

***Au-Ag-Te-Se deposits***

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**Gold-silver paragenetic evolution in ore deposits of the  
Magnitogorsk paleoisland arc, Southern Urals**

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**Abstract.** Economic gold deposits in the Southern Urals are found within structures of the Magnitogorsk paleoisland arc system, and are also associated with later collisional processes and syn-collisional granite intrusions. Each stage of island arc evolution is characterized by a specific ore type, featuring specific mineral associations and forms of the noble metals. These features in turn reflect the conditions of mineral formation.

**Key words:** gold, silver, island arc, massive sulphide, epithermal deposit, supergenesis

**Introduction**

Noble metals have traditionally been exploited in the Urals. Their recovery was initiated in the Middle Ages, and expanded dramatically at the end of the 19<sup>th</sup> and beginning of the 20<sup>th</sup> Centuries. Gold exploitation continues today.

At first, coarse gold was extracted from placers and quartz-vein deposits by gravitational methods. Since the end of 19<sup>th</sup> Century, amalgamation (with mercury) was used to achieve a more complete gold extraction from different deposit types, including the 'iron caps' of sulphide-rich orebodies. Tun and heap leaching by cyanidation of the oxidized ores was carried out since the mid-20<sup>th</sup> Century. Today, gold is also extracted from Cu and Zn flotation concentrates.

Knowledge of the size of gold grains, the associated minerals and the mineral form of gold, which all depend on the genetic type of gold deposit, are very important both for practical use and for scientific understanding.

**Geodynamic and geological background**

In the Southern Urals, economic concentrations of gold are found in deposits located in structures of the Magnitogorsk paleoisland arc system and within quartz-veins from beresite-listvenite formation, which are related to collisional processes and syn-collisional granite intrusions. These collisional products are not exclusively located within the paleoisland arc structural complexes.

The Magnitogorsk paleoisland arc system was formed during the Silurian-Devonian. It was complete in the Carboniferous Age when 'soft collisional' processes were initiated. It can be structurally reconstructed to show two island arcs (Western and Eastern) separated by an inter-arc basin. Rock associations determined to have been formed during island arc condition can be found in the Eastern-Urals Trough.

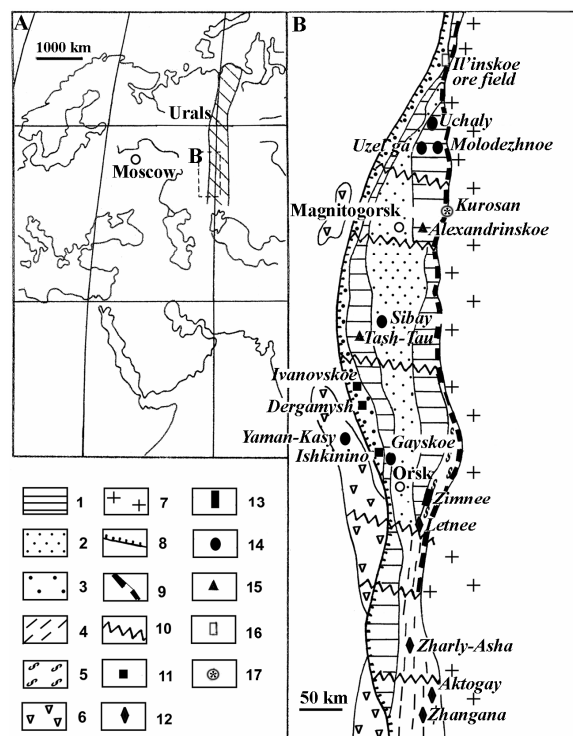


Fig. 1 Scheme of distribution of paleocean structures in the South Urals (Zaykov et al., 2001). A – geographical setting; B – geodynamic scheme. 1 – paleoisland arcs; 2 – inter-arc basin; 3-6 – ophiolitic zones: 3 – fragment Silurian spreading basin, 4 – back-arc basin in the rear of the West-Magnitogorsk paleoisland arc, 5 – back-arc basin in the rear of the East-Magnitogorsk paleoisland arc, 6 – marginal allochthones; 7 – East-Mugodzharsky microcontinent; 8-9 – suture zones: 8 – Main Urals fault, 9 – Katsbakh fault; 10 – buried transform faults; 11-15 ore formations: 11 – cobalt-copper-pyrite, 12 – copper-pyrite (Cyprus type), 13 – copper-pyrite (Besshy type), 14 – copper-zinc-pyrite (Urals type), 15 – gold-pyrite-polymetallic (Kuroko type), 16 – gold-polymetallic, 17 – gold-silver

Deposits of the VHMS, gold-poly-metallic, Au-Ag mesothermal and epithermal type are related to volcanic and volcanic-sedimentary rocks from the island arc. Gold-quartz and gold-sulphide-quartz vein mineralization and remobilization, and redeposition of the noble metals within the framework of pre-existing ore concentrations are connected both with tectonical activity of ‘soft collision’ and with granite intrusives from the ‘hard collision’ phase (Prokin and Buslaev, 1999; Sazonov and Murzin, 1995; Melekestseva and Zaykov, 2003). Weathering during the Mezozoic-

Cenozoic led to redistribution of the gold and to new gold concentrations at the oxidation zones.

Gold-bearing deposits are located at all levels in the island arc cross-section. The Co-bearing Cu-enriched VHMS deposits are located at the base, which is built of fragments of sub-oceanic type crust. Cu-Zn VHMS deposits are abundant within the lower part of island arc, which contains bimodal rhyolite-basalt volcanic complexes. The Au-Ag-adularia deposit type relating to andesite-basalt complexes occurs at the upper part of the

island-arc. Epithermal, mesothermal and Au-bearing porphyry Cu deposits belong to the andesite subvolcanic stocks that developed in the latter stage of island arc formation.

### **Gold and gold-bearing deposit types and parageneses.**

#### *Volcanic-hosted massive sulphides (VHMS)*

On the basis of ore composition, VHMS deposits in the Urals can be subdivided into the following types: Co-Cu (Cyprus type), Cu-Zn (Uralian type), Au- and Pb-enriched Cu-Zn (Kuroko type). Their geochemical specificity is the result of many different factors. The leading factor is the composition of the underlying rocks.

Co-bearing deposits lie within the earlier island arc sequences where a transition from tholeiitic to calc-alkaline basalts is noted, as well as an association with ultramafic rocks. Some deposits of this type (Ishkinino, Ivanovka) are located at the slope of the Western-Magnitogorsk accretion prism (Melekestseva and Zaykov, 2003). Average Au and Ag contents in ores in which the late mineral association is prevalent are about 1.5-3 and 5 g/t, respectively. Owing to the superposed collision processes, Au contents can reach 16 g/t, but the Ag content is only 3 g/t (Melekestseva and Zaykov, 2003). Collisional processes are interpreted to lead to modification of the Au concentration and thus the Au-Ag ratio.

Urals-type deposits lying in the bimodal rhyolite-basalt complexes are emplaced on the oceanic crust. Typical of this type are the large and giant deposits with reserves of >1 Mt (Zn+Cu). Examples include Molodezhnoye, Uchaly and Gayskoye. Average grades are 0.2-2.2 g/t Au and 4-68 g/t Ag. The Au/Ag ratio varies from 6 to 30. Gold forms both sub- $\mu$ m inclusions in sulphides (typically pyrite and chalcopyrite) and also occurs in telluride and native form.

Gold and Pb-enriched Cu-Zn deposits display similarity with Kuroko-type deposits and are related to rhyolite-dacite-basalt island-

arc complexes, with fragments of continental crust at the base. Examples include Alexandrinskoye and a second orefield in the same region, the Baymak group of deposits (Tash-Tau, Balta-Tau and Bakr-Tau). Average Au contents vary from 1.1 to 3.2 g/t. The richest mineralogical ore types of these deposits can contain up to 100 g/t Au and n\*100 g/t Ag. Gold contents commonly display a positive correlation with the barite content in the deposit. Au/Ag ratios are 1:10 to 1:50. Native gold in the different ore types typically contains 20-23 % Ag.

There is a relationship between mineral form of the noble metals and the mineral association, reflecting the role of ore facies. Finely-dispersed gold is characteristic of some collomorph pyrite. The Au-bearing tellurides are common in the relict black smoker tubes found in the Yaman-Kasy and Alexandrinskoye deposit (Maslennikov, 1999). Some relationships for the Ag content of gold were established in the Tash-Tau deposit. Gold from the pyrite- and sphalerite-bearing stockwork contains 27 % Ag, whereas gold from chalcopyrite- and bornite-bearing ores contains only 17 % Ag (mean data, Zaykov et al., 2001). Some authors (e.g., Vikentyev, 2004) have suggested that gold composition reflects metamorphism of the primary ores.

Sulphides, sulphosalts, and sulphotellurides are Ag-carriers, as well as the native form. Electrum, Ag-bearing sulphides (stromeyerite, jalpaite, mckinstryite), tellurides (hessite, stützite) and (Cu-bearing) cervelleite are associated with galena, tennantite, tetrahedrite, and sphalerite. Küstelite is rare and is associated with sphalerite. Maslennikov (1999) interpreted that this mineral assemblage formed as the result of interaction between earlier sulphide ores and late oxidative solutions, which were probably seawater-derived.

#### *Gold-polymetallic deposits*

Such deposits are represented by disseminated and veinlet-disseminated ores and belong to the continuous Mid- to Upper Devonian dacite-

andesite-basalt formation characteristic of mature island arcs. Ore mineralization is accompanied by chloritization, sericitization, carbonatization and silification. The mean Au content is 5-7 g/t, locally up to >10 g/t; the Ag/Au ratio is about 3. The Il'inskoye orefield is representative of this type. There are three main economic mineral associations: 1) early pyrite, associated with fine gold included in the pyrite; 2) chalcopyrite-sphalerite with gold and Ag-tellurides; 3) later carbonate-sphalerite-galena association with coarse gold.

The main ore minerals are pyrite of few morphological types, sphalerite, chalcopyrite, and galena. Rare minerals include tennantite, arsenopyrite and Ag-sulphosalts. Gangue minerals are quartz, chlorite, sericite and Mn-bearing calcite. Gold forms fine grains with complex morphologies, rims enclosing other minerals, and also veinlets in sulphides.

#### *Epithermal (mesothermal?) deposits*

Accepting contemporary theories of ore formation (e.g., Hedenquist et al., 1996), some deposits in the Southern Urals can be regarded as epithermal. Gold-silver occurrences are related to small central-type volcanic edifices of Middle-Devonian andesitic basalts and basalts. Such deposits carry little economic importance. One example of this type is the Kurosan deposit, where ore is associated with adularia-quartz-sericite alteration. Gold contents vary from 1-2 g/t to 6 g/t; Au/Ag ratio is 2/5.

The ores are both disseminated and veinlet-disseminated. Pyrite is a main ore mineral, but sphalerite, galena, tetrahedrite-tennantite and chalcopyrite are also common. Rare minerals include molybdenite and pyrrhotite. The main gangue minerals are adularia, quartz, sericite, illite, and calcite; barite and chalcedony are rare. Silver contents in native gold vary from 13 to 36%. The main perspectives for this type of ore is in the Gumbeika zone of the Eastern-Magnitogorsk island arc (Mikhailov et al., 2003), where one deposit (Kurosan) is currently exploited.

The Berezhnyaki Au-Ag deposit can also be assigned to the epithermal type, even if such a classification is the subject of discussion. Sazonov et al. (1999) regard the deposit as a gold-porphyry, whereas Lehmann et al. (1999) consider that it is epithermal, and Kisters (2000) considers it to be mesothermal. The deposit is located within a fragment of the island arc emplaced onto continental crust. This structure is not immediately connected with the Magnitogorsk system, but may be a part of that system which became separated during the Uralian orogeny.

The ore is associated with an andesite-dacite stock (D<sub>3</sub>-C<sub>1</sub>) that cuts andesite tuffs of S<sub>2</sub>-D<sub>1</sub>. The host rocks are altered by sericitization, silicification, propylitization and minor carbonatization. The silicified rocks with the highest Au concentrations form a stockwork in the central part of deposit and are considered a phreatic breccia by I. Savinov (pers. comm., 2003). Ores are both disseminated and veinlet-disseminated. Pyrite ore is disseminated, whereas pyrite-tennantite and pyrite-enargite-tennantite ores are veinlet-disseminated.

Economic mineral associations includes native gold and tellurium, Hg-bearing electrum, and the following tellurides: hessite, petzite, altaite, calaverite, pilsenite, aikinite, sylvanite, clausthalite, tellurobismuthite, weissite, coloradoite and kostovite (Sazonov et al., 1999; Lehmann et al., 1999). Gangue minerals are quartz, chalcedony-like quartz, sericite, and paragonite; calcite and adularia are rare.

Specific collomorph, concentric zonal textures in pyrite-tennantite were found in the deposit. Petzite and calaverite, in association with tennantite and pyrite, are located in the central part of such structures. Native gold, (Au<sub>0.90</sub>Cu<sub>0.05</sub>Ag<sub>0.04</sub>), lies at the periphery, in association with pyrite.

The Berezhnyaki deposit displays a spatial relation with the Tominskoye copper-porphyry deposit. These two deposits are possibly parts of a single genetically-related porphyry-epithermal system.

### *Superposition of different mineralization styles*

Superposition of different styles of mineralization is sometimes noted. Such features relate to inheritance of island arc ore-forming structures, island arc evolution and subsequent collisional processes. For example, Au and porphyry Cu-like veinlet mineralization is noted within dykes ( $D_3$ ), which cut rhyolite-basalts complex with pyritic lodes ( $D_2$ ) at the Sabanovka VHMS ore occurrence in the Alexandrinka orefield.

Native gold,  $Au_{0.75}Ag_{0.25}$ , and petzite are here associated with sphalerite, chalcopyrite, hessite, tellurobismuthite, and aikinite. Gangue minerals are quartz and calcite. Alteration styles include carbonatization, silicification, chloritization and sericitization (Belogub et al., 2002).

Gold-bearing arsenide-sulphoarsenide mineral associations relating from the collisional stage are superimposed on Co-bearing pyritic ores in the Ishkinino deposit, which lies in the Main Urals Fault zone (Zaykov et al., 2001).

Quartz-albite veins with visible gold cut orebodies consisting of quartz-pyrite metasomatites with  $\mu\text{m}$ -scale inclusions of gold in sulphides from the Krasnaya Zhila (Red Vein) deposit, Il'inskoye orefield. The primary disseminated ores are volcanoclastic and relate to the late stage of island arc formation; they contain about 3-5 g/t Au. The main minerals are pyrite and quartz, with minor chalcopyrite. The superposed ores relate to the syn-collisional granitoids. The main minerals are quartz and albite. Gold may form bonanza ores, with nuggets, 5 mm in size, and containing no more than 5-6% Ag. A similar situation can be recognized in another gold occurrence in this area (see Novoselov et al., this volume).

### *Continental weathering and supergene zones*

The most economically important sources of gold from the oxidized ores are the 'iron caps' of VHMS deposits and the oxidized parts of

gold-polymetallic and epithermal deposits. Supergene gold enrichment in the VHMS deposits can reach 100 g/t in the leaching zone, in contrast with 2-3 g/t in the primary ores. Enrichment is the result of the remobilization of fine gold during exposure to high acidity porous solutions (Sergeev et al., 1996). There is no serious supergene gold concentration associated with the low-pyritic epithermal deposits.

A purification of gold is associated with the weathering processes. Real supergene gold is fine and free of impurities; the Au/Ag ratio in the supergene gold is high. Embolite,  $Ag(Br,Cl)$ , and another halogenides are Ag-carriers, as well as amalgam alloys of silver with mercury.

### **Conclusion**

The paleoisland structures in the Southern Urals contain many different types of Au-bearing deposits. Each stage of island arc evolution is characterized by a specific ore type, characterised by specific mineral associations and forms of the noble metal, in turn reflecting the conditions of mineral formation.

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