

Formation Conditions of Gold–Silver Deposits in the Northern Okhotsk Region, Russia

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Abstract—The paper considers the results of geochemical studies of gold–silver ore–magmatic systems and deposits in two of the largest ore districts of the northern Okhotsk region: the Evensk (Turomchinsk ore–magmatic system, the Dal'nee and Kwartsevoe deposits) and Omsukchan (the Dukat deposit) districts. New data on behavior of ore and alkaline elements and fluid inclusions are presented. Two genetic types of hydrothermal gold–silver ore-forming systems (volcanic and volcano–plutonic) are distinguished. The main peculiar feature of volcanic gold–silver ore–magmatic systems is their single-megastage development and bimetal pattern. The volcano-genic trend of magmatism is prevalent. The andesite–granodiorite volcano–plutonic rock association specialized for Au, Ag, and K is a potentially ore-bearing one. The Turomchinsk ore–magmatic system, where the hydrothermal process begins with formation of zones with disseminated sulfide mineralization and extended multicomponent low-contrast geochemical fields, is a typical example of such systems. The main peculiarity of volcano–plutonic gold–silver ore–magmatic systems is their multimegastage and polymetallic mode, as well as their long-term and intricate development, which can be exemplified by the Dukat ore–magmatic system. There, two stages can be distinguished in the magmatic and hydrothermal activity related to ore-bearing volcano–plutonic associations: andesite–granodiorite (the early stage) and rhyolite–granite–leucogranite (the late, terminal stage). The last stage is distinctly specialized for F, B, Ag, Sn, Mo, W, and Pb. In the Dukat system, Sn–Ag and Sn–rare metal mineralization is intensely developed, along with Ag–Pb and Au–Ag ores. Nevertheless, general regularities in formation of ores and related geochemical fields are preserved. The formation of Au–Ag ores in the multimegastage polymetallic volcano–plutonic Dukat ore-forming system and the single-megastage compositionally relatively simple volcanic Turomchinsk system occurred in similar environments: (1) under close temperatures (355–205°C for the Evensk group of deposits and 340–175°C for the Dukat deposit) and pressures (170–20 bar and 135–70 bar, respectively); (2) from low-concentration fluids of similar salt composition (NaCl, KCl, CaCl₂, and MgCl₂)—3.9–0.4 and 6.4–0.4 wt % for the Evensk group of deposits and the Dukat deposit, respectively; (3) at depths less than 1000 m; and (4) in a hydrothermal structure less than 1.5 km long. Mineral-forming solutions that formed Au–Ag and Ag ores substantially differ in composition from magmatic and postmagmatic fluids, which can be explained by dilution of the latter by meteoric waters.

INTRODUCTION

We have carried out a complex study of geochemical and physicochemical conditions of formation of gold–silver ore–magmatic systems and deposits in northeastern Russia. The regional and local ore-forming systems (deposits) under consideration are situated in two of the largest districts of the northern Okhotsk region—the Evensk and Omsukchan districts (Fig. 1). They are confined to several volcano–tectonic structures of the central type located in the central part of the Okhotsk–Chukotsk volcano-genic belt (OCHVB). These are the Turomchinsk ore–magmatic system in the Evensk ore district, exemplified by the Dal'nee and Kwartsevoe deposits, and the Dukat ore–magmatic system, represented by the Dukat deposit (Umitbaev, 1986; Bogdanov and Til'man, 1992).

The ore mineralization of the areas studied formed owing to Late Cretaceous magmatism and accompanying hydrothermal activity. The onset of ore deposition is characterized by wide development of disseminated sulfide mineralization. The most intense mineralization is connected with terminal phases of the hydrothermal stage, represented by ores of gold–silver type (Sidorov *et al.*, 1989; Shilo *et al.*, 1992; Kravtsova and Zakharov, 1996; Kravtsova, 1997, 1998; Konstantinov *et al.*, 1998). The Omsukchan district is also characterized by tin–silver, silver–polymetallic, and various tin–rare metal mineralization (Kalinin *et al.*, 1984; Rodnov and Zaitsev, 1985; Plyashkevich, 1986; Konstantinov *et al.*, 1993; Kravtsova *et al.*, 1996, 1998). The Evensk district is marked only by slight Ag–Pb mineralization in addition to the Au–Ag mineralization (Kostyrko *et al.*, 1974; Boldyrev and Yarantseva, 1991; Kravtsova, 1998).

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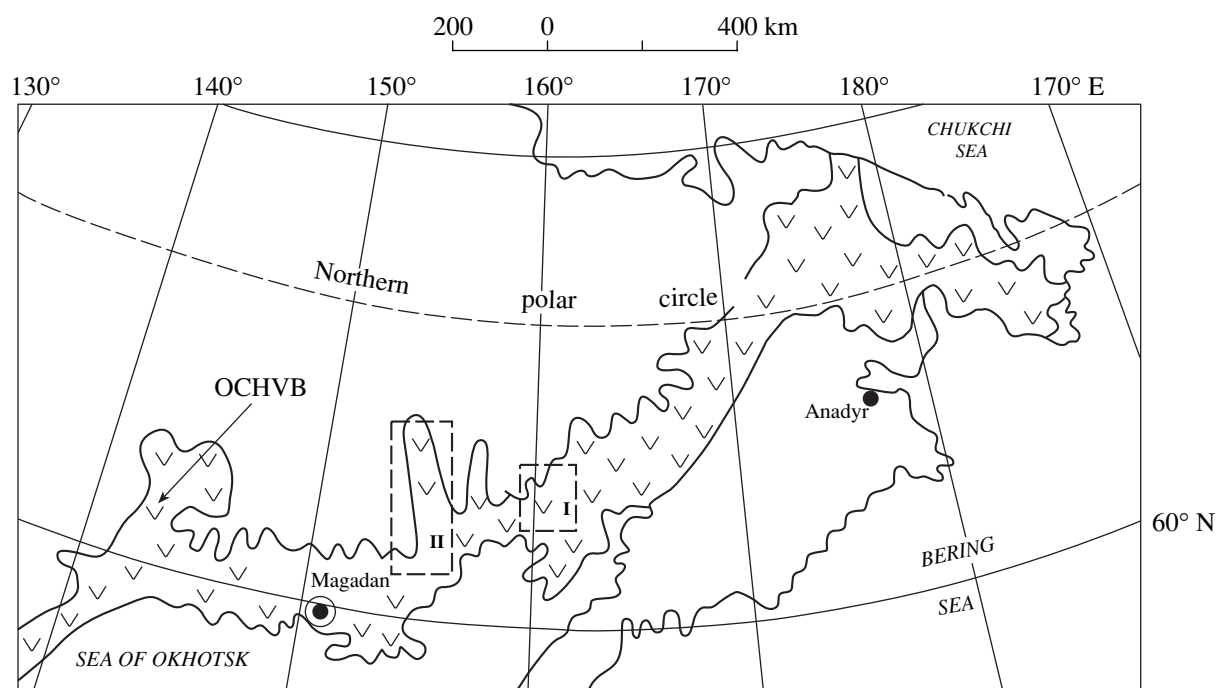


Fig. 1. Geographic location of the Evensk (I) and Omsukchansk (II) ore districts.

The areas examined are intriguing primarily because of the fact that deposits of the Evensk group and the Dukat deposit substantially differ from each other in scale, structure, and metallogeny, as well as in their mineral and geochemical associations. They can probably be considered to represent extreme members of a common-vein low-sulfide epithermal gold–silver series formed under conditions of marginal–continental mobile zones of the Pacific segment, with the Okhotsk–Chukotsk volcanic belt as its largest structure.

METHODS

A great deal of analytical measurements were performed in the laboratories of the Vinogradov Institute of Geochemistry, Irkutsk, during geochemical studies of gold–silver ore–magmatic systems and deposits (geochemical typization of ore-enclosing magmatic rock associations, ore mineralization, and related geochemical anomalies). All samples were analyzed using the spectral approximate–quantitative method to determine a number of elements (analyst, V.S. Kischechnikova) and the atomic absorption method to measure the Au content (analysts, A.A. Khlebnikova and O.I. Bessarabova) with preliminary extraction by oil sulfides (Torgov and Khlebnikova, 1977). The measurements were controlled by methods of quantitative spectral analysis (*Emissionnyi spectral'nyi...*, 1976). The same method was used to determine F, B, and Be (analysts, E.V. Smirnova, A.I. Kuznetsova, and O.N. Chernysheva). The direct atomic absorption method without the chemical treatment of samples (Vorob'eva *et al.*, 1987) was used to estimate the Ag,

As, Sb, and Bi contents (analyst, S.E. Vorob'eva). This is a rapid method of high preciseness and reproducibility. Hg was analyzed by the atomic absorption method (Novikov *et al.*, 1971) using acid decomposition (analyst, L.D. Andrulaitis). K, Na, Rb, Li, and Cs were determined by the flame photometry method (Poluektov, 1959) and the atomic absorption method (analysts, M.N. Ufimtseva and L.V. Altukhova). The total S and Cl contents were estimated using the volumetric iodometric (Ponomarev, 1966) and argentometric (*Metody khimicheskogo analiza...*, 1977) methods, respectively.

The method of “multidimensional fields” (Evdokimova, 1978; Kitaev, 1990) was used for processing of analytical data to define geochemical associations and their distribution in wallrocks. The method is characterized by high efficiency and low labor expense because the main operations used for the analysis of the geochemical field and compilation of geochemical maps and sections are computer-aided. The essence of the method consists in representing the natural system (geological space) by a quantity of points characterized by a totality of geochemical features. This quantity of points is subjected to processing in the form of a matrix—a table of analytical data with coordinates. For dividing the empirical material of the matrix by a system of uniform values, an automatic classification, which defines the most frequently occurring combinations of geochemical elements with their close quantitative values, is elaborated. Thus, monoelement geochemical fields are compiled. Then, using combinations of chemical elements (classes or associations), the natural system is described, with discrimination of uniform areas and their comparison between each other.

Classes (geochemical associations) are discriminated based on percentage contrast ratios, with account taken of their dispersal and the dependence between contrast ratios of different elements ($CR = C_i/C_b$, where C_i is a content and C_b is a background). Then, the multidimensional field is compiled. The eventual result is presented in the form of maps and sections of multielement geochemical fields (geochemical associations of elements), which contain a great deal of information.

The following methods were used for the study of fluid inclusions (Ermakov, 1972; Borisenko, 1977, 1982; Redder, 1987) to reconstruct physicochemical formation conditions of gold–silver ores, as well as magmatic and postmagmatic processes: thermometry (for estimation of mineral-formation temperatures), cryometry (for determination of the vapor-rich phase composition and concentration of solutions), and Raman spectroscopy (for the study of vapor-rich phase composition). Homogenization temperatures were measured in the heating chamber designed by Dolgov and Bazarov (1965) and Kalyuzhnyi (1958), and cryometric studies were performed using a cryogenic chamber designed at the Joint Institute of Geology, Geophysics, and Mineralogy and a cryogenic chamber designed by Simonov (1993). The vapor-rich phase of individual inclusions was examined using a Ramanor U-1000 laser spectrometer. Dry residues of solutions from individual inclusions were analyzed with a Camebax-Micro X-ray spectral microprobe (Borisenko *et al.*, 1994). Both primary and pseudosecondary fluid inclusions (Ermakov, 1972; Roedder, 1987) in quartz of ore veins were studied. In quartz phenocrysts from magmatic rocks, the so-called associating secondary fluid inclusions that were trapped in the course of fluid phase separation at final stages of crystallization of magmatic melts were subjected to examination.

Compositionally complex solutions with low eutectic temperatures (-98 to -62°C) and ice melt temperatures of -61 to -29°C were established in study of fluid inclusions. The salt components lowering eutectic temperatures could be CaCl_2 , FeCl_2 , FeCl_3 , ZnCl_2 , MnCl_2 , LiCl , and CaBr_2 (Borisenko, 1977; Borovikov *et al.*, 2001₂). The integral content of salts in such solutions was estimated for the salt system CaCl_2 – NaCl – H_2O . The presence of Ca and Na was established using the microprobe. The total concentration of solutions from inclusions (in wt %) was measured according to Potter *et al.*, (1978). The pressure of mineral-forming fluids was estimated using inclusions of heterogeneous fluids, taking into account the data from Lemlein and Klevtsov (1956). The fluid density was determined based on the salt concentration in the solution from an inclusion and its T_{hom} taking into account for data from Bodnar (1983).

MAGMATIC ROCKS AND ORE MINERALIZATION

Magmatic rocks. Two potentially ore-bearing volcano–plutonic associations were distinguished in study

of the composition of magmatic rock complexes: andesite–granodiorite and rhyodacite–leucogranite. They are confined to the Turomchinsk and Dukat ore–magmatic systems, respectively.

The gold–silver mineralization proper is closely connected with the formation of the andesite–granodiorite association that is a constituent of the subduction-related calc-alkaline magmatic rock series of the Okhotsk–Chukotsk volcanic belt. Volcanics of this petrochemical association form a continuous succession from high-alumina basalts to rhyolites. Small andesite intrusions and dikes are dominant. Andesites are compositionally uniform, show similar concentrations of SiO_2 and petrogenic elements, and are characterized by elevated alkali contents (maximum concentrations of K amount to 6.7%). Among rare elements, high concentrations are characteristic only of Au and Ag. The average contents and average contrast ratios in andesites are 0.25 g/t and 2.5 for Ag and 0.005 g/t and 1.7 for Au, respectively. Geochemical gold specialization is most distinct in compositionally contrasting rocks. Remarkable in this regard are small intrusions and dikes of granodiorites in biotite and accessory pyrite that contain high Au concentrations, up to 900 g/t (Zakharov and Kravtsova, 1999).

The formation of various silver, tin, and rare-metal mineralization is mainly related to development of postsubduction acidic magmatism of the contrasting trachyliparite–basalt series, which can be exemplified by the Dukat system with the thus-named silver deposit, the largest in Russia. Acidic members of the trachyliparite–basalt series form within this system an autonomous leucogranite volcano–plutonic association specialized for tin, silver, and rare metals. The intrusion of a rare-metal granite pluton in the Dukat deposit resulted in unique gold–silver mineralization, in addition to various silver mineralization and rare-metal anomalies formed during rejuvenation of early “primary” Au–Ag ores related to the subduction stage of magmatism (Goncharov and Sidorov, 1979; Berman *et al.*, 1993). Rejuvenated gold–silver ores substantially prevail over “primary” ones preserved as relicts.

The rocks of the rhyodacite–leucogranite volcano–plutonic association from the Dukat ore–magmatic system are characterized by persistently anomalous contents of most main ore elements, whose concentrations noticeably exceed their Clarke values. The average contents and average contrast ratios in rhyodacites are 0.6 g/t and 6 for Ag, 50 g/t and 5 for Pb, 8 g/t and 4 for Sn, 150 g/t and 3 for Zn, and 6 g/t and 3 for Mo, respectively. The elevated concentrations of these elements correlate with higher K and B contents. Maximum contents of B and K recorded in acidic volcanics are as high as 148 g/t and 6%, respectively. According to the $\text{Rb}/(\text{Y} + \text{Nb})$ value (Pearce diagram), these granites can be classed with intraplate rocks. Their ore-bearing potential is determined by accumulation of volatile and ore elements in residual melt. The rocks are enriched in F, B, Ag, Sn, Mo, W, and Pb (up to 2200, 90, 0.4, 29, 8, 4, and 30 g/t, respectively). The rare-metal specializa-

Table 1. Geological–geochemical characteristics of the Evensk and Omsukchansk ore districts of the Okhotsk–Chukotsk volcanic belt

Characteristic	Evensk district	Omsukchansk district
Type of ore–magmatic system	Volcanic	Volcano–plutonic
Type of magmatism	Volcanic	Volcanic, then plutonic
Magmatic association	Andesite–granodiorite	Andesite–granodiorite Rhyolite–granite–leucogranite
Geochemical specialization	K, Au, Ag	K, Au, Ag K, B, F, Ag, Pb, Sn, Zn, Mo, W
Megastages of ore formation	One	Several
Ore-forming elements	Au, Ag, Hg, Sb, As	Au, Ag, Sn, W, Mo, Bi, B, Pb, Zn, Mn, Be, Li, TR

tion of granites from the Omsukchan ore district and their ore-bearing potential are evident from high values of the accumulated concentration index. For instance, this value for rare-metal leucogranites from the Levoomsukchan pluton is as high as +14.0 and that for rare-metal granites of the Dukat pluton is +7.1. For comparison, the Dzhet'sk granite pluton (Turomchinsk system), lacking ore mineralization, is characterized by an index below 1 (Zakharov *et al.*, 2002).

Ore mineralization. The Dal'nee and Kwartsevoe gold–silver deposits of the Turomchinsk ore–magmatic system are classic representatives of low-sulfide gold–silver epithermal deposits that formed in active continental margins. Ores formed during a single stage and are characterized by a simple mineral and low-component composition (Kostyrko *et al.*, 1974; Kostyrko, 1983; Kravtsova, 1997, 1998). The host rocks are represented by Upper Cretaceous intermediate volcanics—latiandesites, andesites, and dacites with the K–Ar age ranging from 92 ± 2 to 81 ± 2 Ma (Gundobin *et al.*, 1980). The Ar–Ar age of quartz–adularia veins varies from 82.5 ± 0.2 to 80.5 ± 0.2 Ma (Layer *et al.*, 1994). Ore veins are composed of quartz (90–95%), adularia (1–10%), sericite, hydromica, carbonate, kaolinite (5–10%), and ore minerals (1–3%). Main ore minerals are pyrite, argentite, electrum, proustite, pyrrhotite, polybasite, and stromeyerite. Less common are galena, sphalerite, chalcopyrite, gold, miargyrite, and pearceite. Main ore- and halo-forming elements include Au, Ag, Hg, Sb, As, and, to a lesser degree, Pb, Zn, and Cu (Kravtsova, 1997, 1998) with an insignificant admixture of Bi and Mo.

Gold–silver ores from the Dukat deposit have a longer and more intricate development history than deposits of the Evensk group. Problems of the geology and mineralogy of this deposit are considered in the most detail in a special monograph by Konstantinov *et al.* (1998).

The ores from the Dukat deposit formed under the influence of a large granite pluton penetrated by boreholes at depths of 950–1320 m. The present-day structure of the ore field represents an intrusion–dome uplift composed of magmatic rocks that intruded in the fol-

lowing succession: rhyodacite ignimbrite and intrusive rhyodacites, diorite porphyrites and monzogranites, leucocratic granites and granite–porphyries, and Early Paleogene postore dikes of subalkaline basaltoids. The Rb–Sr age of mineralization-enclosing rhyodacite ignimbrites is 99.1 ± 4 Ma and that of leucogranites ranges from 82 ± 2 to 80 ± 2 Ma (Zakharov *et al.*, 1990; Kravtsova and Zakharov, 1996). Granitoids host Sn–W mineralization. The onset of the Late Cretaceous hydrothermal activity is characterized by wide lateral development of preore metasomatites and compositionally variable zones of disseminated sulfide mineralization. Younger ores and halos of the Dukat deposit are characterized by multistage development and by complex mineral and component composition (Natalenko *et al.*, 1980; Konstantinov *et al.*, 1998; Shilo *et al.*, 1992; Kravtsova and Zakharov, 1996; Kravtsova, 1997). The deposit is a typical example of rejuvenated early Au–Ag mineralization under the influence of granitoid intrusion, which provided an additional influx of Sn, W, Mo, Bi, B, Ag, Pb, Zn, Mn, Be, Li, and TR.

Ores are represented by several types: (1) mostly silver–quartz–pyrolusite and quartz–rhodonite veins; (2) gold–silver–quartz–rhodonite–feldspar, quartz–feldspar, and quartz–feldspar–sulfide veins; (3) silver–lead–quartz–rhodonite–sulfide, and quartz–rhodonite–sulfide, quartz–rhodonite–chlorite–sulfide veins; and (4) tin–silver–quartz–chlorite–sulfide veins. Based on the prevalent mineral and component composition, three main productive ore stages can be defined: (1) early Ag–Pb, (2) Au–Ag, and (3) late mainly Ag. According to Struzhkov *et al.*, (1994), the Rb–Sr age of preserved early quartz–feldspar veins is 84 ± 1 Ma and that of later quartz–rhodonite–feldspar and quartz–rhodonite veins is 74 ± 1 Ma. The Ag–Pb, Au–Ag, and Ag veins are characterized by different constituting minerals: (1) feldspar, chlorite, and carbonates; (2) rhodonite, chlorite, and sericite; and (3) rhodochrosite and pyrolusite, respectively. The subore intervals are marked by distinct noncommercial polysulfide Sn–Ag mineralization. Anomalous Sn concentrations (4–10 g/t) are characteristic also of ore levels. Maximum Sn contents (up to 50 g/t) are recorded in ores of the Ag–Pb stage. As a whole, ores from the deposit under consideration

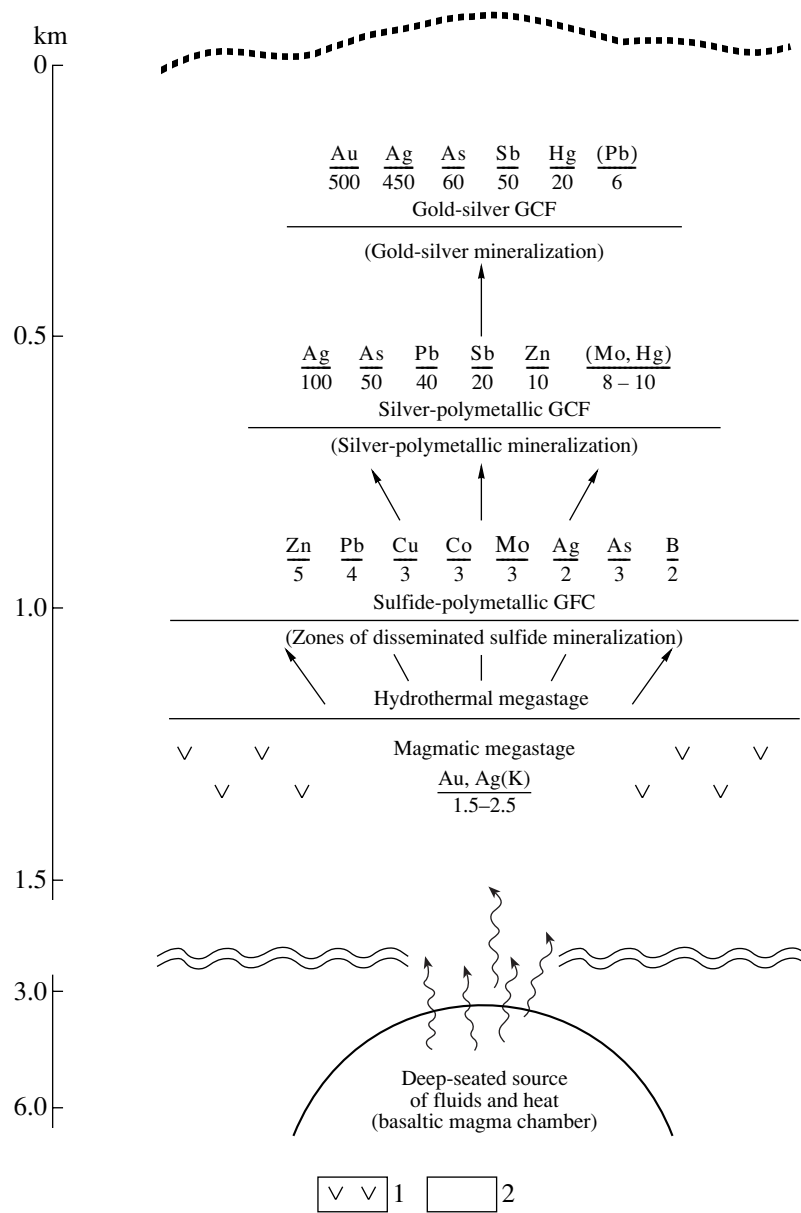


Fig. 2. Schematic distribution of ore mineralization and geochemical concentration fields (GCFs) in the Turomchinsk volcanic gold-silver ore-forming system. (1) Andesites; (2) dacitic andesite. Here and in Fig. 3, the denominator corresponds to average values of the concentration coefficient of the element shown in the numerator. Normalized for the background.

are referred to the low-sulfide type, although locally, particularly at large depths, the sulfide contents reach 10% and higher. Main ore minerals are argentite (acanthite), kuzelkite, proustite, and pyrargyrite. The Ag ores are usually dominated by native gold, kuzelkite, and Ag sulfoantimonides. There are also untypical rare metal minerals such as helvite, spessartine, and axinite in Ag ores; electrum and sulfoarsenides in Au-Ag ores; and stannite, freibergite, galena, sphalerite, chalcocopyrite, and pyrite in Ag-Pb and Sn-Ag ores. Main ore- and halo-forming elements are Ag, Au, Sb, As, Hg, Pb, Zn, and Cu, which are accompanied by accessory Bi, Sn, W, and Mo.

ORE-FORMING SYSTEMS

On the basis of geochemical peculiarities of magmatic rocks, composition of ore mineralization, and geochemical fields of ore element concentrations, two genetic types of gold-silver ore-forming systems are distinguished: volcanic and volcano-plutonic. Their comparative characteristics, with the Evensk and Omsukchan ore districts used as examples, are presented in Table 1.

The single-megastage and bimetal functioning mode is the main peculiar feature of volcanic gold-silver ore-magmatic systems. Ores consist only of two elements, Au and Ag, formed under a dominant vol-

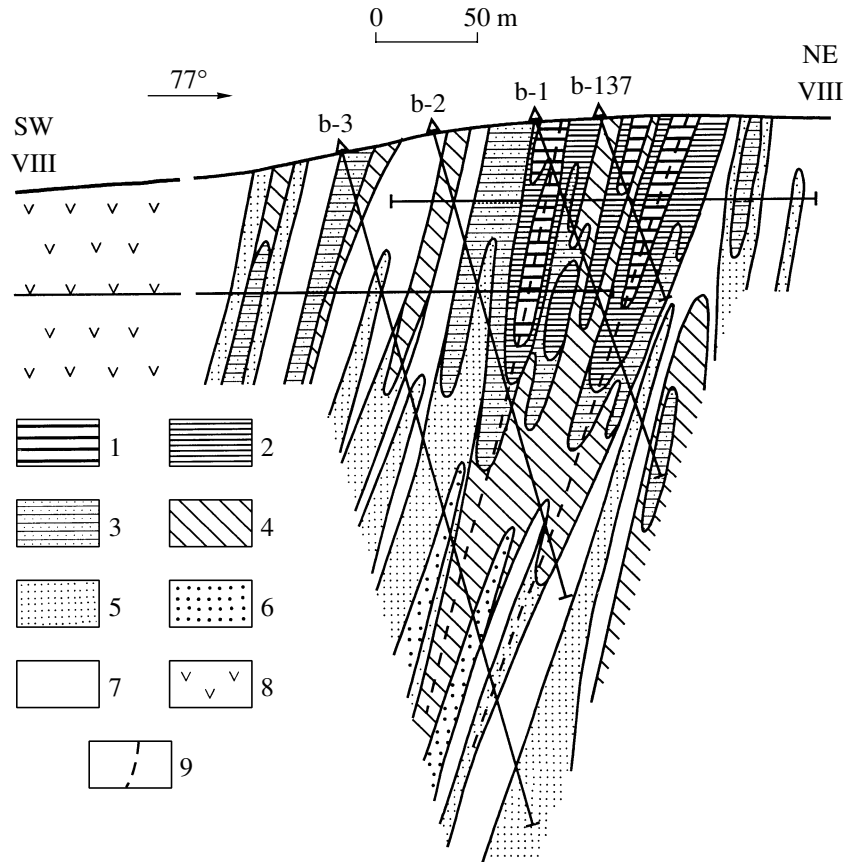


Fig. 4. The Dal'nee deposit. Cross section along profile VII. Schematic distribution of geochemical associations of elements.

(1–7) Associations of elements: (1–4) ore: (1) $\text{Au} \left(\frac{2.5}{500} \right)$ $\text{Ag} \left(\frac{32}{320} \right)$ $\text{As} \left(\frac{60}{60} \right)$ $\text{Sb} \left(\frac{10}{50} \right)$ $\text{Hg} \left(\frac{0.5}{10} \right)$, (2) $\text{Au} \left(\frac{1.3}{260} \right)$ $\text{Ag} \left(\frac{24}{240} \right)$ $\text{Sb} \left(\frac{26}{26} \right)$, (3) $\text{Ag} \left(\frac{9}{90} \right)$ $\text{Au} \left(\frac{0.23}{46} \right)$ $\text{As} \left(\frac{26}{26} \right)$ $\text{Sb} \left(\frac{2}{10} \right)$, (4) $\text{Ag} \left(\frac{5}{50} \right)$ $\text{Au} \left(\frac{0.18}{36} \right)$ $\text{As} \left(\frac{24}{24} \right)$ $\text{Mo} \left(\frac{10}{5} \right)$ $\text{Pb} \left(\frac{30}{3} \right)$, (5, 6) subore: $\text{Ag} \left(\frac{2.5}{25} \right)$ $\text{As} \left(\frac{20}{20} \right)$ $\text{Mo} \left(\frac{6}{4} \right)$ $\text{Pb} \left(\frac{60}{6} \right)$, (7) background; (8) andesites; (9) quartz and quartz-adularia veins.

halo-forming elements. The final stages are marked by formation of Au–Ag ores and local highly contrasting, but relatively low-grade (in element composition) Au–Ag geochemical fields with Au, Ag, As, Sb, and Hg being main typomorphic elements.

The main peculiarity of volcano–plutonic gold–silver ore–magmatic systems is their multimegastage and polymetallic mode. They are characterized by more prolonged and intricate development, which can be exemplified by the Dukat ore–magmatic system (Fig. 3). This deposit shows two main stages of magmatic and hydrothermal activities. Two potentially ore-bearing volcano–plutonic associations are distinguished there: andesite–granodiorite (early stage) and the main, rhyolite–granite–leucogranite association (late, final stage). The latter is distinctly specialized for F, B, Ag, Sn, Mo, W, and, to a lesser extent, Pb and K. The late, terminal stage is dominated by intrusive magmatism, whereas the beginning of the postmagmatic activity is marked by a distinct heterogeneous state of the postmagmatic

fluid and associated noncommercial tin–rare metal and rare metal mineralization. The Dukat ore–magmatic system is characterized by along with Au–Ag ores, widely developed Ag (with Ag, As, Sb, Pb, and Mn being main typomorphic elements), Ag–Pb (Ag, Pb, As, Sb, Hg, Zn, Mn), and Sn–Ag (Sn, As, Ag, Bi, Pb, Zn, Sb, Cu) mineralization. Nevertheless, similar regularities in formation of Au–Ag ores and related geochemical fields are preserved, which is reflected in the same elements (Au, Ag, As, Sb, Hg, Pb), a similarly high contrast ratio, and a similar spatial position relative to Ag–Pb ores and zones with disseminated sulfide mineralization. Despite differences, the general development scenario characteristic of ore-forming systems in epithermal Au–Ag deposits is similar, although it is simpler in the case of volcanic systems and more intricate in volcano–plutonic systems.

Figures 2 and 3 show that zoning, which is also characteristic of local systems (Au–Ag, Ag–Pb, and Sn–Ag deposits) is an inalienable property of regional

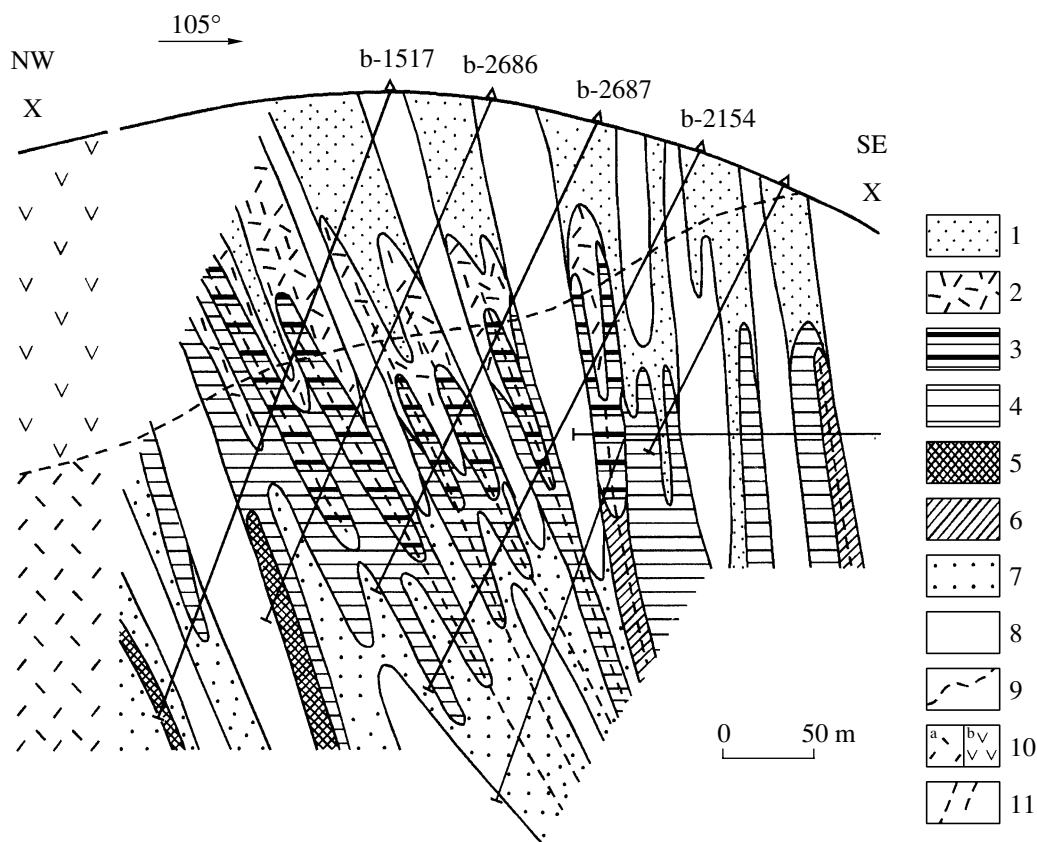


Fig. 5. The Dukat deposit. The Smelyi area. Cross section along profile X. Schematic distribution of geochemical associations of ore elements. (1–8) Associations of elements: (1, 2) supraore: (1) $\text{As} \left(\frac{30}{30} \right)$ $\text{Ag} \left(\frac{1.4}{14} \right)$, (2) $\text{As} \left(\frac{160}{160} \right)$ $\text{Sb} \left(\frac{30}{60} \right)$ $\text{Ag} \left(\frac{5.6}{56} \right)$ $\text{Hg} \left(\frac{0.5}{10} \right)$, (3–6) ore: (3) $\text{Ag} \left(\frac{70}{700} \right)$ $\text{As} \left(\frac{140}{140} \right)$ $\text{Au} \left(\frac{0.6}{120} \right)$ $\text{Sb} \left(\frac{20}{40} \right)$ $\text{Mn} \left(\frac{3000}{6} \right)$, (4) $\text{Ag} \left(\frac{14}{140} \right)$ $\text{As} \left(\frac{100}{100} \right)$ $\text{Pb} \left(\frac{100}{100} \right)$ $\text{Mn} \left(\frac{4000}{8} \right)$ $\text{Cu} \left(\frac{120}{6} \right)$ $\text{Bi} \left(\frac{0.5}{5} \right)$ $\text{Zn} \left(\frac{500}{5} \right)$ $\text{Mo} \left(\frac{10}{5} \right)$, (5) $\text{Ag} \left(\frac{20}{200} \right)$ $\text{As} \left(\frac{100}{100} \right)$ $\text{Pb} \left(\frac{300}{30} \right)$ $\text{Bi} \left(\frac{2}{20} \right)$ $\text{Sn} \left(\frac{30}{15} \right)$ $\text{Cu} \left(\frac{80}{4} \right)$ $\text{Zn} \left(\frac{300}{3} \right)$, (6) $\text{Ag} \left(\frac{8}{80} \right)$ $\text{As} \left(\frac{60}{60} \right)$ $\text{Au} \left(\frac{0.15}{30} \right)$ $\text{Pb} \left(\frac{100}{10} \right)$ $\text{Cu} \left(\frac{100}{5} \right)$ $\text{Zn} \left(\frac{1000}{10} \right)$ $\text{Mn} \left(\frac{5000}{10} \right)$, (7) subore: $\text{Pb} \left(\frac{1500}{150} \right)$ $\text{Ag} \left(\frac{4}{40} \right)$ $\text{As} \left(\frac{40}{40} \right)$ $\text{Zn} \left(\frac{2000}{20} \right)$ $\text{Bi} \left(\frac{1}{10} \right)$ $\text{Mn} \left(\frac{6000}{12} \right)$ $\text{Cu} \left(\frac{100}{5} \right)$ $\text{Mo} \left(\frac{8}{4} \right)$, (8) background; (9) lithological boundaries; (10) rhyolites (a), andesites (b); (11) quartz–feldspar, quartz–feldspar–rhodonite, and quartz–rhodonite veins.

gold–silver ore–magmatic systems (Kravtsova and Zakharov, 1996; Kravtsova *et al.*, 1996, 1998; Kravtsova, 1997, 1998). The geochemical zoning is most remarkable in this respect.

The zoned distribution patterns of geochemical associations of ore elements (multicomponent geochemical concentration fields) typical of single-megastage Au–Ag ores can be exemplified by one section across the Dal’nee deposit of the Turomchinsk system (Fig. 4). Up the dip of ore-bearing zones, low-contrast associations (Ag, As, Mo, Pb) of subore intervals are replaced by more highly contrasting (Ag, As, Mo) associations at lower ore levels (marked by an appearance of Au) and then by contrasting (Au, Ag, As) asso-

ciations at middle ore levels (with Sb). The middle–upper ore levels are characterized by wide development of highly contrasting (Au and Ag) and contrasting (As and Sb) associations accompanied by Hg.

The geochemical zoning characteristic of multimegastage Au–Ag ores of the Dukat system can be exemplified by the Smelyi area of the Dukat deposit (Fig. 5). There, ores and halos formed during two productive phases: gold–silver and, later, silver. The composition and structure of anomalous geochemical fields becomes more complicated. Locally, elements untypical of halos of Au–Ag deposits such as Sn, Bi, and Mn occur. The contrast ratio of Ag, Pb, and Zn increases. Nevertheless, the main typomorphic composition of

Table 2. Average K and Na contents and their proportions in wallrock metasomatites in different-depth Au–Ag deposits

Levels	Number of samples	K, %	Na, %	K/Na
Near-surface Au–Ag deposits (Dukat)				
Upper	250	6.5 (4.6–8.7)	0.20 (0.12–0.55)	32
Lower	200	3.6 (2.5–4.2)	0.80 (0.69–1.11)	4.5
Shallow Au–Ag deposits (Dal'nee)				
Upper	350	6.0 (4.0–7.0)	0.30 (0.25–1.54)	20
Lower	250	2.9 (2.2–3.8)	1.41 (1.11–2.10)	2.1
Small deep Au–Ag deposits (Kvartsevoe)				
Upper	300	4.3 (3.1–5.0)	0.67 (0.62–2.00)	6.4
Lower	200	2.4 (2.3–2.7)	2.00 (1.80–2.52)	1.2

Note: Concentration range is shown in parentheses.

geochemical associations and the zoning remain unchanged: polymetals, Ag, and Mo of subore intervals are replaced by more contrasting associations of Ag, As, and Mo at lower ore levels and then by highly contrasting Ag, Au, As, and Sb at middle and upper ore levels. As, Sb, and Hg prevail in upper ore and supraore levels.

The zoning is characteristic also of nonore elements, which is demonstrated by regular distribution of alkali (K, Na, Rb, Li, Cs) in wallrocks. The zoned distribution of alkali in Au–Ag, Ag–Pb, and Sn–Ag deposits is considered in detail in several works (Gundobin and Kravtsova, 1979; Kravtsova and Gundobin, 1989; Kravtsova and Stepina, 1992; Kravtsova *et al.*, 2000; Kravtsova and Korkina, 2002). In this paper, we dwell only on the behavior of K and Na in ores and metasomatites of the Au–Ag deposits and their role in ore concentration processes. The distributions of K and Na along sections across the Dal'nee and Dukat deposits are considered for the first time.

Both deposits are characterized by the stable removal of Na from all internal zones of altered rocks and a similarly stable influx of K to these zones (Figs. 6, 7). The change in concentrations of these elements directly depends on newly formed mineral parageneses and is closely related to orebodies and wallrock metasomatites.

In metasomatites developed after andesites and rhyolites, maximum contents of K exceed 6.0 and 8.0%, whereas its minimal concentrations are 2.0 and 2.5%, respectively, against their average values of 2.3% in andesites and 2.9% in rhyolites. Only in internal silicification zones (ore veins) and at supraore levels are the K contents characterized by lower values (Figs. 7, 8). The K distribution up the dip of ore zones is remarkable: its content increases from the base toward the middle part of the section and then decreases in its upper part. Such patterns reflect the replacement of sericite, dominant in the lower parts of orebodies, by adularia in the middle parts and by hydromicas in the upper parts; i.e., the ore process developed under con-

ditions of changing K activity, with the peak of K metasomatism at the middle levels.

The Na distribution is controlled by the degree of stability of primary plagioclase and newly formed albite and oligoclase. In all zones of the metasomatic section, the primary plagioclase appears to be unstable, whereas the newly formed albite and oligoclase are stable only in propylitic associations (deposit flanks, subore and supraore levels), which determines the decrease in Na contents from external toward internal zones. In vertical cross section, they are close to background concentrations (2.5–3.0%) in external zones of metasomatites (peripheral areas and supraore levels) and minimal (<0.5%) in central zones. The background values of the Na content are 3.0 and 2.7% in andesites and rhyolites, respectively. Ore zones are characterized by an intense Na loss, increasing upward (Figs. 6, 7).

There is a dependence between the relative depth of formation of Au–Ag deposits and intensity of these processes. Different trends in changes in K and Na concentrations in processes of wallrock alteration and the stable distribution of these elements allow the K/Na value to be used for estimation of relative formation depths (Table 2). An intense influx of K in the internal zones of the metasomatic section and almost complete removal of Na from them are characteristic of near-surface deposits, K influx and more moderate Na loss are observed in shallow deposits, and moderate K influx and insignificant Na removal are peculiar to deeper deposits. Simultaneously, the K/Na values vary from 4.5 to 32 for the first, from 2.1 to 20 for the second, and from 1.2 to 6.4 for the third type of deposits.

The role of K in ore concentration processes is evident from the vertical distribution of K, Au, and S in ore veins of Au–Ag deposits (Fig. 8), where areas with maximum Au contents occur above maximums of the K and S concentrations. In other words, Au deposition occurs against the background of the decreasing sulfide potential after precipitation of the main share of K from solutions, which results in formation of thick adularization zones in Au–Ag deposits. The presence of K and S

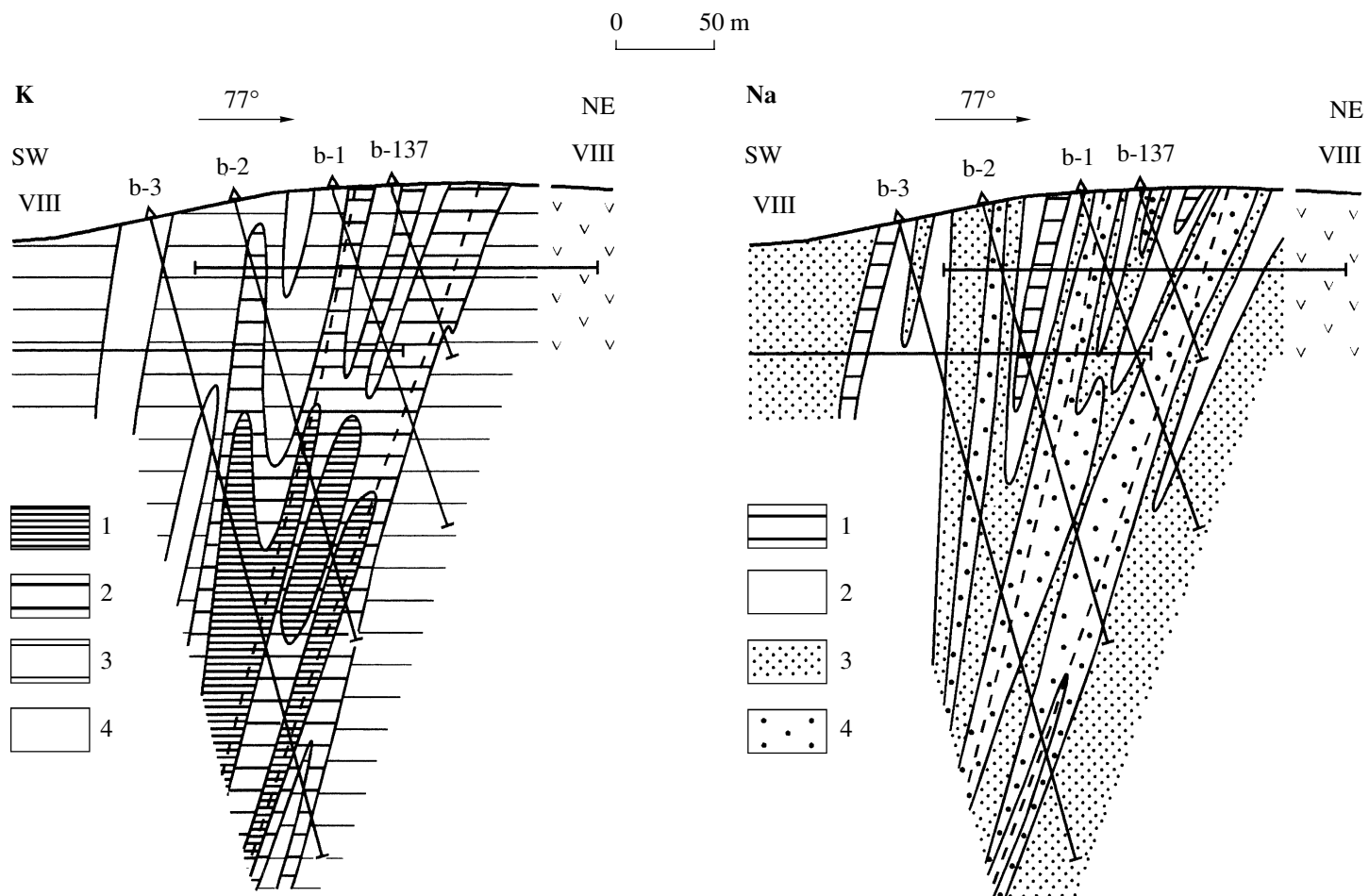


Fig. 6. The Dal'nee deposit. Cross section along profile VIII. Distribution of alkaline elements. Contents of K and Na (%): K (1–4): (1) >6.0, (2) 5.0–6.0, (3) 3.0–5.0, (4) 2.0–3.0; Na (1–4): (1) 2.5–3.0, (2) 1.5–2.5, (3) 0.5–1.5, (4) <0.5. Other symbols are as in Fig. 4.

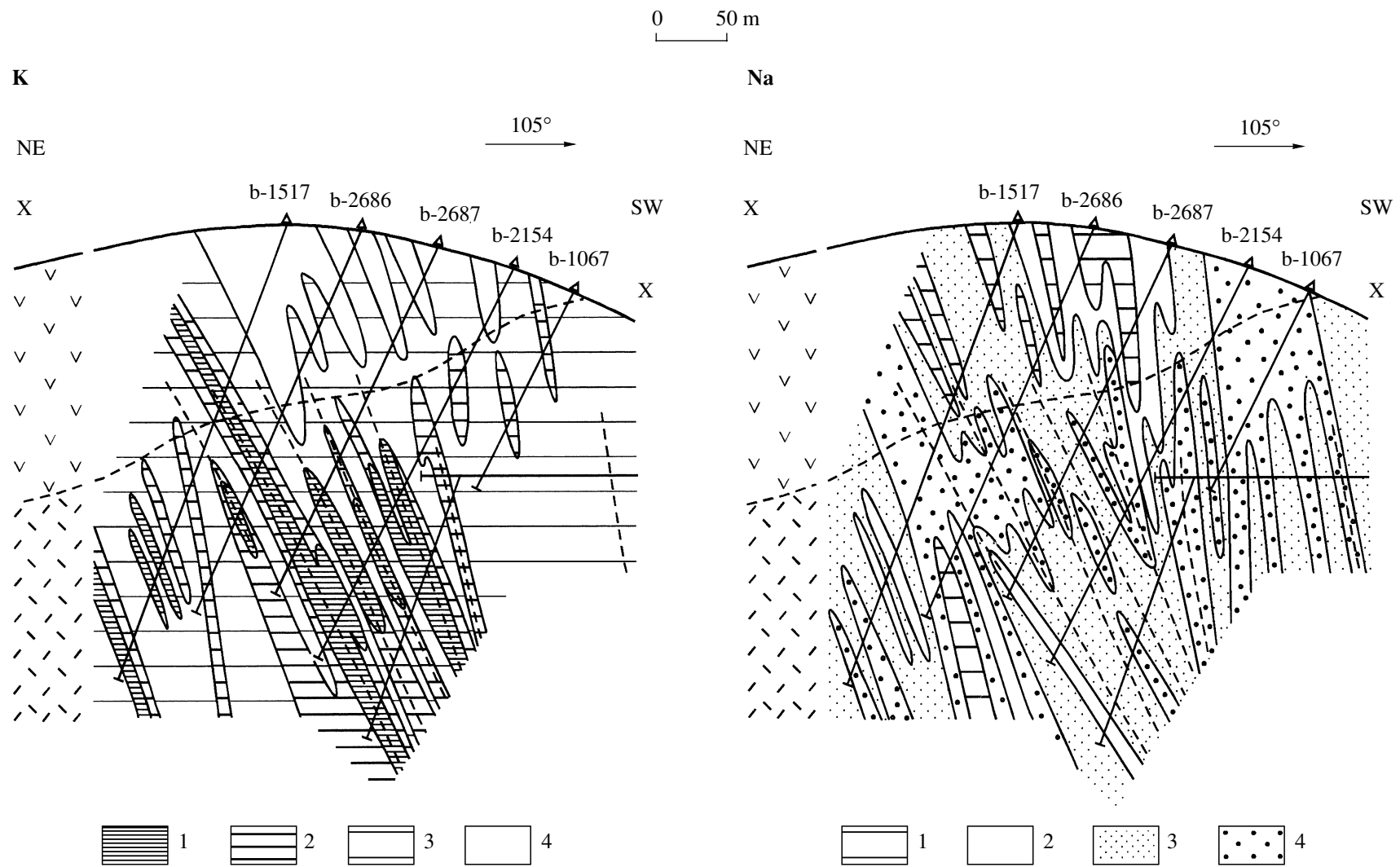


Fig. 7. The Dukat deposit. The Smelyi area. Cross section along profile X. Distribution of alkaline elements. Contents of K and Na (%): K (1–4): (1) 6.0–8.0, (2) 4.5–6.0, (3) 2.0–4.5, (4) <2.5; Na (1–4): (1) 2.5–3.0, (2) 1.0–2.5, (3) 0.2–1.0, (4) <0.2. Other symbols are as in Fig. 6.

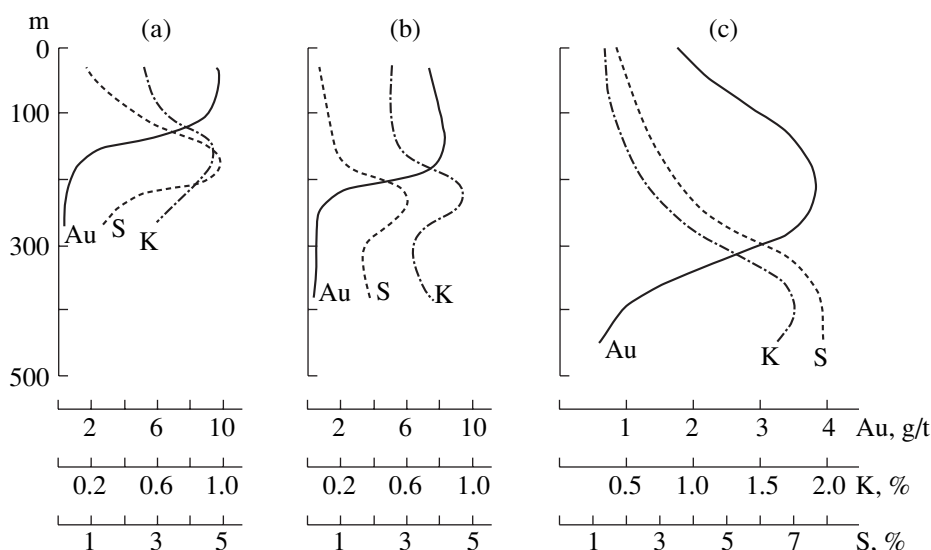


Fig. 8. Distribution of contents of Au, S, and K (ore veins) up the dip of ore-bearing zones in epithermal Au–Ag deposits: (a) Dal'nee; (b) Kwartsevoe; (c) Dukat, Smelyi area.

in ore-forming solutions of Au–Ag deposits is also confirmed by the results of fluid inclusion studies.

FLUID INCLUSIONS

The Turomchinsk Ore–Magmatic System

The physicochemical formation conditions of Au–Ag ores in volcanic ore–magmatic systems were studied in the Dal'nee deposit (Table 3). Quartz of ore veins from this deposit was established to enclose primary and primary–secondary two-phase fluid inclusions 10–30 μm across. They are frequently accompanied by syngenetic vapor-rich inclusions, indicating heterogenization of the fluid and allowing its pressure to be estimated. It was established that Au–Ag ores (quartz and quartz–adularia veins) formed from fluids of low mineralization degree (3.9–0.4 wt %) in the temperature interval of 355–205°C. The eutectic temperatures changed from –29...–24 to –36...–33°C, which corresponds to the water–salt system $\text{MgCl}_2\text{--NaCl(KCl)–H}_2\text{O}$. The pressure in the ore-forming system regularly decreased from 170–60 bar at lower levels of the deposit to 75–20 bar in its upper horizons. The fluid density was 0.59–0.87 g/cm^3 . Assuming that the pressure was lithostatic, the formation depth of ores can be estimated as approximately 600 m.

The Dukat Ore–Magmatic System

The physicochemical formation conditions in ore–magmatic systems of the volcano–plutonic type were studied in the Dukat deposit. Samples of quartz from magmatic rocks, mineralized zones, and ore veins were taken from a vertical interval exceeding 1800 m (underground workings, deep boreholes). This allowed changes in fluid parameters to be traced within the

entire ore-forming system from the magmatic (rhyodacites and granites) to postmagmatic (early Sn–W ores) and hydrothermal (Sn–Ag, Ag–Pb, Au–Ag, and Ag ores) stages (Table 4).

Granites and granite–porphyries. Quartz phenocrysts of granite–porphyries contain three- and four-phase (vapor, solution, halite, and prismatic hardly soluble phase) inclusions of salt magmatic fluids and also vapor-rich inclusions (gas, solution) representing the low-density phase of magmatic fluids. These phases probably coexisted at the magmatic stage. The dimensions of fluid inclusions do not exceed 20 μm . Under heating, the multiphase and three- to four-phase inclusions frequently undergo decrepitation before complete homogenization. Temperatures of complete or partial homogenization of these inclusions show no dependence on the depth and occur in the interval of 270–450°C (Table 4). The eutectic temperatures of solutions from multiphase inclusions are in the interval of –96 to –48°C, while the ice melting temperatures vary from –61 to –28°C. These data imply high mineralization of these solutions and the presence of substantial quantities of salts (CaCl_2 , MnCl_2 , FeCl_2 , LiCl , CaBr_2 , and others) in them that are capable of reducing the temperature of eutectic melting. The X-ray spectral analysis of dry salt residues of individual inclusions (sample R-6469) revealed significant contents of Na, K, and Cl in solutions and registered the presence of Ca, Mn (up to 24 g/kg), Fe (up to 10 g/kg), S (up to 3–5 g/kg), and Ag (up to 0.4 g/kg). The total salt content amounts to 45 wt %-equiv of the water–salt system $\text{CaCl}_2\text{--NaCl–H}_2\text{O}$. With an increase in depth from 680 to 590 m (Table 4), the solution concentration also increases from 38 to 45 wt %. Two-phase inclusions become homogenized at temperatures of 350 to 300°C and contain low- and moderately concentrated (23–9.2 wt %)

Table 3. Chemical compositions of ores and characteristics of fluid inclusions in quartz from veins of the Dal'nee Au–Ag deposit (Evensk ore district, Turomchinsk ore–magmatic system)

No.	Ore veins	Content, g/t										$T_{\text{hom.}}, ^\circ\text{C}$	$T_{\text{eut.}}, ^\circ\text{C}$	$T_{\text{i.m.}}, ^\circ\text{C}$	$C_{\text{salt}}, \text{wt } \%$	P, bar	$d, \text{g/cm}^3$
		Au	Ag	Hg	Sb	As	Pb	Zn	Cu	Bi	Mo						
R-3415/1	Quartz–adularia vein, surface, upper–middle level	0.86	30	0.05	9.6	16	50	100	100	0.4	<2	235–205 (26)	–29...–24	–1.5...–1.0	2.6–1.7	30–20	0.87–0.84
G-1288	Quartz–adularia vein, adit 1, upper–middle level	1.75	60	0.04	12.6	8.2	30	100	80	0.7	<2	295–285 (28)	–31...–29	–1.7...–0.7	2.9–1.2	80–75	0.75–0.74
G-1291	Quartz veinlets in adularia, adit 1, upper–middle level	1.58	30	0.2	14.0	15	50	100	200	0.9	<2	235–220 (16) 335 (2)	–29 –25	–0.4...–0.3 –0.9	0.7–0.4 1.6	– 120	0.84–0.82 0.78
R-4607/2	Quartz–adularia vein, central part, adit 10, middle level	6.1	10	0.02	18.0	20	30	100	300	0.8	2	265 (22) 300–290 (18)	–28 –29	–1.2 –1.0...–0.5	2.1 1.7–0.9	– 80–75	0.78 0.73–0.68
R-4607/1	Quartz–adularia–sulfide part of vein, at the contact with host rocks, adit 10, middle level	2.6	200	0.02	19.0	60	200	1000	500	5	4	330–315 (15)	–30...–25	–2.1...–0.7	3.5–1.2	120–100	0.69–0.65
R-5108	Quartz–sulfide vein, adit 11, lower level	0.45	40	0.01	7.2	20	100	300	200	0.4	2	260 (40) 345–330 (65)	–34...–33	0.5 –2.3...–0.2	0.9 3.9–0.4	– 145–90	0.78 0.66–0.63
R-5105	"	0.13	6	0.07	6.4	30	100	200	100	0.3	<2	355–280 (27)	–36...–33	–0.4...–0.2	0.7–0.4	170–60	0.76–0.59

Note: Au, Hg, Sb, and As were determined by the atomic absorption method (analysts, L.D. Andrulaitis and S.E. Vorob'eva); other elements, by the spectral semi-quantitative method (analyst, A.A. Nesterova). The number of examined inclusions is shown in parentheses.

Table 4. Chemical compositions and characteristics of fluid inclusions in quartz from magmatic rocks and ore veins of the Dukat Au–Ag deposit (Omsukchansk ore district)

No.	Ore veins and rocks	Altitude, m	Contents of ore elements, g/t												$T_{\text{hom.}}$, °C	$T_{\text{eut.}}$, °C	$T_{\text{i.m.}}$, °C	C_{salt} , wt %
			Au	Ag	Hg	Sb	As	Pb	Zn	Cu	Bi	Sn	W	Mo				
Central Dukat, quarry (ore level)																		
3-32	Quartz–pyrolusite vein (Ag ores)	1250	0.14	200	0.01	30	20	30	150	100	–	10	20	10	305–290 (40)	–27...–25	–0.4...–0.2	0.7–0.4
3-11b/1	Quartz–rhodonite vein (Ag ores)	1200	1.6	400	0.03	30	20	50	100	500	<0.3	4	<2	<2	340–300 (46)	–28...–26	–1.3...–0.2	2.2–0.4
III-G	Quartz–rhodonite–feldspar vein (Ag ores)	1200	5.5	>1000	–	60	80	50	200	100	<0.3	4	<2	<2	320–285 (64)	–35...–32	–1.1...–0.9	1.6–0.7
III-G/2	Quartz–feldspar vein (Au–Ag ores)	1200	15.4	>1000	0.03	100	300	100	300	300	<0.3	4	<2	2	335–325 (24) 235 (30)	–32...–29 –35	–3.2...–3.1 –1.7	5.2–5.1 2.9
III-G/1	Quartz–feldspar–sulfide vein (Au–Ag ores)	1200	1.7	1000	–	100	60	700	1000	300	<0.3	10	<2	<2	355–335 (49) 195 (58)	–49...–47 –49...–47	–3.0...–2.0 –2.0...–1.0	4.9–3.2 3.2–1.7
Central Dukat, VII ore zone (ore levels)																		
K-1028	Quartz–feldspar vein (Au–Ag ores)	1155	0.14	5	0.02	20	60	100	60	300	<0.3	4	<2	6	335–330 (11)	–24...–23	–4.0... 2.0	6.4–3.3
K-1015	Quartz–feldspar–sulfide vein (Au–Ag ores)	1080	0.35	200	0.02	30	20	1000	1500	2000	0.5	5	<2	4	230–220 (12)	–50...–48	–4.0... 2.0	6.4–3.3
Smelyi area, adit 60 (ore level)																		
R-7582	Quartz–rhodonite vein (Ag ores)	860	0.1	1000	–	30	30	40	300	80	<0.3	6	<2	2	195–175 (47)	–25...–24	–2.0...–0.5	3.3–0.7
R-6346/1	Quartz–rhodonite–sulfide vein (Ag–Pb ores)	860	0.2	>1000	0.08	30	60	300	800	300	0.4	6	<2	3	350–330 (18) 315 (5)	–36...–28 –29	–1.1...–0.9 –0.9	1.9–1.6 1.6
R-6346/2	Quartz–rhodonite–sulfide vein (Ag–Pb ores)	860	0.2	>1000	0.09	30	80	500	900	400	0.5	8	2	3	355–315 (13)	–25...–24	–1.1...–0.6	1.9–1.0
R-6346	Quartz–rhodonite–chlorite–sulfide vein (Sn–Ag and Ag–Pb ores)	860	0.5	>1000	0.25	20	80	>1000	>1000	>1000	1.5	50	2	6	195–190 (26) 375–370 (23)	–64...–62 –50...–48	–2.0...–1.0 –6.0...–5.0	3.3–1.7 9.2–7.9

Table 4. (Contd.)

No.	Ore veins and rocks	Altitude, m	Contents of ore elements, g/t												$T_{\text{hom.}}, ^\circ\text{C}$	$T_{\text{eut.}}, ^\circ\text{C}$	$T_{\text{i.m.}}, ^\circ\text{C}$	$C_{\text{salt}}, \text{wt } \%$
			Au	Ag	Hg	Sb	As	Pb	Zn	Cu	Bi	Sn	W	Mo				
Structural borehole 101 (subore intervals)																		
101/245	Quartz–chlorite–sulfide vein (Sn–Ag ores)	680	0.5	300	0.22	60	500	1000	1000	5000	5.0	150	<2	3	215 (8)	–40	–5.0...–4.8	8.0–7.6
101/296	Slightly altered rhyodacite with sulfides	620	0.3	1.1	0.15	20	20	100	400	300	0.3	6	<2	2	435–365 (31) 365–290 (10)	–64...–51 –65...–58	–28...–15 –21...–17	27.7–18.9 23.0–20.0
R-6379a	Quartz–muscovite vein with carbonate, scheelite, and pyrite (Sn–W ores)	620	0.0019	0.9	0.15	6	10	400	1000	200	10.5	110	20.2	2	300–265 (14) 215–175 (21)	–56...–54 –56...–54	–22...–20 –6...–4	37.0 9.2–6.4
R-6410	Rhyodacite ignimbrite	250	0.0003	0.2	0.01	N.d.	N.d.	80	50	10	0.5	4.0	5.0	<2	330–300 (10)	–50...–48	–12...–10	16.0–13.9
R-6468	Granite–porphyry	–415	0.001	0.2	0.01	1.2	7.0	31	25	9	1.7	3.8	2.2	<2	> 410D (12) 350–300 (6)	–56...–54 –64...–62	–29...–28 –7...–6	>38 10.5–9.2
R-6469	Granite with quartz–muscovite veinlets, calcite, scheelite, and pyrite	–430	0.001	0.2	0.06	24	90	110	170	27	6.9	45	2.5	<2	370–340 (9)	–98...–96	–44...–42	41
R-6471	Granite–porphyry	–445	0.0009	0.17	0.02	2.0	28.5	37	52	9	0.6	6.5	3.5	<2	> 450D (6) 385–380 (11)	–66...–64 –39...–34	–44...–42 –28...–22	>40 >23
R-6381	Granite–porphyry	–540	0.0088	0.9	0.17	6.0	11.5	90	67	27	1.3	14	2.1	<2	390–350D (13)	–98...–96	–50...–48	>38
R-6486	Granite	–590	0.0032	0.6	0.02	1.8	19.0	32	38	9	1.6	12	2.6	<2	320–265D (10)	–76...–74	–61...–60	>45

Note: Hg was determined by the atomic absorption method (analysts, L.D. Andrulaitis and S.E. Vorob'eva), other elements, by the spectral semiquantitative method (analysts, E.V. Smirnova and A.I. Kuznetsova). D, temperature of inclusion decrepitation. The number of examined inclusions is shown in parentheses.

solutions with eutectic temperatures ranging from -54 to -64°C and ice melting temperatures of -28 to -6°C . According to Raman spectroscopy, the vapor-rich phase from inclusions is represented by CO_2 and N_2 in the proportion of 6 : 4.

Rhyodacite ignimbrites. Quartz phenocrysts from rhyodacites contain two-phase inclusions with homogenization temperatures of 330 – 300°C . The eutectic temperatures range from -50 to -48°C , which indicates the proximity of inclusion solutions to CaCl_2 – KCl – H_2O and CaCl_2 – H_2O water–salt systems. The ice melting temperature is in the interval of -12 to -10°C and salt concentrations vary from 16.0 to 13.9 wt % (Table 4).

Quartz–muscovite veins (Sn–W ores). Quartz from chlorite–muscovite–quartz veins with pyrite and scheelite contains primary and pseudosecondary three-phase (solution, gas, and halite) and two-phase (solution and gas) inclusions 10 – $15\ \mu\text{m}$ across. Homogenization of three-phase inclusions occurs in the interval of 300 – 290°C . The eutectic temperatures are in the interval of -56 to -54°C and the ice melting temperatures are -22 ... -20°C . The similarity of the eutectic temperatures of the solutions from the inclusions to those of the system CaCl_2 – NaCl – H_2O (-55°C) allows the composition of these solutions to be interpreted using a triple diagram (Borisenko, 1977, 1982). The solution concentration is 34 wt % NaCl and 3 wt % CaCl_2 . Two-phase inclusions are homogenized at temperatures of 215 – 175°C . The eutectic temperatures are in the interval of -56 to -54°C , and the ice melting temperatures vary from -6 to -4°C . The total solution concentration amounts to 9.2–6.4 wt % (Table 4).

Zones of disseminated sulfide mineralization. Quartz from these zones (flanks of the Dukat deposit) encloses three- and two-phase inclusions 5 – $10\ \mu\text{m}$ across, which are homogenized at temperatures of 435 – 290°C . Eutectic temperatures range from -65 to -51°C and the ice melting temperatures vary from -27.7 to -16.5°C . The total concentration of solutions is in the interval of 27.7–11.8 wt %-equiv NaCl. Judging from the eutectic temperatures (Table 4), the salt compositions may correspond to the water–salt systems CaCl_2 – KCl – H_2O and CaCl_2 – NaCl – H_2O with admixture of Li or Br. The pressure was 390–150 bar during formation of these zones.

The Dukat deposit. Quartz from ore veins is represented by two generations: early brecciated quartz with abundant secondary two-phase and vapor-rich inclusions and newly formed crystalline quartz with primary inclusions in growth zones. Quartz crystals frequently contain accumulations of ore minerals: sphalerite, galena, chalcopyrite, sulfosalts of silver and Ag minerals. Such quartz crystals are usually characterized by a zoned structure. Their central parts are comprised of transparent quartz, which encloses relatively large two-phase inclusions (up to $40\ \mu\text{m}$ across). Peripheral parts of the crystals are composed of opaque quartz with abundant two-phase inclusions of variable size (1 – $30\ \mu\text{m}$

across) and with elongated vacuoles extended perpendicular to the crystal facets. There are also one-phase and vapor-rich inclusions. The presence of syngenetic vapor-rich and liquid–vapor inclusions implies the heterogeneous state of hydrothermal fluids.

Sn–Ag and Ag–Pb ores. Two-phase inclusions in zoned quartz from veins representing Sn–Ag and Ag–Pb ores become homogenized at temperatures of 375 – 190°C (Table 4). The eutectic temperatures range from -64 to -24°C and the ice melting temperatures, from -6 to -0.9°C . The solution concentration is in the interval of 9.2–1.0 wt %-equiv NaCl. The eutectic temperatures indicate the water–salt systems CaCl_2 – KCl – H_2O , CaCl_2 – NaCl – H_2O , and KCl – NaCl – H_2O . According to x-ray spectral analysis of salt residues of individual fluid inclusions (sample R-6346), the solution composition is dominated by NaCl, KCl, and CaCl_2 , accompanied by Fe, Zn, and S (up to 0.2–5.0 g/kg). The admixture of these elements determines lowered (up to -64°C) eutectic temperatures of solutions. The homogenization temperatures are characterized by wavelike changes in growth zones from central parts of individual quartz crystals toward their peripheral areas: $290 \rightarrow 375$ – $370 \rightarrow 185$ – 175°C . The solution concentration also changes in the same direction: 7.9 \rightarrow 9.2 \rightarrow 1.7 wt % (Smelyi area, sample R-6346). The vapor-rich phase of fluid inclusions is characterized by low density. Denser CO_2 that is sublimated under temperatures of -58 to -60°C occurs only in substantially gas fluids. According to Raman spectroscopy, CO_2 in two-phase and vapor-rich inclusions prevails with N_2 in the proportion of 1 : 1. The pressure in the ore-forming system was within the interval of 170–30 bar and the fluid density varied from 0.61–0.75 g/cm³.

Ag and Au–Ag ores. Fluid inclusions in quartz from silver and gold–silver veins are homogenized at 340 – 175°C (Table 4). The eutectic temperatures vary from -49 to -24°C and the ice melting temperatures range from -4 to -0.2°C . Total mineralization of solutions decreases from lower levels upward from 6.4 to 0.7 wt % in the depth interval of 1080 to 1200 m (Au–Ag ores) and from 3.3 to 0.4 wt %-equiv NaCl at depths of 860 to 1250 m (Ag ores). Judging from the eutectic temperatures, the salt composition of solutions from inclusions corresponds, in its main components, to the water–salt systems CaCl_2 – H_2O and NaCl – KCl – H_2O with an admixture of MgCl_2 . The temperature of inclusion homogenization in growth zones shows wavelike changes (340 – $335 \rightarrow 195$ – $190 \rightarrow 335^{\circ}\text{C}$) from the central parts of individual quartz crystals toward their peripheries (Central Dukat, quarry, sample III-G/1). The concentration of solutions changes in a similar manner: 3.2 \rightarrow 1.7 \rightarrow 4.9 wt %. The gas phase of solutions is not condensed under cooling and, according to Raman spectroscopy, contains CO_2 and N_2 . The share of methane is below 1 mol %. The pressure in the ore-forming system was within the range of 135–70 bar and the fluid density, 0.63–0.94 g/cm³.

DISCUSSION

Despite differences in mineralization intensity, character and peculiarities of magmatic processes, and mineral and geochemical associations in the multimegastage volcano–plutonic Dukat ore-forming system and the single-megastage compositionally simpler volcanic Turomchinsk system, they demonstrate a generally similar scenario of development. Gold–silver mineralization and related geochemical concentration fields are characterized by a unidirectional trend and distinct hierarchical structure. Local geochemical fields of deposits develop against the background of a common geochemical field of ore–magmatic systems (Kravtsova and Zakharov, 1996; Kravtsova, 1997, 1998). According to fluid inclusion studies, the ore-forming systems under consideration can be referred to the open type (Prokof'ev, 1998, 2000). Their development began at low depths and terminated in near-surface environments.

When compiling multifactor models of such systems (Figs. 2, 3) we included, in addition to geochemical data and results of examination of fluid inclusions, some elements of thermodynamics (parameters of the hydrothermal structure, depth occurrence of the magmatic chamber) obtained in our previous studies. The experimental imitation modeling of physicochemical processes of gold solution, transfer, and deposition in epithermal deposits of the active continental margin and its results are discussed in detail in works by Karpov *et al.* (2000, 2001). Figure 9 demonstrates a generalized multireservoir thermodynamic model of an ore-forming system for epithermal Au–Ag deposits and the main results of imitation experiments (Karpov *et al.*, 2001), which are needed to make the further consideration of the data more understandable. This thermodynamic model is quite consistent with newly obtained results. A deep-seated andesite asthenolith (a deep-seated source of fluids and heat—the andesite magma chamber in Fig. 2) 50–100 km³ in size and with an initial H₂O content of 3.5%, moving up to upper levels of the Okhotsk–Chukotsk volcanic belt (3–6 km below the surface), can stimulate initiation and development of a hydrothermal structure 1.5 km long in vertical section. According to estimates of hydrostatic and lithostatic pressures, the formation depth of the studied deposits does not exceed 1.2 km. Thus, the total formation depth of the ore-forming systems in question is 1200–1500 m. Losing 1% of water in its upward movement, the asthenolith forms a fluid flow, whose potential resources are sufficient for formation of Au deposits with reserves of 10–100 t in favorable geological–geochemical environments. In line with this scenario, gold was deposited in reservoirs 7–10 at depths of approximately 500–1000 m below the surface at temperatures ranging from 300 to 150°C. According to thermobarogeochemical and geochemical data, Au–Ag ores of the studied ore–magmatic systems formed at depths of 600–800 m under temperatures of 355–205°C

(Turomchinsk system) and 340–175°C (Dukat deposit).

Thermodynamic modeling (Karpov *et al.*, 2001) shows that the composition of hydrothermal fluids results from interaction of the andesite–water system in the zone of accumulation of hydrothermal solutions from peripheral magmatic chambers. According to calculations, gold and silver, which are present in both andesites and rhyolites at Clarke values, are involved into the fluid phase with enrichment coefficients of 200–500 and 100–200 for Au and Ag, respectively. It is assumed that there exist different intermediate magmatic chambers—derivatives of the parental andesite magma (an intermediate chamber with acid magma is a source of fluids and heat in Fig. 3).

An important role in formation of ore deposits belongs to K and Na. These elements represent constituents of fluids that participate in ore formation and are closely related to orebodies and enclosing wallrock metasomatites. Variations in concentrations of alkaline elements are consistent with compositional changes of metasomatites. Like ore elements, alkalis clearly reflect peculiarities in ore formation during development of ore–magmatic systems as a whole and at its different megastages and stages. The behavior of K and Na in ores and wallrock metasomatites indicates the composition of ore-forming solutions and their evolution. Ore-forming fluids are usually enriched in Na (Karpov *et al.*, 2000, 2001; Borovikov and Kravtsova, 2001₁), although they always contain K as well. During ore deposition, when ore-bearing fluids migrate upward, the differently oriented trend in the behavior of K and Na is preserved. The increase of the Na content in solutions correlates distinctly with the increase in intensity of Na removal from internal zones of wallrock metasomatites (Figs. 7, 8).

Potassium also plays a substantial role in the ore deposition processes. This is well demonstrated by the distribution of K, Au, and S in ore veins (Fig. 8). Gold deposition occurs against the background of decreasing sulfide potential and K precipitation from solutions. The data on fluid inclusions also confirm the presence of K and S in ore-forming solutions of gold–silver deposits. It is likely that K influences the transport and deposition of gold. The close relation between Au, K, and S was discussed elsewhere (Kravtsova, 1998). The regularities defined are sufficiently well explained by migration of ore components in the form of hydrosulfide complexes. According to thermodynamic calculations, Au(HS)₂⁻ represents the main form of gold transport by solutions (Karpov *et al.*, 2001). Chloride complexes of gold play a subordinate role. Silver occurs in both hydrosulfide and chloride forms.

Summing up all the data obtained, one can assume that intermediate magmas served as a source of fluids and gold. Younger postsubduction crustal melts merely captured the gold. A more intricate scenario is characteristic of silver. Some Ag-bearing fluids were carried

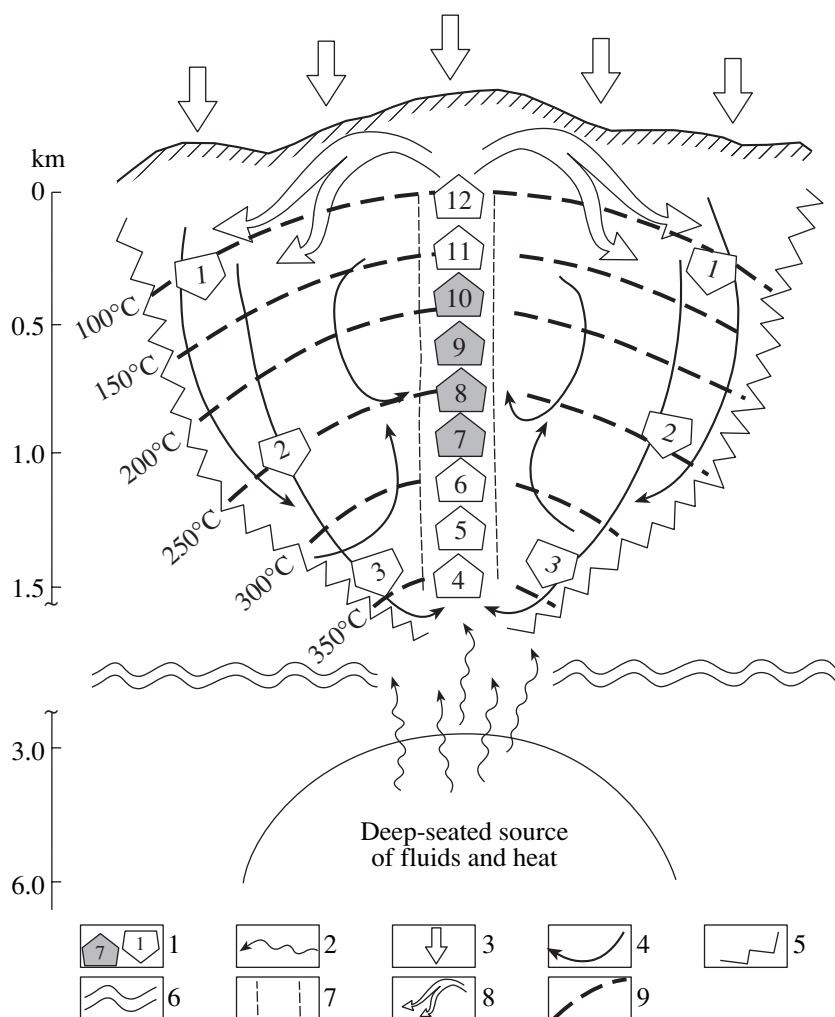


Fig. 9. Thermodynamic model of the volcanogenic ore-forming system of epithermal gold-silver deposits of northeastern Asia. (1) Reservoirs and their numbers; (2) ascending flows of deeply sourced fluids; (3) meteoric waters; (4) descending flows of infiltration waters; (5) boundaries of the hydrothermal system; (6) boundary separating the zone of hydrostatic pressure from the lower zone with prevailing lithostatic pressure; (7) fissured channel, which serves as a conduit of ascending flows of hydrothermal solutions; (8) discharge of hydrothermal solutions in an environment of dispersion and spread; (9) isotherms.

by deep subduction-related magmas, whereas most of them were produced by postsubduction rhyodacite crustal melts formed in intermediate chambers, which also served as a source for Sn and rare metals.

The study of fluid inclusions shows that magmatic fluids in granite-porphyrries from the Duklat deposit are heterogeneous and represented by vapor-rich and water-salt phases. The dense water-salt phase of the magmatic fluid is characterized by an elevated content of metals (Mn, Zn, Fe, S, Ag), a complex salt composition, and high salt concentrations (over 45 wt %). The main share among fluid salts belongs to the chlorides NaCl and KCl, with a subordinate proportion of CaCl₂, FeCl₂, and other salts present. Such high-concentration metalliferous fluids are characteristic of many Ag-Sn ore fields: Bazardarinsk (Pamirs), Deputatsk (Yakutia), and Yustydsk (Gornyi Altai) (Borisenko *et al.*, 1990, 1997, 1999, 2001). The vapor-rich phase of magmatic

fluids from granite-porphyrries of the Duklat deposit contain low-density CO₂ and N₂, which distinguishes them from reduced methane-bearing fluids in granitoids of plutogenic As-Sn ore fields. The salt concentrations in fluids increase with depth. Magmatic fluids from rhyodacites differ from those in granite-porphyrries by a lack of noticeable quantities of salt admixtures with low eutectic temperatures. The formation of zones with disseminated sulfide mineralization occurred with participation of high-temperature (435–290°C) concentrated fluids similar in their salt composition to magmatic fluids from granite-porphyrries. Quartz-muscovite veins with Sn, W, and Mo formed from Ca-Na chloride fluids with variable concentrations (37–6.4 wt %) at temperatures of 300–290°C.

Mineral associations of Ag-Sn and Ag-Pb ores (Dukat deposit) were deposited from chloride hydrothermal solutions with moderate and low concentra-

tions (9.2–1 wt %) at temperatures of 375–175°C and insignificant pressure (170–30 bar). The aggregate state of ore-forming fluids was likely heterogeneous. The salt composition of hydrothermal fluids was determined by NaCl, KCl, CaCl₂, and MgCl₂. At deep levels, mineral-forming fluids contain Fe, Zn, and S, typical of magmatic fluids in granite–porphyries. This may point to participation of magmatic fluids in formation of Ag–Sn and Ag–Pb ores.

During formation of Au–Ag and Ag mineralization, the temperature of mineral deposition and the salt concentration in hydrothermal systems varied in a wavelike manner. Some types of silver ores (Dukat deposit) show a tendency toward a decrease in the total salt concentration in mineral-forming solutions from lower levels of the deposit toward the surface. Temperatures of mineral formation decrease only slightly in the same direction. Characteristic features of magmatic and ore-forming fluids are an insignificant content of dissolved gases and an almost complete absence of methane. In general, the formation of Au–Ag and Ag ores occurred at similar temperatures and pressures: 355–205°C and 170–20 bar in the Evensk group of deposits and 340–175°C and 135–70 bar in the Dukat deposit. Au–Ag and Ag ores were deposited from compositionally similar (NaCl, KCl, CaCl₂, and MgCl₂) fluids of low concentration (3.9–0.4 and 6.4–0.4 wt % for the Evensk group and the Dukat deposit, respectively).

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