

## Weissbergite, $\text{TlSbS}_2$ , a new mineral from the Carlin gold deposit, Nevada

FRANK W. DICKSON

Department of Geology, Stanford University  
Stanford, California 94305

AND ARTHUR S. RADTKE

U.S. Geological Survey  
Menlo Park, California 94025

### Abstract

Weissbergite,  $\text{TlSbS}_2$ , occurs as irregular, broken or fractured grains, 0.5 mm in maximum dimension, in silicified, brecciated, dolomitic carbonate rocks in the east pit of the Carlin gold deposit, Nevada. Weissbergite is opaque, steel-gray in thick plates, and bright metallic in luster on fresh surfaces. The mineral is triclinic and apparently lacks a center of symmetry. Approximate cell constants are  $a = 11.8$ ,  $b = 6.4$ ,  $c = 6.1\text{\AA}$ ;  $\alpha = 109.9^\circ$ ,  $\beta = 81.8^\circ$ , and  $\gamma = 105.4^\circ$ ;  $Z = 4$ ; cell volume =  $420\text{\AA}^3$ . Strongest X-ray diffraction lines and their relative intensities (subject to strong preferred orientation) are: 2.971 (100), 3.583 (9), 3.651 (9), and 2.839 (7); 40 lines were observed. Weissbergite displays several cleavages: one, perfect; two, excellent; and at least one, good. Its Vickers hardness is about  $35\text{ kg mm}^{-2}$  (Mohs hardness, about 1.5). The measured density of synthetic  $\text{TlSbS}_2$  is  $5.79(5)\text{ g cm}^{-3}$ ; calculated density is  $6.1\text{ g cm}^{-3}$ . In reflected light the mineral is creamy white, weakly birefractant, and strongly anisotropic, with polarization colors of blue-green, blue-black, orange-brown, and gray. Reflectances ( $R$ ) in air are:  $650\text{nm} = 32.1\text{--}33.8$ ;  $589\text{nm} = 34.5\text{--}35.8$ ;  $546\text{nm} = 35.0\text{--}36.8$ ; and  $470\text{nm} = 36.0\text{--}38.4$ . Thin plates in transmitted light show pleochroism in deep colors, ranging from red to orange-red and yellow-orange. Weissbergite is essentially pure  $\text{TlSbS}_2$ ; electron microprobe analyses gave Tl 52.7, Sb 31.2, S 16.4, sum 100.3 weight percent. The most abundant trace elements, determined by emission spectrographic analysis, are 300 ppm As and 200 ppm Fe. The mineral is named in honor of Dr. Byron G. Weissberg, Chemistry Division, D.S.I.R., New Zealand.

### Introduction

A new mineral, weissbergite, with a composition  $\text{TlSbS}_2$ , was found in the Carlin gold deposit, Eureka County, Nevada, as a result of a deliberate search for the antimony analogue of lorandite,  $\text{TlAsS}_2$ , which also occurs in the deposit (Radtke *et al.*, 1974). Other thallium minerals found to date only at Carlin are carlinite,  $\text{Tl}_2\text{S}$  (Radtke and Dickson, 1975), christite,  $\text{TlHgAsS}_3$  (Radtke *et al.*, 1977), and ellisite<sup>1</sup>,  $\text{Tl}_3\text{AsS}_3$  (Dickson and Radtke, unpublished manuscript).

The mineral  $\text{TlSbS}_2$  is named weissbergite after Dr. Byron G. Weissberg of the Chemistry Division, D.S.I.R., New Zealand, in recognition of his contri-

butions to the geochemistry of epithermal hydrothermal processes. He was the first to point to a similarity in the heavy-element geochemistry among the Carlin-type gold deposits and to show that the same elements occur in some hot-spring sinters of New Zealand (Weissberg, 1969). The mineral name and designation as a new mineral have been approved by the Commission of New Minerals and Mineral Names of the International Mineralogical Association.

Type material is deposited in the Epithermal Minerals Collection, Department of Geology, Stanford University, Stanford, California.

### Occurrence

Weissbergite occurs in small amounts with stibnite and quartz in silicified dolomitic carbonate rocks

<sup>1</sup> Mineral name and designation as a new mineral approved by Commission of New Minerals and Mineral Names, International Mineralogical Association, December 1977.

along breccia zones and high-angle faults through the upper part of the Roberts Mountains Formation in the east ore zone of the Carlin gold deposit. Individual weissbergite grains ranging in size from about 0.005 to 0.5 mm in length are locked within small masses of quartz, and locally are in contact with larger stibnite grains, up to 12 mm in length; in most places the weissbergite, stibnite, and quartz appear to have formed in open spaces between breccia fragments.

Weissbergite in this association has been found in samples collected at two localities in the east ore zone; these areas are near mine coordinates 23,000 N, 19,800 E, 6450 bench, and 23,850 N, 22,700 E, 6350 bench (Radtke, 1973).

### Physical and optical properties

Weissbergite occurs as irregular grains, many of which are broken or fractured (Fig. 1). A few of the grains were prismatic or tabular in form and showed striations parallel to the long dimension. Synthetic TlSbS<sub>2</sub> grains usually are equant to tabular in shape, and are bounded by simple combinations of pedions.

Broken grains of weissbergite display several cleavages which we were not able to relate to crystal forms. The cleavages include one perfect, two excellent, and at least one good. Cleaved fragments which lie on the perfect cleavage show steps of increased thickness typical of micaceous minerals. The traces of some of the other cleavages on the micaceous cleavage intersect at acute angles (57° and 67°), but the true angles between cleavages could not be measured.

The Vickers hardness measured with a Leitz hardness indenter with a 25 g load ranged from 26.0 to

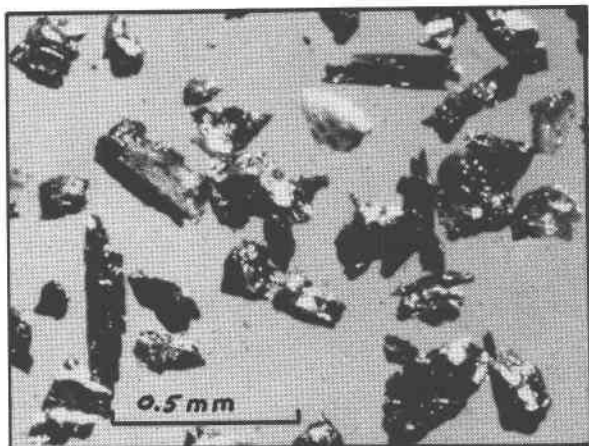


Fig. 1. Grains of weissbergite from the Carlin gold deposit. White and colorless grains are quartz.

Table 1. Reflectivities of weissbergite and synthetic TlSbS<sub>2</sub>

Phase	Wavelength (nm)			
	470	546	589	650
Weissbergite	36.0-38.4	35.0-36.8	34.5-35.8	32.1-33.8
Synthetic TlSbS <sub>2</sub>	31.1-40.2	33.0-39.3	29.5-36.9	27.1-33.4

37.1 and averaged 34.6 kg mm<sup>-2</sup> (10 determinations); the hardness of synthetic TlSbS<sub>2</sub> measured under similar conditions ranged from 28.0 to 40.6 and averaged 35.3 kg mm<sup>-2</sup> (8 determinations). These average values correspond to a Mohs hardness of about 1.5. The density of synthetic TlSbS<sub>2</sub> determined on a Berman balance is 5.79 ± 0.05 g cm<sup>-3</sup>; grains of weissbergite suitable for density measurement were not found. The density calculated from unit-cell parameters is 6.1 g cm<sup>-3</sup>. Weissbergite is opaque, steel-gray in color, and has a bright metallic luster. The streak is dark gray. Optical properties in reflected light for synthetic TlSbS<sub>2</sub> and for weissbergite are similar. In reflected light the mineral is creamy white, weakly birefractant, and strongly anisotropic. Polarization colors include blue-green, blue-black, orange-brown, and gray. Reflectivity data for weissbergite and synthetic TlSbS<sub>2</sub> are given in Table 1.

Optical properties in transmitted light were difficult to measure because of the deep color and high indices of refraction. One thin crystal displayed an acute bisectrix figure with a 2*V* of about 70°, and was optically positive. Thin edges showed strong colors: deep orange-red to deep yellow-orange for grains lying on the perfect cleavage; deeper orange-red for grains lying on the excellent cleavage, which display only slight changes in deepness of color on rotation.

### Crystallography

X-ray powder diffraction data for weissbergite and synthetic TlSbS<sub>2</sub>, both of which showed strong preferred orientation, are given in Table 2. The agreement between the *d* spacings of the mineral and synthetic TlSbS<sub>2</sub> is excellent. Our data do not agree with the data of Semiletev and Man (1959) or of Palatnick *et al.* (1972), who reported cubic and hexagonal modifications of thin films of TlSbS<sub>2</sub>. Thin, rapidly deposited TlSbS<sub>2</sub> is perhaps metastable or possibly a polymorphic form.

Approximate measurements of the unit-cell constants were made by Dr. Kevin Brown, Chemistry Division, D.S.I.R., New Zealand. He used a single

Table 2. X-ray diffraction powder data for weissbergite and synthetic  $TlSbS_2$ 

Weissbergite Carlin, Nevada		Synthetic $TlSbS_2$	
Obs. $d$ (Å)	I	Obs. $d$ (Å)	I
---	---	13.7	<1
---	---	10.7	<1
9.2	2	9.4	1
5.87	<1	5.88	1
4.812	2	4.798	2
---	---	4.441	1
3.811	2	3.822	4
3.743	5	3.752	5
3.708	5	3.712	5
3.651	9	3.650	8
3.583	9	3.583	7
---	---	3.336	<1
---	---	3.181	<1
3.058	3	3.058	2
2.971	100*	2.973	100*
2.839	7	2.839	7
2.761	1	2.758	1
2.716	4	2.718	6
---	---	2.609	<1
2.511	<1	2.511	1
2.449	1	2.448	1
2.360	5	2.362	5
2.351	5	2.351	6
2.273	3	2.274	3
---	---	2.223	<1
---	---	2.209	<1
2.095	1	2.096	1
2.054	1	2.056	1
2.012	2	2.013	2
1.979	1	1.980	1
1.964	3	1.963	3
1.912	1	1.910	2
1.905	1	1.903	2
1.843	3	1.845	3
1.830	3	1.831	3
1.801	3	1.802	3
1.787	3	1.789	3
1.687	<1	1.684	1
1.647	<1	1.643	1
1.573	1	1.575	1
1.519	1	1.518	2
1.506	<1	1.505	1
1.486	3	1.487	5
1.467	1	1.463	2
1.428	2	1.428	2
1.256	1	1.255	1
1.199	1	1.200	1
1.130	1	1.130	1

Diffraction patterns obtained with Ni-filtered Cu radiation,  $\lambda$  Cu  $K\alpha_1$ , = 1.54051 Å, Si used as an internal standard, scanning speed 0.25° 2 $\theta$  per minute. \*Intensities are affected by strong preferred orientation.

Table 3. Microprobe chemical analyses of weissbergite

Grain no.	Weight Percent			
	Tl	Sb	S	Total
1	52.6	30.8	16.4	99.8
2	52.3	31.3	16.3	99.9
3	52.9	31.1	16.5	100.5
4	52.9	31.4	16.3	100.6
Average	52.7	31.2	16.4	100.2
$TlSbS_2$	52.37	31.20	16.43	100.00

crystal of synthetic weissbergite; natural materials proved unsuitable for study. Unfortunately, only one of the several crystals examined yielded an ordered pattern. This crystal was so small that the uncertainties in the cell measurements were large. Attempts to index the X-ray diffraction powder data using the approximate cell constants were not successful. Both the single crystal data and the crystal morphologies are consistent with triclinic symmetry. The approximate cell constants are:  $a = 11.8$ ,  $b = 6.4$ , and  $c = 6.1$  Å;  $\alpha = 109.9^\circ$ ,  $\beta = 81.8^\circ$ , and  $\gamma = 105.4^\circ$ . The unit-cell volume is 420 Å<sup>3</sup> and  $Z = 4$ . The mineral apparently lacks a center of symmetry, judging from the absence of parallel equivalent faces on the synthetic euhedral single crystals, and thus it may belong to the rare triclinic pedial class.

### Chemical composition

Microprobe analyses show that weissbergite is  $TlSbS_2$ . Results of chemical analyses of 4 grains of the mineral using synthetic  $TlSbS_2$  as a standard are shown in Table 3. An emission spectrographic analysis for a composite sample of 5 grains of weissbergite indicates that the only elements present in other than trace amounts are arsenic (300 ppm) and iron (200 ppm) (Table 4).

### Synthesis

Synthetic weissbergite can be prepared by heating Tl, Sb and S, or  $Tl_2S$  and  $Sb_2S_3$ , in stoichiometric proportions in sealed evacuated pyrex tubes at 350°C or higher for several days. Cooling melted  $TlSbS_2$  commonly produces massive buttons of polycrystalline weissbergite, which can be broken with ease into cleavage fragments. The deformation accompanying the cleavage process apparently disrupts the crystal structure, causing cleavage fragments to be useless for single-crystal study.

The single crystals examined during the X-ray study were synthesized by subjecting pure powdered  $\text{TlSbS}_2$  in a horizontal sealed evacuated pyrex tube to a slight vertical temperature gradient in a Globar furnace held at about  $450^\circ\text{C}$  for 6 days. The gradient resulted from a flux of heat supplied by radiation from above. Tiny (less than about 0.03 mm) equant crystals of weissbergite grew on the upper part of the glass tube; X-ray diffraction examination of powdered crystals showed that they had atomic spacings identical to the natural and massive synthetic weissbergite. Four euhedral crystals were studied by single-crystal techniques in efforts to measure cell parameters; three of the crystals produced disordered patterns, and one gave an ordered but faint pattern.

### Phase relations

The phase relationships of weissbergite to other solid phases in the system  $\text{Tl}_2\text{S}-\text{Sb}_2\text{S}_3$ , as determined by Bohac *et al.* (1974) by differential thermal analysis (DTA) methods, are shown in Figure 2. Weissbergite melts congruently at  $484^\circ\text{C}$ . It shows a eutectic with  $\text{Tl}_3\text{SbS}_3$  ( $\alpha$ ) at  $322^\circ\text{C}$  and 30 mole percent  $\text{Sb}_2\text{S}_3$ , and with  $\text{TlSb}_5\text{S}_8$  (parapierrrotite; Johan *et al.*, 1975) at  $392^\circ\text{C}$  and about 73 mole percent  $\text{Sb}_2\text{S}_3$ . The  $\alpha$  phase,  $\text{Tl}_3\text{SbS}_3$ , has not been found in nature, but it appears likely that it exists at the Carlin deposit, judging from the occurrence there of two minerals, carlinitite ( $\text{Tl}_2\text{S}$ ) and weissbergite ( $\text{TlSbS}_2$ ), with compositions along the carlinitite- $\alpha$ -weissbergite join. The DTA studies revealed no evidences of significant solid solution. Bohac *et al.* (1974) used materials of high purity, originally processed by zone refining; their melting temperatures for two other mineral phases that occur on the diagram, carlinitite ( $\text{Tl}_2\text{S}$ ),  $452^\circ\text{C}$ , and stibnite ( $\text{Sb}_2\text{S}_3$ ),  $566^\circ\text{C}$ , are somewhat higher than values reported before, attesting to the purity of their phases.

Table 4. Semiquantitative spectrographic analysis of weissbergite

Element	Weight Percent	Element	Weight Percent
Ag	0.0005	Mn	0.0001
As	0.03	Mo	0.0002
B	0.0015	Ni	0.005
Ba	0.005	Pb	0.005
Bi	0.00015	Sb	Major
Co	0.0015	Sn	0.0003
Cr	0.001	Ti	0.0003
Cu	0.002	Tl	Major
Fe	0.02	V	0.0003

Analysis of 5 grains of weissbergite  
 [Sought but not found: Al, Au, Be, Ca, Cd, Ce, Eu, Ga, Ge, Hf, In, K, La, Li, Mg, Na, Nb, P, Pd, Pt, Re, Sc, Si, Sr, Ta, Te, Th, U, W, Y, Yb, Zn, Zr.] Analyst: Chris Heropoulos, U.S. Geological Survey.

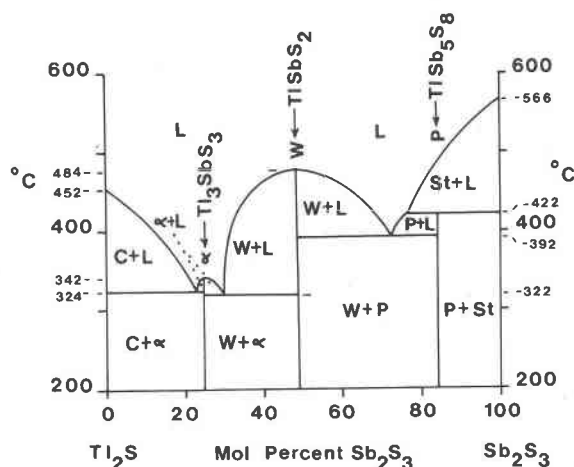


Fig. 2. System  $\text{Tl}_2\text{S}-\text{Sb}_2\text{S}_3$  as a function of temperature and bulk composition, at the vapor pressure; slightly modified, after Bohac *et al.* (1974). Symbols: C = carlinitite,  $\text{Tl}_2\text{S}$ ;  $\alpha$  =  $\text{Tl}_3\text{SbS}_3$ ; W = weissbergite,  $\text{TlSbS}_2$ ; P = parapierrrotite,  $\text{TlSb}_5\text{S}_8$ ; St = stibnite; and L = liquid,  $\text{Tl}_2\text{S}-\text{Sb}_2\text{S}_3$ .

$\text{TlSbS}_2$  reacts with  $\text{TlAsS}_2$  (lorandite) to form a series of solid solutions (Dickson, 1976, unpublished data). The compounds show  $d$  spacings that vary from those of weissbergite (pure  $\text{TlSbS}_2$ ) to a modified weissbergite pattern at 50 mole percent  $\text{TlSbS}_2$ . Inasmuch as lorandite is monoclinic and weissbergite is triclinic, an unlocated structural discontinuity must exist in this system somewhere between 50 and 0 mole percent  $\text{TlSbS}_2$ .

### Geochemical implications

Weissbergite is another member of the suite of unique minerals formed in the Carlin gold deposit by late-stage processes (Dickson and Radtke, 1977). In addition to weissbergite, thallium minerals found only at Carlin include carlinitite,  $\text{Tl}_2\text{S}$ ; christite,  $\text{TlHgAsS}_3$ ; and ellisite,  $\text{Tl}_3\text{AsS}_3$ , a recently-named mineral. Rare minerals include lorandite,  $\text{TlAsS}_2$ ; galkhaite,  $\text{Hg}(\text{As},\text{Sb},\text{Tl})\text{S}$ ; getchellite,  $\text{SbAsS}_3$ ; and avicennite,  $\text{Tl}_2\text{O}_3$  (Radtke *et al.*, 1978a). Common minerals are stibnite,  $\text{Sb}_2\text{S}_3$ ; orpiment, nearly pure  $\text{As}_2\text{S}_3$ , or with some Tl in solid solution; realgar,  $\text{AsS}$ ; and cinnabar,  $\text{HgS}$ .

The vein minerals formed during the latter part of the hydrothermal episode when the solutions were boiling (Radtke *et al.*, 1978b) and changing in composition. They lost  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{H}_2\text{O}$ , and became more alkaline and concentrated. Little is known of the solubility behavior of thallium sulfosalts under these conditions, and specific precipitation mechanisms cannot be stated. Obviously, some unusual

combination of supply or depositional conditions are required to form the unique suite of minerals. Possibly the suite of elements requires special kinds of rocks, such as carbonates, which can react with solutions and cause precipitation. A hint that the suite of elements may occur commonly in hot-spring waters was given by the observations of Weissberg (1969), who reported high levels of Tl, Au, Ag, As, Sb, and Hg in siliceous sinter deposits at Ohaki and other hot-spring outlets of New Zealand. Dilute waters of geothermal systems may commonly carry these heavy elements. The elements probably do not precipitate in observable quantities, except where they encounter reactive rocks such as the carbonate host rocks of the Carlin deposit. During boiling, the solutions become enriched in the heavy elements. Unusually high concentrations in solution would cause precipitation of minerals, either by replacement of carbonate, or by deposition in open fractures.

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