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GEOLOGY

Nature of the Ural Platinum Belt and Its Chromite–Platinum Metal Deposits

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The Urals is a world-known standard for study of the genesis of platinum deposits in zoned mafic–ultramafic complexes of the Uralian or Uralian–Alaskan type. However, many principle aspects of their geology and geochemistry need additional study at the modern level to substantiate formation models and develop criteria for forecasting ores. The data on new platinum occurrences (Dunitov and Syrkov) and extensive materials from the Gosshakhta, Krutoi Log, and other abandoned deposits provided the basis for the study of processes of rock and ore formation. In total, over 400 samples have been studied, 245 samples from the Solov'evy Gory Massif included. Contents of PGE (Pt, Pd, Rh, Ir, Os, and Ru) in them were determined by the chemical–spectral and spectral photometric methods. Some samples were studied by the ICP-MS method in the BRGM laboratory (France).

The Uralian Platinum Belt (UPB), a classical object, has attracted the attention of researchers for more than 120 years [1–15 and others]. This giant structure (approximately 1000 km long) is represented in the Middle, North, and Cis-Polar Urals by a chain of 13 gabbro and granitoid massifs located in the westernmost part of the paleoisland-arc segment of the Urals east of the Main Uralian Deep Fault (MUDF). The internal structure and composition of the UPB, where gabbroids constitute no less than 80%, are well studied [1–8, 15, and others]. At the same time, the nature of the UPB and its place in the geological history of the Urals have remained unclear for a long time. Recent studies resulted in the development of a new hypothesis that explains the formation of the UPB in the following way: this unique (in size and diversity of rocks and ores) belt is an island-arc structure composed of crystallization products of melts generated at different depths above the subduction zone. This assumption is based on studies showing that the MUDF represented a subduction zone with an eastward-dipping seismofocal plane in the Early–Middle Paleozoic, whereas the main volcanogenic zones of the Urals are relicts of island arcs and back-arc basins [10 and others]. The island-arc nature of the belt is reflected in geochemistry: gabbroids are similar to island-arc tholeiites in terms of contents of most elements.

It was established long ago [3, 4, 8, and others] that rock complexes of the UPB demonstrate distinct (although complicated) lateral trends: the SiO_2 content in rocks increases from west to east, while ultramafic–gabbroic complexes are replaced in this direction by relatively younger and shallower granitoid counterparts. Hence, the erosion depth of the Tagil island-arc terrane decreases in the eastern direction. Moreover, volcanogenic complexes of the Tagil megazone overlie the UPB section, which represents, probably, its magmatic basement and induces the Uralian gravity supermaximum. The gradual narrowing and subsequent closure of the western Ordovician ocean, which is represented now by the relict Salatim serpentinite suture, was probably responsible for generation of silicic magmas (and syenites) at the terminal stage of UPB formation. At the same time, sedimentary sequences of the continental base of the East European Platform, which were water-saturated and enriched in sialic material (including the associated trace elements and minerals, such as zircon), were gradually involved and melted in the UPB-underlying subduction zone represented by the MUDF (at first, this process also involved the oceanic crust). Metasomatism and hydrometamorphism of the amphibolite and greenschist facies, which are widespread in the UPB, and development of mafic–ultramafic pegmatites were promoted by the fluid flow (primary oceanic waters) ascending from the subduction zone due to dehydration of subducted material. These fluids also fostered migration and redistribution of PGEs (up to the formation of deposits) [4, 6, and others].

Rocks of the UPB are reliably dated. The age of hornblendites and clinopyroxenites of the Kachkanar Massif is estimated by the K–Ar method (isochron included) at 415–432 Ma [8 and others]. Sm–Nd isochrons determined for gabbronorites of the Chistop and

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Kumba massifs indicate ages of 419 ± 12 and 423 ± 18 Ma, respectively [13 and others]. The U–Pb (ID-TIMS) method provided ages of 417 ± 2 and 415 ± 10 Ma for zircons from plagiogranites of the Kytlym Massif that terminate magmatism in the UPB [7]. The age of gabbronorites of the UPB coincides with the age of eastern basaltic andesites of the Imennov Formation of the mature island-arc setting. This age was specified in [10] based on the bed-by-bed study of conodont assemblages from the Uralian superdeep borehole (SD-4) as corresponding to the Llandoverian–Wenlockian boundary (*Pterospathodus amorphognathoides* Zone). The REE trends in volcanics of the Imennov Formation and calc-alkaline gabbroids of the UPB are also similar. This fact indicates the comagmatic nature of intrusive and volcanic members of the Tagil island-arc terrane.

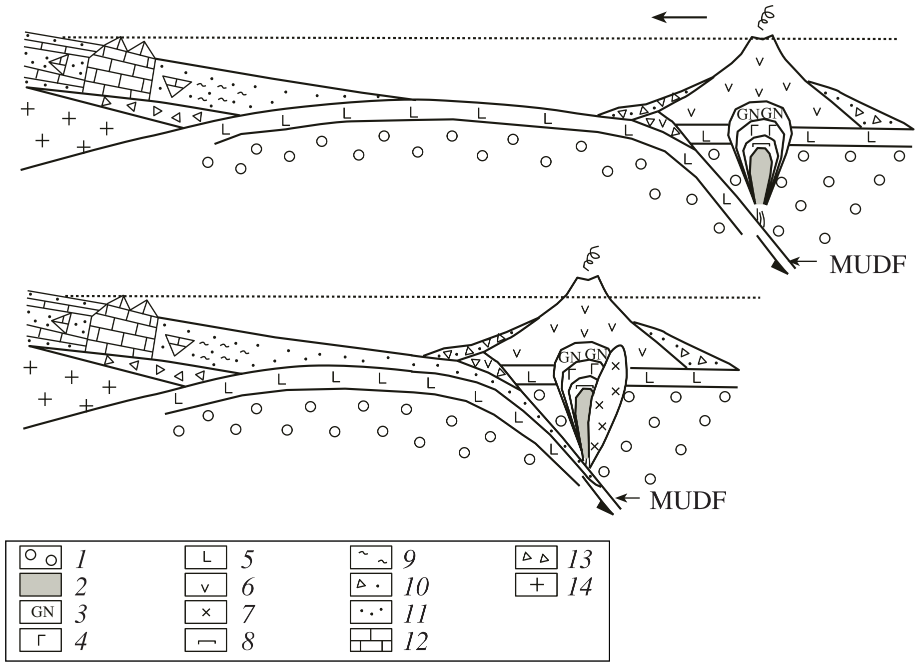
The above-mentioned facts and others suggest that rocks younger than 410–415 Ma are absent in the UPB and dates below these values reflect stages of plastic deformation and metamorphism of rocks of the UPB. These processes distorted isotopic systems and occurred in the Devonian and Carboniferous, in particular, during the collision of the Tagil Terrane with the East European Platform. For example, structural data on the Solov'evy Gory dunite body (the largest one in the UPB) and other objects demonstrate that large chromite–platinum ore bodies (Gosshakhta and others) are characterized by orientations similar to those in chromite schlieren in the surrounding dunites. Frequently, they crosscut older and high-temperature orientations of olivine. In addition to fractures, folds of different temperature generations are also developed in ultramafic rocks. Structural evolution of the UPB proceeded generally under decreasing temperatures and pressures. They were dominated by two processes: (1) ascent of diapir-shaped cooling magmatic bodies to the upper crust (this was accompanied by superposition of structures of plastic deformations on magmatic structures and formation of concentric (nearly isometric) megastructures of magmatic bodies with steeply dipping lineation); (2) younger sinistral deformations that formed linear massifs with nearly horizontal lineation probably due to oblique collision [10 and others] of the Tagil Terrane with the East European Platform. The present-day structures of rock massifs of the UPB are related to these processes. Nearly isometric bodies are largely recorded in the middle part of the UPB, while linear (tectonically crushed) massifs are concentrated in its marginal southern and northern parts.

Important results were obtained recently for the so-called Kachkanar Complex of the UPB, i.e., dunites, clinopyroxenites, and olivine–anorthosite gabbro. The Sm–Nd isochron yields an age of 561 ± 28 Ma for olivine–anorthosite gabbro from the Kumba Massif [11]. The Sm–Nd isochron based on 14 samples of dunites, wehrlites, and clinopyroxenites from the Kytlym Massif provides an age of 551 ± 32 Ma [12]. Thus, these dates obtained in different laboratories suggest that the UPB includes Vendian–Early Cambrian rocks that constitute a large volume of the Kytlym, Kumba, and, likely, other massifs.

What is the nature of the Vendian–Early Cambrian rocks? When and why did they appear among other rocks of the Later Ordovician–Silurian island arc? We propose a geodynamic interpretation of Vendian dates (Fig. 1) based on the suprasubduction model of the UPB [9]. It is understandable that suprasubduction magmatism could hardly generate the dunite–wehrlite–clinopyroxenite complex, because it is well known that melting of hydrated basalts of the subducted oceanic crust produces substantially more silicic basaltic andesite and andesite magmas. The most realistic formation mechanism of the dunite–wehrlite–clinopyroxenite association is the interaction of basaltic andesite melts ascending from the subduction zone with ultramafic rocks of the overlying mantle, i.e., with the mantle wedge formed during the initiation of the ensimatic island arc. Hence, the lower (Kachkanar) complex of the UPB, i.e., at least the major portion of dunites, clinopyroxenites, and olivine–anorthosite gabbro, was formed according to this scenario. According to this hypothesis, the Vendian–Early Cambrian dates indicate the age of upper mantle rocks at the base of the Tagil island arc. In addition to interaction with andesitic melts, some fragments of the mantle wedge were accreted and incorporated as blocks in ascending diapirs. This process was accompanied by deformations and plastic flow of the blocks together with younger gabbronorites. These features are well documented in massifs of the UPB [3, 8, 15, and others].

Recent studies also revealed independent facts, which may be used for testing the proposed model. These facts are represented by direct data on the age of ophiolitic massifs in the northern Urals. The determinations concern large alpine-type ultramafic rock massifs (Voikar–Syn'ya and Syum-Keu) with exposures of the most complete sections of the oceanic crust and upper mantle. According to [5], harzburgites, lherzolites, and gabbronorites of the Syum-Keu Massif have a Vendian age (604 ± 39 Ma; isochron date based on nine bulk samples and minerals in them). The U–Pb (SHRIMP-II) dating [14] of seven zircon grains from chromites of the Voikar–Syn'ya Massif yielded a concordant age of 586 ± 6 Ma. The good agreement between Vendian dates of the Kachkanar Complex and dates obtained for alpine-type ultramafic massifs supports our model, according to which the major part of dunites, clinopyroxenites, and olivine gabbro of the UPB was produced by interaction between andesitic melts ascending from the Silurian subduction zone and ultramafic rocks of the so-called mantle wedge.

The dunite–wehrlite–clinopyroxenite–tylaite association of the UPB is characterized by universal geochemical platinum specialization and the following succession of decrease in contents of noble metals: Pt, refractory PGEs (Ru, Ir, and Os), Rh, Pd, and Au. The average Pt content increases regularly from tylaites and



Schematic geodynamic formation of the Uralian Platinum Belt. (*1*) Mantle; (*2*) dunites; (*3*) gabbronorites; (*4*) Ol–An gabbro; (*5*) oceanic crust; (*6*) andesitoids; (*7*) granitoids; (*8*) clinopyroxenites; (*9*) cherts; (*10*) accretionary prism; (*11*) terrigenous sequences; (*12*) reef limestones; (*13*) rift formations; (*14*) basement of the East European Platform.

troctolites to olivine clinopyroxenites, wehrlites, and dunites (5–10, 20–30, and 50–70 ppm, respectively). The geochemical distribution of PGEs in dunites is controlled by their compositions and positions in the sections of dunite bodies. The study of equilibrium parageneses of coexisting minerals in dunites and chromite–platinum metal ores (chrome-spinels, olivines, and Pt) demonstrates the heterogeneity of ore-enclosing dunites and the polygenic nature of platinum metal ores of the Uralian type [2]. The most widespread ordinary (background) dunites related to the magmatic stage of the formation of zoned complexes are supplemented with many other varieties related to the postmagmatic stage of rock transformation under the influence of deformations and fluids during their ascent to the upper crust under conditions of lower temperatures and pressures. The low content of dispersed Pt (from 10 to 70 mg/t) in background dunites correlates with their composition and position in the dunite section. In the thin-banded chromite-bearing varieties and segregation chromite schlieren confined to the dunite bodies, the Pt content is also low (up to 100–200 mg/t) and the composition of chrome-spinels is similar to that of their counterparts from background dunites. In ordinary dunites, we have discovered paired (negative and positive) geochemical platinum anomalies and standard megazonality in dunite bodies: background dunite–negative geochemical anomaly–positive geochemical anomaly (chromite–platinum orebody). All large chromite–platinum concentrations and conjugate negative aureoles are associated with brittle deformation zones. For example, we have discovered a new platinum ore zone in the Dunitovyi area at the front of a large negative geochemical aureole located in the northern part of the Solov'evy Gory dunite quarry. The Pt content within the negative anomaly ranges from traces (<10 mg/t) to 50 mg/t. According to data on quarries and boreholes, the width of anomalies varies from 30–50 to >100 m and they are traced to a depth of >100 m along the dip. Areas with negative anomalies are characterized by a sharp (5–50 times) decrease of Pt concentrations as compared with ordinary background concentrations (from traces to 5–20 ppm) and a simultaneous notable decrease in the Fe index of olivine to 6.0–7.5 mol %.

The detailed mapping [1, 4, 6, 8, 15, and others] of dunite bodies in the UPB made it possible to establish the spatial distribution of different dunite types, which emphasize their heterogeneity, and to outline main structural elements of dunite cores. The finest grained structural dunite varieties usually constitute small areas and near-meridional linear zones in the central and western parts of massifs. More abundant fine-grained dunites are widespread in central parts of massifs and along peripheries of dunite cores. Medium- to coarse-grained dunites are spatially confined to their central (near-apical) parts. Dunite members of the dunite–wehrlite–clinopyroxene–tylaite association in rocks of the UPB were formed under *PT* conditions of the magmatic stage [6, 8, and others]. The results show that the geochemical distribution of Pt within dunites, which represent magmatic products, does not produce anomalous ore concentrations or, moreover, platinum ore deposits. Ore concentrations of PGEs are observed only in some areas of dunite bodies controlled by the structural and compositional properties of dunites as the result of redeposition and input of PGEs by ore-forming fluids at the postmagmatic stage of dunite evolution. The postmagmatic evolution is reflected in the sharp change of textural–structural and compositional characteristics, as well as regular replacement of coexisting chrome-spinels, olivine, and platinum parageneses in ores.

The initial stage of the formation of ores of the Uralian type (chromite subtype) is characterized by minerals of the high-temperature paragenesis: chrome-spinels with maximal Cr and Mg contents, olivines with minimal Fe (6–7%) and CaO (0.18–0.25%) concentrations, and isoferroplatinum with the highest Ir and lowest Fe contents and inclusions of iridium minerals. The sharply dominant large- and medium-sized Pt (400–1000 μm or more) provides the high placer-forming potential of ores at this stage.

The next stage of ore formation (dunite subtype) is characterized by minerals of a different paragenesis: chrome-spinels with moderate Cr, lower Mg, and higher Fe contents; olivines with higher Fe (7–8%) and CaO (0.25–0.32%) concentrations; and tetraferroplatinum with higher Fe, Cu, and Ni contents and lower Ir concentrations (iridium minerals are absent). The sharply dominant small and fine grains (approximately 100 μm or less) of such platinum reduce sharply the placer-forming potential of ores at this stage.

The terminal low-temperature stage of ore formation (pegmatite subtype) is characterized by the following paragenesis: chrome-spinels with minimal Cr and Mg contents and maximal Fe and Ti contents; olivines with the highest Fe (8–9%) and CaO (0.50–0.60%) concentrations; tetraferroplatinum with minimal Ir contents and maximal Pd and Cu contents, Pd-tulameenite, and a wide spectrum of Pt- and Pd-bearing copper alloys. Ores of this stage virtually lack the placer-forming potential because of the sharp predominance of fine- to micro-grained metal (<100–50 μm). Terminal stages of the formation of Uralian-type ores are characterized by a decrease in temperature, a simultaneous increase in f_{O_2} and f_{S_2} (this is evident from variation of the olivine composition, e.g., an increase in the Fe index from 4–6 to 9–10 mol %), increase in the degree of Fe oxidation in coexisting silicates, and abundance of sulfide minerals in Pt–Pd ores of the pegmatite subtype.

Thus, the formation and transformation of chromite–platinum metal ores of the Uralian type are related to the postmagmatic stage of their evolution. The placer-forming potential of these ores decreases sharply at terminal stages of their formation. The relative degree of development of different platinum metal ores with sharply different placer-forming potentials in dunite massifs of the UPB represents an essential criterion for forecasting platinum metal placers.

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