

# Benleonardite, a new mineral from the Bambolla mine, Moctezuma, Sonora, Mexico

C. J. STANLEY, A. J. CRIDDLE AND J. E. CHISHOLM

Department of Mineralogy, British Museum (Natural History), Cromwell Road, London SW7 5BD

**ABSTRACT.** Benleonardite, ideally  $\text{Ag}_8(\text{Sb,As})\text{Te}_2\text{S}_3$  with  $\text{Sb} > \text{As}$ , is a new mineral species that occurs in ore specimens collected from the dumps of the disused Bambolla mine, Moctezuma, Mexico. The associated minerals are acanthite, hessite, an unnamed  $\text{Ag}_4\text{TeS}$  phase, pyrite, sphalerite, and native silver. Together with benleonardite, these form thin black crusts in fractures filled with quartz and dolomite in highly altered, tuffaceous, andesitic and rhyolitic rocks. Benleonardite is an opaque mineral and, in reflected plane-polarized light in air, it is weakly bireflectant from very pale light blue to slightly darker blue. It is not pleochroic. Luminance values (relative to the CIE illuminant C) for  $R_0$  and  $R'_c$  computed from visible spectrum reflectance data for the most bireflectant grain, are 33.6 and 31.7% in air, and 18.3 and 16.5% in Zeiss oil ( $N_D$  1.515) respectively. Vickers micro-indentation hardness is 105–125 (VHN<sub>25</sub>). The X-ray powder diffraction pattern could be indexed on a tetragonal cell with  $a$  6.603(5) and  $c$  12.726(6) Å; for  $Z = 2$ , the calculated density is 7.79 g/cm<sup>3</sup> for the average analysis. The strongest five lines in the X-ray powder pattern are [ $d$  in Å ( $hkl$ ): 12.7 (70) (001); 3.188 (30) (021,004); 2.936 (100) (022); 2.608 (35) (023); 2.158 (35) (124).

**KEYWORDS:** benleonardite, new mineral, Bambolla mine, Moctezuma, Mexico, reflectance data, X-ray data.

**BENLEONARDITE**,  $\text{Ag}_8(\text{Sb,As})\text{Te}_2\text{S}_3$ , is a new mineral species found in a polished section of one of a number of ore specimens collected (by AJC) from the spoil tips of the abandoned Bambolla mine (also known as Mina La Bambolla and Mina La Moctezuma; Gaines, 1970), Moctezuma, Sonora, Mexico (29° 41' N, 109° 43' W). It is associated with native silver, acanthite, hessite, an unnamed  $\text{Ag}_4\text{TeS}$  mineral, pyrite, and sphalerite. These occur as thin black powdery crusts (1–2 mm thick) which, together with gangue quartz and dolomite, occupy irregular fractures in a highly altered rock described by Williams (1982) as an intensely silicified rhyolitic vitrophyre. Gaines (1965) suggested that other volcanic rocks in the vicinity were andesitic and probably of Late Cretaceous age.

Benleonardite is named in recognition of the contribution to ore mineralogy of Dr Benjamin Franklin Leonard (b. 12 May 1921) of the United

States Geological Survey, Denver; Vice Chairman of the Commission on Ore Microscopy, International Mineralogical Association 1982–6. The mineral and the name benleonardite have been approved by the Commission on New Minerals and Mineral Names, International Mineralogical Association.

Type material is preserved at the British Museum (Natural History) in polished mount E.1161; BM 1985, 354.

*Qualitative optical properties.* The section containing benleonardite was polished using the method of Criddle *et al.* (1983). Benleonardite takes a perfect polish and its polishing hardness is low, although greater than that of hessite.

Benleonardite forms monomineralic crusts (< 1 mm across) around hessite and around partially altered acanthite and it is intergrown with hessite, acanthite, an unnamed  $\text{Ag}_4\text{TeS}$  phase and an unidentified gangue mineral (fig. 1). It is fine-grained, the largest grains being no more than 40  $\mu\text{m}$  wide. Typically, these form aggregates in which the anhedral grains show random growth impingement boundaries. Where benleonardite is closely associated with hessite and the unnamed  $\text{Ag}_4\text{TeS}$  phase it shows a strong tendency to form laths 5–20  $\mu\text{m}$  by 50–60  $\mu\text{m}$  (fig. 1).

In plane-polarized light (colour temperature about 3200 K), in air, benleonardite is weakly bireflectant from very pale light blue to slightly darker blue. It is not pleochroic. In immersion oil ( $N_D$  1.515), it is moderately bireflectant and apparently pleochroic from light grey to pale bluish grey (but see below). Benleonardite appears darker and blue against the creamy, slightly pink, hessite. Between crossed polars its anisotropy in air is moderate to strong. The sequence of anisotropic rotation tints is: dark brown, dark blue, blue-grey, dark brown, light brown. With the polars uncrossed by 3° the tints are: mid-greenish brown, light brown-grey, muddy brown, steel blue. The tints are darker but unchanged in hue in immersion oil. Simple twinning is common.

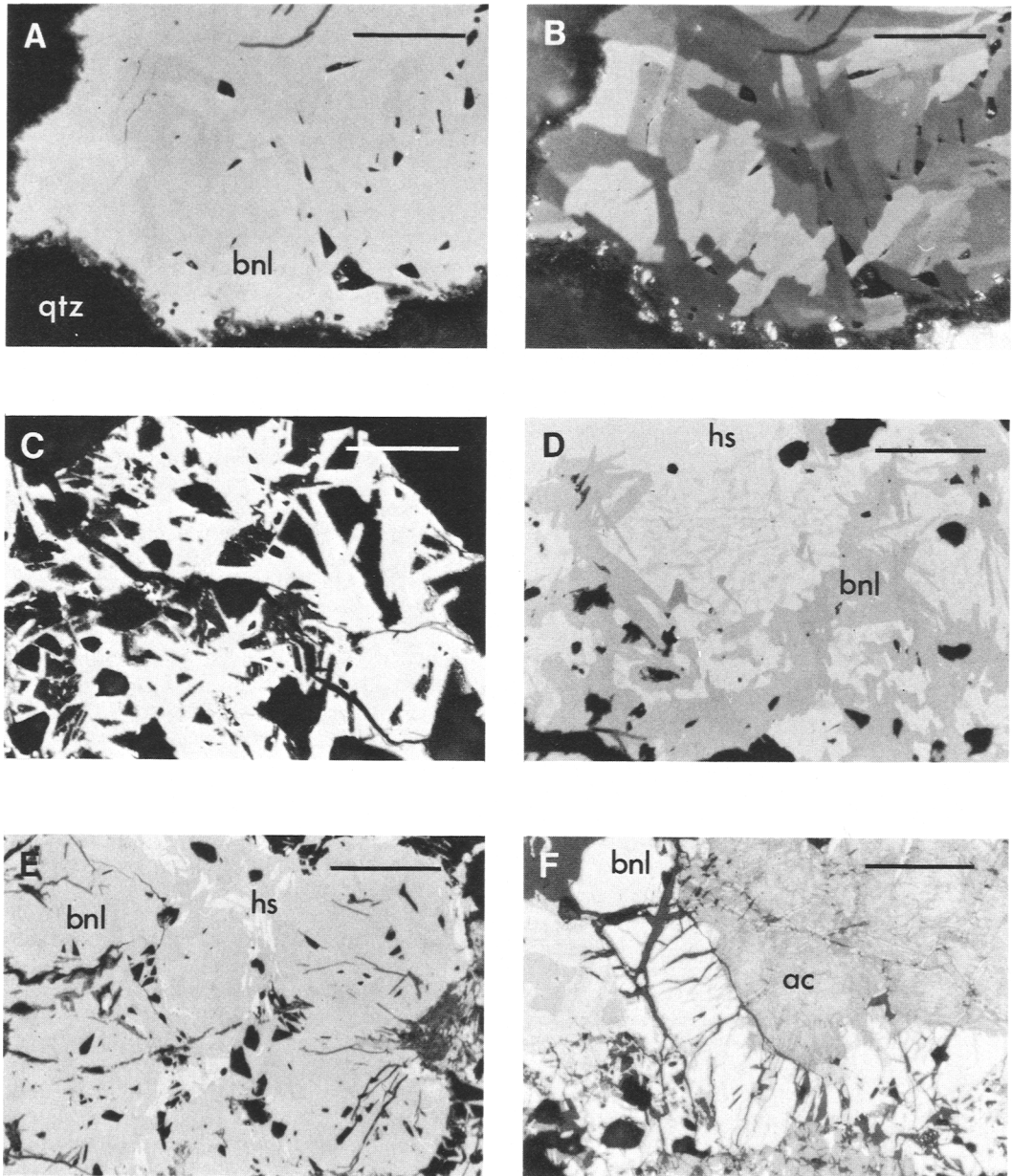


FIG. 1. Reflected light photomicrographs of benleonardite; plane-polarized light with oil immersion. A. Part of a crust of benleonardite illustrating its weak bireflectance. Scale bar: 30  $\mu\text{m}$ . B. Same area as for A (but with crossed polars) illustrating the randomly oriented anhedral grains of benleonardite. Scale bar: 30  $\mu\text{m}$ . C. Lath-like development of benleonardite with voids suggesting cavity infill. Scale bar: 60  $\mu\text{m}$ . D. Laths and aggregates of benleonardite intergrown with hessite and the unnamed  $\text{Ag}_4\text{TeS}$  phase. Scale bar: 60  $\mu\text{m}$ . E. Crusts of benleonardite with inclusions of hessite. Scale bar: 80  $\mu\text{m}$ . F. Fractured rim of benleonardite surrounding acanthite, the latter extensively replaced by an unidentified gangue phase. Scale bar: 80  $\mu\text{m}$ .

TABLE I. Reflectance data for three grains of benleonardite

$\lambda$ nm	AIR					OIL				
	1		2		3	1		2		3
	$R_o$	$R_e'$	$R_o$	$R_e'$	$R_o$	$R_o$	$R_e'$	$R_o$	$R_e'$	
400	35.5	35.35	37.0	35.6	36.8	20.2	21.0	21.9	20.6	21.2
10	35.5	35.4	36.85	35.7	36.7	20.2	21.0	21.75	20.7	21.2
20	35.5	35.5	36.7	35.8	36.6	20.3	21.0	21.5	20.7	21.1
30	35.6	35.5	36.6	35.8	36.4	20.3	20.9	21.3	20.7	21.0
40	35.5	35.6	36.4	35.85	36.2	20.2	20.85	20.95	20.7	20.7
450	35.5	35.5	36.2	35.8	35.95	20.1	20.8	20.6	20.6	20.5
60	35.4	35.4	35.9	35.7	35.6	20.0	20.6	20.3	20.5	20.1
70	35.3	35.3	35.6	35.6	35.3	19.9	20.5	20.0	20.3	19.8
80	35.1	35.2	35.2	35.5	34.9	19.8	20.3	19.6	20.2	19.4
90	34.9	35.0	34.9	35.3	34.5	19.6	20.1	19.3	20.0	19.0
500	34.7	34.85	34.5	35.1	34.1	19.3	19.9	18.9	19.8	18.6
10	34.5	34.7	34.1	35.0	33.6	19.1	19.7	18.5	19.55	18.2
20	34.2	34.4	33.6	34.7	33.2	18.8	19.35	18.1	19.3	17.8
30	33.9	34.1	33.2	34.4	32.7	18.5	19.1	17.7	19.0	17.4
40	33.6	33.9	32.75	34.1	32.2	18.3	18.8	17.4	18.8	17.0
550	33.3	33.6	32.3	33.8	31.8	18.0	18.5	17.0	18.5	16.6
60	32.9	33.3	31.9	33.5	31.4	17.75	18.3	16.65	18.2	16.3
70	32.65	33.0	31.5	33.2	31.0	17.5	18.0	16.3	17.9	16.0
80	32.3	32.8	31.2	32.9	30.7	17.2	17.8	16.0	17.7	15.7
90	32.1	32.5	30.8	32.6	30.3	17.0	17.5	15.75	17.4	15.4
600	31.8	32.3	30.5	32.4	30.0	16.8	17.3	15.5	17.2	15.1
10	31.6	32.1	30.2	32.2	29.7	16.6	17.1	15.3	17.0	14.9
20	31.4	31.9	30.0	32.0	29.5	16.45	16.95	15.1	16.9	14.7
30	31.25	31.8	29.75	31.8	29.25	16.3	16.8	14.9	16.7	14.5
40	31.1	31.6	29.6	31.6	29.1	16.15	16.7	14.7	16.6	14.4
650	30.9	31.4	29.35	31.5	28.9	16.0	16.55	14.55	16.45	14.2
60	30.7	31.3	29.2	31.4	28.7	15.8	16.4	14.4	16.35	14.1
70	30.5	31.1	29.0	31.2	28.55	15.7	16.3	14.3	16.2	13.9
80	30.4	31.0	28.8	31.1	28.4	15.6	16.1	14.2	16.1	13.8
90	30.25	30.85	28.7	30.9	28.2	15.5	16.0	14.0	16.0	13.7
700	30.1	30.7	28.6	30.8	28.1	15.4	15.9	13.9	15.85	13.6

COLOUR VALUES:

Relative to illuminant C at 6774 K

x	.3002	.3014	.2952	.3009	.2945	.2939	.2940	.2856	.2941	.2846
y	.3094	.3104	.3038	.3102	.3027	.3041	.3039	.2940	.3043	.2929
y%	33.1	33.4	32.1	33.6	31.7	17.9	18.4	16.9	18.3	16.5
$\lambda_{\frac{d}{e}}\%$	482	482	480	483	480	481	481	479	481	479
$P_e\%$	4.3	3.8	6.8	4.0	7.2	7.2	7.2	11.4	7.1	11.9

Relative to illuminant A at 2856 K

x	.4373	.4385	.4327	.4379	.4322	.4309	.4311	.4231	.4311	.4211
y	.4067	.4070	.4047	.4070	.4042	.4053	.4052	.4014	.4054	.4009
y%	32.7	33.1	31.6	33.2	31.1	17.5	18.05	16.4	18.0	16.1
$\lambda_{\frac{d}{e}}\%$	493	494	492	494	491	493	493	491	493	490
$P_e\%$	2.5	2.2	3.6	2.3	3.8	4.0	4.0	6.1	4.0	6.3

Instrument: Zeiss MPW 03 microscope photometer; Reflector: Coated plane glass  
 Filter: Line interference filter, band-width ~12nm  
 Photomultiplier: Hamamatsu R928 S20  
 Objectives: x40 with effective numerical apertures adjusted to 0.28  
 Standard: WTIC (Zeiss, 314) Oil: Zeiss  $n_D$  1.515 at 21°C

*Quantitative optical properties.* Spectral reflectance measurements were made on three grains in air and in oil; the results, together with details of the instrumentation and standard used are given in Table I and the data are plotted on fig. 2.

The specimen and standard were levelled and brought into the same focal plane on a modified Lanham levelling superstage. Some difficulty was experienced in locating grains of benleonardite suitable for measurement because of its small grain size and irregular grain shape. Of the three grains chosen, one was isotropic (grain 1) and the others (grains 2 and 3) were as strongly anisotropic as could be found. Although the anisotropy of ben-

leonardite is moderate to strong, the extinction positions could only be estimated to within a few degrees by eye; therefore, the photometer was used to establish the  $R$  maxima and  $R$  minima at 560 nm for grains 2 and 3. Measurements were made by step-scanning at an interval of 10 nm from 400 to 700 nm, first on the specimen, then on the standard and, for the anisotropic grains, returning to the specimen. The procedure was repeated in oil. The results were plotted with an HP 9872A plotter and the reflectance curves obtained were smoothed graphically and digitized. The digitized values were used to compute the colour values for the COM-IMA recommended illuminants  $C$  and  $A$ , and to

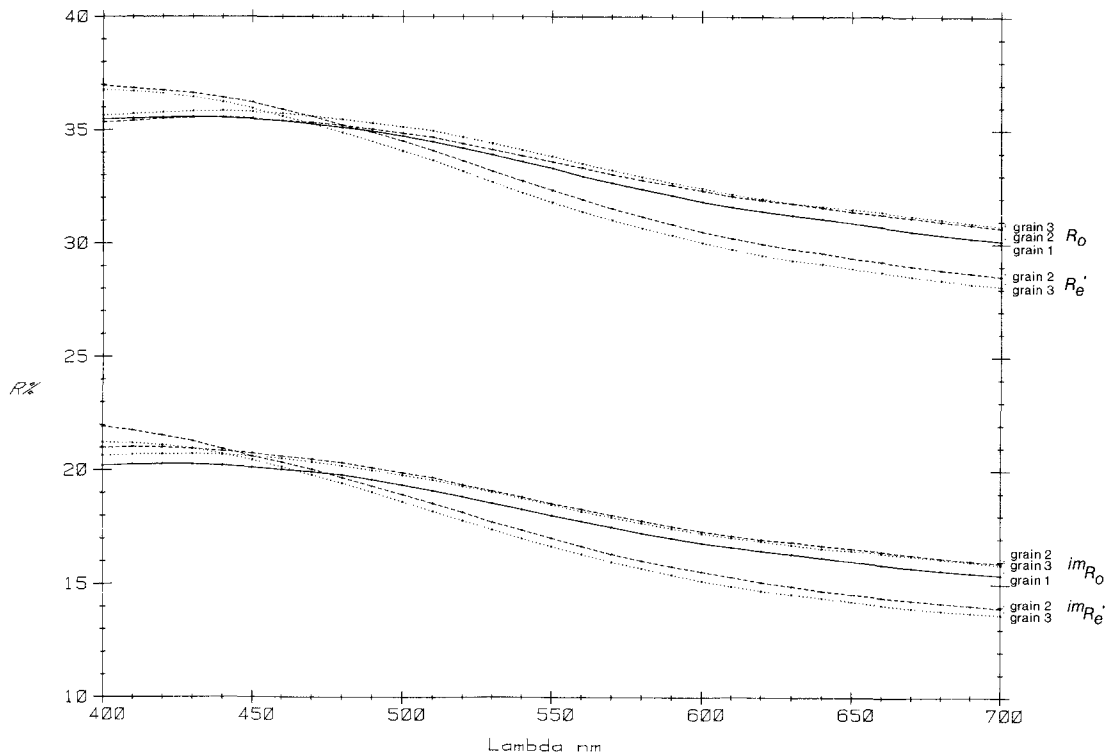


FIG. 2. Reflectance spectra, in air and in oil, for three grains of benleonardite.

check errors in the air and oil measurements (as recommended by Embrey and Criddle, 1978). The computer programs were written by G. S. Bearne.

$R_0$  was determined by measurement of the isotropic grain.  $R_0$  for the anisotropic grains 2 and 3 differs slightly from this, a difference that is explicable in terms of the uncertainty of determining  $R_{\max}$  photometrically (in the absence of definite extinction positions). An alternative explanation is that grain 1 was, in fact, very slightly anisotropic, and the maximum value was not measured. This could easily happen given the high-power objectives used for observation and measurement. Nevertheless, the data are within the limits of accuracy ( $\pm 0.5$ – $1.0\%$  relative) for the instrument. It is clear from fig. 2 that, other than at the blue end of the spectrum, there is little difference in the dispersion of  $R_0$  and  $R'_e$  in air or in oil, hence the pleochroism observed in oil (see above) cannot be regarded as real, but is a consequence of the luminance difference between  $R_0$  and  $R'_e$ , i.e. the bireflectance.

There is neither qualitative nor quantitative evidence for benleonardite exhibiting sensitivity to light, unlike many silver-bearing minerals.

**Microhardness.** A Leitz Miniload 2 microhardness tester was used to determine the Vickers microhardness of benleonardite. For a load of 25 g the range obtained from 10 indentations was 105–125 (mean 117). The shape of the indentations was perfect, but with slight fracturing at the corners. The indentations could not be made on single grains of benleonardite due to its small grain size; thus, these results are for aggregates of the mineral.

**Chemical composition.** Electron microprobe analyses of benleonardite are summarized in Table II. Analyses 1, 2 and 3 correspond to the areas measured for reflectance, respectively of grains 1, 2 and 3.

The initial analyses (1–5) were obtained using pure metal standards and troilite. The formulae, calculated to 14 atoms, from these analyses approximate to  $\text{Ag}_{7.8}\text{Sb}_{0.8}\text{As}_{0.2}\text{Te}_{1.9}\text{S}_{3.3}$  and show a small silver deficiency and sulphur excess. In order to check the reliability of the ZAF correction and the standards used for Ag and Te, further analyses were made using the coexisting hessite as standard for Ag and Te (the hessite was taken to be stoichiometric  $\text{Ag}_2\text{Te}$ ). The average of these 14 analyses gave a formula almost identical to that

TABLE II. Electron microprobe analyses of benleonardite

	wt%						Sum to 14 atoms						
	Ag	Cu	Sb	As	Te	S	Total	Ag	Cu	Sb	As	Te	S
1	65.8	0.1	9.0	0.7	18.6	8.0	100.2	7.73	0.01	0.97	0.13	1.90	3.26
2	65.0	--	7.4	1.8	18.4	8.1	100.7	7.78	--	0.78	0.31	1.86	3.26
3	65.0	--	7.8	1.2	18.7	8.2	100.9	7.77	--	0.83	0.21	1.89	3.30
4	65.1	--	7.6	1.1	18.5	8.1	100.4	7.84	--	0.81	0.20	1.88	3.28
5	65.6	--	7.2	1.8	18.7	8.0	101.3	7.83	--	0.76	0.31	1.89	3.21
6	64.9	--	7.8	1.3	18.6	8.1	100.7	7.78	--	0.83	0.22	1.89	3.28
7	64.5	0.1	7.3	1.4	18.7	8.0	100.0	7.80	0.02	0.78	0.24	1.90	3.25
8	64.6	--	9.1	--	19.1	7.2		8.00	--	1.00	--	2.00	3.00

1-5 analyses of five grains of benleonardite using Ag, Te, Sb, As, and FeS standards

6 average of analyses 1-5

7 average of 14 analyses of benleonardite using  $Ag_2Te$ , Sb, As, and FeS standards

8 theoretical  $Ag_8Sb_8As_8Te_8S_8$

Instrument: Cambridge Instruments Microscan IX

Operating conditions: accelerating voltage 20kV; beam current  $2.50 \times 10^{-8}$  amps on Faraday cage.

Radiations:  $AgL\alpha$ ,  $CuK\alpha$ ,  $SbL\alpha$ ,  $AsK\alpha$ ,  $TeL\alpha$ ,  $S K\alpha$ .

obtained from the average of the initial analyses and this supports the silver deficiency relative to the idealized formula  $Ag_8(Sb,As)Te_2S_3$ .

The sulphur excess could be related to the use of troilite as standard, but this would not explain the silver deficiency since, if sulphur were overestimated, all the other atoms would then be underestimated in the same proportion when calculated to 14 atoms; this is not the case.

There remains the possibility that benleonardite is sensitive to the electron beam, but there were no 'burn marks', changes in counts with time, or other such evidence for this. Any slight analytical error would have a disproportionate effect on the estimation of sulphur in the formula because of its low atomic number compared to Sb, Te and Ag.

The usual formal charges cannot be balanced in the formula given: such formal charge imbalance occurs in other minerals containing a high proportion of metallic and semi-metallic elements.

*X-ray data.* It was not possible to extract grains of benleonardite for single-crystal X-ray studies because of its small grain size. However, sufficient material was extracted for an X-ray powder photograph, the data from which are given in Table III.

The simple powder pattern suggested a high symmetry. Successive orders of  $00l$  were recognized and a tetragonal cell derived by trial and error. All but four weak lines (believed to be due to impurity) of the twenty-six in the powder pattern could be indexed on a tetragonal unit cell with  $a$  6.603(5), and  $c$  12.726(6) Å (refined from the powder pattern). The indexed powder lines do not show any systematic absences except possibly  $hh0$  reflections with  $h$  odd (110 and 330 are both absent). However, Table 3.2 of Int. Tab. A (p. 45) shows that the reflection condition  $h$  even in  $hh0$  cannot occur in isolation and the space group is therefore taken to be one of the tetragonal symmorphic space groups  $P4/mmm$ ,  $P4m2$ ,  $P42m$ ,  $P4mm$ ,  $P422$ ,  $P4/m$ ,  $P4$  or  $P4$ .

Again, due to the small grain size and lack of material, the density of benleonardite could not be determined directly. The density was calculated for  $Z = 1, 2, 3 \dots$  and compared with those of other minerals having elements in common with benleonardite. For  $Z = 2$  the calculated density for benleonardite is 7.76 which is reasonable when

TABLE III.

X-ray powder diffraction data for benleonardite

(indexed on a tetragonal cell with  
 $a$  6.603(5) Å and  $c$  12.726(6) Å)

$l$	$d_{meas.}$	$d_{calc.}$	$hkl$
70	12.7	12.726	001
15	6.62	6.602	010
15	6.34	6.363	002
15	5.87	5.861	011
15	4.61	4.582	012
50	3.188	{ 3.195 3.181	{ 021 004
100	2.936	2.930	022
25	2.863	2.866	014
35	2.608	2.605	023
10	2.542	2.545	005
15	2.455	2.455	n.i.
15	2.376	2.375	015
20	2.328	2.334	220
10	2.291	{ 2.296 2.291	{ 221 024
10	2.206	2.201	030
35	2.158	2.164	124
20	2.120	2.121	006
10	2.084	{ 2.088 2.080	{ 130 032
15	2.020	2.019	016
10	1.965		n.i.
15	1.914		n.i.
15	1.819	1.818	007
10	1.786	1.784	026
15	1.744	1.746	134
15	1.591	1.591	008
15	1.531		n.i.

Philips 11.46cm diameter powder camera;  $FeK\alpha$  radiation ( $\lambda$  1.937355 Å); Intensities from peak heights on microdensitometer traces; n.i. = not indexable.

compared with hessite (8.35—benleonardite contains the lighter elements Sb, S) and with acanthite (7.0–7.2) and aguilarite (7.5) (benleonardite has a higher proportion of heavy elements).

*Structural speculation.* The structure may be an ordered arrangement based on a body centred packing of the atoms. Taking 1.44 Å as an average metallic radius for Ag, Sb, Te, such an arrangement would have a cubic cell edge of 3.3 Å, which is approximately  $\frac{1}{2}a$ ,  $\frac{1}{4}c$ . The full tetragonal cell ( $a$  6.6,  $c$  13.2 Å) would then contain 32 atoms. Omitting one plane of four atoms parallel to (001) would reduce this to the 28 atoms required by the formula ( $Z = 2$ ) and shorten  $c$  to about 12.8 Å.

*Relationship to other species.* There does not appear to be any mineral species to which benleonardite is related. However, there are two incompletely characterized phases mentioned in the literature which may be equivalent to benleonardite: mineral C of Karup-Møller and Pauly (1979); and mineral X of Aksenov *et al.* (1969). Karup-Møller and Pauly (1979) suggest a formula of  $\text{Ag}_9\text{Sb}(\text{Te},\text{S})_6$  for mineral C on the basis of partial analyses (due to small grain size and apparent breakdown in the electron beam), and their qualitative description is in reasonable agreement with ours for benleonardite. Aksenov *et al.* (1969) give reflectance data for mineral X which are similar to those for benleonardite in the range 400–500 nm but which are significantly higher at 500–700 nm. This might reflect the slightly different chemistry which they give for mineral X. Both mineral C and mineral X occur in association with an  $\text{Ag}_4\text{TeS}$  phase, as does benleonardite.

*Acknowledgements.* A.J.C. thanks Drs S. A. Williams and F. P. Cesbron who accompanied him to the remote Bambolla locality. We thank Dr P. J. Dunn (Smithsonian Institution) for his helpful comments, and Peter Embrey, Andrew Clark and Dr A. C. Bishop for reading the manuscript.

## REFERENCES

- Aksenov, V. S., Gavrilina, K. S., Litvinovich, A. N., Bespaev, K. H. A., Pronin, A. P., Kosyak, E. A., and Slyasarev, A. P. (1969) Occurrence of new minerals of silver and tellurium in ores of the Zyranov deposits in the Altai (in Russian). *Izvest. Akad. Nauk. Kazakh. SSR, Ser. Geol.* Pt. 3, 74–8.
- Criddle, A. J., Stanley, C. J., Chisholm, J. E., and Fejer, E. E. (1983) Henryite, a new copper-silver telluride from Bisbee, Arizona. *Bull. Mineral.* **106**, 511–17.
- Embrey, P. G., and Criddle, A. J. (1978) Error problems in the two-media method of deriving the optical constants  $n$  and  $k$  from measured reflectances. *Am. Mineral.* **63**, 853–62.
- Gaines, R. V. (1965) Moctezumite, a new lead uranyl tellurite. *Ibid.* **50**, 1158–63.
- (1970) The Moctezuma tellurium deposit. *Mineral. Record*, **1**, 40–3.
- Karup-Møller, S., and Pauly, H. (1979) Galena and associated ore minerals from the cryolite at Ivigtut, S. Greenland. *Meddelels. Grønland, Greenland Geosci.* **2**, 1–25.
- Williams, S. A. (1982) Cuztite and eztlite, two new tellurium minerals from Moctezuma, Mexico. *Mineral. Mag.* **46**, 257–9.

[Manuscript received 19 February 1986]