

Bortnikovite, $\text{Pd}_4\text{Cu}_3\text{Zn}$, a New Mineral Species from the Unique Konder Placer Deposit, Khabarovsk Krai, Russia¹

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Abstract—Bortnikovite, a new mineral species that is an intermetallic compound of Pd, Cu, and Zn with the simplified formula $\text{Pd}_4\text{Cu}_3\text{Zn}$ has been detected at the unique Konder placer deposit in the Ayan–Maya district, Khabarovsk krai. The primary source of this placer is a concentrically zoned alkaline ultramafic massif. The X-ray diffraction pattern is indexed on the assumption of a tetragonal unit cell: $a = 6.00 \pm 0.02 \text{ \AA}$ and $c = 8.50 \pm 0.03 \text{ \AA}$, $V = 306 \pm 0.01 \text{ \AA}^3$, $Z = 3$, probable space group $P4/mmm$. The calculated density is 11.16 g/cm^3 ; the mean microhardness VHN is 368 kg/mm^2 . In reflected light, the new mineral is white with a slight grayish beige tint; birefractance, anisotropy, and internal reflections are not observed. The reflectance spectrum belongs to the concave group of the anomalous type. The measured values of reflectance are as follows: 56.9 (470 nm), 61.7 (546 nm), 63.4 (589 nm), and 65.4% (650 nm). The new mineral is intergrown with isoferroplatinum, titanite, perovskite, V-bearing magnetite, bornite, and chlorite. The origin of bortnikovite is related to the effect of alkaline fluid on ultramafic rocks. The new mineral is named in honor of Professor Nikolai Stefanovich Bortnikov, a prominent mineralogist and researcher of ore deposits and a corresponding member of the Russian Academy of Sciences. Bortnikovite is the first platinum group mineral that contains Zn as a major mineral-forming element.

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INTRODUCTION

The Konder PGM placer deposit, in the Ayan–Maya district of Khabarovsk krai, was discovered and explored in 1979–1988 by the Ayan–Maya Geological Exploration Expedition (V.E. Krot, A.G. Mochalov, G.D. Malykh, L.O. Sakh'yanov, S.T. Gimadeev, S.A. Lushev, L.K. Sagnaev, and others). The first information on economic PGE mineralization in the upper tributaries of the Konder River was obtained in 1958 by the Aldan Expedition of the All-Union Aerogeological Trust (A.N. Mil'to and A.A. El'yanov). In 1985, the Amur prospectors' team commenced operation of this deposit.

In degree of geological complexity, the Konder placer deposit (Fig. 1) pertains to the second group. This is a large alluvial placer relatively consistent in length and width with a nonuniform distribution of ore components (*Methods...*, 1992). The placer, 60 km in length (including tributaries of the first, second, and third orders at the headwaters of the Konder River) and

approximately 360 m in width, is located in the Konder and Uorgalan valleys of the fourth to fifth orders. PGM-bearing sands are hosted in near-gutter parts of Pliocene to Lower Pleistocene, Middle Pleistocene, Upper Pleistocene, and Holocene alluvial sediments of valleys, terraces, and terrace ridges. The mean thickness of the PGE-bearing sands at the deposit is 2.4 m; the overburden is 5.5 m thick. The mean PGM grade of sands is 2–5 g/m³. In PGM composition of heavy concentrate, the placer may be classed as the iridium–platinum and subordinate platinum mineralogical–geochemical types. The head of the placer is located at the site of its primary source, which is the eroded Konder alkaline ultramafic massif (Mochalov, 1997; Mochalov and Khoroshilova, 1998).

The Konder alkaline ultramafic massif comprises Neoproterozoic ultramafic rocks and a superimposed Mesozoic monzodiorite igneous complex (Fig. 1); both cut through the Archean crystalline basement and the Neoproterozoic sedimentary cover of the Aldan Shield. The long-term geological evolution of the Konder massif, including the tectonomagmatic activation of the Aldan Shield, was accompanied by formation of diverse metasomatic rocks (Bogomolov, 1968) and recrystallization of ultramafics (Yarosh and Tsaritsyn, 1976; Yarosh, 1980).

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The main primary source of PGM is dunite, which is inhomogeneous in composition (variable contents of Fe, Ca, and Ni) and grain size of olivine, distribution and composition of chrome spinel, and degree of recrystallization. The first-order lateral concentric zoning is expressed in the change of the marginal contact zone of fine-grained dunite to the porphyritic, medium- to coarse-grained dunite at the massif's core. The fine-grained dunite is enriched in Fe and Ca and contains uniformly distributed fine (0.1–0.25 mm), very fine (0.05–0.1 mm), and powderlike (<0.05 mm) PGM fractions in the front of the porphyritic dunite core. These fractions are regarded as the magmatic placer-forming platinum assemblage (Fig. 1).

The highest PGM concentrations were detected within the contact zone of medium- to coarse-grained dunite formed as a product of recrystallization of the pegmatoid variety. The largest segregations of isoferroplatinum (nuggets) and morphologically diverse impregnated and veined clots of chromitite and euhedral metacrysts of chrome spinel occur in this zone.

This second-order inhomogeneity has a mosaic-block character, and the PGM involved make up a placer-forming iridium–platinum assemblage of fluid–metamorphic genesis (Fig. 1). The placer-forming PGM segregations of the Ir–Pt type from the Konder Massif are products of fluid–metamorphic recrystallization of dunite affected by multiple younger intrusions. The placer-forming potential is determined by the PGE fractionation from magmatic melt and the subsequent fluid concentration of PGE in the course of recrystallization of solid rocks. As a result, the Ir–Pt and Pt types of PGM are juxtaposed in the Konder placer. In addition, primary PGE mineralization has been established in pyroxenite, kosvite, alkaline pegmatite, titanomagnetite–biotite–amphibole–clinopyroxene metasomatic rock, and sulfide–malachite segregations (*Geology* ..., 1994; Mochalov, 2001, 2005).

The Konder alkaline ultramafic massif is surrounded by a ring range that towers above the Omnya–Maya tableland by 400–500 m (Fig. 1, section). This range is a result of intrusive and protrusive doming, currently continuing and combined with selective weathering and erosion of alkaline and ultramafic rocks. The outer range is composed of Archean and Proterozoic rocks, whereas the inner depression is occupied by plutonic rocks. The inner slopes of the range and the depression are drained by streams of the first to fourth orders that make up a centripetal system with the valley of the Konder and Uorgolan rivers as a common outlet (Mochalov and Khoroshilova, 1998).

The PGM heavy concentrate at the Konder deposit consists mainly of monomineralic segregations of isoferroplatinum. An insignificant amount of isoferroplatinum occurs as single crystals or twins; sperrylite, laurite, and native osmium are very rare. Minor PGM (tetraferroplatinum, tulameenite, native iridium, and native osmium) and more than 35 rare species occur as inclu-

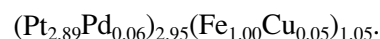
sions hosted in or intergrown with isoferroplatinum grains (Rozhkov et al., 1962; Mochalov et al., 1988; Mochalov, 1994, 2001; Makhorkina et al., 1994; *Geology*..., 1994; Nekrasov et al., 1994; Cabri and Laflamme, 1997).

To date, five rare PGM have been described from the Konder placer deposit for the first time: cuproiridsite (CuIr₂S₄); cuprorhodsite (CuRh₂S₄); ferrorhodsite (FeRh₂S₄); konderite (Cu₃PbRh₈S₁₆) (Rudashevsky et al., 1984, 1985, 1998); and an intermetallic compound of Pd, Cu, and Zn with the simplified formula Pd₄Cu₃Zn (this study). The latter mineral species was named bortnikovite in honor of Professor Nikolai Stepanovich Bortnikov, a prominent mineralogist and researcher of volcanic-hosted massive sulfide deposits and modern ore formation at the ocean bottom and a corresponding member of the Russian Academy of Sciences.

MODE OF OCCURRENCE

Bortnikovite was detected within an isoferroplatinum grain (Mochalov et al., 1988; Makhorkina et al., 1994) in a heavy concentrate sample from alluvial boulder–sand–pebble sediments of the first terrace of the left wall of the Konder Valley downstream of the mouth of Pryamoi Creek (Fig. 1). Alluvium of the terrace is enclosed in bedrock composed of magnetite-bearing porphyritic medium-grained dunite with rare veins and schlieren of diopside pyroxenite. Numerous veins of alkaline pegmatites cut dunite. Massive lenticular bodies of titanomagnetite–biotite–amphibole–clinopyroxene metasomatic rock locally occur in dunite.

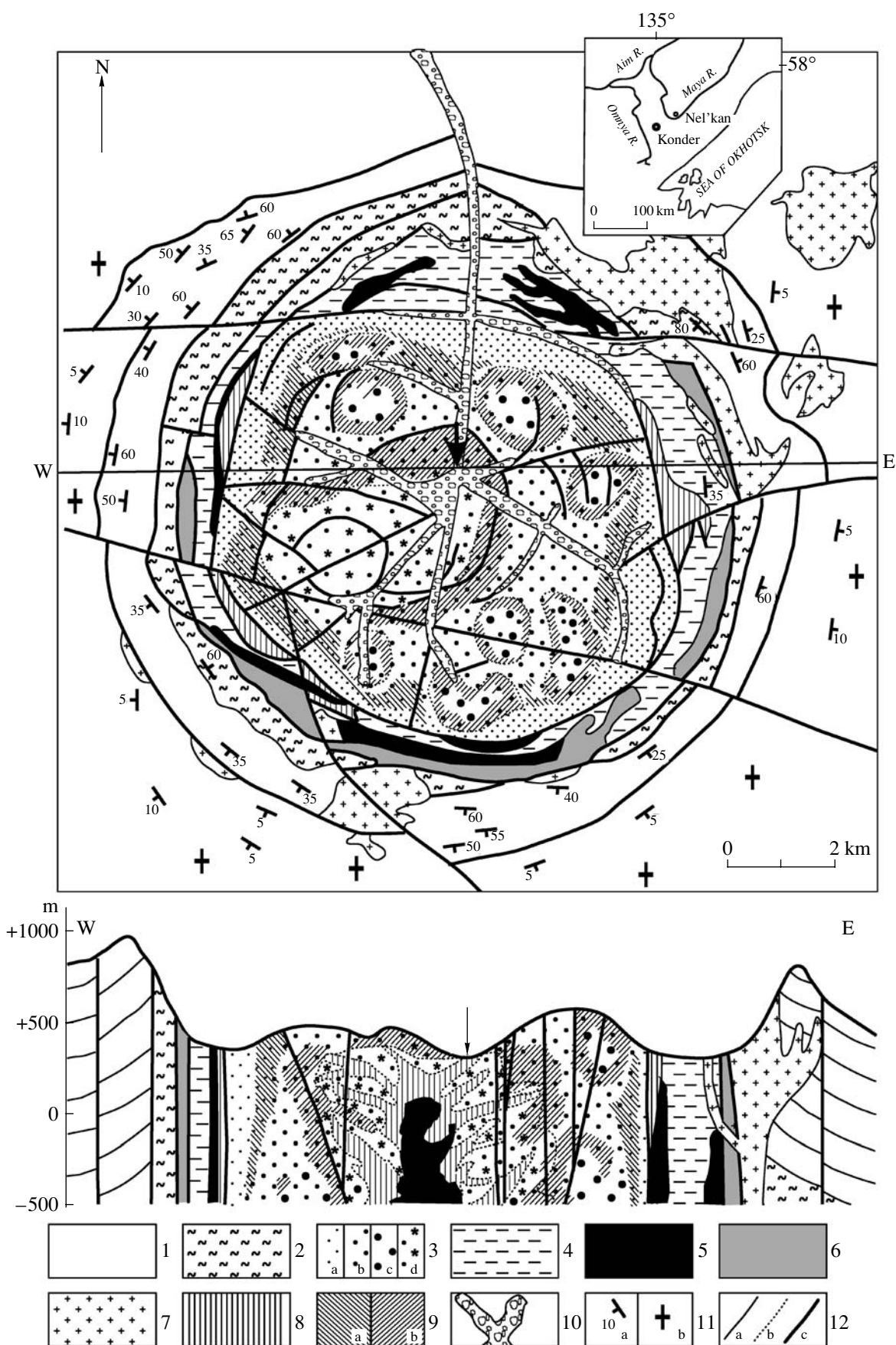
The grain of isoferroplatinum that contains bortnikovite is a tetragonal prism 1.2 × 0.6 × 0.5 mm in size (Fig. 2a). The chemical composition of isoferroplatinum is recalculated to the formula



Isoferroplatinum is overgrown by bortnikovite, which forms a discontinuous outer rim up to 50–60 μm thick. Domains of bortnikovite are 50–150 μm long (Fig. 1). The boundaries between minerals are sharp and straight (Figs. 2b, 2c). Titanite and chlorite are intergrown with bortnikovite and isoferroplatinum (Fig. 2c). Discrete crystals and segregations of perovskite, V- and Ti-bearing magnetite, and bornite have been identified as inclusions in isoferroplatinum (Figs. 2d–2f).

PHYSICAL PROPERTIES

Bortnikovite is steel-white, with a slight cream tint and a metallic luster. The new mineral is opaque. It is poorly malleable and polishes well; cleavage is not observed. Streak color was not determined due to the small crystal size.



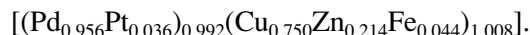
In reflected light, bortnikovite is white with a slight grayish beige tint. It is less bright than isoferroplatinum (Figs. 2, 3; Table 1).

The reflectance of bortnikovite is higher than the mean value; bireflectance, anisotropy, and internal reflections are not observed. The reflectance spectrum (Fig. 3) belongs to the concave group of the anomalous type (Shumskaya, 1985). The reflectance value of bortnikovite is lower than that of native palladium and higher than that of ferronickelplatinum Pt₂NiFe (Fig. 3; Table 1). In its reflectance spectrum, bortnikovite is close to potarite PdHg.

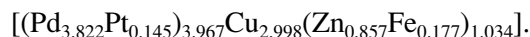
The microhardness VHN measured at three points with a PMT-3 device equipped with an automated indenter with a load of 50 g ranges from 353.8 to 382.0 kg/mm²; the mean value (H_{mean}) is 367.9 kg/mm². Anisotropy of hardness is not observed. Thus, bortnikovite pertains to minerals of medium hardness in the classification proposed by Lebedeva (1977). Among palladium minerals, the microhardness of bortnikovite is close to that of atokite (Pd, Pt)₃Sn and paolovite Pd₂Sn, with H_{mean} of 357 and 380 kg/mm², respectively (Platinum-Group..., 1989).

CHEMICAL COMPOSITION

Electron microprobe study has shown that different domains of bortnikovite are homogeneous and stable in chemical composition (Table 2). All analyses are well calculated on the basis of two atoms Pd(Cu,Zn). The resulting empirical formula calculated from 18 analyses (Table 2) is as follows:



At the same time, the calculation of the available analyses of bortnikovite yields the divisible atomic ratios of crystallochemically cognate chemical elements (Pd + Pt) : Cu : (Zn + Fe) = 4 : 3 : 1. In other words, the formula of bortnikovite is calculated on the basis of eight atoms (Pd₄Cu₃Zn). Thus, the true formula calculated from 18 analyses (Table 2) looks as follows:



All major components probably occupy definite sites in the mineral structure.

Table 1. Optical characteristics of bortnikovite, isoferroplatinum, ferronickelplatinum, native palladium, and potarite

Wavelength (λ), nm	Values of reflectance R, %				
	1	2	3	4	5
400	63.2	56.0	—	—	—
420	57.0	56.8	56.5	62.0	—
440	54.7	57.2	56.4	63.4	57.5
460	55.8	58.5	56.8	64.6	58.1
470	56.9	—	57.0	—	—
480	58.0	59.9	57.4	65.6	58.4
500	59.4	61.0	58.2	66.4	59.0
520	60.5	62.6	58.7	67.2	60.0
540	61.4	64.0	59.0	67.8	61.0
546	61.7	—	59.1	—	—
560	62.2	64.6	59.3	68.3	61.7
580	63.1	65.5	59.7	68.9	62.4
589	63.4	—	60.0	69.1	62.7
600	63.7	66.3	60.2	69.5	63.0
620	64.2	67.1	60.5	70.2	63.8
640	64.8	68.4	60.9	70.9	64.5
650	65.4	—	61.2	—	—
660	65.9	69.6	61.4	71.7	65.4
680	66.9	70.7	62.0	72.5	66.0
700	68.6	71.1	62.8	73.4	66.8

Note: (1) Bortnikovite Pd₄Cu₃Zn, average spectrum on the basis of four points; (2) isoferroplatinum Pt₃Fe intergrown with bortnikovite; (3) ferronickelplatinum Pt₂NiFe (Rudashevsky et al., 1982); (4) native palladium (Pd, Hg); (5) potarite PdHg (Platinum-Group..., 1989). R values were measured with an MSF-10 microspectrophotometer; metallic Si is the standard.

CRYSTALLOGRAPHY

The X-ray study of the new mineral was carried out only with Gandolfi and RKD-57.3 cameras due to the limited amount of material. Material was collected from the surface of a polished section using a sampling device created by L.N. Vyal'sov. The X-ray powder diffraction patterns of the Gandolfi and RKD-57.3 cameras are identical and do not contain a great amount of reflections (Table 3).

Fig. 1. Geological sketch map of the concentrically zoned Konder alkaline ultramafic pluton, after geological maps on scales of 1 : 10000 and 1 : 25000 compiled by the Dal'geologiya Regional Geological Survey (Geology..., 1994). The arrow indicates the type locality of bortnikovite. (1) Middle Riphean siltstone and sandstone; (2) Early Archean gneiss, crystalline schist, marble, and calciphyre; (3, 4) ultramafic rocks of the Neoproterozoic Konder complex: (3) dunite: (a) fine-grained, (b) porphyritic, (c) pegmatoid, and (d) magnetite-bearing porphyritic (altered in the Mesozoic); (4) pyroxenite; (5–7) igneous rocks of the Aldan Mesozoic complex: (5) kosvite, (6) gabbro, (7) monzodiorite (dike and vein complexes are not shown); (8) olivine–diopside metasomatic rock related to the inner marginal fault and central alkaline metasomatic zone (in section), other metasomatic rocks are not shown; (9) dunite enriched in PGM: (a) mainly microscopic Pt magmatic mineral assemblage and (b) relatively coarse-grained Ir–Pt fluid–metamorphic mineral assemblage; (10) PGM placer; (11) inclined (a) and horizontal (b) beds; (12) geological boundaries (a), facies boundaries (b), and faults (c).

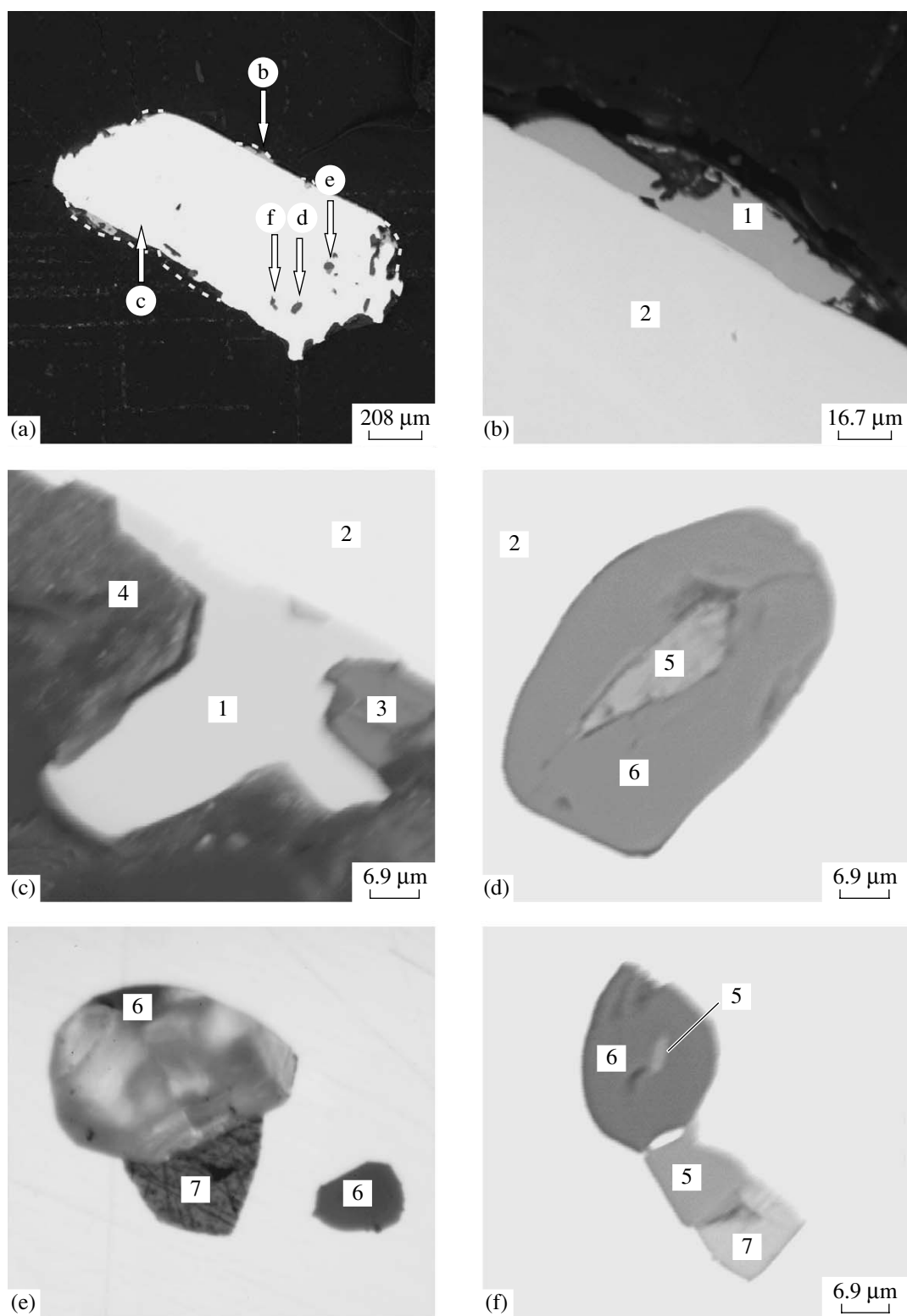


Fig. 2. Isoferroplatinum grain with a rim of bortnikovite, a cemented polished section. (a, b, d–f) BSE images, a LINK-AN-10000 energy dispersive system; (f) photomicrograph, plane light, magn. 500. (a) The dashed line shows the initial location of bortnikovite; the arrows and letters in circles indicate the location of the images in (b–f). (1) Bortnikovite; (2) isoferroplatinum; (3) titanite; (4) chlorite; (5) magnetite; (6) perovskite; (7) bornite.

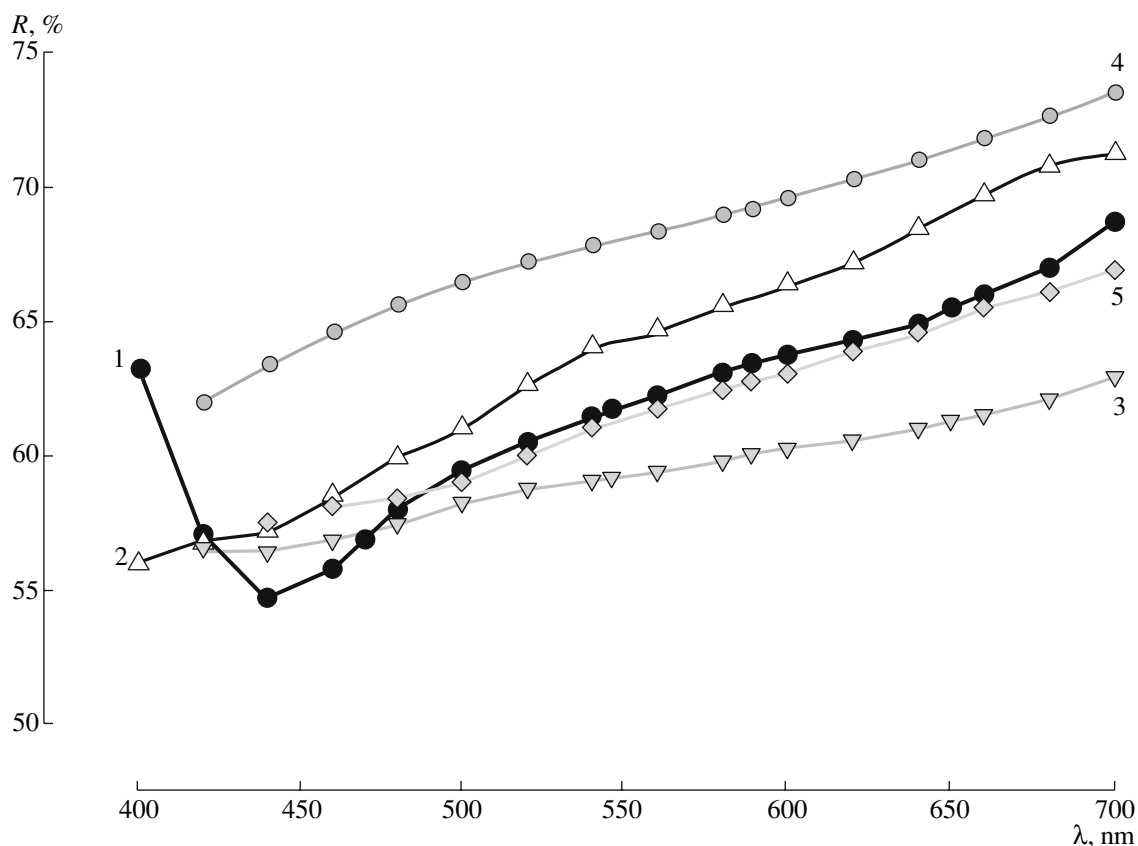


Fig. 3. Reflectance spectra of bortnikovite (1), isoferroplatinum (2), ferronickelplatinum (3), native palladium (4), and potarite (5).

Taking into account the simplified formula Pd(Cu,Zn) and optical isotropy of bortnikovite, it may be suggested that the new mineral is structurally akin to two-component compounds PdCu and PdZn. However, indexing of the mineral X-ray pattern in a cubic unit cell close to PdCu ($a \approx 4.25$ Å) failed. Indexing on the assumption of double cubic unit cell with $a \sim 2a_0$ ($a_0 = 3$ Å) cannot be completed due to $d_\alpha = 2.36$ Å (Table 3).

The compounds PdCu and PdZn are known to have modifications of the CsCl structural type. The structure of tetraferroplatinum PtFe, space group $P4/mmm$, is close to this type. On the basis of the CsCl structure and taking into account the divisible distribution of Cu and Zn within a unit cell, the simplest version of the bortnikovite structure is characterized by tetragonal symmetry, with $a \sim 2a_0$ and $c \sim 3a_0$ at $a_0 \approx 3$ Å. On the assumption of these parameters, the set of d_α spacings of bortnikovite is indexed with a good compatibility of measured and calculated d_α values (Table 3). The refinement of the tetragonal unit cell parameters with the least squares method yields $a = 6.00 \pm 0.02$ Å, $c = 8.50 \pm 0.03$ Å, and $(V) = 306 \pm 0.01$ Å³; $c : a = 1.4167$. On the basis of $Z = 3$ and 24 atoms [12Pd + 12(Cu + Zn)], the calculated density of bortnikovite equals 11.16 g/cm³. In fact, the unit cell of bortnikovite Pd₄Cu₃Zn is equal to 12 unit cells of the CsCl type. At

the same time, the set of hkl for the tetragonal unit cell does not allow determination of the space group of the new mineral unambiguously. However, it is highly probable that atoms in the unit cell of bortnikovite are distributed as in tetraferroplatinum, which belongs to the $P4/mmm$ space group.

Furthermore, the completely disordered distribution of Pd, Cu, and Zn atoms in the structure of the new mineral as in solid solutions (native elements) may be suggested. In this case, the set of d_α (Table 3) is indexed on the assumption of a tetragonal unit cell with $a = 4.23$ and $c = 8.50$ Å. However, this version is not consistent with the stoichiometry of bortnikovite (Table 2).

FORMATION CONDITIONS

The composition of isoferroplatinum intergrown with bortnikovite (Table 4, analysis 1) is distinguished by the presence of Pd and Cu admixtures. Such chemistry is not characteristic of isoferroplatinum from dunites of either the Ir–Pt (Table 4, analysis 3) or Pt (Table 4, analysis 4) mineralogical-geochemical types, which contain Ir + Rh and Rh + Pd admixtures, respectively (Mochalov, 1994, 2001; Mochalov et al., 2002).

Table 2. Chemical composition of bortnikovite

Element	1	2	3	4	5	6	7	8	9	10
Wt %										
Pt	4.45	4.94	2.87	6.30	4.51	6.13	3.97	2.31	3.94	3.73
Pd	58.20	57.77	59.49	56.98	58.05	58.10	58.37	58.74	58.02	58.74
Fe	1.66	1.73	1.42	1.78	1.69	1.66	1.38	1.19	1.38	1.02
Cu	28.10	27.19	27.61	27.06	27.50	27.49	27.16	26.82	27.05	27.64
Zn	7.57	8.38	8.60	7.89	8.27	8.14	8.04	7.95	7.64	7.75
Total	99.98	100.01	99.99	100.00	100.02	101.51	98.92	97.01	98.03	98.88
At %										
Pt	1.97	2.19	1.26	2.82	2.00	2.26	1.88	1.05	1.78	1.67
Pd	47.25	46.99	47.98	46.72	47.10	47.30	47.77	48.90	48.14	48.30
Fe	2.57	2.68	2.18	2.77	2.61	2.59	2.10	1.89	2.18	1.60
Cu	38.21	37.04	37.29	37.16	37.37	36.90	37.54	37.39	37.58	38.06
Zn	10.00	11.09	11.29	10.53	10.92	10.94	10.71	10.77	10.32	10.37
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Formula units										
Pt	0.16	0.18	0.10	0.23	0.16	0.18	0.15	0.08	0.14	0.13
Pd	3.78	3.76	3.84	3.74	3.77	3.78	3.82	3.91	3.85	3.86
Fe	0.21	0.21	0.17	0.22	0.21	0.21	0.17	0.15	0.17	0.13
Cu	3.06	2.96	2.98	2.97	2.99	2.95	3.00	2.99	3.01	3.04
Zn	0.80	0.89	0.90	0.84	0.87	0.88	0.86	0.86	0.83	0.83
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Element	11	12	13	14	15	16	17	18	X(18)	S
Wt %										
Pt	4.29	3.84	4.57	4.89	4.56	4.11	2.37	2.82	4.06	0.99
Pd	57.63	58.06	59.48	56.80	57.16	57.76	59.37	58.93	58.19	0.81
Fe	1.52	1.21	1.21	1.20	1.30	1.50	1.23	1.32	1.41	0.22
Cu	27.26	27.39	27.37	26.69	26.86	26.91	27.06	27.40	27.26	0.35
Zn	8.15	8.15	8.39	8.10	7.88	7.57	7.67	8.25	8.02	0.30
Total	98.85	98.65	101.02	97.68	97.76	97.85	97.70	98.72	98.94	
At %										
Pt	1.92	1.72	2.01	2.23	2.07	1.86	1.07	1.26	1.82	0.45
Pd	47.32	47.75	48.06	47.48	47.66	48.03	49.14	48.19	47.78	0.64
Fe	2.38	1.90	1.86	1.91	2.07	2.38	1.94	2.06	2.21	0.34
Cu	37.49	37.72	37.03	37.36	37.51	37.48	37.51	37.52	37.48	0.33
Zn	10.89	10.91	11.03	11.02	10.69	10.25	10.33	10.98	10.72	0.35
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
Formula units										
Pt	0.15	0.14	0.16	0.18	0.17	0.15	0.09	0.10	0.15	0.04
Pd	3.79	3.82	3.84	3.80	3.81	3.84	3.93	3.85	3.82	0.05
Fe	0.19	0.15	0.15	0.15	0.17	0.19	0.16	0.16	0.18	0.03
Cu	3.00	3.02	2.96	2.99	3.00	3.00	3.00	3.00	3.00	0.03
Zn	0.87	0.87	0.88	0.88	0.86	0.82	0.83	0.88	0.86	0.03
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	

Note: Analyses 1–13 were performed on a LINK-AN-10000 energy dispersive system operating at 25 kV and 1–3 nA, with a beam diameter 2–3 μm and exposition time 100 s. Analyses 14–18 were performed on a Camebax electron microprobe at the Northeast Interdisciplinary Research Institute, Far East Division, Russian Academy of Sciences, operating at 20 kV and 20–30 nA, with a beam diameter 2–3 μm and exposition time 60 s. Analytical lines are L_{α} for the platinum group metals except Pd, L_{β} for Pd, and K_{α} for other metals. The following standards were used: pure metals Pt, Os, Ir, Ru, Rh, Pd, Au, Ag, Fe, Ni, Cu, Pb, and Zn, as well as PbS, Cu₂S, FeAsS, and PtAs₂. $\bar{X}$ is the mean value; the number of analyses is given in parentheses; S is the standard deviation.

Table 3. X-ray powder diffraction pattern of bortnikovite

<i>I</i>	<i>d</i> _{α meas} (Å)	<i>hkl</i>	<i>d</i> _{α calc} (Å)	<i>hkl</i>	<i>d</i> _{α calc} (Å)
1	3.00	200 112	3.00 3.00	200	3.00
1	2.67	120	2.68	120	2.68
0.5*	2.36	113	2.36	—	
10	2.13	004 220	2.125 2.121	220	2.12
1	1.737	132	1.732	222	1.732
3	1.501	400 224	1.500 1.501	400	1.500
2	1.346	240 332	1.342 1.342	240	1.342
8	1.224	404	1.225	224	1.225
1br	1.161	151	1.166	333	1.155
4	1.059	440	1.060	440	1.059
		Tetragonal unit cell <i>a</i> = 6.00 ± 0.02 Å <i>c</i> = 8.50 ± 0.03 Å		Cubic unit cell <i>a</i> = 6.00 ± 0.02 Å	

Note: Gandolfi camera (diameter 57.3 mm) and RKD-57.3 camera (asymmetric film loading; the sample is a rubber bowl 0.2 mm in diameter); Fe_{α+β} irradiation (β lines are filtered by calculation).

* Taking into account superposition of the β line from *d*_α = 2.13 Å.

Titanite and chlorite are intergrown with bortnikovite and isoferroplatinum (Table 5; Fig. 2c). Separate crystals and segregations of perovskite, V- and Ti-bearing magnetite, and bornite were identified as inclusions in isoferroplatinum (Table 5; Figs. 2d–2f). Perovskite occurs as both separate crystals (Fig. 2e) and pseudomorphs after magnetite (Figs. 2d, 2f). In addition to relics in perovskite, magnetite occurs as crystals intergrown with bornite (Fig. 2d).

Table 4. Chemical composition of isoferroplatinum and bornite intergrown with bortnikovite

Component, wt %	1	2	3	4	5
	X(2)	X(2)	X(37)	X(16)	X(17)
Pt	89.03	n.d.	86.66	87.75	89.76
Ir	n.d.	"	2.25	0.37	n.d.
Os	"	"	0.29	0.24	"
Ru	"	"	0.05	0.04	"
Rh	"	"	0.48	1.08	0.06
Pd	0.94	"	0.22	0.70	0.08
Fe	8.85	11.55	8.89	8.43	9.70
Cu	0.51	63.52	0.70	0.74	0.78
Ni	n.d.	n.d.	0.16	0.07	n.d.
Co	"	"	0.01	0.02	"
S	"	24.74	n.d.	n.d.	"
Total	99.33	75.07	99.71	99.44	100.38

Note: (1) Isoferroplatinum intergrown with bortnikovite; (2) bornite intergrown with bortnikovite; (3, 4) isoferroplatinum from dunite of the Konder pluton; (3) recrystallized porphyritic dunite of the Ir–Pt fluid–metamorphic type, (4) fine-grained dunite of the Pt magmatic type; (5) separate crystals and twins of isoferroplatinum from titanomagnetite–biotite–amphibole–clinopyroxene metasomatic rock in the Konder pluton (Fig. 1). Analyses were performed on a LINK-AN-10000 energy dispersive system operating at 25 kV and 1–3 nA, with a beam diameter 2–3 μm and exposition time 100 s. X is the mean value; the number of analyses is given in parentheses; n.d. denotes not detected.

V- and Ti-bearing magnetite is the major mineral of titanomagnetite–biotite–amphibole–clinopyroxene metasomatic rock that replaces dunite in the Konder alkaline ultramafic massif (Fig. 1), whereas titanite is an accessory mineral (Bogomolov, 1968; *Geology*..., 1994; Nekrasov et al., 1994). Perovskite is abundant in metasomatic rocks at the contacts between ultramafics and the Mesozoic monzodiorite–syenite complex (Bogomolov, 1968; Orlova et al., 1979). Bornite occurs in malachite–

Table 5. Chemical composition of mineral inclusions in bortnikovite and isoferroplatinum, wt %

Analysis	Mineral	TiO ₂	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	V ₂ O ₅	Total
1	Titanite	42.36	26.39	n.d.	1.86	n.d.	29.03	n.d.	99.64
2	Perovskite	58.33	0.55	"	1.39	"	37.56	"	97.87
3	"	58.49	0.72	"	1.07	"	37.79	"	98.06
4	"	59.28	0.34	"	1.66	"	38.32	"	99.60
5	Magnetite	1.05	0.62	0.66	96.03	0.68	n.d.	0.16	99.19

Note: Analyses were performed on a LINK-AN-10000 energy dispersive system operating at 25 kV and 1–3 nA, with a beam diameter 2–3 μm and exposition time 100 s. FeO is total iron in the form of FeO; n.d. denotes not detected.

sulfide segregations at the contacts between dunite and alkaline pegmatite. Such occurrence of magnetite, perovskite, and bornite, along with pseudomorphs of perovskite after magnetite, indicates that bortnikovite probably was formed as a result of metasomatic reaction between titanomagnetite–biotite–amphibole–clinopyroxene rock and high-temperature alkaline fluids derived from the Mesozoic monzodiorite–syenite igneous complex. The specific PGE mineralization represented mainly by individual crystals and twins of isoferroplatinum (Table 4, analysis 5) was formed simultaneously with titanomagnetite–biotite–amphibole–clinopyroxene metasomatic rock. The effect of the Mesozoic intrusions gave rise to a new redistribution of PGE and other ore components (Fe, Ti, and Cu), expressed, in particular, in the formation of isoferroplatinum associated with bortnikovite. The incorporation of Zn into bortnikovite testifies to its gain during the multiple metasomatic process.

CONCLUSIONS

One more new mineral species, bortnikovite, an intermetallic compound of Pd, Cu, and Zn, has been identified in the unique PGE placer extending along the Konder River. A concentrically zoned alkaline ultramafic pluton was the primary source of this placer. The simplified formula of the new mineral is $\text{Pd}_4\text{Cu}_3\text{Zn}$, and the parameters of the tetragonal unit cell are as follows: $a = 6.00 \pm 0.02 \text{ \AA}$ and $c = 8.50 \pm 0.03 \text{ \AA}$, $V = 306 \pm 0.01 \text{ \AA}^3$, and $Z = 3$; the probable space group is $P4/mmm$.

Bortnikovite is a result of metasomatic alteration of titanomagnetite–biotite–amphibole–clinopyroxene rock affected by high-temperature alkaline fluids derived from monzodiorite–syenite magma.

Bortnikovite is the first PGM that contains zinc as a major mineral-forming element. Thus, bortnikovite leads off a novel group of natural Zn-bearing PGE compounds.

The cemented polished section containing the grain of isoferroplatinum intergrown with bortnikovite was deposited in the Mineralogical Museum at St. Petersburg State University.

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