Yangite, PbMnSi$_3$O$_8$·H$_2$O, a new mineral species with double wollastonite silicate chains, from the Kombat mine, Namibia

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ABSTRACT

A new chain-silicate mineral species, yangite, ideally PbMnSi$_3$O$_8$·H$_2$O, has been found on a specimen from the Kombat mine, Otavi Valley, Namibia. Associated minerals are melanotekite and rhodochrosite. Yangite is colorless to pale brown in transmitted light, transparent with white streak and vitreous luster. Broken pieces of yangite crystals are bladed or platy, and elongated along [010]. It is sectile with a Mohs hardness of ~5; cleavage is perfect on {101} and no twinning or parting was observed. The measured and calculated densities are 4.14(3) and 4.16 g/cm$^3$, respectively. Optically, yangite is biaxial (–), with $n_a = 1.690(1), n_p = 1.699(1), n_g = 1.705(1), Y = b, Z = c = 11^\circ$, and $2V^\|$ = 77(2)^\circ. It is insoluble in water, acetone, and hydrochloric acid. An electron microprobe analysis demonstrated that the sample was relatively pure, yielding the empirical formula (with calculated H$_2$O) Pb$_{1.00}$Mn$_{1.00}$Si$_3$O$_8$·H$_2$O. Yangite is triclinic and exhibits space group symmetry $\overline{P}$ with unit-cell parameters $a = 9.6015(9), b = 7.2712(7), c = 7.9833(8)$ Å, $\alpha = 105.910(4), \beta = 118.229(4), \gamma = 109.935(5)^\circ$, and $V = 392.69(7)$ Å$^3$. Its crystal structure is based on a skeleton of double wollastonite SiO$_4$ tetrahedral chains oriented parallel to [010] and interlinked with ribbons of Mn- and Pb-polyhedra. Yangite represents the first chain silicate with two-connected double chains and possesses all of the structural features of a hypothetical triclinic Ca$_3$Si$_2$O$_8$·2H$_2$O phase proposed by Merlino and Bonaccorsi (2008) as a derivative of the okenite structure. The difference in the H$_2$O component between the hypothetical phase and yangite likely is a consequence of the larger Pb$^{2+}$ with its lone-pair electrons in yangite replacing the smaller Ca$^{2+}$ in the hypothetical phase.

Keywords: Yangite, chain silicate, wollastonite chains, crystal structure, X-ray diffraction, Raman spectra

INTRODUCTION

A new mineral species and new type of chain silicate, ideal formula PbMnSi$_3$O$_8$·H$_2$O, has been found on a specimen from the Kombat mine, Otavi Valley, Namibia. It is named yangite to honor the contributions of Hexiong Yang, Department of Geosciences, University of Arizona, to the fields of chain silicates in particular and mineralogy in general, and his stewardship of the RRUFF project’s (http://rruff.info) ambitious attempt to characterize the known minerals chemically, structurally, and spectrographically. The new mineral and its name have been approved by the Commission on New Minerals and Nomenclature and Classification (CNMNC) of the International Mineralogical Association (IMA2012-052). Part of the co-type sample has been deposited at the University of Arizona Mineral Museum (Catalog no. 19341), the RRUFF Project (deposition no. R090031), and the Smithsonian Institution, Washington, D.C., U.S.A. (catalog number 175983). This paper describes the physical and chemical properties of yangite, and its single-crystal X-ray diffraction and Raman spectroscopic data.

SAMPLE DESCRIPTION AND EXPERIMENTAL METHODS

Occurrence, physical, and chemical properties, and Raman spectra

Yangite was found on a single specimen from the Kombat mine, Namibia, in the collection of the late John Innes (Fig. 1). Innes was a senior mineralogist in the employ of the Tsumeb Corporation and has been honored for his studies of the geology and mineralogy of the Tsumeb and Kombat mines with a mineral name, johninnesite (cf. Innes and Chaplin 1986). He gave the piece to co-author Bill Pinch with the recognition that it was unique.

A brief summary of relevant geological information follows, taken from a detailed presentation of the geology of the Kombat Mine authored by Innes and Chaplin (1986). The Kombat mine, located in the Otavi Valley, 37 km east of Otavi and 49 km south of Tsumeb, is in a sequence of weakly metamorphosed, thin to massive bedded, shallow-water dolostones of the Upper Proterozoic Hüttenberg Formation. Six discrete bodies of brecciated, hydrothermally deposited massive sulfide ores are present along a disconformity separating dolostone from younger slate. Elements that occur in economic concentrations include copper, lead, and silver. Iron and manganese are abundant. Other elements found at Kombat in significant concentrations include zinc, barium, arsenic, chromium, molybdenum, chlorine, and germanium.

Yangite occurs in an epithermal association, one of seven described ore types. The others are massive and semi-massive sulfides, mineralized net-vein fracture systems, galena-rich alteration breccias, a pyrite-sericite association, an iron-manganese oxide/silicate association, and mineralized fracture fillings. The epithermal association postdates main mineralization and consists of vuggy veins.
basis of 9 O atoms (from the structure determination), is Pb₂₀Mn₁₆Si₂₀O₇·H₂O, or simply PbMnSi₂O₇·H₂O.

The Raman spectrum of yangite was collected from a randomly oriented crystal on a Thermo-Almega microRaman system, using a 532 nm solid-state laser with a thermoelectric cooled CCD detector. The laser is partially polarized with 4 cm⁻¹ resolution and a spot size of 1 μm.

X-ray crystallography

Both powder and single-crystal X-ray diffraction data of yangite were collected on a Bruker X8 APEX2 CCD X-ray diffractometer equipped with graphite-monochromated MoKα radiation. However, it is difficult to unambiguously index all powder X-ray diffraction peaks due to severe peak overlaps. Table 1 lists the measured powder X-ray diffraction data, along with those calculated from the determined structure using the program XPow (Downs et al. 1993).

Single-crystal X-ray diffraction data for yangite were collected from an unwinned, elongated tabular crystal (0.06 × 0.04 × 0.03 mm) with frame widths of 0.5° in θ and 30 s counting time per frame. All reflections were indexed on the basis of a triclinic unit cell (Table 2). No satellite or super-lattice reflections were observed. The intensity data were corrected for X-ray absorption using the Bruker program SADABS. The absence of any systematic absences of reflections suggest possible space groups P1 or P1̅. The crystal structure was solved and refined using SHELX97 (Sheldrick 2008) based on the space group P1̅ because it produced the better refinement statistics in terms of bond lengths and angles, atomic displacement parameters, and R factors. The positions of all atoms were refined with anisotropic displacement parameters, except for H atoms, which were

<table>
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<tr>
<th>Table 1. Powder X-ray diffraction data for yangite</th>
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</table>

The mineral is colorless to pale brown in transmitted light under microscope, transparent with white streak and vitreous luster. It is sectile and has a Mohs hardness of ~5; cleavage is perfect on {101} and no parting was observed. Fractures are uneven. The measured (by heavy-liquid) and calculated densities are 4.14(3) and 4.16 g/cm³, respectively. Originally, yangite is biaxial (+), with ɳ₁ = 1.699(1), ɳ₂ = 1.705(1), ɳ₃ = 1.699(1), ɳ₁ - ɳ₂ = 0.006(1), ɳ₁ - ɳ₃ = 0.006(1), b = c = 10.7(1) Å, 2Vₘₘ = 77(2)°, and 2Vₘₘ = 78°.

The chemical composition of yangite was determined with a Cameca SX100 electron microprobe at 15 kV and 5 nA with a beam diameter of 20 μm. The standards include diopside for Si, rhodonite for Mn, and NBS_K0229 (Pb-glass) for Pb, yielding an average composition (wt%) (10 points) of SiO₂, 36.59(19), MnO 14.45(11), PbO 45.46(41), H₂O 3.66 added on the basis of structural results, resulting in a total of 100.16(34). The presence of H₂O in yangite was confirmed by Raman spectroscopic measurements and structure determination (see below). Trace amounts of Fe and Ca were observed from WDS, but they were under the detection limits of the analysis. The resultant chemical formula, calculated on the
not located from the difference Fourier maps. Final coordinates and displacement parameters of the atoms in yangite are listed in Table 3 and selected bond distances in Table 4. A CIF is available.

**DISCUSSION**

**Crystal structure**

The crystal structure of yangite consists of double wollastonite SiO$_2$ tetrahedral chains running parallel to b and sharing corners with birdb's Mn- and Pb-polyhedra (Fig. 2a). These double chains are characterized by alternating 4- and 6-membered tetrahedral rings, like those found in okenite, Ca$_6$Si$_6$O$_{18}$H$_2$O (Fig. 2b) (Merlino 1983). In okenite, however, layers of parallel double chains stacked along c* alternate with sheets of tetrahedra composed of 5- and 8-membered rings. Similar double wollastonite chains have also been found in synthetic compounds (Haile and Wuensch 1997, 2000; Radić and Kahlenberg 2001; Radić et al. 2003).

There are three distinct tetrahedral Si sites in yangite, Si1, Si2, and Si3, with average Si-O bond distances of 1.622, 1.622, and 1.624 Å, respectively. Among them, the Si3 tetrahedron is the most distorted and the Si2 the least, as measured by tetrahedral angle variance and quadratic elongation (Robinson et al. 1971) (Table 4), but none are unusually distorted.

The Mn$^{2+}$ cation is octahedrally coordinated. Bond-valence sums calculated using the parameters given by Brese and O’Keeffe (1991) indicate that Mn is 2+, rather than 3+, and that O9W is H$_2$O (Table 5). The cation coordination octahedron is relatively undistorted, especially given that one corner is anchored by a water molecule, with an angle variance of 34.06 and a quadratic elongation of 1.01.

The bonding topology of yangite was calculated using the procrystal representation of its electron density. Procrystal electron density is computed by summing the contributions of the spherically averaged electron density of neutral atoms placed at the experimentally determined locations of the atoms in a crystal (cf. Downs et al. 2002, Downs 2003 for details of the method and evidence of its accuracy and efficacy). Calculations

**Table 3.** Atomic coordinates and displacement parameters for yangite

<table>
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<tr>
<th>Atom</th>
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<td>0.004(3)</td>
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<td>O9W</td>
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**Table 4.** Selected bond distances (Å) in yangite

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<th>Bond</th>
<th>Distance (Å)</th>
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<tbody>
<tr>
<td>Si-O1</td>
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<tr>
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<td>1.624</td>
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<tr>
<td>Si-O3</td>
<td>1.624</td>
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<td>Si-O4</td>
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<td>Si-O5</td>
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<td>Si-O6</td>
<td>1.622</td>
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<td>Si-O7</td>
<td>1.622</td>
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<tr>
<td>Si-O8</td>
<td>1.624</td>
</tr>
<tr>
<td>Si-O9W</td>
<td>1.622</td>
</tr>
</tbody>
</table>

**Note:** TAV = tetrahedral angle variance; TQE = tetrahedral quadratic elongation.
were performed with in-house software using the most accurate available analytical Hartree-Fock wave functions (Koga et al. 1999, 2000; Thakkar and Koga 2003).

The results suggest that Pb\(^{2+}\) is fivefold-coordinated, with all Pb-O bond distances shorter than 2.770 Å (Table 4). As explained in the companion paper (Thompson et al. this issue), geometrical constraints in pyroxenoids arising from the nature of the octahedral and tetrahedral chains dictate that at least one M site must be very distorted.

Procystal calculations also indicate the presence of a three weak O9W-O bonds and a weak, long O9W-Pb interaction that bridges the channel between the parallel bands of Mn/Pb polyhedra. Interestingly, the computation was performed using an oxygen atom at the location of O9W, i.e., without the protons. It is not possible to determine the nature of these bonds given that the unlocated hydrogen atoms were disregarded in the computation, but it is certainly possible that the Pb\(^{2+}\) lone pair is involved in a hydrogen bond with O9W. However, it is not obvious how the hydrogens fit into the structure. A more extensive discussion of this issue is in the companion paper (Thompson et al. this issue).

**Figure 2.** (a) Crystal structure of yangite, showing the double chains of SiO\(_4\) tetrahedra and ribbons of Mn- and Pb-polyhedra. (b) A portion of the okenite structure (Merlino 1983), showing its similarity to the yangite structure. The spheres in both figures represent H\(_2\)O. (Color online.)

**Figure 3.** Crystal structure of yangite. The large and small spheres represent Pb and H\(_2\)O groups, respectively. The octahedra and tetrahedra represent MnO\(_6\) and SiO\(_4\) groups, respectively. For clarity, no chemical bonds are drawn for Pb. (Color online.)

**Figure 4.** Raman spectrum of yangite, along with the Raman spectra of xonoltite and elpidite for comparison. The spectra are shown with vertical offset for more clarity.
The bulk structure of yangite can be regarded as layers of SiO₄ tetrahedra alternating with those of Mn- and Pb-polyhedra stacked along c* (Fig. 3). For an analysis of the structural relationships between yangite and other pyroxenoids, see the companion paper, Thompson et al. (this issue).

Raman spectra

There have been numerous Raman spectroscopic studies on materials with wollastonite-like silicate chains (e.g., Mills et al. 2005; Makreski et al. 2006; Wierzbia-Wieczorek et al. 2010; Can et al. 2011). In particular, Frost et al. (2012) measured the Raman spectra of xonolite, a mineral with one-connected double wollastonite chains (the n-connected terminology describes the number of connecting tetrahedra between chains and is due to Merlino and Bonaccorsi 2008). The Raman spectrum of yangite is displayed in Figure 4, along with the Raman spectra of xonolite and elpidite taken from the RRUFF Project (R120029 and R060200, respectively) for comparison.

Due to extremely strong sample fluorescence, we were unable to improve the spectral quality of yangite above 1500 cm⁻¹. Nonetheless, the broad bands between 3200 and 3850 cm⁻¹ may be ascribed to the O-H stretching vibrations. The two sharp bands at 1015 and 916 cm⁻¹ are due to the Si-O stretching vibrations within the SiO₄ groups, whereas the bands between 300 and 900 cm⁻¹ are primarily attributable to the O-Si-O and Si-O-Si angle bending vibrations (Dowty 1987; Makreski et al. 2006; Frost et al. 2012). The bands below 320 cm⁻¹ are of a complex origin, mostly associated with the rotational and translational modes of SiO₄ tetrahedra, Mn-O and Pb-O interactions.

**Implications**

A great number of natural and synthetic phases, mostly hydrous Ca-silicates, display crystal structures characterized by the presence of double wollastonite chains. Merlino and Bonaccorsi (2008) presented a thorough review of such compounds and classified them into three categories based on the number of tetrahedra shared between two single chains: one-, two-, and three-connected chains, exemplified by those in xonolite, okenite, and elpidite, respectively. However, unlike xonolite or elpidite, okenite is not a "pure" chain silicate, as its structure consists of both silicate chains and sheets (Merlino 1983). Therefore, yangite represents the first chain silicate with two-connected double chains. Furthermore, the discovery of yangite implies that more Pb-silicate compounds or minerals with the chemical formula Pb₅Si₆O₁₈·2H₂O (M = Fe²⁺, Ca²⁺, Mg²⁺, and other divalent cations) may be synthesized or found in nature, as substitution between Mn and other divalent cations is common in pyroxenoids.

By eliminating the crystal tetrahedral sheets in the okenite structure, Merlino and Bonaccorsi (2008) derived a hypothetical structure with the composition Ca₃Si₂O₇·2H₂O, space group PT, and unit-cell parameters a = 9.69, b = 7.28, c = 8.11 Å, α = 103.0°, β = 118.5°, γ = 112.1° (Table 2). Most remarkably, comparison of yangite and the model structure proposed by Merlino and Bonaccorsi (2008) reveals that, except for the amount of H₂O, this hypothetical phase possesses all of the structural features found in yangite (Table 2, Fig. 2). The differences in the H₂O contents and unit-cell parameters between the hypothetical phase and yangite are most likely to result from the substitution of larger Pb²⁺ with its lone-pair electrons for smaller Ca²⁺.

**Acknowledgments**

This study was funded by Science Foundation Arizona. We are grateful to Stefano Merlino for providing us with his unpublished data and Ajit Thakkur for providing us with his electron wave functions. We also thank Merlino and two anonymous reviewers, along with Associate Editor Fernando Colombo, for their comments, which have improved the quality of this manuscript.

**References Cited**


Manuscript received January 13, 2016
Manuscript accepted July 6, 2016
Manuscript handled by Fernando Colombo