Sorosite, Cu(Sn,Sb), a new mineral from the Baimka placer deposit, western Chukotka, Russian Far East

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ABSTRACT

Sorosite, ideally Cu(Sn,Sb), is a new mineral species from the Baimka gold-platinum-group mineral placer deposit, Chukotka, Russian Far East. It occurs as large subhedral to euhedral crystals (0.1–0.4 mm in length), hexagonal in cross section, minute crystals ($\leq$ 15 μm, also hexagonal), and anhedral grains. Sorosite forms inclusions in Sb-bearing native tin, is often intergrown with stistaite ($Sn_{1.12-1.13}Sb_{0.87-0.88}$) and occurs with herzenbergite (SnS), native lead, and trace cassiterite. Sorosite is brittle with a microhardness $VHN_{40;50}$ = 443.7 kg/mm^2 (n = 3). No cleavage is observed. In reflected light, the large crystals are nearly white with a pinkish tint, whereas the microcrystals show a pronounced pinkish tint. Bireflectance is variable. The average of nine electron microprobe analyses gave Cu 35.33, Fe 1.18, Sn 58.18, and Sb 4.77, sum 99.46 wt%, corresponding to $(Cu_{1.00}Fe_{0.04})_{\Sigma1.04}$ $(Sn_{0.89}Sb_{0.07})_{\Sigma0.96}$. The powder pattern is close to those of natural Cu(Sn,Sb) and synthetic η-Cu_6Sn_5; it was indexed for a hexagonal cell, with a = 4.217(4) Å, c = 5.120(6) Å, and V = 78.85 Å^3. For Z = 2, the calculated density is 7.6 g/cm^3. The strongest lines in the pattern are at 2.970 (011), 2.112 (110), and 2.094 Å (012). The sorosite-bearing mineral assemblage apparently formed under low f_{O_2} and f_{S_2} conditions.

INTRODUCTION

The Baimka gold placer deposit, western Chukotka, Russian Far East, is situated in the River Bolshoy Anyuy area, near the Baimka River (Fig. 1). Various platinum-group minerals, PGM, (but principally Pt-Fe alloys) occur in close spatial association with Au in the placer (Gornostaev 1994; Gornostaev et al. 1994). During examinations by reflected light microscopy, an unusual composite grain (3 mm in the longest dimension) was encountered. Electron microprobe analyses of several fragments from this grain showed it to consist of an unnamed Cu-(Fe)-Sn-Sb mineral, in close association with Sb-bearing native tin and stistaite (ideally SnSb). Characteristics of this mineral are reported here. We have named it sorosite after George Soros (born in 1930), well-known American financier, in recognition of his important support to science (the ISF, established by G. Soros, has been a great help to scientists in republics of the former Soviet Union during the current financial crisis) and efforts to promote open societies throughout the world. Both the new mineral and its name have been approved by the IMA Commission on New Minerals and Mineral Names prior to publication (no. 94-047). Type material is deposited at the Mining Museum, St. Petersburg Mining University, St. Petersburg (catalog no. 2083/1).

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GEOLOGICAL BACKGROUND

The remote Baimka area is characterized by very complicated geology and by various ore deposits. The Baimka gold-PGM placer is located in the Aluchin horst, which contains widespread ophiolitic rocks (Dovgal 1964). In the vicinity of the placer, two principal complexes are recognized. First, the Aluchin complex is a large ultramafic ophiolitic complex of a Permian (or Triassic) age. It occurs as three separate (north to northwest trending) bodies that are controlled by a regional fault system (Fig. 1). The largest body ($\sim$250 km^2) extends along strike for about 40 km. The complex consists mainly of peridotite (harzburgite), subordinate dunite, and pyroxenite. The ultramafic rocks are serpentinized to various degrees. Abundant dikes of olivine dolerite, trachydolerite, diorite porphyrite, aplite, and numerous quartz veins are observed at the contact (Aksenova et al. 1970; Lychagin 1985; Surnin and Okrugin 1989). The second complex, the Yegdegkychsky gabbro-syenite-(monzonite) complex (Jurassic to Cretaceous?) is the product of two (or three) major intrusive phases: an early gabbro and gabbro-diorite phase; a later phase of various syenites (some quartz-bearing and some of alkaline affinity); and quartz-bearing diorites (Berlimble and Gorodinskii 1978; Gorodinskii et al. 1982; Volchkov et al. 1982). Of particular interest are clinopyroxenite-gabbro intrusions (up to $\sim$4.5 km in diameter; V.P. Fomin, unpublished data), which are attrib-
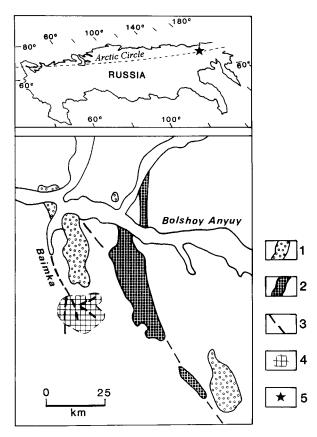
FIGURE 1. Schematic geological map showing principal complexes in the Baimka area (western Chukotka, Russian Far East). 1 = Yegdegkychsky complex; 2 = Aluchin complex; 3 = faults; 4 = Baimka placer; 5 = location (shown in the insert) of the Baimka deposit in Russia.

uted to the early intrusive sequence of the Yegdegkych-sky complex. Some of them resemble Alaskan-type complexes not only in their roughly concentric zonal patterns, but also in petrological and geochemical characteristics (Gornostaev 1994). Various hypabyssal intrusive bodies are widely developed in the area (Gulevich 1974). The biggest of them (12 × 3–4 km) consists predominantly of trachyliparite. The subvolcanic bodies are surrounded by hornfelse rocks (Gorodinskii et al. 1982).

The mineralized zones in the Baimka and adjacent areas are diverse, including the chromite- and associated Ni-(Fe) sulfide mineralization of the Aluchin complex (Aksenova et al. 1970); the porphyry copper and Au-Ag-bearing polysulfide ores in quartz-bearing porphyry monzonite and related hypabyssal rocks in the Yegdegkych-sky complex (Berlimble and Gorodinskii 1978; Volchkov et al. 1982; Kaminskii 1987)—the source of the gold placer deposits in the region (Kaminskii 1989); and a (quartz)-Mo-Cu-(Au) ore mineralization in altered monzonite (Gulevich 1974). The probable primary source of the PGM in the Baimka placer is the Alaskan-type intrusions (Gornostaev et al. 1994).

APPEARANCE AND ASSOCIATED MINERALS

Native tin is the chief ore mineral in all the polished mounts examined, followed by sorosite and stistaite. A tin sulfide (herzenbergite), cassiterite and native lead are the only minor constituents. Sorosite occurs as inclusions in native tin. Large crystals (LC) are up to 0.4 mm in length, well-developed, and commonly broken (in polished mount) crystals with hexagonal crystal outlines (e.g., Figs. 2a and 2b). Minute crystals (MC) are ≤ 15 μm subhedral to euhedral (hexagonal) crystals and elongate anhedral grains (Fig. 2b). Skeletal appearance and cavities (filled by Sn), characteristic of the MC, are rarely observed in the LC (Fig. 2b). No cleavage is observed.

Stistaite appears as lath-shaped crystals (up to 0.3 mm long), closely associated with the Sn and sorosite. It was also observed as an inclusion in sorosite. The presence of the sorosite-stistaite intergrowths is noteworthy (e.g., Fig. 2a). Rare herzenbergite typically occurs relatively close to the contact of native tin as small (up to 25 μm) subhedral to euhedral crystals and anhedral grains, which are isolated within native tin (Fig. 2d) and, more rarely, within sorosite (Fig. 2c). A fine-grained cassiterite that is locally in contact with herzenbergite (Fig. 2d) occurs sporadically in trace quantities, and its aggregates are typically less than 0.06 mm in the longest dimension. Experimental data indicate that cassiterite can coexist with SnS (herzenbergite) in the whole range of geologically probable temperatures (Drábek and Štemprok 1974), and these minerals occur together (in opposite textural relationships) in several mineralized zones (Smeds 1993 and references therein). Native lead is present as minute inclusions in native tin and veinlets (up to 15 μm), which may partly replace the sorosite MC.

MICROHARDNESS AND OPTICAL PROPERTIES

Sorosite is very brittle and fractures easily during micro-indentation under loads ≥50 g. This property is presumably responsible for the appearance of the broken sorosite crystals in polished mount. Two measurements carried out with a Neophot-2 tester (Kola Science Center) gave VHN_{40} = 452 and 498 kg/mm². An additional measurement (made for another LC at the University of Hamburg) gave VHN_{50} = 381 kg/mm² (M. Tarkian, written communication). The average is 443.7 kg/mm².

Owing to a high reflectance, the LC seem to be nearly white in reflected light. However, a pinkish tint is observable under high magnification. The MC show a pronounced pinkish tint. Typically, bireflectance is not observed in air, although weakly to distinctly bireflectant grains are present. Anisotropy is distinct to moderate, from brownish gray to bluish gray.

Reflectance data show a strong bireflectance for one LC grain and weak for another (Table 1a and 1b). Measurements were carried out at the Kola Science Center (in air; MSFP-2 microphotometer, Si standard: R_{589} in air = 35.7%) and the University of Hamburg (in air and oil; Zeiss MPM microphotometer, WTiC standard: R_{589} in air
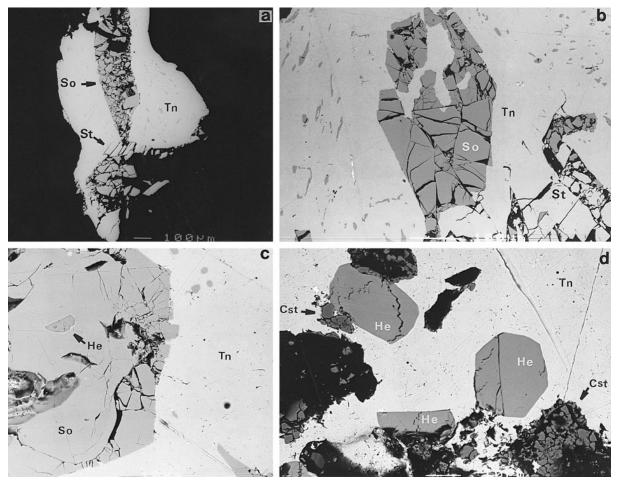
FIGURE 2. (**a**) A large (broken) crystal of sorosite (So), associated with stistaite (St = lath-shaped crystals) and native tin (Tn); black = epoxy. (**b**) Large sorosite crystal (So = partly skeletal) adjacent to stistaite (St). Tn = native tin. Note abundant microcrystals of sorosite isolated within native tin. (**c**) Subhedral sorosite (So) containing a subhedral inclusion of herzenbergite (He). Note that crystal faces of the inclusion are sub-parallel to those of the host sorosite. Tn = native tin. (**d**) Subhedral herzenbergite (He), enclosed within native tin (Tn). Cst = fine-grained cassiterite. Back-scattered electron images. Scale bar is equivalent to 100 μm in **a** and **b**, and 10 μm in **c** and **d**.

= 49.5, R_{589} in oil = 35.5%), respectively. Sorosite has an exceptionally high reflectance, e.g., R(max)$_{589}$ in air ≅ 78%. The dependence of the reflectance on wavelength and the maximum reflectance values obtained for the two grains are very similar to each other. However, the first grain displays lower minimum values (Table 1), implying that sorosite is optically negative, but more measurements are required.

COMPOSITION

Wavelength-dispersion (WDS) analyses were carried out with a Cameca MS-46 electron microprobe (Kola Science Center), operated at 20 kV and 20 nA. The X-ray lines used were $K\alpha$ for Cu and Fe, and $L\alpha$ for Sn and Sb; synthetic $Fe_{10}S_{11}$ and pure elements were used as standards. Quantitative energy-dispersion analyses (EDS) were carried out at the Institute of Electron Optics, University of Oulu, at 15 kV and 1.2 nA, using a JEOL JSM-6400 scanning-electron microscope equipped with a

LINK eXL energy-dispersion spectrometer. The X-ray lines used were K for Cu and Fe, and L for Sn and Sb; pure elements were used as standards. The most finely focused beam was applied (~1 μm in diameter). Counting periods were 100 s. The spectra were processed by Link ISIS (revision 3.00) on-line program. Owing to the small grain-sizes of sorosite MC, native lead, and cassiterite, these were only analyzed with EDS.

The WDS and EDS electron microprobe analyses of sorosite (Table 2) are in agreement with each other as they are with an average WDS analysis obtained using a JEOL-733 electron microprobe on LC from a newly found placer grain at Baimka (no. 3, Table 2). Copper and Sn are the chief constituents of sorosite, however Fe, Sb, and, to a lesser extent, Ni may also be essential. The three LC, studied in more detail (EDS and WDS), appear to be zoned with respect to Fe; the Fe content is below detection limits (or relatively low) near the edges, whereas the central areas of the crystals yield ≥3 wt% Fe. In

TABLE 1A. Reflectance data for sorosite

λ nm	In air				In oil	
	R_1*	R_2*	R_1†	R_2†	R_1†	R_2†
400	n.m.	n.m.	68.5	68.9	57.4	58.1
420	n.m.	n.m.	69.3	70.0	59.5	59.9
440	62.9	70.5	71.8	72.5	61.2	62.4
460	64.2	72.0	73.7	74.1	62.2	63.9
470	64.8	72.9	74.0	74.4	62.3	64.2
480	65.3	73.8	74.9	74.9	62.4	64.7
500	66.4	75.2	75.7	75.9	62.8	65.4
520	67.2	76.3	76.4	76.4	63.3	65.9
540	67.9	77.1	76.8	77.1	64.0	66.4
546	68.2	77.4	76.9	77.2	64.0	66.4
560	68.4	77.9	77.3	77.3	64.1	66.6
580	68.8	78.3	77.8	78.0	65.0	67.2
589	68.9	78.5	77.8	78.1	65.1	67.3
600	69.0	78.7	77.8	78.2	65.3	67.6
620	69.0	78.9	78.1	78.7	66.0	68.0
640	69.0	79.0	78.0	78.6	65.8	68.1
650	69.0	79.0	78.0	78.6	66.0	68.1
660	69.1	79.0	78.0	78.6	66.1	68.2
680	69.1	79.0	77.9	78.8	66.3	68.2
700	69.1	79.1	77.9	78.9	66.8	68.6

* MSFP-2 microphotometer; n.m. = not measured.
† Zeiss MPM microphotometer (courtesy of M. Tarkian).

TABLE 1B. Color values: C illuminant*

	x	y	Y%	P_e%	$λ_d$
In air					
R_1	0.316	0.324	77.1	3.5	573
R_2	0.316	0.323	77.3	3.4	575
In oil					
R_1	0.316	0.322	64.3	3.0	578
R_2	0.316	0.323	66.7	3.5	575

* Zeiss MPM microphotometer (courtesy of M. Tarkian).

Stistaite varies little in composition (nos. 7 and 8, Table 2) with empirical formulae $Sn_{1.12-1.13}Sb_{0.87-0.88}$, which are close to those of stistaite from the type occurrence ($Sn_{1.15}Sb_{0.85}$; Nikolaeva et al. 1970) and from Colombia ($Sn_{1.12}Sb_{0.87}$; Rose 1981). Nikolaeva et al. (1970) hypothesized that the Sb-deficient composition of stistaite (derived from their electron-microprobe analyses) resulted from interference from the associated Sn, and that the actual composition is close to ideal SnSb. However, this proposal is rejected by the microprobe data in Rose (1981) and in the present study, which reveal the Sn-rich composition of stistaite. The low Sb content (43.3–43.9 at% Sb) in the Baimka stistaite is very close to that of the Sb-poorest sample of synthetic $Sn_{1+x}Sb_{1-x}$ (Hansen and Anderko 1958).

The Baimka native tin (Table 2) invariably contains more than 1 wt% Sb in solid solution. Herzenbergite grains analyzed, including those in Figures 2c and 2d, gave the ranges: Sn 78.6–81.6 and S 20.6–19.5 wt%, and average formula $Sn_{1.04}S_{0.96}$ (Σ atoms = 2). The cassiterite analysis agrees with the theoretical formula. The native lead is close to 100 wt% Pb.

addition to the textural differences, the coexisting MC and LC are also distinct in composition; the latter appear to be richer in Sb (Table 2).

The ideal formula is Cu(Sn,Sb) for both types of sorosite at Baimka. This formula is corroborated by the compositional data (Table 2) on related Cu(Sn,Sb) phases, obvious precursors of sorosite from Uzbekistan (Nikolaeva et al. 1970) and Colombia (Rose 1981). The $η$-Cu_6Sn_5 phases from Borneo (Stumpfl and Clark 1965) and Portugal (Clark 1972) are also related to sorosite, despite a relative excess in Cu and the virtual absence of Sb (and Fe) in their compositions.

TABLE 2. Representative compositions of sorosite and associated minerals

No.	Weight percent					Atomic proportions*					
	Cu	Fe	Sn	Sb	Total	Cu	Fe	Cu+Fe	Sn	Sb	Sn+Sb
1†	36.12	0.92	57.99	4.93	99.96	1.02	0.03	1.05	0.88	0.07	0.95
2‡	35.33	1.18	58.18	4.77	99.46	1.00	0.04	1.04	0.89	0.07	0.96
3‡§	35.96	1.26	56.78	4.89	99.53	1.01	0.04	1.07	0.86	0.07	0.93
4†	36.45	n.d.	62.59	0.91	99.95	1.04	—	1.04	0.95	0.01	0.96
5†	36.88	n.d.	62.98	0.87	100.73	1.04	—	1.04	0.95	0.01	0.96
6†	36.92	n.d.	62.49	1.11	100.52	1.04	—	1.04	0.94	0.02	0.96
7†	n.d.	n.d.	56.38	44.13	100.51	—	—	—	1.13	0.87	2.00
8‡	n.d.	n.d.	55.42	44.41	99.83	—	—	—	1.12	0.88	2.00
9†	n.d.	n.d.	98.17	1.71	99.88	—	—	—	0.98	0.02	1.00
10	39.8	—	61.0	—	100.8	1.10	—	1.10	0.90	—	0.90
11	33.4	0.5	56.5	8.2	98.6	0.98	0.02	1.00	0.88	0.12	1.00
12	38.6	—	61.15	—	99.75	1.08	—	1.08	0.92	—	0.92
13	35.99	—	56.12	7.89	100.00	1.03	—	1.03	0.86	0.12	0.98

Note: Nos. 1–3 = large sorosite crystals from Baimka; 4–6 = sorosite microcrystals from Baimka; 7 and 8 = stistaite from Baimka; 9 = native tin from Baimka; 10 = unnamed Cu_6Sn_5 from Borneo (Stumpfl and Clark 1965); 11 = unnamed Cu(Sn,Sb) from Uzbekistan (Nikolaeva et al. 1970); 12 = unnamed Cu_6Sn_5 from Portugal (Clark 1972); 13 = unnamed Cu(Sn,Sb) from Colombia (Rose 1981). No. 1, average of 18 individual analyses; no. 2, n = 9; no. 6, n = 12; nos. 7 and 8, n = 6; no. 9, n = 4; and no. 12, n = 2.
* Atomic proportions calculated on the basis: Σ atoms = 2 (sorosite, stistaite, and phases related to sorosite) and Σ atoms = 1 (native tin).
† EDS electron-microprobe analyses.
‡ WDS electron-microprobe analyses.
§ Jeol-733 electron microprobe: n = 151 (Barkov et al., unpublished data). Total includes 0.64 wt% Ni; 0.02 Ni atoms pfu are added to the Cu+Fe value. This analysis and analyses nos. 1 and 2 refer to sorosite from different placer grains at Baimka.

TABLE 3. X-ray powder data for sorosite and related phases

	Sorosite*			Cu(Sn,Sb)†		η-Cu$_6$Sn$_5$‡		η-Cu$_6$Sn$_5$§	
I	D_{meas}	D_{calc}	hkl	I	D_{meas}	I/I_1	D_{meas}	I/I_1	D
10	2.970	2.973	011	100	2.97	9	2.96	100	2.95
1	2.560	2.560	002	37	2.56	4	2.57	50	2.54
8	2.112	2.109	110	52	2.11	9	2.09	100	2.09
9	2.094	2.096	012	72	2.09	10	2.08	100	2.08
3	1.720	1.720	021	21	1.716	7	1.705	70	1.71
2	1.627	1.628	112	27	1.627	5	1.621	50	1.62
2	1.546	1.546	013	—	—	10	1.546	100	1.54
5	1.487	1.487	022	22	1.486	9	1.485	100	1.48
4	1.333	1.333	211			8	1.322	100	1.32
2	1.279	1.280	004					50	1.27
1	1.248	1.247	203					50	1.24
5	1.218	1.217	300					100	1.21
5	1.212	1.215	212					20	1.20
		1.208	104						
4	1.095	1.094	114					20	1.09
2	1.072	1.073	213					100	1.09
2	1.054	1.054	220						

Note: D is in angstroms.
* 114.6 mm Debye-Scherrer camera, Fe-K radiation; intensities estimated visually. a = 4.217, c = 5.120 Å.
† Unnamed Cu(Sn,Sb) from Colombia (Rose 1981). a = 4.212, c = 5.114 Å.
‡ Unnamed Cu$_6$Sn$_5$ from Portugal (Clark 1972).
§ Synthetic η-Cu$_6$Sn$_5$; A.S.T.M. 2-0713 (Westgren and Phragmén 1928). a = 4.190, c = 5.086 Å.

X-RAY STUDY

The material available was insufficient for single-crystal study. The fully indexed X-ray powder diffraction pattern of a ground LC (~0.2 mm) (Table 3) compares well with those for synthetic and natural η-Cu$_6$Sn$_5$ (Westgren and Phragmén 1928; Clark 1972), and natural Cu(Sn,Sb) from Colombia (Rose 1981). The sorosite pattern was indexed for a hexagonal cell with the following unit-cell parameters refined by least-squares from the powder data: a = 4.217(4) Å, c = 5.120(6) Å, and V = 78.85 Å^3. By analogy with synthetic ε-FeSb, which is crystallized with NiAs structure type (PDF-34-1053), the space group P6$_3$/mmc is probable, and sorosite may thus represent a new member of the nickeline group. With Z = 2, the density calculated for average compositions of LC nos. 1 and 2 in Table 2 is 7.6 g/cm^3, close to the calculated density of 7.9 g/cm^3 for the Colombian Cu(Sn,Sb) phase (Rose 1981).

DISCUSSION

The sorosite-bearing mineral assemblage at Baimka is closely related to those reported by Nikolaeva et al. (1970) from Uzbekistan and Rose (1981) from a gold-PGM-bearing placer in Colombia. The precursors of sorosite from these localities are also enriched in Sb and are intimately associated with native tin and stistaite. Structurally, sorosite is closely related to unnamed Cu(Sn,Sb) from Colombia (Rose 1981), to synthetic η-Cu$_6$Sn$_5$ (Westgren and Phragmén 1928; Carlsson and Hägg 1932), and to natural η-Cu$_6$Sn$_5$ from Portugal (Clark 1972). However, microhardness and reflectance values of the latter phase (VHN$_{15}$ = 61.5; R(max)$_{589}$ in air = 62.6%) are both reported to be much lower than those of sorosite. The reason for these differences is unknown, but a possibility is that the grain from Portugal, which is

found in the oxidized ore, may itself have been oxidized to a certain extent. The η-Cu$_6$Sn$_5$ phase is reported from a placer in Borneo (Stumpfl and Clark 1965), where both Au and PGM are present. Copper-tin alloys are also described from Sumatra in spatial association with alluvial gold and PGM; however, no η-Cu$_6$Sn$_5$ phase is reported (Bowles et al. 1984).

The composite Sn-Sb-Cu-rich grains, Au, and PGM are concentrated in placers because of their high specific gravities; no genetic relationships appear to exist between them. The primary source for the sorosite-bearing assemblage cannot be unequivocally suggested. However, it is well known that the Siberian (Noril'sk) trap rocks contain widespread Pd-Cu-Sn alloys (Genkin et al. 1981; Cabri 1994), which may reach a few mm across. These occurrences are indicative of conditions favorable for large-scale alloy formation and relative enrichments in Cu, (Pd), and Sn in the trap rocks. Obviously, Pd-free Cu-Sn alloys could occur in similar but Pd-deficient environments, and the Baimka sorosite-bearing assemblage may be derived from rocks (probably sulfide-poor) similar to Siberian traps. A complete analogy is not necessarily implied, and, for instance, a mineralized zone in the Yeg-degkychsky complex could be a quite reasonable alternative as the primary source. This suggestion is consistent with the geological features (Fig. 1). However, other possibilities also cannot be excluded; for instance, native tin and lead are known in skarns, formed under granite influence (Damman and Kieft 1990).

The LC and MC appear to have formed by a direct crystallization and by exsolution from the native tin, respectively. The Baimka sorosite may have evolved during crystallization from the Sb-(Fe)-rich LC to the later Sn-rich, Sb-(Fe)-poor MC.

The sorosite-bearing association formed under reduc-

ing conditions; otherwise, abundant cassiterite would have formed. A low sulfur fugacity (f_{S_2}) in the mineral-forming system is implied by the lack of Sn sulfides apart from the rare herzenbergite. The latter is known to crystallize under low f_{O_2} and relatively low f_{S_2} conditions (Smeds 1993 and references therein); the position of Sn/SnS buffer is close to that of Fe/FeS (Drábek and Stemprok 1974). Textural data imply that the Baimka herzenbergite was predominantly formed at a late stage when a higher f_{S_2} prevailed in the environment.

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