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GEOLOGY

New Data on Formation Conditions and Composition of Ore-Forming Fluids in the Promezhutochnoe Gold–Silver Deposit (Central Chukotka, Russia)

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According to the conventional concept based on a great body of empirical data, volcanogenic or epithermal deposits do not grade into mesothermal or plutonogenic ones with depth [1, 2]. However, in the Maisk ore group of central Chukotka (Fig. 1), epithermal Promezhutochnoe (Northeast), Sil'noe, and Sopka Rudnaya gold–silver deposits have been discovered in terrigenous flysch sequences at the basement of the Okhotsk–Chukot volcanogenic belt (OCVB) [3]. Similar epithermal ore deposits and occurrences have also been discovered in the terrigenous–sedimentary framing of intrusive domes in transmagmatic reactivation zones of the central Kolyma region (e.g., Pechal'noe and Vetvistoe deposits in the Khurchan–Orotukan zone and Rogovik deposit in the Balagychan–Sugoi zone). Analogous gold–silver deposits are also known in other regions. For example, the central Kyzyl Kum region incorporates the Vysokovol'tnoe and Kosmanychi deposits, while the Transbaikal region includes the Balei and Taseevka deposits. In this connection, let us recall the Hishikari deposit, Japan (Au reserve 250 t). In terrigenous rocks of the basement beneath the volcanic cover of this deposit, geologists have discovered a second level of epithermal auriferous veins with an average grade of as much as 25–75 g/t [4]. However, all epithermal gold–silver orebodies (except the Hishikari, Balei, and Taseevka deposits) have small and medium reserves. This phenomenon is probably related to their significant erosion.

The Promezhutochnoe deposit is confined to a domal uplift at the southern end of the Kukenei Pluton located 18 km from the Maisk gold–sulfide deposit of disseminated ores. Volcanic rocks are completely eroded in the ore field. Effusive rocks of the OCVB are developed at a distance of no more than 15 km. The ore field is crosscut by numerous faults and is confined to a neotectonic domal uplift. The dissected mountainous morphology of this area is very prominent in the smoothed hillocky topography of the region.

Terrigenous rocks of the deposit are composed of an intercalation of siltstones and shales with lenses of flyschoid fine-grained sandstones. The ore deposit is confined to the southwestern limb of a brachysyncline with rocks usually characterized by low-angle dip (10°–15°). The dip angle increases to 45° or more as a result of local folding near faults.

Orebodies of the deposit are mainly located on the southern side of the sublatitudinal belt of basaltic andesite dikes that make up nearly vertical ramified bodies with stepwise (sometimes, Z-shaped) contacts (Fig. 1). The dikes are 0.5–5 m thick and more than 3 km long along the strike. They contain abundant xenoliths of sandstones, siltstones, granodiorites, and granite porphyries similar to granitoids in marginal facies of the Kukenei Pluton exposed 25 km northeast of the ore field.

The majority of ore-bearing veins are traced along oriented debris of quartz boulders. The veins are exposed by mining (surface and underground) works and boreholes. The submeridional veins cut the sublatitudinal basaltic andesite dikes at right angles. The central area of the deposit includes an aureole of sericitized and silicified siltstones and shales. The aureole, 100 × 300 m in area, widens with depth. Together with the finding of granitoid xenoliths in dikes, this fact testifies to the presence of a pluton beneath the deposit.

The Promezhutochnoe deposit incorporates 11 orebodies outlined as slightly mineralized shear zones with axial quartz veins. The northern block hosts Au-rich orebodies (Au/Ag = 2 : 1–10 : 1), while the southern block includes both Au- and Ag-rich orebodies (Au/Ag = 1 : 10–1 : 100).

The Au/Ag ratio in the northern block is typical of gold–rare metal mineralization developed in porphyry gold and gold–telluride zones. This type of mineralization is probably associated with the apical portion of the

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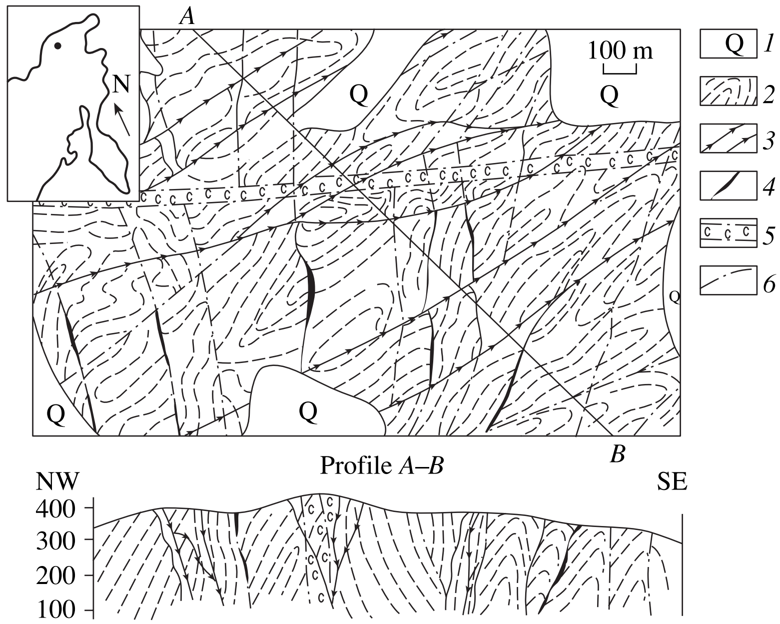

Fig. 1. Schematic geostructural map and cross section of the Promezhutochnoe deposit. (*1*) Quaternary sediments; (*2*) Triassic flysch sequence; (*3*) basaltic andesite dikes; (*4*) shear and foliation zones with orebodies; (*5*) Major sublatitudinal fault; (*6*) secondary faults.

hidden pluton. The ore-bearing zone extends over 200–300 m as a metalliferous fan approximately 1 km wide in the north and 500 m wide in the south. The length of individual echelon-type veins varies from 30 to 50 m. The orebodies are characterized by the NE-oriented subvertical dip. The ore-bearing veins have diverse (crustification, skeletal-lamellar, agate-type, colloform, brecciated, cristate, and cockade) structures that are typical of epithermal deposits.

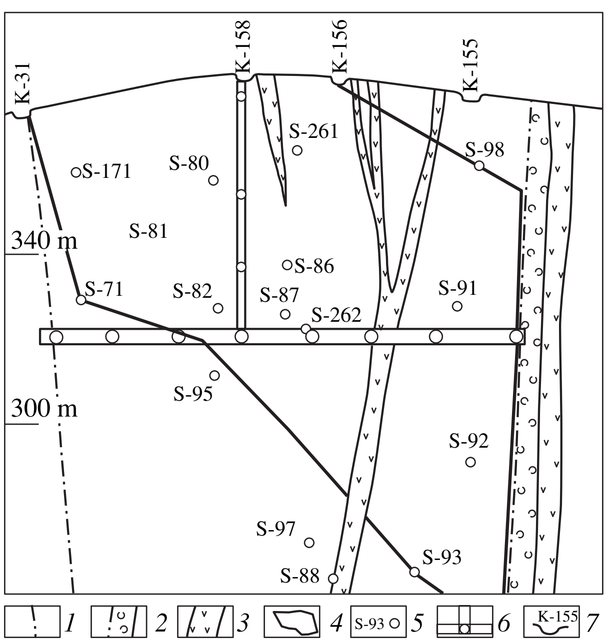

Fig. 2. Projection of orebody 3 of the Promezhutochnoe deposit on the vertical plane (based on geoexploration data). (*1*) Projection of ore-controlling faults; (*2*) projection of the major sublatitudinal fault; (*3*) basaltic andesite dikes; (*4*) contour of the orebody; (*5*) boreholes; (*6*) mining drift and raise; (*7*) ditches.

Thus, veins of the Promezhutochnoe deposit represent products of the active disintegration of enclosing rocks by hydrothermal solutions that percolated along fractures at the first stage and filled up the open space in tensile fractures at the second stage.

Geomorphological and geostructural signatures of the deposit indicate its significant erosion. However, one can see relicts of some bonanza ores with the Au content of 15–50 g/t (orebodies 1, 3, and 5) and the Ag content of as much as 1500 g/t (orebody 11). Drilling data indicate that the orebodies pinchout at a depth of 50–80 m (Fig. 2).

In order to examine formation conditions of high-grade ores, we investigated the quartz-hosted fluid inclusions (FI) in orebodies 3 and 11 of the Promezhutochnoe deposit. Quartz grains have crustification, skeletal-lamellar, and drusy structures. They make up intergrowths with the native gold, electrum, tetrahedrite, sphalerite, and silver minerals (küstelite, pyrargyrite, stephanite, freibergite, naumannite, aguilarite, freieslebenite, and argentite) [3].

Microthermometric investigations of the FIs were carried out in a THMSG-600 (Linkam Co.) device that makes it possible to measure phase transition temperatures ranging from –196 to 600°C and to check the FIs at high magnifications. The salt concentration in them was estimated on the basis of the ice melting temperature according to data in [5]. Pressure in the heterogeneous fluid was estimated on the basis of syngenetic FIs enriched in the gaseous and gaseous–liquid phases as the sum total of partial pressures of water vapor and CO_2 [6]. The pressure was estimated with the isochor intersection method based on the gaseous phase of FIs and the isotherm method based on the homogenization temperature of water-rich FIs [7]. Concentration of salts, densities of water fluid and CO_2, and pressures were calculated with the application of the FLINCOR software package [8].

Quartz in orebody 3 includes primary FIs enriched in the syngenetic gaseous and gaseous–liquid phases that testify to the heterogeneous state of the fluid. The gaseous FIs contain low-density (0.30 g/cm^3) carbon dioxide that homogenizes into the gaseous phase at +28.5°C. The gaseous–liquid FIs contain a water solution of Na–K chlorides with a salt concentration of 4.1–3.8 wt % NaCl equiv. They homogenize at 221–194°C (P = 270–230 atm, P_{tot}/P_{H_2O} = 13.4–21.3).

The quartz of orebody 11 also includes syngenetic FIs enriched in the gaseous and gaseous–liquid phases (Fig. 3). Parallel layers of such quartz-hosted FIs represent relicts of chalcedony- and agate-type (lamellar and skeletal-lamellar) structures of silica. However, the gaseous FIs in the quartz contain only water vapor. The gaseous–liquid FIs are filled with the water solution of sodium chlorides with a salt concentration of 4.2–2.9 wt % NaCl equiv. The homogenization temperature of such FIs is 247–241°C (water vapor pressure ~30 atm, P_{tot}/P_{H_2O} = 1). In addition, the outer zone of quartz crystals contains low-temperature gaseous–liquid FIs with a salt concentration of 4.3–3.6 wt % NaCl equiv (T_{hom} = 193–178°C) that are not accompanied by syngenetic gaseous FIs. Hence, the solution did not boil in the course of their entrapment.

The composition of the quartz-hosted FI solution in orebody 11 was investigated by gas chromatography, ion chromatography, and ICP-MS (according to [9]). The FI composition was analyzed in the quartz sample (0.5 g, fraction 0.5–0.25 mm) at the Central Institute of Geological Exploration for Base and Precious Metals, Moscow (Yu.V. Vasyuta, analyst). The water content in the FI was preliminarily measured in the same sample for the calculation of concentrations of all elements in the hydrothermal solution. We also analyzed carbon dioxide and methane. After the preparation of leachate, we measured the concentrations of Cl, K, Na, Ca, Mg, dissolved silica, and several trace elements in the solution.

Data obtained on the composition of water leachates from the vein quartz-hosted FIs (Fig. 4) made it possible to estimate concentrations of many components in the FI solution (in g/kg of water, unless otherwise stated). The major components are Na (4.6) and Cl^- (1.4), while the subordinate components are K (0.5), Ca

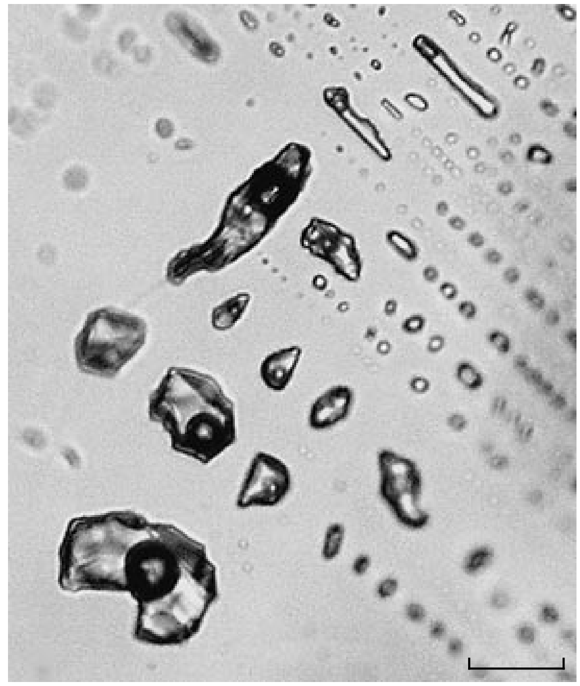

Fig. 3. Primary two-phase quartz-hosted fluid inclusions in orebody 11 of the Promezhutochnoe deposit. (T_{hom} 240°C; scale bar 10 μm).

(0.2), and Mg (0.001). The FIs are also enriched in carbon dioxide (15.3), methane (0.7), HCO_3^- (11.0), Br (0.19), As (0.13), Li (0.40), and B (1.2). The additional components are as follows (mg/kg of the solution): Rb (1.0), Cs (0.3), Sr (4.3), Mo (4.38), Ag (22.9), Sb (51), Cu (1.9), Zn (14), Cd (6.2), Pb (.1.4), Bi (0.03), Th (0.04), Ga (0.07), Ge (3.7), Sc (26), Ti (1.7), Mn (2.8), Fe (26), Co (0.04), Ni (0.16), Nb (0.03), Zr (0.37), Ba (6.3), W (0.7), Hg (0.34), Tl (0.85), and REE (0.18). Ag, Sb, and Fe are the major trace elements. The trace element distribution is consistent with the geochemical profile of the deposit. The total salt concentration in the leachate is 37.5 g/kg of water. This value matches the cryometric data on the FIs. Low salt concentrations and relatively low temperatures indicate the hydrosulfide mode of occurrence of Au in the solution.

High B and Li concentrations in the FIs suggest the participation of granitoid-related fluids in the ore-forming process. At the same time, the high K/Rb value (556) indicates the involvement of genetically different solutions as well [10]. Pressure estimates suggest various tectonic settings in the course of the formation of orebodies. For example, fractures were open during the formation of orebody 11, whereas they were semienclosed and less permeable for carbon dioxide during the formation of orebody 3. Orebody 11 could be formed near the main discharge zone of the hydrothermal system indicating a high ore potential of this part of structure of the deposit.

Results of thermometric and cryometric investigations of quartz-hosted fluid inclusions in high-grade ores of the Promezhutochnoe deposit

Sample no.	Mineral	n	Temperature, °C					C_{salt}, wt % NaCl equiv	d, g/cm^3	P, atm	$\frac{P_{tot}}{P_{2_2O}}$
			homogenization	eutectics	ice melting	CO_2 melting	CO_2 homogenization				
Orebody 5											
10	Quartz*	7	221	–33	–2.3	–	–	3.8	0.88	270–230	13.4–21.3
	The same*	6	194	–24	–2.5	–	–	4.1	0.90		
	″*	17	–	–	–	–58.0	28.5 H	–	0.30		
Orebody 11											
9	Quartz*	9	247	–33	–1.7	–	–	2.9	0.83	30	1.0
	The same*	5	244	–32	–2.5	–	–	4.2	0.84	30	1.0
	″*	17	241	–34	–1.9	–	–	3.2	0.85	30	
	″	8	193	–30	–2.1	–	–	3.6	0.90	–	–
	″	3	179	–32	–2.4	–	–	4.0	0.92	–	–
	″	2	178	–31	–2.6	–	–	4.3	0.92	–	–

Note: (*) Heterogeneous state of fluid (effervescence); (H) CO_2 homogenization in gas.

The results obtained are consistent with the Hishikari deposit model, in which the confinement of the Honko bonanza ore zone (Au 70 g/t) to the structural unconformity between the terrigenous sequence and the overlying volcanic sequence is explained by the combination of two processes [4]. First, boiling of high-temperature fluids beneath the volcanic sequence promoted the precipitation of initial portions of gold. Second, the subsequent mixing of deep waters and water vapor near the structural unconformity fostered the rapid cooling and oxidation of groundwaters and the ultimate precipitation of ores.

Our results show that high-grade ores of the Promezhutochnoe deposit formed according to the Hishikari model. Moreover, the apical section of the hidden pluton in the study region can incorporate porphyry gold–rare metal (gold–telluride) mineralization. This type of mineralization is insufficiently well studied for the Asian sector of the Pacific belt. It is quite probable that the geological setting discussed in this paper is also typical of Sopka Rudnaya, Pechal'naya, Vetvistoe, and other deposits confined to perivolcanic zones.

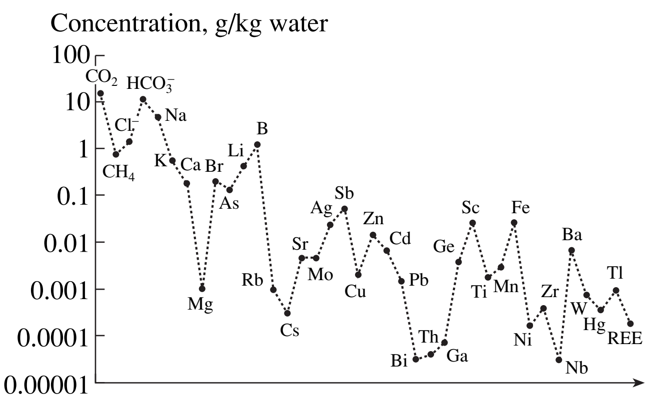

Fig. 4. Composition of the ore-forming fluid in orebody 11.

As was mentioned in [11], the OCVB and its perivolcanic framing are favorable for the multistage mineralization. We confidently predict the second level of anomalously high-grade epithermal veins in tectonomagmatic reactivation zones around volcanic belts of the Russian Northeast. Ore fields with relicts of volcanic domes can be considered the top priority objects for prospecting works. Such structures are intensely eroded because of the exhumation of terrigenous rocks of the basement.

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