

## The crystal structure of esperite, with a revised chemical formula, $\text{PbCa}_2(\text{ZnSiO}_4)_3$ , isostructural with beryllonite

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### ABSTRACT

Esperite from Franklin, New Jersey, was first described by Moore and Ribbe (1965) as monoclinic with a well-developed “superlattice”  $a = 2 \times 8.814(2) \text{ \AA}$ ,  $b = 8.270(3) \text{ \AA}$ ,  $c = 2 \times 15.26(1) \text{ \AA}$ ,  $\beta \approx 90^\circ$ , space group  $P2_1/n$  (subcell), and the chemical formula  $\text{PbCa}_3(\text{ZnSiO}_4)_4$ . They attributed “superlattice” reflections to the ordered distributions of Pb and Ca cations over four beryllonite-type subcells for esperite with the Ca:Pb ratio greater than 2:1.

We examined two esperite fragments from the type sample using single-crystal X-ray diffraction, electron microprobe analysis, and Raman spectroscopy. Although both fragments have Ca:Pb  $\approx 1.8$ , one exhibits the “superlattice” reflections as observed by Moore and Ribbe (1965), whereas the other does not. The sample without “superlattice” reflections has unit-cell parameters  $a = 8.7889(2)$ ,  $b = 8.2685(2)$ ,  $c = 15.254(3) \text{ \AA}$ ,  $\beta = 90.050(1)^\circ$ ,  $V = 1108.49(4) \text{ \AA}^3$ , and the chemical composition  $\text{Pb}_{1.00}(\text{Ca}_{1.86}\text{Fe}_{0.07}^{2+}\text{Mn}_{0.04}\text{Cr}_{0.02}^{3+})_{\Sigma=1.99}(\text{Zn}_{1.00}\text{Si}_{1.00}\text{O}_4)_3$ . Its crystal structure was solved in space group  $P2_1/n$  ( $R_1 = 0.022$ ). Esperite is isostructural with beryllonite,  $\text{NaBePO}_4$ , and its ideal chemical formula should, therefore, be revised to  $\text{PbCa}_2(\text{ZnSiO}_4)_3$ ,  $Z = 4$ . The  $\text{ZnO}_4$  and  $\text{SiO}_4$  tetrahedra in esperite share corners to form an ordered framework, with  $\text{Pb}^{2+}$  occupying the nine-coordinated site in the large channels and  $\text{Ca}^{2+}$  occupying the two distinct octahedral sites in the small channels. The so-called “superlattice” reflections are attributed to triple twins, a trilling of  $\sim 60^\circ$  rotational twinning around the  $b$  axis, similar to those observed in many other beryllonite-type materials. A phase transformation from a high-temperature polymorph to the esperite structure is proposed to be responsible for the twinning formation.

**Keywords:** Esperite, beryllonite, Pb-Zn silicates, crystal chemistry, X-ray diffraction

### INTRODUCTION

Two Pb-Zn silicate minerals, larsenite  $\text{PbZnSiO}_4$  and “calcium-larsenite”  $(\text{Pb,Ca})\text{ZnSiO}_4$ , from a metamorphosed stratiform zinc orebody in Franklin, New Jersey, were first described by Palache et al. (1928a, 1928b), who, based on morphological and chemical data, proposed that the two minerals were structurally related to olivine with orthorhombic symmetry. Subsequent X-ray diffraction studies by Layman (1957) and Moore and Ribbe (1965), however, revealed that neither of the two minerals is isomorphous with olivine. Furthermore, from various single-crystal X-ray diffraction photographs, Moore and Ribbe (1965) found that “calcium-larsenite” is also structurally different from larsenite, leading them to give the mineral a new name, esperite (also after Esper S. Larsen), with the ideal chemical formula  $\text{PbCa}_3(\text{ZnSiO}_4)_4$ . They described esperite as monoclinic with a well-developed superstructure: the subcell (excluding superlattice reflections) gives  $a = 8.814$ ,  $b = 8.270$ ,  $c = 15.26 \text{ \AA}$ ,  $\beta \approx 90^\circ$ , and space group  $P2_1/n$ , whereas the supercell (including superlattice reflections) is  $B$ -centered with doubled  $a$  ( $=2 \times 8.814 \text{ \AA}$ ) and  $c$  ( $=2 \times 15.26 \text{ \AA}$ ) dimensions. Intriguingly, without the structure determination, Moore and Ribbe (1965) noted that esperite might be structurally related to beryllonite  $\text{NaBePO}_4$  or trimerite  $\text{CaMn}_2^{3+}$

( $\text{BeSiO}_4$ )<sub>3</sub>, but its chemical formula did not correspond. From X-ray diffraction experiments on both natural (from the type locality) and synthetic esperite specimens, Ito (1968) found that, unlike the natural sample, synthetic esperite displays no superlattice reflections and has a pseudo-orthorhombic cell with  $a = 8.79$ ,  $b = 8.29$ , and  $c = 15.25 \text{ \AA}$ . Dunn (1985) conducted a series of electron microprobe analyses on Pb-silicates from Franklin, New Jersey, and concluded that the chemical composition of esperite varies principally in the Ca:Pb ratio, with an empirical formula  $\text{Ca}_{2.80}\text{Pb}_{1.15}\text{Mn}_{0.08}\text{Mg}_{0.09}\text{Zn}_{3.80}\text{Si}_{4.04}\text{O}_{16}$ . To date, esperite has only been reported from one other locality, the El Dragón mine, Potosi, Bolivia (Grundmann et al. 1990), but no chemical composition has been given for that occurrence. Since then, no detailed crystallographic study on esperite has been reported. In this paper, we report the results of our re-examination of esperite from the holotype sample by means of single-crystal X-ray diffraction, electron microprobe analysis, and Raman spectroscopy and re-define its ideal chemical formula as  $\text{PbCa}_2(\text{ZnSiO}_4)_3$ , based on our determined structure model.

### EXPERIMENTAL METHODS

A fragment of esperite from the holotype sample [CMNMC 56855 in the Canadian Museum of Nature Mineral Collection in Ottawa, originally studied by Moore and Ribbe (1965)], Parker Shaft, Franklin, Sussex Co., New Jersey, U.S.A., was obtained for this study, which is now in the collection of the RRUFF project

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(deposition no. R070512; <http://rruff.info/R070512>). Based on optical examination and X-ray diffraction peak profiles, two nearly equi-dimensional single crystals, sample 1 with dimensions  $0.05 \times 0.05 \times 0.06$  mm and sample 2 with dimensions  $0.07 \times 0.06 \times 0.06$  mm, were selected for the experiments. X-ray diffraction data were collected on a Bruker X8 APEX2 CCD X-ray diffractometer using graphite-monochromatized MoK $\alpha$  radiation. Detailed procedures for data collections and processes were similar to those described by Yang and Downs (2008). To our surprise, the two selected crystals yielded different outcomes: The unit-cell dimensions of samples 1 and 2 correspond, respectively, to those for the subcell and supercell reported by Moore and Ribbe (1965) (Fig. 1). Further analysis demonstrated that the pseudo-hexagonal unit-cell dimensions of sample 2 are actually a result of triple twins corresponding to a  $\sim 60^\circ$  rotation around the  $b$  axis of the monoclinic cell (Fig. 2). If we use  $a_H$ ,  $b_H$ , and  $c_H$  to represent the pseudo-hexagonal cell (or “supercell”) parameters,  $a_1$ ,  $b_1$ , and  $c_1$  for monoclinic cell 1,  $a_2$ ,  $b_2$ , and  $c_2$  for monoclinic cell 2, and  $a_3$ ,  $b_3$ , and  $c_3$  for monoclinic cell 3, then the transformation from the pseudo-hexagonal cell to monoclinic cell 1 is

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0 & 1 \\ 0.5 & 1 & 0 \end{bmatrix} \begin{bmatrix} a_H \\ b_H \\ c_H \end{bmatrix}.$$

The matrix for the transformation from monoclinic cell 1 to 2 is

$$\begin{bmatrix} 0.5 & 0 & 0.5 \\ 0 & 1 & 0 \\ -1.5 & 0 & 0.5 \end{bmatrix}$$

and that for the transformation from monoclinic cell 1 to 3 is

$$\begin{bmatrix} -0.5 & 0 & 0.5 \\ 0 & 1 & 0 \\ -1.5 & 0 & -0.5 \end{bmatrix}.$$

Subsequently, the X-ray intensity data of sample 2 were processed with the software TWINABS (Sheldrick 2007). All reflections of both samples were indexed on the basis of a monoclinic unit cell. The systematic absences of reflections point to the unique space group  $P2_1/n$ . The structures of both esperite crystals were solved and refined using SHELXL97 (Sheldrick 2008). Though the two samples produced rather comparable structural data, only the results from sample 1 are given here because of its better refinement statistics (e.g.,  $R_1 = 0.022$  for sample 1 vs. 0.047 for sample 2). The effects of including the trace amounts of Fe, Mn, and Cr on the crystal structure were tested in the refinements and they were found to be insignificant, so the crystal chemistry was assumed to be ideal,  $\text{PbCa}_2(\text{ZnSiO}_4)_4$ , throughout the structure refinements. Final crystallographic and refinement statistics data are listed in Table 1, atomic coordinates and isotropic displacement parameters in Table 2, anisotropic displacement parameters in Table 3, and selected interatomic distances in Table 4. (CIF<sup>1</sup> is on deposit.)

The chemical compositions of the two crystals examined by X-ray diffraction were analyzed with a Cameca SX50 electron microprobe with an accelerating potential of 15 kV and a beam current of 20 nA. Standards included diopside for Si and Ca, rhodonite for Mn, wulfenite for Pb, fayalite for Fe, chromite for Cr, and willemite for Zn. Online reduction of the raw data was done using the ZAF matrix correction. The average results (eight analysis points for each sample) are given Table 5.

The Raman spectrum of esperite was collected from a randomly oriented crystal at 100% power on a Thermo Almega microRaman system, using a solid-state laser with a frequency of 780 nm, and a thermoelectrically cooled CCD detector. The laser is partially polarized with  $4 \text{ cm}^{-1}$  resolution and a spot size of 1  $\mu\text{m}$ . The Raman spectra of the two esperite crystals used for the X-ray diffraction experiments are essentially indiscernible.

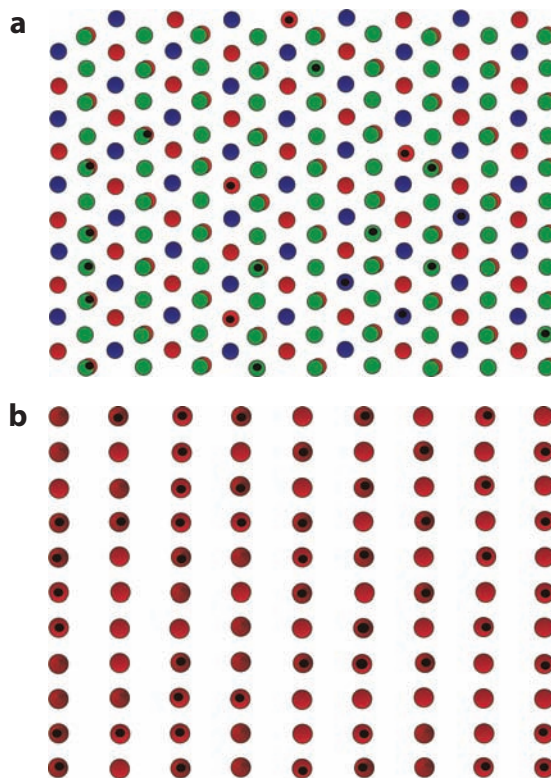


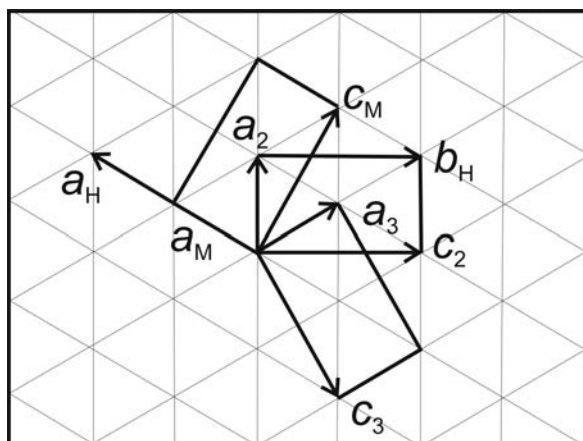
FIGURE 1. Reciprocal plots of X-ray reflections (viewed down  $b^*$ ) from (a) twinned and (b) untwinned esperite samples. The blue, green, and red spheres in **a** represent reflections from three different twin domains, whereas the small black spheres in **b** represent weak reflections [ $I < 5\sigma(I)$ ].

## DISCUSSION

### Crystal structure

Esperite is isotopic with beryllonite,  $\text{NaBePO}_4$  (Golovastikov 1961; Giuseppetti and Tadini 1973), a stuffed derivative of tridymite. Materials belonging to the large family of tridymite derivatives have been of growing interest owing to their structural properties, such as the open-framework architecture and polymorphism, as well as their physical properties, including ferroic properties or potential as hosts for fluorescent materials (e.g., Hammond et al. 1998). A review on the structural behavior of tetrahedral framework compounds as a function of temperature, pressure, and composition has been presented by Taylor (1983, 1984). In addition to esperite, many other compounds exhibit the beryllonite-type structure, such as trimerite  $\text{CaMn}_2^{2+}(\text{BeSiO}_4)_3$  (Aminoff 1926; Klaska and Jarchow 1977), synthetic  $\text{NaBSiO}_4$  (Graetsch and Schreyer 2005),  $\text{NaAlGeO}_4$  (Sandomirskii et al. 1986; Barbier and Fleet 1987, 1988; Chen et al. 1994),  $\text{NaGaSiO}_4$  (Barbier and Fleet 1987; Chen et al. 1994),  $\text{NaGaGeO}_4$  (Barbier and Fleet 1987),  $\text{CaAl}_2\text{O}_4$  (Hörkner and Müller-Buschbaum 1976),  $\text{CaAl}_{1.8}\text{Fe}_{0.2}\text{O}_4$  (Kahlenberg 2001),  $\text{AgXPO}_4$  ( $X = \text{Be, Zn}$ ) (Hammond et al. 1998), and  $\text{BaZnGeO}_4$  (Iijima et al. 1982). Another closely related mineral is malinkoite  $\text{NaBSiO}_4$  (Sokolova et al. 2001), which has a synthetic polymorph that is isostructural with beryllonite (Graetsch and Schreyer 2005).

<sup>1</sup> Deposit item AM-10-026, CIF. Deposit items are available two ways: For a paper copy contact the Business Office of the Mineralogical Society of America (see inside front cover of recent issue) for price information. For an electronic copy visit the MSA web site at <http://www.minsocam.org>, go to the *American Mineralogist* Contents, find the table of contents for the specific volume/issue wanted, and then click on the deposit link there.

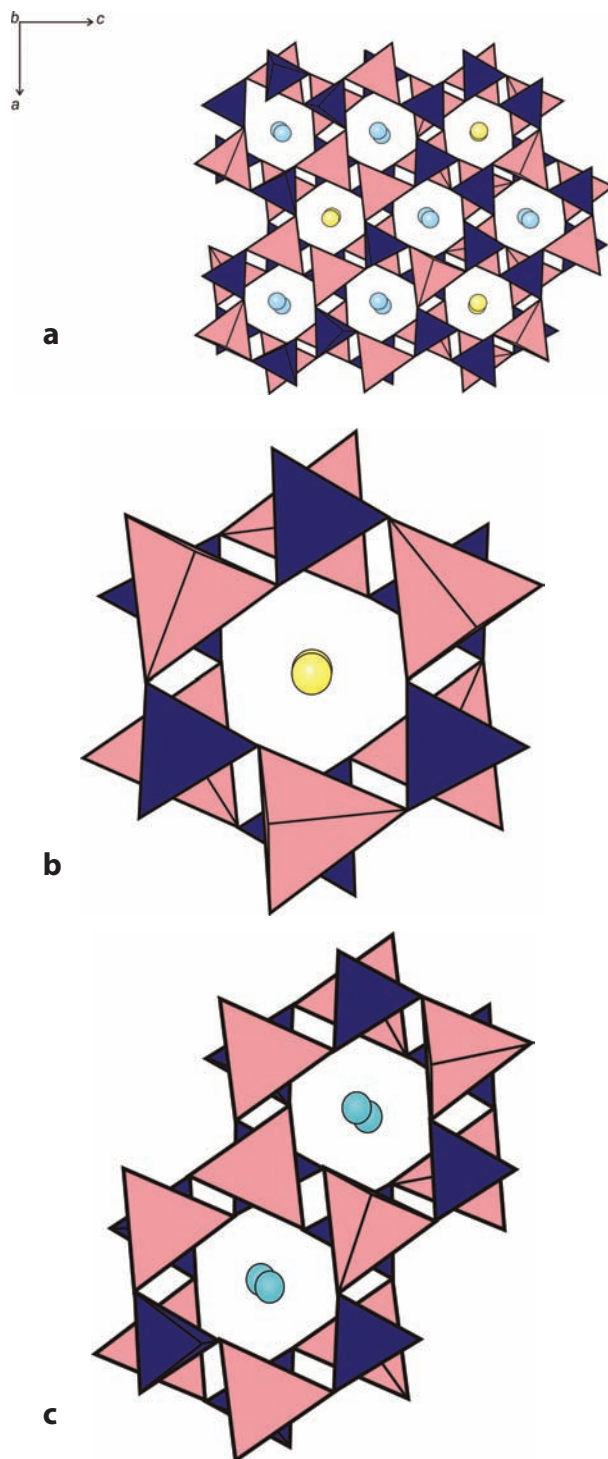


**FIGURE 2.** Illustration of triple twins, viewed along the  $b$  axis of the esperite cell, and their relationships with the pseudo-hexagonal cell. The  $a$  and  $b$  dimensions of the pseudo-hexagonal cell are indicated by  $a_H$  and  $b_H$ , respectively. The three monoclinic esperite cells, indicated by  $a_1$  and  $c_1$  for cell 1,  $a_2$  and  $c_2$  for cell 2, and  $a_3$  and  $c_3$  for cell 3, are related by a trilling of  $\sim 60^\circ$  rotational twinning around the  $b$  axis.

**TABLE 1.** Crystallographic and refinement statistics data for esperite

Ideal chemical formula	$\text{PbCa}_2(\text{ZnSiO}_4)_3$
$a$ (Å)	8.7889(2)
$b$ (Å)	8.2685(2)
$c$ (Å)	15.2535(3)
$\beta$ (°)	90.050(1)
$V$ (Å <sup>3</sup> )	1108.49(4)
Space group	$P2_1/n$ (no. 14)
$Z$	4
$\mu$ (mm <sup>-1</sup> )	22.96
$D$ (calc) (g/cm <sup>3</sup> )	4.564
$\theta$ range for data collection (°)	2.67–40.81
Reflections collected	24487
Unique reflections	7025
$I > 2\sigma(I)$	5935
Parameters refined	191
$R$ (int) (%)	3.21
$R$ (%) [ $I > 2\sigma(I)$ ]	$R_1 = 2.22$ and $wR_2 = 4.41$
$R$ (%) (all data)	$R_1 = 3.07$ and $wR_2 = 4.61$
Goodness of fit	1.001

In tridymite and its stuffed derivatives, corner-sharing of the tetrahedra results in a three dimensional framework in which the tetrahedra form layers made up of six-membered rings [see reviews by Taylor (1983, 1984)]. Various derivatives of tridymite differ chiefly in the stacking of tetrahedral layers and the configurations of six-membered rings. In tridymite, nepheline, and kalsilite, there is only one type of six-membered ring of tetrahedra, with apices that point alternately up (U) and down (D), when viewed along the hexagonal or pseudo-hexagonal axis. In the beryllonite-type materials, however, only a third of the rings are of the UDUDUD type, whereas two thirds of the rings are of the UUUDDUD type. The general chemical formula for beryllonite-type materials can be expressed as  $AYXO_4$  or  $AB_2(YXO_4)_3$ , where  $X$  and  $Y$  are the tetrahedral framework formers and  $A$  and/or  $B$  are the framework modifiers. In the esperite structure, the three-dimensional framework consists of the corner-shared  $\text{ZnO}_4$  and  $\text{SiO}_4$  tetrahedra, with the UDUDUD and UUUDDUD rings encapsulating two distinct channels that run parallel to the  $b$  axis (Fig. 3a). The channels made of the



**FIGURE 3.** (a) The tetrahedral framework of the esperite structure viewed down the  $b$  axis. The  $\text{SiO}_4$  and  $\text{ZnO}_4$  tetrahedra are colored dark blue and pink, respectively. There are two types of rings in the esperite structure: (b) the larger UDUDUD rings and (c) the smaller UUUDDUD rings, where U and D represent apices of tetrahedra pointing up and down, respectively. There are twice as many UUUDDUD rings as UDUDUD rings, which are occupied by  $\text{Ca}^{2+}$  (turquoise spheres) and  $\text{Pb}^{2+}$  (yellow spheres) cations, respectively.

**TABLE 2.** Coordinates and isotropic displacement parameters of atoms in esperite

	x	y	z	$U_{iso}$
Pb	0.245756(8)	0.055200(9)	0.250826(5)	0.00928(2)
Ca1	0.73827(4)	0.46078(5)	0.07414(3)	0.00779(6)
Ca2	0.76071(4)	0.03835(5)	0.08855(3)	0.00768(6)
Zn1	0.57626(3)	0.33526(3)	0.24338(2)	0.00795(4)
Zn2	0.07422(3)	0.33879(3)	0.09038(2)	0.00789(4)
Zn3	0.09274(3)	0.33936(3)	0.41626(2)	0.00797(4)
Si1	0.91112(6)	0.22833(7)	0.26527(4)	0.00588(9)
Si2	0.43933(6)	0.22969(7)	0.41207(4)	0.00581(9)
Si3	0.39507(6)	0.22585(7)	0.07455(4)	0.00596(9)
O1	0.4095(2)	0.2295(2)	0.1819(1)	0.0094(2)
O2	0.4339(2)	0.7366(2)	0.2947(1)	0.0093(2)
O3	0.2698(2)	0.2303(2)	0.3661(1)	0.0095(2)
O4	0.7684(2)	0.2503(2)	0.1979(1)	0.0087(2)
O5	0.9125(2)	0.2422(2)	0.0170(1)	0.0082(2)
O6	0.5655(2)	0.2541(2)	0.0346(1)	0.0086(2)
O7	0.5464(2)	0.3672(2)	0.3678(1)	0.0097(2)
O8	0.2762(2)	0.3633(2)	0.0417(1)	0.0099(2)
O9	0.9147(2)	0.3644(2)	0.3420(1)	0.0097(2)
O10	0.5889(2)	0.5519(2)	0.1881(1)	0.0115(3)
O11	-0.0172(2)	0.5545(2)	0.1060(1)	0.0102(3)
O12	0.1723(2)	0.5508(2)	0.4532(1)	0.0103(3)

**TABLE 3.** Anisotropic displacement parameters of atoms in esperite

Atom	$U_{11}$	$U_{22}$	$U_{33}$	$U_{12}$	$U_{13}$	$U_{23}$
Pb	0.01076(3)	0.00671(3)	0.01038(3)	0.00027(2)	0.00008(2)	-0.00001(2)
Ca1	0.0082(2)	0.0068(2)	0.0084(2)	-0.0006(1)	0.0008(1)	0.0004(1)
Ca2	0.0095(2)	0.0060(2)	0.0076(2)	-0.0006(1)	-0.0010(1)	0.0004(1)
Zn1	0.00805(9)	0.00877(9)	0.00704(9)	-0.00053(7)	0.00070(7)	-0.00056(7)
Zn2	0.00759(9)	0.00824(9)	0.00786(9)	-0.00036(7)	0.00004(7)	0.00054(7)
Zn3	0.00828(9)	0.00850(9)	0.00713(9)	0.00048(7)	-0.00057(7)	-0.00032(7)
Si1	0.0062(2)	0.0058(2)	0.0057(2)	0.0005(2)	-0.0001(2)	-0.0003(2)
Si2	0.0062(2)	0.0059(2)	0.0053(2)	-0.0003(2)	0.0005(2)	0.0000(2)
Si3	0.0060(2)	0.0058(2)	0.0062(2)	-0.0005(2)	0.0002(2)	0.0001(2)
O1	0.0095(6)	0.0121(6)	0.0066(6)	-0.0038(5)	0.0005(5)	-0.0003(5)
O2	0.0075(6)	0.0121(6)	0.0083(6)	-0.0016(5)	0.0007(5)	-0.0038(5)
O3	0.0079(6)	0.0117(6)	0.0089(6)	0.0023(5)	-0.0019(5)	-0.0038(5)
O4	0.0080(6)	0.0109(6)	0.0071(6)	0.0019(5)	-0.0012(4)	-0.0016(5)
O5	0.0097(6)	0.0096(6)	0.0052(5)	-0.0020(5)	0.0004(4)	-0.0002(4)
O6	0.0067(6)	0.0104(6)	0.0088(6)	-0.0015(5)	0.0012(4)	-0.0018(5)
O7	0.0130(6)	0.0088(6)	0.0073(6)	-0.0034(5)	0.0019(5)	0.0002(4)
O8	0.0091(6)	0.0087(6)	0.0118(6)	0.0021(5)	0.0013(5)	0.0041(5)
O9	0.0107(6)	0.0085(6)	0.0098(6)	0.0015(5)	-0.0029(5)	-0.0036(5)
O10	0.0173(7)	0.0063(6)	0.0108(6)	-0.0007(5)	0.0033(5)	-0.0009(5)
O11	0.0096(6)	0.0055(6)	0.0156(7)	-0.0006(4)	0.0012(5)	0.0004(5)
O12	0.0123(6)	0.0067(6)	0.0120(6)	0.0011(5)	-0.0034(5)	0.0005(5)

UDUDUD rings (Fig. 3b) are larger than those made of the UDUDD rings (Fig. 3c), which are hereafter abbreviated as L- and S-channels, respectively, for simplicity. The S-channels contain two nonequivalent, face-sharing  $\text{CaO}_6$  octahedral sites (Ca1 and Ca2), with the Ca-Ca distances alternating as 3.505 and 4.785 Å, whereas the L-channels contain the nine-coordinated Pb cations, with a Pb-Pb separation of 4.135 Å.

The two distinct  $\text{CaO}_6$  octahedra display a similar average  $\langle\text{Ca-O}\rangle$  distance of  $\sim 2.40$  Å, with individual bond lengths ranging between 2.3 and 2.6 Å. As is typical for face-sharing polyhedra, the bonds associated with the three face-shared O atoms, O4, O5, O6, are longer than the rest of the Ca-O bonds within the distorted  $\text{CaO}_6$  octahedra. The Pb cation is situated in a nine-coordinated, highly distorted tricapped trigonal antiprism, with an average  $\langle\text{Pb-O}\rangle$  distance of 2.887 Å. However, the individual Pb-O bond lengths vary remarkably: While the Pb-O1, Pb-O2, and Pb-O3 bond distances are only  $\sim 2.29$  Å, the other six Pb-O bonds are greater than 3.0 Å, indicating that Pb is considerably off-centered. In fact, the three short Pb-O bond distances in esperite are even

**TABLE 4.** Selected interatomic distances in esperite

Pb-O1	2.293(1)	Si1-O2	1.643(2)
Pb-O1	3.189(2)	Si1-O4	1.631(2)
Pb-O2	2.286(1)	Si1-O9	1.624(2)
Pb-O2	3.182(2)	Si1-O10	1.623(2)
Pb-O3	2.288(1)	$\langle\text{Si1-O}\rangle$	1.630
Pb-O3	3.228(2)		
Pb-O10	3.086(2)	Si2-O3	1.646(2)
Pb-O11	3.233(2)	Si2-O5	1.635(2)
Pb-O12	3.196(2)	Si2-O7	1.623(2)
	2.887	Si2-O11	1.626(2)
		$\langle\text{Si2-O}\rangle$	1.632
Ca1-O4	2.581(2)		
Ca1-O5	2.524(2)	Si3-O1	1.643(1)
Ca1-O6	2.364(2)	Si3-O6	1.634(2)
Ca1-O8	2.292(2)	Si3-O8	1.622(2)
Ca1-O10	2.306(2)	Si3-O12	1.620(2)
Ca1-O11	2.335(2)	$\langle\text{Si3-O}\rangle$	1.63
$\langle\text{Ca1-O}\rangle$	2.401		
Ca2-O4	2.421(2)	Zn1-O1	1.947(2)
Ca2-O5	2.411(1)	Zn1-O4	1.957(1)
Ca2-O6	2.608(2)	Zn1-O7	1.934(1)
Ca2-O7	2.306(2)	Zn1-O10	1.983(1)
Ca2-O9	2.360(1)	$\langle\text{Zn1-O}\rangle$	1.955
Ca2-O12	2.325(2)	Zn2-O2	1.947(1)
$\langle\text{Ca2-O}\rangle$	2.405	Zn2-O5	1.977(1)
		Zn2-O8	1.936(1)
		Zn2-O11	1.971(1)
		$\langle\text{Zn2-O}\rangle$	1.958
		Zn3-O3	1.955(1)
		Zn3-O6	1.978(1)
		Zn3-O9	1.942(2)
		Zn3-O12	1.965(1)
		$\langle\text{Zn3-O}\rangle$	1.96

**TABLE 5.** Chemical composition of esperite

Oxide (wt%)	1	2	3	4	5	6
ZnO	31.47	31.07	30.61	32.3	34.5	
PbO	29.55	29.12	27.63	26.8	26.1	
SiO <sub>2</sub>	23.83	23.76	24.10	25.3	27.1	
CaO	13.53	13.18	16.36	16.4	14.3	
FeO <sub>tot</sub>	0.70	1.24	0.48			
MnO	0.33	0.33	0.57	0.6		
MgO			0.23	0.4		
Cr <sub>2</sub> O <sub>3</sub>	0.20	0.44				
Total	99.62	99.14	99.98	101.8	102.0	
<b>Cation numbers normalized based on 12 O atoms</b>						
Ca	1.86	1.79	2.18	2.11	1.80	2.07
Fe	0.07	0.13	0.05	0.00		
Mn	0.04	0.04	0.06	0.06		
Cr	0.02	0.04	0.00	0.00		
Σ	1.99	2.00	2.29	2.17	1.80	2.07
Pb	1.00	0.99	0.92	0.87	0.83	0.93
Zn	3.00	3.00	2.81	2.86	3.00	3.00
Si	3.00	3.00	2.99	3.01	3.19	3.00

Notes: 1 and 2 = samples 1 and 2 of this study, respectively; 3 = Palache et al. (1928); 4 = Dunn (1985). 5 = Ito (1968), natural sample; 6 = Ito (1968), synthetic sample. No values for weight percentage were given.

shorter than the shortest Ca-O bonds (Table 4). They are also shorter than the corresponding Ca-O bond lengths ( $\sim 2.388$  Å) in isostructural  $\text{CaAl}_2\text{O}_4$  and  $\text{CaAl}_{1.8}\text{Fe}_{0.2}\text{O}_4$  (Kahlenberg 2001), despite the larger ionic radius of  $\text{Pb}^{2+}$  (1.35 vs. 1.18 Å for  $\text{Ca}^{2+}$  in the nine-coordination). By comparing  $\text{SrAl}_2\text{O}_4$  and  $\text{BaAl}_2\text{O}_4$  with  $\text{CaAl}_2\text{O}_4$  and  $\text{CaAl}_{1.8}\text{Fe}_{0.2}\text{O}_4$ , Kahlenberg (2001) suggested that the magnitude of the coordination distortion of cations in the channels formed by the UDUDUD rings increases with decreasing cation radius, and  $\text{Ca}^{2+}$  shows the worst adaptation to such an environment and is  $\sim 33\%$  under-bonded with regard to the ideal valence value of 2. Our data apparently contradict this statement. Moreover, the calculation of bond-valence sums

using the parameters given by Brese and O'Keeffe (1991) shows that  $\text{Pb}^{2+}$  in esperite is actually slightly over-bonded (2.192 v.u.) due to its pronounced "one-sided" coordination. The calculated bond valences for the three short Pb-O bonds sum to 1.861 v.u., making up 85% of its total bond valence. It should be pointed out that the one-sided coordination for  $\text{Pb}^{2+}$  we report here has also been observed in litharge and massicot (dimorphs of PbO), as well as in several other complex lead salts (e.g., Sahl 1970; Abel 1973; Hill 1985).

The strongly under-bonded nature of  $\text{Ca}^{2+}$  in the L-channels in beryllonite-type  $\text{CaAl}_2\text{O}_4$  and  $\text{CaAl}_{1.8}\text{Fe}_{0.2}\text{O}_4$  (Kahlenberg 2001) indicates that there is a geometrical mismatch between the  $\text{Ca}^{2+}$  size and the topology of the UDUDUD rings, which could potentially lower the stability of these two phases and make this site a possible target of attack by water (Kahlenberg 2001). Accordingly, accommodation of  $\text{Ca}^{2+}$  by the nine-coordinated site in the L-channels in beryllonite-type materials should be energetically unfavorable and avoided. For esperite, however, this site may be able to accommodate a certain amount of  $\text{Ca}^{2+}$ , owing to its over-bonded nature when it is fully occupied by  $\text{Pb}^{2+}$ . For the same reason, we think that the  $\text{Pb}^{2+}$  substitution for  $\text{Ca}^{2+}$  in the six-coordinated sites in the S-channels in esperite is probably very limited, as both Ca1 and Ca2 are only slightly under-bonded, with bond-valence sums of 1.936 and 1.899 v.u., respectively. In other words, it is not the short face-sharing contact between the Ca1 and Ca2 sites (3.505 Å) that precludes the accommodation of  $\text{Pb}^{2+}$  in the S-channels, since short Pb-Pb distances (~3.5 Å) have been found in Pb-metal and in the channels of lead aluminosilicate hollandite (Downs et al. 1995). Instead, it is most likely to result from the bonding requirements of the cations in the two sites. Similar arguments have also been given by Taylor (1983, 1984) and Barbier and Fleet (1987) for other tetrahedral framework materials.

### Chemical formula of esperite

Given the determined structure, the chemical formula of esperite should therefore be revised based on 12 O atoms, rather than on 16, as previously suggested (Moore and Ribbe 1965; Dunn 1985). Accordingly, for our sample 1, we have a chemical formula of  $\text{Pb}_{1.00}(\text{Ca}_{1.86}\text{Fe}_{0.07}^{\text{IV}}\text{Mn}_{0.04}\text{Cr}_{0.02}^{\text{VI}})_{\Sigma=1.99}(\text{Zn}_{1.00}\text{Si}_{1.00}\text{O}_4)_3$ , or ideally  $\text{PbCa}_2(\text{ZnSiO}_4)_3$ . Recasting the chemical data reported by Palache et al. (1928a) and Dunn (1985) for esperite (Table 5) based on 12 O atoms yields  $(\text{Pb}_{0.92}\text{Ca}_{0.08})_{\Sigma=1}\text{Ca}_{2.10}(\text{Zn}_{2.81}\text{Mn}_{0.06}\text{Fe}_{0.05})_{\Sigma=2.92}\text{Si}_{2.99}\text{O}_{12}$  (assuming tetrahedral Mn and Fe) and  $(\text{Pb}_{0.87}\text{Ca}_{0.11})_{\Sigma=0.98}\text{Ca}_{2.00}(\text{Zn}_{2.86}\text{Mn}_{0.06})_{\Sigma=2.92}\text{Si}_{3.01}\text{O}_{12}$  (assuming tetrahedral Mn), respectively.

The Ca:Pb and Si:Zn ratios are noticeably different in all examined esperite samples from the type locality (Table 5). These two ratios are 2.35:1 and 1.07:1, respectively, as given by Palache (1935), and 2.43:1 and 1.06:1 by Dunn (1985). Though Moore and Ribbe (1965) did not report the detailed chemistry of their esperite sample, they stated that the Ca:Pb and Si:Zn ratios "are very close to 3:1 and 1:1, respectively." To establish a relationship between esperite and larsenite, Ito (1968) synthesized a series of Pb-Zn-Ca silicates with the general formula  $\text{Pb}_x\text{Ca}_y\text{Zn}_z\text{SiO}_{2+n}$  ( $n = x + y + z$ ;  $x < 2$ ;  $y \leq 1$ ;  $z \leq 2$ ), which include larsenite  $\text{PbZnSiO}_4$ , barysilite  $(\text{Pb},\text{Mn})_3\text{Si}_2\text{O}_7$ , esperite  $(\text{Ca}_{0.69}\text{Pb}_{0.31})_4\text{Zn}_4\text{Si}_4\text{O}_{16}$ , margarosanite  $\text{Ca}_2\text{PbSi}_3\text{O}_9$ ,

phase  $\text{X}_1$   $\text{Pb}_2\text{CaZn}_3\text{Si}_3\text{O}_{12}$ , phase  $\text{X}_2$  (possibly a high-temperature polymorph of nasonite  $\text{Ca}_2\text{Pb}_3\text{Si}_3\text{O}_{11}$ ), and phase  $\text{X}_3$  (probable formula  $\text{CaZnSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$ ). However, he was unable to obtain esperite with the Ca:Pb ratio of 3:1 as suggested by Moore and Ribbe (1965) because there was always a small amount of other phases coexisting with esperite, such as phase  $\text{X}_1$  and hardystonite  $\text{Ca}_2\text{ZnSi}_2\text{O}_7$ . Nonetheless, if we recast the chemical data for esperite synthesized by Ito (1968) on the basis of 12 O atoms, then we have a chemical formula of  $\text{Pb}_{0.93}\text{Ca}_{2.07}(\text{ZnSiO}_4)_3$ , which is obviously very close to the ideal formula we proposed above. Interestingly, the chemistry of synthetic phase  $\text{X}_1$  (Ito 1968),  $\text{Pb}_2\text{Ca}(\text{ZnSiO}_4)_3$ , is very similar to that of esperite,  $\text{PbCa}_2(\text{ZnSiO}_4)_3$ , except for the Ca:Pb ratio, implying that this phase may be a tetrahedral framework material as well. The distinct powder X-ray diffraction patterns of the two phases (Ito 1968) point to an incomplete solid solution between them. By analogy with  $\text{KNa}_2(\text{AlGeO}_4)_3$  (the beryllonite-type structure) and  $\text{K}_2\text{Na}(\text{AlGeO}_4)_3$  (hexagonal kalsilite-type structure) (Klaska et al. 1979; Barbier and Fleet 1988), we postulate that phase  $\text{X}_1$  may be isostructural with or topologically similar to kalsilite.

### Raman spectroscopic data

There have been numerous investigations on various tetrahedral framework compounds (e.g., silica, feldspars, sodalites, zeolites, etc.) with Raman spectroscopy. Nevertheless, there is no Raman spectroscopic study on beryllonite-type materials in the literature. Plotted in Figure 4 is the Raman spectrum of esperite, along with that of beryllonite (taken from the RRUFF project: R060299) for comparison. The Raman spectra of both esperite and beryllonite can be tentatively classified into four regions. Region 1 includes the bands between 800 and 1100  $\text{cm}^{-1}$ , which are assigned to X-O stretching vibrations within the strongly bonded  $\text{XO}_4$  tetrahedra. These bands are characteristic of tetrahedral frameworks (e.g., Swainson et al. 2003; Zhang et al. 2003; Kihara et al. 2005; Khavryuchenko et al. 2007). The bands in region 2, between ~470 and 650  $\text{cm}^{-1}$ , are attributed to the X-O-Y bending vibrations. In region 3, from 320 to 470  $\text{cm}^{-1}$ , the bands are associated mainly with Y-O stretching vibrations within the more weakly bonded  $\text{YO}_4$  tetrahedra. The bands

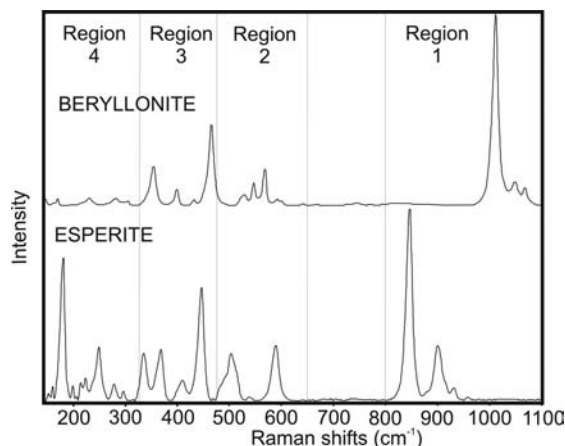


FIGURE 4. Raman spectrum of esperite, along with that of beryllonite for comparison.

in region 4, which span from 50 to 320  $\text{cm}^{-1}$ , are of complex nature, primarily due to lattice modes involving *A-O* (and/or *B-O*) interactions, as well as *X-O-Y* bending and tetrahedral ( $\text{XO}_4$  and  $\text{YO}_4$ ) librations. Specifically, for the Raman spectrum of esperite, the strong, narrow band at 846  $\text{cm}^{-1}$  in region 1 is assigned to the Si-O symmetric stretching vibrations within the  $\text{SiO}_4$  group and three weak peaks at 900, 931, and 958  $\text{cm}^{-1}$  to asymmetric stretching of Si-O bonds. There are three major Si-O-Zn bending modes at 504, 538, and 589  $\text{cm}^{-1}$  in region 2. The bands in region 3 are characterized by a Zn-O symmetric stretching mode at 447  $\text{cm}^{-1}$ , and three asymmetric stretching modes at 335, 368, and 409  $\text{cm}^{-1}$ .

### Origin of “superlattice” reflections in esperite

Based on the striking similarities in X-ray diffraction patterns between esperite and beryllonite, Moore and Ribbe (1965), without solving the esperite structure, proposed a Ca-Pb ordering scheme to account for the observed “superlattice” reflections in esperite, by assuming that Ca in excess of 2 apfu will have to enter the L-channels. They described such ordering in esperite in terms of four beryllonite-like subcells with Pb substituted in the larger, nine-coordinated Na1 site in each subcell, and (Ca+Pb) in the Na1 site of the immediately adjacent subcells. The Ca cations are substituted in the smaller, octahedrally coordinated Na2 or Na3 sites of the beryllonite structure. The alternate subcells are of different compositions, thus resulting in the superlattice reflections. This ordering model predicts no superstructure for esperite with the Ca:Pb ratio smaller than 2:1, since all Ca cations can be accommodated into the smaller sites in the S-channels, and none will enter the larger sites in the L-channels. Evidently, this is not the case for our samples because the two crystals we examined both have Ca:Pb ratios smaller than 2:1, with 1.86:1 for sample 1 and 1.79:1 for sample 2 (Table 5). Yet, sample 2 exhibits the “superlattice” reflections as Moore and Ribbe (1965) described, but sample 1 does not, indicating that cation ordering is not the cause of “superlattice” reflections in esperite.

A survey of materials with the beryllonite-type structure reveals that many of them have been found to display “superlattice” reflections similar to those observed by Moore and Ribbe (1965), such as trimerite (Aminoff 1926; Klaska and Jarchow 1977), (K,Na)GaGeO<sub>4</sub> (Barbier and Fleet 1987), (K,Na)AlGeO<sub>4</sub> (Barbier and Fleet 1988), BaMSiO<sub>4</sub> (*M* = Co, Zn, Mg) (Liu and Barbier 1993), and Na(Al,Ga)SiO<sub>4</sub> (Chen et al. 1994). In all these cases, the “superlattice” reflections, which give rise to a marked orthohexagonal or pseudo-hexagonal character, are attributed to the presence of triple twins, often called trillings (drillings in German, e.g., Sheldrick 1997). In fact, the crystal structure of trimerite was solved from triply twinned data (Klaska and Jarchow 1977).

Barbier and Fleet (1988), in their investigation of phase relations in the (Na,K)AlGeO<sub>4</sub> system over a temperature range of 700–1100 °C, found four distinct structure types, including the beryllonite-, nepheline-, kalsilite-, and KAlGeO<sub>4</sub>-types in order of increasing KAlGeO<sub>4</sub> content. Most interesting to note is that the diffraction pattern for the NaAlGeO<sub>4</sub> phase quenched from 1100 °C is “somewhat different from that of the beryllonite phase (stable below 900 °C),” showing a pronounced pseudo-hexagonal character. Barbier and Fleet (1988) ascribed

this pseudo-hexagonal symmetry to triple twins on the basis of their TEM observations. Although the structure of the high-temperature form of NaAlGeO<sub>4</sub> was undetermined, Barbier and Fleet (1988) demonstrated that the transformation between the low- and high-temperature phases is completely reversible between 900 and 1100 °C. A similar reversible transition (from a high-temperature hexagonal phase to a low-temperature form of lower symmetry) has also been reported by Henderson and Roux (1977) in the (Na,K)AlSiO<sub>4</sub> system. This then begs the question about the formation mechanism of triple twins in beryllonite-type materials—does it originate from a growth morphology due to the pseudo-hexagonal character of these compounds or from a hexagonal-to-monoclinic transformation as a consequence of changing temperature or chemical compositions? More detailed research is apparently needed on beryllonite-type materials as a function of temperature and composition to address this question. As for NaAlGeO<sub>4</sub>, because the material synthesized below 900 °C does not show “superlattice” reflections, but that quenched from 1100 °C does (Barbier and Fleet 1988), we propose that the twinning in NaAlGeO<sub>4</sub> is most likely to result from the structural transformation from a high-temperature form to the beryllonite-type structure. By the same token, we think that the twinning in esperite also stems from a phase transformation, since the crystals synthesized between 550 and 680 °C do not exhibit “superlattice” reflections (Ito 1968), but natural materials do (Moore and Ribbe 1965; Ito 1968), including our sample 2. In other words, we propose that there exists an unquenchable high-temperature form of esperite, which, according to the phase diagram determined by Ito (1968), will convert to  $P2_1/n$  esperite below 680 °C. Indeed, the high-temperature X-ray diffraction experiment by Moore and Ribbe (1965) lends strong support to our inference, because they detected a phase transformation in esperite at high temperature, which involves the development of a hexagonal array of stacking faults when a single crystal is quenched from ~710 °C.

As to why our sample 2 is twinned and sample 1 is not, a probable explanation is as follows. Due to the slight chemical difference between the two samples (Table 5), the highest metamorphic temperature ( $T_{\text{HM}}$ ) that our sample had reached during its formation might be just high enough for sample 2, but not high enough for sample 1, to undergo the transformation process to the high-temperature form detected by Moore and Ribbe (1965). Since esperite starts to decompose to hardystonite + larsenite + zincite between 700 and 800 °C, depending on its chemical composition (Moore and Ribbe 1965; Ito 1968), we estimate the  $T_{\text{HM}}$  value that our sample reached to be ~700 °C. This temperature is in good agreement with that (720 to 750 °C) estimated by many previous studies for the metamorphosed marine-exhalative deposits in Franklin, New Jersey (e.g., Mason 1947; Hewins and Yersak 1977; Carvalho and Sclar 1988; Sclar 1990; Leavens and Nelen 1990; Moore et al. 2003). If the argument we presented above holds true, then the twinning in esperite, despite the rarity of the mineral, may serve as a potential geothermometer.

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