# Lead-tellurium oxysalts from Otto Mountain near Baker, California: II. Housleyite, $\mathrm{Pb}_{6} \mathrm{CuTe}_{4} \mathrm{O}_{18}(\mathrm{OH})_{2}$, a new mineral with Cu -Te octahedral sheets 

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#### Abstract

Housleyite, $\mathrm{Pb}_{6} \mathrm{CuTe}_{4} \mathrm{O}_{18}(\mathrm{OH})_{2}$, is a new tellurate from Otto Mountain near Baker, California, named in honor of Robert M. Housley. The new mineral occurs on fracture surfaces and in small vugs in brecciated quartz veins. Housleyite is directly associated with acanthite, cerussite, gold, iodargyrite, khinite- $4 O$, wulfenite, and three other new tellurates: markcooperite, ottoite, and thorneite. A variety of other secondary minerals occur in the veins, including three other new secondary tellurium minerals, paratimroseite, telluroperite, and timroseite. Housleyite is monoclinic, space group $P 2_{1} / n$, $a=7.8552(5), b=10.4836(7), c=11.0426(8) \AA, \beta=95.547(2)^{\circ}$, and $Z=2$. Crystals are prismatic to bladed with elongation parallel to $\mathbf{b}$ and typically occur in bow tie-like aggregates, drusy balls, and irregular sprays. It is pale to medium greenish blue and transparent, with pale blue streak and adamantine luster. Mohs hardness is estimated at 3 . The mineral is brittle, with an irregular fracture. Cleavage was not observed, but is likely on $\{10 \overline{\}}\}$. The calculated density is $7.845(1) \mathrm{g} / \mathrm{cm}^{3}$. Housleyite is biaxial ( + ), with $2 V=50^{\circ}$ to $60^{\circ}$ and strong inclined dispersion, $r>v$, but indices of refraction are too high to be measured. The optic orientation is $Y=\mathbf{b}, Z^{\wedge} \mathbf{c} \approx 40^{\circ}$ in obtuse $\beta$ and pleochroism is $Y$ (medium green-blue) $>Z$ (light green-blue) $>X$. Energy dispersive spectroscopy provided PbO 62.53 , $\mathrm{CuO} 3.77, \mathrm{TeO}_{3} 32.85, \mathrm{H}_{2} \mathrm{O} 0.84$ (structure), total $99.99 \mathrm{wt} \%$.; the empirical formula (based on $\mathrm{O}=$ 20) is $\mathrm{Pb}_{5.99} \mathrm{Cu}_{1.01} \mathrm{Te}_{4.00} \mathrm{O}_{18}(\mathrm{OH})_{2}$. The strongest powder X-ray diffraction lines are [ $d_{\text {obs }}$ in $\left.\AA(\mathrm{hkl}) \mathrm{I}\right]$ : $3.336(\overline{2} 02,031,122) 69,3.292(\overline{1} 13) 50,3.195(130,103) 100,3.068(\overline{2} 21,202) 47,3.007(023) 49$, $2.942(032,212) 80,2.723(123, \overline{2} 13,132) 29,2.580(230, \overline{3} 01, \overline{2} 31) 38$. The crystal structure $\left(R_{1}=\right.$ 0.028 ) consists of corner-sharing chains of $\mathrm{TeO}_{6}$ octahedra along [101] linked into slabs parallel to $\{10 \overline{1}\}$ by sharing edges and corners with strongly Jahn-Teller (4+2) distorted and severely skewed $\mathrm{CuO}_{6}$ octahedra. Lead $(\mathrm{Pb})$ atoms in lopsided nine- and elevenfold coordinations form additional links within and between the octahedral sheets.


Keywords: Housleyite, new mineral, tellurate, crystal structure, Otto Mountain, California

## INTRODUCTION

Housleyite, $\mathrm{Pb}_{6} \mathrm{CuTe}_{4} \mathrm{O}_{18}(\mathrm{OH})_{2}$, is one of seven new secondary tellurium minerals discovered recently at Otto Mountain near Baker, California. Detailed information on the mining history, geology, mineralogy, and mineral paragenesis of the deposit, as well as the discovery of the new minerals, is provided in Kampf et al. (2010b).

Housleyite is named in honor of Robert M. Housley (b. 1934), Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, U.S.A. Robert Housley's scientific career in experimental solid-state physics and materials characterization has spanned nearly five decades. While much of his professional work has focused on planetary/meteoritic materials, he has always had a strong interest in terrestrial mineralogy. In recent years, his personal mineral collecting efforts have brought to light many unusual occur-

[^0]rences of rare minerals in southern California and surrounding areas. His chemical analytical work has served to identify and characterize several new minerals. He has been very involved in work on the unusual secondary tellurium mineral assemblages in the mine workings on Otto Mountain near Baker, California. Robert Housley has agreed to the naming of the mineral in his honor. The new mineral and name have been approved by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association (IMA 2009-024). Three cotype specimens are deposited in the Natural History Museum of Los Angeles County, catalog numbers 62261, 62262, and 62263.

## OCCURRENCE

Housleyite was found at the Aga mine, $\left(35^{\circ} 16.399^{\prime} \mathrm{N} 116^{\circ}\right.$ $05.665^{\prime} \mathrm{W}$ ) on Otto Mountain, $\sim 2 \mathrm{~km}$ northwest of Baker, San Bernardino County, California, U.S.A., and in the Bird Nest drift on the southwest flank of Otto Mountain 0.7 km northwest of the Aga mine ( $35^{\circ} 16.606^{\prime} \mathrm{N} 116^{\circ} 05.956^{\prime} \mathrm{W}$ ).

Housleyite is rare and occurs on fracture surfaces and in small vugs in quartz veins. Species observed in direct association with the new mineral include acanthite, cerussite, gold, iodargyrite, khinite- $4 O$, wulfenite, and three other new tellurates: markcooperite $\left[\mathrm{Pb}_{2}\left(\mathrm{UO}_{2}\right) \mathrm{TeO}_{6}\right]$ (IMA2009-045; Kampf et al. 2010a), ottoite [ $\mathrm{Pb}_{2} \mathrm{TeO}_{5}$ ] (IMA2009-063; Kampf et al. 2010b), and thorneite $\left[\mathrm{Pb}_{6}\left(\mathrm{Te}_{2} \mathrm{O}_{10}\right)\left(\mathrm{CO}_{3}\right) \mathrm{Cl}_{2}\left(\mathrm{H}_{2} \mathrm{O}\right)\right]$ (IMA2009-023; Kampf et al. 2010c). Other species identified in the assemblages include: anglesite, atacamite, boleite, brochantite, burckhardtite, calcite, caledonite, celestine, chalcopyrite, bromine-rich chlorargyrite, chrysocolla, devilline, diaboleite, fluorite, fornacite, galena, goethite, hessite, jarosite, kuranakhite, linarite, malachite, mimetite, mottramite, munakataite, murdochite, muscovite, perite, phosphohedyphane, plumbojarosite, pyrite, schieffelinite, vanadinite, vauquelinite, and three other new minerals: paratimroseite $\left[\mathrm{Pb}_{2} \mathrm{Cu}_{4}^{2+}\left(\mathrm{Te}^{6+} \mathrm{O}_{6}\right)_{2}\left(\mathrm{H}_{2} \mathrm{O}\right)_{2}\right]$ (IMA2009-065; Kampf et al. 2010d), telluroperite $\left[\mathrm{Pb}_{3} \mathrm{Te}^{4+} \mathrm{O}_{4} \mathrm{Cl}_{2}\right]$ (IMA2009-044; Kampf et al. 2010e), and timroseite $\left[\mathrm{Pb}_{2} \mathrm{Cu}_{5}^{2+}\left(\mathrm{Te}^{6+} \mathrm{O}_{6}\right)_{2}(\mathrm{OH})_{2}\right]$ (IMA2009-064; Kampf et al. 2010d). Other potentially new species are still under investigation.

Housleyite and most other secondary minerals of the quartz veins are interpreted as having formed from the partial oxidation of primary sulfides (e.g., galena and chalcopyrite) and tellurides (e.g., hessite) during or following brecciation of the quartz veins.

## PHYSICAL AND OPTICAL PROPERTIES

The mineral occurs as prismatic-to-bladed crystals with elongation parallel to $\mathbf{b}$. They are up to 0.15 mm in length and typically occur in bow tie-like aggregates, drusy balls, and irregular sprays (Fig. 1). Crystals exhibit the forms $\{001\},\{10 \overline{1}\}$, $\{011\}$, and $\{010\}$ (Fig. 2). Penetration twinning appears to occur occasionally with individual prisms intersecting at about $60^{\circ}$, the plane containing the intersecting crystals being parallel to one of the prominent prism faces. Unfortunately, efforts to remove an intact twin from matrix for study were unsuccessful, so the twin law could not be determined.

Housleyite is pale to medium greenish blue and transparent, with pale blue streak. The luster is adamantine, although crystal faces are sometimes frosted giving them a dull luster. The mineral is nonfluorescent. The Mohs hardness is estimated at 3. The tenacity is brittle and the fracture is irregular. Cleavage was not observed, but is likely on $\{10 \overline{1}\}$ based upon the crystal structure. The density could not be measured because it is greater than


Figure 1. Backscatter SEM image of housleyite crystals on quartz (FOV $120 \mu \mathrm{~m}$ ).
those of available high-density liquids and there is insufficient material for physical measurement. The density calculated for the ideal formula is $7.845(1) \mathrm{g} / \mathrm{cm}^{3}$.

The indices of refraction exceed those of available index fluids. The Gladstone-Dale relationship (Mandarino 1981) predicts $n_{\mathrm{av}}=2.169$ based on the ideal formula. Orthoscopic and conoscopic optical examination using a Leitz Ortholux I polarizing microscope equipped with a Supper spindle stage showed housleyite to be biaxial $(+)$, with $2 V=50^{\circ}$ to $60^{\circ}$ and strong inclined dispersion, $r>v$. Because the interference figure is relatively diffuse, the 2 V could not be determined more precisely. The optic orientation is $Y=\mathbf{b}, Z^{\wedge} \mathbf{c} \approx 40^{\circ}$ in obtuse $\beta$. The mineral is pleochroic with $Y($ medium green-blue $)>Z$ (light green-blue) $>X$.

## Chemistry

Three chemical analyses carried out using a JEOL8200 electron microprobe (WDS mode, $15 \mathrm{kV}, 15 \mathrm{nA}, 5 \mu \mathrm{~m}$ beam diameter) at the Division of Geological and Planetary Sciences, California Institute of Technology, provided the averages (and ranges): PbO 58.93 (57.67-59.95), $\mathrm{TeO}_{3} 33.22$ (32.43-33.98), CuO 3.48 (3.37-3.56), $\mathrm{H}_{2} \mathrm{O} 0.84$ (structure), total 96.47 (95.32-97.36) $\mathrm{wt} \%$. Note that the crystals are prone to electron beam damage. This and sample porosity contributes to the low analytical total, even though we used the mildest analytical conditions feasible. This problem of sample instability in the electron beam appears to be common in tellurates (cf. Grundler et al. 2008; Mills et al. 2008, 2009b, 2010). We found that beam damage tends to yield significantly lower Pb and Cu contents relative to Te . Standards used were $\mathrm{PbS}, \mathrm{Cu}$ metal, and Te metal.

Three other analyses were carried out using a Philips XL30 FESEM equipped with an Oxford Inca thin-window EDS detector and IMIX data analysis software (EDS mode, 15 kV , low beam current) providing the averages (and ranges): PbO 62.53 (60.74-64.09), CuO 3.77 (3.17-3.72), $\mathrm{TeO}_{3} 32.85$ (32.66-32.96), $\mathrm{H}_{2} \mathrm{O} 0.84$ (structure), total $99.99 \mathrm{wt} \%$. Oxygen was determined by stoichiometry and individual analysis totals (excluding $\mathrm{H}_{2} \mathrm{O}$ ) were between 98 and $100 \mathrm{wt} \%$. Standards used were $\mathrm{PbF}_{2}, \mathrm{Cu}$ metal, and HgTe .

The EMP (after normalization) and EDS empirical formulae (based on $\mathrm{O}=20$ ) are $\mathrm{Pb}_{5.74} \mathrm{Cu}_{0.95} \mathrm{Te}_{4.11} \mathrm{O}_{18}\left(\mathrm{OH}_{0.98}\right)_{2}$ and $\mathrm{Pb}_{5.99} \mathrm{Cu}_{1.01} \mathrm{Te}_{4.00} \mathrm{O}_{18}(\mathrm{OH})_{2}$, respectively. The simplified formula is $\mathrm{Pb}_{6} \mathrm{CuTe}_{4} \mathrm{O}_{18}(\mathrm{OH})_{2}$ that requires $\mathrm{PbO} 62.60, \mathrm{CuO} 3.72, \mathrm{TeO}_{3}$ $32.84, \mathrm{H}_{2} \mathrm{O} 0.84$, total $100.00 \mathrm{wt} \%$.

## X-RAY CRYSTALLOGRAPHY AND STRUCTURE DETERMINATION

Both powder and single-crystal X-ray diffraction data were obtained on a Rigaku R-Axis Spider curved imaging plate microdiffractometer utilizing monochromatized $\mathrm{Mo} K \alpha$ radiation.


Figure 2. Housleyite crystal drawing (clinographic projection).

The powder data presented in Table 1 show good agreement with the pattern calculated from the structure determination.

The Rigaku CrystalClear software package was used for processing the structure data, including the application of an empirical absorption correction. The structure was solved by direct methods using SIR92 (Altomare et al. 1994) and the location of all non-hydrogen atoms was straightforward. The SHELXL-97 software (Sheldrick 2008) was used, with neutral atom scattering factors, for the refinement of the structure. Bond-valence calculations indicate that one O atom (designated OH ) is bonded to an H atom. A difference Fourier revealed a likely location for this H atom, the position of which was constrained to an $\mathrm{H}-\mathrm{OH}$ distance of 0.90 (3) $\AA$ in the final refinement.

The details of the data collection and the final structure refinement are provided in Table 2. The final atomic coordinates and displacement parameters are in Table 3. Selected interatomic distances are listed in Table 4 and bond valences in Table 5. Note that structure factors and CIF data are on deposit ${ }^{1}$.

[^1]TABLE 2. Data collection and structure refinement details for housleyite Diffractometer Rigaku R-Axis Spider with curved imaging plate X-ray radiation/power $\quad \operatorname{MoK} \alpha(\lambda=0.71075 \AA$ ) / $50 \mathrm{kV}, 40 \mathrm{~mA}$ Temperature Formula
Space group
Unit-cell dimensions
$Z$
Volume
Density (for ideal formula)

| Absorption coefficient | $63.168 \mathrm{~mm}^{-1}$ |
| :---: | :---: |
| F(000) | 1780 |
| Crystal size | $0.045 \times 0.035 \times 0.015 \mathrm{~mm}^{3}$ |
| $\theta$ range | $3.05^{\circ}$ to $27.48^{\circ}$ |
| Index ranges | $-10 \leq h \leq 10,-13 \leq k \leq 12,-14 \leq I \leq 14$ |
| Reflections collected/unique | 19181/2071 [ $\left.\mathrm{R}_{\text {int }}=0.0718\right]$ |
| Reflections with $F_{0}>4 \sigma F$ | 1832 |
| Completeness to $\theta=27.50^{\circ}$ | 99.6\% |
| Max. and min. transmission | 0.4509 and 0.1633 |
| Refinement method | Full-matrix least-squares on $F^{2}$ |
| Parameters refined | 146 |
| GoF | 1.090 |
| Final $R$ indices [ $F_{0}>4 \sigma F$ ] | $R_{1}=0.028, \mathrm{w} R_{2}=0.048$ |
| $R$ indices (all data) | $R_{1}=0.036, \mathrm{w} R_{2}=0.050$ |
| Largest diff. peak/hole | 1.755/-1.849 e/Å ${ }^{3}$ |
| $\begin{aligned} & \text { Notes: } R_{\text {int }}=\Sigma \mid F_{o}^{2}-F_{o}^{2}(\text { mean }) \mid / \Sigma \\ & -\left\|F_{c}\right\|\|/ \Sigma\| F_{0} \mid \cdot w R_{2}=\left\{\Sigma\left[W\left(F_{o}^{2}-F_{c}^{2}\right\}^{2}\right)^{2}\right. \\ & \text { is } 0.0020, b \text { is } 19.9615, \text { and } P \text { is } \end{aligned}$ | GoF $=S=\left\{\Sigma\left[w\left(F_{o}^{2}-F_{c}^{2}\right)^{2}\right] /(n-p)\right\}^{1 / 2} \cdot R_{1}=$ $\left.\left.w\left(F_{o}^{2}\right)^{2}\right]\right\}^{1 / 2} \cdot w=1 /\left[\sigma^{2}\left(F_{o}^{2}\right)+(a P)^{2}+b P\right]$ wh + $\left.\operatorname{Max}\left(F_{0}^{2}, 0\right)\right] / 3$. |

Table 1. X-ray powder-diffraction data for housleyite

| $I_{\text {obs }}$ | $d_{\text {obs }}$ | $d_{\text {calc }}$ | $I_{\text {calc }}$ | hkl | $\underline{I_{\text {obs }}}$ | $d_{\text {obs }}$ | $d_{\text {calc }}$ | $I_{\text {calc }}$ | hkl |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 16 | 6.681 | 6.689 | 27 | $\overline{1} 01$ * |  |  | 2.030 | 6 | 143 |
| 11 | 6.119 | 6.112 | 15 | $101^{*}$ | 16 | 2.026 | 2.028 | 5 | 115 |
| 17 | 4.743 | 4.736 | 21 | 021 * |  |  | 2.028 | 6 | 150 |
| 10 | 3.968 | 3.988 | 12 | 112 * |  |  | 2.007 | 6 | 125 |
| 8 | 3.805 | 3.796 | 12 | 022 * |  |  | 2.007 | 8 | $\overline{3} 2$ |
| 13 | 3.579 | 3.579 | 15 | 211** | 27 | 2.002 | 2.003 | 19 | 151 |
| 18 | 3.460 | 3.460 | 18 | 013 * |  |  | 1.994 | 17 | 224 |
|  |  | 3.392 | 15 | 211 | 6 | 1.921 | 1.926 | 10 | 410 |
|  |  | 3.344 | 48 | 202* | 6 | 1.900 | 1.908 | 6 | 332 |
| 69 | 3.336 | 3.334 | 11 | 031 | 6 | 1.900 | 1.899 | 6 | 323 |
|  |  | 3.331 | 25 | 122 |  |  | 1.873 | 8 | 4 12 |
| 50 | 3.292 | 3.276 | 58 | 113 |  |  | 1.869 | 15 | $\overline{2} 5$ |
|  |  | 3.205 | 12 | 103 | 29 | 1.867 | 1.867 | 19 | 411 |
| 100 | 3.195 | 3.194 | 100 | 130 * |  |  | 1.861 | 14 | $\overline{3} 24$ |
|  |  | 3.139 | 40 | $\underline{2} 20$ | 27 |  | 1.806 | 16 | 341 |
| 47 | 3.068 | 3.081 | 43 | 221** | 27 | 1.801 | 1.796 | 16 | -1 16 |
| 4 | 3.068 | 3.056 | 34 | 202 * | 15 | 1.784 | 1.789 | 8 | 4 22 |
| 49 | 3.007 | 3.005 | 58 | 023 * |  |  | 1.774 | 7 | 413 |
|  |  | 2.952 | 56 | 032 * | 13 | 1.749 | 1.756 | 7 | 153 |
| 80 | 2.942 | 2.934 | 69 | $\underline{2} 12$ * | 1 | 1.74 | 1.743 | 10 | $\overline{3} 15$ |
|  |  | 2.882 | 17 | $\underline{1} 23$ | 18 | 1.728 | 1.730 | 15 | 026 |
| 13 | 2.811 | 2.810 | 14 | 132 * |  |  | 1.711 | 11 | 324 |
|  |  | 2.749 | 20 | 004 | 26 | 1.697 | 1.699 | 20 | $\overline{3} 43$ |
|  |  | 2.735 | 11 | 123 |  |  | 1.696 | 10 | 422 |
| 29 | 2.723 | 2.717 | 23 | 213* | 15 | 1.682 | 1.685 | 4 | 045 |
|  |  | 2.717 | 16 | 132 |  |  | 1.682 | 7 | 161 |
| 13 | 2.653 | 2.659 | 19 | 014 | 8 | 1.668 | 1.668 | 7 | 431 |
|  |  | 2.609 | 18 | 230 | 8 | 1.668 | 1.666 | 4 | $\underline{2} 4$ |
| 38 | 2.580 | 2.597 | 17 | 了 01 | 8 | 1.636 | 1.640 | 6 | 162 |
|  |  | 2.576 | 37 | 231* |  |  | 1.636 | 4 | 350 |
| 12 | 2.538 | 2.534 | 9 | 310 | 14 | 1.619 | 1.623 | 6 | 253 |
| 16 | 2.522 | 2.521 | 13 | $\overline{3} 11$ | 14 | 1.619 | 1.621 | 14 | 162 |
| 15 | 2.481 | 2.485 | 14 | $\underline{213 *}$ | 6 | 1.582 | 1.584 | 12 | $\underline{216}$ |
| 15 | 2.447 | 2.443 | 14 | 141** |  |  | 1.560 | 7 | 163 |
| 8 | 2.296 | 2.301 | 12 | 214* | 6 | 1.557 | 1.552 | 4 | 117 |
| 7 | 2.248 | 2.248 | 8 | 321 |  | 1.507 | 1.518 | 6 | 055 |
|  | 2.125 | 2.133 | 10 | 043 * | 17 |  | 1.512 | 10 | 414155 |
| 13 |  | 2.125 | 8 | 134* |  |  | 1.509 | 7 |  |
| 13 |  | 2.117 | 10 | 241 * | Notes: $I_{\text {obs }}$ based upon peak heights. $I_{\text {calc }}$ calculated from the crystal structure using Powder Cell (Kraus and Nolze 1996). $d_{\text {calc }}$ based on the cell refined from the powder data (*) using UnitCell (Holland and Redfern 1997). Refined cell: $a=$ $7.871(1), b=10.495(1), c=11.046(1) \AA, \beta=95.46(1)^{\circ}, V=908.5(1) \AA^{3}$. |  |  |  |  |
|  | 2.059 | $\left\{\begin{array}{l} 2.067 \\ 2.062 \\ \hline \end{array}\right.$ | 8 | $\begin{array}{r} 105 \\ 051 \end{array}$ |  |  |  |  |  |  |  |
|  |  |  | 11 |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |

TABLE 3. Atomic coordinates and displacement parameters ( $\AA^{2}$ ) for housleyite

|  | $x$ | $y$ | $z$ | $U_{\text {eq }}$ | $U_{11}$ | $U_{22}$ | $U_{33}$ | $U_{23}$ | $U_{13}$ | $U_{12}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Cu | 0.5000 | 0.5000 | 1.0000 | 0.0099(4) | 0.0108(8) | 0.0094(8) | 0.0092(9) | -0.0006(7) | -0.0009(7) | -0.0012(7) |
| Te1 | 0.15518 (8) | 0.36603(6) | 0.80124(6) | 0.0064(1) | 0.0069(3) | 0.0071(3) | 0.0050(3) | -0.0001(2) | -0.0003(2) | -0.0001(2) |
| Te2 | 0.79491 (8) | 0.24012(6) | $0.60876(6)$ | 0.0067(1) | 0.0071(3) | 0.0075(3) | 0.0055(3) | 0.0002(2) | -0.0001(2) | -0.0002(2) |
| Pb1 | $0.34533(5)$ | $0.18063(4)$ | $0.57768(4)$ | 0.0127(1) | 0.0139(2) | 0.0141(2) | 0.0098(2) | 0.0007(2) | -0.0005(2) | 0.0011(2) |
| Pb2 | 0.45212(6) | 0.53120(4) | $0.66438(4)$ | 0.0195(1) | 0.0243(2) | 0.0236(2) | 0.0117(2) | -0.0038(2) | 0.0075(2) | -0.0124(2) |
| Pb3 | 0.97051 (5) | 0.62715(4) | 0.60367 (4) | 0.0184(1) | 0.0143(2) | 0.0239(2) | 0.0166(2) | 0.0046(2) | -0.0009(2) | -0.0046(2) |
| O1 | 0.9867(9) | 0.1837(7) | 0.5294(6) | 0.011(2) | 0.011(3) | 0.014(4) | 0.011(4) | 0.003(3) | 0.006(3) | 0.000(3) |
| O2 | 0.3556(8) | 0.4708(6) | 0.8464(6) | 0.009(1) | 0.006(3) | 0.012(4) | 0.009(4) | 0.002(3) | -0.002(3) | -0.006(3) |
| O3 | 0.6314(8) | 0.1811(7) | 0.4692(6) | 0.008(1) | 0.008(3) | 0.014(3) | 0.002(3) | $0.001(3)$ | 0.001(3) | -0.004(3) |
| O4 | 0.9378(8) | 0.2708(6) | 0.7623(6) | 0.009(1) | 0.006(3) | 0.011(3) | 0.008(4) | 0.001(3) | -0.003(3) | -0.003(3) |
| O5 | 0.2719(8) | 0.2069(6) | 0.7829(6) | 0.009(1) | 0.012(3) | 0.008(3) | 0.006(3) | 0.002(3) | -0.002(3) | 0.005(3) |
| O6 | 0.1875(9) | 0.4107(7) | 0.6398(6) | 0.015(2) | 0.020(4) | 0.019(4) | 0.005(3) | 0.000(3) | 0.000(3) | -0.009(3) |
| 07 | 0.4811(9) | 0.0130(7) | 0.6798(7) | 0.012(2) | 0.012(3) | 0.010(3) | 0.016(4) | -0.001(3) | 0.004(3) | -0.001(3) |
| O8 | 0.8162(9) | 0.4033(7) | $0.5396(7)$ | 0.016(2) | 0.020(4) | 0.011(4) | 0.016(4) | 0.002(3) | -0.002(3) | -0.001(3) |
| 09 | 0.5924(9) | 0.2811 (7) | 0.6814(6) | 0.014(2) | 0.013(4) | 0.021(4) | 0.009(4) | -0.002(3) | 0.002(3) | -0.003(3) |
| OH | 0.7945(9) | 0.0613(7) | 0.6673(7) | 0.015(2) | 0.009(4) | 0.020(4) | 0.015(4) | 0.004(3) | 0.000(3) | 0.000(3) |
| H | 0.695(10) | 0.081(14) | 0.697(13) | 0.050 |  |  |  |  |  |  |

Table 4. Selected bond distances ( A ) for housleyite

| Pb1-O7 | 2.294(7) | Pb2-O2 | $2.305(7)$ | Pb3-O5 | 2.423(6) |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Pb1-09 | 2.399(7) | Pb2-O6 | 2.426(7) | Pb3-08 | $2.434(8)$ |
| $\mathrm{Pb} 1-\mathrm{O} 5$ | 2.408(7) | Pb2-OH | 2.608(7) | Pb3-01 | 2.510 (7) |
| $\mathrm{Pb} 1-\mathrm{O} 3$ | 2.647(7) | $\mathrm{Pb} 2-\mathrm{O} 5$ | 2.651(7) | Pb3-07 | 2.668 (7) |
| $\mathrm{Pb} 1-\mathrm{O} 1$ | 2.816(7) | Pb2-04 | 2.753(7) | Pb3-08 | 2.704 (7) |
| Pb1-O6 | 2.826(8) | Pb2-09 | 2.843(7) | Pb3-06 | 2.843(8) |
| $\mathrm{Pb} 1-\mathrm{O} 2$ | 2.879(7) | Pb2-O8 | 3.012(7) | Pb3-O6 | 2.877(7) |
| $\mathrm{Pb} 1-\mathrm{O} 4$ | 3.661(7) | Pb2-03 | 3.394(7) | Pb3-09 | 2.951 (7) |
| $\mathrm{Pb} 1-\mathrm{OH}$ | 3.792(7) | Pb2-O8 | 3.555(8) | Pb3-OH | 3.496(8) |
| $\mathrm{Pb} 1-\mathrm{O} 3$ | 3.834(7) | <Pb2-O> | 2.839 | <Pb3-O> | 2.767 |
| Pb1-O7 | 3.849(7) |  |  |  |  |
| <Pb1-O> | 3.037 |  |  |  |  |
| $\mathrm{Cu}-\mathrm{O} 1$ | 1.957(7) | Te1-O6 | 1.884(7) | Te2-O8 | 1.887(7) |
| $\mathrm{Cu}-01$ | 1.957(7) | Te1-O7 | 1.899(7) | Te2-09 | $1.899(7)$ |
| $\mathrm{Cu}-\mathrm{O} 2$ | 1.971(7) | Te1-O5 | 1.923(7) | Te2-O1 | $1.909(7)$ |
| $\mathrm{Cu}-\mathrm{O}_{2}$ | 1.971(7) | Te1-O2 | 1.944(6) | Te2-O4 | 1.967 (7) |
| $\mathrm{Cu}-\mathrm{OH}$ | 2.648(8) | Te1-O3 | $1.946(7)$ | Te2-OH | 1.984(8) |
| $\mathrm{Cu}-\mathrm{OH}$ | 2.648(8) | Te1-O4 | 1.989(6) | Te2-O3 | 2.006(6) |
| <Cu-O> | 2.192 | <Te1-O> | 1.931 | <Te2-O> | 1.942 |
| Hydrogen bonds ( $\mathrm{D}=$ donor, $\mathrm{A}=$ acceptor) |  |  |  |  |  |
| D-H | d(D-H) | $\mathrm{d}(\mathrm{H}-\mathrm{A})$ | D-H-A | d(D-A) | A |
| $\mathrm{OH}-\mathrm{H}$ | 0.90(3) | 1.81(11) | $135^{\circ}$ | 2.530(10) | 07 |
| OH-H | 0.90(3) | 2.25(13) | $120^{\circ}$ | 2.811(11) | 09 |

## DESCRIPTION OF THE STRUCTURE

The structure of housleyite (Fig. 3) consists of corner-sharing chains of $\mathrm{TeO}_{6}$ octahedra along [101] linked into undulating sheets parallel to $\{10 \overline{1}\}$ by sharing edges and corners with $\mathrm{CuO}_{6}$ octahedra. Bonds to Pb atoms form additional links within and between the octahedral sheets.

The $\mathrm{TeO}_{6}$ octahedra exhibit moderate distortion. For the Te 1 and Te 2 octahedra, $\mathrm{Te}-\mathrm{O}$ distances range from 1.884 to $1.989 \AA$ and from 1.887 to $2.006 \AA$, respectively, and $\mathrm{O}-\mathrm{Te}-\mathrm{O}$ angles range from 85.4 to $97.7^{\circ}$ and from 83.3 to $97.8^{\circ}$. The $\mathrm{CuO}_{6}$ octahedra
are strongly Jahn-Teller (4+2) distorted and severely skewed. The Cu forms short bonds to O 1 of $1.957(\times 2)$ and to O 2 of $1.971 \AA$ $(\times 2)$ yielding a fairly regular square-planar array with $\mathrm{O}-\mathrm{Cu}-\mathrm{O}$ angles of 87.4 and $92.6^{\circ}$. The apical OH atoms of the Cu octahedron are at distances of $2.648 \AA$ and have $\mathrm{O} 1-\mathrm{Cu}-\mathrm{OH}$ angles of 66.4 and $113.6^{\circ}$ and $\mathrm{O} 2-\mathrm{Cu}-\mathrm{OH}$ angles of 77.1 and $102.9^{\circ}$. The Pb atoms have lopsided nine- and elevenfold coordinations (Fig. 4) attributable to the $6 \mathrm{~s}^{2}$ lone-electron-pair effect typically exhibited by $\mathrm{Pb}^{2+}$ (e.g., Moore 1988; Cooper and Hawthorne 1994; Kharisun et al. 1997; Mills et al. 2009a). In fact, the Pb atoms in the structures of all seven recently discovered new minerals from Otto Mountain exhibit this effect. The hydrogen atom of the hydroxyl group appears to form a bifurcated hydrogen bond to O 7 and O 9 . The hydrogen bond to O 9 is unusual in that OH and O 9 form one of the edges of the Te 2 octahedron; however, the bonding geometry (Fig. 5) and bond-valence analysis (Table 5) support this $H$ bond assignment.

A corner-sharing chain of $\mathrm{Te}^{6+} \mathrm{O}_{6}$ octahedra is found in one other mineral, ottoite (Kampf et al. 2010b); however, the configurations of the chains in the two structures are different. The octahedral chains in housleyite consist of two different $\mathrm{Te}^{6+} \mathrm{O}_{6}$ octahedra that alternate along the chains. The Tel octahedra share cis corners and the Te 2 octahedra share trans corners. In ottoite there is only one type of $\mathrm{Te}^{6+} \mathrm{O}_{6}$ octahedron and it links to equivalent octahedra by sharing trans corners. Another difference is that the chains in ottoite are linked to one another only via $\mathrm{Pb}-\mathrm{O}$ bonds.

Housleyite is chemically most closely allied with khinite (khinite- $4 O$ and khinite- $3 T$ ), $\mathrm{PbCu}_{3} \mathrm{TeO}_{6}(\mathrm{OH})_{2}$ (Burns et al. 1995; Cooper et al. 2008; Hawthorne et al. 2009). Although all three structures are based upon layers of $\mathrm{Te}^{6+} \mathrm{O}_{6}$ and Jahn-Teller

TABLE 5. Bond-valence analysis for housleyite

|  | O1 | O 2 | O3 | O4 | O5 | O6 | O7 | O8 | O9 | OH | $\sum v_{\text {c }}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Pb1 | 0.175 | 0.154 | 0.2480 .022 | 0.031 | 0.403 | 0.172 | 0.5090 .021 |  | 0.411 | 0.024 | 2.170 |
| Pb2 |  | 0.498 | 0.054 | 0.199 | 0.246 | 0.389 |  | 0.1180 .039 | 0.166 | 0.268 | 1.977 |
| Pb3 | 0.327 |  |  |  | 0.391 | 0.1660 .155 | 0.237 | 0.3820 .220 | 0.133 | 0.044 | 2.055 |
| Cu | $0.472 \times 2 \rightarrow$ | $0.454 \times 2 \rightarrow$ |  |  |  |  |  |  |  | $0.073 \times 2 \rightarrow$ | 1.998 |
| Te1 |  | 0.930 | 0.925 | 0.823 | 0.984 | 1.093 | 1.050 |  |  |  | 5.805 |
| Te2 | 1.022 |  | 0.786 | 0.874 |  |  |  | 1.084 | 1.050 | 0.834 | 5.650 |
| H |  |  |  |  |  |  | 0.182 |  | 0.080 | 0.738 | 1.000 |
| $\Sigma V_{\mathrm{a}}$ | 1.996 | 2.036 | 2.035 | 1.927 | 2.024 | 1.975 | 1.999 | 1.843 | 1.840 | 1.981 |  |

Notes: Values are expressed in valence units. Multiplicity is indicated by $\times \rightarrow$; $\mathrm{Pb}^{2+}-\mathrm{O}$ bond strengths from Krivovichev and Brown (2001); $\mathrm{Cu}^{2+}-\mathrm{O}$ and $\mathrm{Te}^{6+}-\mathrm{O}$ bond strengths and hydrogen-bond strengths based on $\mathrm{H} \cdots \mathrm{O}$ bond lengths from Brown and Altermatt (1985).


Figure 3. Structure of housleyite viewed down [101] (top) and [10 $\overline{1}]$ (bottom). The $\mathrm{Pb} 1, \mathrm{~Pb} 2$, and Pb 3 atoms are shown as spheres.


Figure 4. Coordinations of the $\mathrm{Pb} 1, \mathrm{~Pb} 2$, and Pb 3 atoms in housleyite. The lopsided distributions of bond lengths are attributable to the localization of the lone-pair electrons. Bond lengths are given in angstroms.


Figure 5. Hydrogen bonding in housleyite.
distorted $\mathrm{Cu}^{2+} \mathrm{O}_{6}$ octahedra, the layers in the housleyite structure are quite different from those in the khinite polymorphs.

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