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Classification of the Amphiboles

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INTRODUCTION

Classification is always a highly contentious issue, particular when dealing with a group of minerals as structurally and chemically complicated as the amphiboles, and when trying to satisfy the needs and different scientific philosophies of crystallographers, mineralogists, petrologists and geochemists. As a result, the classification of the amphiboles has long been a *work in progress*. Leake (1968) provided a classification for calcic amphiboles, and this was expanded into the IMA (International Mineralogical Association) classification of Leake (1978). An IMA Subcommittee on Amphibole Classification was formed, and eleven years and approximately 1200 pages of memos later, Leake et al. (1997) reported on the current classification, as modified by Leake et al. (2003) to incorporate new discoveries in amphibole compositions in the intervening years. Here, we will (1) describe the current IMA-approved classification scheme, (2) discuss some shortcomings of the current scheme, and (3) discuss some of the features that may be considered as desirable in any new scheme of amphibole classification that may emerge in the future. We make no apology for dealing with these issues here; if the community who deals with amphiboles is to get the classification that it wants, that community has to be prepared to involve itself in the process of developing such a classification.

THE CURRENT CLASSIFICATION SCHEMES

The first thing to note is that the above title refers to classification schemes. There are two distinct classification schemes:

(1) Hand-specimen and thin-section classification;

(2) Classification by chemical formula.

Virtually all attention has focused on classification (2) and classification (1) seems to have escaped the attention of most critics of amphibole classification. Here, we will describe both schemes which are given by Leake et al. (1997, 2003).

HAND-SPECIMEN (FIELD) CLASSIFICATION OF AMPHIBOLES

To quote from Leake et al. (1997), “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 assign a precise name. The nearest assigned amphibole name should then be made

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into an adjective followed by the word *amphibole*. Thus, anthophyllitic amphibole, tremolitic amphibole, etc. The familiar word *hornblende* can still be used where appropriate for calcic amphiboles in both hand specimen and thin section, because hornblende is never used without an adjective in the (chemical) classification....".

Although the need for a hand-specimen (field) and thin-section classification is recognized, the scheme that is provided cannot be considered as adequate. First, identification of amphiboles in hand specimen and in thin section are two very different processes; polarized-light microscopy is capable of being far more discerning than recognition by the naked eye alone, and two classification schemes are more appropriate than one to deal with these two situations. Secondly, each classification will be precise, and the accuracy of the process depends on the expertise of the practitioner. Thus it is to be hoped that any new generation of amphibole classification will provide suitable classification schemes for amphiboles identified in hand specimen and thin section.

Asbestiform amphiboles should be named such that their asbestiform character is conveyed by their name. Where the type of amphibole is unknown, *asbestos* or *amphibole asbestos* is appropriate. Where the approximate nature of the amphibole is known, the name of the amphibole is turned into an adjective and used as a prefix to the word asbestos: *anthophyllitic asbestos, tremolitic asbestos*. Where the chemical composition of the amphibole is known, the exact name of the amphibole is used, followed by the suffix -asbestos: *anthophyllite-asbestos, tremolite-asbestos*.

AMPHIBOLE CLASSIFICATION BY CHEMICAL FORMULA

The production of a satisfactory classification of the amphiboles seems to be a process with a long gestation period. The first IMA 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. 2003). Hawthorne and Oberti (2006) considered the classification of amphiboles in general, and discussed many aspects of classification that impact on the establishment of a new classification scheme. Here, we will describe the current classification scheme (Leake et al. 1997, as modified by Leake et al. 2003), and then will discuss aspects of amphibole classification that will/should be considered in any new classification scheme that will be developed in the future.

Prefixes

The topic of prefixes and adjectival modifiers has generated much discussion since Leake et al. (1978) formalized their use for amphiboles. First, it must be noted that *the use of prefixes has nothing to do with the number of species*; the number of species is dictated (1) by the details of the classification criteria, and (2) by Nature herself; the issue here is what kind of names are preferable. There are two types of names that we may use: (1) each distinct species is a trivial name; (2) we may identify root names corresponding to distinct charge arrangements, and indicate homovalent variants by prefixes. The amphibole classifications of Leake (1978) and Leake et al. (1997) chose the second option and discarded 220 trivial names for amphiboles, and few would wish to return to a situation where there are several hundred trivial names for amphiboles. Thus we use root names plus indicators of homovalent variants. We prefer word prefixes to element suffixes, although recent classification schemes for other mineral groups have adopted multiple element suffixes. However, the complexity of the amphibole formula, combined with the variations in space group, may require an unwieldy concatenation of suffixes (see below for additional discussion). Prefixes defined by Leake et al. (1997, 2003) are listed in Table 1. Burke and Leake (2004) specified in which order prefixes (when more than one is used) must be attached to the root-name. Their sequence is proto-parvo (magno)-fluoro (chloro)-potassic (sodic)-

Table 1. Prefixes (from Leake et al. 1997, 2003).

Prefix	Meaning (apfu)	Applicable to
Alumino	$^{[6]}Al > 1.00$	Calcic and sodic-calcic groups only
Chloro	$Cl > 1.00$	All groups
Chromio	$Cr > 1.00$	All groups
Ferri	$Fe^{3+} > 1.00$	All groups except sodic
Ferric	$Fe^{3+} > 1.00$	Sodic amphiboles only
Fluoro	$F > 1.00$	All groups
Mangano	$1.00 < Mn^{2+} < 4.99$	All groups, except for kozulite and ungarettiite
Permangano	$3.00 < Mn^{2+} < 4.99$	All groups, except for kozulite
Mangani	$Mn^{3+} > 1.00$	All groups, except for kornite and ungarettiite
Magno	$^{B}Li \le 0.50$ $^{B}(Mg+Fe^{2+}+Mn+Li) > 1.00$	Na-Ca-Mg-Fe-Mn-Li group only
Parvo	$^{B}Li \le 0.50$ $^{B}(Ca+Na) > 1.00$	Na-Ca-Mg-Fe-Mn-Li group only
Potassic	$K > 0.50$	All groups
Sodic	$Na > 0.50$	Mg-Fe-Mn-Li group only
Titano	$Ti > 0.50$	All groups, except for kaersutite
Zinco	$Zn > 1.00$	All groups

ferri (alumino, mangani)-ferro(mangano, magnesio). In addition, the first prefix attached to the root name does not involve a hyphen (e.g., ferropargasite, ferritaramite) *unless* the conjunction of the two words involves two adjacent vowels (e.g., ferro-edenite instead of ferroedenite) or an inelegant combination of consonants (e.g., potassic-richterite instead of potassicrichterite).

Adjectival modifiers

Although their suggested ranges are specified, adjectival modifiers are *not* part of previous classifications of amphiboles (Leake 1978; Leake et al. 1997, 2003); 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 (International Mineralogical Association Commission on New Minerals and Mineral Names) 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.

THE CURRENT CLASSIFICATION SCHEME (LEAKE ET AL. 1997, 2003)

The general chemical formula of the amphiboles can be written as

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

where $A = Na, K, \square, Ca, Li$
$B = Na, Li, Ca, Mn^{2+}, Al, Fe^{3+}, Mn^{3+}, Ti^{4+}, Li;$
$T = Si, Al, Ti^{4+};$
$W = (OH), F, Cl, O^{2-}.$

Minor elements such as Zn, Ni^{2+}, Co^{2+}, V^{3+}, Sc, Cr^{3+} and Zr are also observed as C cations.

The primary classification of the amphiboles is on the basis of the identity and amounts of the B cations:

Group 1: ^{B}(Mg,Fe,Mn,Li) ≥ 1.5 apfu defines the *magnesium-iron-manganese-lithium group*.

Group 2: ^{B}(Mg,Fe,Mn,Li) ≤ 0.5, ^{B}(Ca,Na) ≥ 1.5 and ^{B}Na < 0.5 apfu defines the *calcic group*.

Group 3: ^{B}(Mg,Fe,Mn,Li) ≤ 0.5, ^{B}(Ca,Na) ≥ 1.5 and 0.50 < ^{B}Na < 1.5 apfu defines the *sodic-calcic group*.

Group 4: ^{B}(Mg,Fe,Mn,Li) ≤ 0.5 and ^{B}Na ≥ 1.5 apfu defines the *sodic group*.

Group 5: 0.5 < ^{B}(Mg,Fe,Mn,Li) < 1.5 and 0.5 ≤ ^{B}(Ca,Na) < 1.5 apfu defines the *sodium-calcium-magnesium-iron-manganese-lithium group*.

The magnesium-iron-manganese-lithium amphiboles

These amphiboles may be orthorhombic (*Pnma* or *Pnmn*) or monoclinic (*C*2/*m*, $P2_1/m$). The classification is shown graphically in Figure 1 and end-member compositions are listed in Table 2.

Orthorhombic amphiboles. The space group *Pnma* is assumed, the space group *Pnmn* is indicated by the prefix *proto*.

(1) The anthophyllite series has the general formula $Na_x\ Li_z\ (Mg,Fe^{2+},Mn^{2+})_{7-y-z}\ Al_y\ (Si_{8-x-y+z}Al_{x+y-z})\ O_{22}\ (OH,F,Cl)_2$ where Si > 7.00 apfu and Li < 1.00 apfu. This definition is not satisfactory as the end-member composition for sodicanthophyllite lies on the edge of the anthophyllite field (according to the above definition, it is actually excluded from the anthophyllite series). Note that the composition $Na\ Mg_7\ (Si_7Al)\ O_{22}\ (OH)_2$ corresponds to that of end-member sodicanthophyllite, whereas the composition $Na\ (Mg_{6.9}Al_{0.1})\ (Si_{6.9}Al_{1.1})\ O_{22}\ (OH)_2$ lies in the compositional field of gedrite.

(2) The gedrite series has the general formula $Na_x\ Li_z\ (Mg,Fe^{2+},Mn^{2+})_{7-y-z}\ Al_y\ (Si_{8-x-y+z}\ Al_{x+y-z})\ O_{22}\ (OH,F,Cl)_2$ where $(x + y - z) \geq 1.00$ apfu (and hence Si < 7.00 apfu) and Li < 1.00 apfu.

(3) The holmquistite series has the general formula $\square\ Li_2\ (Mg,Fe^{2+})_3\ (Al,Fe^{3+})_2\ Si_8\ O_{22}\ (OH,F,Cl)_2$ with Li ≥ 1.00 apfu.

Monoclinic amphiboles. Most members of the cummingtonite-grunerite series have the space group *C*2/*m*; those with the space group $P2_1/m$ may optionally have this symbol added as a suffix at the end of the name.

(1) The cummingtonite-grunerite series has the general formula $\square\ (Mg,Fe^{2+},Mn^{2+},Li)_7\ Si_8\ O_{22}\ (OH,F,Cl)_2$ where Li < 1.00 apfu.

(2) The clinoholmquistite series has the general formula $\square\ Li_2\ (Mg,Fe^{2+})_3\ (Al,Fe^{3+})_2\ Si_8\ O_{22}\ (OH,F,Cl)_2$ with Li ≥ 1.00 apfu.

The calcic amphiboles

The classification is shown graphically in Figure 2 and end-member compositions are listed in Table 3.

The sodic-calcic amphiboles

The classification is shown graphically in Figure 3 and end-member compositions are listed in Table 4.

Table 2. End-member compositions for Mg-Fe-Mn-Li amphiboles (Leake et al. 1997, 2003).

Orthorhombic	
Anthophyllite	$\square Mg_7Si_8O_{22}(OH)_2$
Ferro-anthophyllite	$\square Fe^{2+}{}_7Si_8O_{22}(OH)_2$
Sodic-anthophyllite	$NaMg_7Si_7AlO_{22}(OH)_2$
Sodic-ferro-anthophyllite	$NaFe^{2+}{}_7Si_7AlO_{22}(OH)_2$
Gedrite	$\square Mg_5Al_2Si_6Al_2O_{22}(OH)_2$
Ferrogedrite	$\square Fe^{2+}{}_5Al_2Si_6Al_2O_{22}(OH)_2$
Sodicgedrite	$NaMg_6AlSi_6Al_2O_{22}(OH)_2$
Sodic-ferrogedrite	$NaFe^{2+}{}_6AlSi_6Al_2O_{22}(OH)_2$
Holmquistite	$\square (Li_2Mg_3Al_2)Si_8O_{22}(OH)_2$
Ferroholmquistite	$\square (Li_2Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$
Monoclinic	
Cummingtonite	$\square Mg_7Si_8O_{22}(OH)_2$
Grunerite	$\square Fe^{2+}{}_7Si_8O_{22}(OH)_2$
Manganocummingtonite	$\square Mn_2Mg_5Si_8O_{22}(OH)_2$
Manganogrunerite	$\square Mn_2Fe^{2+}{}_5Si_8O_{22}(OH)_2$
Permanganogrunerite	$\square Mn_4Fe^{2+}{}_3Si_8O_{22}(OH)_2$
Manganogrunerite	$\square Mn_2Fe^{2+}{}_5Si_8O_{22}(OH)_2$
Clinoholmquistite	$\square (Li_2Mg_3Al_2)Si_8O_{22}(OH)_2$
Clinoferroholmquistite	$\square (Li_2Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$
Clino-ferriholmquistite	$\square (Li_2Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$
Clino-ferri-ferroholmquistite	$\square (Li_2Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$
"Sodicpedrizite"	$NaLi_2(Mg_2Al_2Li)Si_8O_{22}(OH)_2$
Sodic-ferripedrizite	$NaLi_2(Mg_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$
Sodic-ferri-ferropedrizite	$NaLi_2(Fe^{2+}{}_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$

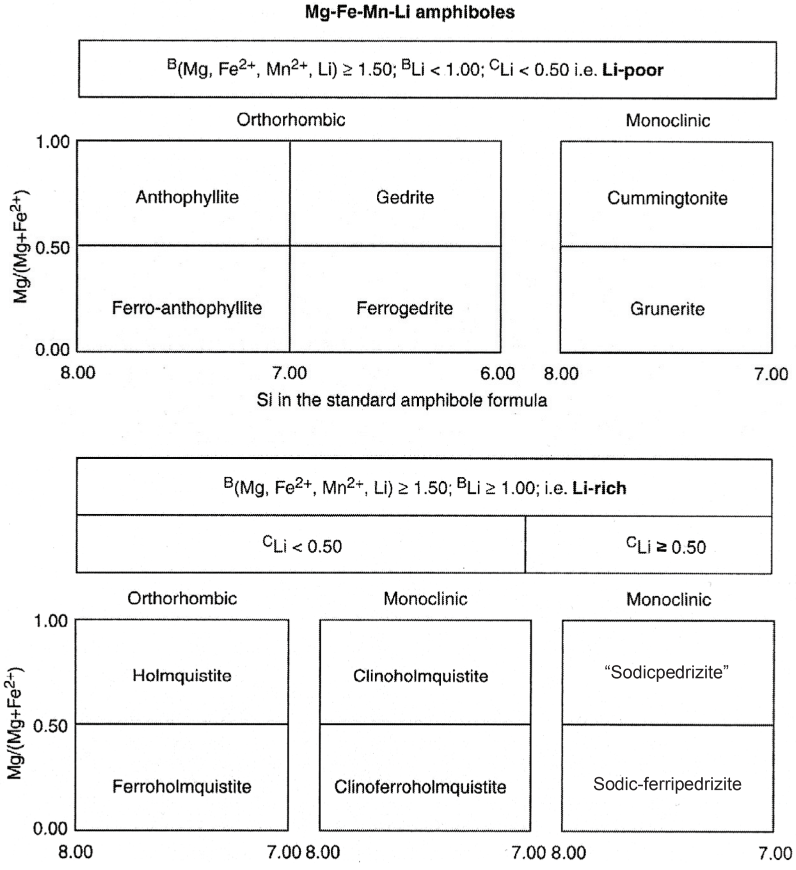

Figure 1. Classification of the magnesium-iron-manganese-lithium amphiboles; amounts of atoms are expressed in apfu (modified from Leake et al. 2003).

Table 3. End-member compositions for Ca amphiboles (Leake et al. 1997, 2003).

Tremolite	□ $Ca_2Mg_5Si_8O_{22}(OH)_2$
Ferro-actinolite	□ $Ca_2Fe^{2+}{}_5Si_8O_{22}(OH)_2$
Magnesiohornblende	□ $Ca_2[Mg_4(Al,Fe^{3+})]Si_7AlO_{22}(OH)_2$
Ferrohornblende	□ $Ca_2[Fe^{2+}{}_4(Al,Fe^{3+})]Si_7AlO_{22}(OH)_2$
Tschermakite	□ $Ca_2(Mg_3AlFe^{3+})Si_6Al_2O_{22}(OH)_2$
Ferrotschermakite	□ $Ca_2(Fe^{2+}{}_3AlFe^{3+})Si_6Al_2O_{22}(OH)_2$
Aluminotschermakite	□ $Ca_2(Mg_3Al_2)Si_6Al_2O_{22}(OH)_2$
Alumino-ferrotschermakite	□ $Ca_2(Fe^{2+}{}_3Al_2)Si_6Al_2O_{22}(OH)_2$
Ferritschermakite	□ $Ca_2(Mg_3Fe^{3+}{}_2)Si_6Al_2O_{22}(OH)_2$
Ferri-ferrotschermakite	□ $Ca_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_6Al_2O_{22}(OH)_2$
Edenite	$NaCa_2Mg_5Si_7AlO_{22}(OH)_2$
Ferro-edenite	$NaCa_2Fe^{2+}{}_5Si_7AlO_{22}(OH)_2$
Pargasite	$NaCa_2(Mg_4Al)Si_6Al_2O_{22}(OH)_2$
Ferropargasite	$NaCa_2(Fe^{2+}{}_4Al)Si_6Al_2O_{22}(OH)_2$
Magnesiohastingsite	$NaCa_2(Mg_4Fe^{3+})Si_6Al_2O_{22}(OH)_2$
Hastingsite	$NaCa_2(Fe^{2+}{}_4Fe^{3+})Si_6Al_2O_{22}(OH)_2$
Magnesiosadanagaite	$NaCa_2[Mg_3(Fe^{3+},Al)_2]Si_5Al_3O_{22}(OH)_2$
Sadanagaite	$NaCa_2[Fe^{2+}{}_3(Fe^{3+},Al)_2]Si_5Al_3O_{22}(OH)_2$
Kaersutite	$NaCa_2(Mg_4Ti)Si_6Al_2O_{23}(OH)$
Ferrokaersutite	$NaCa_2(Fe^{2+}{}_4Ti)Si_6Al_2O_{23}(OH)$
Cannilloite	$CaCa_2(Mg_4Al)Si_5Al_2O_{22}(OH)_2$

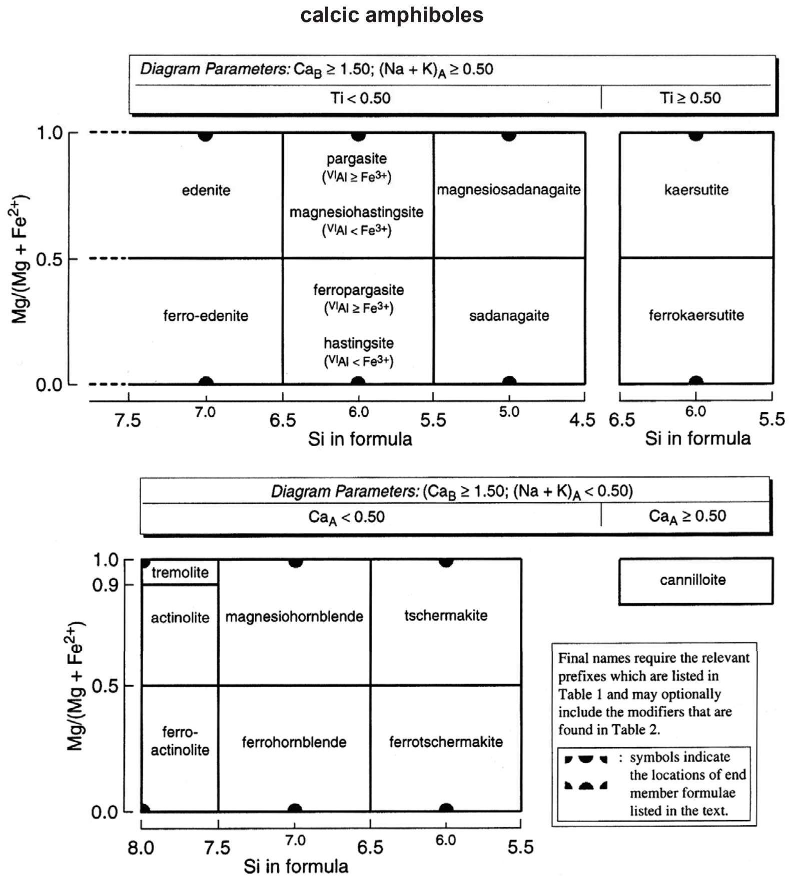

Figure 2. Classification of the calcic amphiboles; amounts of atoms are expressed in apfu (from Leake et al. 1997).

Table 4. End-member compositions for Ca-Na amphiboles (Leake et al. 1997, 2003).

Richterite	$Na(CaNa)Mg_5Si_8O_{22}(OH)_2$
Ferrorichterite	$Na(CaNa)Fe^{2+}{}_5Si_8O_{22}(OH)_2$
Winchite	$\square(CaNa)Mg_4(Al,Fe^{3+})Si_8O_{22}(OH)_2$
Ferrowinchite	$\square(CaNa)Fe^{2+}{}_4(Al,Fe^{3+})Si_8O_{22}(OH)_2$
Barroisite	$\square(CaNa)Mg_3AlFe^{3+}Si_7AlO_{22}(OH)_2$
Ferrobarroisite	$\square(CaNa)Fe^{2+}{}_3AlFe^{3+}Si_7AlO_{22}(OH)_2$
Aluminobarroisite	$\square(CaNa)Mg_3Al_2Si_7AlO_{22}(OH)_2$
Alumino-ferrobarroisite	$\square(CaNa)Fe^{2+}{}_3Al_2Si_7AlO_{22}(OH)_2$
Ferribarroisite	$\square(CaNa)Mg_3Fe^{3+}{}_2Si_7AlO_{22}(OH)_2$
Ferri-ferrobarroisite	$\square(CaNa)Fe^{2+}{}_3Fe^{3+}{}_2Si_7AlO_{22}(OH)_2$
Magnesiokatophorite	$Na(CaNa)Mg_4(Al,Fe^{3+})Si_7AlO_{22}(OH)_2$
Katophorite	$Na(CaNa)Fe^{2+}{}_4(Al,Fe^{3+})Si_7AlO_{22}(OH)_2$
Magnesiotaramite	$Na(CaNa)Mg_3AlFe^{3+}Si_6Al_2O_{22}(OH)$
Taramite	$Na(CaNa)Fe^{2+}{}_3AlFe^{3+}Si_6Al_2O_{22}(OH)$
Alumino-magnesiotaramite	$Na(CaNa)Mg_3Al_2Si_6Al_2O_{22}(OH)_2$
Aluminotaramite	$Na(CaNa)Fe^{2+}{}_3Al_2Si_6Al_2O_{22}(OH)_2$
Ferri-magnesiotaramite	$Na(CaNa)Mg_3Fe^{3+}{}_2Si_6Al_2O_{22}(OH)_2$
Ferritaramite	$Na(CaNa)Fe^{2+}{}_3Fe^{3+}{}_2Si_6Al_2O_{22}(OH)_2$

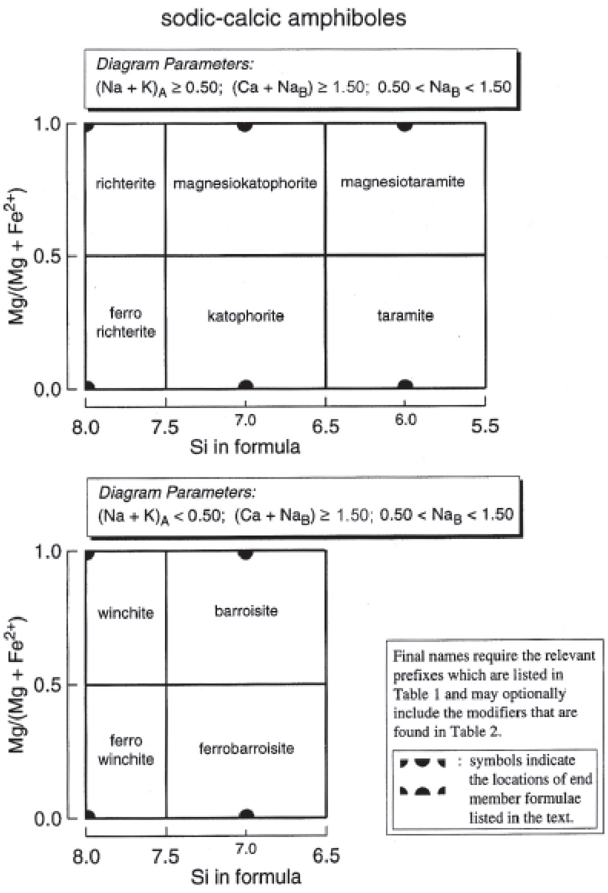

Figure 3. Classification of the sodic-calcic amphiboles; amounts of atoms are expressed in apfu (modified from Leake et al. 1997).

The sodic amphiboles

The classification is shown graphically in Figure 4 and end-member compositions are listed in Table 5.

Table 5. End-member compositions for Na amphiboles (Leake et al. 1997).

Glaucophane	□ $Na_2(Mg_3Al_2)Si_8O_{22}(OH)_2$
Ferroglaucophane	□ $Na_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$
Magnesioriebeckite	□ $Na_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$
Riebeckite	□ $Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$
Eckermannite	$NaNa_2(Mg_4Al)Si_8O_{22}(OH)_2$
Ferro-eckermannite	$NaNa_2(Fe^{2+}{}_4Al)Si_8O_{22}(OH)_2$
Magnesio-arfvedsonite	$NaNa_2(Mg_4Fe^{3+})Si_8O_{22}(OH)_2$
Arfvedsonite	$NaNa_2(Fe^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$
Kozulite	$NaNa_2Mn^{2+}{}_4(Fe^{3+},Al)Si_8O_{22}(OH)_2$
Nyböite	$NaNa_2(Mg_3Al_2)Si_7AlO_{22}(OH)_2$
Ferronyböite	$NaNa_2(Fe^{2+}{}_3Al_2)Si_7AlO_{22}(OH)_2$
Ferric-nyböite	$NaNa_2(Mg_3Fe^{3+}{}_2)Si_7AlO_{22}(OH)_2$
Ferric-ferronyböite	$NaNa_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_7AlO_{22}(OH)_2$
Leakeite	$NaNa_2(Mg_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$
Ferroleakeite	$NaNa_2(Fe^{2+}{}_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$
Kornite*	$KNa_2(Mg_2Mn^{3+}{}_2Li)Si_8O_{22}(OH)_2$
Ungarettiite	$NaNa_2(Mn^{2+}{}_2Mn^{3+}{}_2)Si_8O_{22}O_2$

*Although Leake et al. (1997) write the formula of kornite as (Na, K) $Na_2(Mg_2Mn^{3+}{}_2Li)Si_8O_{22}(OH)_2$, the original chemical composition reported by Armbruster et al. (1993) gives K as the dominant A cation.

The sodium-calcium-magnesium-iron-manganese-lithium amphiboles

The classification is shown graphically in Figure 5 and end-member compositions are listed in Table 6. As a general criterion, a root name is attributed where $^{B}Li > 0.50$ apfu; where $^{B}Li \leq 0.50$ apfu, the root name for the dominant B cations (large: Ca, Na; or small: Mg, Fe, Mn) is adopted, and the prefix "parvo-" or "magno-" is used to indicate the presence of a smaller or larger constituent, respectively.

Named amphiboles

The IMA-CNMMN introduced a new category of amphibole: *named amphiboles* (Burke and Leake 2004). These are names that are in accord with the current IMA-approved nomenclature scheme but have not been formally approved as accredited mineral species by the IMA-CNMMN. The use of these names is thus allowed, but a formal description for official recognition is still requested.

SIGNIFICANT ISSUES INVOLVED IN THE CLASSIFICATION OF AMPHIBOLES

The above classification has generated a lot of critical discussion in the community. Having been involved in the development of the current classification, we (the authors) are (hopefully) aware of all the issues, the most difficult of which is the balancing of diametrically opposed opinions by different sectors of the community involved in work on amphiboles. In addition,

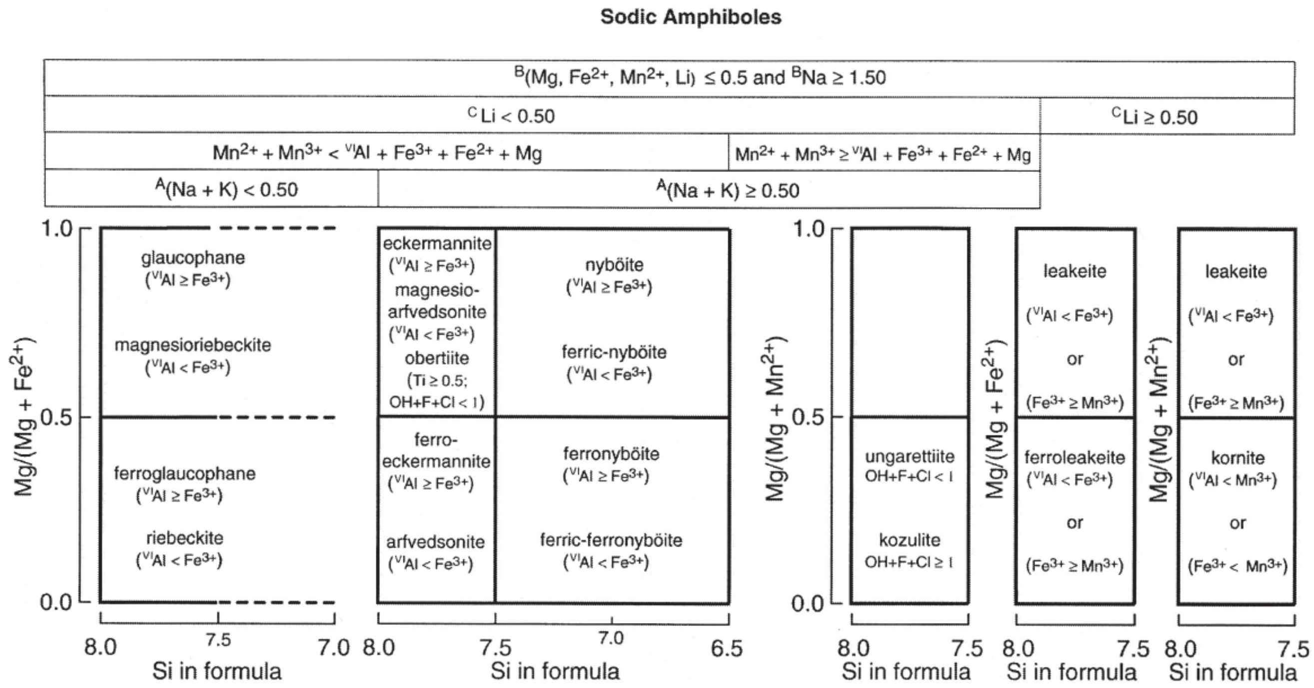

Figure 4. Classification of the sodic amphiboles; amounts of atoms are expressed in apfu (modified from Leake et al. 2003).

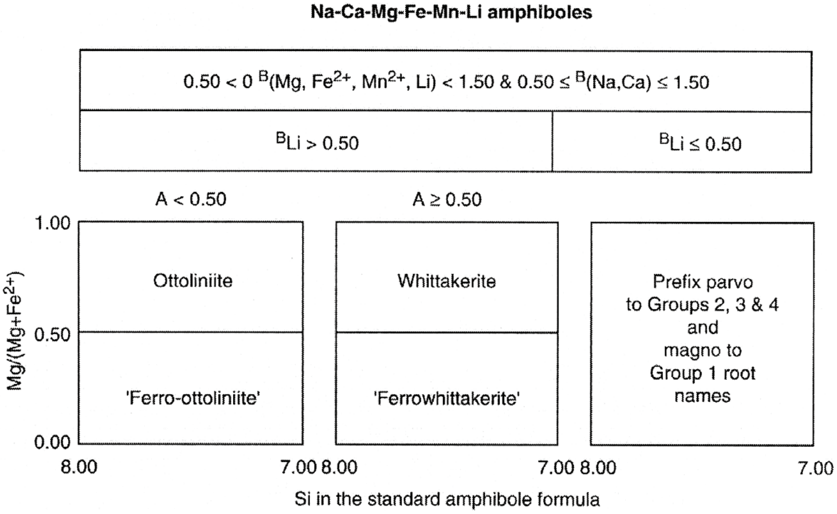

Figure 5. Classification of the sodic-calcic-magnesium-iron-manganese-lithium amphiboles; amounts of atoms are expressed in apfu (from Leake et al. 2003).

Table 6. End-member compositions for Na-Ca-Mg-Fe-Mn-Li amphiboles (Leake et al. 2003).

Ottoliniite	$\square$ (Na Li) (Mg$_3$ Fe^{3+} Al) Si$_8$ O$_{22}$ (OH)$_2$
Ferro-ottoliniite	$\square$ (Na Li) (Fe$^{2+}{}_3$ Fe^{3+} Al) Si$_8$ O$_{22}$ (OH)$_2$
Ferri-ottoliniite	$\square$ (Na Li) (Fe$^{2+}{}_3$ Fe$^{3+}{}_2$) Si$_8$ O$_{22}$ (OH)$_2$
Whittakerite	Na (Na Li) (Li Mg$_2$ Fe^{3+} Al) Si$_8$ O$_{22}$ (OH)$_2$
Ferrowhittakerite	Na (Na Li) (Li Fe$^{2+}{}_2$ Fe^{3+} Al) Si$_8$ O$_{22}$ (OH)$_2$
Ferriwhittakerite	Na (Na Li) (Li Fe$^{2+}{}_2$ Fe$^{3+}{}_2$) Si$_8$ O$_{22}$ (OH)$_2$

new analytical techniques have become available and/or more widely available, allowing better chemical characterization of amphiboles than was possible 20 years ago, when the development of the current classification scheme began. Also, the IMA-CNMMN has adopted new principles involving the definition of new mineral species, and the current amphibole classification is not compatible with these principles. As a result of this, Hawthorne and Oberti (2006) considered the general problem of amphibole classification, taking into account (1) new analytical techniques, (2) the discovery of extensive ^{B}(Na,Li) solid-solution, (3) the recently clarified major complexity of the crystal-chemistry and ordering of the C cations, and (4) the principle that minerals are defined by *the dominant cation or anion at a site*, rather than the specific amount of a cation or anion in the formula of the mineral. They presented two distinct classification schemes *in order to illustrate the problems associated with amphibole classification*. These issues will now be considered here in the hope that the problems inherent in amphibole classification will be better understood. In particular, it must be realized that all communities (crystallographers, mineralogists, petrologists, geochemists) must relax their requirements in order for a consensus to emerge with regard to amphibole classification.

The role of Fe, (OH) and Li

Prior to the development of the electron microprobe, all major and minor constituents in amphiboles were analyzed 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, making 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-dehydrogenation (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.

All previous amphibole classifications have obscured this issue by not incorporating C 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 for the analysis 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 structure refinement 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; EELS (Electron Energy-Loss Spectroscopy) can measure $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ at a scale of ≥ 1 μm, and milli-Mössbauer spectroscopy can measure $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ at a scale of ≥ 50 μm. For "big-laboratory" instrumentation, usually involving a synchrotron light-source, single-crystal refinement of the structure can characterize Li, Fe^{2+} and Fe^{3+} at a scale of ≥ 2 μm, and milli-XPS (X-ray Photoelectron Spectroscopy) 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 (as H_2O) content. 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 cations (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 chemistry 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]. Previous classifications have 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 vs. Fe^{2+}) or anions (e.g., OH vs. F) are indicated by prefixes. The expression "a distinct arrangement of formal charges" was not defined in previous classifications. Moreover, the 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 $B_2 = M^{2+}{}_2$ in both these groups. The definition that only distinct arrangements of formal charges for each amphibole group warrant distinct root names applies only to the A, B and T cations in the 1978 and 1997 classifications, and it applies only to the A, B and C 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 present two possible classification schemes. In SCHEME 1 [which includes the sodic-calcic 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 sodic-calcic 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, glaucophane. However, (1) some amphiboles were originally described as the ferro- and/or ferri- equivalent of the Mg-Al-containing species, and (2) some amphiboles are defined without specifying the dominant trivalent cation [e.g., winchite = $\square$ (CaNa) $Mg_4\ (AlFe^{3+})\ Si_8\ O_{22}\ (OH)_2$]. We may define all root names as referring to the Mg-Al-dominant compositions; thus, for example, leakeite, currently Na $Na_2\ (Mg_2Fe^{3+}{}_2Li)\ Si_8\ O_{22}\ (OH)_2$, becomes Na $Na_2\ (Mg_2Al_2Li)\ Si_8\ O_{22}\ (OH)_2$, and winchite becomes $\square$ (CaNa) $(Mg_4Al)\ Si_8\ O_{22}\ (OH)_2$. 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 has not been strictly adhered to in previous classifications. There are several problems involved in the strict application of this criterion: (1) this criterion 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 Geochemistry, 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, despite the fact that it does not have a dominant B cation.

In order to expose the problems inherent in the often conflicting goals of simplicity and conservatism, we will develop two different classifications, one 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 use of prefixes greatly decreases the number of trivial names, and although it has generated a lot of complaint in the community, we cannot believe that the community would prefer several hundred new trivial amphibole names instead of the use of prefixes. One possibility that has been advanced is the use of element suffixes [e.g., ferro-actinolite = actinolite-(Fe^{2+})]. We prefer word prefixes to element suffixes on two counts: (1) ease of use of multiple prefixes; at least for us, the meaning of fluoro-potassic-ferri-ferrohornblende is much more transparent than "hornblende-(F)-(K)-(Fe^{3+})-(Fe^{2+})", and much easier to use in speech; (2) 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.

Current usage. The current use of prefixes cannot be considered as satisfactory for several reasons. Burke and Leake (2004) define three types of prefixes for amphiboles: (i) primary prefixes that "are an essential part of the root name," e.g. *ferro*, *magnesio*; (ii) secondary prefixes such as *proto*, *clino*, *magno*, *parvo*; (iii) prefixes such as *potassic*, *titano*, *chloro*, *ferri* "which indicate richness in particular elements." First, there is no definition given of a root-name prefix. Second, we emphasize that there is no difference between prefix types (i) and (iii). *Ferro* (type i) indicates dominance of Fe^{2+} and *ferri* (type iii) indicates dominance of Fe^{3+}; there is no crystal-chemical difference between these two prefixes, as they do not change the charge distribution over the sites in the amphibole structure which, in turn, defines a root composition that is associated with a root name. The claimed appearance "in the IMA-CNMMN classification diagrams" is not a good argument to identify primary prefixes. Burke and Leake (2004) state that "root-name prefixes should never be split apart from their root names." However, many type (iii) prefixes must be considered as root-name prefixes, e.g. *ferri*, and hence should not be split from the root name according to Burke and Leake (2004): thus "ferriferrohornblende."

Leake et al. (1997) state that a prefix should be used with a hyphen where "an unhyphenated name is awkward, and a hyphen assists in deciphering the name." It seems to be left to the user when to use a hyphen; thus some users will insert a hyphen and some will not *for the same amphibole*. Where there is juxtaposition of two vowels, a hyphen should be used according to current amphibole nomenclature. Where a consonant and a vowel are in juxtaposition, normal pronunciation emphasizes combination of consonant and vowel. Thus sodicanthophyllite will tend to be pronounced "*sodi-canthophyllite*." A hyphen is obviously desirable to indicate correct pronunciation. Where there is juxtaposition of two consonants, the situation is much more complicated and also undefined. Three distinct situations can be identified:

(1) Adjacent consonants that retain their individual sounds: in such cases, there is no linguistic ambiguity as to pronunciation, e.g., potassicpargasite, and a hyphen need not be used.

(2) *A consonant blend*: here, adjacent consonants from the prefix and root name blend smoothly to form a single sound. As an example, the consonants *c* and *l* blend to form *cl*, as in the work *click*; in terms of amphiboles, potassicleakeite will contain the *cl* sound and be pronounced as *potassi-cleakeite*. Obviously, this is not satisfactory; such examples warrant use of a hyphen.

(3) A *consonant digraph*: here, adjacent consonants from the prefix and root name combine to form a single different sound (as distinct from a blend of two sounds). As an example, the consonants *c* and *h* blend to form *ch*, as in the work *chocolate*; in terms of amphiboles, potassichastingsite will contain the *ch* sound and be pronounced as *potassi-chastingsite*. Such examples warrant use of a hyphen.

It should be noted that the above suggestions are within the general IMA amphibole-nomenclature guideline that a prefix should be used with a hyphen where "an unhyphenated name is awkward, and a hyphen assists in deciphering the name."

Recommendations for the future. We recommend retaining the use of a set of redefined prefixes, each of which is always followed by a hyphen so that root names are easily identified in the complete name. This latter feature is particularly desirable in this age of databases. In addition, it is preferable to use prefixes in a specific order as comparison of names is made simpler in this case. Burke and Leake (2004) specified in which order prefixes (when more than one is used) must be attached to the root-name. Their sequence is proto (clino)-parvo (magno)-fluoro (chloro)-potassic (sodic)-ferri (alumino, mangani)-ferro(mangano, magnesio). We recommend 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.

Synthetic amphiboles

There are many recent studies focusing on the synthesis and characterization of amphibole compositions which 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 simpler 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 quoted within commas, 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 it 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 cations and W anions as their primary classification parameters. However, are these the best parameters to use in this context? We will examine this issue next.

The T cations

Consider the following points:

(1) In most scientific problems, one focuses on the variables that show the greatest degree of relative variation, as these are the most informative;

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

The W 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 constituents. These considerations suggest that the W constituents be used to divide amphiboles into two broad classes: (1) hydroxy-fluoro-chloro-amphiboles with $(OH,F,Cl) \geq 1.00$ 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 constituents are used to classify the amphiboles further.

The B cations

Previous classifications have been based on the type of B cations as the primary (first) classification parameter, which gives five main groups (see above). The compositional fields of these groups are shown in Figure 6; this Figure is obviously not in accord with the dominance criterion. Moreover, there are many problems with this stage of the current amphibole classification; 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: $Na\ Na_2\ (Fe^{3+}{}_2Mg_2Li)\ Si_8\ O_{22}\ (OH)_2 - Na\ Li_2\ (Fe^{3+}{}_2Mg_2Li)\ Si_8\ O_{22}\ (OH)_2$, Oberti et al. (2003); magnesioriebeckite–clino-ferriholmquistite: $\square\ Na_2\ (Fe^{3+}{}_2Mg_3)\ Si_8\ O_{22}\ (OH)_2 - \square\ Li_2\ (Fe^{3+}{}_2Mg_3)\ Si_8\ O_{22}\ (OH)_2$, 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 B cation (analogous to the *sodic* group), or (2) include ^{B}Li with ^{B}Na as a 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 are also expected to occur with monoclinic $P2_1/m$ symmetry (clinoholmquistite). Hence, the simpler solution is to define a distinct group for ^{B}Li amphiboles.

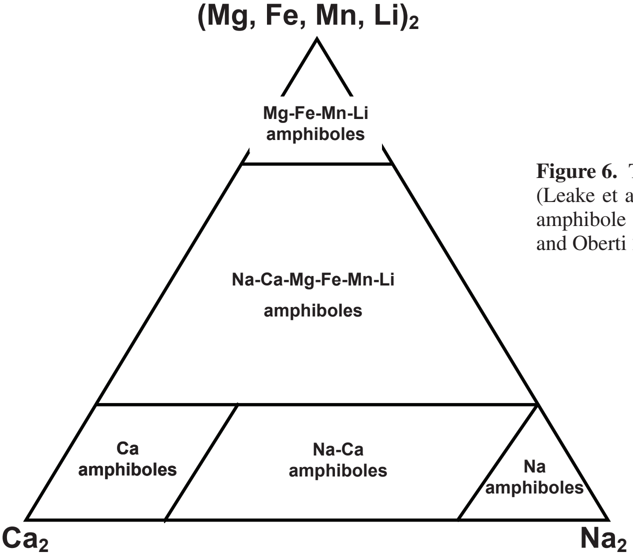

Figure 6. The present classification (Leake et al. 2003) for the five main amphibole groups (from Hawthorne and Oberti 2006).

The names of the principal groups. If we recognize a separate group with Li as the dominant B 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. 2003) 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, as long as they are used consistently.

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 $2.00 > \text{Ca} > 1.00$ apfu would belong to the calcium group, and amphiboles with $2.00 > \text{Na} > 1.00$ 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 7 shows that use of this criterion will have a problem with richterite.

This issue is investigated in Figure 7, which shows A-B-C compositional space for amphiboles with only Ca and Na as B cations (note that this excludes magnesium-iron-manganese and lithium amphiboles). Compositions of previous 'end-members' are shown as black squares and white circles. Note that the compositions represented by white 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 7; richterite is thus a true end-member according to the criteria of Hawthorne (2002). However, IMA criteria for the recognition of a valid mineral species do not involve its status as a valid end-member. The

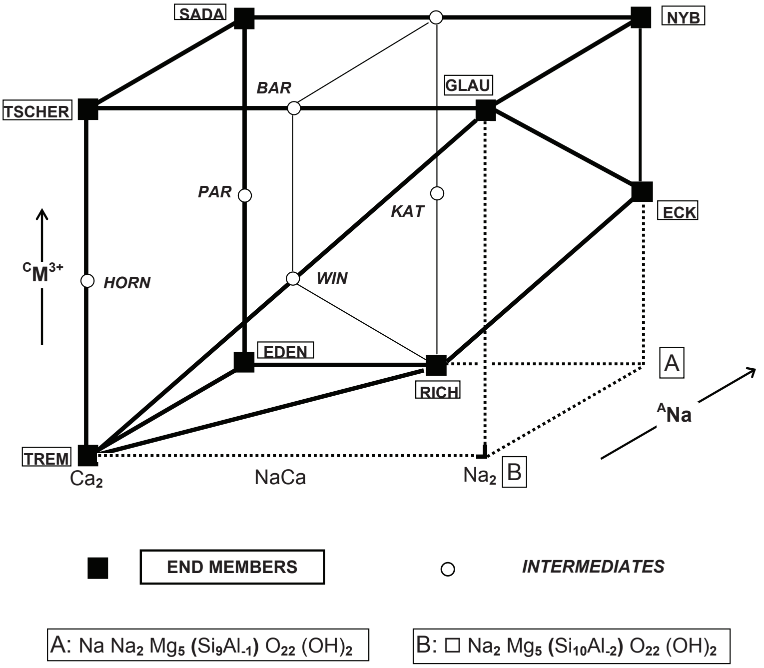

Figure 7. A-B-C amphibole space; the plane TREM-RICH-ECK-GLAU-WIN-TREM outlined by heavy black lines shows the limit of amphibole compositions (to the right of this plane, electroneutrality is not satisfied for positive numbers of cations in the amphibole structure). Formal end-member compositions are shown as black squares, and their names are shown in boxes; intermediate compositions corresponding to distinct charge-arrangements are shown as white circles, and their names are shown in boxes; the 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 (modified from Hawthorne and Oberti 2006).

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 amphibole species. 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 B-cation-pairings. Thus B_2 = (LiCa), (LiMg), (NaMg) and their ${}^{B}Fe^{2+}$ and ${}^{B}Mn^{2+}$ analogues will all result in end-member compositions of the type Na B_2 Mg_5 Si_8 O_{22} W_2 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 and Ghose (1993). This amphibole is close to the root composition $^{A}\square$ $^{B}(NaMn)$ $^{C}(Mg_4Fe^{3+})$ $^{T}Si_8$ O_{22} $(OH)_2$ and is presently named fluorian manganoan parvowinchite (IMA-CNMMN 2003-066; Leake et al. 2003). 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, but not in SCHEME 2.

The ^{B}(NaMg) and ^{B}(LiMg) joins have been investigated by synthesis; intermediate compositions with a "richterite-like" charge-arrangement are stable and have $P2_1/m$ symmetry at room temperature (Cámara et al. 2003; Iezzi et al. 2004, 2005a,b; see Oberti et al. (2007) for more details). We will take the pragmatic course of not considering the existence of synthetic 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., 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 cations

Having divided amphiboles into five groups based on the B cations, we have the A and C cations to classify within these groups and to assign specific names to specific compositional ranges and root compositions. For the A 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 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 $C\overline{1}$ structures, where there are five and eight *M* sites, respectively). Most heterovalent variations occur at the *M*(2) site, where there is complete 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. Lithium can become dominant at the *M*(3) site, normally being accompanied by Fe^{3+} at the *M*(2) site.

Representation of C cations. We need to be able to represent the variation in C cations by a single variable, which therefore must be their aggregate formal charge. The most common variation in C involves divalent and trivalent cations. If we consider C 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 $M^{3+} = Al + Fe^{3+} + Cr^{3+} + V^{3+} + Sc + 2 \text{ x } Ti^{4+} + 2 \times Zr^{*}$. 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 thus the high-charge cations cannot exceed 2 apfu, although the aggregate charge, M^{3+}, can exceed 2. However, real amphiboles have two compositional characteristics that can modify this situation: (1) the presence of Li as a C cation, and (2) the presence of O^{2-} as a non-dominant component of the W anions.

^{C}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 7 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}Li.

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[*] 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 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 $2 \times {}^{C}Ti^{4+}$ 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 anion]; in this role, it will not contribute to M^{3+}. The same is true for Fe^{3+} occurring at the *M*(1) and *M*(3) sites in calcic oxo-amphiboles from volcanic environments, where dehydrogenation is related to post-crystallization oxidation processes (more detail in Oberti et al. 2007b). However, without detailed structural and analytical work (SIMS and Mössbauer), correct assignment of Ti^{4+} and Fe^{3+} to the *M*(1,2,3) sites is not possible. The oxo component must be accounted for by subtracting a proper amount of Fe^{3+} or Ti^{4+} trivalent cations from M^{3+} before classification.

NEW SCHEMES FOR THE CLASSIFICATION OF AMPHIBOLES

First, amphiboles are divided into two classes according to the dominant W species:

(1) ^{W}(OH,F,Cl)-dominant amphiboles;

(2) ^{W}O-dominant amphiboles.

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

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

	SCHEME 1	SCHEME 2
Magnesium-iron-manganese	$\sum Mg$	$\sum Mg$
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)	$\sum Mg + {}^{B}Na$	—

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 occurs is defined by the ratio $^{B}Ca / {}^{B}(Ca + Na)$ as indicated below.

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

The magnesium-iron-manganese amphiboles

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

Amphiboles of this group may be orthorhombic (space groups *Pnma* or *Pnmn*) or monoclinic (space groups *C*2/*m* or $P2_1/m$). Although we distinguish between the B and C cations in amphiboles in general, we cannot identify accurately the partitioning of Mg and Fe^{2+} between the B and C cations in the magnesium-iron-manganese-group 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 cations. However, Mn^{2+} has a significant site preference for $M(4)$, and hence distinct species are recognized with Mn^{2+} as the dominant B cation.

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 (Table 7). The composition $Na\ Mg_2\ Mg_5\ (Si_7Al)\ O_{22}\ (OH)_2$ 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 $Na\ Ca_2\ Mg_5\ (Si_7Al)\ O_{22}\ (OH)_2$ 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. There are four homovalent analogues involving Fe^{2+} instead of Mg dominant at (B + C) with the following compositions. The compositional ranges of the orthorhombic magnesium-iron-manganese amphiboles are shown in Figure 8.

Monoclinic magnesium-iron-manganese amphiboles. The space group *C*2/*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 (B + C) and at B 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 $\square\ Mn^{2+}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$ as all other prefixes are used to indicate compositions at the *A* and *C* sites. Thus the composition $\square\ Mn^{2+}_2\ Mg_5\ Si_8\ O_{22}\ (OH)_2$ warrants a new root name: rootname3, $\square\ Mn^{2+}_2\ Fe^{2+}_5\ Si_8\ O_{22}\ (OH)_2$ is ferro-rootname3, and $\square\ Mn^{2+}_2\ Mn^{2+}_5\ Si_8\ O_{22}\ (OH)_2$ is mangano-rootname3; note that the prefix mangano is used only for $^{C}Mn^{2+}_2$.

The compositional ranges of the monoclinic Mg-Fe-Mn amphiboles are shown in Figure 9 and end-member compositions are given in Table 7.

The calcium amphiboles

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 given in Figure 10 and Table 8. 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 classification schemes. Also, 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 and ferric-iron analogues are generally named by the prefix *ferro-* and *ferri-* (Table 8). However, in SCHEME 1, some compositions retain their traditional name (e.g., hastingsite, magnesio-hastingsite) because of the petrological importance of these names. Ferrous- and ferric-iron analogues are generally named by the prefixes *ferro-ferri-* (Table 8).

Table 7. End-member compositions in the magnesium-iron-manganese amphiboles in SCHEME 1 and SCHEME 2.

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
$\square Fe^{2+}{}_2 Fe^{2+}{}_5 Si_8 O_{22} (OH)_2$	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
$\square Mg_2 Mg_5 Si_8 O_{22} (OH)_2$	Cummingtonite	Cummingtonite
$\square Fe^{2+}{}_2 Fe^{2+}{}_5 Si_8 O_{22} (OH)_2$	Grunerite	Ferro-cummingtonite
$\square Mn^{2+}{}_2 Mg_5 Si_8 O_{22} (OH)_2$	Rootname3	Rootname3
$\square Mn^{2+}{}_2 Fe^{2+}{}_5 Si_8 O_{22} (OH)_2$	Ferro-rootname3	Ferro-rootname3

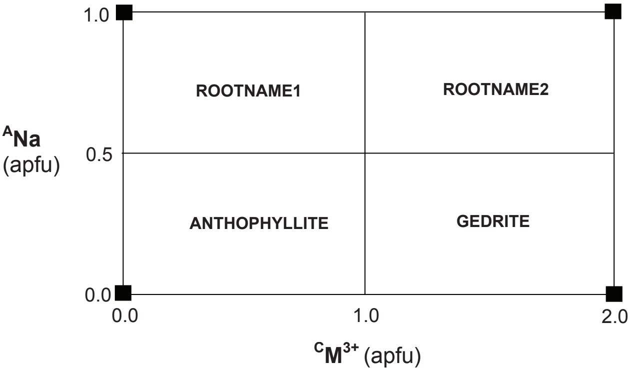

Figure 8. Root compositions for the orthorhombic magnesium-iron-manganese amphiboles; note that compositions with Na dominant at A require new root names in SCHEMES 1 and 2 (modified from Hawthorne and Oberti 2006).

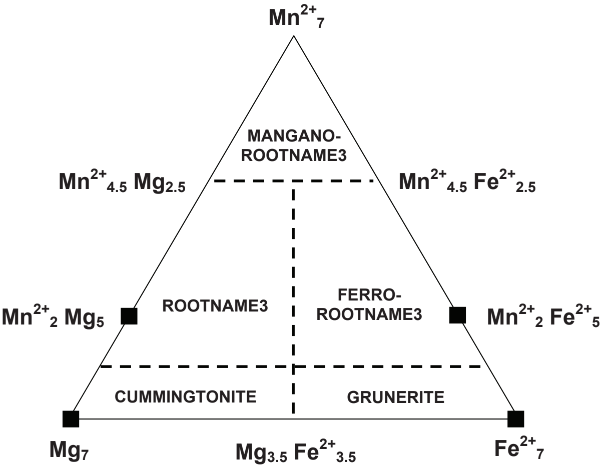

Figure 9. Root compositions and compositional variations for the monoclinic magnesium-iron-manganese amphiboles; note that compositions with Mn^{2+} dominant at C require a new root name in SCHEMES 1 and 2 (modified from Hawthorne and Oberti 2006).

Table 8. End-member compositions in the calcium amphiboles in SCHEME 1 and SCHEME 2.

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
$\square Ca_2 Fe^{2+}{}_5 Si_8 O_{22} (OH)_2$	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
$\square Ca_2 (Mg_4 Fe^{3+}) (Si_7 Al) O_{22} (OH)_2$	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
$\square Ca_2 (Fe^{2+}{}_4 Fe^{3+}) (Si_7 Al) O_{22} (OH)_2$	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

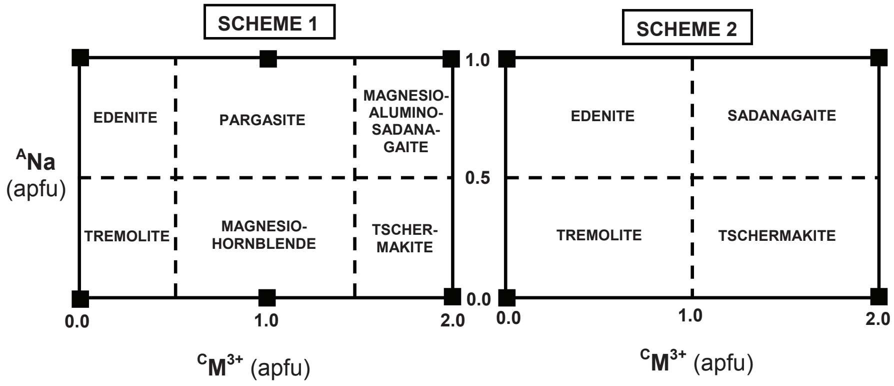

Figure 10. Root compositions and compositional variations for the calcium amphiboles; Na = Na + K (modified from Hawthorne and Oberti 2006).

The sodium-calcium amphiboles

Defined as follows:

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

There are five root compositions with Mg and Al dominant at C, together with their ferrous-iron, ferric-iron and ferrous-ferric-iron analogues (Table 9). However, some compositions retain their traditional name (e.g., katophorite) because of the petrological importance of this name. The compositional ranges of the root sodium-calcium amphiboles are shown in Figure 11.

Table 9. End-member compositions in the sodium-calcium amphiboles in SCHEME 1 and SCHEME 2.

End-member formula	SCHEME 1	SCHEME 2
$\square CaNa(Mg_4Al)Si_8O_{22}(OH)_2$	Winchite	—
$\square CaNa(Mg_3Al_2)(Si_7Al)O_{22}(OH)_2$	Barroisite	—
$NaCaNaMg_5Si_8O_{22}(OH)_2$	Richterite	—
$NaCaNa(Mg_4Al)(Si_7Al)O_{22}(OH)_2$	Magnesio-katophorite	—
$NaCaNa(Mg_3Al_2)(Si_6Al_2)O_{22}(OH)_2$	Magnesio-taramite	—
$\square CaNaFe^{2+}{}_5Si_8O_{22}(OH)_2$	Ferro-richterite	—
$\square CaNa(Fe^{2+}{}_4Al)Si_8O_{22}(OH)_2$	Ferro-winchite	—
$\square CaNa(Fe^{2+}{}_3Al_2)(Si_7Al)O_{22}(OH)_2$	Ferro-barroisite	—
$NaCaNa(Fe^{2+}{}_4Al)(Si_7Al)O_{22}(OH)_2$	Katophorite	—
$NaCaNa(Fe^{2+}{}_3Al_2)(Si_6Al_2)O_{22}(OH)_2$	Taramite	—
$\square CaNa(Mg_4Fe^{3+})Si_8O_{22}(OH)_2$	Ferri-winchite	—
$\square CaNa(Mg_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferri-barroisite	—
$NaCaNa(Mg_4Fe^{3+})(Si_7Al)O_{22}(OH)_2$	Magnesio-ferri-katophorite	—
$NaCaNa(Mg_3Fe^{3+}{}_2)(Si_6Al_2)O_{22}(OH)_2$	Magnesio-ferri-taramite	—
$\square CaNa(Fe^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	Ferro-ferri-winchite	—
$\square CaNa(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferro-ferri-barroisite	—
$NaCaNa(Fe^{2+}{}_4Fe^{3+})(Si_7Al)O_{22}(OH)_2$	Ferri-katophorite	—
$NaCaNa(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_6Al_2)O_{22}(OH)_2$	Ferri-taramite	—

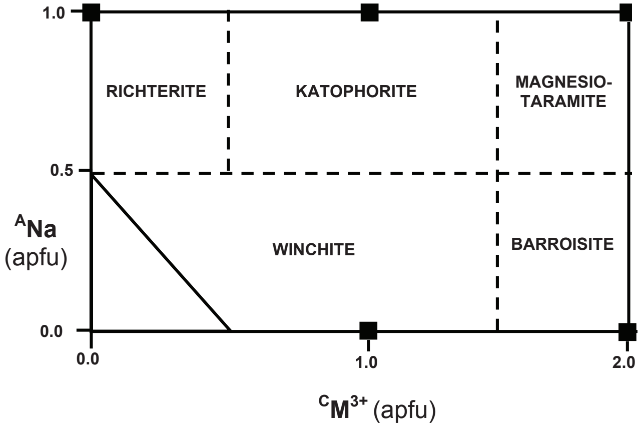

Figure 11. Root compositions and compositional variations for the sodium-calcium amphiboles; note that the amphiboles of this group only exist in scheme 1 (modified from Hawthorne and Oberti 2006).

The sodium amphiboles

Defined as follows:

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

The root compositions are shown in Figure 12 and all end-member compositions are listed in Table 10. For the sodium amphiboles, there are also Mn^{2+} analogues that are denoted by root (trivial) names (Table 10). 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.

Table 10. End-member compositions in the sodium amphiboles in SCHEME 1 and SCHEME 2.

End-member formula	SCHEME 1	SCHEME 2
$\square Na_2(Mg_3Al_2)Si_8O_{22}(OH)_2$	Glaucophane	Glaucophane
$NaNa_2(Mg_4Al)Si_8O_{22}(OH)_2$	Eckermannite	Eckermannite
$NaNa_2(Mg_3Al_2)(Si_7Al)O_{22}(OH)_2$	Nyböite	Nyböite
$NaNa_2(Mg_2Al_2Li)Si_8O_{22}(OH)_2$	Alumino-leakeite	Leakeite
$\square Na_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$	Ferro-glaucophane	Ferro-glaucophane
$NaNa_2(Fe^{2+}{}_4Al)Si_8O_{22}(OH)_2$	Ferro-eckermannite	Ferro-eckermannite
$NaNa_2(Fe^{2+}{}_3Al_2)(Si_7Al)O_{22}(OH)_2$	Ferro-nyböite	Ferro-nyböite
$NaNa_2(Fe^{2+}{}_2Al_2Li)Si_8O_{22}(OH)_2$	Ferro-alumino-leakeite	Ferro-leakeite
$\square Na_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Magnesio-riebeckite	Ferri-glaucophane
$NaNa_2(Mg_4Fe^{3+})Si_8O_{22}(OH)_2$	Magnesio-arfvedsonite	Ferri-eckermannite
$NaNa_2(Mg_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferri-nyböite	Ferri-nyböite
$NaNa_2(Mg_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Leakeite	Ferri-leakeite
$\square Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Riebeckite	Ferro-ferri-glaucophane
$NaNa_2(Fe^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	Arfvedsonite	Ferro-ferri-eckermannite
$NaNa_2(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferro-ferri-nyböite	Ferro-ferri-nyböite
$NaNa_2(Fe^{2+}{}_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Ferro-leakeite	Ferro-ferri-leakeite
$NaNa_2(Mn^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	Kozulite	Mangano-ferri-glaucophane
$NaNa_2(Mg_2Mn^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Kornite	Mangani-leakeite

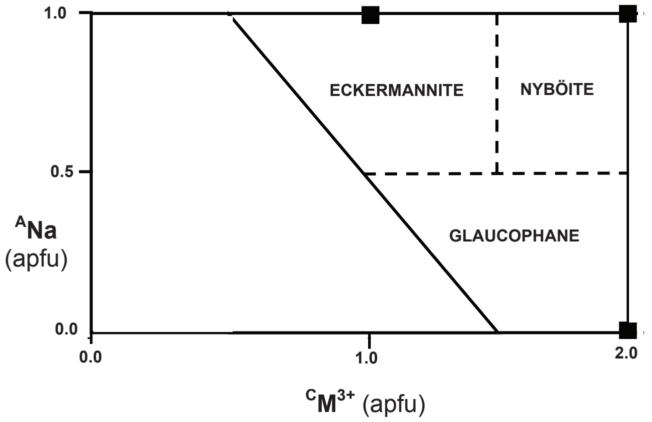

Figure 12. Root compositions and compositional variations for the sodium amphiboles (modified from Hawthorne and Oberti 2006).

The lithium amphiboles

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

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 (Table 11).

Monoclinic lithium amphiboles. There are two root compositions plus their ferro-, ferri- and ferro-ferri- analogues (Table 11). Note that "clino-holmquistite" has recently been discredited (Oberti et al. 2005); also, current knowledge and comparison with cummingtonite suggests that compositions close to that of end-member "clino-holmquistite" (if stable) should have the space group $P2_1/m$.

Table 11. End-member compositions in the lithium amphiboles in SCHEME 1 and SCHEME 2.

End-member formula	SCHEME 1	SCHEME 2
$\square Li_2(Mg_3Al_2)Si_8O_{22}(OH)_2$	Holmquistite	Holmquistite
$\square Li_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$	Ferro-holmquistite	Ferro-holmquistite
$\square Li_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Ferri-holmquistite	Ferri-holmquistite
$\square Li_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Ferro-ferri-holmquistite	Ferro-ferri-holmquistite
$\square Li_2(Mg_3Al_2)Si_8O_{22}(OH)_2$	"Clino-holmquistite"	"Clino-holmquistite"
$NaLi_2(Mg_2Al_2Li)Si_8O_{22}(OH)$	Pedrizite	Pedrizite
$\square Li_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$	Clino-ferro-holmquistite	Clino-ferro-holmquistite
$NaLi_2(Fe^{2+}{}_2Al_2Li)Si_8O_{22}(OH)_2$	Ferro-pedrizite	Ferro-pedrizite
$\square Li_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Clino-ferri-holmquistite	Clino-ferri-holmquistite
$NaLi_2(Mg_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Ferri-pedrizite	Ferri-pedrizite
$\square Li_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Clino-ferro-ferri-holmquistite	Clino-ferro-ferri-holmquistite
$NaLi_2(Fe^{2+}{}_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Ferro-ferri-pedrizite	Ferro-ferri-pedrizite

The sodium-magnesium-iron-manganese amphiboles

Defined as follows:

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

At the moment, there is only one root composition, $\square\,(Mn^{2+}Na)\,(Mg_4Fe^{3+})\,Si_8\,O_{22}\,(OH)_2$, found in Nature (Oberti and Ghose 1993). A new name must be assigned in SCHEME 1. The analogues with ferrous iron at C are generally named by the prefix *ferro-,* and the analogues with ferric iron at C 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 B cation (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 13.

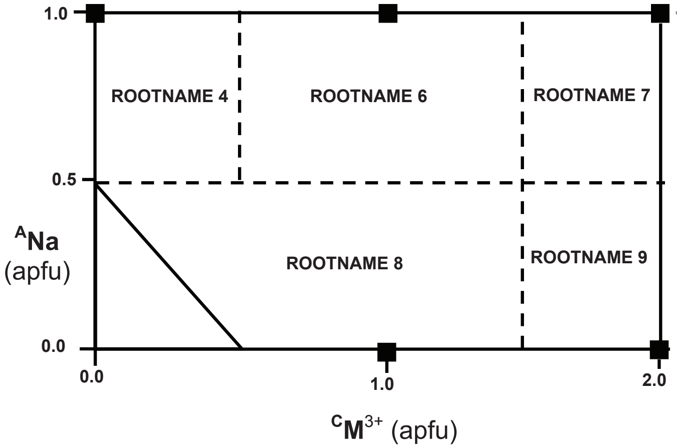

Figure 13. Root compositions and compositional variations for the sodium-(magnesium-iron-manganese) amphiboles (modified from Hawthorne and Oberti 2006).

AMPHIBOLES WITH O^{2-} DOMINANT AT W

Dominance of W by O^{2-} is accompanied by the occurrence of additional high-charge (≥ 3^+) C cations ordered at the *M*(1) and/or *M*(3) sites; this means the aggregate charge at C may exceed 12^+. There are four distinct root-compositions (Table 12) and ferrous-iron analogues can be indicated by the prefix *ferro*- (or any other as appropriate).

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 14. In principle, the inclusion of "Ti-rich pargasite" in Figure 14 is not formally correct as the term "Ti-rich" is functioning as an adjectival modifier (and adjectival modifiers are not part of a classification scheme). However, we suggest that the term "Ti-rich pargasite" be used as it fulfills a very useful function from a petrological perspective.

MAJOR DIFFERENCES BETWEEN THE CURRENT CLASSIFICATION 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, 2003).

(1) We have changed the criterion to identify the different groups, bringing it more into accord with the *dominant-cation* criterion of current IMA-CNMMN nomenclature. Leake et al. (1997, 2003) 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 $^{B}(Mg,Fe^{2+},Mn^{2+}, Li) \leq 0.50$, $^{B}(Ca,Na) \geq 1.50$ and $^{B}Na \leq 0.50$ 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}Ca is dominant over $\sum Mg$, ^{B}Na and ^{B}Li.

(2) Leake et al. (1997, 2003) considered ^{B}Li together with $^{B}(Mg,Fe^{2+},Mn^{2+})$, ^{B}Ca and ^{B}Na to define a sodium-calcium-magnesium-iron-manganese-lithium group, in which

Table 12. End-member compositions in the oxo amphiboles in SCHEMES 1 and 2.

End-member formula	SCHEME 1	SCHEME 2
$NaNa_2(Mg_3Fe^{3+}Ti^{4+})Si_8O_{22}O_2$	Obertiite	Ferri-obertiite
$NaNa_2(MgMn^{3+}{}_2Ti^{4+}Li)Si_8O_{22}O_2$	Dellaventuraite	Mangani-dellaventuraite
$NaNa_2(Mn^{2+}{}_2Mn^{3+}{}_3)Si_8O_{22}O_2$	Ungarettiite	Mangano-mangani-ungarettiite
$NaCa_2(Mg_3Ti^{4+}Al)(Si_6Al_2)O_{22}O_2$	Kaersutite	Kaersutite
$NaCa_2(Fe^{2+}{}_3Ti^{4+}Al)(Si_6Al_2)O_{22}O_2$	Ferro-kaersutite	Ferro-kaersutite

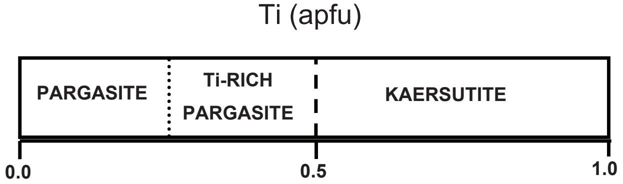

Figure 14. Compositional variation and classification for kaersutite (modified from Hawthorne and Oberti 2006).

intermediate compositions require (1) new root name if $^{B}Li > 0.50$ apfu, or (2) the prefixes *parvo* and *magno* if $^{B}Li \leq 0.50$ apfu.

The crystal-chemical behavior of Li is very different from that of (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 complete solid-solution between ^{B}Li and ^{B}Na, behavior that is different from that of the $^{B}(Mg,Fe^{2+},Mn^{2+})$ amphiboles. Moreover, the existence of ^{B}Li amphibole with orthorhombic and monoclinic primitive symmetries indicates that ^{B}Li-dominant amphiboles should be a distinct group.

(3) Leake et al. (1997, 2003) 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, 2003) used the A, B and T cations for classification purposes. However, the dominant T cation does not change: it is invariably Si, and hence compositional variation at T 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 cations are more appropriate for classification purposes and accord with the dominant-cation principle currently used in IMA nomenclature. This point is the major difference between the two schemes. The use of C cations for classification may be implemented by considering the variation in $^{C}M^{3+}$, the amount of highly charged C cations not involved in the processes related to the oxo component, as a classification variable.

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}Li, and (b) the occurrence of dominant O^{2-} at W. In both these cases, electroneutrality is maintained by incorporation of “unusual” cations at sites containing “normal” C cations: (a) $^{M(3)}Li$ is accompanied by $^{M(2)}Fe^{3+}$; (b) $^{W}O^{2-}$ is accompanied by $^{M(1)}Ti^{4+}$ or $^{M(1,3)}(Fe^{3+},Mn^{3+})$. For classification purposes, these components can be dealt with by subtracting the relevant amounts of Fe^{3+} and Ti^{4+} from $^{C}M^{3+}$ before using the standard compositional diagrams.

(5) The schemes introduced here recognize a distinct group of amphiboles with O^{2-} as the dominant W anion (oxo-amphiboles). These amphiboles contain high-charge C cations, 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. Appendix I lists the root names that are redefined here.

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-).

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 B cation, having B_2 = NaCa and B_2 = $Li(Mg,Fe,Mn)_2$, and 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 (1) adherence to the dominant-cation principle, and (2) 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. 7). 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 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.

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 $\square\,Ca_2\,(Mg_4Al)\,(Si_7Al)\,O_{22}\,(OH)_2$, 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, $\square\,Ca_2\,(Mg_3Al_2)\,(Si_6Al_2)\,O_{22}\,(OH)_2$ in SCHEME 2. Similarly, the composition $Na\,Ca_2\,(Mg_4Al)\,(Si_6Al_2)\,O_{22}\,(OH)_2$, 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, $Na\,Ca_2\,(Mg_3Al_2)\,(Si_5Al_3)\,O_{22}\,(OH)_2$, in SCHEME 2. Elimination of these two end members would produce a major simplification in terms of the number of root compositions and names. Conversely, 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:

(1) to outline the problems associated with any classification of the amphiboles;

(2) 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;

(3) to propose that any future classification be based on chemical variations of the A, B and C cations of the amphibole general formula, rather than the A, B and T cations as was done in previous classifications;

(4) 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 classification scheme.

ACKNOWLEDGMENTS

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

End-member formula**	Leake et al. (1997, 2003)	SCHEME 1	SCHEME 2
$Na\,Mg_2\,Mg_5\,(Si_7Al)\,O_{22}\,(OH)_2$	Sodicanthophyllite	Rootname1	Rootname1
$Na\,Fe^{2+}{}_2\,Fe^{2+}{}_5\,(Si_7Al)\,O_{22}\,(OH)_2$	Sodic-ferro-anthophyllite	Ferro-rootname1	Ferro-rootname1
$Na\,Mg_2\,(Mg_4Al)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Sodicgedrite	-------	-------
$Na\,Mg_2\,(Mg_3Al_2)\,(Si_5Al_3)\,O_{22}\,(OH)_2$	-------	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	-------	-------
☐ $Mn^{2+}{}_2\,(Mn^{2+}{}_2\,Fe^{2+}{}_2)\,Si_8\,O_{22}\,(OH)_2$	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
☐ $Ca_2\,[Mg_4\,(Al,Fe^{3+})]\,(Si_7Al)\,O_{22}\,(OH)_2$	Magnesiohornblende	-------	-------
☐ $Ca_2\,(Mg_4Al)\,(Si_7Al)\,O_{22}\,(OH)_2$	-------	Magnesio-hornblende	-------
☐ $Ca_2\,[Fe^{2+}{}_4\,(Al,Fe^{3+})]\,(Si_7Al)\,O_{22}\,(OH)_2$	Ferrohornblende	-------	-------
☐ $Ca_2\,(Mg_4\,Fe^{3+})\,(Si_7Al)\,O_{22}\,(OH)_2$	-------	Ferri-hornblende	-------
☐ $Ca_2\,(Fe^{2+}{}_4Al)\,(Si_7Al)\,O_{22}\,(OH)_2$	-------	Ferro-hornblende	-------
☐ $Ca_2\,(Fe^{2+}{}_4\,Fe^{3+})\,(Si_7Al)\,O_{22}\,(OH)_2$	-------	Ferro-ferri-hornblende	-------
☐ $Ca_2\,[Mg_3\,Al\,Fe^{3+}]\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Tschermakite	-------	-------
☐ $Ca_2\,(Mg_3Al_2)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Aluminotschermakite	Tschermakite	Tschermakite
☐ $Ca_2\,[Mg_3\,Fe^{3+})\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Ferritschermakite	Ferri-tschermakite	Ferri-tschermakite
☐ $Ca_2\,[Fe^{2+}{}_3\,Al\,Fe^{3+}]\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Ferrotschermakite	-------	-------
☐ $Ca_2\,(Fe^{2+}{}_3Al_2)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Alumino-ferrotschermakite	Ferro-tschermakite	Ferro-tschermakite
☐ $Ca_2\,(Fe^{2+}{}_3\,Fe^{3+}{}_2)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Ferri-ferrotschermakite	Ferro-ferri-tschermakite	Ferro-ferri-tschermakite
$Na\,Ca_2\,(Mg_4Al)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Pargasite	Pargasite	-------
$Na\,Ca_2\,(Fe^{2+}{}_4Al)\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Ferropargasite	Ferro-pargasite	-------
$Na\,Ca_2\,(Mg_4\,Fe^{3+})\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Magnesiohastingsite	Magnesio-hastingsite	-------
$Na\,Ca_2\,(Fe^{2+}{}_4\,Fe^{3+})\,(Si_6Al_2)\,O_{22}\,(OH)_2$	Hastingsite	Hastingsite	-------

End-member formula**	Leake et al. (1997, 2003)	SCHEME 1	SCHEME 2
$NaCa_2[Mg_3(Fe^{3+},Al)_2](Si_5Al_3)O_{22}(OH)_2$	Magnesiosadanagaite	-------	-------
$NaCa_2[Fe^{2+}{}_3(Fe^{3+},Al)_2](Si_5Al_3)O_{22}(OH)_2$	Ferrosadanagaite	-------	-------
$NaCa_2(Mg_3Al_2)(Si_5Al_3)O_{22}(OH)_2$	-------	Magnesio-alumino-sadanagaite	Sadanagaite
$NaCa_2(Fe^{2+}{}_3Al_2)(Si_5Al_3)O_{22}(OH)_2$	-------	Alumino-sadanagaite	Ferro-sadanagaite
$NaCa_2(Mg_3Fe^{3+}{}_2)(Si_5Al_3)O_{22}(OH)_2$	-------	Magnesio-sadanagaite	Ferri-sadanagaite
$NaCa_2(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_5Al_3)O_{22}(OH)$	-------	Sadanagaite	Ferro-ferri-sadanagaite
☐ $CaNa[Mg_4(Al,Fe^{3+})]Si_8O_{22}(OH)_2$	Winchite	-------	-------
☐ $CaNa[Fe^{2+}{}_4(Al,Fe^{3+})]Si_8O_{22}(OH)_2$	Ferrowinchite	-------	-------
☐ $CaNa(Mg_4Al)Si_8O_{22}(OH)_2$	-------	Winchite	-------
☐ $CaNa(Mg_4Fe^{3+})Si_8O_{22}(OH)_2$	-------	Ferri-winchite	-------
☐ $CaNa(Fe^{2+}{}_4Al)Si_8O_{22}(OH)_2$	-------	Ferro-winchite	-------
☐ $CaNa(Fe^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	-------	Ferro-ferri-winchite	-------
☐ $CaNa(Mg_3AlFe^{3+})(Si_7Al)O_{22}(OH)_2$	Barroisite	-------	-------
☐ $CaNa(Fe^{2+}{}_3AlFe^{3+})(Si_7Al)O_{22}(OH)_2$	Ferrobarroisite	-------	-------
☐ $CaNa(Mg_3Al_2)(Si_7Al)O_{22}(OH)_2$	Aluminobarroisite	Barroisite	-------
☐ $CaNa(Mg_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferribarroisite	Ferri-barroisite	-------
☐ $CaNa(Fe^{2+}{}_3Al_2)(Si_7Al)O_{22}(OH)_2$	Alumino-ferrobarroisite	Ferro-barroisite	-------
☐ $CaNa(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_7Al)O_{22}(OH)_2$	Ferri-ferrobarrosite	Ferro-ferri-barrosite	-------
$NaCaNaMg_5Si_8O_{22}(OH)_2$	Richterite	Richterite	-------
☐ $CaNaFe^{2+}{}_5Si_8O_{22}(OH)_2$.	Ferrorichterite	Ferro-richterite	-------
$NaCaNa[Mg_4(Al,Fe^{3+})](Si_7Al)O_{22}(OH)_2$	Magnesiokatophorite	-------	-------
$NaCaNa[Fe^{2+}{}_4(Al,Fe^{3+})](Si_7Al)O_{22}(OH)_2$	Katophorite	-------	-------
$NaCaNa(Mg_4Al)(Si_7Al)O_{22}(OH)_2$	-------	Magnesio-katophorite	-------
$NaCaNa(Mg_4Fe^{3+})(Si_7Al)O_{22}(OH)_2$	-------	Magnesio-ferri-katophorite	-------
$NaCaNa(Fe^{2+}{}_4Al)(Si_7Al)O_{22}(OH)_2$	-------	Katophorite	-------
$NaCaNa(Fe^{2+}{}_4Fe^{3+})(Si_7Al)O_{22}(OH)_2$	-------	Ferri-katophorite	-------

End-member formula**	**Leake et al. (1997, 2003)**	**SCHEME 1**	**SCHEME 2**
$NaCaNa(Mg_3AlFe^{3+})(Si_6Al_2)O_{22}(OH)_2$	Magnesiotaramite	-------	-------
$NaCaNa(Fe^{2+}{}_3AlFe^{3+})(Si_6Al_2)O_{22}(OH)_2$	Taramite	-------	-------
$NaCaNa(Mg_3Al_2)(Si_6Al_2)O_{22}(OH)_2$	Alumino-magnesiotaramite	Magnesio-taramite	-------
$NaCaNa(Mg_3Fe^{3+}{}_2)(Si_6Al_2)O_{22}(OH)_2$	Ferri-magnesiotaramite	Magnesio-ferri-taramite	-------
$NaCaNa(Fe^{2+}{}_3Al_2)(Si_6Al_2)O_{22}(OH)_2$	Aluminotaramite	Alumino-taramite	-------
$NaCaNa(Fe^{2+}{}_3Fe^{3+}{}_2)(Si_6Al_2)O_{22}(OH)_2$	Ferritaramite	Ferri-taramite	-------
All other sodium-calcium amphiboles are the same as in Leake et al. (1997) and SCHEME 1.			
$NaNa_2(Mg_2Al_2Li)Si_8O_{22}(OH)_2$	-------	Alumino-leakeite	Leakeite
$NaNa_2(Fe^{2+}{}_2Al_2Li)Si_8O_{22}(OH)_2$	-------	Ferro-alumino-leakeite	Ferro-leakeite
$NaNa_2(Mg_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Leakeite	Leakeite	Ferri-leakeite
$NaNa_2(Fe^{2+}{}_2Fe^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Ferroleakeite	Ferro-leakeite	Ferro-ferri-leakeite
$NaNa_2(Mg_2Mn^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Sodic-kornite	Kornite	Mangani-leakeite
$KNa_2(Mg_2Mn^{3+}{}_2Li)Si_8O_{22}(OH)_2$	Kornite	Potassic-kornite	Potassic-kornite
$NaNa_2(Mg_3Fe^{3+}{}_2)Si_7AlO_{22}(OH)_2$	Ferric-nyböite	Ferri-nyböite	Ferri-nyböite
$NaNa_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_7AlO_{22}(OH)_2$	Ferric-ferronyböite	Ferro-ferri-nyböite	Ferro-ferri-nyböite
$\square Na_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Magnesioriebeckite	Magnesio-riebeckite	Ferri-glaucophane
$NaNa_2(Mg_4Fe^{3+})Si_8O_{22}(OH)_2$	Magnesio-arfvedsonite	Magnesio-arfvedsonite	Ferri-eckermannite
$\square Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Riebeckite	Riebeckite	Ferro-ferri-glaucophane
$NaNa_2(Fe^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	Arfvedsonite	Arfvedsonite	Ferro-ferri-eckermannite
$NaNa_2Mn^{2+}{}_4(Al,Fe^{3+})Si_8O_{22}(OH)_2$	Kozulite	-------	-------
$NaNa_2(Mn^{2+}{}_4Fe^{3+})Si_8O_{22}(OH)_2$	-------	Kozulite	Mangano-ferri-eckermannite
$\square Li_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$	Ferroholmquistite	Ferro-holmquistite	Ferro-holmquistite
$\square Li_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Ferriholmquistite	Ferri-holmquistite	Ferri-holmquistite
$\square Li_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Ferri-ferroholmquistite	Ferro-ferri-holmquistite	Ferro-ferri-holmquistite
$\square Li_2(Mg_3Al_2)Si_8O_{22}(OH)_2$	Clinoholmquistite	Clino-holmquistite	Clino-holmquistite
$\square Li_2(Fe^{2+}{}_3Al_2)Si_8O_{22}(OH)_2$	Clino-ferroholmquistite	Clino-ferro-holmquistite	Clino-ferro-holmquistite
$\square Li_2(Mg_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Clino-ferriholmquistite	Clino-ferri-holmquistite	Clino-ferri-holmquistite
$\square Li_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$	Clino-ferri-ferroholmquistite	Clino-ferro-ferri-holmquistite	Clino-ferro-ferri-holmquistite
$NaLi_2(Mg_2Al_2Li)Si_8O_{22}(OH)_2$	Sodicpedrizite	Pedrizite	Pedrizite

End-member formula**	Leake et al. (1997, 2003)	SCHEME 1	SCHEME 2
$\mathrm{Na\,Li_2\,(Fe^{2+}{}_2\,Al_2\,Li)\,Si_8\,O_{22}\,(OH)_2}$	Sodic-ferropedrizite	Ferro-pedrizite	Ferro-pedrizite
$\mathrm{Na\,Li_2\,(Mg_2\,Fe^{3+}{}_2\,Li)\,Si_8\,O_{22}\,(OH)_2}$	Sodic-ferripedrizite	Ferri-pedrizite	Ferri-pedrizite
$\mathrm{Na\,Li_2\,(Fe^{2+}{}_2\,Fe^{3+}{}_2\,Li)\,Si_8\,O_{22}\,(OH)_2}$	Sodic-ferri-ferropedrizite	Ferro-ferri-pedrizite	Ferro-ferri-pedrizite
$\square\,\mathrm{(Na\,Li)\,(Mg_3\,Al_2)\,Si_8\,O_{22}\,(OH)_2}$	Ottoliniite	-------	-------
$\mathrm{Na\,(Na\,Li)\,(Mg_2\,Al_2Li)\,Si_8\,O_{22}\,(OH)_2}$	Whittakerite	-------	-------
$\square\,\mathrm{(Na\,Li)\,(Mg_3\,Fe^{3+}{}_2)\,Si_8\,O_{22}\,(OH)_2}$	Ferri-ottoliniite	-------	-------
$\mathrm{Na\,(Na\,Li)\,(Mg_2\,Fe^{3+}{}_2\,Li)\,Si_8\,O_{22}\,(OH)_2}$	Ferri-whittakerite	-------	-------
$\mathrm{Na\,(Na\,Mg)\,Mg_5\,Si_8\,O_{22}\,(OH)_2}$	-------	Rootname 4	-------
$\mathrm{Na\,(Na\,Mn^{2+})\,Mg_5\,Si_8\,O_{22}\,(OH)_2}$	-------	Rootname 5	-------
$\mathrm{Na\,(Na\,Mg)\,(Mg_4\,Al)\,(Si_7\,Al)\,O_{22}\,(OH)}$	-------	Rootname 6	-------
$\mathrm{Na\,(Na\,Mg)\,(Mg_3\,Al_2)\,(Si_6\,Al_2)\,O_{22}\,(OH)}$	-------	Rootname 7	-------
$\square\,\mathrm{(Na\,Mg)\,(Mg_4\,Al)\,Si_8\,O_{22}\,(OH)}$	-------	Rootname 8	-------
$\square\,\mathrm{(Na\,Mg)\,(Mg_3\,Al_2)\,(Si_7\,Al)\,O_{22}\,(OH)}$	-------	Rootname 9	-------
$\square\,\mathrm{(Na\,Mn^{2+})\,(Mg_4\,Al)\,Si_8\,O_{22}\,(OH)}$	-------	Rootname 10	-------
$\square\,\mathrm{(Na\,Mn^{2+})\,(Mg_4\,Fe^{3+})\,Si_8\,O_{22}\,(OH)}$	Parvowinchite	Ferri-rootname 10	-------
$\mathrm{Na\,Ca_2\,(Mg_4\,Ti^{4+})\,(Si_6\,Al_2)\,O_{22}\,(OH)\,O}$	Kaersutite	-------	-------
$\mathrm{Na\,Ca_2\,(Mg_3\,Ti^{4+}\,Al)\,(Si_6\,Al_2)\,O_{22}\,O_2}$	------	Kaersutite	Kaersutite
$\mathrm{Na\,Na_2\,(Mg_3\,Fe^{3+}\,Ti^{4+})\,Si_8\,O_{22}\,O_2}$	Obertiite	Obertiite	Ferri-obertiite
$\mathrm{Na\,Na_2\,(Mg\,Mn^{3+}{}_2\,Ti^{4+}\,Li)\,Si_8\,O_{22}\,O_2}$	Dellaventuraite	Dellaventuraite	Mangani-dellaventuraite
$\mathrm{Na\,Na_2\,(Mn^{2+}{}_2\,Mn^{3+}{}_3)\,Si_8\,O_{22}\,O_2}$	Ungarettiite	Ungaretiite	Mangano-mangani-ungarettiite

* 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 nomenclature scheme.