Low Temperature Origin of the Ural-Alaskan Type Platinum Deposits: Geological, Mineralogical and Geochemical Evidence

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Alaskan-type mafic-ultramafic intrusions are well known as a source of platinum placers in the Urals, Far-East, Southeastern Alaska, Colombia, Australia and in other regions. More than one hundred and fifty years ago, some of the biggest platinum placers in the World were discovered and operated in the Urals, yielding about 400 tons of platinum during the first hundred years. The platinum placers are related with fourteen huge intrusive massifs situated in a mafic-ultramafic belt, extending about 900 km from the Central to the Northern Urals, along the 60th eastern meridian and between the 56th and 64th northern parallels and known among the geologists as the "Ural Platinum-bearing Belt" (UPB). Ore platinum deposits started to be worked in the Nizhny-Tagil dunite-clinopyroxenite massif (Central Urals) since the beginning of the 20th century, and produced several hundred kilograms of metal. These platinum ore deposits are among the best studied in the Urals to date, and have been described in several papers by Zavaritsky (1928), Wyssotzky (1913; 1928), Betekhtin (1935) and others. Zavaritsky and then Betekhtin argued that platinum minerals begin to precipitate together with chromite and continue after chromite crystallization down to the latest stage of ore formation, possibly in the presence of an alkali-rich fluid, however the details of such geochemical process in general were not clearly defined. Our study of Ural-Alaskan type complexes constrains to assume that platinum mineralization related with them forms in a wide time span, down to temperatures, much lower than those of the main magmatic events. This paper reports the results of our investigation.

Geological settings, morphology and relationship with the dunite host

Platinum mineralization is strongly related with chromitite within dunite. Commonly chromitites form isolated small pods, vein-like bodies or schlieren from 5 to 50-60 cm in length and 1-20 cm in thickness. Two types of chromitites have bean distinguished by Zavaritsky (1928) and Betekhtin (1935). The first type consists of massive ore grading into disseminated chromite toward the host dunite. This type, considered to be "syngenetic", characterizes for high-temperature olivine-spinel subsolidus equilibration and underwent the same high-temperature plastic deformation as the host dunite. Syngenetic chromitite usually does not contain economic grade of Platinum. The second type has not-ductile fabric, shows active relationship with the host dunite marked by sharp a boundary with serpentine rims. This type of chromitite is known as "epigenetic", and is extremely enriched in platinum, which often forms the cement of chromite grains. Only this type of platinum ore will be considered below.

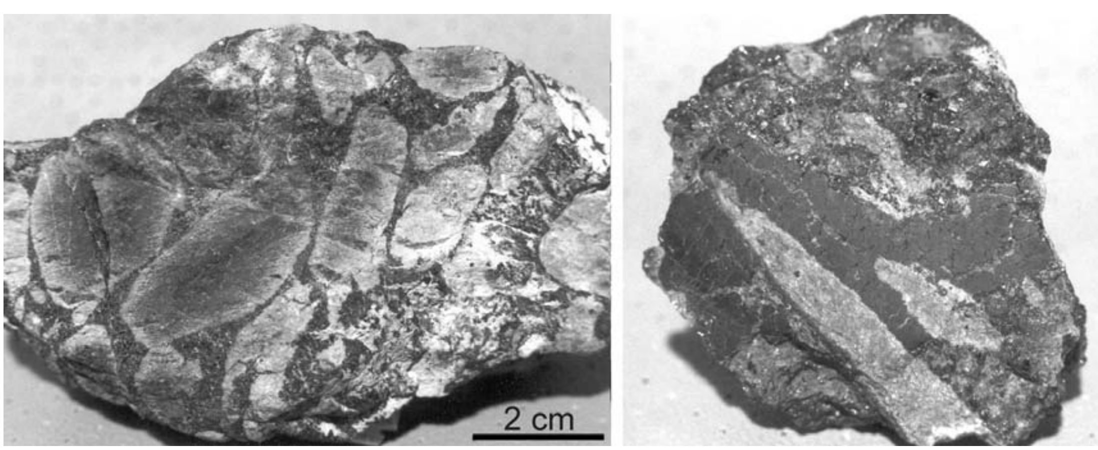

Figure 1. *Dunite-chromitite breccia. Chromite is in cement.*

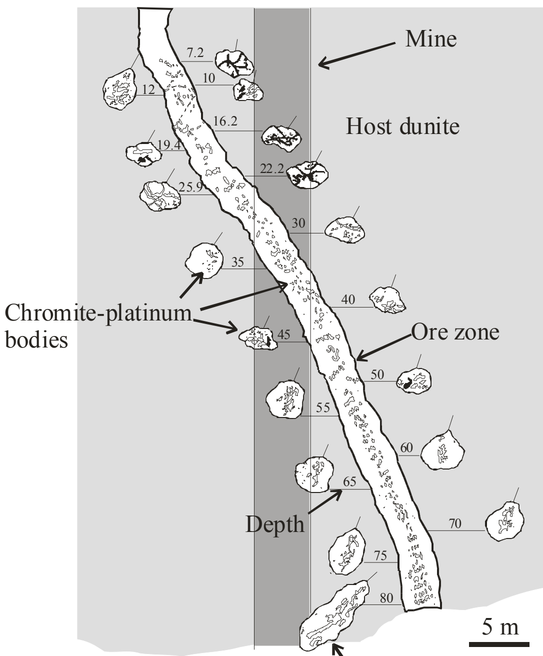

Figure 2. *Geological crossection of the "Gosshakhta" platinum deposit of the Nizhny Tagil massif, up to depth of 80 m. (Smirnov, 1978).*

The epigenetic ore is situated within recrystallized, medium- to coarse-grained dunite, often next to pegmatoid-dunite bodies. Sometimes they have clear active relationship with host dunite, that it is exemplified by the presence of breccia structure, in which dunite fragments are cemented by chromite (fig. 1), althoug the chromitites never cross the boundary of the dunite bodies. These chromitites have a clear postcinematic origin. They have undeformed mineral assemblages in the cement often with colloform structures. Chromite grains are affected only by brittle deformation possibly related with on-cooling shrinking, and form very typical polygonal contraction-shape network of cracks, which do not cross the ore-body boundaries. From time to time small pits filled with idiomorphic crystals of garnet, carbonate, micas, apatite, etc are preserved in the central part of cracks. These features support the conclusion that the ore body did not undergo any syncinematic plastic deformation as the host dunite. Numerous isolated small bodies of epigenetic chromitite are particularly frequent in some zones of the massif, forming the famous platinum ore deposits of Nizhny-Tagil: Gosshakhta, Krutoy Log etc (fig. 2).

Mineral composition and order of crystallization

At least three stages of ore formation were distinguished. During the first stage, the main chromite christallization event took place. It is accompanied by the inclusion of small grains of Platinum group minerals (PGM) along with single-phase (mainly olivine) and /or composite grains of silicate minerals (diopside, hornblende, phlogopite, chlorite, garnet etc). Platinum minerals (mainly isoferroplatinum and tetraferroplatinum) form during the second stage of crystallization together with diopside, pargasite, chromium and calcium-rich garnet, phlogopite, vesuviane etc. Deposits of the Urals are characterized by development of PGM as the cement of chromite grains. Olivine is absent, but a lot of serpentine occurs as the intersticial filling. In the most cases, serpentine is the dominant silicate in ore. The silicate minerals have similar composition in the cement and in the inclusions. In the third stage of ore formation, development of colloform serpentine, chlorite and garnet took place. Calcite and apatite are also present. This assemblages fill miarolitic cavities among chromite grains and holes in the central parts of the contraction-cracks cutting across the chromitite.

Epigenetic chromitites have contoured by narrow (5-10 mm) rims of pure serpentine. The degree of serpentinization of the host dunite is less than 40-60%. We suppose that these rims are the result of high temperature (400-500^oC) reaction between the fluid-rich ore forming system and the surrounding ultramafites. The main stage of serpentinization of the dunite has been related with meteoritic water and took place under low-temperature. Generally it is well known, that the ore chromite is more Mg and Cr rich in comparison with the accessory spinel. Using Mossbauer spectroscopy we have shown also, that ore chromite is more oxidized than the accessory chromite (Chaschukhin et. al, 2002). But at the first time the wide variations of chromite composition in some ore bodies of the Nizhny-Tagil massif were arranged (fig. 3). The thickness of the studied bodies varies from 2 to 5 cm. Chromite compositions display symmetrical zoning in the ore bodies. The Cr_2O_3 content increases on 2-5wt. % from the margin to the core of the ore body. Although, the maximum differences in Cr_2O_3 between ore and accessory chromite approaches 8-10wt %. Al_2O_3, MgO, *mg*-number, $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ increase and FeO decreases, from boundary to core in the ore bodies, although the Cr/(Cr+Al) is constant close to 0.81-0.82. Such distinct chemical variation of chromite composition even in very small bodies could be preserved only under low temperature when all exchange processes were finished.

Olivine occurs as inclusions only in massive chromites. It forms subidiomorphic grains of 10-100 µm in size. *Mg*-number is very high, usually in the range 0.95-0.98. Olivine is enriched in CaO (0.2-0.4wt. %) and Cr_2O_3 (0.5-1.5wt. %) and poor in Ni. All other Fe-Mg silicates from the inclusions and from the ore cement (diopside, pargasite, phlogopite, chlorite, garnets) are also characterized by low Fe/Mg ratio and enrichment in chromium. Phlogopite from the inclusions is K-rich , but it becomes Na-rich in miarolitic cavities and in cement. Amphibole is chromium and sodium rich pargasite. High chromium chlorite has absolutely unusual composition extremely enriched in sodium, up to 2-3wt. %. Minerals enriched in alkalis and volatiles are frequent in the inclusions, ore cement, miarolitic cavity paragenesis, and in the intergranular material of the dunite. Native metals (iron, copper, nickel) nickel sulfides, magnetite, Ti-Fe-K-Na-Ca-rich spherules formed during the latest stage of ore formation, at low temperature. The coexistence of magnetite and native iron also reflects low temperature equilibrium at less than 565^{o}C, according to magnetite-iron buffer. This is taken as a demonstration that alkaline fluids were present in the platinum all through the platinum-precipitation event, in a wide range of temperatures. Similarity of the mineral compositions reflects similar condition of crystallization. We suppose that the main PGM and silicate minerals are post-chromite phases crystallized above the olivine-H_2O fluid reaction, which took place at the temperature about 400-500^{o}C.

T-fO_2 condition of the chromite-olivine equilibrium in the platinum ore

Using Mossbauer spectroscopy for determination of real Fe^{3+}/Fe^{2+} ratio in chromite and a new empiric coefficient for Ti, reflecting its influence on the temperature, we have calculated the T-fO_2 conditions for olivine-chromite equilibrium in both the platinum ore and the host dunite of the Nizhny-Tagil massif (Chaschukhin et. al, 2002) on the basis of the Ballhaus-Berry-Green oxygen geobarometer (Ballhaus et. al, 1991).

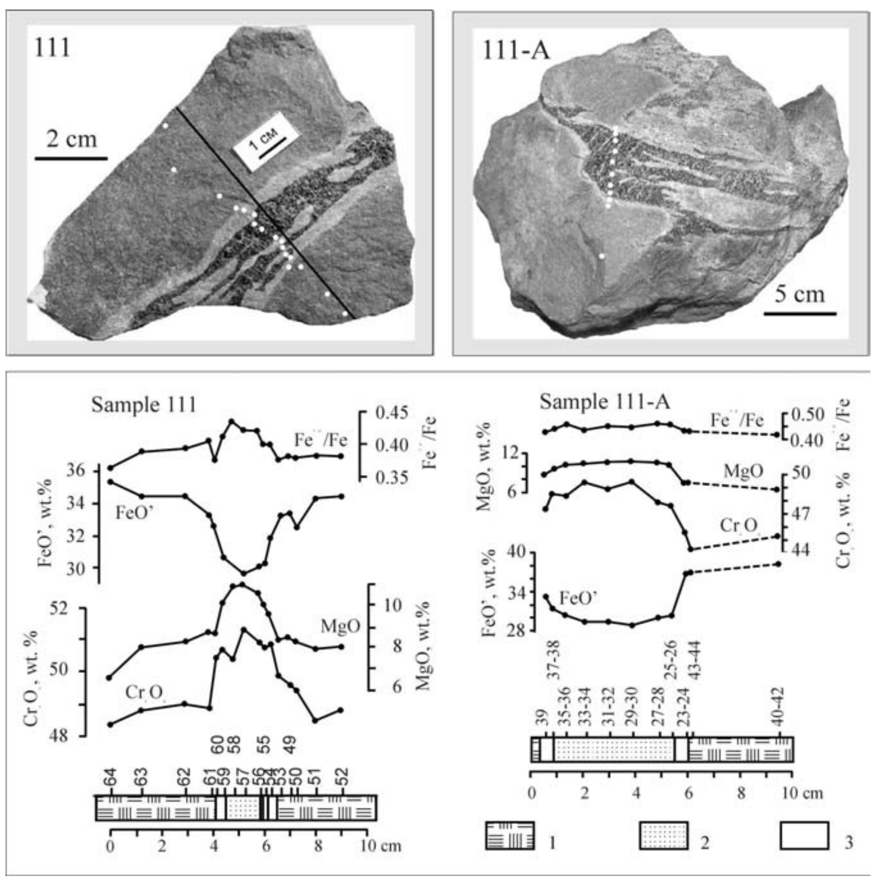

***Figure 3**. Photos of the 111 and 111-A chromitite bodies from the Nizhny-Tagil massif and variations of chemical compositions of chromite across these bodies. 1 – hosted dunite; 2 – chromitites; 3 – serpentinite rim.*

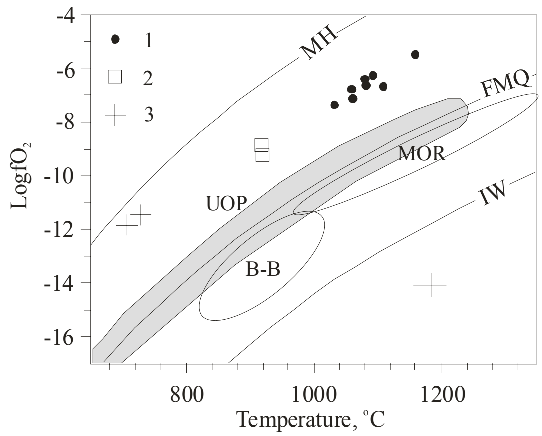

Figure 4. *Log*fO_2*-T diagram for dunite and platinum ore of the Nizhny-Tagil massif. 1 – dunite; 2 – recrystallized coarse grained and pegmatitic dunite; 3 – epigenetic chromite-platinum ore. MOR – Middle ocean ridge peridotites (Ballhaus et al, 1991); B-B – Beni-Bousera lherzolite (Ballhaus et al, 1991); 4 – UOP – Uralian ophiolite peridotite (Chaschukhin et al, 1998).*

Average temperature of Ol-Sp equilibrium for dunite and syngenetic chromitites is about 1100°C, for the re-crystallized dunite pegmatoids is about 900°C, and for platinum-enriched epigenetic ore is less than 750°C (fig. 4). Platinum-rich epigenetic chromitites are more oxidized (+4 unit logfO_2 QFM) in comparison with the host dunite and syngenetic chromite segregation (+2 unit logfO_2 QFM). These geochemical features support a late origin for the platinum ore deposits of the Urals.

Conclusion

1) Nizhny-Tagil type chromite-Pt ore forms at the latest stage of dunite consolidation, after high temperature plastic deformation and recrystallization of rocks. This is supported by the presence of dunite-chromite breccias and well-preserved colloform textures in the ore cement. 2) Ore bodies have distinct zonal structure, reflecting that they have formed at temperatures lower than those required for exchange processes. 3) The largest amount of Platinum-group minerals precipitated after chromite together with chromium-rich silicates enriched in alkalis and calcium. Water-rich fluid was present during the entire sequence of mineral crystallization. All the elements incompatible with the chromite-platinum ore association (i.e.: Ca, Na, K, P, Ti, H_2O etc) were extracted from the interstitial assemblage of the host dunite during the latest stage of rock deformation. Perhaps, this mechanism was also responsible for the chromite and platinum enrichment. 4) Olivine-chromite equilibrium reflects low temperature (<750°C) and high oxidation conditions (+4 unit logfO_2 QFM) for the formation of the platinum ore.

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