

SUPPLEMENTARY TABLES 1-6

Sources of Ore Material in the Platinum-Group Element Deposits of Polar Siberia and the Middle Urals, Based on the Data from Radiogenic (Re–Os, Pt–Os) and Stable (Cu, S) Isotopes

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Table S1. Concentrations of highly siderophile elements (ppb) in chromitite and clinopyroxenite from the Guli and Nizhny Tagil massifs

Sample No.	Os	Ir	Ru	Rh	Pt	Pd	Au	Re	ΣHSE	Pt/Pd	Pt/Ir
G-40	277.8	215.9	370.6	—	1.0	0.27	n.a.	0.14	865.71	3.7	0.005
G-3	43	62	212	6.7	1.3	1.0	n.a.	0.29	326.29	1.3	0.021
G-5	94	34	56	4.6	1.1	1.0	n.a.	0.15	190.85	1.1	0.032
G-86	0.10	0.24	0.11	0.30	7.25	4.25	n.a.	0.54	12.79	2.0	31.97
NT-14	4	76	8	29	1190	16	22	n.a.	1345	74.38	15.67

Note. Samples G-40, G-3, G-5 – chromitites from the Guli massif; sample G-86 – clinopyroxenite from the Guli massif; sample NT-14 – chromitite from the Nizhny Tagil massif; «n.a.» – not analyzed.

Table S2. Chemical and S-isotope data for laurite and erlichmanite from the Guli massif

Analysis No.	Mineral, Figure	Ru	Os	Ir	Rh	Fe	Ni	S	As	Total	Ru#	$\delta^{34}\text{S}$
1	Lr, Fig. 5b	60.02	0.74	0.13	0.26	<d.l.	<d.l.	38.84	<d.l.	99.99	99	0.6
2	Lr, Fig. 5b	32.48	32.31	2.06	0.37	<d.l.	<d.l.	32.62	<d.l.	99.84	65	
3	Lr, Fig. 5b	34.01	30.71	2.32	0.27	<d.l.	<d.l.	32.77	<d.l.	100.08	68	0.0
4	Lr, Fig. 5b	52.34	9.11	1.60	0.23	<d.l.	<d.l.	36.81	<d.l.	100.09	92	
5	Lr, Fig. 5c	26.32	36.98	4.77	0.29	<d.l.	<d.l.	31.49	<d.l.	99.85	57	1.5
6	Erl, Fig. 5c	4.75	62.99	5.87	<d.l.	<d.l.	<d.l.	26.25	<d.l.	99.86	12	1.2
7	Erl, Fig. 5c	2.56	66.33	5.49	<d.l.	<d.l.	<d.l.	25.63	<d.l.	100.01	7	1.4
8	Lr, Fig. 5c	25.56	37.55	5.19	0.33	<d.l.	<d.l.	31.18	<d.l.	99.81	56	2.1
9	Lr, Fig. 5c	40.77	21.17	3.41	0.43	<d.l.	<d.l.	34.28	<d.l.	100.06	78	
10	Erl, Fig. 5c	4.40	63.79	5.14	<d.l.	<d.l.	<d.l.	26.31	<d.l.	99.64	11	
11	Erl	0.81	65.97	4.99	<d.l.	<d.l.	<d.l.	25.83	0.26	99.20	2	1.3
12	Erl	0.84	67.03	5.37	<d.l.	1.34	<d.l.	25.21	0.56	99.55	2	2.2
13	Erl	1.26	67.11	5.34	<d.l.	0.32	<d.l.	24.55	1.12	99.96	3	2.7
14	Erl	0.79	66.84	5.35	<d.l.	0.54	<d.l.	25.16	1.24	99.69	2	0.8
15	Lr, Fig. 5d	53.79	5.77	1.45	1.22	0.58	<d.l.	37.48	<d.l.	99.71	95	-2.0
16	As–Erl, Fig. 5f	3.96	48.47	16.24	<d.l.	0.31	<d.l.	23.91	5.93	99.68	13	6.0
17	As–Erl, Fig. 5f	3.35	49.84	16.01	<d.l.	<d.l.	<d.l.	23.74	5.79	99.91	11	4.7
18	As–Erl, Fig. 5f	1.63	50.76	16.86	<d.l.	0.83	0.34	23.18	6.13	99.78	6	6.0

Note. Lr – laurite, Erl – erlichmanite, As–Erl – As-bearing erlichmanite; an. 1–14: Ru–Os sulfides of the first type (assembled with Os–Ir alloys); an. 15: laurite of type 2 (assembled with ferroan platinum and Ru–Os–Ir alloys); an. 16–18: As-bearing erlichmanite of type 3 (in association with Os–Ir alloy); «<d.l.» – below the detection limit; detection limits (wt.%) were as follows: Rh – 0.27, Fe – 0.22, Ni – 0.12, As – 0.20; Ru# = 100 * Ru_{at.%} / (Ru + Os)_{at.%}.

Table S3. Chemical and Cu-isotope data for Pt–Fe minerals from clinopyroxenite–dunite massifs

Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample	60-1	70-3	60-4	NL-104	NL-107	248	258	K2-1	K2-2	K1-3	K1-5	K2-7	K2-8	K2-9
wt.%														
Fe	12.28	11.44	9.75	11.77	10.46	12.55	12.95	8.40	8.74	8.15	7.98	8.71	8.40	8.46
Ni	0.58	0.33	0.35	0.91	0.34	0.42	1.02	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.
Cu	0.51	0.53	0.99	0.42	0.22	0.76	0.71	0.57	0.59	0.71	0.87	0.40	0.50	0.64
Ru	0.64	<d.l.	0.32	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.	<d.l.
Rh	1.81	1.04	2.53	0.94	0.80	0.67	0.84	0.62	0.78	0.58	0.53	0.36	0.44	0.97
Pd	<d.l.	3.54	<d.l.	0.52	0.41	<d.l.	<d.l.	<d.l.	0.30	0.30	0.34	0.39	<d.l.	<d.l.
Os	0.53	<d.l.	0.22	0.63	0.24	0.21	0.27	2.73	0.13	0.29	0.22	0.25	0.24	0.26
Ir	5.62	1.51	4.57	3.11	2.03	4.22	4.49	2.80	0.76	1.40	2.09	1.01	2.45	2.31
Pt	78.28	82.11	81.20	81.75	85.39	81.09	79.66	84.83	88.83	88.61	88.13	88.94	87.82	87.14
Total	100.25	100.50	99.93	100.05	99.89	99.92	99.94	99.95	100.13	100.04	100.16	100.06	99.85	99.78
at.%														
Fe	31.64	29.65	26.25	30.75	28.48	32.61	33.05	23.91	24.60	23.22	22.73	24.68	24.00	24.01
Ni	1.42	0.81	0.90	2.26	0.88	1.04	2.48	—	—	—	—	—	—	—
Cu	1.16	1.22	2.35	0.96	0.53	1.73	1.58	1.43	1.47	1.77	2.18	1.00	1.25	1.59
Ru	0.91	—	0.48	—	—	—	—	—	—	—	—	—	—	—
Rh	2.53	1.46	3.69	1.34	1.18	0.94	1.16	0.96	1.19	0.90	0.82	0.55	0.68	1.49
Pd	0.00	4.81	—	0.71	0.59	—	—	—	0.44	0.45	0.51	0.58	—	—
Os	0.40	—	0.17	0.48	0.19	0.16	0.20	2.28	0.11	0.24	0.18	0.21	0.20	0.22
Ir	4.21	1.14	3.58	2.36	1.60	3.19	3.33	2.31	0.62	1.16	1.73	0.83	2.03	1.90
Pt	57.73	60.91	62.58	61.14	66.55	60.33	58.20	69.11	71.57	72.26	71.85	72.15	71.84	70.79
Total of PGE	65.78	68.31	70.50	66.03	70.12	64.62	62.89	74.66	73.94	75.01	75.1	74.32	74.75	74.40
Fe+Cu+Ni	34.22	31.68	29.50	33.97	29.88	35.38	37.11	25.34	26.06	24.99	24.90	25.68	25.25	25.60
$\delta^{65}\text{Cu}$, ‰	0.27	0.31	-0.02	-0.12	-0.38	-0.34	-0.19	-0.09	0.06	-0.24	0.25	-0.04	-0.04	-0.31

Note. Ferroan platinum from Quaternary deposits of the Gule River (an. 1–3) within the Guli massif, Novy Log Creek (an. 4 and 5) and chromitites (an. 6 and 7) of the Nizhny Tagil massif; isoferroplatinum from chromitite of the Svetly Bor massif (an. 8–14); <d.l. – below the detection limit; detection limits (wt.%) were as follows: Os – 0.13, Ru – 0.28, Rh – 0.27, Pd – 0.22, Ni – 0.12.

Table S4. Chemical and S-isotope data for laurite and Ir–Rh sulfides from the Svetly Bor and Nizhny Tagil massifs

Analysis, Figure	PGM	wt.%						at.%					Ru #	$\delta^{34}\text{S}$, ‰
		Ru	Os	Ir	Rh	S	Total	Ru	Os	Ir	Rh	S		
1	Lr	44.89	12.76	5.35	1.17	35.81	99.98	26.64	4.02	1.67	0.68	66.99	87	0.1
2	Lr	47.98	8.98	5.24	1.13	36.34	99.67	28.03	2.79	1.61	0.65	66.92	91	-0.4
3	Lr	44.80	12.98	5.26	1.17	35.76	99.97	26.61	4.10	1.64	0.68	66.97	87	0.0
4, Fig. 5g	Lr	47.19	9.62	5.91	1.20	35.68	99.60	27.91	3.02	1.84	0.70	66.53	90	-0.6
5	Lr	44.97	12.96	4.94	1.21	35.59	99.67	26.79	4.10	1.55	0.71	66.85	87	0.2
6	Lr	44.35	13.84	4.73	0.89	35.90	99.71	26.36	4.37	1.48	0.52	67.27	86	0.0
7	Lr	43.15	15.81	4.68	0.88	35.30	99.82	25.97	5.06	1.48	0.52	66.97	84	-1.1
8	Lr	44.10	13.90	5.18	0.93	35.75	99.86	26.28	4.40	1.62	0.54	67.16	86	-0.1
9	Lr	46.88	10.78	4.82	1.05	36.05	99.58	27.61	3.37	1.49	0.61	66.92	89	-0.7
10	Lr	45.48	12.98	4.72	1.07	35.74	99.99	26.98	4.09	1.47	0.62	66.84	87	-0.2
11	Lr	50.65	5.56	5.67	1.19	37.01	100.08	29.04	1.69	1.71	0.67	66.89	94	0.0
Mean (n=11)														-0.3±0.4
12	Ka	<d.l.	<d.l.	50.07	24.80	25.07	99.94	—	—	20.29	18.78	60.93	—	-0.2
13	Ka	<d.l.	<d.l.	49.96	24.85	25.02	99.83	—	—	2028	18.84	60.88	—	-0.8
14	Ka	<d.l.	<d.l.	50.77	23.92	25.04	99.73	—	—	20.67	18.20	61.13	—	-0.3
15	Ka	<d.l.	<d.l.	67.97	9.56	22.27	99.80	—	—	30.99	8.14	60.87	—	1.4
16	Ka	<d.l.	<d.l.	60.83	15.82	22.96	99.61	—	—	26.67	12.96	60.37	—	-0.1
17	Ka	<d.l.	<d.l.	51.21	23.79	24.75	99.75	—	—	20.98	18.21	60.81	—	-0.5
18	Ka	<d.l.	<d.l.	52.95	22.96	23.99	99.90	—	—	22.09	17.90	60.01	—	0.4
19	Ka	<d.l.	<d.l.	52.13	23.59	24.17	99.89	—	—	21.62	18.28	60.10	—	0.1
20	Bo	<d.l.	<d.l.	42.46	31.42	26.07	99.95	—	—	16.49	22.80	60.71	—	-0.5
21, Fig. 5h	Ka	<d.l.	<d.l.	57.22	18.99	24.17	100.38	—	—	24.57	15.23	60.20	—	0.7
22	Ka	<d.l.	<d.l.	57.75	18.05	23.51	99.31	—	—	24.85	14.50	60.65	—	-0.3
Mean(n=11)														0.0±0.6
23, Fig. 5i	Lr	56.24	2.73	2.43	0.31	37.99	99.70	31.41	0.81	0.71	0.17	66.90	97	1.7

Note. Lr – laurite, Ka – kashinite, Bo – bowieite. Svetly Bor: an. 1–11 – laurite from alluvial deposits; an. 12–22 – PGM from chromitite; Nizhny Tagil: an. 23 – laurite from chromitite; Ru#=100*Ru_{at.%}/(Ru+Os)_{at.%}; <d.l. – below the detection limit; detection limits (wt.%) were as follows: Os – 0.13, Ru – 0.28, Rh – 0.27, Pd – 0.22, Ni – 0.12.

Table S5. Os-isotope LA MC-ICP-MS data and calculated $\gamma^{187}\text{Os}(T)$ values of PGM from placer deposits of the Guli massif

Sample No., Mineral*, Figure	Atomic Proportions	$^{187}\text{Re}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}(T)$	$\gamma^{187}\text{Os}(T)$
Gule River					
H3-1, Os	Os _{1.0}	0.000019±8	0.12451±2	0.12451	-0.66±1
H3-2, Os	Os _{1.0}	0.000032±9	0.12450±3	0.12450	-0.67±2
H5-1, Os	Os _{0.93} Ir _{0.04} Ru _{0.03}	0.000073±9	0.12439±3	0.12439	-0.76±2
H6-1, Os	Os _{0.90} Ir _{0.07} Ru _{0.03}	0.00011±1	0.12446±2	0.12446	-0.70±1
H7-1, Os	Os _{0.92} Ir _{0.05} Ru _{0.03}	0.000039±9	0.12449±3	0.12449	-0.68±2
G1.5-1, (Os,Ir), Fig. 5d	(Os _{0.37} Ir _{0.30} Ru _{0.29} Pt _{0.03})	0.000005±4	0.12414±5	0.12414	-0.95±4
G1.5-2, Lr, Fig. 5d	(Ru _{0.30} Os _{0.02} Rh _{0.01})(S _{0.67})	0.000002±1	0.12409±3	0.12409	-1.00±2
7028-1, Lr, Fig. 5e	(Ru _{0.32} Os _{0.01})S _{0.67}	0.00015±19	0.12433±19	0.12433	-0.81±15
7028-2, Lr, Fig. 5e	Ru _{0.33} S _{0.67}	0.00002±4	0.12432±7	0.12432	-0.81±6
Ingaringda River					
6021-1, Os	Os _{1.0}	0.00002±1	0.12445±3	0.12445	-0.70±2
6021-2, Os	Os _{1.0}	0.000016±9	0.12449±3	0.12449	-0.68±2
6027, Os	Os _{0.87} Ir _{0.09} Ru _{0.04}	0.000139±7	0.12440±3	0.12440	-0.75±3
23-1, Os, Fig. 5e	Os _{0.66} Ir _{0.24} Ru _{0.11}	0.00048±1	0.12446±3	0.12446	-0.70±1
23-2, As-Erl, Fig. 5e	(Os _{0.22} Ir _{0.07} Ru _{0.05} Fe _{0.01})(S _{0.61} As _{0.06})	0.000041±6	0.12444±1	0.12444	-0.72±2
Mean (n=14)				0.12439	-0.76
2SD (n=14)				0.00013	0.10

*PGM abbreviations: Os – native osmium, (Os,Ir) – Ir-bearing osmium, Lr – laurite, As–Erl – As-bearing erlichmanite. The initial $^{187}\text{Os}/^{188}\text{Os}$ and $\gamma^{187}\text{Os}(T)$ values were calculated for the time of formation of the Os-rich alloys at 250 Ma using the parameters specified in the text. The uncertainty on the measured $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ is 2SE of the mean in the last decimal place; SD – standard deviation.

Table S6. Re–Os and Pt–Os isotopic N-TIMS data for chromitite and native osmium from the Guli massif

Sample No., Figure	$^{187}\text{Re}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}(T)$	$\gamma^{187}\text{Os}(T)$	$^{190}\text{Pt}/^{188}\text{Os}$	$^{186}\text{Os}/^{188}\text{Os}$	$^{186}\text{Os}/^{188}\text{Os}(T)$	$\mu^{186}\text{Os}(T)$
G-40, Fig. 4f	0.000250±12	0.1244256±7	0.12442	-0.7280±6	0.0000034±2	0.1198378±7	0.1198377	-2±6
67, Fig. 4a	0.00006±28	0.1246370±5	0.12464	-0.5585±4	0.0000044±0	0.1198397±5	0.1198397	+14±4
7-71, Fig. 4b	0.00006±28	0.1244995±5	0.12450	-0.6682±4	0.0000041±0	0.1198403±5	0.1198403	+19±4

Note. Sample G-40 – chromitite, samples 67 and 7-71 – native osmium (Os₈₇Ir₈Ru₅ and Os₉₄Ir₃Ru₃, respectively). The uncertainties on the isotopic ratios and the initial Os isotopic composition are quoted at 2SD based on the long-term reproducibility of the Johnson–Matthey Os standard at IGL (Puchtel et al., 2020). The initial $\mu^{186}\text{Os}(T)$ and $\gamma^{187}\text{Os}(T)$ values were calculated for the time of formation of chromitite and native osmium at 250 Ma using the parameters specified in the text. The uncertainty on the measured $^{187}\text{Re}/^{188}\text{Os}$, $^{187}\text{Os}/^{188}\text{Os}$, $^{190}\text{Pt}/^{188}\text{Os}$, $^{186}\text{Os}/^{188}\text{Os}$ is 2SE of the mean in the last decimal place.