

Lead-tellurium oxysalts from Otto Mountain near Baker, California: IV. Markcooperite, $\text{Pb}(\text{UO}_2)\text{Te}^{6+}\text{O}_6$, the first natural uranyl tellurate

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ABSTRACT

Markcooperite, $\text{Pb}_2(\text{UO}_2)\text{Te}^{6+}\text{O}_6$, is a new tellurate from Otto Mountain near Baker, California, named in honor of Mark A. Cooper of the University of Manitoba for his contributions to mineralogy. The new mineral occurs on fracture surfaces and in small vugs in brecciated quartz veins. Markcooperite is directly associated with bromian chlorargyrite, iodargyrite, khinite-4O, wulfenite, and four other new tellurates: housleyite, thorneite, ottoite, and timroseite. Various other secondary minerals occur in the veins, including two other new secondary tellurium minerals: paratimroseite and telluoperite. Markcooperite is monoclinic, space group $P2_1/c$, $a = 5.722(2)$, $b = 7.7478(2)$, $c = 7.889(2)$ Å, $\beta = 90.833(5)^\circ$, $V = 349.7(2)$ Å³, and $Z = 2$. It occurs as pseudotetragonal prisms to 0.2 mm with the forms {100} and {011} and as botryoidal intergrowths to 0.3 mm in diameter; no twinning was observed. Markcooperite is orange and transparent, with a light orange streak and adamantine luster, and is non-fluorescent. Mohs hardness is estimated at 3. The mineral is brittle, with an irregular fracture and perfect {100} cleavage. The calculated density is 8.496 g/cm³ based on the empirical formula. Markcooperite is biaxial (+), with indices of refraction $\alpha = 2.11$, $\beta = 2.12$, $\gamma = 2.29$ calculated using the Gladstone-Dale relationship, measured α - β birefringence of 0.01 and measured $2V$ of $30(5)^\circ$. The optical orientation is $X = c$, $Y = b$, $Z = a$. The mineral is slightly pleochroic in shades of orange, with absorption: $X > Y = Z$. No dispersion was observed. Electron microprobe analysis provided PbO 50.07, TeO₃ 22.64, UO₃ 25.01, Cl 0.03, O=Cl -0.01, total 97.74 wt%; the empirical formula (based on O+Cl = 8) is $\text{Pb}_{2.05}\text{U}_{0.80}\text{Te}_{1.18}^{6+}\text{O}_{7.99}\text{Cl}_{0.01}$. The strongest powder X-ray diffraction lines are [d_{obs} in Å (hkl) I]: 3.235 (120, 102, $\bar{1}02$) 100, 2.873 (200) 40, 2.985 ($\bar{1}21$, 112, 121) 37, 2.774 (022) 30, 3.501 (021, 012) 29, 2.220 (221, $\bar{2}21$, 212) 23, 1.990 (222, $\bar{2}22$) 21, and 1.715 (320) 22. The crystal structure ($R_1 = 0.052$) is based on sheets of corner-sharing uranyl square bipyramids and tellurate octahedra, with Pb atoms between the sheets. Markcooperite is the first compound to show Te^{6+} substitution for U^{6+} within the same crystallographic site. Markcooperite is structurally related to synthetic $\text{Pb}(\text{UO}_2)\text{O}_2$.

Keywords: Markcooperite, new mineral, tellurate, uranyl, crystal structure, Otto Mountain, California

INTRODUCTION

Markcooperite, $\text{Pb}_2(\text{UO}_2)\text{Te}^{6+}\text{O}_6$, is one of seven new secondary lead-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. (2010a). Markcooperite is the first natural uranyl tellurate discovered; however, three uranyl tellurites are known: cliffordite, $\text{UTe}^{4+}\text{O}_6$ (Gaines 1969), moctezumite, $\text{PbUO}_2(\text{Te}^{4+}\text{O}_3)_2$ (Gaines 1965), and schmitterite $\text{UO}_2\text{Te}^{4+}\text{O}_3$ (Gaines 1971).

Markcooperite is named in honor of Mark A. Cooper (b. 1963) of the University of Manitoba for his contributions to mineralogy. He has been involved in the description of many new minerals (~35), and the determination of the crystal structures of many minerals containing uranium (e.g., schoepite, guillemit-

nite, marthozite, rutherfordine) and tellurium (e.g., khinite-4O, khinite-3T, spiroffite). Cooper 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 2009-045). Three cotype specimens are deposited in the Natural History Museum of Los Angeles County, catalog numbers 62510, 62511, and 62512.

OCCURRENCE

Markcooperite was found at the Aga mine, ($35^\circ 16.399'N$ $116^\circ 05.665'W$) on Otto Mountain, ~2 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 ($35^\circ 16.606'N$ $116^\circ 05.956'W$).

Markcooperite is very rare and occurs on fracture surfaces and in small vugs in quartz veins. Species observed in direct association with the new mineral include bromine-rich chlorar-

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gyrite, iodargyrite, khinite-4O, wulfenite and four new tellurates: housleyite $[\text{Pb}_6\text{Cu}^{2+}\text{Te}_4^{6+}\text{O}_{18}(\text{OH})_2]$ (IMA2009-024; Kampf et al. 2010c), ottoite $[\text{Pb}_2\text{Te}^{6+}\text{O}_5]$ (IMA2009-063; Kampf et al. 2010b), thorneite $[\text{Pb}_6(\text{Te}_2^{6+}\text{O}_{10})(\text{CO}_3)\text{Cl}_2(\text{H}_2\text{O})]$ (IMA2009-023; Kampf et al. 2010a), and timroseite $[\text{Pb}_2\text{Cu}_3^{2+}(\text{Te}^{6+}\text{O}_6)_2(\text{OH})_2]$ (IMA2009-064; Kampf et al. 2010d). Other species identified in the assemblages include acanthite, anglesite, atacamite, boleite, brochantite, burckhardtite, calcite, caledonite, celestine, cerussite, chalcopyrite, chrysocolla, devilline, diaboite, eztlite, fluorite, fornacite, galena, goethite, gold, hessite, jarosite, kuranakhite, linarite, malachite, mimetite, mottramite, munakataite, murchisonite, muscovite, perite, phosphohedyphane, plumbojarosite, pyrite, schiefelinite, vanadinite, vauquelinite, and two other new minerals: paratimroseite $[\text{Pb}_2\text{Cu}_4^{2+}(\text{Te}^{6+}\text{O}_6)_2(\text{H}_2\text{O})_2]$ (IMA2009-065; Kampf et al. 2010d) and telluoperite $[\text{Pb}_3\text{Te}^{4+}\text{O}_4\text{Cl}_2]$ (IMA2009-044; Kampf et al. 2010e). Other potentially new species are still under investigation.

Markcooperite and most of the other secondary minerals of the quartz veins are interpreted as having formed from the partial oxidation of primary sulfides (e.g., galena) and tellurides (e.g., hessite) during or following brecciation of the quartz veins. The U may have originated from one or more primary U-bearing phases (possibly uraninite in the form of inclusions); however, the source of the U is yet to be determined.

PHYSICAL AND OPTICAL PROPERTIES

Markcooperite crystals are pseudotetragonal prisms exhibiting $\{100\}$ as the basal form and $\{011\}$ as the prism form. Crystals range from tiny, thin, tapering prisms, $<5\ \mu\text{m}$ in length (Fig. 1), to larger squat prisms to 0.2 mm in length. Most commonly, the mineral occurs as botryoidal aggregates to 0.3 mm in diameter, which consists of tightly intergrown crystals (Fig. 2).

Markcooperite is orange and transparent, with a light orange streak and adamantine luster. It is non-fluorescent and has an estimated Mohs hardness of 3. The tenacity is brittle, the fracture is irregular, and the cleavage is perfect on $\{100\}$. Density could not be measured because it is greater than those of available high-density liquids and there is insufficient material for physical measurement. The calculated density is $8.496\ \text{g/cm}^3$ for the empirical formula. In dilute HCl, markcooperite immediately decomposes, turning white and opaque, and then dissolves slowly.

Optically, markcooperite is biaxial (+); however, the indices of refraction are higher than the available high-density liquids. The Gladstone-Dale relationship (Mandarino 1981) predicts $n_{\text{av}} = 2.175$ from the empirical formula. This value can be used with the measured $2V$ of $30(5)^\circ$ and the α - β birefringence (0.01) to predict the indices of refraction: $\alpha = 2.11$, $\beta = 2.12$, $\gamma = 2.29$. The optical orientation is $X = \mathbf{c}$, $Y = \mathbf{b}$, $Z = \mathbf{a}$. The mineral is slightly pleochroic in shades of orange, with absorption: $X > Y = Z$. No dispersion was observed.

CHEMISTRY

Five chemical analyses were carried out using a JEOL8200 electron microprobe (WDS mode, 15 kV, 10 nA, focused beam) at the Division of Geological and Planetary Sciences, California Institute of Technology. The standards used were PbS, UO_2 , Te metal, and sodalite (for Cl). No other elements were detected

in EDS analyses, and in the microprobe S, Cr, Cu, and Bi were below detection limits. Crystal structure and bond-valence considerations (see below) indicate the absence of H_2O and OH in the structure. The averages (and ranges) of the analyses are: PbO 50.07 (49.23–51.60), TeO_3 22.64 (21.11–23.18), UO_3 25.01 (24.22–25.83), Cl 0.03 (0.01–0.06), $\text{O}=\text{Cl}$ –0.01, total 97.74 wt%. Although no damage was noted in a subsequent SEM examination of the probe mount, tellurates 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), Mills et al. (2009c),

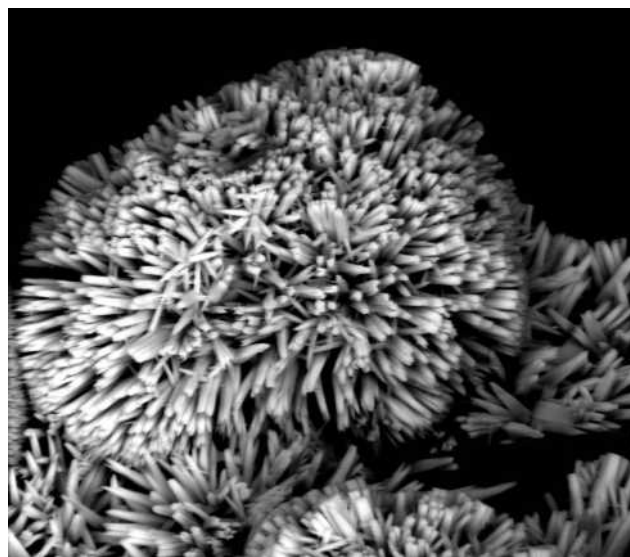


FIGURE 1. Backscatter SEM image of a cluster markcooperite crystals (FOV $30\ \mu\text{m}$).

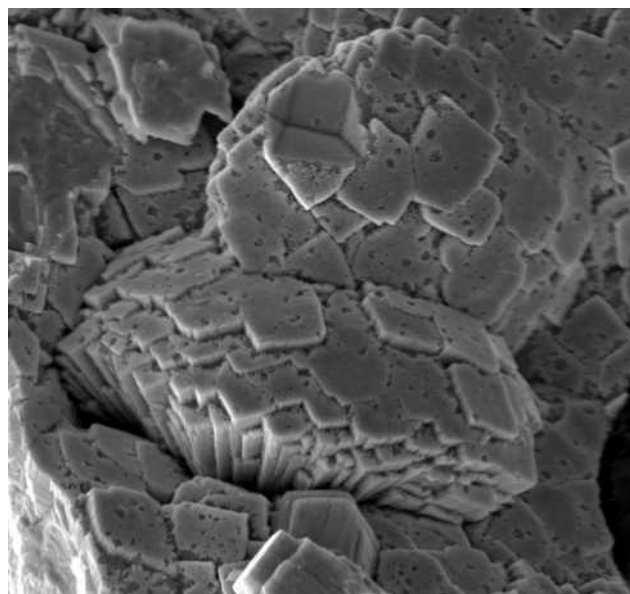


FIGURE 2. SEM image of the surface of a botryoidal aggregate of markcooperite crystals (FOV $75\ \mu\text{m}$).

and Mills et al. (2010).

The empirical formula (based on O+Cl = 8) is $\text{Pb}_{2.05}\text{U}_{0.80}\text{Te}_{1.18}^{6+}\text{O}_{7.99}\text{Cl}_{0.01}$. The simplified formula is $\text{Pb}_2(\text{UO}_2)\text{TeO}_6$, which requires 49.16 PbO, 19.34 TeO_3 , and 31.50 UO_3 , total 100.00 wt%.

X-RAY CRYSTALLOGRAPHY AND STRUCTURE DETERMINATIONS

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

TABLE 1. X-ray powder-diffraction data for markcooperite

l_{obs}	d_{obs}	d_{calc}	l_{calc}	hkl
12	3.993	{ 4.002 3.970	{ 10 10	{ $\bar{1}11^*$ 111^*
29	3.501	{ 3.514 3.489	{ 26 45	{ 012 021^*
100	3.235	{ 3.266 3.231 3.221 3.011	{ 71 67 100 14	{ $\bar{1}02$ 102 120^* $\bar{1}12$
37	2.985	{ 2.988 2.984 2.975	{ 28 18 27	{ $\bar{1}21^*$ 112 121^*
40	2.873	2.871	58	200^*
30	2.774	2.768	46	022^*
9	2.490	2.488	10	013
7	2.462	2.464	8	031
6	2.279	2.274	5	113
16	2.239	2.235	9	$\bar{2}12$
		2.222	14	$\bar{2}21$
23	2.220	{ 2.212 2.211	{ 4 12	{ 212 221
5	2.177	2.177	5	023
4	2.043	2.042	3	$\bar{1}23$
21	1.990	{ 2.001 1.985	{ 18 16	{ $\bar{2}22$ 222
13	1.881	{ 1.891 1.889	{ 4 7	{ 213 041
18	1.838	1.843	18	140^*
12	1.817	{ 1.818 1.806	{ 8 6	{ $\bar{1}14$ 114
13	1.795	{ 1.796 1.793	{ 7 7	{ $\bar{1}41$ 141
16	1.764	{ 1.761 1.744	{ 10 10	{ $\bar{1}33^*$ 042
18	1.731	1.729	10	$\bar{3}02^*$
22	1.715	1.718	15	320^*
15	1.673	{ 1.682 1.675 1.675	{ 5 5 5	{ $\bar{3}21$ 124^* 321^*
9	1.577	{ 1.582 1.580 1.576	{ 5 3 3	{ $\bar{2}14$ $\bar{2}41$ $\bar{2}41$
8	1.497	1.494	5	$\bar{2}42$
6	1.440	1.436	5	400^*

Notes: l_{obs} based upon peak heights. l_{calc} calculated from the crystal structure using Powder Cell (Kraus and Nolze 1996). d_{calc} based on the cell refined from the powder data (*) using UnitCell (Holland and Redfern 1997). Refined cell: $a = 5.7427(6)$, $b = 7.782(1)$, $c = 7.878(2)$ Å, $\beta = 90.66(2)^\circ$ and $V = 352.06(9)$ Å³.

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 SHELXS-97 and refined, with neutral atom scattering factors, using SHELXL-97 (Sheldrick 2008). 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. CIF and structure factors are available on deposit¹.

DESCRIPTION OF THE STRUCTURE

In the markcooperite structure (Fig. 3), uranyl square bipyramids and tellurate octahedra link to one another by sharing corners along **b** and **c** to form sheets parallel to (100). The sheets are linked in the **a** direction via bonds to Pb atoms residing between the sheets. The $[\frac{1}{2}(\text{TeO}_6)^{2-} \cdot \frac{1}{2}(\text{UO}_2\text{O}_4)^{2-}]$ sheet is unique,

¹ Deposit item AM-10-046, CIF and structure factors. 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.

TABLE 2. Data collection and structure refinement details for markcooperite

Diffractometer	Rigaku R-Axis Spider
X-ray radiation/power	$\text{MoK}\alpha$ ($\lambda = 0.71075$ Å)/50 kV, 40 mA
Temperature	298(2) K
Structural formula	$\text{Pb}_2(\text{U}_{0.75}\text{Te}_{0.25}\text{O}_2)\text{TeO}_6$
Space group	$P2_1/c$
Unit-cell dimensions	$a = 5.722(2)$ Å $b = 7.748(2)$ Å $c = 7.889(2)$ Å $\beta = 90.833(5)^\circ$
Z	2
Volume	$349.7(2)$ Å ³
Density (for above formula)	8.361 g/cm ³
Absorption coefficient	70.483 mm ⁻¹
$F(000)$	724
Crystal size	$45 \times 45 \times 15$ µm
θ range	3.56° to 20.76°
Index ranges	$-5 \leq h \leq 5$, $-7 \leq k \leq 7$, $-7 \leq l \leq 7$
Reflections collected/unique	3886/362 [$R_{\text{int}} = 0.1058$]
Reflections with $F_o > 4\sigma F$	287
Completeness to $\theta = 27.50^\circ$	99.5%
Max. and min. transmission	0.4178 and 0.1436
Refinement method	Full-matrix least-squares on F^2
Parameters refined	60
GoF	1.083
Final R indices [$F_o > 4\sigma F$]	$R_1 = 0.052$, $wR_2 = 0.131$
R indices (all data)	$R_1 = 0.064$, $wR_2 = 0.139$
Largest diff. peak/hole	$3.052/-2.335$ e/Å ³

Notes: $R_{\text{int}} = \sum |F_o - F_s(\text{mean})| / \sum |F_o|$. $\text{GoF} = S = \{\sum [w(F_o - F_s)^2] / (n - p)\}^{1/2}$. $R_1 = \sum |F_o| - |F_s| / \sum |F_o|$. $wR_2 = \{\sum [w(F_o - F_s)^2] / \sum [w(F_s)^2]\}^{1/2}$. $w = 1/[\sigma^2(F_o) + (aP)^2 + bP]$ where a is 0.0945, b is 0, and P is $[2F_o^2 + \text{Max}(F_o, 0)]/3$.

TABLE 3. Atomic positions and displacement parameters for markcooperite

	x	y	z	U_{eq}	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
U/Te*	0.0000	0.0000	0.0000	0.0386(12)	0.035(2)	0.039(2)	0.042(2)	0.002(1)	0.003(1)	0.003(1)
Te	0.0000	0.5000	0.0000	0.0339(13)	0.029(2)	0.034(3)	0.039(2)	0.002(2)	-0.001(2)	-0.003(2)
Pb	0.4972(3)	0.1689(3)	0.6919(2)	0.0531(10)	0.044(1)	0.051(2)	0.064(2)	0.002(1)	-0.003(1)	-0.003(1)
O1	0.699(5)	-0.068(4)	-0.061(3)	0.054(8)	0.05(2)	0.05(2)	0.07(2)	0.01(2)	-0.03(1)	0.01(2)
O2	-0.137(5)	0.234(3)	0.505(3)	0.038(7)	0.06(2)	0.02(2)	0.03(2)	0.00(1)	-0.02(1)	0.00(1)
O3	0.295(4)	0.085(4)	0.429(3)	0.045(7)	0.02(1)	0.05(2)	0.06(2)	0.03(2)	0.00(1)	0.00(1)
O4	-0.114(4)	0.532(3)	-0.237(3)	0.040(7)	0.03(1)	0.02(2)	0.07(2)	0.01(1)	-0.01(1)	-0.00(1)

* Occupancy: 0.75(2)/0.25(2).

in that it has not been described in any natural or synthetic structure; however, it is derived from the more fundamental sheet $[(\text{UO}_2\text{O}_4)]^\infty$ found in synthetic $\text{Li}_2[(\text{UO}_2\text{O}_2)]$ (Gebert et al. 1978), $\text{Ba}[(\text{UO}_2\text{O}_2)]$ (Reis et al. 1976), $\text{Sr}[(\text{UO}_2\text{O}_2)]$ (Loopstra and Riet-

veld 1969), $\text{Pb}[(\text{UO}_2\text{O}_2)]$ (Cremers et al. 1986), $\gamma\text{-}[(\text{UO}_2(\text{OH})_2)]$ (Siegel et al. 1972), $\beta\text{-}[(\text{UO}_2(\text{OH})_2)]$ (Taylor and Bannister 1972), and $\beta\text{-Na}_2[(\text{UO}_2\text{O}_2)]$ (Kovba 1971). No natural mineral has thus far been described with this $[(\text{UO}_2\text{O}_4)]^\infty$ sheet, although the parent sheet, as described by Burns (2005), is found in the autunite structure-type (Burns et al. 1996).

The structure of markcooperite is topologically equivalent to the orthorhombic (*Pbcm*) structure of $\text{Ba}[(\text{UO}_2\text{O}_2)]$, $\text{Sr}[(\text{UO}_2\text{O}_2)]$, and $\text{Pb}[(\text{UO}_2\text{O}_2)]$ (Fig. 3) in which there is only one U site located on the origin. The replacement of alternating (UO_2O_4) square bipyramids by TeO_6 octahedra to form the markcooperite sheet leads to a reduction in symmetry to the monoclinic space group, $P2_1/c$. The increase in the β angle to $90.833(5)^\circ$ also apparently serves to better accommodate the smaller TeO_6 octahedra within the sheet. During structure analysis, we tested an orthorhombic *Pbcm* model in which U and Te were refined on the origin; however, it yielded unreasonable bond lengths and higher *R*-factors.

Another interesting feature of markcooperite is the partial substitution of Te for U on the origin. The refined U:Te occupancy of 0.75(2):0.25(2) matches very closely the empirical formula, $\text{Pb}_{2.05}\text{U}_{0.80}\text{Te}_{1.18}\text{O}_{7.99}\text{Cl}_{0.01}$. To the best of our knowledge, this is the first case of Te^{6+} for U^{6+} substitution. In spite of the

TABLE 4. Selected bond lengths (Å) in markcooperite

Pb-O3	2.45(3)	Te-O3 (x2)	1.90(2)
Pb-O4	2.46(2)	Te-O2 (x2)	1.98(2)
Pb-O3	2.49(3)	Te-O4 (x2)	1.98(3)
Pb-O1	2.54(3)	<Te-O>	1.95
Pb-O2	2.63(3)		
Pb-O1	2.90(3)	U/Te-O1 (x2)	1.86(3)
Pb-O3	2.92(3)	U/Te-O2 (x2)	2.20(3)
Pb-O1	3.23(3)	U/Te-O4 (x2)	2.20(3)
Pb-O2	3.30(3)	<U/Te-O>	2.09
Pb-O4	3.63(3)		
<Pb-O>	2.86		

TABLE 5. Bond-valence analysis for markcooperite

	O1	O2	O3	O4	Sum
Pb	0.31, 0.15, 0.08	0.26, 0.07	0.37, 0.34, 0.14	0.36, 0.03	2.10
Te	0.84 x2→		1.05 x2→	0.84 x2→	5.46
U/Te	1.40 x2→	0.71 x2→		0.71 x2→	5.64
Sum	1.94	1.88	1.90	1.95	

Notes: Values are expressed in valence units. Multiplicity is indicated by x→; Pb^{2+} -O bond strengths from Krivovichev and Brown (2001); Te^{6+} -O bond strengths from Brown and Altermatt (1985); $^{60}\text{U}^{6+}$ -O bond strengths ($r_0 = 2.074$, $b = 0.554$) from Burns et al. (1997); U/Te site occupancy (0.75/0.25) used in calculations.

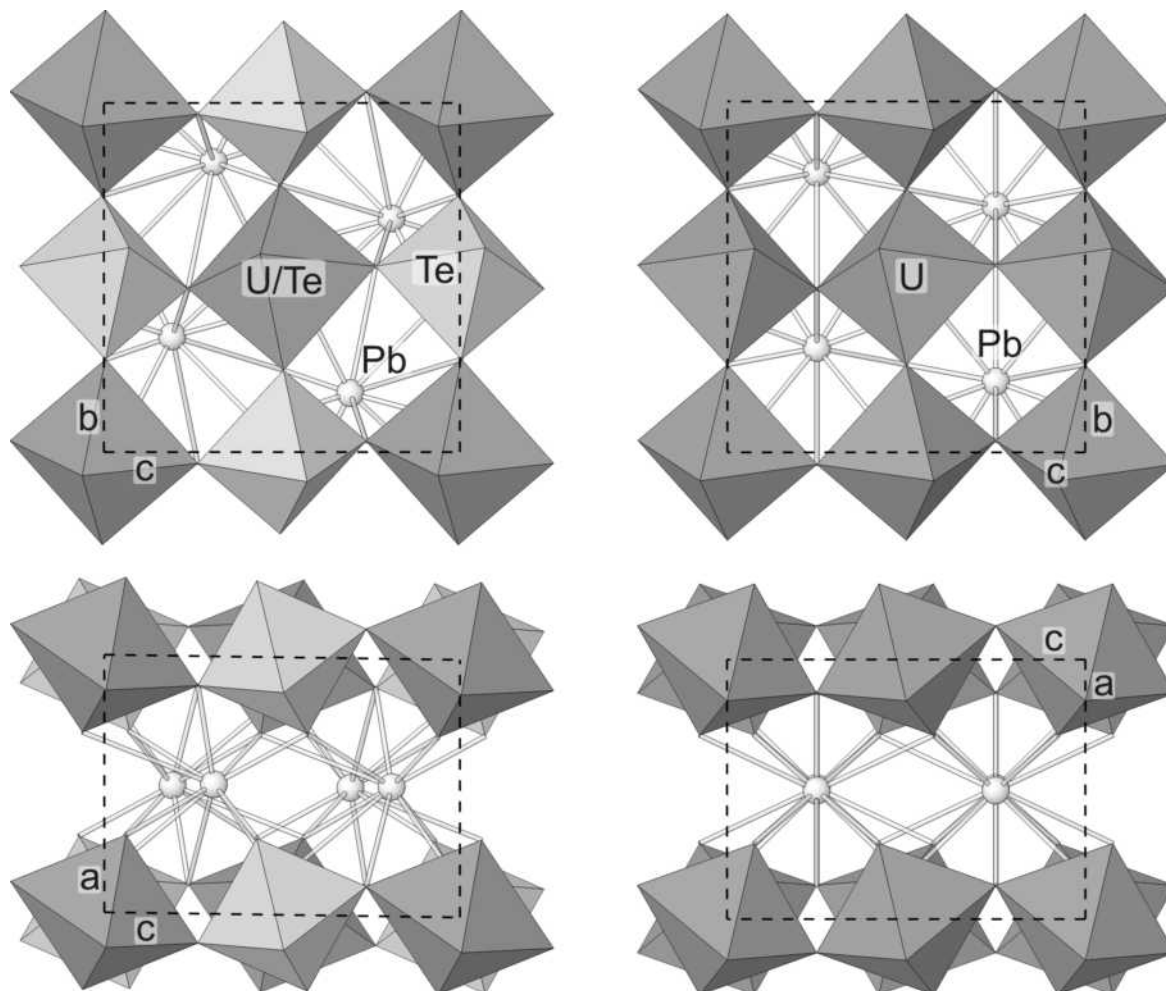


FIGURE 3. Structures of markcooperite (left) and $\text{Pb}[(\text{UO}_2\text{O}_2)]$ (right; Cremers et al. 1986), viewed along *a* (top) and along *b* (bottom).

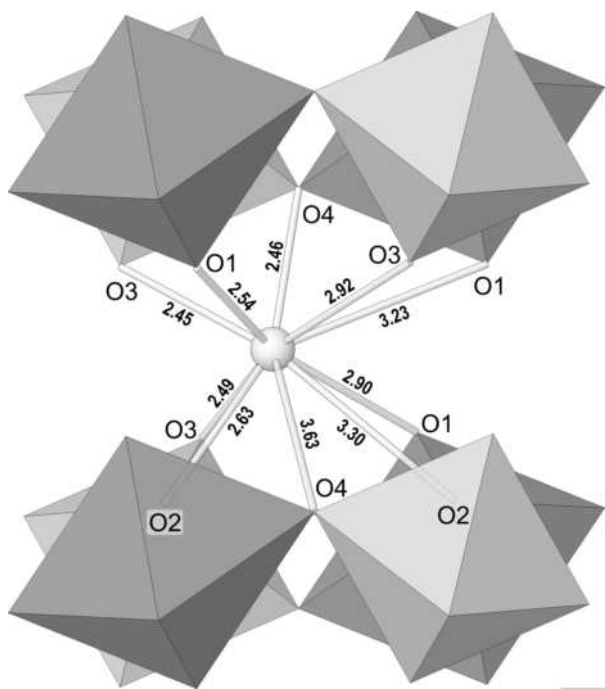


FIGURE 4. Coordination of the Pb atom in markcooperite viewed along **b**. The lopsided distribution of bond lengths is attributable to the localization of the lone-pair electrons. Bond lengths are given in angstroms.

25% occupancy by Te, the bond lengths for the site are reasonably normal for a uranyl group. The apical bond lengths of 1.86 Å, are slightly longer than the average of 1.79 Å noted by Burns et al. (1997), but are consistent with the structure type {e.g., 1.85 Å for Pb[(UO₂O₂)]—Cremers et al. (1986)} and the equatorial U–O bond lengths, 2.20 Å, are also consistent with those in Pb[(UO₂O₂)], 2.19 Å (Cremers et al. 1986).

It is typical for square bipyramidal uranyl groups to link to one another via their more distant equatorial corners, as this best accommodates the repulsion between the highly charged U⁶⁺ cations. This is the case in the Ba[(UO₂O₂)], Sr[(UO₂O₂)], and Pb[(UO₂O₂)] structures, and it is also noted in the markcooperite structure for the linkages between the uranyl square pyramids and the tellurate octahedra. Furthermore, in markcooperite the repulsion between U⁶⁺ and Te⁶⁺ results in significant distortion of the tellurate octahedron, manifest in four long equatorial Te–O bonds of 1.98 Å, corresponding to the corners shared with the uranyl square bipyramids, and two short apical Te–O bonds of 1.90 Å projecting into the interlayer region. The average Te–O bond length of 1.95 Å is quite normal for octahedrally coordinated Te⁶⁺ (e.g., Mills et al. 2010; Kampf et al. 2010a). We note that the U and Pb bond-valence parameters have been refined with a new r_0 – b pair with $b \neq 0.37$, whereas Te⁶⁺ has not. Fixing $b = 0.37$ also contributes to large displacements in the bond-valence fits (Burns et al. 1997; Locock and Burns 2004; Mills et al. 2009a).

The Pb atom is in 10-fold lopsided coordination (Fig. 4), which is indicative of the 6s² lone-pair being stereochemically active. This feature is often noted in Pb oxysalts (e.g., Moore 1988; Cooper and Hawthorne 1994; Kharisun et al. 1997; Mills et al. 2009b) and, in fact, the Pb atoms in the structures of all seven

recently discovered new minerals from Otto Mountain exhibit this feature. All 10 Pb–O bonds are unique and range from 2.45 to 3.63 Å, with an average of 2.86 Å. In Pb[(UO₂O₂)] (Cremers et al. 1986), Pb is in 10-fold coordination and also exhibits a stereoactive lone-electron-pair, with Pb–O bonds ranging from 2.48 to 3.81 Å and with an average bond length of 2.89 Å.

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