Cannonite, $Bi_2O(OH)_2SO_4$, a new mineral from Marysvale, Utah, USA*

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Abstract

Cannonite, ideally $Bi_2O(OH)_2SO_4$, is a new mineral from the Tunnel Extension mine, Ohio Mining District, Marysvale, Utah, USA. It occurs mostly as intergrown crystalline aggregates (<1 mm) of subhedral to euhedral equant to prismatic crystals (<200 μm) in cavities in quartz gangue. Other associated minerals are cuprobismutite, bismuthinite, and covelline. Cannonite is colourless and transparent with an adamantine lustre and white streak. It is brittle with an uneven to conchoidal fracture. In reflected light it is low reflecting, weakly to moderately bireflectant and weakly anisotropic. Internal reflections (colourless to white) are abundant. Measured reflectance values in air and oil are tabulated. Colour values relative to the CIE illuminant *C* for R_1 and R_2 in air respectively are: *Y*% 10.4, 11.7; Lambda$_d$ 475, 475; P_e% 2.6, 3.0. Calculated refractive indices at 589 nm: R_1 1.91 and R_2 1.99. VHN_{100} 229 (range 183–280); calculated Mohs hardness is 4.

X-ray studies show that cannonite is monoclinic with space group $P2_1/c$ and *a* 7.700(3), *b* 13.839(6), *c* 5.686(2) Å, β 109.11(3)°. It has a cell volume of 572.5(4) Å^3 with Z = 4. $D_{calc.}$ is 6.515 g/cm^3. The strongest six lines of the X-ray powder pattern are [*d* in Å (I) (hkl)] 3.206 (100) ($\bar{2}21$); 1.984 (90) (340, $\bar{1}52$); 2.924 (70) (131); 3.644 (60) (111); 3.466 (60) (040); 2.782 (50) ($\bar{1}12$). Averaged probe analyses gave the empirical formula $Bi_{1.99}O(OH_{1.04})_2S_{0.99}O_4$ on the basis of 7 oxygen atoms. The name is for Benjamin Bartlett Cannon of Seattle, Washington, United States of America.

Keywords: cannonite, new mineral, bismuth, Marysvale, Utah.

Introduction and general geology

Cannonite, ideally $Bi_2O(OH)_2SO_4$, is a new mineral species found in a specimen collected from the Tunnel Extension mine of the Ohio Mining District, Marysvale, Utah, USA [latitude 38°28′N, longitude 112°14′W]. A description of the deposit is given in Radtke *et al.*, (1967); in short, the mineralisation occurs as steeply dipping fissure infillings, along faults or shear zones, which cut the Bullion Canyon volcanics of middle Tertiary age. Radtke *et al.* also give an account of the mineralogy: 'Primary ore minerals include cuprobismutite, bismuthinite, tetrahedrite, emplectite, chalcopyrite, native gold and tetradymite. Secondary or alteration minerals include covellite, chalcocite, and a new hydrated bismuth sulfate. Most of the gangue is composed of quartz'. Cassiterite also occurs in the quartz gangue. Their 'hydrated bismuth sulfate' is the mineral which we characterise and describe as cannonite. It appears to have formed as an alteration product of the primary Cu-Bi-S mineral assemblage. Cannonite is named after Benjamin Bartlett Cannon (the fifth) (1950–) who donated specimens from the mine and who first brought this hitherto uncharacterised mineral to our attention. The mineral and its name have been approved by the Commission on New Minerals and Mineral Names of the International Mineralogical Association. Type specimens are preserved at the Natural History Museum, Great Britain, as specimen BM 1992, 240, and polished section E.1456, and in the Systematic Reference Series of the National Mineral Collection at the Geological Survey of Canada, Ottawa, under the catalogue number NMC 67428.

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Physical properties

Cannonite is colourless and transparent, with a white streak and adamantine lustre. It is brittle with an uneven to conchoidal fracture and shows no evidence of either a cleavage or a parting, nor is the mineral fluorescent. Crystal forms are only well developed where cannonite has formed in cavities in the quartz gangue. Mostly it occurs as intergrown crystalline aggregates (<1 mm) of subhedral to euhedral equant to prismatic crystals (<200 μm) or as irregular intergrown aggregates (Fig. 1) which have altered cuprobismutite and bismuthinite at grain boundaries and along cleavages.

Polished sections of the ore-bearing material were prepared using the techniques described in Stanley *et al.* (1991) with polishing finished by 0.25 μm diamond. Together with the associated minerals, cannonite takes a good polish. It has a VHN_{100} of 229 with a range of 183–280 from 10 indentations, the shapes of which were perfect with slight fracturing at the corners. The equivalent Moh's hardness is 4. The specific gravity could not be determined due to a lack of pure material and because of the size of the individual crystals.

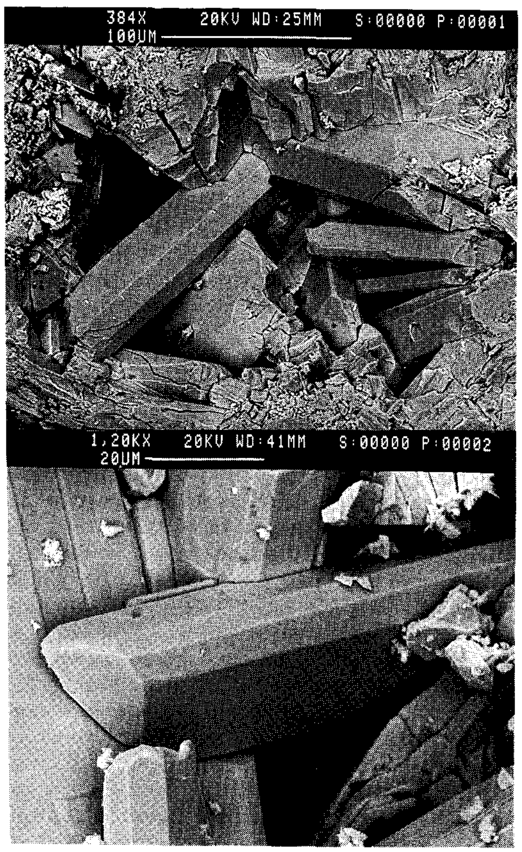

FIG. 1. Scanning electron photomicrographs of intergrown prismatic cannonite crystals (Scale bar: top 100 μm; bottom 20 μm).

In reflected light, cannonite is weakly to moderately bireflectant from grey to darker grey and is weakly anisotropic. Internal reflections, colourless to white, are abundant and the usual precautions were taken to ensure accurate reflectance measurements, which were obtained in air and in oil using the procedures summarised in Criddle *et al.*, (1983), with a SiC standard (Zeiss no 472). Pleochroism is absent. The data are given in Table 1 and Fig. 2. Calculated refractive indices at 589 nm are (for R_1 and R_2 respectively) 1.91 and 1.99 (using Koenigsberger equations).

Chemical composition

Electron probe microanalysis was used to determine the chemistry of cannonite, with H_2O being determined both by difference and by analogy to the synthetic compound. Initial micro-

TABLE 1. Reflectance data and colour values for cannonite

λ nm	R_1	R_2	$^{im}R_1$	$^{im}R_2$
400	11.2	12.9	2.04	3.01
420	11.1	12.8	1.98	2.85
440	11.0	12.5	1.93	2.73
460	10.9	12.3	1.87	2.64
470	10.8	12.2	1.86	2.59
480	10.8	12.1	1.83	2.55
500	10.7	12.0	1.78	2.48
520	10.5	11.9	1.75	2.42
540	10.4	11.7	1.72	2.37
546	10.4	11.7	1.71	2.35
560	10.3	11.6	1.70	2.33
580	10.3	11.6	1.68	2.30
589	10.3	11.6	1.68	2.29
600	10.3	11.5	1.68	2.29
620	10.2	11.5	1.67	2.28
640	10.2	11.5	1.67	2.27
650	10.2	11.5	1.67	2.26
660	10.2	11.4	1.66	2.26
680	10.2	11.4	1.65	2.23
700	10.1	11.4	1.64	2.23

COLOUR VALUES RELATIVE TO CIE ILLUMINANT *C*

	R_1	R_2	$^{im}R_1$	$^{im}R_2$
x	.305	.304	.300	.298
y	.310	.309	.304	.301
Y%	10.4	11.7	1.72	2.36
λ_d	475	475	473	473
P_e%	2.6	3.0	5.1	6.5

probe analyses at the Natural History Museum, Great Britain, were undertaken at 20 kV, with a beam current of 2.50×10^{-8} amps on the Faraday cage. There was some evidence of beam damage, even when a moving or rastered beam was used, and the results (using pure Bi and FeS standards) suggested an ideal formula of $Bi_8O_9(SO_4)_3$, a common decomposition product of hydrated bismuth oxide sulphates (Margulis *et al.*, 1967).

Analyses performed on a Cameca SX-50 electron microprobe at the Geological Survey of Canada with a moving and slightly defocused beam (~10 μm diameter) at 15 kV and 20 nA (with synthetic bismuthinite, natural baryte standards and the PAP correction program of Pouchou and Pichoir, 1984) gave an empirical formula based on 7 oxygen atoms of $Bi_{1.99}O(OH_{1.04})_2S_{0.99}O_4$. This is identical to synthetic $[Bi_2O(OH)_2]SO_4$, the structure of which has been described by Aurivillius (1964) and by Golič *et al.* (1982).

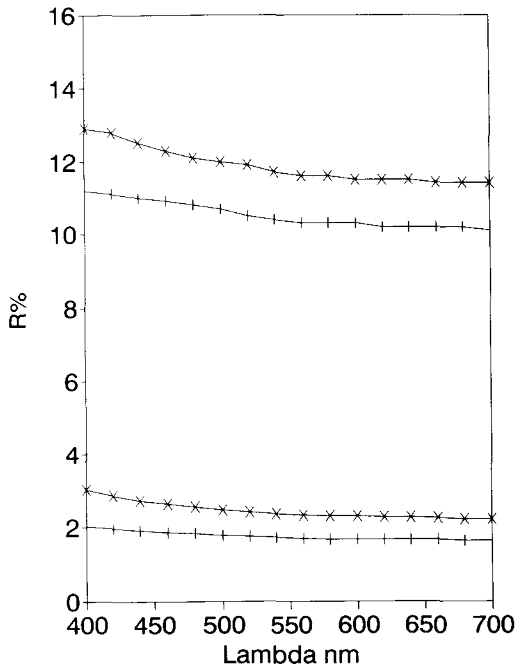

FIG. 2. Reflectance spectra in air and in oil for cannonite.

Although there was no direct evidence to suggest OH rather than H_2O, there being insufficient pure material for water analysis, structural considerations (Aurivillius, 1964; Golič *et al.*, 1982) suggest infinite double chains of formula $Bi_2O(OH)_2^{2+}$ and thus the preferred ideal formula is $Bi_2O(OH)_2SO_4$ rather than $Bi_2O_2.SO_4.H_2O$. The electron microprobe analyses are given in Table 2.

X-ray powder and single-crystal study

Two crystals, elongate [$\bar{1}02$], were mounted and studied by precession single-crystal methods employing Zr-filtered Mo radiation. One crystal was mounted approximately parallel, and the other approximately normal to the precession camera dial axis. The reciprocal lattice levels collected were: $hk0 \rightarrow hk2$, $h0l \rightarrow h3l$, $0kl \rightarrow 2kl$, $\bar{1}02^* \wedge b^*$ and $\bar{1}01^* \wedge b^*$.

Cannonite is monoclinic with space group $P2_1/c$ (14). The refined unti-cell parameters: *a* 7.700(3), *b* 13.839(6), *c* 5.686(2)Å, β 109.11(3)°, *V* 572.5(4)Å^3 and a:b:c = 0.5564:1:0.4109, are based on 32 reflections, between 4.162 and 1.489 Å, in the X-ray powder pattern for which unambiguous indexing was possible. All possible reflections down to 1.45 Å were visually examined on single-crystal precession films. These unit-cell parameters are in their reduced form as indicated by a cell reduction computer program, and are virtually identical to those reported by Golič *et al.* (1982) for synthetic $[Bi_2O(OH)_2]SO_4$. The crystallography, combined with the formula

TABLE 2. Electron microprobe data for cannonite

	Bi	S	O	H_2O	Total (wt%)
1	74.03	5.68	16.97	[3.32]	[100.00]
range	72.87-75.01	5.55-5.81			
2	74.10	5.69	17.02	3.19	100.00

1 - Average of 10 analyses with O calculated by stoichiometry and H_2O calculated by difference.

2 - Ideal formula $Bi_2O(OH)_2SO_4$.

TABLE 3. X-ray powder data for cannonite

*I*est.	*d*Åmeas.	*d*Åcalc.	*hkl*
30	7.30	7.28	100
30	6.94	6.92	020
30	6.45	6.44	110
35	5.02	5.01	120
		5.01	011
5	4.87	4.88	$\bar{1}11$
3	4.24	4.24	021
20	4.162	4.164	$\bar{1}21$
10	3.896	3.896	130
60	3.644	3.639	111
		3.518	210
40	3.513	3.500	031
		3.494	$\bar{2}11$
60	3.466	3.460	040
25	3.314	3.312	121
100	3.206	3.201	$\bar{2}21$
70	2.924	2.920	131
20	2.840	2.843	$\bar{2}31$
50	2.782	2.782	$\bar{1}12$
3	2.690	2.686	002
5	2.609	2.607	$\bar{2}02$
5	2.558	2.562	$\bar{2}12$
10	2.500	2.498	$\bar{2}41$
5	2.460	2.465	221
		2.445	$\bar{1}51$
25	2.423	2.425	300
10	2.389	2.389	310
10	2.308	2.307	060
20	2.290	2.288	102
10	2.225	2.228	$\bar{3}31$
30	2.200	2.203	250
		2.192	$\bar{3}02$
3	2.146	2.147	330
15	2.116	2.119	061

*I*est.	*d*Åmeas.	*d*Åcalc.	*hkl*
10	2.080	2.082	$\bar{2}42$
3	2.049	2.050	$\bar{3}41$
90	1.984	1.986	340
		1.982	$\bar{1}52$
25	1.945	1.944	$\bar{2}61$
30	1.907	1.909	142
		1.904	321
3	1.884	1.886	202
15	1.868	1.869	212
		1.855	071
15	1.851	1.855	$\bar{4}21$
		1.852	$\bar{3}42$
30	1.822	1.824	350
		1.822	$\bar{1}23$
20	1.791	1.790	$\bar{4}12$
3	1.773	1.776	$\bar{4}31$
		1.776	013
25	1.750	1.751	171
35	1.733	1.734	023
		1.686	$\bar{3}23$
10	1.684	1.682	$\bar{4}41$
		1.681	$\bar{4}32$
5	1.671	1.671	360
5	1.656	1.656	242
3	1.639	1.642	$\bar{1}81$
20	1.626	1.626	$\bar{3}33$
		1.592	072
10	1.589	1.590	043
		1.589	$\bar{3}62$
3	1.575	1.575	$\bar{2}72$
		1.572	181
40	1.561	1.560	$\bar{2}81$
		1.559	252
10	1.514	1.518	$\bar{4}23$
		1.512	$\bar{4}52$
20	1.501	1.501	$\bar{5}21$
10	1.489	1.489	431

- 114.6 mm Debye-Scherrer powder camera; Cu radiation, Ni filter (λCu $K\alpha$ = 1.54178 Å)
- intensities visually estimated
- not corrected for shrinkage and no internal standard
- indexed with *a* 7.700, *b* 13.839, *c* 5.686 Å, β 109.11°

derived from the electron microprobe analyes, confirm that cannonite is the naturally occurring analogue of this synthetic compound.

Fully indexed 114.6 mm Debye-Scherrer camera X-ray powder data are presented in Table 3. The data are unique and do not bear resemblance to any inorganic compound listed in the PDF file up to and including Set 41. With Z = 4 and using the empirical formula of $Bi_{1.99}O(OH_{1.04})_2S_{0.99}O_4$, the calculated density is

6.515 g/cm^3, in excellent agreement with the measured density of 6.5(1) g/cm^3 given by Golič *et al.* (1982) for the synthetic analogue.

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