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Paleogeodynamics

First data on the concentrations and distribution of noble metals in Ni-Cu sulfide ores of the South Maksut deposit (East Kazakhstan)

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The magmatic sulfide deposits in the Central Asian orogenic belt are hosted in a series of mafic–ultramafic intrusions in the Maksut zone (E Kazakhstan), the Kalatongke and the Huangshan zones in Xinjiang (NW China) and the Hongqiling zone in NE China. In the Maksut zone there are several intrusions, the best studied from which is the South Maksut intrusion with Cu–Ni–PGE mineralization.

The South Maksut Ni–Cu deposit contains 0.08 Mt nickel and 0.1 Mt copper with average grades of 0.4 wt. % Ni and 0.5 wt. % Cu, respectively (BAST, 2017). Since the South Maksut Ni–Cu sulfide deposits were discovered in the 1970s, many studies have been carried out [*Khromykh et al., 2013*]. This paper focuses on noble metal concentrations and mineralization of the South Maksut sulfide ores and crust of weathering, which is located on the eastern part of massif (Fig. 1).

Deposit geology and petrography. Early studies showed that the pluton is a small lopolith-like body [*Ermolov et al., 1983; Khromykh et al., 2013*]. The Maksut intrusion is mainly composed of olivine dolerite, olivine norite, and gabbronorite (Fig. 1, *a*). Olivine dolerite displays ophitic and poikilophitic textures. It consists of olivine with *f*=20–24 (10–20 %); two generations (60–70 vol. %) of plagioclase: 85–55 % An and 40–25 % An; clinopyroxene as subcalcic augite with *f*=30–40 (10–25 %); biotite (3–4 vol. %); ortho-

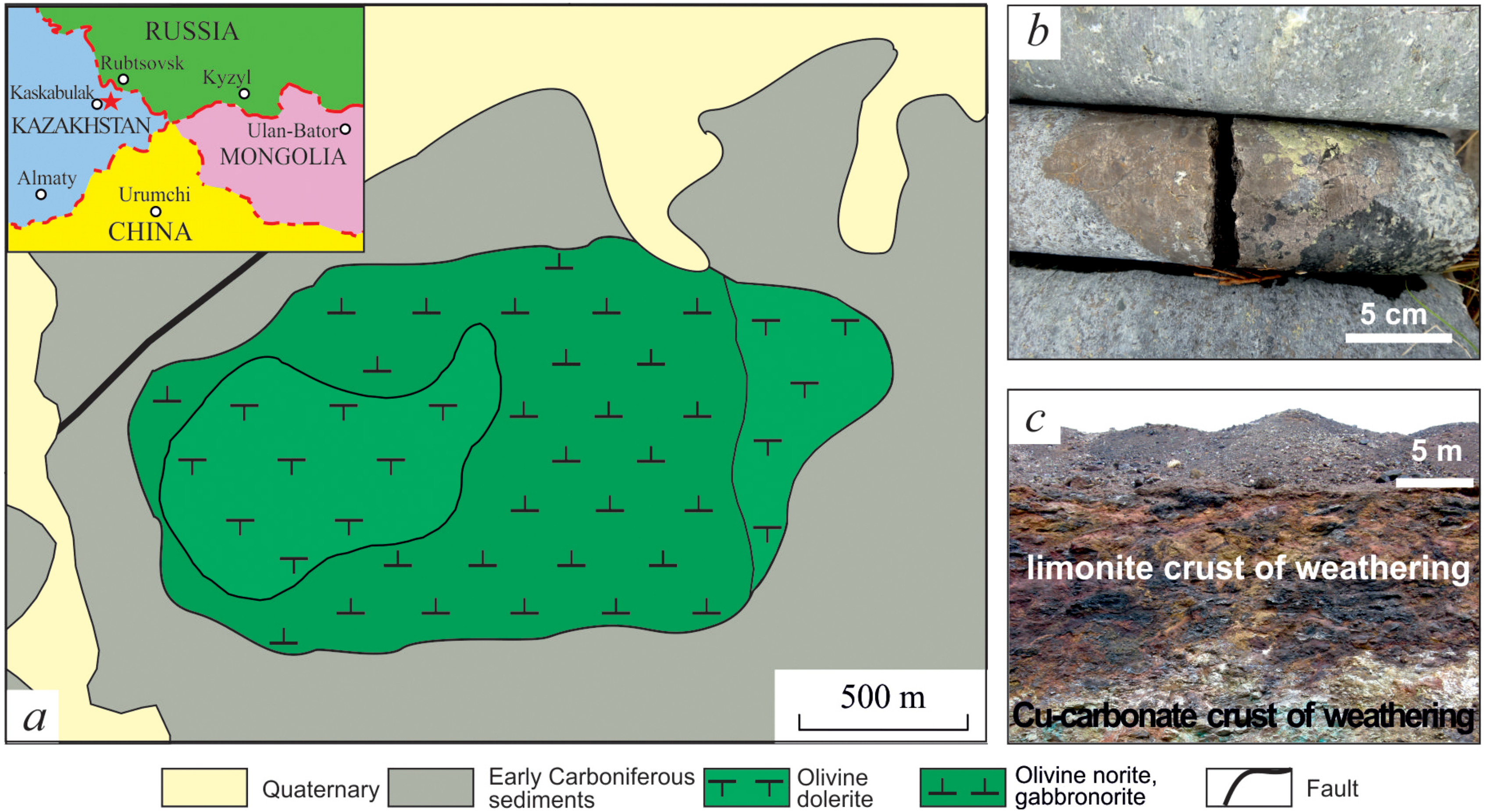

Fig. 1. *a* – simplified geological map of the South Maksut deposit (after [*Khromykh et al., 2013*]); *b* – sulfide ore drill-core samples; *c* – cross section through a weathering crust (open pit mine).

pyroxene with *f*=32–35 (1–2 %); brown hornblende (~1 vol. %); titanomagnetite (2–3 vol. %); and apatite (up to 1 vol. %). The textural relationships of olivine dolerite indicate the following crystallization sequence: olivine → olivine + plagioclase → plagioclase + clinopyroxene + orthopyroxene + magnetite. Olivine norite and gabbronorite are coarse-grained rocks with a gabbroic or, less often, gabbrodoleritic texture. They are composed of labradorite (65–70 %, 62–50 % An), olivine with *f*=30–35 (4–6 vol. %), orthopyroxene with *f*=22–25 (8–12 %), clinopyroxene with *f*=20–22 (1–2 %), hornblende (5–8 %), biotite (3–5 %), apatite, zircon, magnetite, and ilmenite. Disseminated, net-textured and massive Ni-Cu sulfide ores occur at the South Maksut deposit (Fig. 1, *b*). Limonite and Cu-carbonate crusts of weathering are in the eastern part of intrusion (Fig. 1, *c*).

Methods. We used the rock and ore samples collected from outcrops of the massif, from open pit mines and from the diamond drilling core. Analytical studies were carried out in the Institute of Geochemistry, SB RAS and in the Baikalian Analytical Center of Shared Use, Irkutsk Science Center, SB RAS. The contents of PGE (Ru, Rh, Pd, Pt, Ir, and Os), Au, and Re were defined by MS-ICP method at an Element 2 (Finnigan MAT) high-resolution mass spectrometer, with the use of an open acid decomposition and separation of matrix elements on KU-2-8 cation exchanger by the technique from [*Men'shikov et al., 2016*]. Precision and accuracy as demonstrated by analyzing reference materials, such as Zh-3, RP-1, Jp-1, are better than 10 %. The compositions of sulfides and PGM were defined in the IGC SB RAS by EPMA at a JXA8200 microprobe (JEOL, Japan). Mineral grains from polished samples were examined.

Results. *Ore mineralogy.* Major ore sulfide minerals at the South Maksut are pyrrhotite, chalcopyrite, and pentlandite. Pyrite and Fe-Ti oxides are also present in significant amounts (~1 and ~3 %, respectively). The dominant ores are the disseminated, its contain 10–50 vol % ore minerals and variable amounts of gangue minerals and consist of 75–80 % pyrrhotite, 15–20 % chalcopyrite, and 3–7 % pentlandite. The net-textured and massive Ni-Cu ores are composed of 46–75 % pyrrhotite, 3–16 % chalcopyrite, and 8–11 % pentlandite.

The precious minerals consist of electrum and platinum group mineral (PGM). They occur as numerous minute inclusions (<3 μm) and large (5–30 μm) grains (Fig. 2). Electrum was identified in chalcopyrite of the massive ore (Fig. 2, *a*). PGM are PdTe phase and were identified in pyrrhotite of the disseminated ores (Fig. 2, *b*).

Chalcophile elements (*PGE, Ni, and Cu*). The Ni contents in the sulfide ores increase with increasing sulfur content. Ni and Cu contents in the Cu-carbonate crust of weathering are higher then in the limonite ones (Table). The Au contents of the massive sulfides are higher then other types of ore and both type of weathered rocks. Total PGE contents of the disseminated ores are lower than those of the net-textured and the massive ores (Table, Fig. 3). However, on the basis of 100 % sulfide, PGE contents of the massive sulfides are lower than those of the disseminated sulfides. Compared with the typical magmatic sulfide deposits in the Tarim and Emeishan Large Igneous Provinces, the PGE contents of the South Maksut disseminated ores (Fig. 3, *b*) are similar to those of the Kalatongke and Limahe Ni–Cu sulfide deposits [*Song, Li, 2009; Gao et al., 2012*].

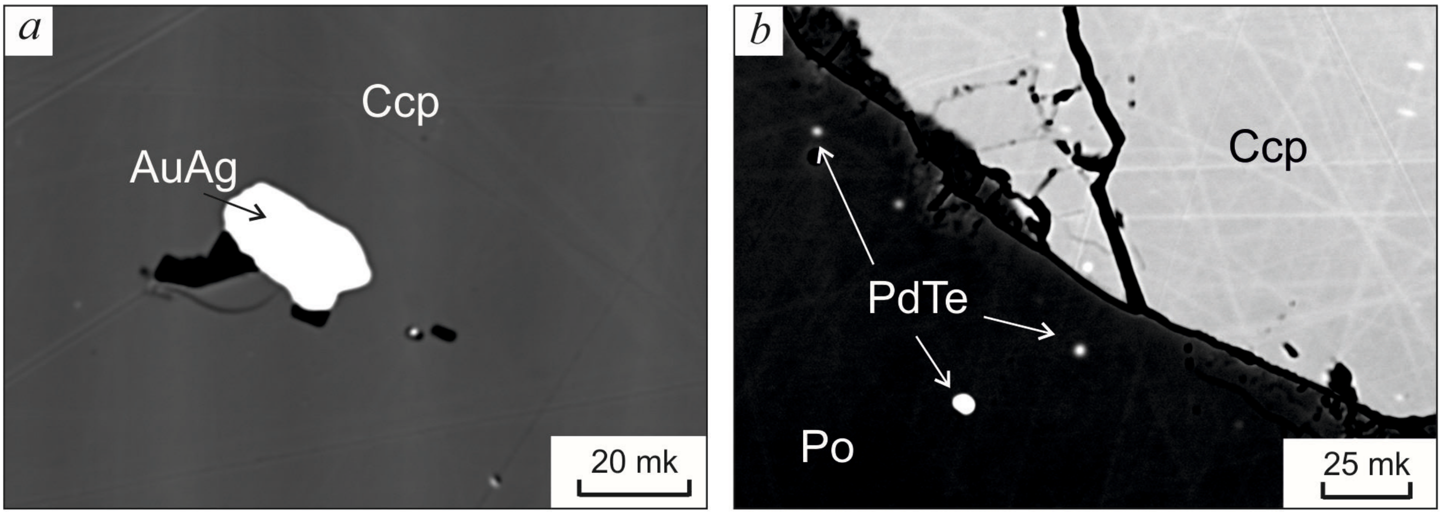

Fig. 2. Backscattered electron images of electrum (AuAg) and kotulskite associated with chalcopyrite (Ccp) and pyrrhotite: *a* – massive ores, *b* – net-textured ores.

Noble metal (ppb) and Ni, Cu (wt. %) contents of sulfide ores and crust of weathering (CW)

Sample	massive	Net–textured	disseminated	limonite CW	Cu–carbonate CW
Au	2150	40	210	45	200
Os	3.5	2	1.5	1.8	1.1
Ir	17.1	3.4	0.7	3.3	3.6
Ru	12	2.5	2.7	1.5	19
Rh	13.7	2.5	0.3	2.7	5.6
Pt	130	15	22	39	30
Pd	58	12.2	18.1	17.4	76.4
Ni	2.58	1.39	0.14	0.53	0.67
Cu	0.32	0.50	0.06	0.61	26.60
Cu/Pd	$5.5 \cdot 10^4$	$4.1 \cdot 10^4$	$3.3 \cdot 10^4$		
Pt/Pd	2.2	1.23	1.22	2.24	0.39
Pd/Ir	3.4	3.6	25.9		

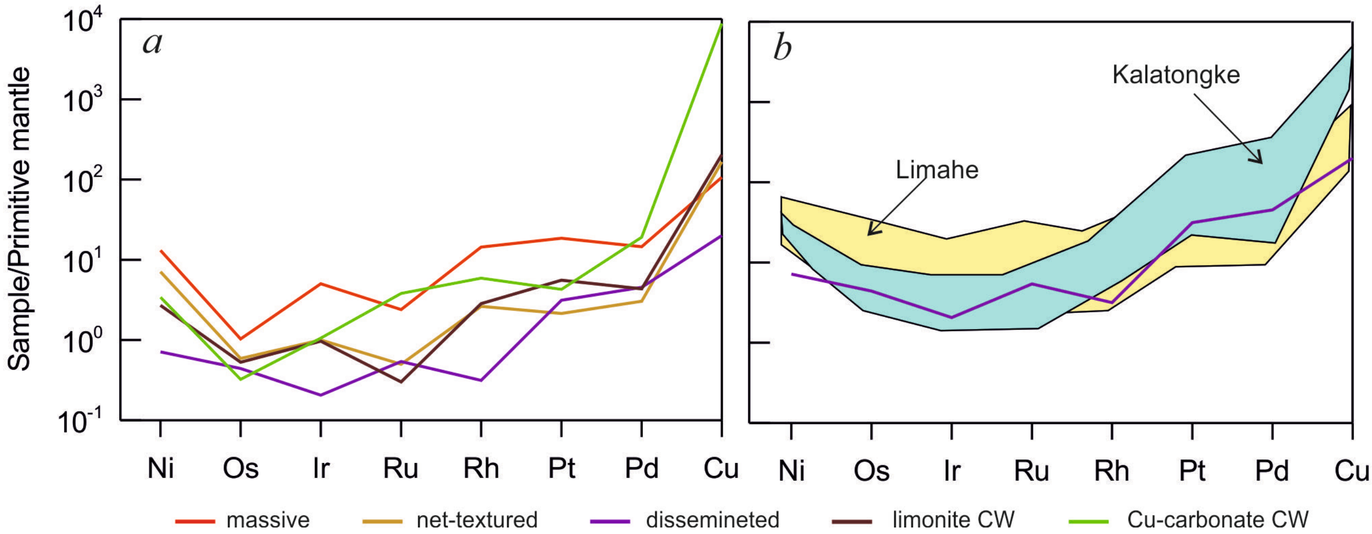

Fig. 3. Primitive-mantle-normalized chalcophile element patterns of the sulfide ores and crust of weathering (*a*) and disseminated sulfide ores on 100 % sulfide basis (*b*) of the South Maksut intrusion. The sulfide ores of the Limahe and Kalatongke magmatic sulfide deposits on 100 % sulfide basis are from [*Song, Li, 2009; Gao et al., 2012*]. Normalization values are from [*Barnes, Maier, 1999*].

Discussion and conclusion. Contents of PGE, Ni, and Cu of sulfides separated from silicate magmas are originally controlled by concentration of these metals in the silicate magmas and the ratio between silicate melt and sulfide liquid. The abundances of these metals in the sulfide ores would also be modified by reaction with portion of fresh magma, fractionation of the sulfide melt, and overprinted by late hydrothermal fluids. The South Maksut ores have Pd/Ir ratios much less than 100, indicating that the effects of late hydrothermal fluids are weak.

Very high Cu/Pd ratios indicate that the South Maksut sulfides segregated from PGE-depleted magma produced by prior sulfide saturation and separation.

The South Maksut Ni–Cu sulfide deposit has a typical magmatic genesis. The associated primary magma was produced by partial melting of metasomatized mantle in a postcollisional environment, that improve exploration potential of this deposit [*Song, Li, 2009*]. Noble metals accumulation in the crust of weathering is not observed.

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