

BOWIEITE: A NEW RHODIUM-IRIDIUM-PLATINUM SULFIDE IN PLATINUM-ALLOY NUGGETS, GOODNEWS BAY, ALASKA

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ABSTRACT

Bowieite (Rh, Ir, Pt)₂S₃, a new mineral species, is found in three nuggets of platinum from Goodnews Bay, Alaska. In linearly polarized reflected light, and compared to the host, higher reflecting white platinum-iridium alloy, bowieite is pale grey to pale grey-brown; neither bireflectance nor reflectance pleochroism is apparent. With polars crossed, its anisotropic rotation tints vary from grey to dark brown. Luminance values (relative to the CIE illuminant C) for R_1 and R_2 , computed from full spectral data for the most bireflectant grain, are 45.8% and 48.2% in air, and 30.5% and 33.0% in oil, respectively. VHN_{100} 1,288 (858 to 1,635). Bowieite is orthorhombic, space group *Pnca*, with a 8.454(7)–8.473(8), b 5.995(1)–6.002(7), c 6.143(1)–6.121(8) Å, $Z = 4$. The strongest six powder-diffraction lines [d in Å(hkl)] are: 0.7726(vvs)(10,31), 3.00(vss)(211,020), 0.7877(vvs)(471,237), 0.7768(vvs)(237), 1.757(vs)(213), 2.143(s)(022). D_{calc} 6.91–6.96 g/cm³. Some grains that are 2.6 to 3.8 atomic % metal-deficient occur as an optically coherent rim on bowieite; the rim and the bowieite grain are not optically continuous. The powder patterns of the metal-deficient phase and of bowieite are identical, and no distinction can be detected between these phases using quantitative measurements of reflectance.

Keywords: bowieite, rhodium-iridium-platinum sulfide, new mineral species, Alaska.

SOMMAIRE

On trouve la bowieïte (Rh, Ir, Pt)₂S₃, nouvelle espèce minérale, dans trois pépites de platine provenant de la baie de Goodnews (Alaska). En lumière réfléchie linéairement polarisée, elle est gris pâle à gris-brun pâle en comparaison du minéral hôte, un alliage Pt-Ir blanc plus réfléchant. On n'observe ni biréflexance, ni pléochroïsme de réflexion. Avec polariseurs croisés, les teintes de rotation anisotrope vont du gris foncé au brun foncé. Les valeurs de la luminance (par rapport à l'illuminant C du CIE) pour R_1 et R_2 , calculées à partir des données sur le spectre complet pour le grain le plus biréflexant, sont: 45.8% et 48.2% dans l'air, 30.5% et 33.0% dans l'huile, respectivement. $VHN_{100} = 1,288$ (valeurs entre 858 et 1,635). C'est un minéral orthorhombique, groupe spatial *Pnca*, dont les paramètres a , b et c varient de 8.454(7) à 8.473(8), de 5.995(1) à 6.002(7), et de 6.143(1) à 6.121(8) Å, respectivement; $Z = 4$. Les six raies les plus intenses du cliché de diffraction [méthode des poudres; d en Å(hkl)] sont:

0.7726(vvs)(10,31), 3.00(vvs)(211,020), 0.7877(vvs)(471,237), 0.7768(vvs)(237), 1.757(vs)(213), 2.143(s)(022). La densité calculée varie entre 6.91 et 6.96. On observe un liseré optiquement cohérent sur la bowieïte qui accuse un déficit de 2.6 à 3.8% (atomique) en métaux; toutefois, les deux phases ne sont pas en continuité optique. Leurs clichés de diffraction sont identiques, et aucune distinction dans les mesures quantitatives de la réflectivité n'a pu être décelée.

(Traduit par la Rédaction)

Mots-clés: bowieïte, sulfure de rhodium, iridium et platine, nouvelle espèce minérale, Alaska.

INTRODUCTION

Three platinum nuggets between 5 and 7 mm in diameter and weighing 2.5 to 3.5 grams were recovered from dredging operations on the Salmon River at Goodnews Bay, Alaska. These were acquired by John B. Mertie, Jr. and donated for study in 1973. Each was mounted in epoxy, sliced into several 2 mm-thick wafers and polished for study in reflected light. The exterior of these silver-colored nuggets, though rounded on protuberance, had impressions or moulds of subhedral, nearly equant grains that had apparently been removed by weathering. In addition to the Pt-Ir, Pt and Ir-Pt alloys, sparse native osmium, laurite and silicate inclusions, we found an unidentified, slightly anisotropic, anhedral grey phase as abundant inclusions measuring 0.02 to 0.5 mm in the largest dimensions. Preliminary electron-microprobe analysis indicated that this phase contains major rhodium, iridium and sulfur, with minor platinum. High-purity synthetic rhodium, sulfur and rhodium-iridium alloy wire were used to synthesize sulfides that were used as standards for the determination of the composition and to establish an M_2S_3 stoichiometry.

Bowieite is named for Dr. Stanley Hay Umphray Bowie, formerly of the Institute of Geological Sciences, London. Both mineral and name have been approved by the I.M.A. Commission on New Minerals and Mineral Names. Polished sections containing analyzed bowieite (Table 1) have been

TABLE 1. ELECTRON-MICROPROBE DATA FOR BOWIEITE

grain	WEIGHT PERCENT*					ATOMIC PROPORTIONS				
	Rh	Ir	Pt	S	Total	Rh	Ir	Pt	S	
Nugget SRA-2										
<u>BOWIEITE</u>										
E1	31.2	32.4	8.8	25.2	97.6	1.16	0.64	0.17	1.97	3.00
B3A	33.5	32.0	8.0	23.9	99.4	1.21	0.62	0.15	1.98	3.00
C	32.4	30.6	9.7	24.6	97.3	1.23	0.62	0.19	2.04	3.00
D2	31.7	31.8	8.5	24.5	96.5	1.21	0.65	0.17	2.03	3.00
G1	30.8	35.4	8.8	25.3	100.3	1.14	0.70	0.17	2.01	3.00
K	34.3	31.0	9.1	24.9	99.3	1.29	0.62	0.18	2.09	3.00
Nugget SRB-3										
A1	42.5	20.4	10.5	26.0	99.4	1.53	0.39	0.20	2.12	3.00
D	42.4	21.0	11.5	26.1	101.0	1.52	0.40	0.22	2.14	3.00
E	42.5	20.5	10.6	26.0	99.6	1.53	0.39	0.20	2.12	3.00
Nugget MCr-69-1										
B	38.1	27.1	7.0	25.8	98.0	1.38	0.52	0.13	2.03	3.00
<u>BOWIEITE, METAL-DEFICIENT</u>										
Nugget SRA-2										
A	28.4	42.5	1.0	27.2	99.1	0.98	0.78	0.02	1.78	3.00
B3	36.4	31.4	0.3	29.3	97.4	1.16	0.54	0.01	1.71	3.00
D1	34.6	35.5	1.2	28.3	99.6	1.14	0.63	0.02	1.79	3.00
F	34.6	36.6	0.3	28.9	100.4	1.12	0.63	0.01	1.76	3.00
G2	34.6	36.6	0.3	28.8	100.3	1.12	0.64	0.01	1.77	3.00
M1	37.9	32.8	0.2	29.4	100.3	1.20	0.56	—	1.76	3.00
Nugget SRB-3										
B	45.8	23.0	1.5	30.7	101.0	1.39	0.37	0.02	1.78	3.00
Nugget MCr-69-1										
F	26.5	46.2	0.5	27.2	100.4	0.91	0.85	0.01	1.77	3.00

*Synthetic standards, X-ray lines, and operating voltage: PdS and Rh₂S₃ S Ka, 7.5 kV; Rh₅₀Ir₅₀, Rh₆₀Ir₄₀ Ir Ma, 7.5 kV, Ir La, 15kV; Pt₈₀Ir₂₀ Pt La, 20 kV.

deposited as follows: SRA-2 (E.813) BM1983, 70 in the British Museum (Natural History), London and MCr-69-1 in the U.S. National Museum, Smithsonian Institution, Washington, D.C.

Begizov *et al.* (1975) first reported the occurrence of an isotropic (Rh, Ir)₂S₃ from the Gusevogorskiy massif, Urals; this phase has a composition of Rh 29.2, Ir 44.6, S 24.1 wt. % and was not previously described. Subsequently, Cabri *et al.* (1981) described a moderately anisotropic unnamed "Rh₂S₃" in a Pt-Fe alloy nugget from Ethiopia, with a composition Rh 55.3, Ir 16.1, Pt 1.2, Ru 0.17, S 29.2 wt. %, and gave reflectance data, but the grain was too small for X-ray-diffraction studies. Parthé *et al.* (1967) studied synthetic Rh₂S₃, determined the structure by single-crystal studies, and obtained the cell parameters by least-squares refinement of X-ray powder-diffraction data as measured by diffractometer; Ir₂S₃ was also synthesized and determined to be structurally isotypic with Rh₂S₃.

Keqiao *et al.* (1981, 1982) described strongly anisotropic Rh₂S₃ from Gaositai, Hebei Province, China, with a composition of Rh 68.80 and S 31.05 wt. %; "X-ray single-crystal study showed that it is of the orthorhombic system with *a* 6.167, *b* 8.493, *c* 5.987 Å, space group *Pnca*, *Z* = 4." Sixteen X-ray

powder-diffraction lines are reported and the strongest five lines [*d* in Å(1)] are: 3.01(100), 2.161(70), 1.761(60), 1.729(80) and 1.269(60). In Table 4 of Keqiao *et al.* (1982), the indexed powder-lines do not agree with the given cell-parameters, *e.g.*, for the 2.115 Å line indexed as 400, *a* must equal 8.46 Å instead of 6.167 Å as given in Table 4 and the text (p. 494). If the cell parameters given by Keqiao *et al.* (1981, 1982) are transposed to be consistent with convention, they become *a* 8.493, *b* 5.987 and *c* 6.167 Å. These are all slightly larger than those reported by Parthé *et al.* (1967) for synthetic Rh₂S₃. Keqiao *et al.* (1982, p. 493) reported a *VHN*₂₀ of 575, and mentioned that the mineral "is light greenish-grey in colour, with a pinkish tint" (1981, p. 767). Reflectance values for 12 wavelengths are given for one grain (1982, p. 493) and are only slightly higher than those of Cabri *et al.* (1981) and the data reported here.

PHYSICAL PROPERTIES

Grains of bowieite are usually anhedral (Fig. 1A), range from 60 to 400 μm in size and occur as individual crystallographic units according to anisotropism and extinction positions in polarized reflected light. The only visible inclusions are white Ir-Pt-Rh alloy grains, about 10–14 μm in size, which are sparse in some grains and relatively abundant in others (Fig. 1A,B). Scanning-electron-microscope studies of polished specimens at magnifications of 25,000× show no other phases in the optically coherent domains. Many of the bowieite grains are irregularly fractured (Fig. 1A,B), but the large fractures are not related to recognizable crystallographic directions. A phase more resistant to polishing abrasion than bowieite was found as a partial rim up to 0.06 mm wide adjacent to some bowieite grains (Fig. 1C). In all of these composite grains, the extinction positions of the bordering phase are different from those of bowieite *i.e.*, the two phases are not in optical continuity. The composition of this subordinate phase, although grossly similar to bowieite, differs in that it consistently has lower platinum and higher sulfur contents. In spite of attempts to distinguish the bordering phase by X-ray-diffraction studies, all the powder lines not belonging to inclusions of the Ir-Pt-Rh alloy can be attributed to bowieite by indexing. Similarly, quantitative studies of reflectance indicate that if the bordering phase is a different mineral, reflectance values cannot be used to distinguish it from bowieite. Indenting bowieite and the bordering phase produced some minor or major degree of fracturing at the corners of the indentations (Fig. 1c). Variation of Vickers hardness within grains equalled or exceeded variation between grains; thus no distinction could be made between bowieite and the lower-Pt, higher-sulfur phase by the indent-

ing technique. The mean value obtained for 24 slightly fractured indentations on five grains of bowieite and two grains of the bordering phase are: VHN_{100} 1,288, σ 320, range 858–1,635.

The data for bowieite are unequivocally unique for M_2S_3 compounds in which M is dominantly Rh, based on the study of the data for both the natural occurrences and synthetic systems presently known. Several attempts to synthesize the lower-Pt, higher-S phase produced compounds attributable to those already known in the ternary system Rh-Ir-S, on the basis of both X-ray powder-diffraction and quantitative electron-microprobe analysis of the synthetic products.

COMPOSITION

The chemical compositions of bowieite and metal-deficient bowieite were determined by quantitative electron-microprobe analysis using synthetic Rh-Ir and Pt-Ir alloys and PdS and Rh_2S_3 . Elements other than Rh, Ir, Pt, and S were sought but not detected at the 0.1 wt.% level.

Electron-microprobe data for ten bowieite grains in three platinum-alloy nuggets are given in Table 1. Each composition represents the mean of 7 to 10 analyses on individual grains having optical continuity in reflected light. The range in composition within each grain does not exceed about 4% of the amount present for Rh and Ir, 5% for Pt, and 1% for S. Atomic proportions were calculated on the basis of S = 3. The compositional variation is illustrated in terms of the pseudoternary system Rh-Ir(Pt)-S in Figure 2, which also shows compositions of the minerals of Begizov *et al.* (1975) and Cabri *et al.* (1981) and of the Ir-Pt-Rh alloy inclusions in bowieite. Mixtures corresponding to bulk compositions ranging from $(Rh, Ir)_{0.67}S_{0.23}$ to $(Rh, Ir)_{0.40}S_{0.60}$ produced $(Rh, Ir)_2S_3$; no phase with a higher proportion of sulfur was found in these synthetic materials. The compositions of nine $(Rh, Ir)_2S_3$ synthetic phases quantitatively analyzed by electron microprobe and studied by X-ray diffraction are shown in Figure 2.

Compositional data for eight grains of metal-deficient bowieite are also given in Table 1. Chemical homogeneity in these grains is comparable to that in bowieite. The variations of composition among grains are shown on an enlarged part of the sulfur-rich portion of the pseudoternary system Rh-Ir(+Pt)-S (Fig. 3). Compositions of the minerals of Begizov *et al.* (1975) and Cabri *et al.* (1981) are also shown. Data for bowieite, metal-deficient bowieite and adjacent pairs of the two (e.g., grain SRA-2-D, Fig. 1C) are joined with dashed lines. Whereas there is a variation in the proportions of Ir(+Pt) and Rh (Fig. 3), the metal:sulfur ratio for each group is essentially invariant, within analytical error. A study

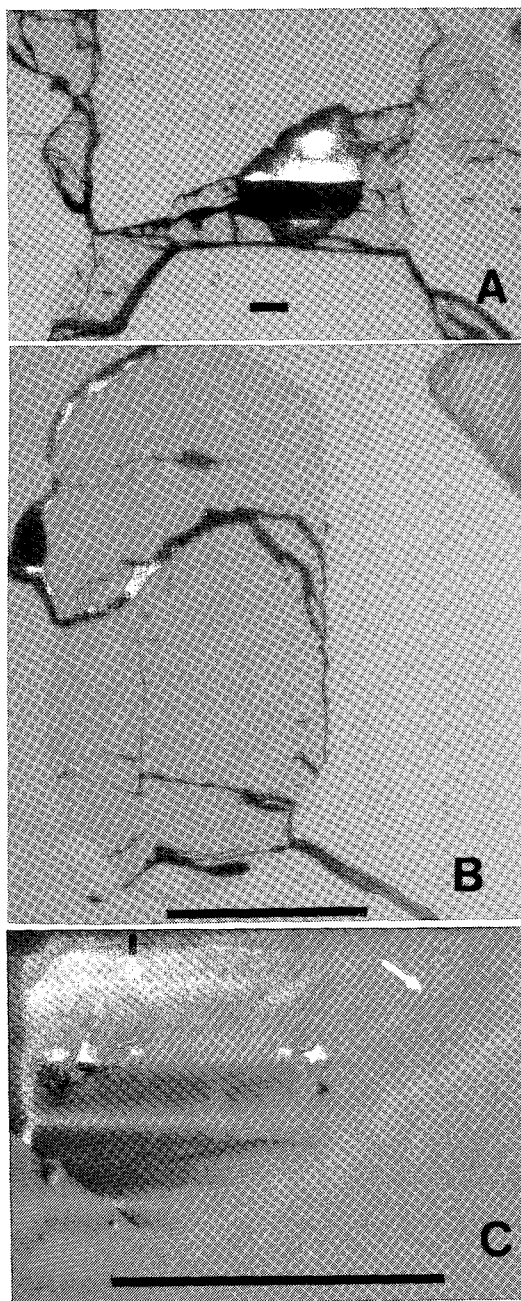


FIG. 1. Reflected light photomicrographs of bowieite. Bar scale is 100 μm . A. Fractured grey grains of bowieite in white Pt-Ir alloy of nugget SRA-2. B. Bowieite (grey) with white Ir-Pt alloy inclusions, grain SRA-2-G. Black (upper right) is silicate. C. Nomarski objective photo of overpolished section showing grain boundary (arrows) and metal-deficient bowieite (hardness-indentation damage), grain SRA-2-D. Lower part of photo is Pt-Ir alloy with small inclusions of Ir-rich alloy.

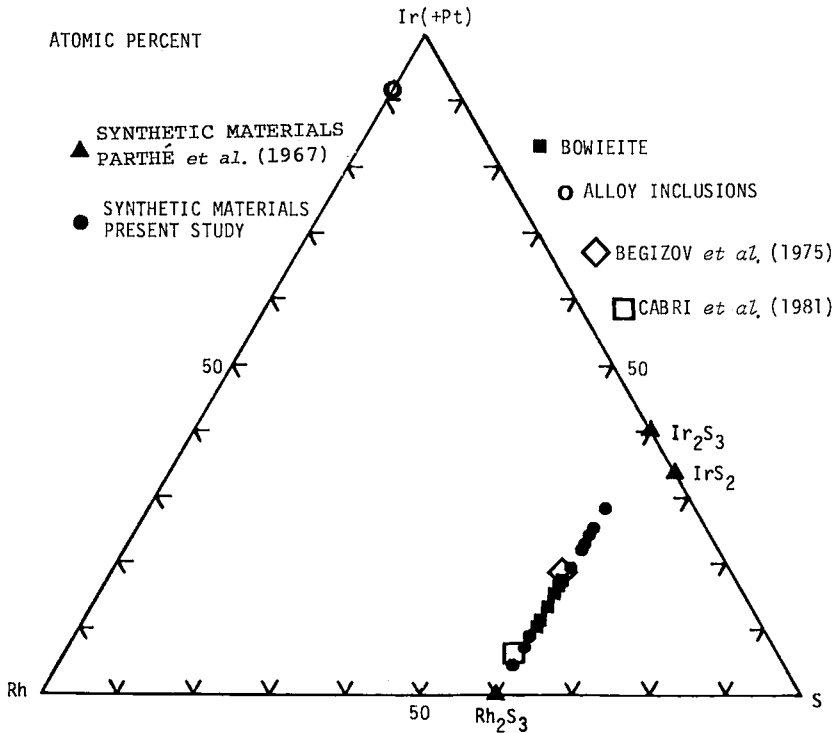


FIG. 2. The composition of bowieite, alloy inclusions, synthetic phases, and compositions reported by Begizov *et al.* (1975) and Cabri *et al.* (1981), in terms of the pseudoternary system Rh-Ir(+Pt)-S.

of the variability of sulfur content was carried out by performing six analyses on each of 33 grains of bowieite and metal-deficient bowieite; this shows that the average standard deviation from the mean of each is only 0.25 wt.%. The data of Table 1 show, upon recalculation, that the composition of metal-deficient bowieite differs from the ideal M_2S_3 stoichiometry of bowieite by 2.6 to 3.8 atomic %. Thus the difference between the two phases may be due only to a metal deficiency in the first, because the X-ray-diffraction data show the two to be isostructural.

CRYSTALLOGRAPHY

Material was extracted after microprobe analysis and mounted for X-ray diffraction using a Gandolfi 114.6-mm-diameter camera. Fragments of four separate grains were used, two each of bowieite and metal-deficient bowieite. X-ray powder-diffraction data for chemically analyzed bowieite (SRA-2-B1, Table 1) and metal-deficient bowieite SRA-2-F, Table 1) are given in Table 2. Fifty-nine lines of bowieite and 58 lines of metal-deficient bowieite were indexed on the basis of the given cell-parameters and

the orthorhombic cell *Pnca* in setting *cab*. The *cab* setting of Parthé *et al.* (1967) is retained because symmetry is more readily deduced from it than from the standard setting *abc*, $c < a < b$, of space group *Pbcn*.

Three lines that are present in the metal-deficient bowieite pattern (Table 2) are not listed because they are due to a face-centred cubic Ir-Pt-Rh alloy with a 3.868 Å; these lines are indexed as follows: 2.235 Å (111), 1.933 Å (200) and 0.8649 Å (420). The rather large calculated errors for the cell parameters of bowieite (*e.g.*, 0.007 and 0.008 Å, Table 2) are due to the extreme line-broadening at high- 2θ values and to the associated uncertainty in the indexation of some spacings smaller than 1.00 Å. This line broadening is attributable chiefly to the poor quality of the spindle mounts, rather than to intrinsic mosaic structure, because the lines of the Ir-Pt-Rh alloy are also very broad on X-ray patterns of the mounts.

The first 30 X-ray lines (Table 2) of both bowieite and metal-deficient bowieite can be indexed as those of synthetic Rh_2S_3 given by Parthé *et al.* (1967) as listed on PDF card 21-1017. However, the “*hk0* 440” line is not present in any of the natural material of the present study, and Parthé *et al.* (1967, Table

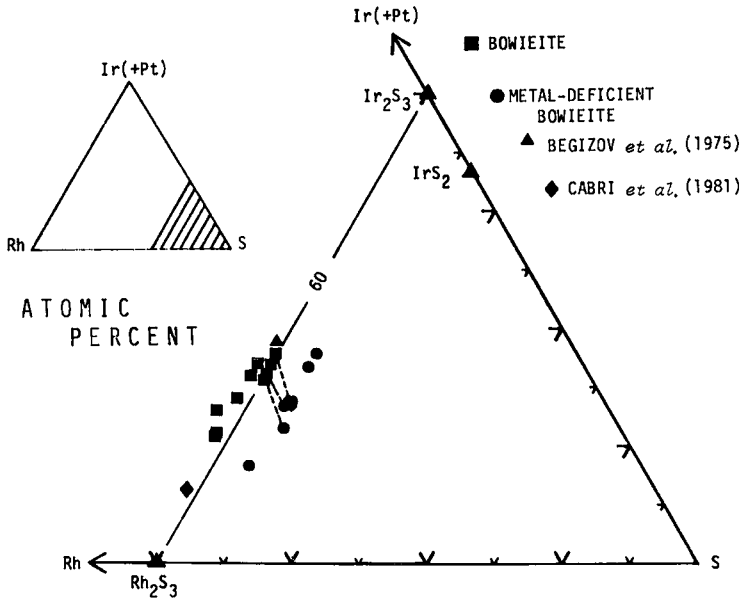


FIG. 3. The composition of bowieite, metal-deficient bowieite, and compositions reported by Begizov *et al.* (1975) and Cabri *et al.* (1981), in terms of the sulfur-rich portion of the pseudoternary system Rh-Ir(+Pt)-S.

4) observed a "weak" intensity for this line. Only five lines of bowieite and metal-deficient bowieite are indexed differently, and the only lines not common to both are weak or very weak (Table 2).

X-ray powder-diffraction lines measured on additional separate grains of bowieite and metal-deficient bowieite confirm that these two compositionally slightly different natural materials could not be uniquely distinguished on the basis of space group, although their cell parameters differ slightly (Table 3). The cell volumes of these natural materials and the synthetic end-members Rh_2S_3 and Ir_2S_3 differ by less than 1%. For all of these reasons, we believe that there should be only one mineral name until further research shows otherwise. Only highly accurate and precise chemical analyses can distinguish bowieite from metal-deficient bowieite, but X-ray diffraction on powder and quantitative reflectance and Vickers hardness measurements do not distinguish them. The name *bowieite* should include isotropic orthorhombic minerals having only minor deviation from M_2S_3 stoichiometry, in which M is dominantly Rh, and the space group, *Pnca*.

OPTICAL PROPERTIES IN REFLECTED LIGHT

Qualitative evaluation

In plane-polarized light, in air (at $\sim 3,200$ K),

bowieite is, in comparison with the white to creamy-white matrix, pale grey; neither bireflectance nor reflectance pleochroism is apparent. In oil, its reflectance is diminished appreciably and it appears a darker grey, but still without obvious bireflectance. Anisotropy is weak; rotation tints range from dark grey to very dark brown. With the analyzer uncrossed by 3° , the rotation tints are light khaki, kjaki, grey, blue-grey, steel grey, khaki. It extinguishes symmetrically. An isotropic grain was not found (*cf.* Begizov *et al.* 1975), although grain 5 of the reflectance study is only slightly anisotropic. Several of the grains are partly "rimmed" by metal-deficient bowieite; the rim, up to $60 \mu m$ wide (Fig. 1C), is not in optical continuity with bowieite.

In specimens prepared for the electron probe, a marked difference in polishing hardness was found between bowieite and the metal-deficient phase, bowieite being much the softer of the two (Fig. 1C). Polishing "relief" is not, however, characteristic of these minerals since, when the specimens were reground and polished prior to the measurement of their reflectance, no difference in hardness was perceptible (Fig. 1B).

Quantitative evaluation

An attempt was made to measure reflectances of bowieite in the visible spectrum on the grains that had first been analyzed by electron microprobe.

made with a continuous-spectrum filter, "check measurements" were made between 400 and 470 nm at an interval of 10 nm with homogeneous monochromatic filters supplied by Oriel. It was found that the results obtained are in excellent agreement. A further check on the reproducibility of the reflectance spectra was made at the laboratory of Drs. H. Piller and G. Schwartz, at Carl Zeiss in Oberkochen, West Germany. Here, an automated microscope-photometer was used in the wavelength-scanning mode to measure one grain of bowieite under slightly different optical conditions. A Latham stage was not available, so the specimen was mounted on plasticine and leveled by hand. Grain 5 of Tables 4, 5, and 6 was measured from 400 to 700 nm using a quartz halogen lamp and WTiC standard and from 380 to 780 nm using a xenon arc lamp and an SiC standard. A grating monochromator was used in both instances. The results obtained deviate by not more than 0.6% absolute from the results obtained by specimen-standard interchange in London.

The selection of areas for measurement was based on the absence of polishing scratches and alloy inclusions and on the presence of "sharp" extinctions. Grain 5 was the only "borderline" case in this

respect, since it is very nearly isotropic. A photometric check of the light measured at the selected "extinction positions" confirmed the settings. Flaw-free grains of metal-deficient bowieite for which electron-microprobe data were available were not found.

REFLECTANCE DATA

In the visible spectrum, the reflectance spectra of bowieite in air and oil are remarkably featureless (Fig. 4), and the measured bireflectance for individual grains is very low (Tables 4, 5). The simplest way of assessing bireflectance from such spectra is to use the difference in their calculated values of luminance ($Y\%$); this reveals (Table 6) that the bireflectance varies from about 1% for the least anisotropic grain, Grain 5, to about 2.5% for Grain 2. The color values of Table 6 also show that, with the exception of the R_1 value in oil of Grain 2, the dominant wavelengths λ_d are all in the yellow-orange range, between 569 and 591 nm; however, their levels of excitation purity ($P_e\%$) are very low, from 0.4 to 3.1%; indeed, their x and y values are almost coincident with those of the C illuminant. Thus in subjective terms, the eye will not distinguish

TABLE 4. REFLECTANCE VALUES, IN AIR, FOR FIVE GRAINS OF BOWIEITE, NUGGET SRA

λ_{nm}	Grain:	R_1					R_2				
		G1	2	E2	J	5	G1	2	E2	J	5
400	43.5	46.6	44.55	45.2	44.5	44.5	45.3	45.0	48.85	45.1	
410	43.9	46.3	44.7	45.2	44.7	44.9	45.7	45.2	45.9	45.2	
420	44.2	46.1	44.85	45.25	44.9	45.2	46.05	45.4	46.0	45.3	
430	44.55	45.9	45.0	45.3	45.1	45.55	46.4	45.55	46.05	45.45	
440	44.85	45.7	45.2	45.4	45.3	45.85	46.7	45.8	46.15	45.6	
450	45.1	45.55	45.4	45.4	45.4	46.2	47.0	46.1	46.3	45.7	
460	45.3	45.45	45.6	45.5	45.5	46.5	47.2	46.4	46.4	45.8	
470	45.5	45.4	45.85	45.5	45.6	46.7	47.5	46.7	46.55	46.0	
480	45.7	45.4	46.0	45.6	45.7	46.9	47.7	47.0	46.7	46.1	
490	45.8	45.45	46.1	45.7	45.75	47.1	47.85	47.25	46.95	46.2	
500	45.9	45.5	46.2	45.8	45.8	47.3	48.0	47.5	47.15	46.35	
510	46.0	45.55	46.35	45.9	45.9	47.45	48.1	47.7	47.35	46.45	
520	46.1	45.6	46.5	46.0	45.9	47.6	48.2	47.9	47.55	46.55	
530	46.1	45.65	46.6	46.05	46.0	47.7	48.25	48.05	47.7	46.7	
540	46.2	45.7	46.7	46.1	46.05	47.8	48.3	48.2	47.8	46.8	
550	46.25	45.8	46.9	46.2	46.1	47.9	48.3	48.35	47.95	46.9	
560	46.3	45.8	47.0	46.25	46.2	48.0	48.3	48.5	48.05	47.0	
570	46.4	45.85	47.1	46.3	46.2	48.1	48.3	48.6	48.1	47.1	
580	46.45	45.9	47.2	46.4	46.3	48.2	48.3	48.6	48.25	47.2	
590	46.5	45.95	47.25	46.5	46.35	48.25	48.3	48.7	48.3	47.3	
600	46.5	46.0	47.4	46.5	46.4	48.3	48.25	48.75	48.4	47.3	
610	46.6	46.05	47.5	46.6	46.4	48.3	48.2	48.8	48.4	47.35	
620	46.6	46.1	47.6	46.6	46.45	48.35	48.2	48.9	48.5	47.4	
630	46.7	46.2	47.65	46.7	46.5	48.4	48.2	48.9	48.6	47.4	
640	46.75	46.3	47.7	46.8	46.6	48.5	48.2	48.95	48.6	47.4	
650	46.8	46.4	47.7	46.85	46.65	48.5	48.2	48.9	48.7	47.45	
660	46.8	46.5	47.7	46.9	46.7	48.55	48.2	48.9	48.7	47.4	
670	46.85	46.6	47.7	46.9	46.8	48.6	48.1	48.9	48.7	47.4	
680	46.9	46.7	47.75	46.95	46.85	48.65	48.1	48.9	48.7	47.3	
690	46.95	46.75	47.75	46.95	46.9	48.65	48.0	48.8	48.7	47.2	
700	47.0	46.9	47.8	47.0	47.0	48.7	47.9	48.8	48.75	47.1	

TABLE 5. REFLECTANCE VALUES, IN OIL, FOR FIVE GRAINS OF BOWIEITE, NUGGET SRA

λ_{nm}	R_1					R_2				
	Grain: G1	2	E2	J	5	G1	2	E2	J	5
400	30.5	32.1	29.9	29.8	29.75	31.6	31.05	30.1	30.75	30.1
410	30.4	31.165	30.0	29.9	31.5	31.5	31.25	30.25	30.85	30.2
420	30.25	31.2	30.05	30.0	30.0	31.4	31.4	30.45	31.0	30.3
430	30.15	30.9	30.1	30.1	30.1	31.35	31.6	30.7	31.1	30.4
440	30.1	30.6	30.15	30.2	30.2	31.3	31.75	30.9	31.3	30.5
450	30.1	30.4	30.2	30.3	30.2	31.35	31.9	31.2	31.5	30.6
460	30.2	30.25	30.3	30.4	30.3	31.4	32.1	31.4	31.65	30.7
470	30.3	30.2	30.4	30.45	30.4	31.6	32.3	31.65	31.8	30.8
480	30.4	30.2	30.5	30.6	30.4	31.75	32.5	31.9	32.0	30.9
490	30.6	30.2	30.6	30.7	30.5	32.0	32.7	32.2	32.15	31.0
500	30.7	30.2	30.7	30.8	30.5	32.15	32.8	32.45	32.3	31.1
510	30.8	30.2	30.95	30.9	30.55	32.35	32.95	32.65	32.5	31.25
520	30.9	30.25	31.15	31.0	30.6	32.55	33.0	32.85	32.7	31.4
530	31.05	30.3	31.35	31.05	30.6	32.7	33.05	33.0	32.8	31.5
540	31.15	30.3	31.55	31.15	30.7	32.9	33.1	33.1	33.0	31.6
550	31.2	30.4	31.75	31.2	30.75	33.0	33.1	33.25	33.1	31.7
560	31.35	30.5	31.9	31.3	30.8	33.1	33.1	33.35	33.2	31.8
570	31.4	30.5	32.0	31.35	30.9	33.25	33.1	33.5	33.25	31.95
580	31.45	30.6	32.15	31.4	31.0	33.35	33.05	33.6	33.3	32.05
590	31.5	30.7	32.3	31.45	31.0	33.4	33.0	33.65	33.4	32.1
600	31.55	30.8	32.4	31.5	31.1	33.45	33.0	33.65	33.45	32.2
610	31.6	30.9	32.45	31.6	31.2	33.5	32.95	33.7	33.5	32.25
620	31.6	31.0	32.5	31.65	31.3	33.6	32.95	33.75	33.5	32.3
630	31.7	31.1	32.6	31.7	31.35	33.65	32.9	33.8	33.6	32.3
640	31.7	31.15	32.65	31.8	31.5	33.7	32.9	33.85	33.65	32.35
650	31.7	31.25	32.7	31.8	31.6	33.7	32.9	33.85	33.7	32.35
660	31.7	31.3	32.7	31.85	31.65	33.7	32.9	33.9	33.7	32.3
670	31.75	31.35	32.7	31.85	31.7	33.7	32.85	33.85	33.75	32.3
680	31.8	31.45	32.7	31.85	31.75	33.65	32.8	33.8	33.7	32.2
690	31.8	31.55	32.6	31.85	31.8	33.65	32.8	33.8	33.7	32.15
700	31.85	31.6	32.6	31.9	31.8	33.65	32.8	33.75	33.7	32.1

a hue, but rather it will "see" the mineral as white or grey. In fact, in polished section where the mineral is surrounded by the more highly reflecting Pt-Ir alloy, it is perceived as light grey in air and a darker grey in oil, and its measurably low bireflectance is not detected. For Grain 2, the complementary wavelength λ_c for R_1 in oil is also a consequence of the proximity of the calculated x and y values to those of the C illuminant; they are so close that the angular relationship used to calculate the wavelength produces a value that is without meaning.

In order to show the differences between the reflectance spectra for the five grains of bowieite, the scale of the ordinate on Figure 4 has been deliberately exaggerated (note that the variation for all five grains from the lowest value of R_1 to the highest of R_2 is about 3% throughout the spectrum). The data available are too few to attempt to obtain the sign of the bireflectance; it is doubtful, in view of the very low bireflectance of the mineral, whether or not a statistical approach would produce R_g , R_m , and R_p with any degree of certainty. Of all the grains measured, only Grain 2 shows R_1 crossing R_2 at 420 nm in air and at about 417 nm in oil.

TABLE 6. COLOR VALUES REFERRED TO CIE ILLUMINANT C FOR FIVE GRAINS OF BOWIEITE AND $(Rh, Ir)_2S_3$ OF CABRI *et al.* (1981)

Grain	R_1					R_2				
	x	y	Y%	λ_d	$P_{\theta}^{\#}$	x	y	Y%	λ_d	$P_{\theta}^{\#}$
AIR										
G1	0.313	0.320	46.3	574	1.5	0.314	0.321	47.9	575	2.2
2	.311	.317	45.8	591	0.4	.312	.320	48.2	569	1.4
E2	.314	.320	46.9	577	2.0	.315	.322	48.3	576	2.6
J	.312	.318	46.2	579	1.1	.314	.320	47.9	577	2.1
5	.312	.318	46.1	577	1.0	.313	.319	46.9	577	1.6
*	.313	.319	48.4	577	1.4	.314	.321	49.2	575	2.1
OIL										
G1	0.314	0.320	31.2	577	2.1	0.315	0.323	33.0	577	2.9
2	.312	.316	30.5	494c	0.5	.312	.320	33.0	569	1.7
E2	.316	.322	31.8	579	3.1	.316	.324	33.2	575	3.7
J	.314	.320	31.1	577	1.9	.315	.322	33.1	576	2.9
5	.313	.318	30.8	581	1.3	.314	.321	31.8	578	2.3
*	.313	.320	33.4	574	1.7	.314	.321	34.2	576	2.2

*These data are those of Cabri *et al.* (1981), and refer to a grain with a higher rhodium and lower iridium content than grains reported on here.

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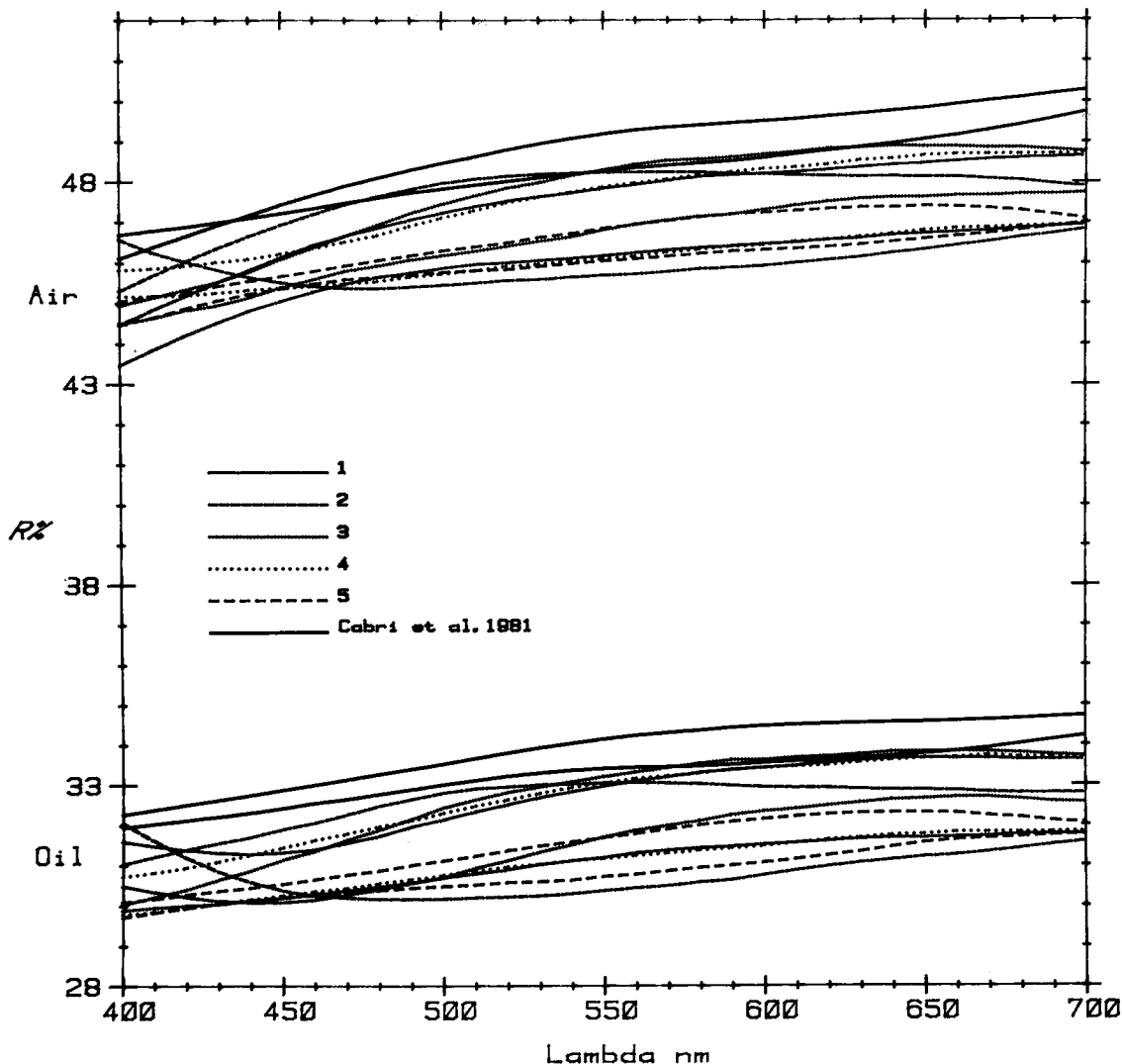


FIG. 4. Quantitative reflectance spectra, in air and oil, for R_1 and R_2 measured on six grains of bowieite.

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