-XPS (X-ray Photoelectron Spectroscopy), one can measure Fe^{3+} / (Fe^{2+} + Fe^{3+}) at a scale of ≥ 40 μm. Where only small amounts of separate are available (a few milligrams), hydrogen-line extraction and Karl–Fischer titration can give accurate values for H content (as H_2O). Values for Fe^{3+} / (Fe^{2+} + Fe^{3+}) can also be calculated using assumed site-occupancy limitations and the electroneutrality principle, and although the values obtained are not very accurate (Hawthorne 1983), they are in general better than assuming Fe^{3+} / (Fe^{2+} + Fe^{3+}) = 0.0 (unless additional evidence indicates otherwise).

Below, we make a case for basing amphibole classification on the contents of the *A*, *B* and *C* groups (see general formula above). This being the case, the Fe^{3+} content of an amphibole will play a major role in the classification scheme. Hopefully, this forced recognition of the present deficiencies in amphibole analysis will encourage us to use some of the techniques outlined above, in addition to electron-microprobe analysis, to characterize the amphiboles in which we are interested, and to characterize their chemical formulae accurately. To make an analogy with 40 years ago, wet-chemical analysis was in widespread use, and the electron microprobe was a novel instrument. However, the ability of the electron microprobe to deal with heterogeneous material and obviate problems of sample contamination led to its current extensive use. We are in a similar situation today. The electron microprobe is in widespread use, and the techniques outlined above are far less widespread. However, these techniques considerably increase our ability to analyze minerals accurately. To increase our knowledge of the composition of minerals in general (and amphiboles in particular), as a community we need to acquire this instrumentation so that in the near future, it becomes as routine as electron-microprobe analysis.

ROOT NAMES

Compositional variation may involve cations of the same valence [***homovalent variation***] or cations of different valence [***heterovalent variation***]. In previous classifications, the IMA CNMNN has recognized that distinct arrangements of formal charges at the sites (or groups of sites) in the amphibole structure warrant distinct **root names**, and are, by implication, distinct species; for a specific root name, different homovalent cations (*e.g.*, Mg *versus* Fe^{2+}) or anions (*e.g.*, OH *versus* F) are indicated by prefixes. Although we will maintain this approach here, we note that the expression "a distinct arrangement of formal charges" was not defined in previous classifications. Moreover, the authors of 1978 and 1997 classifications actually do not adhere to the definition that only distinct arrangements of formal charges warrant distinct root names. If they did, they would not differentiate, for instance, between the magnesium–iron–manganese group and the calcic group, as $B = M^{2+}$ in both these groups. The definition that only distinct arrangements of formal charges warrant distinct root names applies only to the *A*, *B* and *T* groups of cations in the 1978 and 1997 classifications, and it applies only to the *A*, *B* and *C* groups of cations in the present discussions. Furthermore, this issue of what constitutes a "distinct arrangement of formal charges" needs to be clarified, as it is at the core of any classification that takes this approach; it is examined in the next paragraph.

Authors of the 1978 and 1997 classifications tacitly assumed that a distinct arrangement of formal charges in the amphibole structure is one in which the numbers and types of integer charge in each group is unique. Thus, in calcic amphiboles, the arrangement $\{{}^{A}0_1\ {}^{B}2_2\ {}^{C}2_5\ {}^{T}4_8\ O_{22}\ {}^{W}1^{-}{}_{2}\}$ (where numbers associated with cation sites are assigned a positive charge) is different from the arrangement $\{{}^{A}0_1\ {}^{B}2_2\ {}^{C}(2_4\ 3_1){}^{T}(4_7\ 3_1)\ O_{22}\ {}^{W}1^{-}{}_{2}\}$; for convenience, we may denote the former as the *tremolite* arrangement, and the latter as the *hornblende* arrangement (the italics serving to indicate that the names do not refer to specific chemical species at the sites or groups of sites). However, consider the arrangement $\{{}^{A}0_1\ {}^{B}2_2\ {}^{C}(2_3\ 3_2)\ {}^{T}(4_6\ 3_2)\ O_{22}\ {}^{W}1^{-}{}_{2}\}$, which we may denote as the *tschermakite arrangement*. The *hornblende* arrangement can be factored into 50% *tremolite* arrangement and 50% *tschermakite* arrangement, and it is not clear that we should necessarily recognize the *hornblende* arrangement as distinct, because it is not irreducible. This issue is at the heart of the classification problem, and we see no clear solution to it. Here, we offer two schemes: in SCHEME 1 [which includes the sodium–calcium group], we identify all different arrangements of integer charges (corresponding to the cations and anions found in amphiboles), and in SCHEME 2 [which does not include the sodium–calcium group], we recognize only irreducible arrangements of integer charges that are crystal-chemically compatible with the amphibole structure [note: richterite and Na NaMg Mg_5 Si_8 O_{22} $(OH)_2$ are irreducible, but are not present in scheme 2].

MORE ON ROOT NAMES

It would be good to have consistent use of prefixes in amphibole names. Most root names apply to the Mg–Al-dominant species, *e.g*, tremolite, pargasite, winchite, glaucophane. However, some amphiboles were originally described as the ferro- or ferri- equivalent of the Mg–Al-containing species. We may define all root names as referring to the Mg–Al-dominant compositions; thus, for example, leakeite, currently Na Na_2 (Mg_2 $Fe^{3+}{}_2$ Li) Si_8 O_{22} $(OH)_2$, becomes Na Na_2 (Mg_2 Al_2 Li) Si_8 O_{22} $(OH)_2$. If this is done, we may dispense with the prefixes *magnesio* and *alumino*. Can we do this? Yes, but only at a price; for example, riebeckite will become "ferro-ferri-glaucophane", and arfvedsonite will become "ferro-ferri-eckermannite", and a riebeckite–arfvedsonite granite will become.... On the other hand, uncommon amphiboles may possibly be redefined without hardship. Again, we offer two extreme schemes: in SCHEME 1, we retain all current root names, whereas in SCHEME 2, we define all root names as the equivalent Mg–Al-dominant species.

CRITERIA FOR THE RECOGNITION OF DISTINCT SPECIES

The IMA CNMMN uses the criterion of the dominant species at a site to recognize the existence of a distinct mineral species. This is not necessarily a satisfactory criterion for rock-forming minerals, and it has not been strictly adhered to in previous classifications. There are several problems involved in the strict application of this criterion: (1) it requires recognition only of irreducible charge-arrangements as distinct species; this would result in discreditation of such minerals as *pargasite* and *hornblende*, names (and amphibole compositions) that are embedded not only in Mineralogy but also in Petrology, and are used in the nomenclature of rocks. (2) With this criterion, one cannot recognize amphiboles such as richterite, Na (NaCa) Mg_5 Si_8 O_{22} $(OH)_2$, which is a formal end-member in amphibole composition space (Fig. 1), despite the fact that it does not have a dominant cation at the *B* group.

In order to expose the problems inherent in the often-conflicting goals of simplicity and conservatism, we will develop two different classifications, one

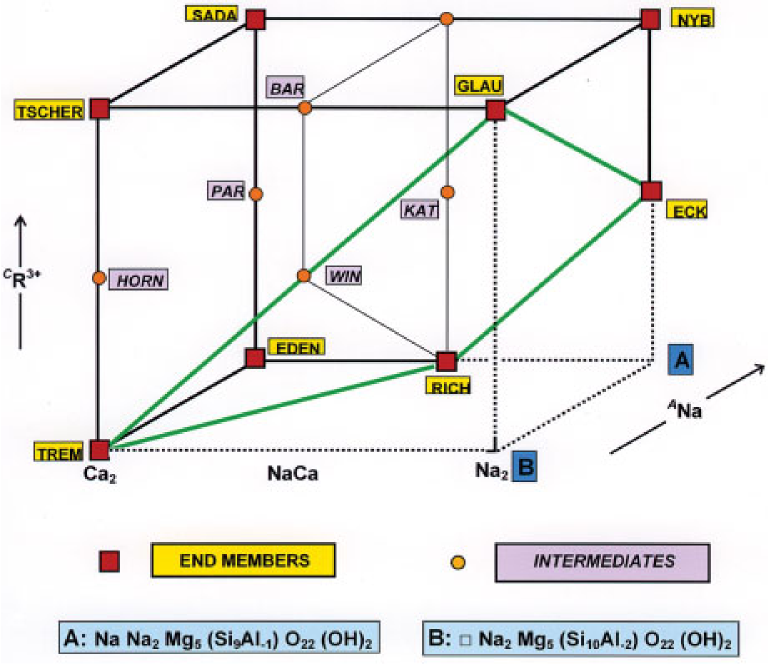

FIG. 1. A–B–C amphibole space; the plane outlined in green shows the limit of amphibole compositions (to the right of this plane, electroneutrality is not satisfied for positive numbers of cations in the amphibole structure). Formal end-member compositions are shown as red squares, and their names are shown in yellow boxes; intermediate compositions corresponding to distinct charge-arrangements are shown as orange circles, and their names are shown in mauve boxes; the blue boxes marked A and B denote compositions that are algebraically in accord with the general amphibole formula, but that contain negative coefficients and hence are physically impossible.

adhering to current convention, and the other striving for simplicity of naming. A pragmatic combination of these two schemes may be the best solution.

PREFIXES

The topic of prefixes and adjectival modifiers has generated much discussion since the 1978 classification formalized their use for amphiboles. It must be noted that *the use of prefixes has nothing to do with the number of species*; the number of species is dictated first by the details of the classification criteria, and then by Nature herself. The issue here is what kind of names are preferable. There are three types of names that we may use: (1) each distinct species is a trivial name, or (2) we may identify root names corresponding to distinct charge arrangements, and indicate homovalent variants by (a) prefixes, or (b) suffixes. The amphibole classifications of Leake (1978) and Leake *et al.* (1997) led to the discreditation of 220 trivial names, and few would wish to return to a situation where there are several hundred trivial names for amphiboles; thus we discard possibility (1) and are left with situation (2): root names plus indicators of homovalent variants. We prefer word prefixes to element suffixes on two counts. Firstly, one must consider ease of use of multiple prefixes; at least for us, the meaning of potassic-ferro-ferri-fluor-hornblende is much more transparent than "hornblende-(K)–(Fe^{2+})–(Fe^{3+})–(F)", and much easier to use in speech. Secondly, some space groups are indicated by suffixes (*e.g.*, cummingtonite-$P2_1/m$). Having to combine space-group symbols with element or cation and anion suffixes further complicates this approach. Thus we propose retaining the use of prefixes (as defined in Leake *et al.* 1997), and having all prefixes followed by a hyphen (thus root names are easily identified in the complete name). It is preferable to use prefixes in a specific order, as comparison of names is made simpler in this case. Burke & Leake (2004) recently specified in which order prefixes (where more than one is used) must be attached to the root-name. Their sequence is proto-parvo (magno)-fluoro (chloro)-potassic (sodic)-ferri (alumino, mangani)-ferro(mangano, magnesio). We propose a different sequence, which follows the order of the amphibole formula itself: $A\ B_2\ C_5\ T_8\ O_{22}\ W_2$; hence, *proto-potassic-ferro-ferri-fluoro-* followed by the root name.

ADJECTIVAL MODIFIERS

Adjectival modifiers are *not* part of previous classifications of amphiboles (Leake 1978, Leake *et al.* 1997, 2004); their use is optional, and they are used to provide more information about an amphibole composition than is present in its formal name. For example, the presence of 0.89 Cl *apfu* in an amphibole is obviously of considerable crystal-chemical and petrological interest, but is not represented in the name of the amphibole; in the interest of propagating this information (particularly in this age of databases and keywords), the use of the adjectival modifier is a useful option both for an author and for a reader interested in Cl in amphiboles. However, a recent IMA–CNMMN decision (voting proposal 03A; Bayliss *et al.* 2005) discredits the use of Schaller modifiers. Hence we suggest using expressions of the type *Cl-rich* or *Cl-bearing* preceding the root-name.

SYNTHETIC AMPHIBOLES

There are many recent studies focusing on the synthesis and characterization of amphibole compositions that are important in understanding such issues as (1) stability, (2) symmetry, (3) thermodynamics, and (4) short-range order. Some of these studies have produced compositions that have not (yet) been observed in Nature, either because the chemical systems in which they occur are enriched in geochemically rare elements or because the synthetic system is chemically more simple than is usual in geological systems. As a result, there is a need to find a logical and practical system to handle synthetic amphiboles. Bayliss *et al.* (2005) recently stated that any synthetic species that is still unknown in Nature should be named with the mineral name followed by a suffix indicating the exotic substitution, and that the whole name must be reported in quotation marks, *e.g.,* "topaz-(OH)".

In the case of the amphiboles, the situation is more complicated, as new root compositions may occur in synthesis experiments. Obviously, it is inappropriate to designate a new name for such compositions (until or unless they are discovered as minerals). It seems natural to designate them by their chemical formula, possibly preceded by the word *synthetic* in order to distinguish them from hypothetical compositions (such as end members) or suggested formulae. Where the natural analogue of the root composition of a synthetic amphibole does exist, the directive of Bayliss *et al.* (2005) seems appropriate.

THE PRINCIPAL VARIABLES USED IN THE CLASSIFICATION PROCEDURE

The total variation in amphibole composition can be described in the quinary system *A–B–C–T–W*; however, this variation is constrained by the electroneutrality principle, and hence only four of these five variables are needed to formally represent this variation. The 1978 and 1997 schemes used variations in the *A*, *B, T* and *W* groups as their primary classification parameters. However, are these the best parameters to use in this context? We will examine this issue next.

The T-group cations

Consider the following points: a) in most scientific problems, one focuses on the variables that show the greatest degree of relative variation, as these are the most informative; b) IMA procedures concerning the definition of distinct minerals focus on the dominant species (cation or anion) at a site.

Of the *A*, *B*, *C*, *T* and *W* groups, all except *T* show a variety of dominant cations or anions in the set of all amphibole compositions; the *T* group is always dominated by Si (*i.e.*, ^{T}Al < 4.0 *apfu*, atoms per formula unit). These issues indicate that the *T*-group cations should *not* be used as a primary parameter in an amphibole classification.

The W-group anions

Although there is continuous variation in (OH,F) and O contents in amphiboles, the great majority of amphiboles have $W_2 \approx$ (OH, F, Cl)$_2$ [and have high-charge cations ordered at the *M*(2) site]. Amphiboles with 1 < (OH, F, Cl) << 2 *apfu* are very uncommon, and amphiboles with (OH, F, Cl) < 1 *apfu* are very rare [and all contain high-charge cations at the *M*(1) and *M*(3) sites].

In general, amphiboles show wide chemical variation in terms of their *A*-, *B*- and *C*-group constituents. These considerations suggest that the *W*-group constituents be used to divide amphiboles into two broad classes: (1) hydroxy-fluoro-chloro-amphiboles with (OH, F, Cl) ≥ 1.00 *apfu*, and (2) oxo-amphiboles with (OH, F, Cl) < 1.00 *apfu* (we do not use the term *oxy* as this has too many associations with the *process* of oxidation–dehydroxylation). Within these two classes, the *A*-, *B*- and *C*-group constituents are used to classify the amphiboles further.

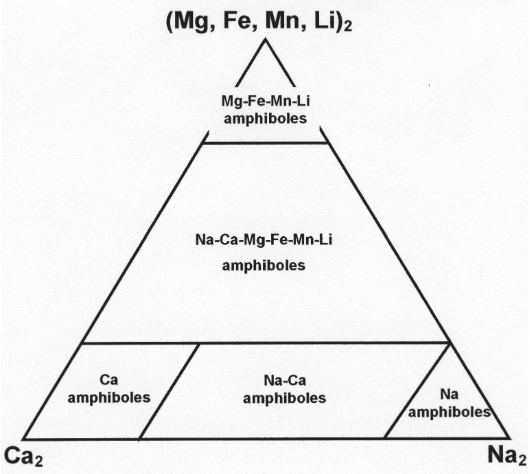

FIG. 2. The present classification (Leake *et al.* 2004) for the five main groups of amphibole.

The B-group cations

Previous classifications have been based on the type of *B*-group cations as the primary (first) classification parameter, which gives the following five main groups. The latest procedure (Leake *et al.* 2004) is as follows:

(1) Where ^{B}(Mg, Fe^{2+}, Mn^{2+}, Li) > 1.50 *apfu*, we have the *magnesium–iron–manganese–lithium group*.

(2) Where ^{B}(Mg, Fe^{2+}, Mn^{2+}, Li) < 0.50, ^{B}(Ca, Na) > 1.50 *apfu*, and ^{B}Na < 0.50 *apfu*], we have the *calcic group*; note that the condition ^{B}(Ca, Na) > 1.00 *apfu* given in Leake *et al.* (2004) is not correct.

(3) Where ^{B}(Mg, Fe^{2+}, Mn^{2+}, Li) < 0.50, ^{B}(Ca, Na) > 1.50 and 0.5 < ^{B}Na < 1.50 *apfu*], we have the *sodic–calcic group*; note that the condition ^{B}(Ca, Na) > 1.00 *apfu* given in Leake *et al.* (2004) is not correct.

(4) Where ^{B}(Mg, Fe^{2+}, Mn^{2+}, Li) < 0.50 and ^{B}Na > 1.50 *apfu*, we have the *sodic group*.

(5) Where 0.50 < ^{B}(Mg, Fe^{2+}, Mn^{2+}, Li) < 1.50 and 0.50 < ^{B}(Ca + Na) < 1.50 *apfu*, we have the *sodic–calcic–magnesium–iron–manganese–lithium group*.

The compositional fields of these groups are shown in Figure 2. There are many problems with this stage of the previous amphibole classifications; some of these issues are discussed next.

The role of ^{B}Li: There is no good crystal-chemical or chemical reason for including Li in the *magnesium–iron–manganese – lithium* group. Lithium is an alkali metal, is formally monovalent, and shows complete solid-solution with Na at the *M*(4) site in monoclinic amphiboles (*e.g.*, leakeite–pedrizite: Na Na$_2$ [Fe$^{3+}_2$ Mg$_2$ Li] Si$_8$ O$_{22}$ (OH)$_2$ – Na Li$_2$ [Fe$^{3+}_2$ Mg$_2$ Li] Si$_8$ O$_{22}$ (OH)$_2$ (Oberti *et al.* 2003); magnesioriebeckite – clino-ferri-holmquistite: $\square$ Na$_2$ [Fe$^{3+}_2$ Mg$_3$] Si$_8$ O$_{22}$ (OH)$_2$ – $\square$ Li$_2$ [Fe$^{3+}_2$ Mg$_3$] Si$_8$ O$_{22}$ (OH)$_2$ (Oberti *et al.* 2004).

These points indicate that amphiboles with Li dominant at *M*(4) should *not* be included as part of the magnesium–iron–manganese group. There are two possible ways in which to treat such amphiboles: (1) recognize a separate group of amphiboles with Li as the dominant constituent of the *B* group (analogous to the *sodic* group), or (2) include ^{B}Li with ^{B}Na as the principal constituent of an alkali amphibole group. However, ^{B}Li amphiboles have some features that are not shared with ^{B}Na amphiboles; for instance, ^{B}Li amphiboles may occur with orthorhombic *Pnma* symmetry (holmquistite) and also are expected to occur with monoclinic $P2_1/m$ symmetry (clinoholmquistite). Hence, the simpler solution is to define a distinct group for ^{B}Li amphiboles.

The names of the principal groups: If we recognize a separate group with Li as the dominant *B*-group cation, it is obvious that the term "lithic", in accord with "calcic" and "sodic", is not suitable. Moreover, the names of the current five groups (Leake *et al.* 2004) are rather inhomogeneous, using both nouns (*e.g.*, magnesium), element symbols (*e.g.*, Mg) and adjectives (*e.g.*, calcic, sodic). Here, we will use nouns to name these groups. The other inhomogeneity with regard to the names of these groups is the use of element symbols: the magnesium–iron–manganese group is frequently referred to as the Mg–Fe–Mn group (indeed, this is done in Leake *et al.* 1997), whereas the calcium group is not referred to as the Ca group. Some sort of consistency is required here; the most democratic solution is to allow either element names or symbols to be used, but requires consistency of use.

The role of the sodium–calcium group: One of the principal origins of the complexity in the classification of amphiboles is the recognition of the sodium–calcium group. This group was defined by Leake (1978) and redefined by Leake *et al.* (1997), but its use was not justified from a nomenclature perspective. As noted above, IMA procedures involving the definition of distinct minerals focus on the dominant species at a site. Using this criterion, the sodium–calcium group of amphiboles would not be recognized: amphiboles with 2.00 > Ca > 1.00 *apfu* would belong to the calcium group, and amphiboles with 2.00 > Na > 1.00 *apfu* would belong to the sodium group. Using this criterion to reduce the number of primary groups would certainly reduce both the complexity of the nomenclature and the number of distinct amphiboles. However, inspection of Figure 1 shows that use of this criterion will lead to a problem with richterite.

This issue is investigated in Figure 1, which shows *A*–*B*–*C* compositional space for amphiboles with only Ca and Na as *B*-group cations (note that this excludes magnesium–iron–manganese and lithium amphiboles). Compositions of previous "end-members" are shown as red squares and orange circles. Note that the compositions represented by orange circles can always be represented as a 50:50 mixture of other "end-member" compositions. Thus hornblende can be represented as 0.50 tremolite and 0.50 tschermakite, and barroisite can be represented as 0.50 tschermakite and 0.50 glaucophane. However, richterite cannot be represented by a combination of two end-members, as is apparent graphically from Figure 1; richterite thus is a true end-member according to the criteria of Hawthorne (2002). However, IMA criteria for the recognition of a valid mineral species do not include its status as a valid end-member. The criteria include the dominance of a specific cation at a site or group of sites. This approach would definitely dispose of pargasite and hornblende as distinct species of amphibole. There are (at least) two opinions on this issue: (1) names that are extremely common, not just in Mineralogy but also in Petrology and Geochemistry, and carry other scientific implications along with their name (*e.g.*, conditions of formation) or are involved in definitions or names of rock types, should be retained as a matter of scientific convenience; (2) a better classification is paramount, and such inconveniences as mentioned in (1) should be endured until the old names are supplanted in the minds of working scientists by the new names.

These are not easy issues with which to deal, and are made more difficult by the fact that few people appreciate the points of view of the "opposing" group of opinions. What we will do here, in part to illustrate the problems, is examine two approaches to classification, one that retains the familiar compositions of "intermediate" amphiboles [SCHEME 1], and one that strives to minimize the number of root names [SCHEME 2].

Calcium–lithium, magnesium–lithium and magnesium–sodium compositions: The above discussion concerning the sodium–calcium amphibole group can be applied to all mixed-valence cation-pairings in the *B* group. Thus (LiCa), (LiMg), (NaMg) and their $^{B}Fe^{2+}$ and $^{B}Mn^{2+}$ analogues will all result in end-member compositions that cannot be decomposed into calcium-, lithium-, magnesium–iron–manganese- or sodium-group compositions. In this regard, consider the composition $^{A}(Na_{0.33}K_{0.03})_{\Sigma 0.36}$ $^{B}(Na_{0.82}Ca_{0.39}Mn_{0.57}Mg_{0.22})_{\Sigma 2.00}$ $^{C}(Mg_{3.83}Mn^{2+}_{0.37}Fe^{3+}_{0.73}Li_{0.07})_{\Sigma 5.00}$ $^{T}(Si_{7.86}Al_{0.11})_{\Sigma 7.97}$ O_{22} $(OH_{1.60}F_{0.40})$, reported from Tirodi, India, by Oberti & Ghose (1993). This amphibole is close to the root composition $^{A}\square$ $^{B}(NaMn)$ $^{C}(Mg_4Fe^{3+})$ $^{T}Si_8O_{22}$ $(OH)_2$ and is presently named fluorian manganoan parvowinchite (IMA–CNMMN 2003–066; Leake *et al.* 2004). This composition gives rise to a new root name, and hence to a new group of $^{B}(Na\ [Mg,Fe,Mn])$ amphiboles in SCHEME 1.

The $^{B}(NaMg)$ and $^{B}(LiMg)$ joins have been investigated by synthesis; intermediate compositions are stable and have $P2_1/m$ symmetry at room temperature (Cámara *et al.* 2003, Iezzi *et al.* 2004, 2005a, b). We will take the pragmatic course of not considering the existence of lithium-calcium or lithium-magnesium amphiboles in SCHEME 1 and SCHEME 2, as these schemes refer to minerals (*i.e.*, natural compositions). We take the boundary between the lithium and calcium, and lithium and magnesium–iron–manganese amphiboles at Li : Ca and Li : (Mg + Fe + Mn) ratios of 0.50 (*i.e.*, we use the criterion of the dominant cation or, in the case of the magnesium–iron–manganese amphiboles, the dominant group of cations) in both SCHEME 1 and SCHEME 2.

The A- and C-group cations

Having divided amphiboles into five groups based on the *B*-group cations, we have the *A*- and *C*-group cations to classify them within these groups and to assign specific names to specific compositional ranges and root compositions. For the *A*-group cations, the variation observed in Nature spans the complete range possible from a structural perspective: □, Na, K and Ca can vary in the range 0–1 *apfu*. The situation for the *C*-group cations is more complicated, as these cations occur at three distinct sites in amphibole structures: *M*(1), *M*(2) and *M*(3) in all common amphibole structure-types (but not in the *P*2/*a* and $C\bar{1}$ structure-types, where there are five and eight *M* sites, respectively). Most heterovalent variations occur at the *M*(2) site, where there is extensive solid-solution among Mg, Fe^{2+}, Al, Fe^{3+} and Ti^{4+}. Some Al can disorder over *M*(2) and *M*(3) in Mg-rich calcium amphiboles (Oberti *et al.* 1995), and some Fe^{3+} can occur at *M*(1) owing to post-crystallization oxidation–dehydroxylation, but trivalent cations are never dominant at *M*(1) or *M*(3) in amphiboles with (OH, F, Cl) ≥ 1.00 *apfu*. For amphiboles in which ${}^{W}O^{2-} > 1$ *apfu*, Ti^{4+} can become dominant at *M*(1), and Fe^{3+} and Mn^{3+} can become dominant at *M*(1) and *M*(3), but this is not a factor in the nomenclature of amphiboles in which (OH,F) is dominant in the *W* group. Lithium can become dominant at the *M*(3) site, normally being accompanied by Fe^{3+} at the *M*(2) site. Thus the principal variation in both charge and chemical species in amphiboles with (OH, F, Cl) ≈ 2 *apfu* occurs at the *C*-group sites.

Representation of the C-group cations

We need to be able to represent the variation in *C*-group cations by a single variable, which therefore must be their aggregate formal charge. The most common variation in the *C* group involves divalent and trivalent cations. If we consider *C*-group cations of formal charge greater than 2^+, *i.e.*, Al, Fe^{3+}, Cr^{3+}, V^{3+}, Ti^{4+}, Sc and Zr, we can express their aggregate formal charge as M^{3+}, where $M^{3+} = Al + Fe^{3+} + Cr^{3+} + V^{3+} + Sc + 2 \times Ti^{4+} + 2 \times Zr$. [Note that replacement of $M^{2+}{}_n$ by $M^{3+}{}_n$ increases the aggregate charge by n^+; replacement of $M^{2+}{}_n$ by $M^{4+}{}_n$ increases the aggregate charge by $2n^+$].The sum of these highly charged cations is less or equal to 2 *apfu*, but the aggregate charge, M^{3+}, can exceed 2. If we are dealing with amphiboles in which $W = (OH, F, Cl)_2$, all of these cations will occur at the *M*(2) site [except for some Al–Mg disorder over *M*(2) and *M*(3) in Mg-rich calcium amphiboles], and M^{3+} cannot exceed 2 *apfu*. However, real amphiboles have two compositional characteristics that can modify this situation: (1) the presence of Li as a *C*-group cation, and (2) the presence of O^{2-} as a non-dominant component of the *W*-group anions.

C-group Li enters the amphibole structure *via* the substitution ${}^{M(3)}Li + {}^{M(2)}Fe^{3+} \rightarrow {}^{M(2,3)}Fe^{2+}{}_2$. As ${}^{C}Li$ is not incorporated into the *A–B–C* classification procedure as represented in Figure 1 but is considered separately, it is necessary to adjust the value of M^{3+} for the effect of the substitution ${}^{M(3)}Li + {}^{M(2)}Fe^{3+} \rightarrow {}^{M(2,3)}Fe^{2+}{}_2$. This is done by subtracting an amount of trivalent cations equal to the amount of *C*-group Li.

The behavior of ${}^{C}Ti^{4+}$ also affects M^{3+} because of the different roles that ${}^{C}Ti^{4+}$ plays in amphiboles: (1) ${}^{C}Ti^{4+}$ may occur at the *M*(2) site, where it contributes $2 \times Ti^{4+}$ to M^{3+}; (2) ${}^{C}Ti^{4+}$ may occur at the *M*(1) site, where it is coupled to the occurrence of O^{2-} at the O(3) site [*i.e.,* as a *W*-group anion]; in this role, it will not contribute to M^{3+}. Of course, we do not know the relative amounts of ${}^{C}Ti^{4+}$ in each of these roles in a specific amphibole without detailed structural and SIMS work, and a pragmatic solution to this issue is required. Current opinion is that where present in small amounts (≤0.15 *apfu*), ${}^{C}Ti^{4+}$ occurs at *M*(2); where present in large amounts (> 0.15 *apfu*), ${}^{C}Ti^{4+}$ occurs primarily at *M*(1). Thus ${}^{C}Ti^{4+}$ contributes to M^{3+} up to a maximum of 2 × 0.15 *apfu*; any ${}^{C}Ti^{4+}$ in excess of this amount is ignored. [Note that this treatment is not entirely satisfactory, as it produces a problem for titano-sadanagaite: $Na\ Ca_2\ (Fe^{2+}{}_3\ Fe^{3+}\ Ti)\ (Si_4\ Al_4)\ O_{22}\ (OH)_2$, as the end-member composition produces an M^{3+} value of 3. However, this argument may not be correct. There is no crystal-structure information on titano-sadanagaite, and hence we are not sure of the site occupancies or of the mechanisms whereby the valence-sum rule is satisfied. Moreover, it is a different charge-arrangement and warrants new rootnames in schemes 1 and 2. Until information on site populations is available, we will not know the best way of treating such compositions in terms of classification.]

NEW SCHEMES OF CLASSIFICATION FOR AMPHIBOLES

First, amphiboles are divided into two classes according to the dominant species of the *W* group: there are ^{W}(OH, F, Cl)-dominant amphiboles, and ^{W}O-dominant amphiboles.

AMPHIBOLES WITH (OH, F, CL) DOMINANT AT W

These are divided into groups according to the dominant cation or group of cations of the *B* group. In order to make the notation simpler, let us write the sum of the small divalent cations as $\Sigma Mg = {}^{B}Mg + {}^{B}Fe^{2+} + {}^{B}Mn^{2+}$, and the sum of the *B*-group cations as $\Sigma B = {}^{B}Li + {}^{B}Na + \Sigma Mg + {}^{B}Ca$ (which generally is equal to 2.00 *apfu*). Thus the dominant constituents of the *B* group may be represented as follows.

	SCHEME 1	SCHEME 2
Magnesium–iron–manganese	ΣMg	ΣMg
Calcium	$^{B}(Ca + Na)$	^{B}Ca
Sodium–calcium	$^{B}(Ca + Na)$	–
Sodium	$^{B}(Ca + Na)$	^{B}Na
Lithium	^{B}Li	^{B}Li
Sodium – (magnesium–iron–manganese)	$\Sigma Mg + Na$	–

The dominant constituent or group of constituents defines the group. In SCHEME 1, $^{B}(Ca + Na)$ defines only the dominance of the calcium, sodium–calcium and sodium groups collectively. Once the dominance of a collective group is established, which group is applicable is defined by the ratio $^{B}Ca / ^{B}(Ca + Na)$ as indicated below.

	SCHEME 1	SCHEME 2
Calcium	$^{B}Ca / ^{B}(Ca + Na) \geq 0.75$	$^{B}Ca / \Sigma B \geq \Sigma Mg / \Sigma B, ^{B}Na / \Sigma B, ^{B}Li / \Sigma B$
Sodium–calcium	$0.75 > ^{B}Ca / ^{B}(Ca + Na) > 0.25$	–
Sodium	$0.25 \geq ^{B}Ca / ^{B}(Ca + Na)$	$^{B}Na / \Sigma B > \Sigma Mg / \Sigma B, ^{B}Ca / \Sigma B, ^{B}Li / \Sigma B$

The Magnesium–Iron–Manganese Group

Defined by $\Sigma Mg / \Sigma B > ^{B}(Ca + Na) / \Sigma B$ and $> ^{B}Li / \Sigma B$

Amphiboles of this group may be orthorhombic (space groups *Pnma* or *Pnmn*) or monoclinic (space groups $C2/m$ or $P2_1/m$). Although we distinguish between the *B*- and *C*-group cations in amphiboles in general, we cannot identify accurately the partitioning of Mg and Fe^{2+} between the *B* and *C* groups in the magnesium–iron–manganese group of amphiboles without crystal-structure refinement or Mössbauer spectroscopy. Hence for this group, we treat the divisions between Mg–Fe^{2+} homovalent analogues in terms of the sum of the *B*- and *C*-group cations. However, Mn^{2+} preferentially occurs in the *B* group relative to the *C* group, and hence distinct species are recognized with Mn^{2+} dominant in the *B* group.

Orthorhombic magnesium–iron–manganese amphiboles

The space group *Pnma* is assumed, the space group *Pnmn* is indicated by the prefix *proto*. There are four root compositions with Mg dominant at *C*.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Mg_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Anthophyllite	Anthophyllite
$Na\ Mg_2\ Mg_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Rootname1	Rootname1
$\square\ Mg_2\ (Mg_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Gedrite	Gedrite
$Na\ Mg_2\ (Mg_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Rootname2	Rootname2

The composition $Na\ Mg_2\ Mg_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$ is named sodicanthophyllite in the current IMA classification. However, this composition has a different charge-arrangement from other root compositions for orthorhombic amphiboles and hence warrants a new root name. For example, the relation between *anthophyllite* and *rootname1* is the same as that between *tremolite* and *edenite*; thus use of the name sodicanthophyllite (1) violates the association of a distinct root-name with a distinct charge-arrangement in *A–B–C* or *A–B–T* space, and (2) would, by analogy, require the name “sodictremolite” for the composition $Na\ Ca_2\ Mg_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$ that is currently named edenite. The composition $Na\ Mg_2\ (Mg_3Al_2)\ (Si_5Al_3)\ O_{22}\ (OH)_2$ is introduced as a new root composition, replacing sodicgedrite, $Na\ Mg_2\ (Mg_4Al)\ (Si_6Al_2)\ O_{22}\ (OH)_2$, in the current IMA classification. The compositional ranges of the orthorhombic magnesium–iron–manganese amphiboles are shown in Figure 3.

There are four homovalent analogues involving Fe^{2+} instead of Mg dominant at the $(B + C)$ groups with the following compositions:

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Fe^{2+}_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$	Ferro-anthophyllite	Ferro-anthophyllite
$Na\ Fe^{2+}_2\ Fe^{2+}_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferro-rootname1	Ferro-rootname1
$\square\ Fe^{2+}_2\ (Fe^{2+}_3\ Al_2)(Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferro-gedrite	Ferro-gedrite
$Na\ Fe^{2+}_2\ (Fe^{2+}_3\ Al_2)(Si_5\ Al_3)\ O_{22}\ (OH)_2$	Ferro-rootname2	Ferro-rootname2

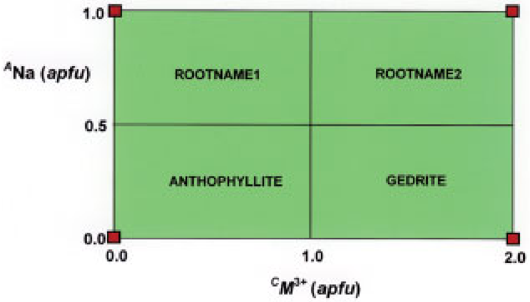

FIG. 3. Root compositions for the orthorhombic magnesium–iron–manganese amphiboles; note that compositions with Na dominant at *A* require new root names in schemes 1 and 2.

Monoclinic magnesium–iron–manganese amphiboles

The space group $C2/m$ is assumed, the space group $P2_1/m$ is indicated by the hyphenated suffix -$P2_1/m$. There is one root composition with Mg dominant at *B* + *C*, one analogue involving Fe^{2+} instead of Mg dominant at *B* + *C*, and two additional analogues with Mn^{2+} dominant at the *B* group only. Leake *et al.* (1997) designated the Mn^{2+} analogues by the prefix *mangano*. However, it is not consistent to apply the prefix *mangano* to the composition ☐ $Mn^{2+}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$, as all other prefixes are used to indicate compositions at the *A* and *C* sites. Thus the composition ☐ $Mn^{2+}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$ warrants a new root name: *rootname3*, ☐ $Mn^{2+}_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$ is ferro-rootname3, and ☐ $Mn^{2+}_2\ Mn^{2+}_5\ Si_8\ O_{22}\ (OH)_2$ is mangano-rootname3; note that the prefix *mangano* is used for Mn^{2+}_2 at the *C*-group sites.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
☐ $Mg_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Cummingtonite	Cummingtonite
☐ $Fe^{2+}_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$	Grunerite	Ferro-cummingtonite
☐ $Mn^{2+}{}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Rootname3	Rootname3
☐ $Mn^{2+}{}_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$	Ferro-rootname3	Ferro-rootname3

The compositional ranges of the monoclinic Mg–Fe–Mn amphiboles are shown in Figure 4.

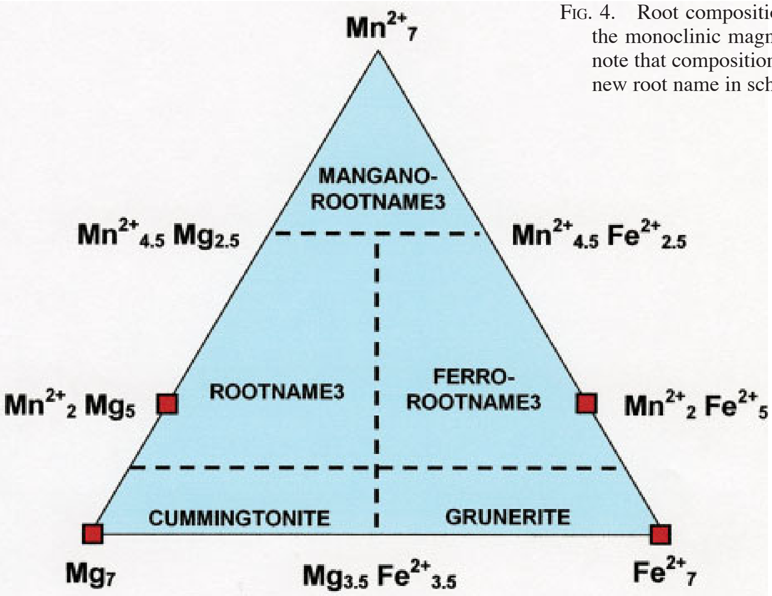

FIG. 4. Root compositions and compositional variations for the monoclinic magnesium–iron–manganese amphiboles; note that compositions with Mn^{2+} dominant at *C* require a new root name in schemes 1 and 2.

THE CALCIUM AMPHIBOLE GROUP

Defined as follows:

SCHEME 1	SCHEME 2
$^{B}(Ca + Na) / \Sigma B \geq \Sigma Mg / \Sigma B, Na / \Sigma B, Li / \Sigma B$ $^{B}Ca / ^{B}(Ca + Na) \geq 0.75$	$^{B}Ca / \Sigma B \geq \Sigma Mg / \Sigma B, Na / \Sigma B, Li / \Sigma B$

The root compositions are shown below. SCHEME 1 accepts current root-names and their compositions. SCHEME 2 has all root compositions with Mg and Al dominant at *C*. Thus in SCHEME 1, one uses the prefixes *magnesio-* and *alumino-* where the root names are defined as the ferrous or ferric analogues (or both), whereas in SCHEME 2, one never uses the prefixes *magnesio-* and *alumino-*. Note that in SCHEME 1, the name *hornblende* is never used without a prefix, as was the case in the previous classification of Leake *et al.* (1997), in order to allow the name to be available for field- or optical-microscopy-based schemes of classification.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Ca_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Tremolite	Tremolite
$\square\ Ca_2\ (Mg_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Magnesio-hornblende	–
$\square\ Ca_2\ (Mg_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Tschermakite	Tschermakite
$Na\ Ca_2\ Mg_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Edenite	Edenite
$Na\ Ca_2\ (Mg_4\ Al)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Pargasite	–
$Na\ Ca_2\ (Mg_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Magnesio-alumino-sadanagaite	Sadanagaite
$Ca\ Ca_2\ (Mg_4\ Al)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Cannilloite	Cannilloite

Note that kaersutite is no longer considered as an $^{W}(OH, F, Cl)$-dominant calcium amphibole; it is classified as an $^{W}O^{2-}$-dominant amphibole.

Ferrous-iron analogues are generally named by the prefix *ferro-*, as indicated below. However, in SCHEME 1, some compositions retain their traditional name (*e.g.*, hastingsite) because of the petrological importance of these names.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Ca_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$	Actinolite	Ferro-tremolite
$\square\ Ca_2\ (Fe^{2+}_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferro-hornblende	–
$\square\ Ca_2\ (Fe^{2+}_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferro-tschermakite	Ferro-tschermakite
$Na\ Ca_2\ Fe^{2+}_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferro-edenite	Ferro-edenite
$Na\ Ca_2\ (Fe^{2+}_4\ Al)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferro-pargasite	–
$Na\ Ca_2\ (Fe^{2+}_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Alumino-sadanagaite	Ferro-sadanagaite
$Ca\ Ca_2\ (Fe^{2+}_4\ Al)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Ferro-cannilloite	Ferro-cannilloite

Ferric-iron analogues are generally named by the prefix *ferri-*, as indicated below. However, some compositions retain their traditional name (*e.g.*, magnesio-hastingsite) because of the petrological importance of the name.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Ca_2\ (Mg_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferri-hornblende	–
$\square\ Ca_2\ (Mg_3\ Fe^{3+}{}_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferri-tschermakite	Ferri-tschermakite
$Na\ Ca_2\ (Mg_4\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Magnesio-hastingsite	–
$Na\ Ca_2\ (Mg_3\ Fe^{3+}{}_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Magnesio-sadanagaite	Ferri-sadanagaite

Ferrous- and ferric-iron analogues are generally named by the prefixes *ferro-ferri-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Ca_2\ (Fe^{2+}_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferro-ferri-hornblende	–
$\square\ Ca_2\ (Fe^{2+}_3\ Fe^{3+}{}_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferro-ferri-tschermakite	Ferro-ferri-tschermakite
$Na\ Ca_2\ (Fe^{2+}_4\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Hastingsite	–
$Na\ Ca_2\ (Fe^{2+}_3\ Fe^{3+}{}_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Sadanagaite	Ferro-ferri-sadanagaite

The compositional ranges of the calcium amphiboles are shown in Figure 5.

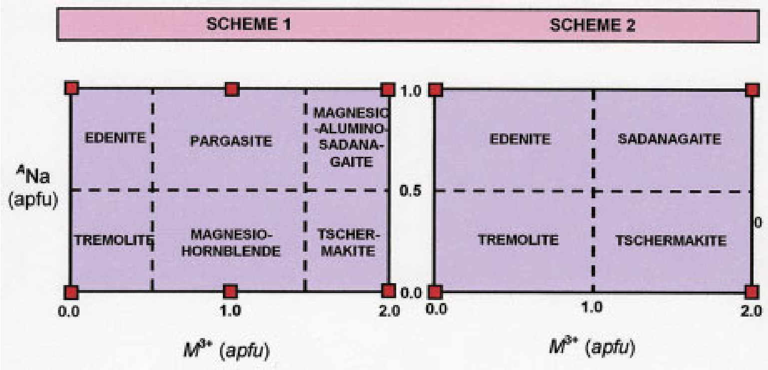

FIG. 5. Root compositions and compositional variations for the calcium amphiboles.

THE SODIUM–CALCIUM AMPHIBOLE GROUP

Defined as follows:

SCHEME 1	SCHEME 2
$^B(\mathrm{Ca + Na}) / \Sigma B \geq \Sigma \mathrm{Mg} / \Sigma B, \mathrm{Na} / \Sigma B, \mathrm{Li} / \Sigma B$	DOES NOT OCCUR
$0.75 > {}^B\mathrm{Ca} / {}^B(\mathrm{Ca + Na}) > 0.25$	

There are five root compositions with Mg and Al dominant at *C*.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
□ CaNa (Mg$_4$ Al) Si$_8$ O$_{22}$ (OH)$_2$	Winchite	–
□ CaNa (Mg$_3$ Al$_2$) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Barroisite	–
Na CaNa Mg$_5$ Si$_8$ O$_{22}$ (OH)$_2$	Richterite	–
Na CaNa (Mg$_4$ Al) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Magnesio-katophorite	–
Na CaNa (Mg$_3$ Al$_2$) (Si$_6$ Al$_2$) O$_{22}$ (OH)$_2$	Magnesio-taramite	–

Ferrous-iron analogues are generally named by the prefix *ferro-*, as indicated below. However, some compositions retain their traditional name (*e.g.*, katophorite) because of the petrological importance of their name.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
□ CaNa Fe$^{2+}_5$ Si$_8$ O$_{22}$ (OH)$_2$	Ferro-richterite	–
□ CaNa (Fe$^{2+}_4$ Al) Si$_8$ O$_{22}$ (OH)$_2$	Ferro-winchite	–
□ CaNa (Fe$^{2+}_3$ Al$_2$) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Ferro-barroisite	–
Na CaNa (Fe$^{2+}_4$ Al) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Katophorite	–
Na CaNa (Fe$^{2+}_3$ Al$_2$) (Si$_6$ Al$_2$) O$_{22}$ (OH)$_2$	Taramite	–

Ferric-iron analogues are generally named by the prefix *ferri-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
□ CaNa (Mg$_4$ Fe^{3+}) Si$_8$ O$_{22}$ (OH)$_2$	Ferri-winchite	–
□ CaNa (Mg$_3$ Fe$^{3+}_2$) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Ferri-barroisite	–
Na CaNa (Mg$_4$ Fe^{3+}) (Si$_7$ Al) O$_{22}$ (OH)$_2$	Magnesio-ferri-katophorite	–
Na CaNa (Mg$_3$ Fe$^{3+}_2$) (Si$_6$ Al$_2$) O$_{22}$ (OH)$_2$	Magnesio-ferri-taramite	–

Ferrous- and ferric-iron analogues are generally named by the prefixes *ferro-ferri-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square$ CaNa $(Fe^{2+}_4\ Fe^{3+})$ Si_8 O_{22} $(OH)_2$	Ferro-ferri-winchite	–
$\square$ CaNa $(Fe^{2+}_3\ Fe^{3+}_2)$ $(Si_7\ Al)$ O_{22} $(OH)_2$	Ferro-ferri-barroisite	–
Na CaNa $(Fe^{2+}_4\ Fe^{3+})$ $(Si_7\ Al)$ O_{22} $(OH)_2$	Ferri-katophorite	–
Na CaNa $(Fe^{2+}_3\ Fe^{3+}_2)$ $(Si_6\ Al_2)$ O_{22} $(OH)_2$	Ferri-taramite	–

The compositional ranges of the sodium–calcium amphiboles are shown in Figure 6.

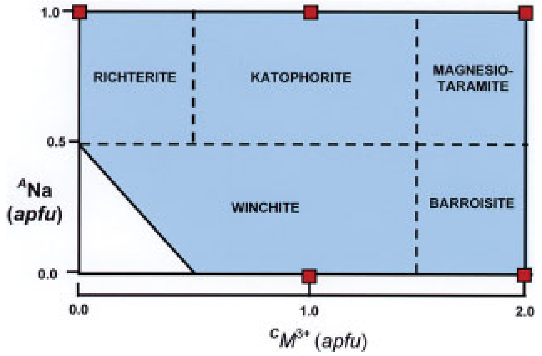

FIG. 6. Root compositions and compositional variations for the sodium–calcium amphiboles; note that the amphiboles of this group only exist in scheme 1.

THE SODIUM AMPHIBOLE GROUP

Defined as follows:

SCHEME 1	SCHEME 2
$^{B}(Ca + Na) / \Sigma B \geq \Sigma Mg / \Sigma B,\ ^{B}Na / \Sigma B,\ Li / \Sigma B$ $^{B}Ca / (\Sigma Mg + {}^{B}Na) \leq 0.25$ $\Sigma Mg / (\Sigma Mg + {}^{B}Na) \leq 0.25$	$^{B}Na / \Sigma B \geq \Sigma Mg / \Sigma B,\ ^{B}Ca / \Sigma B,\ Li / \Sigma B$

The root compositions are shown below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square$ Na_2 $(Mg_3\ Al_2)$ Si_8 O_{22} $(OH)_2$	Glaucophane	Glaucophane
Na Na_2 $(Mg_4\ Al)$ Si_8 O_{22} $(OH)_2$	Eckermannite	Eckermannite
Na Na_2 $(Mg_3\ Al_2)$ $(Si_7\ Al)$ O_{22} $(OH)_2$	Nyböite	Nyböite
Na Na_2 $(Mg_2\ Al_2\ Li)$ Si_8 O_{22} $(OH)_2$	Alumino-leakeite	Leakeite

Ferrous-iron analogues are generally named by the prefix *ferro-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square$ Na_2 $(Fe^{2+}_3\ Al_2)$ Si_8 O_{22} $(OH)_2$	Ferro-glaucophane	Ferro-glaucophane
Na Na_2 $(Fe^{2+}_4\ Al)$ Si_8 O_{22} $(OH)_2$	Ferro-eckermannite	Ferro-eckermannite
Na Na_2 $(Fe^{2+}_3\ Al_2)$ $(Si_7\ Al)$ O_{22} $(OH)_2$	Ferro-nyböite	Ferro-nyböite
Na Na_2 $(Fe^{2+}_2\ Al_2\ Li)$ Si_8 O_{22} $(OH)_2$	Ferro-alumino-leakeite	Ferro-leakeite

Ferric-iron analogues are generally named by the prefix *ferri-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square$ Na_2 $(Mg_3\ Fe^{3+}_2)$ Si_8 O_{22} $(OH)_2$	Magnesio-riebeckite	Ferri-glaucophane
Na Na_2 $(Mg_4\ Fe^{3+})$ Si_8 O_{22} $(OH)_2$	Magnesio-arfvedsonite	Ferri-eckermannite
Na Na_2 $(Mg_3\ Fe^{3+}_2)$ $(Si_7\ Al)$ O_{22} $(OH)_2$	Ferri-nyböite	Ferri-nyböite
Na Na_2 $(Mg_2\ Fe^{3+}_2\ Li)$ Si_8 O_{22} $(OH)_2$	Leakeite	Ferri-leakeite

Ferrous- and ferric-iron analogues are generally named by the prefixes *ferri-ferro-*, as indicated below.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Na_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Riebeckite	Ferro-ferri-glaucophane
$Na\ Na_2\ (Fe^{2+}_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Arfvedsonite	Ferro-ferri-eckermannite
$Na\ Na_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferro-ferri-nyböite	Ferro-ferri-nyböite
$Na\ Na_2\ (Fe^{2+}_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Ferro-leakeite	Ferro-ferri-leakeite

For the sodium amphiboles, there are also the following Mn^{2+} analogues that are denoted by root (trivial) names.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$Na\ Na_2\ (Mn^{2+}_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Kozulite	Mangano-ferri-glaucophane
$Na\ Na_2\ (Mg_2\ Mn^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Kornite	Mangani-leakeite

Kozulite is the mangano- analogue of arfvedsonite, and kornite is the mangani- analogue of leakeite. We strongly suggest that in SCHEME 1, they be named mangano-arfvedsonite and mangani-leakeite, respectively.

The compositional ranges of the sodium amphiboles are shown in Figure 7.

THE LITHIUM AMPHIBOLE GROUP

Defined by $^{B}Li\ /\ \Sigma B > {}^{B}(Mg + Fe^{2+} + Mn^{2+})\ /\ \Sigma B$ and $^{B}(Ca + Na)\ /\ \Sigma B$

Amphiboles of this group may be orthorhombic (space group *Pnma*) or monoclinic (space group *C*2/*m*).

Orthorhombic lithium amphiboles

There is one root composition plus its *ferro-, ferri- and ferro-ferri-* analogues.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Li_2\ (Mg_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Holmquistite	Holmquistite
$\square\ Li_2\ (Fe^{2+}_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Ferro-holmquistite	Ferro-holmquistite
$\square\ Li_2\ (Mg_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Ferri-holmquistite	Ferri-holmquistite
$\square\ Li_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Ferro-ferri-holmquistite	Ferro-ferri-holmquistite

Monoclinic lithium amphiboles

There are two root compositions plus their *ferro-, ferri- and ferro-ferri-* analogues.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$\square\ Li_2\ (Mg_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-holmquistite	Clino-holmquisitite
$Na\ Li_2\ (Mg_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)$	Pedrizite	Pedrizite
$\square\ Li_2\ (Fe^{2+}_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferro-holmquistite	Clino-ferro-holmquistite
$Na\ Li_2\ (Fe^{2+}_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Ferro-pedrizite	Ferro-pedrizite
$\square\ Li_2\ (Mg_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferri-holmquistite	Clino-ferri-holmquistite
$Na\ Li_2\ (Mg_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Ferri-pedrizite	Ferri-pedrizite
$\square\ Li_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferro-ferri-holmquistite	Clino-ferro-ferri-holmquistite
$Na\ Li_2\ (Fe^{2+}_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Ferro-ferri-pedrizite	Ferro-ferri-pedrizite

THE SODIUM–(MAGNESIUM–IRON–MANGANESE) AMPHIBOLE GROUP

Defined as follows:

SCHEME 1	SCHEME 2
$^{B}(Mg + Fe^{2+} + Mn^{2+} + Na)\ /\ \Sigma B > {}^{B}Ca\ /\ \Sigma B$ and $> {}^{B}Li\ /\ \Sigma B$ $0.75 > {}^{B}Na\ /\ {}^{B}(Mg + Fe^{2+} + Mn^{2+} + Na) > 0.25$	DOES NOT OCCUR

At the moment, there is only one root composition, $\square\,(Mn^{2+}Na)\,(Mg_4Fe^{3+})\,Si_8\,O_{22}\,(OH)_2$. A new name must be assigned in Scheme 1. The *C*-group ferrous-iron analogues are generally named by the prefix *ferro-*, and the *C*-group ferric-iron analogues are generally named by the prefix *ferri-*. By analogy with the magnesium–iron–manganese group [*e.g.*, $\square\,Mn^{2+}_2\,Mg_5\,Si_8\,O_{22}\,(OH)_2$ = rootname3], we propose to recognize the dominant cation at the *B* group (where known). Thus Mg, *e.g.*, *B* = NaMg, is recognized by a *root name*; *B* = Na(Mg, Fe^{2+}) cannot be distinguished from *B* = NaMg by chemical analysis and does not receive a separate name, whereas *B* = $NaMn^{2+}$ can be distinguished by chemical analysis and should receive a new rootname. The compositional ranges of the sodium – (magnesium–iron–manganese) amphiboles are shown in Figure 8.

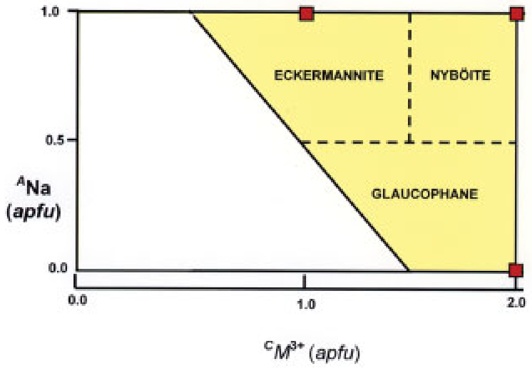

FIG. 7. Root compositions and compositional variations for the sodium amphiboles.

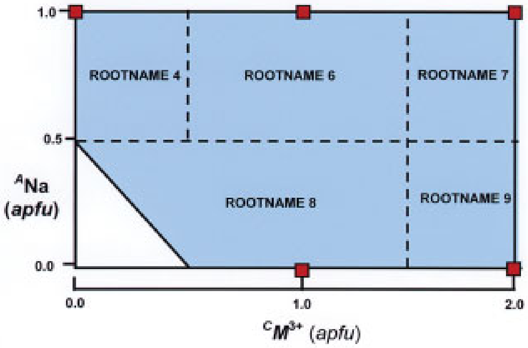

FIG. 8. Root compositions and compositional variations for the sodium – (magnesium – iron – manganese) amphiboles.

AMPHIBOLES WITH O^{2-} DOMINANT AT *W*

Dominance of the *W* group by O^{2-} is accompanied by the occurrence of high-charge ($\geq 3^+$) cations in the *C* group; this means that the aggregate charge at the *C*-group sites exceeds 12^+. There are four distinct root-compositions.

END-MEMBER FORMULA	SCHEME 1	SCHEME 2
$Na\,Na_2\,(Mg_3\,Fe^{3+}\,Ti^{4+})\,Si_8\,O_{22}\,O_2$	Obertiite	Ferri-obertiite
$Na\,Na_2\,(Mg\,Mn^{3+}_2\,Ti^{4+}\,Li)\,Si_8\,O_{22}\,O_2$	Dellaventuraite	Mangani-dellaventuraite
$Na\,Na_2\,(Mn^{2+}_2\,Mn^{3+}_3)\,Si_8\,O_{22}\,O_2$	Ungarettiite	Mangano-mangani-ungarettiite
$Na\,Ca_2\,(Mg_3\,Ti^{4+}\,Al)\,(Si_6\,Al_2)\,O_{22}\,O_2$	Kaersutite	Kaersutite

Ferrous-iron analogues can be indicated by the prefix *ferro-* (or any other as appropriate) as indicated below.

Ferro-kaersutite: $Na\,Ca_2\,(Fe^{2+}_3\,Ti^{4+}\,Al)\,(Si_6\,Al_2)\,O_{22}\,O_2$

Three of these amphiboles (obertiite, ungarettiite and dellaventuraite) are rare, and analysis for H to characterize these species may not be regarded as unduly onerous by the mineralogical community. However, this is not the case for kaersutite, which is a reasonably common and petrologically important amphibole. Thus a different criterion would be convenient for the classification of kaersutite; this can be done on the basis of the Ti content, as indicated in Figure 9.

MAJOR DIFFERENCES BETWEEN IMA97 AND SCHEMES 1 AND 2

It is useful to summarize the principal differences between the classification schemes presented here and those of Leake *et al.* (1997, 2004).

(1) We have changed the criterion to identify the different groups, bringing it into accord with the *dominant-cation* criterion of current IMA–CNMMN nomenclature. Leake *et al.* (1997, 2004) referred to specific atom contents in the formula unit to define the boundary between groups. Thus an amphibole is presently assigned to the calcic group where $^{B}(\mathrm{Mg,Fe^{2+},Mn^{2+},Li}) \leq 0.50$, $^{B}(\mathrm{Ca,Na}) \geq 1.50$ and $^{B}\mathrm{Na} \leq 0.50$ *apfu*. In the two schemes described here, amphiboles are assigned to various groups based on the *dominant cation* (or group of cations) at a site (or group of sites). Thus an amphibole is assigned to the calcium group where $^{B}\mathrm{Ca}$ is dominant over $^{B}\Sigma\mathrm{Mg}$, $^{B}\mathrm{Na}$ and $^{B}\mathrm{Li}$.

(2) Leake *et al.* (1997, 2004) considered $^{B}\mathrm{Li}$ together with $^{B}(\mathrm{Mg,Fe^{2+},Mn^{2+}})$, $^{B}\mathrm{Ca}$ and $^{B}\mathrm{Na}$ to define a sodium–calcium–magnesium–iron–manganese–lithium group, in which intermediate compositions require (1) a new root name if $^{B}\mathrm{Li} > 0.50$ *apfu*, or (2) the prefixes *parvo* and *magno* if $^{B}\mathrm{Li} \leq 0.50$ *apfu*.

The crystal-chemical behavior of Li is very different from that of $(\mathrm{Mg,Fe^{2+},Mn^{2+}})$ and Ca, and is more similar to that of Na. Moreover, extensive recent work (Caballero *et al.* 1998, 2002, Oberti *et al.* 2003, 2004) has shown extensive solid-solution between $^{B}\mathrm{Li}$ and $^{B}\mathrm{Na}$, a pattern of behavior that is different from that of the $^{B}(\mathrm{Mg,Fe^{2+},Mn^{2+}})$ amphiboles. However, the existence of $^{B}\mathrm{Li}$ amphibole with orthorhombic and monoclinic primitive symmetries indicates that $^{B}\mathrm{Li}$-dominant amphiboles should be a distinct group.

(3) Leake *et al.* (1997, 2004) used both nouns and adjectives to define the five main groups of amphiboles (*e.g.,* magnesium–iron–manganese–lithium, calcic, sodic). We propose to use nouns (*e.g.,* magnesium–iron–manganese, calcium, sodium) or element or cation symbols in all cases.

(4) Leake *et al.* (1997, 2004) used the *A*, *B* and *T* groups of cations for classification purposes. However, the dominant *T*-group cation does not change: it is invariably Si, and hence compositional variation in the *T* group is not an appropriate variable to use for classification. All other groups show two or more cations as dominant, and hence the *A*, *B*, and *C* groups are more appropriate for classification purposes and accord with the dominant-cation principle currently used in IMA nomenclature. As this point is the major difference between the two schemes, we examine this in the next paragraph.

Two major crystal-chemical issues have been explored in detail since publication of the current scheme of classification (Leake *et al.* 1997): (a) the behavior of $^{C}\mathrm{Li}$, and (b) the occurrence of dominant $\mathrm{O^{2-}}$ in the *W* group. In both these cases, electroneutrality is maintained by incorporation of "unusual" cations at sites containing "normal" *C*-group cations: (a) $^{M(3)}\mathrm{Li}$ is accompanied by $^{M(2)}\mathrm{Fe^{3+}}$; (b) $^{W}\mathrm{O^{2-}}$ is accompanied by $^{M(1)}\mathrm{Ti^{4+}}$ or $^{M(1),M(3)}(\mathrm{Fe^{3+}, Mn^{3+}})$. For classification purposes, these components can be dealt with by subtracting the appropriate amount of $^{C}\mathrm{R^{3+}}$ before using the standard compositional diagrams.

(5) The two schemes introduced here recognize a distinct group of amphiboles with dominant $\mathrm{O^{2-}}$ at the *W* group (oxo-amphiboles). These amphiboles contain high-charge cations in the *C* group, and have distinct root-names.

(6) With the schemes suggested, we propose a different (and hopefully more rational) use of prefixes. Moreover, if some root compositions are redefined as their magnesio- alumino- analogues, then the prefixes *sodic*, *magnesio* and *alumino* can be eliminated. We list the root-names that are redefined here in Appendix II.

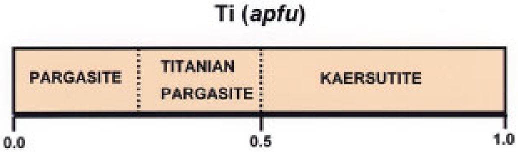

FIG. 9. Compositional variation and classification for kaersutite.

THE TWO SCHEMES: FOR AND AGAINST

Before we consider the two schemes described here, we should state that various features of each of these schemes are not restricted to one or the other scheme. For example, all redefinitions and removal of root names from IMA97 have been done within SCHEME 2, and yet some of the redefinitions can also be incorporated into SCHEME 1 (*e.g.*, for kornite and kozulite or to avoid the use of the prefixes magnesio- and alumino-).

(1) *Recognition of the sodium–calcium and lithium –(magnesium–iron–manganese) groups*

On the basis of the *dominant-cation* principle, these two groups should not be recognized. The root compositions do not have a dominant cation for the *B* group, having *B* = NaCa and *B* = Li(Mg, Fe, Mn). Compositions in these fields can be identified as (1) calcium amphiboles (Ca dominant at *B*) or sodium amphiboles (Na dominant at *B*), and (2) lithium amphiboles (Li dominant at *B*) or magnesium–iron–manganese amphiboles [(Mg,Fe,Mn) dominant at *B*]. SCHEME 2 thus has the advantage of adherence to the dominant-cation principle, and also simplicity.

On the other hand, richterite, root composition $Na (CaNa) Mg_5 Si_8 O_{22} (OH)_2$, is an end-member amphibole in composition space (see Fig. 1). From a geochemical perspective, this needs to be recognized, as richterite will have specific thermodynamic properties that are necessary to quantitatively describe the behavior of amphibole compositions as a function of pressure and temperature. Furthermore, sodium–calcium amphiboles can occur in very specific parageneses (*e.g.*, richterite in lamproite), and substituting the name of a sodium–calcium amphibole by that of a calcium amphibole and a sodium amphibole (where compositions span the composition $B = Na_{1.0}Ca_{1.0}$) may be regarded as undesirable by the petrological community.

(2) *Retention versus removal of intermediate amphibole compositions*

SCHEME 2 seeks to minimize the number of root names, and does so by following the dominant-cation principle. Thus the composition $\square\ Ca_2 (Mg_4 Al) (Si_7 Al) O_{22} (OH)_2$, corresponding to magnesio-hornblende in SCHEME 1, is the boundary composition between tremolite, $\square\ Ca_2 Mg_5 Si_8 O_{22} (OH)_2$, and tschermakite, $\square\ Ca_2 (Mg_3 Al_2) (Si_6 Al_2) O_{22} (OH)_2$ in SCHEME 2. Similarly, the composition $Na Ca_2 (Mg_4 Al) (Si_6 Al_2) O_{22} (OH)_2$, corresponding to pargasite in SCHEME 1, is the boundary composition between tremolite, $\square\ Ca_2 Mg_5 Si_8 O_{22} (OH)_2$, and sadanagaite, $Na Ca_2 (Mg_3 Al_2) (Si_5 Al_3) O_{22} (OH)_2$, in SCHEME 2. On the one hand, this produces a major simplification in terms of the number of root compositions and names. On the other hand, some of these names are in common use in both Mineralogy and Petrology, and their removal may be regarded by many as detrimental to issues of amphibole paragenesis in Petrology.

SUMMARY

We have discussed many issues pertaining to the classification of amphiboles, and we have developed two new schemes of classification. We emphasize that we are not proposing that either of these two schemes be adopted at the moment, or used without due IMA process. Our intentions are as follows:

- to outline the problems associated with any classification of the amphiboles,
- to suggest a different approach to amphibole classification based on the *dominant cation* (or *group of cations*) rather than on a specific number of cation(s), as was done in previous classifications,
- to propose that any future classification be based on chemical variations of the *A*, *B* and *C* groups of the amphibole general formula, rather than the *A*, *B* and *T* groups, as was done in previous classifications,
- to examine issues of simplification *versus* the *status quo* in terms of root compositions and root names.

We emphasize that any classification scheme, particularly one involving a group of minerals as complicated as the amphiboles, is of necessity a compromise: simplicity will often conflict with convenience of use. Moreover, crystallographers, mineralogists and petrologists will generally have different expectations of a classification. Crystallographers will want a classification that encompasses all aspects of the crystal chemistry of the amphiboles in as concise a way as possible, whereas petrologists will be more concerned with the utility and convenience of use from a petrological perspective. The most satisfactory classification will emerge only when all constituents of the community interested in amphiboles recognize the concerns of each other and are sympathetic to their incorporation into a final scheme of classification.

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APPENDIX I: THE AMPHIBOLE STRUCTURE, SITES, AND GROUPS

The general formula for amphiboles may be written as

$$A\ B_2\ C_5\ T_8\ O_{22}\ W_2$$

where A = □, Na, K, Ca, Pb^{2+}; B = Li, Na, Mg, Fe^{2+}, Mn^{2+}, Ca; C = Li, Mg, Fe^{2+}, Mn^{2+}, Zn, Co, Ni, Al, Fe^{3+}, Cr^{3+}, Mn^{3+}, V^{3+}, Ti^{4+}, Zr; T = Si, Al, Ti^{4+}; W = (OH), F, Cl, O^{2-}. The *A, B, C*, *T* and *W* groups of this formula correspond to specific sites or groups of sites in the amphibole structure. Here, we will refer to the *C*2/*m* structure, but the site nomenclature of the other amphibole structures is similar. It should be straightforward to correlate the correspondences given below with any other type of amphibole structure. The *C*2/*m* amphibole structure is shown in Figure A1; this figure may be used to locate in the amphibole structure the sites mentioned below.

A group	*A* site
B group	*M*(4) site
C group	*M*(1), *M*(2), *M*(3) sites
T group	*T*(1), *T*(2) sites
W group	O(3) site

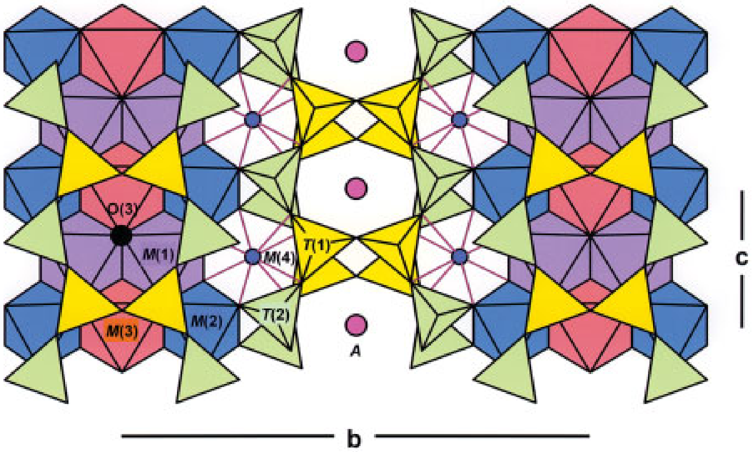

FIG. A1. The structure of *C*2/*m* amphibole projected onto (001); *T*-group polyhedra are shaded yellow, *T*(1), and green, *T*(2); *C*-group polyhedra are shaded mauve, *M*(1), blue, *M*(2), and orange, *M*(3); the *B*-group site is shown by the blue circle, *M*(4); the *A*-group site is shown by the central pink circle, *A*.

APPENDIX II: REJECTED, REDEFINED AND RENAMED END-MEMBERS*

End-member formula**	LEAKE *et al.* (1997)	SCHEME 1	SCHEME 2
$Na\ Mg_2\ Mg_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Sodicanthophyllite	Rootname1	Rootname1
$Na\ Fe^{2+}{}_2\ Fe^{2+}{}_5\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Sodic-ferro-anthophyllite	Ferro-rootname1	Ferro-rootname1
$Na\ Mg_2\ (Mg_4\ Al)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Sodicgedrite	-------	-------
$Na\ Mg_2\ (Mg_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	-------	Rootname2	Rootname2
$Na\ Fe^{2+}{}_2\ (Fe^{2+}{}_3Al_2)\ (Si_5Al_3)\ O_{22}\ (OH)_2$	-------	Sodic-ferro-gedrite	Sodic-ferro-gedrite
☐ $Fe^{2+}{}_2\ Fe^{2+}{}_5\ Si_8\ O_{22}\ (OH)_2$	Grunerite	Grunerite	Ferro-cummingtonite
☐ $Mn^{2+}{}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Manganocummingtonite	Rootname3	Rootname3
☐ $Mn^{2+}{}_2\ Fe^{2+}{}_5\ Si_8\ O_{22}\ (OH)_2$	Manganogrunerite	Ferro-rootname3	Ferro-rootname3
☐ $Mn^{2+}{}_2\ (Mn^{2+}{}_2\ Mg_3)\ Si_8\ O_{22}\ (OH)_2$	Permanganocummingtonite	-------	-------
☐ $Mn^{2+}{}_2\ (Mn^{2+}{}_2\ Fe^{2+}{}_3)\ Si_8\ O_{22}\ (OH)_2$	Permanganogrunerite	-------	-------
☐ $Mn^{2+}{}_2\ Mn^{2+}{}_5\ Si_8\ O_{22}\ (OH)_2$	-------	Mangano-rootname3	Mangano-rootname3
☐ $Ca_2\ Fe^{2+}{}_5\ Si_8\ O_{22}\ (OH)_2$	Ferro-actinolite	Actinolite	Ferro-tremolite
☐ $Ca_2\ [Mg_4\ (Al,Fe^{3+})]\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Magnesiohornblende	-------	-------
☐ $Ca_2\ (Mg_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Magnesio-hornblende	-------
☐ $Ca_2\ [Fe^{2+}{}_4\ (Al,Fe^{3+})]\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferrohornblende	-------	-------
☐ $Ca_2\ (Mg_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Ferri-hornblende	-------
☐ $Ca_2\ (Fe^{2+}{}_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Ferro-hornblende	-------
☐ $Ca_2\ (Fe^{2+}{}_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Ferro-ferri-hornblende	-------
☐ $Ca_2\ [Mg_3\ Al\ Fe^{3+}]\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Tschermakite	-------	-------
☐ $Ca_2\ (Mg_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Aluminotschermakite	Tschermakite	Tschermakite
☐ $Ca_2\ [Mg_3\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferritschermakite	Ferri-tschermakite	Ferri-tschermakite
☐ $Ca_2\ [Fe^{2+}{}_3\ Al\ Fe^{3+}]\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferrotschermakite	-------	-------
☐ $Ca_2\ (Fe^{2+}{}_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Alumino-ferrotschermakite	Ferro-tschermakite	Ferro-tschermakite
☐ $Ca_2\ (Fe^{2+}{}_3\ Fe^{3+}{}_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferri-ferrotschermakite	Ferro-ferri-tschermakite	Ferro-ferri-tschermakite
$Na\ Ca_2\ (Mg_4\ Al)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Pargasite	Pargasite	-------
$Na\ Ca_2\ (Fe^{2+}{}_4\ Al)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferropargasite	Ferro-pargasite	-------
$Na\ Ca_2\ (Mg_4\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Magnesiohastingsite	Magnesio-hastingsite	-------
$Na\ Ca_2\ (Fe^{2+}{}_4\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Hastingsite	Hastingsite	-------
$Na\ Ca_2\ [Mg_3\ (Fe^{3+},Al)_2]\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Magnesiosadanagaite	-------	-------
$Na\ Ca_2\ [Fe^{2+}{}_3\ (Fe^{3+},Al)_2]\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	Ferrosadanagaite	-------	-------
$Na\ Ca_2\ (Mg_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	-------	Magnesio-alumino-sadanagaite	Sadanagaite
$Na\ Ca_2\ (Fe^{2+}{}_3\ Al_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	-------	Alumino-sadanagaite	Ferro-sadanagaite
$Na\ Ca_2\ (Mg_3\ Fe^{3+}{}_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	-------	Magnesio-sadanagaite	Ferri-sadanagaite
$Na\ Ca_2\ (Fe^{2+}{}_3\ Fe^{3+}{}_2)\ (Si_5\ Al_3)\ O_{22}\ (OH)_2$	-------	Sadanagaite	Ferro-ferri-sadanagaite
☐ $Ca\ Na\ [Mg_4\ (Al,Fe^{3+})]\ Si_8\ O_{22}\ (OH)_2$	Winchite	-------	-------
☐ $Ca\ Na\ [Fe^{2+}{}_4\ (Al,Fe^{3+})]\ Si_8\ O_{22}\ (OH)_2$	Ferrowinchite	-------	-------
☐ $Ca\ Na\ (Mg_4\ Al)\ Si_8\ O_{22}\ (OH)_2$	-------	Winchite	-------
☐ $Ca\ Na\ (Mg_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	-------	Ferri-winchite	-------
☐ $Ca\ Na\ (Fe^{2+}{}_4\ Al)\ Si_8\ O_{22}\ (OH)_2$	-------	Ferro-winchite	-------
☐ $Ca\ Na\ (Fe^{2+}{}_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	-------	Ferro-ferri-winchite	-------
☐ $Ca\ Na\ (Mg_3\ Al\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Barroisite	-------	-------
☐ $Ca\ Na\ (Fe^{2+}{}_3\ Al\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferrobarroisite	-------	-------
☐ $Ca\ Na\ (Mg_3\ Al_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Aluminobarroisite	Barroisite	-------
☐ $Ca\ Na\ (Mg_3\ Fe^{3+}{}_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferribarroisite	Ferri-barroisite	-------
☐ $Ca\ Na\ (Fe^{2+}{}_3\ Al_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Alumino-ferrobarroisite	Ferro-barroisite	-------
☐ $Ca\ Na\ (Fe^{2+}{}_3\ Fe^{3+}{}_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Ferri-ferrobarroisite	Ferro-ferri-barroisite	-------
$Na\ Ca\ Na\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	Richterite	Richterite	-------
☐ $Ca\ Na\ Fe^{2+}{}_5\ Si_8\ O_{22}\ (OH)_2$	Ferrorichterite	Ferro-richterite	-------
$Na\ Ca\ Na\ [Mg_4\ (Al,Fe^{3+})]\ (Si_7\ Al)\ O_{22}\ (OH)_2$	Magnesiokatophorite	-------	-------
$Na\ Ca\ Na\ [Fe^{2+}{}_4\ (Al,Fe^{3+})]\ (Si_7\ Al)O_{22}(OH)_2$	Katophorite	-------	-------
$Na\ Ca\ Na\ (Mg_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Magnesio-katophorite	-------
$Na\ Ca\ Na\ (Mg_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Magnesio-ferri-katophorite	-------
$Na\ Ca\ Na\ (Fe^{2+}{}_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Katophorite	-------
$Na\ Ca\ Na\ (Fe^{2+}{}_4\ Fe^{3+})\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Ferri-katophorite	-------

APPENDIX II: REJECTED, REDEFINED AND RENAMED END-MEMBERS*

End-member formula**	LEAKE *et al.* (1997)	SCHEME 1	SCHEME 2
$Na\ Ca\ Na\ (Mg_3\ Al\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Magnesiotaramite	-------	-------
$Na\ Ca\ Na\ (Fe^{2+}_3\ Al\ Fe^{3+})\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Taramite	-------	-------
$Na\ Ca\ Na\ (Mg_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Alumino-magnesiotaramite	Magnesio-taramite	-------
$Na\ Ca\ Na\ (Mg_3\ Fe^{3+}_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferri-magnesiotaramite	Magnesio-ferri-taramite	-------
$Na\ Ca\ Na\ (Fe^{2+}_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Aluminotaramite	Alumino-taramite	-------
$Na\ Ca\ Na\ (Fe^{2+}_3\ Fe^{3+}_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	Ferritaramite	Ferri-taramite	-------
All other sodium–calcium amphiboles are the same as in Leake *et al.* (1997) and SCHEME 1.			
$Na\ Na_2\ (Mg_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	-------	Alumino-leakeite	Leakeite
$Na\ Na_2\ (Fe^{2+}_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	-------	Ferro-alumino-leakeite	Ferro-leakeite
$Na\ Na_2\ (Mg_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Leakeite	Leakeite	Ferri-leakeite
$Na\ Na_2\ (Fe^{2+}_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Ferroleakeite	Ferro-leakeite	Ferro-ferri-leakeite
$Na\ Na_2\ (Mg_2\ Mn^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Kornite	Kornite	Mangani-leakeite
$Na\ Na_2\ (Mg_3\ Fe^{3+}_2)\ Si_7\ Al\ O_{22}\ (OH)_2$	Ferric-nyböite	Ferri-nyböite	Ferri-nyböite
$Na\ Na_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_7\ Al\ O_{22}\ (OH)_2$	Ferric-ferronyböite	Ferro-ferri-nyböite	Ferro-ferri-nyböite
☐ $Na_2\ (Mg_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Magnesioriebeckite	Magnesio-riebeckite	Ferri-glaucophane
$Na\ Na_2\ (Mg_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Magnesio-arfvedsonite	Magnesio-arfvedsonite	Ferri-eckermannite
☐ $Na_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Riebeckite	Riebeckite	Ferro-ferri-glaucophane
$Na\ Na_2\ (Fe^{2+}_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Arfvedsonite	Arfvedsonite	Ferro-ferri-eckermannite
$Na\ Na_2\ (Mn^{2+}_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Kozulite	Kozulite	Mangano-ferri-eckermannite
☐ $Li_2\ (Fe^{2+}_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Ferroholmquistite	Ferro-holmquistite	Ferro-holmquistite
☐ $Li_2\ (Mg_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Ferriholmquistite	Ferri-holmquistite	Ferri-holmquistite
☐ $Li_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Ferri-ferroholmquistite	Ferro-ferri-holmquistite	Ferro-ferri-holmquistite
☐ $Li_2\ (Mg_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Clinoholmquistite	Clino-holmquistite	Clino-holmquistite
☐ $Li_2\ (Fe^{2+}_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferroholmquistite	Clino-ferro-holmquistite	Clino-ferro-holmquistite
☐ $Li_2\ (Mg_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferriholmquistite	Clino-ferri-holmquistite	Clino-ferri-holmquistite
☐ $Li_2\ (Fe^{2+}_3\ Fe^{3+}_2)\ Si_8\ O_{22}\ (OH)_2$	Clino-ferri-ferroholmquistite	Clino-ferro-ferri-holmquistite	Clino-ferro-ferri-holmquistite
$Na\ Li_2\ (Mg_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Sodicpedrizite	Pedrizite	Pedrizite
$Na\ Li_2\ (Fe^{2+}_2\ Al_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Sodic-ferropedrizite	Ferro-pedrizite	Ferro-pedrizite
$Na\ Li_2\ (Mg_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Sodic-ferripedrizite	Ferri-pedrizite	Ferri-pedrizite
$Na\ Li_2\ (Fe^{2+}_2\ Fe^{3+}_2\ Li)\ Si_8\ O_{22}\ (OH)_2$	Sodic-ferri-ferropedrizite	Ferro-ferri-pedrizite	Ferro-ferri-pedrizite
☐ $(Na\ Li)\ (Mg_3\ Al_2)\ Si_8\ O_{22}\ (OH)_2$	Ottoliniite	-------	-------
$Na\ (Na\ Li)\ (Mg_2\ Al_2Li)\ Si_8\ O_{22}\ (OH)_2$	Whittakerite	-------	-------
$Na\ (Na\ Mg)\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	-------	Rootname 4	-------
$Na\ (Na\ Mn^{2+})\ Mg_5\ Si_8\ O_{22}\ (OH)_2$	-------	Rootname 5	-------
$Na\ (Na\ Mg)\ (Mg_4\ Al)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Rootname 6	-------
$Na\ (Na\ Mg)\ (Mg_3\ Al_2)\ (Si_6\ Al_2)\ O_{22}\ (OH)_2$	-------	Rootname 7	-------
☐ $(Na\ Mg)\ (Mg_4\ Al)\ Si_8\ O_{22}\ (OH)_2$	-------	Rootname 8	-------
☐ $(Na\ Mg)\ (Mg_3\ Al_2)\ (Si_7\ Al)\ O_{22}\ (OH)_2$	-------	Rootname 9	-------
☐ $(Na\ Mn^{2+})\ (Mg_4\ Al)\ Si_8\ O_{22}\ (OH)_2$	-------	Rootname 10	-------
☐ $(Na\ Mn^{2+})\ (Mg_4\ Fe^{3+})\ Si_8\ O_{22}\ (OH)_2$	Parvowinchite	Ferri-rootname 10	-------
$Na\ Ca_2\ (Mg_4\ Ti^{4+})\ (Si_6\ Al_2)\ O_{22}\ (OH)\ O$	Kaersutite	-------	-------
$Na\ Ca_2\ (Mg_3\ Ti^{4+}\ Al)\ (Si_6\ Al_2)\ O_{22}\ O_2$	------	Kaersutite	Kaersutite
$Na\ Na_2\ (Mg_3\ Fe^{3+}\ Ti^{4+})\ Si_8\ O_{22}\ O_2$	Obertiite	Obertiite	Ferri-obertiite
$Na\ Na_2\ (Mg\ Mn^{3+}_2\ Ti^{4+}\ Li)\ Si_8\ O_{22}\ O_2$	Dellaventuraite	Dellaventuraite	Mangani-dellaventuraite
$Na\ Na_2\ (Mn^{2+}_2\ Mn^{3+}_3)\ Si_8\ O_{22}\ O_2$	Ungarettiite	Ungarettiite	Mangano-mangani-ungarettiite

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* This list specifically addresses end-member compositions; the ranges of composition of each *species* often differs from one scheme to another.

** All compositions listed below have names; however, these are not given *unless* the composition is defined as an end member in that particular scheme of nomenclature.