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Laurite and Ir-Osmium from Plagioclase Lherzolite of the Yoko–Dovyren Mafic–Ultramafic Pluton, Northern Baikal Region

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Abstract—The near-bottom part of the Yoko-Dovyren layered ultramafic-mafic intrusion host the Baikal deposit of Cu–Ni sulfide ores with Pt–Pd mineralization, whereas horizons and pockets of low sulfide ores with Pt–Pd mineralization occur at higher stratigraphic levels, including the boundary between strata of troctolite and gabbronorite, within these rocks, as well as in strata of peridotite at the lower part of the intrusion. This paper represents a new (for the Yoko-Dovyren intrusion) type of "refractory IPGE-mineralization" discovered in the lower peridotite ranging from two-pyroxene-plagioclase-bearing lherzolite. This mineralization occurs in thin intercalations of plagioclase lherzolite containing as much as 7% of alumochromite, up to 50 ppb Ru, 15 ppb Ir, and 60 ppb Pt. Crystals of cumulate alumochromite with 0.2–0.8 wt % TiO_2 contain hexagonal plates of Ir-osmium up to 5 m in size. Crystals of cumulate alumochromite with 1.2–2.8 wt % TiO_2 host pentagonal dodecahedrons of laurite up to 4 m in size. One of the alumochromite crystals with an inclusion of Os-poor laurite was found inside a crystal of cumulate olivine Fo86. Intergrowth of laurite and Ir-osmium enclosed in alumochromite with 1.1% TiO_2 was observed in one case. Laurite from Yoko-Dovyren contains 93–66%, predominantly 92–82%, RuS_2 endmember ($n = 10$); 3–20, predominantly 5–12%, OsS_2 endmember; 4–5% IrS_2 endmember; and up to 0.7% Pd and 0.5% Au. Ir-osmium is divided into two groups by composition. The first group is enriched in Os (58–73 wt %, on average 64 wt %) and Ru (3–8 wt %, on average 5 wt %), contains 24–34 wt % Ir ($n = 4$), up to 1.4 wt % Au, and no Pt. Compositions of the second group have 57–58 wt % Os, 27–30 wt % Ir, 1.5–5.5 wt % Ru, approximately 10 wt % Pt ($n = 3$), and up to 0.2 wt % Pd. The Cr# and $Fe^{2+}/(Fe^{2+} + Mg)$ values, which range within 58–69 and 61–72, respectively, are identical in alumochromite with both enclosed laurite and Ir-osmium. Alumochromite, relatively enriched in Ti, crystallized slightly later, suggesting later crystallization for hosted laurite. Occurrence of Ir-osmium seems to indicate a picritic magma undersaturated with sulfide sulfur during bulk crystallization of alumochromite Judging from the diagram from (Brennan and Andrews, 2001), intergrowths of laurite and Ir-osmium, evidence that their probable crystallization temperature did not exceed 1250°C. The presence of own minerals of Ru, Os, Ir in the rocks, containing the first ppb of these PGE shows startling degree of magmatic differentiation. In the matrix of plagioclase lherzolites, containing laurite and Ir-osmium, in association with phlogopite, pargasite, pentlandite, troilite and chalcopyrite there were found the smallest crystals of geversite, sperrilite, insizwaite, niggliite, naldrettite, zvyagintsevite, in association with serpentine and chlorite–native platinum, Pd-platinum, osarsite, irarsite, platarsite.

Keywords: Yoko-Dovyren intrusion, plagioclase lherzolites, alumochromite, laurite, iridian osmium
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INTRODUCTION

Platinum group elements (PGE), Ru, Rh, Pd, Os, Ir, Pt, are readily dissolved in any metallic melts and sulfide melts close in properties at high temperature; therefore, PGE behavior is fundamentally distinct in magmatic systems depleted and enriched in sulfide melts (Naldrett, 2004). PGE are noble predominantly at low temperatures, whereas at high temperatures, they are typical chalcophile elements (e.g., the affinity of Ru and Os to sulfur is higher than that of Cu); therefore, sulfides are their common minerals. Refractory (Ru, Os, Ir) and easily melting (Rh, Pt, Pd) PGE were identified on this basis. High contents of all PGE are typical of ultramafic and mafic rocks. Refractory PGE are concentrated in derivatives of magnesian ultramafic rocks, whereas easily melting PGE are concentrated in derivatives of mafic–ultramafic and mafic complexes. The standard trend of noble metals in high-temperature endogenic processes is: Ru (+S) → Os (+S) → Ir (+S) → Rh (+ S, As) → Pt + Au + Ag (±S, As) → Pd + Au + Ag (+ S, As, Sb, Bi, Te, Sn, Pb) → Au + Pd + Ag (±S, As, Sb, Bi, Te, Sn, Pb) (Spiridonov et al., 2015). Refractory PGE are not involved in hydrothermal process. Pt and especially Pd are mobile in hydrothermal process, because they form chloride and other complexes.

YOKO–DOVYREN PLUTON

The Neoproterozoic Yoko–Dovyren layered mafic–ultramafic pluton, with dimensions of 26 × 3.5 × ~5 km, is hosted in Baikalides of the northeastern Baikal region (Gurulev, 1965; Bulgatov, 1983; Konnikov et al., 1994). The Central, thickest part of the pluton is composed of (from bottom to top): a horizon of near-contact olivine gabbrodolerite to picrite; a thick sequence of two-pyroxene–plagioclase-bearing dunite to lherzolite (approximately one-third of the section); a thick sequence of troctolite with schlieren, lenses, and veins of anorthosite (approximately one-third of the section); and an upper thick sequence of olivine and olivine-free gabbronorite and pigeonite gabbro (Gurulev, 1965; Konnikov et al., 1994; Kislov, 1998; Yaroshevsky et al., 2006; Ariskin et al., 2009, 2016). In the center of the pluton, in the water course of Bolshoi Creek, gabbronorite–dolerite of the chilled margin (Kislov, 1998) passes up into olivine and picritic gabbronorite to a distance of 10–15 m and upward into rocks increasingly enriched in Mg and cumulative olivine Fo_{87-85}, up to plagioclase-bearing lherzolite and dunite (Ariskin et al., 2006). There, two types of lherzolite were identified. In one of them, the quantities of plagioclase (bitownite) and pyroxene (augite, bronzite) are close, whereas in the other (upsection), plagioclase predominates over pyroxene. Some lherzolites are enriched in olivine up to 80–85 vol %. The Yoko–Dovyren pluton is surrounded by the thick aureole of the Neoproterozoic contact with metamorphosed sedimentary rocks.

Despite the fact that the pluton was "turned on its head" and broken by a series of diagonal faults during regional geological processes, intrusive rocks, including those enriched in olivine orthopyroxene, are usually fresh.

At the bottom, the pluton hosts the Baikal Cu–Ni sulfide deposit with Pt–Pd mineralization; lenticular horizons and pockets of low-sulfide ores with Pt–Pd mineralization are present at the boundary between troctolite and gabbronorite sequences in the upper part of the section, as well as in these sequences and peridotite of the lower part of the pluton (Kacharovskaya, 1986; Distler and Stepin, 1993; Konnikov et al., 1994, 2000; Orsoev et al., 1995, 2003; Kislov, 1998; Rudashevsky et al., 2003; Tolstykh et al., 2008; Ariskin et al., 2009, 2016).

In a detailed geochemical study, A.A. Ariskin et al. (2016) found a horizon of peridotite locally enriched in refractory PGE at the bottom of the Yoko–Dovyren pluton. It is located 155–185 m above the low contact of the pluton and hosts thin intercalations of plagioclase lherzolite containing 3–7 wt % alumochromite; up to 0.2 wt %, predominantly less than 0.1 wt %, S; and up to 50 ppb Ru, 15 ppb Ir, 60 ppb Pt, 40 ppb Pd, and 20 ppb Rh, whereas their backgrounds in the Yoko–Dovyren peridotite are a few ppb. This rock was described as plagiodunite in the cited paper. Ariskin et al. (2016) reported sporadic tiny mineral grains of refractory PGE in this rock. This paper focuses on platinum group minerals (PGM) from plagioclase lherzolite of this horizon.

SAMPLES

The samples were collected along the right bank of a right tributary of Bolshoi Creek. The coordinates of the starting point are 56°19′04.6″ N and 109°47′21.5″ E. The first sample was taken 7 m upstream from the starting point (156 m above the lower contact in the combined section of the pluton); the last sample was collected 53 m upstream from the starting point (186 m above the lower contact of the pluton).

Plagioclase lherzolite containing the rarest disseminated Ru–Os–Ir minerals are composed of euhedral or partly corroded crystals of cumulative olivine, chrysolite Fo_{87-84}, predominantly frequently $Fo_{86-85,}$ of fractions millimeters to 4 × 2 mm in size, which host small and minute inclusions of Ti-poor (0.2–0.8 wt % TiO_2) alumochromite depleted in Fe^{3+}, Mn, and Zn. Rare very fine exsolved lamellae of chrome spinel and diopside are observed in chrysotile crystals. Small, usually less than 50 μm, oval crystals and clusters of cumulative alumochromite crystals fill interstices between olivine crystals. This alumochromite is enriched in Al and Ti (0.2–2.8 wt % TiO_2) compared to that from inclusions in olivine. The alumochromite content ranges from fractions of a percent to 5–7 vol %. Anhedral poikilitic augite crystals up to 15 mm across (Mg# = 89–87) host olivine and alumochromite. Augite frequently contains numerous fine exsolved lamellae of orthopyroxene. The size of bronzite (Mg# = 87–86) poikilitic crystals usually does not exceed 12 mm. Anhedral unzoned grains of bytownite An_{78-70} rarely exceed 3 mm in size. Quantities of pyroxenes and plagioclase are usually commensurate; plagioclase frequently predominates. Titanomagnetite and ilmenite are associated with pyroxenes and plagioclase. Titanomagnetite underwent oxidative annealing and occurs as ilmenite–magnetite intergrowths (Ti-magnetite matrix with exsolved lamellae of ilmenite). Plagioclase lherzolite contains scattered micropockets of intergrown troilite and pentlandite with subordinate chal-

Table 1. Chemical composition (wt %) of laurite enclosed in alumochromite from plagioclase lherzolite in lower part of Yoko–Dovyren pluton

Components	1	2	3	4	5	6	7	8	9	10
Ru	54.36	52.80	51.26	50.63	49.65	48.75	44.78	44.84	42.77	33.44
Os	3.62	5.17	5.65	7.76	9.01	8.30	12.73	13.04	15.21	29.02
Ir	3.95	3.88	4.46	4.20	4.73	5.56	5.68	5.13	5.52	3.60
Pd	0.45	0.34	0.72	b.d.l.	b.d.l.	0.50	0.59	0.30	0.44	b.d.l.
Au	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.52	b.d.l.	b.d.l.
S	37.46	37.26	36.39	36.12	36.46	35.97	36.06	34.81	34.51	32.22
Total	99.84	99.45	98.48	98.71	99.85	99.10	98.84	98.64	98.45	98.28
Formula calculated based on three atoms										
Ru	0.92	0.905	0.90	0.89	0.87	0.86	0.82	0.82	0.79	0.66
Os	0.03	0.045	0.05	0.07	0.08	0.08	0.12	0.12	0.15	0.30
Ir	0.04	0.035	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.04
Pd	0.01	0.005	0.01	–	–	0.01	0.01	0.005	0.01	–
Au	–	–	–	–	–	–	–	0.005	–	–
S	2.00	2.01	2.00	2.00	2.01	2.00	2.00	2.00	2.00	2.00

(1, 3–10) Isolated crystals, (2) intergrowth with Ir-osmium; b.d.l. hereinafter denotes that the element content is below the detection limit of an electron microprobe; Rh, Pt, As, and Se were not detected.

copyrite and cubanite (frequently with phlogopite lamellae), anhedral grains of phlogopite and/or amphibole (pargasite to edenite), and rare apatite, magnetite, spinel, baddeleyite, zircon, zirconolite, pyrochlore, thorite, thorianite, and monazite. Phlogopite and amphiboles with appreciable Cl contents replaced pyroxene. Minute galena grains are present in rim troilite–pentlandite–chalcopyrite intergrowths. Plagioclase lherzolite is medium-grained massive.

Thirteen thin polished sections and seven polished sections of plagioclase lherzolite enriched in chrome spinels and seven samples prepared from chrome spinel concentrates were examined.

METHODS

Minute grains of PGE minerals and associated minerals were examined on a Jeol JSM-6480 LV electron microscope equipped with EDS according to the conventional procedure at the Laboratory of Analytical High-Spatial Resolution Techniques, Department of Petrology, Moscow State University (analysts N.N. Korotaeva and V.O. Yapaskurt). The following standards were used: pure metals including Ru, Os, Ir, Rh, Pt, Pd, Au, Ag, Bi, Sb, Ni, Co, Cu, Zn, Cr, pyrite (S), altaite (Pb), InAs (As), and CdSe (Cd, Se). Chemical analyses in the text and tables are sequentially numbered.

LAURITE FROM PERIDOTITE OF THE YOKO–DOVYREN PLUTON

Laurite occurs as inclusions in alumochromite crystals in peridotite of the Yoko–Dovyren pluton. A few dozen microcrystals were found; the chemical composition was determined for ten crystals (Table 1). Laurite crystals are pentagonal dodecahedra (Fig. 1a) up to 4 μm in size, predominantly less than 1 μm. Occasionally, laurite crystals are encapsulated in alumochromite hosted in cumulated olivine Fo_{86} (Fig. 1b). Laurite crystals are unzoned in chemical composition. Laurite contains 93–66%, predominantly 92–82%, RuS_2 endmember; 3–30%, predominantly 5–12%, OsS_2 endmember; 4–5% IrS_2 endmember (Fig. 2); from trace to 0.7% Pd; and occasionally up to 0.5% Au. The Ir content in laurite does not change with an increase in the Os concentration. Variations in laurite composition are as follows: $Ru_{0.66-0.92}Os_{0.03-0.30}Ir_{0.04-0.05}Pd_{0-0.01}S_{2.00-2.01}$ (Table 1, analyses 1–10). The composition $Ru_{0.82-0.91}Os_{0.05-0.12}Ir_{0.04-0.05}Pd_{0-0.01}S_{2.00-2.01}$ is the most abundant. Yoko–Dovyren laurite has a stochiometric metal/sulfur ratio. As and Se were not detected in it.

Ir-OSMIUM FROM PERIDOTITE OF THE YOKO–DOVYREN PLUTON

Ir-osmium of the Yoko–Dovyren pluton occurs as hexagonal lamellae up to 5 μm in size, usually less than 1 μm, enclosed in alumochromite crystals. The length to thickness ratio of Ir-osmium lamellae is 2–5 : 1. Two types of Ir-osmium composition have been identified. Type 1 Ir-osmium is enriched in Os (58–73 wt %, on average 64 wt % Os) and Ru (3–8 wt % Ru), contains 24–34 wt % Ir and from trace to 1.4 wt % and 0.16 wt % Cu, and is Pt- and Pd-free. Its composition corresponds to the formula $Os_{0.55-0.72}Ir_{0.23-0.31}Ru_{0.05-0.142}Au_{0-0.015}Cu_{0-0.005}$ (Table 2, analyses 11–14). The composition

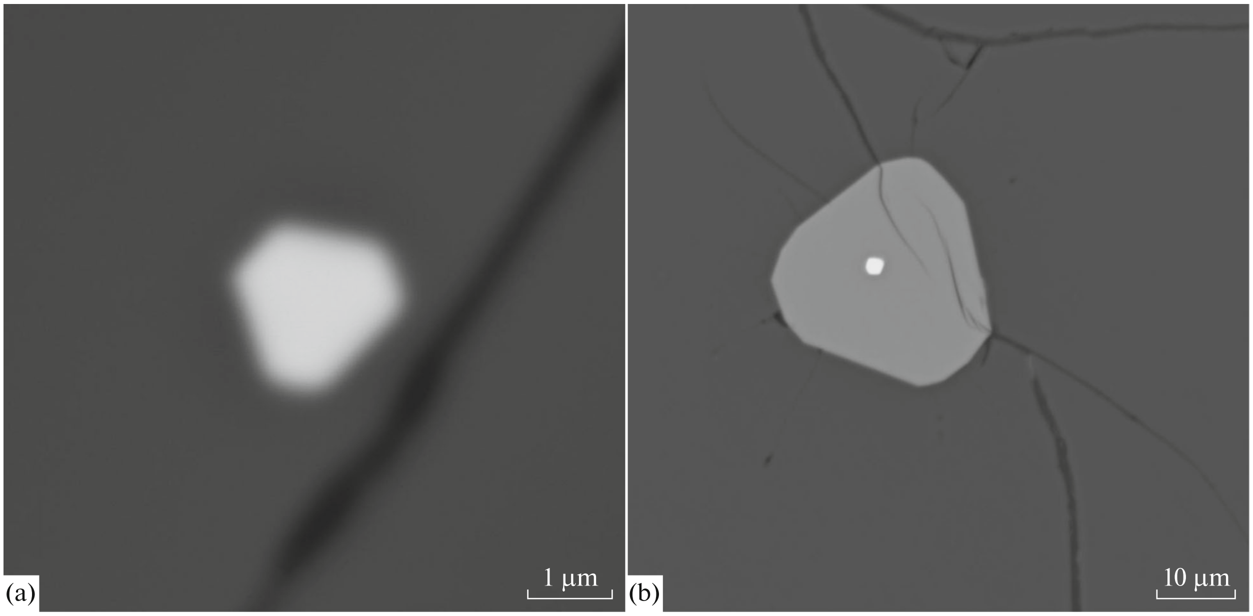

Fig. 1 Backscattered electron images of laurite crystal in (a) alumochromite (analyses 3) and (b) alumochromite enclosed in olivine Fo_{86}.

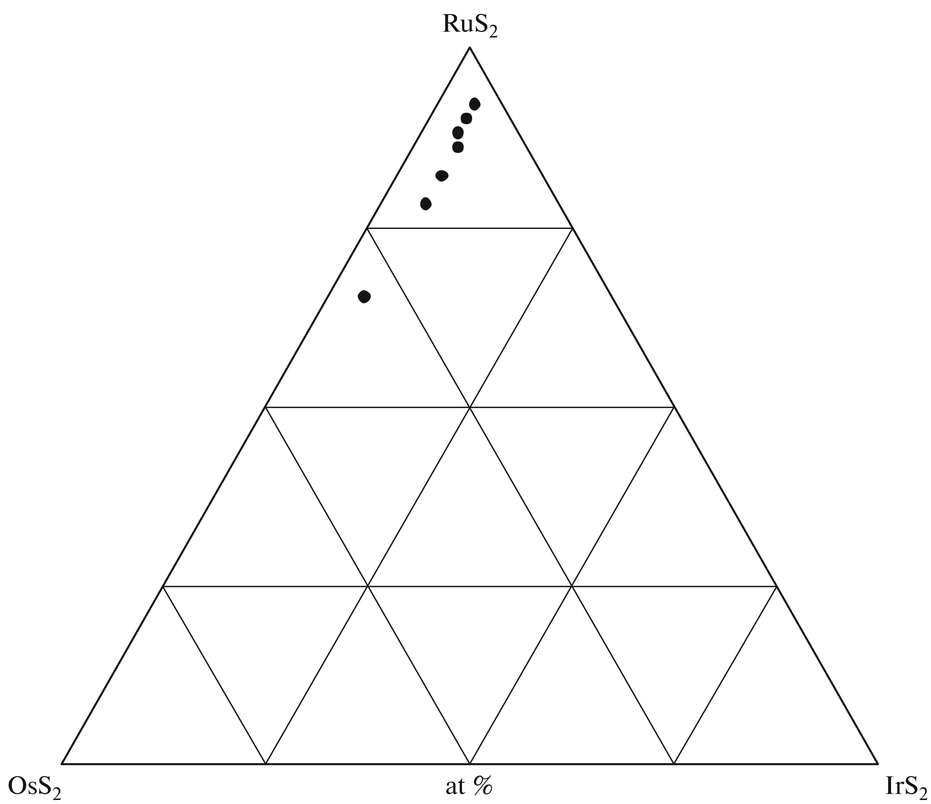

Fig. 2. Composition of laurite from plagiolherzolite of Yoko–Dovyren pluton.

Table 2. Chemical composition (wt %) of Ir-osmium inclusions in alumochromite from plagioclase lherzolite in lower part of Yoko–Dovyren pluton

Components	11	12	13.	14	15	16	17
Os	73.04	63.99	60.07	57.84	58.04	57.21	57.01
Ir	23.73	29.33	33.54	32.85	27.16	28.45	30.08
Ru	2.85	3.52	5.52	7.94	1.49	2.97	5.68
Pt	b.d.l.	b.d.l.	b.d.l.	b.d.l.	10.64	9.71	10.13
Rh	b.d.l.	b.d.l.	b.d.l.	0.06	b.d.l.	b.d.l.	b.d.l.
Pd	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.18
Au	b.d.l.	1.40	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Cu	b.d.l.	0.16	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Total	99.62	98.40	99.13	98.69	97.34	98.34	99.09
Formula calculated based on one atom							
Os	0.72	0.63	0.58	0.55	0.59	0.57	0.51
Ir	0.23	0.285	0.32	0.31	0.27	0.28	0.29
Ru	0.05	0.065	0.10	0.14	0.03	0.06	0.10
Pt	–		–	–	0.11	0.09	0.10
Au	–	0.015	–	–	–	–	–
Cu	–	0.005	–	–	–	–	–

(11–16) Isolated crystals; (17) from intergrowth with laurite.

of type 2 Ir-osmium is, wt %: 57–58 Os, 27–30 Ir, 1.5–5.5 Ru, approximately 10 Pt, from trace to 0.2 Pd; its formula is $Os_{0.51-0.59}Ir_{0.27-0.29}Ru_{0.03-0.10}Pt_{0.09-0.11}$ (Table 2, analyses 15–17). Ir-osmium enriched in Ir, Pt, and Ru (Table 2, analysis 17) is intergrown with laurite. On the Ru–Os–Ir triangle plot (Harris and Cabri, 1991), the compositions of Yoko–Dovyren Ir-osmium fall compactly into the osmium field (Fig. 3). The composition of Ir-osmium from Yoko-Dovyren peridotite is close to that of the experimental alloy obtained at 1250°C and low fS_2 (Andrews and Brenan, 2002).

CHROME SPINELS WITH ENCLOSED LAURITE AND Ir–Os FROM PERIDOTITE OF THE YOKO–DOVYREN PLUTON

Chrome spinels from peridotite in the near-bottom part of the Yoko–Dovyren pluton are alumochromite depleted in Ti, Fe^{3+}, Mn, and Zn (Table 3). Judging from the chemical composition, cumulative alumochromite from plagioclase lherzolite crystallized from a low-alkali picritic melt depleted in water. The composition of alumochromite is relatively stable with slight variations in the Al and Ti contents. The rare finest exsolved lamellae of ilmenite are observed in alumochromite crystals containing higher than 2 wt % TiO_2. As rule, alumochromite is unzoned in composition. Occasionally, their rims are slightly richer in Al and Ti.

Ir-osmium occurs as inclusions in crystals of cumulative alumochromite depleted in Ti (0.2–0.8 wt % TiO_2) (Table 3, analyses 18–21). Laurite is enclosed in crystals of cumulative alumochromite containing 1.2–2.8 wt % TiO_2 (Table 3, analyses 21–25). One such alumochromite crystal with enclosed laurite was found in the crystal core of cumulative olivine Fo_{86} (Fig. 1b). In one case, a cluster of laurite and Ir-osmium was observed in alumochromite with 1.1 wt % TiO_2 (Table 3, analyses 21). The Cr# (58–69) and $Fe^{2+}/(Fe^{2+} + Mg)$ (61–72) values in alumochromite containing both laurite and Ir-osmium are identical. Alumochromite richer in Ti as laurite was enclosed in it crystallized slightly later than Ti-poor alumochromite with Ir-osmium inclusions.

OTHER MINERALS OF NOBLE METALS FROM PERIDOTITE OF THE YOKO–DOVYREN PLUTON

Minute grains of geversite, sperrylite, insizwaite, niggliite, naldrettite, and zvyagintsevite associated with phlogopite, pargasite, pentlandite, troilite, chalcopyrite, and magnetite were identified in the matrix of plagioclase lherzolite containing laurite and Ir-osmium. This mineral assemblage is close to that of pneumatolytic PGM in Norilsk magmatic ores (Spiridonov et al., 2015). Minute grains of native platinum, Pd-platinum, osarsite, irarsite, and platarsite, typical hydrothermal and metamorphic–hydrothermal PGM (Garuti et al., 1999; Naldrett, 2004; Spiridonov et al., 2016) associated with epigenetic serpentine minerals and chlorite were found in plagioclase lherzolite in the lower part of the Yoko–

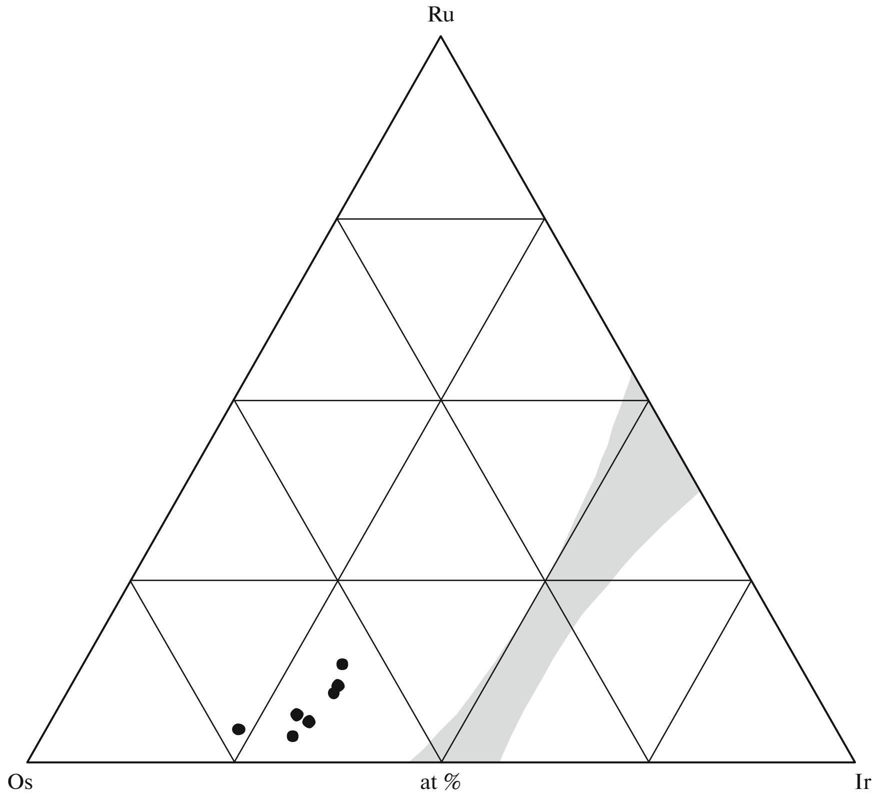

Fig. 3. Composition of Ir-osmium from plagiolherzolite of Yoko–Dovyren pluton. Miscibility gap is gray, after (Harris and Cabri, 1991).

Dovyren pluton. These data point to a long multistage formation of PGM in peridotite in the lower part of the Yoko–Dovyren pluton.

COMPARISON OF LAURITE FROM PERIDOTITE OF THE YOKO–DOVYREN PLUTON AND OTHER OCCURRENCES OF PGE MINERALIZATION

Laurite, Ru disulfide with a pyrite-like structure, is one of the most abundant PGM. Almost any body of chromitite hosted in alpine-type ultramafic rocks contains some and occasionally significant quantities of laurite as euhedral crystals enclosed in chrome spinels (alumomagnesiochromite and magnesiochromite) (Talkington et al., 1984; Andrews and Brenan, 2002; Gonzales-Jimenes et al., 2009). Laurite is abundant in other types of PGE mineralization, including layered plutons. Laurite is a good indicator of magmatic differentiation. During this process, the mineral is enriched in Os up to the transition to its analog, essentially osmium disulfide erlichmanite. Judging from experimental simulation (Andrews and, Brennan, 2002), a decreased crystallization temperature is one of the reasons for this.

The structural position and composition of laurite from peridotite of the Yoko–Dovyren pluton are close to those of laurite from alpine-type chromite-bearing peridotite in the United States (Stockman and Hlava, 1984), northeastern Russia (Dmitrenko and Mochalov, 1987), Greece (Auge, 1988; Garuti et al., 1999; Prichard et al., 2008; Kapsiotis et al., 2009), the Urals (Distler et al., 1989; Anikina et al., 1993), New Caledonia (Auge and Maurizot, 1995), Borneo (Nakagawa and Franco, 1997; Hattori et al., 2004), Oman (Ahmed and Arai, 2003), the Caribbean region (Proenza et al., 2007), Turkey (Uysal et al., 2007), and Iran (Rajabzadeh and Moosavinasab, 2012). Pentagonal dodecahedra of laurite enclosed in chrome spinels of alpine-type ultramafic rocks reach 0.5 mm across, less frequently greater; therefore, economic laurite placers are known. Os-laurite and erlichmanite $(Os,Ru)S_2$, which rim zoned laurite crystals and less frequently occur as isolated grains are present in the large alpine-type ultramafic bodies (Kempirsai, Southern Urals, etc.) along with predominant laurite. In plagioclase lherzolite of the Yoko–Dovyren pluton, erlichmanite and Os-laurite are absent. Consistently low Ir content is characteristic of both laurite–erlichmanite series minerals from the alpine-type peridotite and laurite of the Yoko–Dovyren pluton. The laurite–erlichmanite series minerals in chromitite of Othrys in Greece (Garuti et al., 1999) are a classic example.

Table 3. Chemical composition of alumochromite (wt %) from plagioclase lherzolite in lower part of Yoko–Dovyren pluton

Components	18	19	20	21	22	23	24	25
MgO	7.07	5.74	7.84	7.49	7.23	6.90	7.46	8.55
NiO	b.d.l.	0.09	0.10	0.13	b.d.l.	0.08	0.12	0.14
FeO	23.16	25.34	22.99	23.64	24.16	25.46	24.76	23.06
MnO	0.41	0.34	0.50	0.41	0.50	0.25	0.45	0.35
ZnO	0.30	0.26	0.27	0.26	0.34	0.23	0.26	0.22
Cr_2O_3	52.10	48.15	44.219	46.41	45.74	47.09	43.87	43.54
Al_2O_3	14.91	17.97	19.88	17.42	18.93	17.25	16.10	18.99
Fe_2O_3	1.12	0.48	2.84	2.81	1.39	0.49	3.26	2.60
V_2O_3	0.37	0.32	0.39	0.38	0.50	0.31	0.49	0.39
TiO_2	0.37	0.22	0.84	1.14	1.17	1.98	2.77	2.02
Total	99.81	98.91	99.86	100.09	99.96	99.97	99.54	99.86
Endmembers %								
$MgCr_2O_4$	34.9	28.4	37.7	36.4	35.0	33.7	36.6	41.0
$FeCr_2O_4$	33.3	34.9	18.7	23.3	23.7	27.3	20.5	14.4
$MgAl_2O_4$	–	–	–	–	–	–	–	–
$FeAl_2O_4$	28.4	34.6	37.2	32.9	35.4	32.7	30.7	35.6
$ZnAl_2O_4$	0.7	0.6	0.6	0.6	0.8	0.6	0.6	0.5
FeV_2O_4	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.5
$FeTi_2O_4$	0.9	0.5	2.0	2.8	2.8	4.9	6.9	4.9
$FeFe_2O_4$	1.3	–	1.6	2.1	0.2	–	2.5	1.8
$MnFe_2O_4$	1.2	0.9	1.4	1.1	1.4	0.7	1.2	0.9
$NiFe_2O_4$	–	0.2	0.3	0.3	–	0.2	0.3	0.4
Cr#	69.0	63.9	57.8	61.8	60.7	64.5	61.8	58.6
$Fe^{2+}/(Fe^{2+} + Mg)$	65.4	71.7	63.0	64.6	66.0	67.9	65.8	60.9

(18–21) Crystals with enclosed Ir-osmium; (21–25) crystals with enclosed laurite; FeO and Fe_2O_3 are calculated in terms of stoichiometry.

Zoned crystals of laurite–erlichmanite frequently enriched in Ir are common as inclusions in isoferroplatinum within ferrialumochromite in dunite of dunite–clinopyroxenite–gabbro plutons of the Ural (Tagil)–Alaska (Good News Bay) type in folded areas (Johan et al., 1989; Ivanov et al., 1995; Nazimova et al., 2003). In these rocks, laurite is frequently associated with the bowieite Rh_2S_3–kashinite Ir_2S_3 series minerals. Similar zoned crystals of laurite–erlichmanite enriched in Ir are a member of the PGE mineralization hosted in pegmatoid chromitite and titanomagnetite in dunite of platform ring dunite–wehrlite–clinopyroxenite massifs with elevated alkalinity (Inagli, Aldan Shield, etc.) (Nekrasov et al., 1994).

Laurite depleted in Os is abundant in the Bushveld low-alkali layered peridotite–orthopyroxenite–norite–anorthosite–ferrodiorite pluton in South Africa, where it is concentrated at the lower level of platiniferous cumulative chromitites of the UG-2 reef, the largest PGE deposit in terms reserves; etc. (McLaren, De Villiers, 1982; Merkle, Horsch, 1988; Maier et al., 1999; Zaccarini et al., 2002; Naldrett, 2004). Here, laurite frequently occurs as inclusions in braggite (Pt,Pd)S. Similar laurite is common in chromitites of the Stillwater pluton in Canada (Talkington and Lipin, 1986). Laurite occurs as inclusions in cumulative chromitites of the Sarany dunite–harzburgite–troctolite–gabbro pluton with elevated alkalinity on the western slope of the Urals; the composition of laurite is dominated by Ru at the lower chromitite horizons, whereas it becomes richer in Os at a higher level (Shilova and Vilisov, 1984).

Zoned crystals of As-laurite intergrown with sulfoarsenides (irarsite IrAsS, hollingworthite RhAsS) and thiospinels (cuprorhodsite $CuRh_2S_4$, ferrorhodsite $FeRh_2S_4$, cuproiridsite $CuIr_2S$) are common in layered peridotite–pyroxenite–gabbro–anorthosite plutons, the rocks and ores of which metamorphosed in green schist and amphibolite facies conditions (Barkov et al., 2004).

Thus, laurite from the Yoko–Dovyren peridotite is close in composition and assemblage to that from chromitites of alpine-type ultramafic rocks and close in composition to laurite from Bushveld and Stillwater chromitites.

COMPARISON OF Ir-OSMIUM FROM THE YOKO-DOVYREN PERIDOTITE AND OTHER PGE OCCURRENCES

Intermetallic compounds, osmium, iridium, and ruthenium alloys, are some of the most abundant endogenic PGM. Their compositions depend on many factors. Sulfide sulfur fugacity and temperature are two of the most important factors. These intermetallic compounds are rich in Ru at extremely low fS_2 and very high temperatures: rutheniridosmine, Os-ruthenium, and ruthenium. These minerals are commonly seen as isolated crystals and exsolution lamellae in a matrix of ferroplatinum within chromitite schlieren hosted by dunite of the central-type alkaline pluton, frequently accompanied by carbonatites (Guli and Inagli, East Siberian Platform, etc.) (Nekrasov et al., 1994; Likhachev, 2006). An assemblage of laurite–erlichmanite and Ir-osmium typical of chromitites of alpine-type ultramafic rocks (Stockman and Hlava, 1984; Talkington et al., 1984; Dmitrenko and Mochalov, 1987; Auge, 1988; Distler et al., 1989; Auge and Maurizot, 1995; Nakagawa and Franco, 1997; Ahmed and Arai, 2003; Hattori et al., 2004; Gonzales-Jimenes et al., 2009) or an assemblage of laurite–erlichmanite, bowieite–kashinite, Ir-osmium, and Os-iridium characteristic of chromitites of dunite–wehrlite–clinopyroxenite–gabbro complexes in folded areas (Vysotsky, 1913; Ivanov et al., 1995; Johan et al., 1989; Nazimova et al., 2003) form at moderately low fS_2. All of them are products of solid-phase transformations of high-temperature Pt–Fe–Os–Ir–Ru intermetallic compounds.

Ir-osmium from the Yoko–Dovyren peridotite is close in assemblage and composition to that from chromitites of alpine-type ultramafic rocks, e.g., on Borneo (Nakagawa and Franco, 1997), and in composition to Ir-osmium from dunite of the Guli peridotite massif with carbonatites and from placers in the vicinity thereof (Likhachev, 2006).

CONCLUSIONS

Plagioclase lherzolite from the lower part of the Yoko–Dovyren layered mafic–ultramafic pluton contains disseminated minerals of refractory PGE: laurite and Ir-osmium as minute protogenic inclusions in cumulative alumochromite. The composition of laurite written as endmembers is, %: 93–66, predominantly 92–82 RuS_2; 3–30, predominantly 5–12 OsS_2; 4–5 IrS_2. Two compositional types of Ir-osmium have been identified. Type 1 Ir-osmium is enriched in Os (58–73 wt %, on average 64 wt % Os) and Ru (3–8 wt % Ru) and contains 24–34 wt % Ir. Type 2 Ir-osmium contains, wt %: 57–58 Os, 27–30 Ir, 1.5–5.5 Ru, and approximately 10 Pt. Ir-osmium enriched in Ir, Pt, and Ru is intergrown with laurite. The composition of Ir-osmium from the Yoko–Dovyren peridotite is close to that of the synthetic alloy obtained at 1250°C and low fS_2 (Andrews and Brenan, 2002). Isolated crystals of both laurite and Ir-osmium contain minor Au (0.5 wt % in laurite, 1.4 wt % in Ir-osmium). Ir-osmium occurs as inclusions in crystals of cumulative alumochromite containing 0.2–0.8 wt % TiO_2. Laurite occurs as inclusions in crystals of cumulative alumochromite containing 1.2–2.8 wt % TiO_2. One of the alumochromite crystals with an inclusion of Os-poor laurite is enclosed in a crystal of cumulative olivine Fo_{86}. The only intergrowth of laurite and Ir-osmium is present in alumochromite with 1.1 wt % TiO_2. Alumochromite richer in Ti and laurite enclosed in it probably crystallized slightly later than Ti-poor alumochromite with enclosed Ir-osmium.

Ir-osmium is possibly evidence of a picritic magma undersaturated in sulfide sulfur during crystallization of alumochromite, because Os is one of the most chalcophile chemical elements. Judging from the experimental data of (Brennan and Andrews, 2001), intergrowths of laurite and Ir-osmium are evidence that the probable crystallization temperature of their cocrystallization did not exceed 1250°C.

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