Magnesio-arfvedsonite from Jade Mine Tract, Myanmar: mineral description and crystal chemistry

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ABSTRACT

Magnesio-arfvedsonite, the ^CFe³⁺-dominant analogue of eckermannite, has been found in a sample of "szechenyite" in the mineral collection of the American Museum of Natural History (AMNH H35024). It comes from the northern part of the Jade Mine Tract near Hpakan, Kachin State, Myanmar. Associated minerals are kosmochlor–jadeite solid-solution pyroxene and clinochlore. The ideal formula of magnesio-arfvedsonite is ^ANa^BNa₂^C(Mg₄Fe³⁺)^TSi₈O₂₂^W(OH)₂, and the empirical formula derived from electron microprobe analysis and single-noval structure refinement for the sample of this work is ^A(Na_{0.96}K_{0.04})_{$\Sigma=1.00$}^B(Na_{1.57}Ca_{0.40}Fe³⁺_{0.22}Mn_{0.01})_{$\Sigma=2.00$}^C(Mg_{4.26}Fe³⁺_{0.14}Al_{0.11}Ti⁴⁺_{0.03})_{$\Sigma=5.00$} ^T(Si_{7.99}Al_{0.01})_{$\Sigma=8.00$ O₂₂^W[F_{0.02}(OH)_{1.98}]_{$\Sigma=2.00$}. The unit-cell dimensions are a = 9.867(1), b = 17.928(2), c = 5.284(1) Å, $\beta = 103.80(2)^{\circ}$, V = 907.7 (2) Å³, Z = 2. Magnesio-arfvedsonite is biaxial (–), with $\alpha = 1.624$, $\beta = 1.636$, $\gamma = 1.637$, all ± 0.002 and $2V_{obs} = 36(1)^{\circ}$, $2V_{calc} = 32^{\circ}$. The ten strongest reflections in the X-ray powder pattern [*d* values (in Å), *I*, (*hkl*)] are: 2.708, 100, (151); 3.399, 68, (131); 3.144, 63, (310); 2.526, 60, (202); 8.451, 46, (110); 3.273, 39, (240); 2.167, 37, (261); 2.582, 34, (061); 2.970, 34, (221); 2.326, 33, [(251) (421)].}

Keywords: magnesio-arfvedsonite, eckermannite, amphibole, electron-microprobe analysis, crystal-structure refinement, Jade Mine Tract, Myanmar.

Introduction

It has been shown recently that the supposedly holotype eckermannite from Norra Kärr, Gränna, Jönköping, Småland, Sweden, first described by Adamson (1942) based on chemical analyses reported in Törnebohm (1906), is actually fluoro-leakeite and that the only composition reported so far which falls into the eckermannite compositional field is from the Jade Mine Tract, Myanmar (IMA2013-136; Oberti *et al.*, 2015). While looking for eckermannite, the authors reconsidered the relevant published analyses and

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found, in the mineral collection of the American Museum of Natural History, a mineral with an ^CFe³⁺-dominant composition with the charge arrangement of eckermannite which, according to the rules in force (Hawthorne et al., 2012), must be named magnesio-arfvedsonite. Indeed, the term 'arfvedsonite', to be used instead of 'ferro-ferri-eckermannite', is one of the few exceptions allowed in the new scheme for amphibole nomenclature, the rationale of which is the use of root-names solely for the magnesioand alumino-dominant endmembers. Eckermannite and arfvedsonite actually refer to the same charge arrangement in the crystalchemical formula, and differ only in the amount of the homovalent ${}^{C}Mg_{-1}{}^{C}Fe^{2+1}$ and ${}^{C}Al_{-1}{}^{C}Fe^{3+1}$

substitutions. This exception derives from the fact the term 'arfvedsonite' is embedded strongly in the petrological literature and terminology.

The term "magnesio-arfvedsonite" was introduced by Miyashiro (1957) in his proposal for the classification of alkali amphiboles. Magnesioarfvedsonite has to be considered a (grandfathered) named amphibole and no complete mineral description has been published to date.

A sample with composition close to $(Mn^{3+}$ and Li-bearing) magnesio-arfvedsonite found in a Mn mine in Maharashthra (India) was analysed and refined by Ghose *et al.* (1986), although it was referred to as "winchite" in the discussion. Unfortunately, that sample is no longer available for further characterization. A complete description of holotype magnesio-arfvedsonite AMNH H35024 from the Jade Mine Tract was approved by the IMA-CNMNC (IMA 2013-137, Oberti *et al.* 2014). Mineralogical data and a comparison with the sample of Ghose *et al.* (1986) are reported in this present paper.

Occurrence and paragenesis

The sample studied was acquired from a mineral dealer in 1962 and comes from the Jade Mine Tract near Hpakan, Kachin State, Myanmar. It is a small sample of material once referred to as "szechenyite" (Lacroix, 1930) and it resides in the mineral collections of the American Museum of Natural History, catalogue number AMNH H35024. The crystal refined and analysed in the present work has the code 1214 in the amphibole database of the CNR-IGG Pavia.

The amphibole-rich part of the sample (grey portion in Fig. 1) consists of large (up to 5 mm) partially brecciated grains of amphibole with clinochlore filling fracture boundaries and small grains (~<50 µm) of kosmochlor (Ko₆₄₋₇₈ Jd₁₈₋₂₀Di₃₋₈) decorating the fractured boundaries. The other portion consists of fine-grained kosmochlor with interspersed amphibole prisms and cleavages, also with clinochlore along boundaries. No other minerals have been identified. Mixtures of amphibole and pyroxene are inferred from descriptions observed in the field and in the literature (see Harlow et al., 2014) to form as an amphibole-dominant reaction boundary between jadeitite veins and altering peridotite or dunite. Unfortunately, most 'jade' or jade-like samples that can be acquired, including the one studied here, do not contain complete assemblages of jadeitite-amphibole-ultramafic.

Chromium enrichment is associated with veins cutting chromite-bearing or chromitite pods within the ultramafic assemblage, as at Maw-Sit-Sit in the northern part of the Jade Mine Tract ultramafic body (Harlow and Olds, 1987; Mével and Kiénast, 1986; Hughes *et al.*, 2000).

Appearance, physical and optical properties

The sample (Fig. 1) consists of two parts: one part mostly of amphibole, which may occur as single crystals >6 mm long surrounded by kosmochlorrich pyroxene or intergrown in a massive texture enveloping irregular clots or grains (<10 μ m in diameter) of kosmochlor; the other part is mostly kosmochlor with interstitial slivers of amphibole. In addition to the larger crystals, sodic amphibole often occurs as anhedral grains or as a fine fibrous mesh.

Magnesio-arfvedsonite is light grey in colour; the lustre is vitreous, crystals are transparent and do not fluoresce. Single crystals are brittle and show perfect cleavage parallel to {110}. The density calculated from the empirical formula and unit-cell dimensions is 3.034 g/cm³. A spindle stage was used to orient a crystal for measurement of refractive indices and 2V by extinction curves (Bartelmehs *et al.*, 1992). The optical orientation was determined by transferring the crystal from the spindle stage to a single-crystal diffractometer and measuring the relative axial relations by X-ray diffraction (XRD). In transmitted light, magnesio-arfvedsonite is pleochroic X = light grey (minimum), Y = dark grey (maximum), Z =



FIG. 1. The rock specimen from which holotype magnesio-arfvedsonite was extracted. The intense green portion is kosmochlor dominant and the grey-green portion is amphibole dominant. Brownish areas are clinochlore fracture fillings.

a (Å)	9.8666(11)	Crystal size (mm)	0.15-0.08-0.05
b (Å)	17.9293(19)	Crystal colour	Light grey
c (Å)	5.2839(6)	Total no. of reflections	6808
β (°)	103.799(2)	No. unique reflections	1376
$V(Å^3)$	907.70(17)	No. observed reflections $(I > 3\sigma(I))$	1135
Space group	C2/m	θ range (°)	1-30
Z	2	R_{merge} (%)	1.8
$D_{\rm calc} \ ({\rm g \ cm^{-3}})$	3.034	$R_{\rm obs}$ (%)	2.5
μ MoK α (cm ⁻¹)	15.9	$R_{\rm all}$ (%)	3.2

TABLE 1. Miscellaneous information for magnesio-arfvedsonite AMNH H35024.

medium grey (moderate), $X^{\wedge}a = 30.8^{\circ}$ (in β obtuse), $Y \parallel b$, $Z^{\wedge}c = 17.0^{\circ}$ (β acute). It is biaxial negative with indices of refraction $\alpha = 1.624$, $\beta = 1.636$, $\gamma = 1.637$ all ±0.002 measured with gel-filtered Na light ($\lambda = 589.9$ nm); $2V_{obs} = 36(1)^{\circ}$, $2V_{calc} = 32^{\circ}$.

X-ray diffraction and crystal-structure refinement

The crystal selected for data collection and structure refinement was ~150 μ m × 80 μ m × 50 µm in size. Data collection was performed on a Bruker-AXS Smart-Apex CCD-based diffractometer with graphite-monochromatized MoKa X-radiation ($\lambda = 0.7107$ Å). Omega-rotation frames (scan width 0.3°, scan time 20 s, sampleto-detector distance 50 mm) were processed with the SAINT software package (Bruker, 2003) and intensities were corrected for Lorentz and polarization effects; absorption effects were empirically evaluated by the SADABS software package (Sheldrick, 1996) and an absorption correction was applied to the data. Accurate unit-cell dimensions were calculated by least-squares refinement of the positions of 2492 reflections with $I > 10 \sigma(I)$ in the 20 range 2–60°. The *a:b:c* ratio calculated from the unit-cell parameters is 0.5503:1:0.2947. The number of reflections collected was 6808, this was reduced to 1376 unique reflections (mean redundancy 5, R_{int} 1.8%) and 1135 reflections with $I > 3\sigma(I)$ were considered as observed during unweighted fullmatrix least-squares refinement on F performed with a program written locally to handle complex solid solutions. Scattering curves for fully ionized chemical species were used at sites where chemical substitutions occur; neutral vs. ionized scattering curves were used at the T and anion sites [except O(3)]. Full-matrix least-squares refinement on I >

 $3\sigma(I)$ yielded $R_{obs} = 2.5\%$ and $R_{all} = 3.2\%$. The unit-cell dimensions and details of the crystallographic study are reported in Table 1. Atom coordinates and anisotropic-displacement parameters are reported in Table 2, and selected interatomic distances and parameters related to the conformation of the double-chain of tetrahedra are listed in Table 3. The observed and calculated structure factors have been deposited with the Principal Editor of *Mineralogical Magazine* and are available from www.minersoc.org/pages/ e journals/dep mat.html.

Powder XRD data (CuK α , $\lambda = 1.54178$ Å) were obtained using the *XPREP* utility of *SAINT* (Bruker, 2003) which generates a 2D powder diffraction (Debye-Scherrer technique) starting from the F_{obs} collected on the single crystal and taking into account solely the information concerning the unit-cell dimensions and Laue symmetry. No Lorentz and polarization corrections were applied. Data are given in Table 4.

Chemical composition

The crystal of magnesio-arfvedsonite used for the crystallographic study was embedded in epoxy and analysed by electron microprobe using a Cameca SX-100 operating in wavelength-dispersive mode with excitation voltage 15 kV, specimen current 10 nA, beam diameter 5 µm, peak-count time 20 s and background-count time 10 s. The following standards and crystals were used for $K\alpha$ X-ray lines: Si: diopside, TAP; Ca: diopside, LPET; Ti: titanite, LLiF; Fe: fayalite, LLiF; Mn: spessartine, LLiF; Cr: chromite, LLiF; Mg: forsterite, LTAP; Al, andalusite, TAP; K: orthoclase, LPET; Na: albite, TAP; F: fluororiebeckite, LTAP; Zn: gahnite, LLiF. Data reduction was undertaken using the $\varphi(\rho Z)$ procedure of Pouchou and Pichoir (1985).

Site	SS	<i>x/a</i>	y/b	z/c	$B_{ m eq}$	β ¹¹	β^{22}	β^{33}	β^{12}	β^{13}	β^{23}
0(1)		0.11205(13)	0.08691(7)	0.21497(25)	0.74(3)	17	7	69	-1	9	-3
0(2)		0.11851(14)	0.16938(7)	0.73005(25)	0.83(3)	20	7	79		5	-2
0(3)	16.27(6)	0.10746(19)	0	0.71104(37)	0.88(4)	21	7	86	Ι	7	I
O(4)		0.36231(15)	0.24944(8)	0.79553(27)	1.03(3)	35	7	91	-5	16	0
0(5)		0.34806(14)	0.12899(8)	0.08433(27)	0.98(3)	20	10	85	0	6	10
0(0)		0.34186(14)	0.11724(8)	0.58627(27)	1.00(3)	23	10	LL	0	5	-8
0(1)		0.33811(20)	0	0.28808(40)	1.00(4)	23	5	136	Ι	13	I
T(1)		0.27914(5)	0.08555(3)	0.29283(10)	0.61(1)	16	5	55	0	9	
T(2)		0.28644(5)	0.17171(3)	0.79961(10)	0.66(1)	17	9	59		7	
M(1)	25.49(11)	0	0.08931(5)	1/2	0.72(2)	20	9	64	Ι	11	I
M(2)	32.01(11)	0	0.18136(4)	0	0.79(2)	19	7	76	Ι	10	Ι
M(3)	12.73(4)	0	0	0	0.68(3)	19	9	58	Ι	8	Ι
M(4)	25.49(14)	0	0.27565(6)	1/2	1.39(3)	41	6	164	Ι	46	I
4	3.30(3)	0	1/2	0	2.0(2)	44	18	231	Ι	62	I
4(m)	2.67(9)	0.0269(13)	1/2	0.0789(23)	2.8(4)	56	33	201	Ι	19	I
4(2)	5.26(9)	0	0.4722(3)	0	2.3(2)	63	7	444	Ι	129	Ι
H	1.46(14)	0.190(5)	0	0.743(9)	0.8						

TABLE 2. Refined site-scattering values (ss, electrons per formula unit), fractional atom coordinates and atom-displacement parameters (B_{eq} , \mathring{A}^2 , $\beta^{ij} \times 10^4$) for magnesio-arfvedsonite AMNH H35024.

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	This work	"winchite"		This work	"winchite"
T(1)-O(1) T(1)-O(5) T(1)-O(6) T(1)-O(7) <t(1)-o></t(1)-o>	$\begin{array}{c} 1.601(1) \\ 1.625(1) \\ 1.629(2) \\ \underline{1.643(1)} \\ 1.624 \end{array}$	1.609 1.624 1.624 <u>1.626</u> <u>1.621</u>	T(2)-O(2) T(2)-O(4) T(2)-O(5) T(2)-O(6) <t(2)-o></t(2)-o>	1.610(1) 1.584(2) 1.668(2) <u>1.679(2)</u> 1.635	$ \begin{array}{r} 1.618 \\ 1.592 \\ 1.648 \\ \underline{1.660} \\ \overline{1.630} \end{array} $
$M(1) - O(1) \times 2$ $M(1) - O(2) \times 2$ $M(1) - O(3) \times 2$ < M(1) - O>	2.070(1) 2.056(1) $2.090(1) 2.072$	2.064 2.069 2.074 2.069	$M(2)-O(1) \times 2 M(2)-O(2) \times 2 M(2)-O(4) \times 2 $	$2.186(1) \\ 2.060(1) \\ \underline{1.963(1)} \\ 2.070$	2.064 2.069 <u>2.074</u> <u>2.069</u>
$M(3) - O(1) \times 4$ $M(3) - O(3) \times 2$ < M(3) - O >	$\frac{2.084(1)}{2.056(2)}$	$\frac{2.087}{2.067}$	$M(4)-O(2) \times 2 M(4)-O(4) \times 2 M(4)-O(5) \times 2 M(4)-O(6) \times 2 $	2.408(2) 2.345(2) 2.902(2) 2.583(2)	2.417 2.350 2.864 2.513
$A-O(5) \times 4 A-O(6) \times 4 A-O(7) \times 2 $	$2.848(1) \\ 3.163(1) \\ 2.455(2) \\ \overline{2.896}$	2.848 3.195 <u>2.487</u> 2.915	< M(4) - O > $A(m) - O(5) \times 2$ $A(m) - O(5) \times 2$ $A(m) - O(6) \times 2$	2.559 2.913(1) 2.850(1) 2.852(1)	2.536 3.010 2.818 2.769
$A(2)-O(5) \times 2 A(2)-O(6) \times 2 A(2)-O(7) \times 2 $	2.461(1) 2.857(1) <u>2.505(2)</u> 2.608	2.323 2.783 <u>2.579</u> 2.562	A(m) - O(7) =	$2.382(2) \\ 3.292(2) \\ 2.601(2) \\ 2.834$	$2.497 \\ 3.109 \\ \underline{2.629} \\ 2.825$
T(1) - O(5) - T(2) T(1) - O(6) - T(2) T(1) - O(7) - T(1)	135.2(1) 137.0(1) 138.0(1)	136.0 139.5 141.3	O(5)-O(6)-O(5) O(6)-O(7)-O(6)	170.5(1) 106.6(1)	171.4 109.9

TABLE 3. Selected interatomic distances (Å) and angles (°) in magnesio-arfvedsonite AMNH H35024 and in the "winchite" sample reported by Ghose *et al.* (1986).

TABLE 4. Powder XRD data for magnesio-arfvedsonite AMNH H35024. The ten strongest lines are in bold.

I _{rel}	d(calc)	h	k	l	I _{rel}	d(calc)	h	k	l	$I_{\rm rel}$	d(calc)	h	k	l	I _{rel}	d(calc)	h	k	l
5	8.962	0	2	0	61	2.526	$\overline{2}$	0	2	9	1.906	5	1	0	22	1.509	Ī	6	3
46	8.451	1	1	0	2	2.476	1	7	0	6	1.873	2	4	2	13	1.494	0	12	0
2	5.131	0	0	1	2	2.432	$\overline{2}$	2	2			4	6	1	8	1.485	4	4	2
15	4.863	ī	1	1	7	2.385	3	5	0	9	1.853	ī	9	1			0	6	3
6	4.794	2	0	0	33	2.326	3	5	1	5	1.830	4	4	2	3	1.462	2	10	2
27	4.482	0	4	0			4	2	1	7	1.794	1	9	1	9	1.449	3	11	0
9	4.026	1	1	1	20	2.284	1	7	1			0	10	0			ī	7	3
16	3.859	1	3	1	21	2.266	3	1	2	5	1.740	5	1	2			6	4	2
2	3.662	2	2	1	9	2.201	2	4	2	11	1.686	ī	3	3	31	1.438	6	6	1
68	3.399	1	3	1	37	2.167	2	6	1	12	1.678	0	2	3	3	1.419	5	3	3
39	3.273	2	4	0	10	2.133	3	3	2			$\overline{2}$	8	2	2	1.414	6	2	1
63	3.144	3	1	0	19	2.066	2	0	2	27	1.660	4	6	1	12	1.381	5	1	2
6	3.014	3	1	1	11	2.029	3	5	1	9	1.637	4	8	0	2	1.371	7	3	1
34	2.970	2	2	1	10	2.006	4	0	2	11	1.607	1	11	0	3	1.365	7	1	0
11	2.925	ī	5	1	4	1.961	1	5	2	6	1.597	6	0	0	7	1.353	5	5	3
20	2.817	3	3	0	7	1.950	1	9	0	22	1.578	ī	5	3	6	1.350	5	3	2
100	2.708	1	5	1			4	2	1	3	1.558	2	10	1					
34	2.582	0	6	1	4	1.926	3	5	2	12	1.529	6	0	2					

Oxide	Wt.%			a.p.f.u.
SiO ₂	57.36(60)		Si	7.992
TiO ₂	0.24(13)		Al	0.008
Al_2O_3	0.72(04)		Sum T	8.000
Cr_2O_3	0.04(01)		Ti ⁴⁺	0.025
Fe ₂ O ₃ *	3.95		Al	0.110
FeO	1.76		Cr ³⁺	0.004
FeO _{TOT}	5.32(18)		Fe ³⁺	0.414
MgO	20.53(23)		Fe ²⁺	0.187
MnO ₂	0.06(01)		Mg	4.260
CaO	2.69(29)		Sum C	5.000
Na ₂ O	9.37(26)		$(Fe,Mn)^{2+}$	0.025
K ₂ O	0.23(04)		Na	1.573
H ₂ O**	2.13		Ca	0.402
F	0.05(03)		Sum B	2.000
Less O=F	0.02		K	0.041
Total	99.11		Na	0.958
			Sum A	0.999
Site scattering	(e.p.f.u.)		OH	1.979
Ū.	calc.	obs.	F	0.022
С	68.82	70.23	Sum W	2.000
В	25.99	25.49		
А	11.32	11.23		

TABLE 5. Chemical composition and unit formula (based on 24 anions) for magnesioarfvedsonite AMNH H35024.

* FeO:Fe₂O₃ ratio calculated from single-crystal structure-refinement results.

** based on 24 (O, OH, F) with (O, OH, F) = 2 a.p.f.u.

e.p.f.u. – electrons per formula unit.

Site	Site population (a.p.f.u.)	Site so (e.r	cattering (f.u.)	Mean bond distances (Å)		
		Refined	Calculated	Refined	Calculated	
AMNH	H35024					
M(1)	$1.95 \text{ Mg} + 0.05 \text{ Fe}^{2+}$	25.49	24.70	2.072	2.079	
M(2)	$1.34 \text{ Mg} + 0.10 \text{ Fe}^{2+} + 0.12 \text{ Al} + 0.41 \text{ Fe}^{3+} + 0.03 \text{ Ti}$	32.01	31.56	2.070	2.059	
<i>M</i> (3)	$0.96 \text{ Mg} + 0.04 \text{ Fe}^{2+}$	12.73	12.56	2.074	2.080	
Sum C		70.23	68.82			
"winchit	e" Ghose <i>et al.</i> (1986)					
M(1)	2.0 Mg	24.05	24.00	2.069	2.078	
M(2)	$0.80 \text{ Mg} + 1.14 \text{ Fe}^{3+} + 0.6 \text{ Mn}^{3+}$	43.18	40.74	2.041	2.046	
<i>M</i> (3)	$0.87 \text{ Mg} + 0.13 \text{ Li}^+$	10.83	10.83	2.080	2.083	
Sum C		78.06	75.57			

TABLE 6. Site populations calculated for C cations in magnesio-arfvedsonite.

e.p.f.u. - electrons per formula unit.

Vanadium, Cr, Ni and Cl were below the detection limit. The average of 10 analytical points is given in Table 5, together with a formula based on stoichiometric constraints and the results of structure refinement (full occupancy of the *A* group-sites, absence of the oxo component, comparison between the observed and calculated values of site scattering and mean bond lengths; see below for more details). The unit formula based on 24 O and $^{W}(OH + F) = 2$ atoms per formula unit (a.p.f.u.) is: $^{A}(Na_{0.96}K_{0.04})_{\Sigma=1.00}$ $^{B}(Na_{1.57}Ca_{0.40}Fe_{0.19}^{2+}Fe_{0.19}^{2+}CMn_{0.01})_{\Sigma=2.00}$ $^{C}(Mg_{4.26}Fe_{0.19}^{2+}Fe_{0.41}^{3+}Al_{0.11}Ti_{0.03}^{4+})_{\Sigma=5.00}$ $^{T}(Si_{7.99}Al_{0.01})_{\Sigma=8.00}O_{22}$ $^{W}[F_{0.02}(OH)_{1.98}]_{\Sigma=2.00}$

The formula of end-member magnesio-arfvedsonite is ${}^{A}Na^{B}Na_{2}{}^{C}(Mg_{4}Fe^{3+})^{T}Si_{8}O_{22}{}^{W}(OH)_{2}$, which requires SiO₂ 57.73, Fe₂O₃ 9.59, MgO 19.36, Na₂O 11.16, H₂O 2.16, total 100.00 wt.%. The compatibility index $(1 - (K_{p}/K_{c}))$ is 0.006 (superior).

Crystal chemistry of magnesio-arfvedsonite

In this section a comparison is given between the two sets of crystallographic data available for magnesio-arfvedsonite: the sample of this work and that discussed as "winchite" by Ghose *et al.* (1986). For the latter, the proposed composition is ^A(Na_{0.50}K_{0.17})_{$\Sigma=0.67$} ^B(Na_{1.73}Ca_{0.27})_{$\Sigma=2.00$} ^C (Mg_{3.69}F e_{1.14}Mn_{0.06}³⁺ Li_{0.16})_{$\Sigma=5.05$} ^T(Si_{7.90}Al_{0.10})_{$\Sigma=8.00$ O₂₂^W(OH)_{2.00} and the reported unit-cell parameters are a = 9.7573(5), b = 17.9026(14), c = 5.2886(2) Å, $\beta = 103.814(4)^{\circ}$, V = 897.10 Å³; the relevant geometrical parameters are reported in Table 3.}

Both samples deviate from the ideal chargearrangement, but they do so according to two different exchange vectors: the sample studied in this present work according to ${}^{B}Na_{-1}{}^{C}R_{-1}^{3+}$ ${}^{B}Ca^{C}R^{2+}$ (i.e. moving toward ferri-richterite) and that of Ghose *et al.* (1986) by ${}^{A}R_{-1}^{+}BNa_{-1}{}^{A}\Box^{B}Ca$ (i.e. moving towards ferri-winchite), which adds to the exchange vector internal to the C cations which is due to the presence of ${}^{C}Li$, i.e.: ${}^{M(3)}Mg_{-1}{}^{M(2)}R_{-1}^{3+M(3)}Li^{M(2)}R^{3+}$ (i.e. moving toward ferri-leakeite).

If the C cations are distributed according to current knowledge of amphibole crystal-chemistry (for a review, see Oberti *et al.*, 2007), we obtain, for the two magnesio-arfvedsonite specimens, the site populations reported in Table 6 together with the corresponding values of the site scattering ($\Sigma x_i Z_i$) and mean bond lengths ($\Sigma x_i <$ cati-O>), where Z is the atomic number and <cat-O> is the averaged cation-to-oxygen distance observed in amphiboles (for more detail, see Hawthorne *et al.*, 1995; Hawthorne and Oberti, 2007; Oberti *et al.*, 2007). The agreement between the refined and calculated site-scattering values is good; in contrast, that between the refined and calculated mean bond lengths show that the M(1) and the M(3) octahedra are slightly smaller than expected on the basis of composition. This feature cannot be ascribed to the presence of F⁻ or O²⁻ at the O(3) site as the M(1)–O(3) distance is longer than the other two M(1)–O distances, characteristic of the presence of OH at O(3).

It is interesting to note that Gay et al. (1970), while studying materials that had returned from the lunar surface by the Apollo 11 mission, found dark green crystalline material in a vug on rock 10058. The published electron-microprobe analyses, when recalculated on the basis of 16 cations and 2 (OH,F) a.p.f.u., give $^{A}(Na_{0.75}K_{0.27})$ ${}^{B}(Na_{1.45}Ca_{0.33}Fe_{0.22}^{2+})^{C}(Mg_{3.50}Fe_{0.61}^{2+}Fe_{0.85}^{3+}Mn_{0.02})$ $^{T}(Si_{7.84}Al_{0.13}Ti_{0.02}^{4+})O_{22}^{W}[F_{0.55}(OH)_{1.45}]$. This composition is a ^BFe- and F-rich magnesioarfvedsonite. The measured unit-cell parameters $(a = 9.84(1) \text{ Å}, b = 18.03(2) \text{ Å}, c = 5.30(1) \text{ Å}, \beta =$ 103.25 (25)°) are consistent with those of the sample used in the present work, but more needs to be known about the presence and amount of the oxo component, an issue that can now be addressed based on the present knowledge of amphibole crystal chemistry and on the present work.

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