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SOBOLEVSKITE, TAIMYRITE, AND Pt_2CuFe (TULAMEENITE?) IN COMPLEX MASSIVE TALNAKHITE ORE, NORIL'SK OREFIELD, RUSSIA

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ABSTRACT

Compositional data are given for a suite of minerals present in a particularly PGM-rich ore from Noril'sk region, Russia. A characteristic association of altaite (PbTe) intergrown with sobolevskite [Pd(Bi,Te)] and taimyrite [$(Pd,Pt,Cu)_3Sn$] occurs within talnakhite–galena-rich ores from the Oktyabr' mine, Noril'sk Complex. Associated minerals include Ag–Au alloy and minor amounts of froodite, paolovite, sperrylite and Pd(Bi,Pb). Varying Bi:Te values in sobolevskite are in agreement with the previously proven solid-solution between kotulskite (PdTe) and sobolevskite (PdBi). New compositional and reflectance data are provided for taimyrite with the composition $(Pd_{1.55}Cu_{0.85}Pt_{0.6})_{\Sigma 3}Sn$. An alloy with the composition Pt_2FeCu is common as prismatic and needle-shaped crystals at the outer margin of altaite. This may represent the first report of tulameenite from Noril'sk, albeit morphologically and paragenetically somewhat different from previously reported occurrences. Observed textures, dominated by a range of intergrowths, in part symplectitic, at every scale from cm-size oblong-shaped grains of galena in talnakhite down to μm-scale intergrowths of altaite and sobolevskite, derive from a complex sequence of unmixing in the system Pt–Pd–Bi–Te–Pb–Ag–Au–Sn–Cu–Fe–Ni–S–Te during cooling.

Keywords: platinum-group minerals, sobolevskite, taimyrite, tulameenite, Noril'sk, Russia.

SOMMAIRE

Ce travail fait état de compositions de minéraux présents dans un minerai particulièrement enrichi en minéraux du groupe du platine de la région de Noril'sk, en Russie. Une association impliquant l'altaïte (PbTe) en intercroissance avec la sobolevskite [Pd(Bi,Te)] et la taimyrite [$(Pd,Pt,Cu)_3Sn$] est caractéristique de minerais riches en talnakhite–galène à la mine Oktyabr', complexe de Noril'sk. Leurs sont associés un alliage Ag–Au et des quantités moindres de froodite, paolovite, sperrylite et Pd(Bi,Pb). Le rapport Bi:Te variable de la sobolevskite concorde avec les résultats antérieurs à propos d'une solution solide entre kotulskite (PdTe) et sobolevskite (PdBi). Nous présentons des données nouvelles sur la composition et la réflectance de la taimyrite ayant une composition $(Pd_{1.55}Cu_{0.85}Pt_{0.6})_{\Sigma 3}Sn$. Un alliage de composition Pt_2FeCu est répandu en cristaux prismatiques et aciculaires à la bordure de l'altaïte. Il pourrait s'agir du premier exemple de tulameenite à être signalé à Noril'sk, quoique morphologiquement et paragénétiquement différent des exemples connus ailleurs. Les textures observées, en particulier les intercroissances, en partie symplectitiques, à toutes les échelles à partir des grains centimétriques allongés de galène dans la talnakhite jusqu'aux intercroissances millimétriques d'altaïte et de sobolevskite, résultent d'une séquence complexe de démixion dans le système Pt–Pd–Bi–Te–Pb–Ag–Au–Sn–Cu–Fe–Ni–S–Te au cours du refroidissement.

(Traduit par la Rédaction)

Mots-clés: minéraux du groupe du platine, sobolevskite, taimyrite, tulameenite, Noril'sk, Russie.

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Introduction

Kotulskite (PdTe, Genkin *et al.* 1963) is a relatively common mineral in a number of PGE mineral deposits (Cabri 1981a). Sobolevskite, its Bi-dominant analogue, (PdBi; Evstigneeva *et al.* 1976) is relatively less common. In this paper, we examine the occurrence of sobolevskite and associated minerals in a sample from the Noril'sk Orefield unusually enriched in the platinum-group elements (PGE). The paragenesis of platinum-group minerals (PGM) is described, and reflectance data are given for an intermediate member of the taimyrite–tatyanaite solid-solution series, which characteristically occurs at the margins of altaite–sobolevskite intergrowths. A Pt–Cu–Fe alloy, abundant within altaite, has the composition of tulameenite.

The mineralogy of the Noril'sk and Talnakh ore deposits, situated on the northwestern edge of the Siberian platform in Arctic Russia (Long. 62°21' N, Lat. 88°02' E), was discussed by a number of authors (*e.g.*, Genkin 1968, Genkin *et al.* 1981, Genkin & Evstigneeva 1986, Distler *et al.* 1993, Distler & Kunilov 1994, Tvrdý & Kolesar 1995). Some 280 mineral species are known from Noril'sk, including about 50 or so various platinum-group minerals and incompletely characterized phases. No other deposit is the type locality for such a wide number of PGM, many of which have not been reported from other deposits.

Description of the Sample

The material investigated is an extremely PGM-rich and particularly spectacular sample of massive ore from the Talnakh deposit, consisting of massive talnakhite with macro-scale subgraphic intergrowths of both galena and pentlandite (Figs. 1a, b). It was collected from the –720 level of the Oktyabr' mine, close to the upper contact of Cu–Ni–PGE-rich ore lens with the gabbroic intrusion, and was kindly donated to the authors by Mr. Vladimir S. Balbin (Noril'sk Nickel Company). Galena-rich ores from Noril'sk are almost always strongly enriched in PGE and commonly contain several hundred ppm PGE (total) or even more. Several rare PGM have been found for the first time in such ores (Genkin *et al.* 1981). The sample matrix, <90% of the sample, is composed of massive talnakhite, $Cu_9(Fe,Ni)_8S_{16}$, with subordinate galena, pentlandite and mooihoekite, $Cu_9Fe_9S_{16}$, in a series of unmixing and symplectitic intergrowths textures (Figs. 1a–d). Oval blebs of galena up to 1 cm in size and subhedral grains of pentlandite 1–2 mm in size are set within talnakhite. Both appear to represent unmixing from talnakhite or a higher-temperature Cu–Fe sulfide, but blebs of galena characteristically overprint the bodies of pentlandite (Fig. 1d). Small, elongate grains of djerfisherite, the K- and Cl-bearing sulfide, $K_6(Fe,Cu,Ni)_{25}S_{26}Cl$, are associated with galena or PGM or both. Sphalerite and chalcopyrite are accessory phases.

The PGM are associated with rounded, elongate or lobate intergrowths, 1–16 mm in length, consisting dominantly of a symplectite of altaite, PbTe, and sobolevskite, Pd(Bi,Te) (Fig. 1e). Abundant domains of Ag–Au alloy, as rims and veinlets <50 μm in size, surround the PGM and are found within talnakhite close to the PGM intergrowths as a characteristic part of the assemblage (Fig. 1f). The symplectitic intergrowths of altaite, showing a recognizable bright cream-grey color and faint greenish tint against talnakhite, and pale orange-pinkish sobolevskite (Fig. 2a), indicate cocrystallization of the two minerals. Margins against talnakhite are, however, generally free of sobolevskite. Rounded and elongate grains, typically 80–300 μm in diameter, of a reddish brown phase, with distinct reflectance pleochroism (reddish to chocolate brown), strong anisotropy (tan to dark brown with violet tints) and a hardness exceeding that of altaite or sobolevskite occur at the margin of the symplectite against talnakhite (Fig. 2b). These have a composition approximating to $(Pd,Pt,Cu)_3Sn$ (*i.e.*, taimyrite; see Discussion). Native silver is common at margins between sobolevskite and altaite (Fig. 2c) and throughout the talnakhite matrix. Sobolevskite with inclusions of altaite and Ag–Au alloy also are found as rounded blebs, protruding or enclosed within galena, with flaky grains of talnakhite marking the margin of the blebs (Fig. 3a). Microscopic (<5 μm), pink, needle-shaped grains of a Pt–Cu–Fe alloy (see below) are located within altaite on the outermost margin of the intergrowths (Figs. 2d, 3b–f). Other minerals present in the assemblage in minor amounts are froodite ($PdBi_2$) and sperrylite ($PtAs_2$), the latter showing a deep grey color against altaite. Smaller domains of PGM occur throughout the talnakhite matrix and as rounded inclusions in galena. In such intergrowths, sobolevskite is dominant. More rarely, a Pb-bearing phase, either plumbian sobolevskite or polarite, also is present. Grains of a grey-brown mineral less than 20 μm across, tentatively identified as telargpalite, $(Pd,Ag)_3Te$ (Kovalenker *et al.* 1975), occur intimately intergrown with sobolevskite and native silver. Paolovite, Pd_2Sn (Genkin *et al.* 1975) is a trace constituent of some PGM intergrowths (Figs. 3e, f). Both are intergrown with sobolevskite in assemblages in which taimyrite is absent.

Electron-Probe Micro-Analyses

Electron-probe micro-analyses were carried out with a CAMECA SX–50 instrument at the Mineralogical Institute, Würzburg, Germany. The following standards and radiations were used: pure Bi ($M\alpha$), pure Pt ($M\alpha$), pure Pd ($L\alpha$), PbS (Pb$M\alpha$), FeS_2 (Fe$K\alpha$, S$K\alpha$), pure Cu ($K\alpha$), ZnS (Zn$K\alpha$), pure Ni ($K\alpha$), pure Co ($K\alpha$), pure Te ($L\alpha$), pure Se ($L\alpha$), pure Ag ($L\alpha$), pure Au ($M\alpha$), Sb_2S_3 (Sb$L\alpha$), and SnO_2 (Sn$L\alpha$). No other elements were detected in any of the minerals analyzed. Beam current and accelerating voltage were set at 15 nA and 15 kV, respectively. Beam size was 1–2 μm, with minimum limits of detection of about 0.05 wt.% for all elements. Mineral grains and standards were analyzed under the same operating conditions.

Mean compositions of talnakhite and pentlandite are $Cu_{9.03}(Fe_{7.58}Ni_{0.30})_{\Sigma 7.88}S_{15.98}$ and $Fe_{4.70}Ni_{3.86}Co_{0.11}Cu_{0.10})_{\Sigma 8.77}S_{8.00}$, respectively. Galena compositions are close to being stoichiometric, PbS, but minor Bi, Sb, Se and Te were nevertheless present in all cases. Compositional variation in altaite is equally restricted; compositions are close to being stoichiometric, except for small amounts of Cu, Fe, Ag, Zn, Sb, Sn, Bi and Se, close to minimum limits of detection, in some grains (Table 1). Native silver (mean $Ag_{95.3}Au_{4.7}$) and Ag–Au alloy (mean $Ag_{61.8}Au_{38.2}$) were found not to contain admixtures of Cu, Pt, Pd, Bi or Te.

Analytical results on 44 grains of sobolevskite are summarized in Table 2 and show a range in compositions along the PdBi–PdTe join (Fig. 4). Compositions of the reddish brown phase are close to $(Pd,Pt)_{2.1}Cu_{0.9}Sn$ (Table 3). Compositions of the Pd(Bi,Pb) phase and of the Pt–Cu–Fe alloy are given in Table 4. Because of the very fine grain-size and intergrown character of the latter, the majority of the 26 analyses included some Pb, Te and Bi from adjacent minerals. Exceptions are the two analyses in Table 4, which are both close to Pt_2FeCu. The compositions of other minerals are not tabulated, as these were found to be close to stoichiometry.

Reflectance Data

Reflectance spectra (Fig. 5) were collected for a grain of taimyrite with the composition $(Pt_{1.55}Pd_{0.60}Cu_{0.85})_{\Sigma 3}Sn$, using instrumentation similar to that described by Bernhardt (1987): a Leitz Orthoplan microscope and Hamamatsu R1477 photomultiplier system. A Zeiss WTiC standard was used in air and immersion oil (DIN 58.884). Our data compare reasonably well with earlier data for taimyrite (Begizov *et al.* 1982). However, we note a tight fit both to tatyanaite (Barkov *et al.* 2000b) and also to cabriite (Evstigneeva & Genkin 1983), showing that reflectance data can hardly be considered diagnostic among stannides of the stannopalladinite group.

Discussion

Pd(Bi,Te)

Since there exist hexagonal, orthorhombic and monoclinic polymorphs of PbBi (Bhatt & Schubert 1979, Genkin *et al.* 1981, Bayliss 1990), it is impossible to say, with total certainty, that the studied grains are indeed members of the sobolevskite–kotulskite series. However, on the basis of optical properties, a tentative identification can nevertheless be made. Indeed, Bayliss (1990) proposed that an admixture of a monoclinic polymorph might explain unindexed reflections in the original description of sobolevskite (Evstigneeva *et al.* 1975).

Compositions display a limited range of Bi/(Te + Bi + Pb + Sb + Sn) values, from 0.671 to 0.779 (Fig. 4), within the solid solution between kotulskite (PdTe) and sobolevskite (PdBi). Such a relationship was documented in the original description of sobolevskite (Evstigneeva *et al.* 1976), in which a range of compositions from stoichiometric PdBi to close to end-member kotulskite, PdTe, was reported. Later references to kotulskite and sobolevskite corroborated the existence of a complete solid-solution, with a broad compositional field between the two phases identified in several dozen publications (*e.g.*, Cabri & Laflamme 1981, Vuorelainen *et al.* 1982, Tarkian 1987, Beaudoin *et al.* 1990, Mulja & Mitchell 1990, Trofimov *et al.* 1990, Grokhovskaya *et al.* 1992, Yakovlev *et al.* 1991, Barkov & Lednev 1993, Coghill & Wilson 1993, Farrow & Watkinson 1997, Shvedov *et al.* 1997, Halkoaho *et al.* 1998, Mitrofanov *et al.* 1998). Li & Naldrett (1993a) reported the occurrence of Te-free sobolevskite, *i.e.*, the end member, from the Strathcona deposit, Sudbury, Ontario. Compositions approaching Bi/(Te + Bi) = 0.5, *i.e.*, near the boundary between kotulskite and sobolevskite, have been reported from Blue Lake, Labrador Trough, Quebec (Beaudoin *et al.* 1990) and the Burakovsky Complex, Karelia (Trofimov *et al.* 1990). Kotulskite and sobolevskite are both hexagonal, with comparable unit-cell parameters (*a* 4.19, 4.23; *c* 5.67, 5.69 Å, respectively). Evstigneeva *et al.* (1975) reported similar X-ray data, hardness and reflectance spectra for the two end-members.

Although not named as such, and as pointed out by Beaudoin *et al.* (1990), unnamed minerals UN 1976–5, UN 1973–18, and possibly also UN 1979–1 (Cabri 1981b) plot close to the solid-solution join in Pd–Te–Bi space, with UN 1973–18 (Razin *et al.* 1975) being close

TABLE 1. COMPOSITIONS OF GALENA AND ALTAITE, NORIL'SK OREFIELD, RUSSIA

	Galena			Altaite		
	Mean n = 5	Max.	Min.	Mean n = 17	Max.	Min.
Cu wt.%	-	-	-	0.28	0.61	-
Fe	-	-	-	0.07	0.38	-
Ag	-	-	-	-	0.12	-
Zn	-	-	-	-	0.13	-
Pb	85.91	86.33	85.33	61.33	62.02	60.40
Sb	0.09	0.17	-	0.32	0.60	-
Sn	-	-	-	0.07	0.38	-
Bi	0.33	0.48	0.19	0.10	0.31	-
S	12.98	13.03	12.92	-	-	-
Te	0.73	0.95	0.55	37.33	37.98	35.84
Se	0.13	0.15	0.11	0.06	0.29	-
Total	100.17			99.56		

Note: - indicates below minimum detection limit (0.05 wt.%).

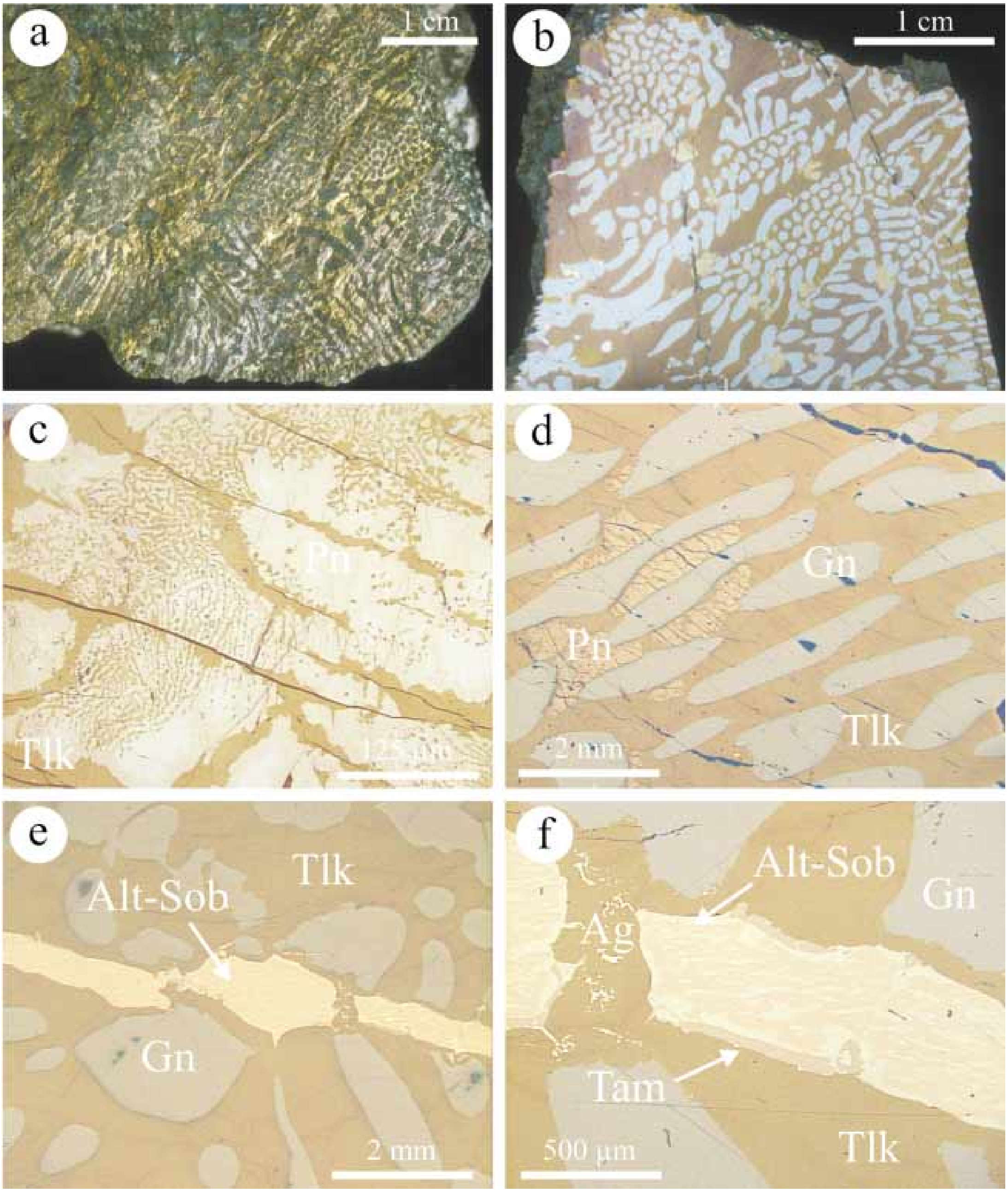

FIG. 1. (a) Massive talnakhite – galena – pentlandite – PGM ore. Subgraphic intergrowth of galena (dark) and talnakhite on unpolished surface. (b) Polished surface of sample showing intergrowth of galena (grey) within tarnished talnakhite (pinkish brown). Minor amounts of pentlandite (yellow) are visible. (c–e) Photomicrographs in reflected light. (c) Symplectitic intergrowth of pentlandite (Pn) in talnakhite (Tlk). (d) Lens-shaped blebs of galena (Gn) in talnakhite (Tlk), overprinting earlier exsolution-induced bodies of pentlandite (Pn). (e) Occurrence of PGM as elongate segregations (Alt–Sob) within talnakhite (Tlk) – galena (Gn) matrix. (f) Detail of area in Figure 2e, showing intergrowths of altaite and sobolevskite, with elongate grains of taimyrite (Tam) along grain margins. Silver (Ag) occurs as irregularly shaped masses at grain margins and in the talnakhite (Tlk) – galena (Gn) matrix.

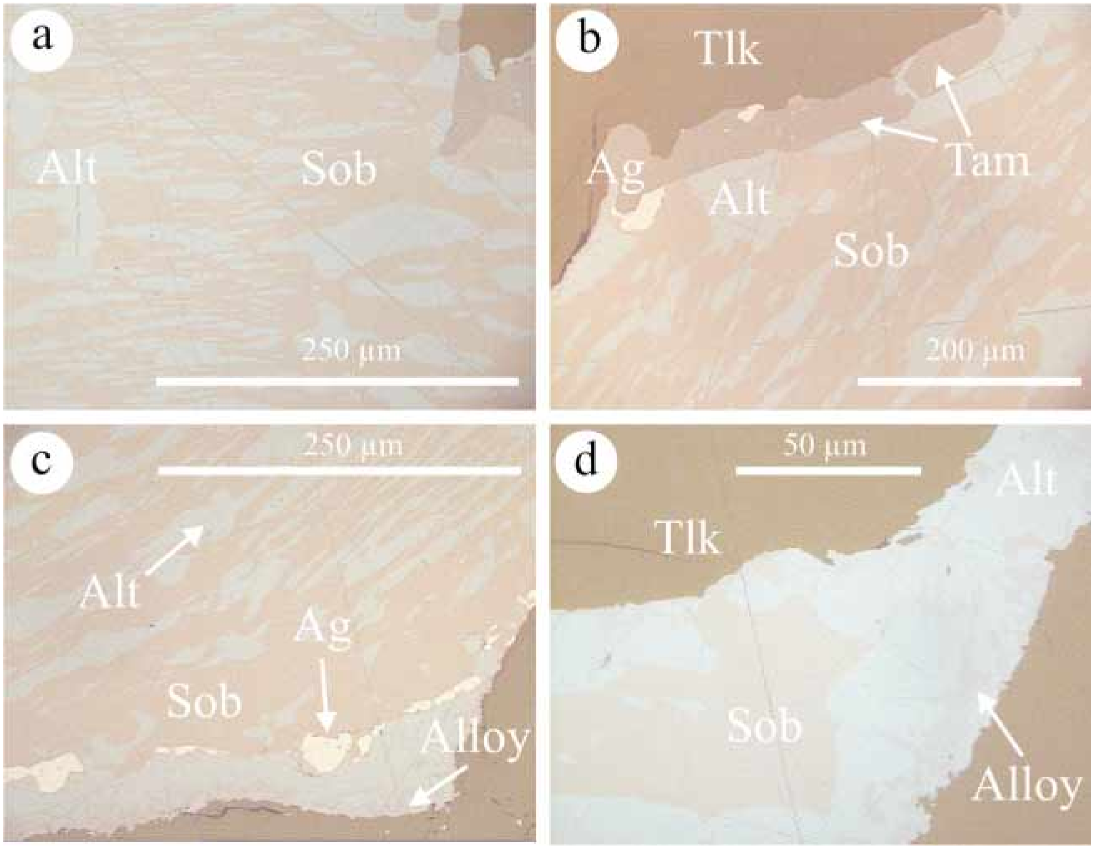

FIG. 2. Photomicrographs in reflected light. (a) Intergrowths of altaite (Alt) and sobolevskite (Sob). (b) Close-up of margin of altaite (Alt) – sobolevskite (Sob) intergrowth, showing elongate grains of taimyrite (Tam) and native silver (Ag). (c) Margin of altaite (Alt) – sobolevskite (Sob) intergrowth showing native silver (Ag) between sobolevskite and altaite and tiny grains of Pt_2FeCu alloy at outer margin. (d) Close-up of the margin of altaite–sobolevskite intergrowths showing needle-shaped pink crystals of Pt_2FeCu.

to end-member sobolevskite. Furthermore, unknown mineral UK2 (Coghill & Wilson 1993), and "polarite" from Messina, Transvaal (Tarkian 1987), are probably also Te-bearing sobolevskite, as is UN 1976–5 (Stumpfl & Tarkian 1976), which also contains significant Sb.

There would appear to be complete solid-solution between kotulskite and sudburyite (PdSb; Cabri & Laflamme 1974), which shares hexagonal symmetry and belongs to the same space group as kotulskite and sobolevskite. Natural members of the series containing Sb (either stiboan sobolevskite or stiboan kotulskite or bismuthoan sudburyite) have been reported in several studies (*e.g.,* Evstigneeva *et al.* 1976, Edgar *et al.* 1989, Tolstykh *et al.* 1997). Dobrovol'skaya *et al.* (1985) reported compositions intermediate in the PdBi–PdSb series, containing 19.01 and 27.13 wt.% Sb (two point analyses). In turn, sudburyite may contain up to 15 wt.% combined (Te + Bi) (Cabri & Laflamme 1981). In the present study, Sb contents do not exceed 1.7 mol.% PdSb.

Most grains of sobolevskite analyzed in this study contain significant Pb (up to 3.44 wt.% in sobolevskite associated with altaite, although back-scattered electron images did not reveal intergrowths at the submicrometer scale). A distinctly Pb-rich variety, either plumboan sobolevskite or polarite, is also noted (Table 4). Questions of nomenclature among these minerals have been addressed by Evstigneeva & Genkin (1990), who distinguished two end-members, informally labeled "plumbopolarite" (PdPb) and "bismuthopolarite" (PdBi).

Kovalenker *et al.* (1973) documented comparable levels of substitution of Pb for (Bi,Te) in kotulskite from Noril'sk. Varieties appreciably richer in Pb, containing up to 9.5 wt.% Pb, were reported by Watkinson & Ohnenstetter (1992). In the absence of structural data, it is impossible to identify these phases with full certainty,

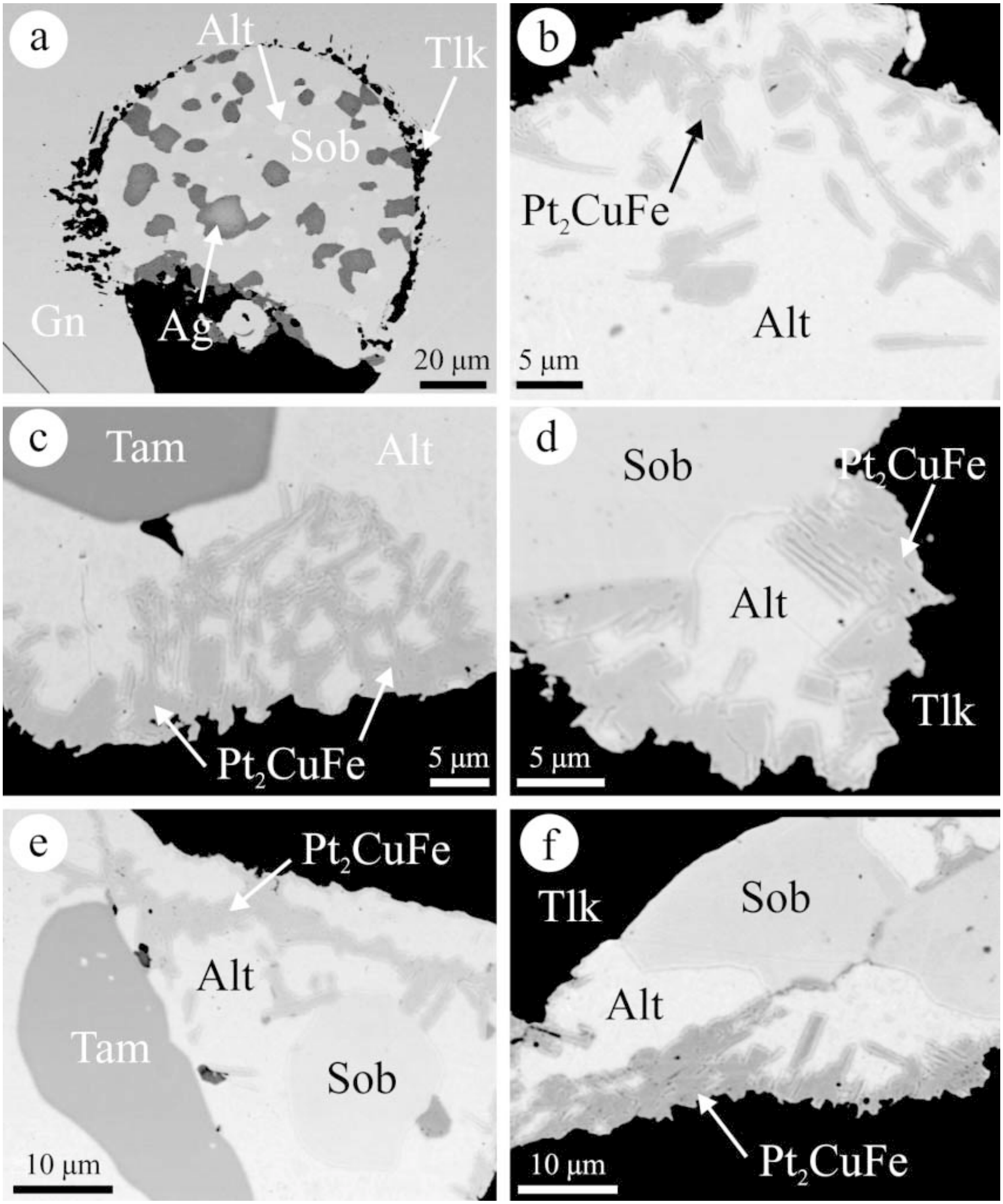

FIG. 3. Back-scattered electron images. (a) Rounded bleb of sobolevskite (Sob) within galena (Gn), containing inclusions of altaite (Alt) and native silver (Ag). Margins between sobolevskite and galena are marked by talnakhite (Tlk). (b)–(f) Skeletal, prismatic and needle-shaped aggregates of Pt_2CuFe alloy (tulameenite?) enclosed within altaite, close to the outer margin of the intergrowths with talnakhite. Sob: sobolevskite, Alt: altaite, Tam: taimyrite.

owing to the existence of polymorphs and as yet incompletely defined solid-solution series in the Pd–Bi–Te–Pb system. Polarite [Pd(Bi,Pb)] (Genkin *et al.* 1969) is orthorhombic and isostructural with synthetic PdBi (Yushko-Zakharova *et al.* 1974). Pt-bearing varieties of sobolevskite also have been reported [*e.g.*, $(Pd_{0.67}Pt_{0.29}Fe_{0.11})_{\Sigma 1.07}(Bi_{0.70}Sb_{0.23})_{\Sigma 0.93}$: Rudashevsky *et al.* 1992], yet the extent of solid solution toward Pt end-members is unknown. In addition, evidence of a solid solution between Pd(Te,Bi) toward NiTe, in an undetermined crystal system, also has been presented (*e.g.*, Cabri & Laflamme 1976, Marchetto 1990).

TABLE 2. COMPOSITIONS OF SOBOLEVSKITE, NORIL'SK OREFIELD, RUSSIA

	1 Mean	Max.	Min.	2	3	4	5	6	7	8
Pd wt.%	35.47	36.55	34.29	35.55	34.85	34.56	35.16	35.04	36.55	36.10
Pt	0.11	0.57	-	0.18	0.34	0.21	-	-	-	-
Ni	-	0.11	-	-	0.10	-	-	-	-	-
Cu	0.12	0.49	-	-	-	-	-	0.17	0.14	0.19
Zn	-	0.21	-	-	-	-	0.21	0.10	-	-
Pb	2.10	3.44	1.09	3.44	1.10	1.31	3.18	2.22	2.10	1.34
Sb	0.09	0.44	-	-	0.15	0.11	-	-	-	0.19
Sn	0.11	0.67	-	0.16	-	-	-	0.12	0.17	-
Bi	54.14	61.90	47.57	48.14	59.94	56.55	53.94	54.04	51.73	53.56
Te	7.65	12.15	3.03	12.15	3.54	6.15	7.42	8.45	9.99	8.97
Total	99.79			99.62	100.02	98.89	99.91	100.14	100.68	100.35

Formulae: 1. $(Pd_{1.00}Cu_{0.01})_{\Sigma 1.01}(Bi_{0.78}Te_{0.18}Pb_{0.03}Sb_{0.005}Sn_{0.005})_{\Sigma 1.00}$
2. $(Pd_{0.972}Pt_{0.003})_{\Sigma 0.975}(Bi_{0.67}Te_{0.28}Pb_{0.05})_{\Sigma 1.00}$
3. $(Pd_{1.02}Pt_{0.01})_{\Sigma 1.03}(Bi_{0.89}Te_{0.15}Pb_{0.02})_{\Sigma 1.00}$
4. $Pd_{1.00}(Bi_{0.83}Te_{0.15}Pb_{0.02})_{\Sigma 1.00}$
5. $(Pd_{1.00}Zn_{0.01})_{\Sigma 1.01}(Bi_{0.78}Te_{0.17}Pb_{0.05})_{\Sigma 1.00}$
6. $(Pd_{0.98}Cu_{0.01}Zn_{0.01})_{\Sigma 1.00}(Bi_{0.77}Te_{0.20}Pb_{0.03})_{\Sigma 1.00}$
7. $(Pd_{1.02}Cu_{0.01})_{\Sigma 1.03}(Bi_{0.73}Te_{0.23}Pb_{0.03})_{\Sigma 1.00}$
8. $(Pd_{1.01}Cu_{0.01})_{\Sigma 1.02}(Bi_{0.76}Te_{0.21}Pb_{0.02}Sb_{0.01})_{\Sigma 1.00}$
Column 1: mean composition ($n = 47$); columns 2–8 list representative compositions; - indicates below minimum detection limit (0.05 wt.%).

TABLE 3. COMPOSITIONS OF "TAIMYRITE", NORIL'SK OREFIELD, RUSSIA

	1 Mean	Max.	Min.	2	3
Pd wt.%	36.34	38.27	35.37	37.01	35.77
Pt	26.15	24.63	22.49	24.06	25.15
Cu	11.73	12.16	11.11	12.26	11.65
Zn	0.01	0.13	-	0.13	-
Sn	24.93	25.38	24.41	25.04	25.15
Bi	0.01	0.10	-	-	-
Te	0.49	0.36	0.14	0.18	0.36
Se	0.17	0.28	0.11	0.21	0.28
Total	97.84			98.89	98.36

Formulae: 1. $(Pd_{1.58}Cu_{0.85}Pt_{0.57})_{\Sigma 3.01}(Sn_{0.97}Te_{0.02}Se_{0.01})_{\Sigma 1.00}$
2. $(Pd_{1.62}Cu_{0.90}Pt_{0.57}Zn_{0.01})_{\Sigma 3.10}(Sn_{0.98}Te_{0.01}Se_{0.01})_{\Sigma 1.00}$
3. $(Pd_{1.54}Cu_{0.84}Pt_{0.59})_{\Sigma 2.97}(Sn_{0.97}Se_{0.02}Te_{0.01})_{\Sigma 1.00}$
Column 1: mean composition ($n = 15$); columns 2–3 list representative compositions. - indicates below minimum detection limit (0.05 wt.%).

Taimyrite

The analyzed phase $(Pd, Pt)_{2.1}Cu_{0.9}Sn$ bears a close resemblance to taimyrite, [$(Pd,Cu,Pt)_3Sn$; Begizov & Sluzhenikin (1976), Cabri (1976), Begizov *et al.* (1982); a revised formula, $(Pd,Pt)_9Sn_4Cu_3$, was given by Evstigneeva & Nekrasov (1984) for synthetic taimyrite], recently redefined as the Pd end-member of the taimyrite–tatyanaite solid-solution series (Barkov *et al.* 2000a, b). In fact, the mean composition, $(Pd_{1.58}Cu_{0.85}Pt_{0.57})_{\Sigma 3.00}Sn$, is nearly identical to that reported by Barkov *et al.* (2000a) from the Oktyabr' deposit (anal. 25 in their Table 3). However, the micro-analytical results are not sufficiently diagnostic by themselves, as taimyrite forms at least a partial solid-solution series with cabriite (Pd_2CuSn; Evstigneeva & Genkin 1983), which it closely resembles both compositionally and structurally (Barkov *et al.* 2000a), and also with stannopalladinite [$(Pd,Pt)_5Sn_2Cu$; Evstigneeva & Nekrasov 1984]. X-ray data are needed to establish the identity of Pd–(Pt)–Cu stannides (the stannopalladinite group) and establish precise stoichiometry and compositional limits.

Pt_2FeCu (tulameenite?)

The composition Pt_2FeCu is identical to that given for tulameenite (Cabri *et al.* 1973), a mineral described from various placer deposits, from ultramafic rocks in the Tulameen Complex, British Columbia, in the Ural Mountains, and elsewhere, but to our knowledge, not previously reported from Noril'sk–Talnakh. The properties and paragenetic position of the Pt_2FeCu phase in this sample, in particular the occurrence as acicular and prismatic exsolved crystals in altaite, against which it displays a slight pink tint, are somewhat at odds with

TABLE 4. COMPOSITIONS OF Pt_2CuFe AND Pd(Bi,Pb), NORIL'SK OREFIELD, RUSSIA

	Pt_2CuFe		Pd(Bi,Pb)	
	1	2	3	4
Pd wt.%	1.08	0.24	34.65	33.62
Pt	72.55	74.08	-	-
Ni	1.22	0.61	-	-
Cu	12.90	10.47	-	-
Fe	11.09	13.18	-	0.22
Pb	-	-	18.34	18.20
Sb	-	-	-	-
Sn	-	-	0.12	-
Bi	-	-	44.47	44.94
Te	-	-	0.23	0.14
Total	98.84	98.58	97.81	97.12

Formulae: 1. $(Pt_{1.85}Ni_{0.10}Pd_{0.05})_{\Sigma 2.00}Cu_{1.01}Fe_{0.99}$
2. $(Pt_{1.94}Ni_{0.05}Pd_{0.01})_{\Sigma 2.00}Cu_{0.84}Fe_{1.20}$
3. $Pd_{1.07}(Bi_{0.70}Pb_{0.29}Te_{0.01})_{\Sigma 1.00}$
4. $(Pd_{1.04}Fe_{0.01})_{\Sigma 1.05}(Bi_{0.71}Pb_{0.29}Te_{0.01})_{\Sigma 1.01}$
Note: - indicates below minimum detection limit (0.05 wt.%).

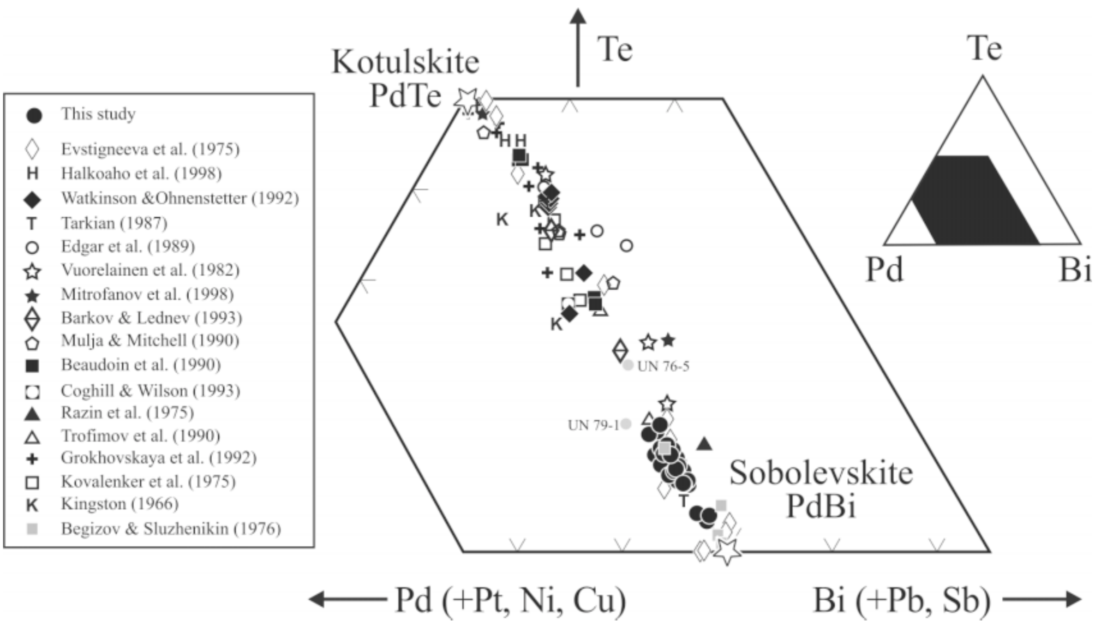

FIG. 4. Compositions of analyzed Pd(Te,Bi) phases plotted in Pd–Te–Bi space, compared to data in the original description of sobolevskite (Evstigneeva *et al.* 1975) and to other published compositional data for kotulskite and sobolevskite. UN–76–5 and UN–79–1 refer to compositions discussed by Cabri (1981b).

the original description of tulameenite (Cabri *et al.* 1973), in which altaite was not present. Cabri & Genkin (1991) noted that tulameenite is a secondary mineral formed during the serpentinization of ultramafic rocks, and usually found as a rim on primary platinum alloys, but that it occurs both in the lode deposits and within placers derived from such deposits. The occurrence in the present samples, exsolved at the margins of altaite–sobolevskite intergrowths, also contrasts with phase-equilibrium studies indicating crystallization directly from a magma (>1178°C) and "not by later processes at lower temperatures" (Shahmiri *et al.* 1985). The small size and intergrown character of the grains have not permitted extraction for a structural study to show conclusively that the Pt_2FeCu phase is indeed tulameenite.

CRYSTALLIZATION HISTORY, TEXTURES, EXSOLUTION AND PARAGENESIS

The crystallization history of the assemblage is undeniably complex, and the large number of components (Pt–Pd–Bi–Te–Pb–Ag–Au–Sn–Cu–Fe–Ni–S–Te) precludes the application of phase equilibria within relatively simple binary or ternary systems, in which phase relationships are well constrained. Kovalenker *et al.* (1980) described subgraphic galena-rich segregations within massive ore from Talnakh–Oktyabr' as forming near-spherical bodies, some cm or tens of cm in size, in the upper parts of massive ore, close to the contact with gabbro dolerites. Temperatures as high as 820–840°C were invoked from the occurrence of glass formed by melting of minerals along the contact (Kovalenker *et al.* 1980). Conventional opinion has been that these spherical bodies, in which a wide variety of incompatible elements (PGE, together with Bi, Te, Pb, among others) are trapped, formed directly from a residual liquid. Phase relationships in the system Cu–Fe–Pb–S (Craig & Kullerud 1967, Toguzov *et al.* 1980) certainly suggest temperatures as high as 800°C for droplet-like unmixing of galena. Subsequent crystallization of intermediate solid-solution at *ca.* 600°C allowed droplets rich in exotic elements (Pt–Pd–Bi–Te–Ag–Au–Sn) to form. Evstigneeva (1989) attributed such assemblages to a temperature range of 450–200°C, arguing that some elements may have been supplied by hydrothermal solutions during post-magmatic transformations of the ore. Observed textures can thus be considered as the results of sequential exsolution as the ore continued to cool. Hydrothermal solutions, related to residual fluids, can also play a significant role in reconcentration in PGE deposits (*e.g.*, Li & Naldrett 1993b), or remobilize PGE and other elements well after crystallization of sulfide and silicate magmas (*e.g.*, Watkinson & Jones 1996). The association of PGM with chlorine-bearing phases

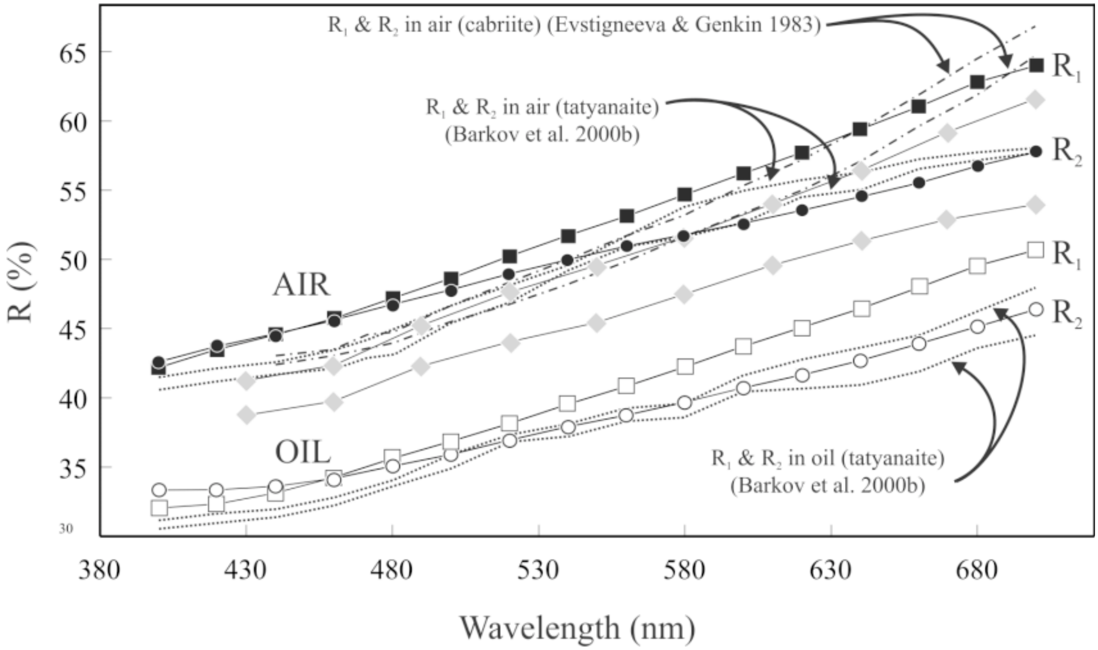

FIG. 5. Reflectance spectra for a taimyrite grain with the composition $(Pt_{1.55}Pd_{0.60}Cu_{0.85})_{\Sigma 3}Sn$ in air (filled circle and square) and oil (white circle and square). For comparison: published reflectance data for taimyrite (grey diamonds; R_1 and R_2; Begizov *et al.* 1982), tatyanaite (dotted lines; R_1 and R_2 in air and oil; Barkov *et al.* 2000b) and cabriite $Pd_{2.04}(Sn_{0.91}Sb_{0.07})_{\Sigma 0.98}Cu_{0.98}$ as broad dashed line (Evstigneeva & Genkin 1983).

has been used as indirect evidence for a late, relatively low-temperature (<400°C) genesis from late volatile-rich fluids (*e.g.*, Li & Naldrett 1993b).

CONCLUSIONS

Coarse symplectitic intergrowths of altaite and sobolevskite occur within a matrix of talnakhite in an assemblage displaying a complex history of exsolution as the ore cooled, either from magmatic temperatures, or from a later hydrothermal event. The textures reflect a protracted series of sequential unmixing and exsolution events. Extensive solid-solution along the kotulskite–sobolevskite join is documented, with broad variation in the ratio Bi/Te. An intermediate member of the taimyrite–tatyanaite series with a composition $(Pd_{1.5}Pt_{0.6}Cu_{0.85})_{\Sigma 3}Sn$ is a common component of such intergrowths, occurring at the margin of altaite–Pd(Bi,Te) symplectites. A Pt–Cu–Fe alloy occurs as small crystals at the outer margin of the altaite. This is probably the first report of a phase with the composition of tulameenite from Noril'sk.

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