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New X-Ray and Compositional Data for Farringtonite, $Mg_3(PO_4)_2$ [1]

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Abstract

New data for the meteoritic mineral farringtonite indicates that it is essentially $Mg_3(PO_4)_2$ with some Fe^{2+} substitution for Mg but with less than 0.05 wt percent Si substitution for P. Farringtonite has $a = 8.79$, $b = 8.22$, $c = 5.07$ Å, $\beta = 120.5°$, and space group $P2_1/a$. Indexed powder data are presented. Farringtonite may co-exist with olivine, iron metal, and schreibersite under equilibrium conditions; its survival in the pallasites does not require rapid cooling.

The empirical formula of farringtonite, a then-new mineral from the Springwater pallasite, was correctly determined by DuFresne and Roy (1961) as $Mg_3(PO_4)_2$. Some of their published data, however, have left doubt that the mineral is equivalent to the synthetic compound. The ASTM card for farringtonite (13-554) contains a question mark after the formula $Mg_3(PO_4)_2$. Similarly the ASTM card (19-767) for the compound $Mg_3(PO_4)_2$ questions the equivalence with the mineral. Because of these uncertainties we have re-examined the composition and X-ray data for farringtonite to establish an exact description. The mineral, as yet unknown terrestrially, has subsequently been identified in several other pallasites by Fuchs (1967). We here include new compositional data for the mineral from the Krasnojarsk and Springwater pallasites and new X-ray data for Springwater farringtonite; the X-ray powder pattern for Krasnojarsk farringtonite is identical and is not included.

The composition given by DuFresne and Roy (1961) was determined by optical spectrography on two concentrated samples. There are considerable differences between the analyses, the major elements deviating several percentage points from the ideal composition. They concluded that the composition approached that of $Mg_3(PO_4)_2$ and furthermore their X-ray powder pattern was nearly identical to that for the synthetic compound. The silica content (about 3 wt percent), in what they considered the better of their two analyses, was considered to be in solid solution. Olsen and Fredriksson (1966) found less than 500 ppm of silica in their microprobe analyses of Springwater farringtonite; this probe analysis, however, totalled 104 percent for some unknown reason.

Electron microprobe analyses were made of the mineral from both the Springwater and Krasnojarsk pallasites (Table 1). The composition is essentially $Mg_3(PO_4)_2$ with some Fe^{2+} substitution for Mg, but with only a trace substitution of Si for P.

The X-ray powder pattern reported by DuFresne and Roy (1961) cites a weak line at 3.45Å (close to the very strong line at 3.41) and a weak, diffuse line at 2.64Å. Neither of these is present in our pattern or in the two patterns for synthetic $Mg_3(PO_4)_2$ in the ASTM file. Additionally, several prominent lines were omitted: 3.20, 2.99, 1.86, 1.83, 1.64 and 1.56Å. Our indexed X-ray powder pattern is presented in Table 2. Cell constants and indexing were obtained from precession and Weissenberg photographs on two selected grains. Rota-

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TABLE 1. Electron Microprobe Analyses of Farringtonite from Two Pallasites*

	Springwater	Krasnojarsk
P_2O_5	53.2	53.9
MgO	43.1	44.9
FeO	4.1	2.7
MnO	0.19	0.13
CaO	0.07	0.08
SiO_2	0.09	0.07
Totals	100.8	101.8

Empirical formulae based on 8 oxygens:

Springwater: $(Mg_{2.84}\ Fe_{0.15}\ Mn_{0.01}\ Ca_{0.003})_{3.00}\ P_{2.00}O_8$

Krasnojarsk: $(Mg_{2.92}\ Fe_{0.10}\ Mn_{0.005}\ Ca_{0.004})_{3.03}\ P_{1.99}O_8$

*Averaged results from 6 grains of each. Data corrected for deadtime, background, absorption, fluorescence and atomic number according to Smith (1965).

tions were made about the *b* and *c* crystallographic axes. Our monoclinic cell constants (underlined) compare favorably with those we determined from Weissenberg photographs for synthetic $Mg_3(PO_4)_2$: *a* 8.79(1), 8.82(2); *b* 8.22(2), 8.23(2); *c* 5.07(1), 5.070(4)Å; *β* 120.5(5), 121.0(5)°. Our constants for the compound deviate slightly from those reported by Calvo (1963) from diffractometer tracings: *a* 8.80; *b* 8.31; *c* 5.07Å; *β* 120.7°. The space group for farringtonite is $P2_1/a$, which is the same as that tentatively assigned by Calvo for $Mg_3(PO_4)_2$.

The optical properties are essentially the same as those published by DuFresne and Roy (1961). Our 2*V* of 47–48° is lower than their 54–55°.

Farringtonite in Springwater has suffered some terrestrial alteration which has not been previously reported. Most grains are surrounded by and often include a straw-yellow powdery material which we have identified as $MgHPO_4 \cdot 3H_2O$. Although its X-ray powder pattern is identical to that listed for this substance on ASTM card 20-153, considerable iron is present, judging by the film darkening taken with Cu radiation. We were careful to select unaltered portions of farringtonite grains for our X-ray and analytical work.

A final point raised by DuFresne and Roy (1961) pertains to the stability of farringtonite in the pres-

TABLE 2. X-Ray Diffraction Data for Farringtonite from the Springwater Pallasite*

(*hkl*)	*d* (obs) Å	*d* (calc)** Å	*I* (obs)†	*I* (calc)††
110	5.58	5.57	12	15
001 $11\bar{1}$	4.34	4.37 4.30	38	20 22
020 $20\bar{1}$	4.09	4.11 4.06	40	26 27
011	3.85	3.86	67	90
$21\bar{1}$ 120	3.65	3.64 3.61	37	28 4
210	3.443	3.440	100	100
$12\bar{1}$	3.192	3.189	25	24
021	2.994	2.994	28	14
111 $22\bar{1}$	2.899	2.944 2.886	7	4 6
220	2.788	2.785	24	16
$20\bar{2}$	2.531	2.527	29	14
121	2.500	2.503	29	35
310 $13\bar{1}$	2.411	2.413 2.408	48	11 31
031	2.322	2.321	15	7
$23\bar{1}$	2.276	2.270	6	13
211	2.242	2.245	8	10
230	2.223	2.220	8	2
002	2.182	2.184	3	5
320	2.151	2.151	5	2
$41\bar{1}$	2.122	2.116	33	17
$12\bar{2}$	2.109	2.109	5	8
131 040	2.062	2.069 2.055	20	6 8
$32\bar{2}$ $40\bar{2}$	2.037	2.034 2.028	25	17 5
140	1.985	1.984	3	2
022	1.930	1.929	5	6
$14\bar{1}$	1.905	1.904	3	1
041 $23\bar{2}$ 330	1.857	1.860 1.858 1.857	12	2 2 3
$13\bar{2}$ $42\bar{2}$	1.826	1.829 1.819	22	5 11
$33\bar{2}$ 311	1.775	1.780 1.778	13	5 10
141	1.722	1.722	14	7
122 $51\bar{1}$	1.692	1.696 1.691	20	9 6
$21\bar{3}$	1.639	1.639	11	7
150	1.609	1.607	6	8
$52\bar{1}$	1.594	1.593	5	6
$32\bar{3}$	1.560	1.559	15	12

plus 36 lines to *d* = 0.96Å.

*Norelco powder camera (diam. 11.45 cm), Cu $K\alpha_1\alpha_2$, Ni filter. Diamond used as an internal standard.

**a(Å) = 8.79(1); b(Å) = 8.22(2); c(Å) = 5.07(1); β = 120.5°(5).

†Densitometer tracing of film.

††Following the suggestion by Calvo (1963) that $Mg_3(PO_4)_2$ was isomorphous with $\gamma Zn_3(PO_4)_2$, we have combined the atomic parameters of the latter with the composition and space group of farringtonite in a computer program (Yvon et al, 1969) to obtain calculated d-spacings and line intensities. Intensities were not corrected for temperature factors or absorption.

ence of Fe-Ni metal and schreibersite, $(Fe,Ni)_3P$. They contended that the phosphate is unstable at its melting point (given as 1180°C) in the presence of metal and therefore its survival required that the meteorite cooled rapidly through "the freezing interval" of a few days. This hypothesis is untenable in light of the following considerations, some of which were not available to them. Short and Goldstein (1967) calculated that the cooling rate of the Springwater pallasite was the lowest of many irons and pallasites they considered—about 0.4°C per million years in the vicinity of 500°C. This rate indicates that the meteorite resided in a well-insulated position in a parent body such that the cooliing rate was low even at higher temperatures. Additional support for the attainment of thermal equilibrium in the pallasites was given by Mason (1963) who showed that the composition of olivine in a given pallasite is uniform (including Springwater) and is related to the composition of the metal according to Prior's rules. Fuchs (1967) has shown that the occurrence of the meteoritic phosphate minerals farringtonite, stanfieldite $[Ca_4(Mg,Fe)_5(PO_4)_6]$, and whitlockite $[Ca_3(PO_4)_2]$ in the pallasites is in accord with the equilibrium diagram of Ando (1958). Olsen and Fredriksson (1966) calculated from thermodynamic data the oxidation conditions for the equilibrium between olivine, iron metal, schreibersite, farringtonite, and oxygen. The co-existence of these phases at a given temperature is related to the fugacity of oxygen. Based on all of these considerations, rapid cooling is not a requirement to account for the observed phases, including farringtonite.

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