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Major impurity elements in native gold and their association with gold mineralization settings in deposits of Asian folded areas

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Abstract

Contents of major impurities (Ag, Cu, and Hg) have been studied in gold from ore deposits of various types: (1) associated with skarns and black shales (Altai–Sayan folded area (ASFA) and North Vietnam), (2) pluton-related porphyry Cu–Mo (ASFA), and (3) volcanic pyritic (Rudny Altai, the Urals, and North Vietnam). Analysis of gold ore mineralization in deposits of these types reveals diverse gold compositions along with diverse compositions of productive mineral assemblages. Silver is the most abundant impurity in gold from all fields studied, but its contents vary broadly even within a field type. The content of silver in gold depends not only on its abundance in hydrothermal solutions but also on other independent solution parameters: sulfur fugacity, temperature, salt composition, and pH. The regular decrease in native gold fineness from early to late generations in sulfide ore deposits is related to temperature decrease and large-scale sulfide formation. These processes reduce sulfur fugacity in the solutions and favor silver deposition in native gold rather than in sulfides. Gold of later generations is enriched in mercury in many deposits studied, whereas copper gravitates to earlier, high-temperature ones. In addition to deposition temperature, the contents of copper in gold are determined by its content in hydrothermal solutions, as evidenced by the association of copper-rich gold with basic–ultrabasic, skarn, and porphyry copper deposits. The processes causing the deposition of gold of various chemical compositions are complex. They correlate, to an extent, with gold mineralization temperature, whereas the spectrum of impurities often depends on the belonging of a gold deposit to a certain igneous complex.

Keywords: gold; impurity elements; skarn, pyrite, and porphyry copper–molybdenum deposits; black shale deposits; silver; copper; mercury; Siberia; Vietnam

Introduction

Hydrothermal deposits contain the bulk of gold ores. With regard to the type of ore-bearing igneous bodies, gold ore assemblages are divided into pluton-related, volcanogenic, and volcanoplutonic (Amuzinskii et al., 1992a; Fogel'man, 1985; Nekrasov, 1991; Petrovskaya et al., 1976; Sher, 1972; Shimizu et al., 1998; Spiridonov, 1995, 2010; Vinogradova et al., 1995). Australian and American scientists recognize orogenic gold deposits located in fold belts and superimposed rift-related structures (Groves et al., 1998). There are also telethermal gold ore bodies and fields of metamorphogenic-hydrothermal nature, mostly associated with black shale series and their regional metamorphism, as in Sukhoi Log and Muruntau (Bragin and Kasavchenko, 1986; Buryak and Khmelevskaya, 1997; Letnikov and Vilor, 1981). Gold-containing copper-oriented deposits—porphyry copper–molybdenum, skarn copper, and pyrite—are also widespread in Siberia, and they constitute a large portion of the global gold resources (Casadevall and Ohmoto, 1977; Gas'kov et al., 2006; Ulrich and Heinrich, 2001). These mineralization types also belong to hydrothermal deposits. Generally, they are produced by long-developing pyrogenetic ore bodies associated with volcanism or intrusions.

There are three major forms of gold in gold ore and gold-bearing deposits: (1) Macro- and microscopic particles of free native gold. (2) Bodies of mineral gold compounds, predominantly tellurides (Au, Ag)Te_2–(Au, Ag)Te_4 (calaverite and krennerite) and AuTe_2 (petzite). Selenides, sulfides, and antimonides are much scarcer. (3) Invisible gold admixtures in sulfides: pyrite, arsenopyrite, chalcopyrite, and antimonite. The composition of native gold and the spectra of impurities are broadly variable among deposits of different types and greatly dependent on genesis conditions. Much attention has been placed on gold composition for many decades. Gold

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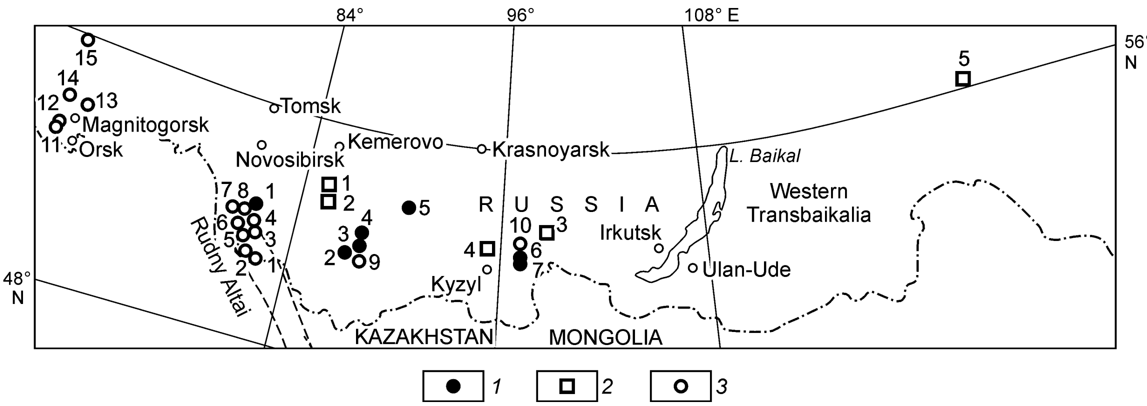

Fig. 1. Locations of gold-oriented and gold-bearing fields in some regions of Siberia and the Urals. *1*, skarn copper: 1, Murzinskoe; 2, Sinyukhinskoe; 3, Choiskoe; 4, Maisko-Lebedskoe; 5, Fedorovskoe, 6, Tardanskoe; 7, Khopto. *2*, porphyry copper–molybdenum: 1, Sorskoe; 2, Kulbichskoe; 3, Aksugskoe; 4, Kyzyk-Chadrskoe; 5, Ryabinovskoe. *3*, pyrite: 1, Novozolotushinskoe; 2, Yubileinoe; 3, Zarechenskoe; 4, Korbalikhinskoe; 5, Stepnoe; 6, Talovskoe; 7, Rubtsovskoe; 8, Zakharovskoe (northeastern Rudny Altai); 9, Urskoe (Salair); 10, Kyzyl-Tashtygskoe (Tuva); 11, Gaiskoe; 12, Tash-Tau; 13, Aleksandrinskoe; 14, Uzel'ginskoe; 15, Saf'yanovskoe (Southern Urals).

typomorphism and the association of composition with ore deposition are considered in many studies and reviewed in (Amuzinskii et al., 1992a; Arif and Baker, 2004; Boyle, 1979; Chapman et al., 2009; Gamyanin, 2001; Goryachev, 2003; Knight and Leitch, 2001; Kotov et al., 1995; Moiseenko, 1977; Moiseenko and Eirish, 1996; Nekrasov, 1991; Petrovskaya, 1973; Savva and Preis, 1990; Spiridonov and Pletnev, 2002; Vikent'ev, 2004; Yurgenson, 2003, 2008).

Numerous impurity elements are detected in native gold. They include Ag, Cu, As, Sb, Hg, Bi, Te, Ti, Cr, Ni, Co, Mn, W, Sn, Få, Pt, Pd, Rh, and Ir. Many scientists associate this wide range with diverse geochemical conditions of the mobilization, transportation, and deposition of gold ores, and with diverse physicochemical conditions of native gold genesis. Most of the impurities are related to mechanical inclusion of various mineral phases, and they are often typomorphic (Nikolaeva et al., 2013; Samusikov, 2003, 2010; Savva and Kolova, 2004). At present, the following types of native gold are recognized with regard to impurities: argentian (electrum, max. 40% Ag and kustelite, max. 70% Ag), cuprian (max. 20% Cu), mercurian (max. 20% Hg), bismuthian (max. 4% Bi); rhodian (rhodite, to 43% Rh), palladian (porpetzite, max. 5.8% Pd), iridian (max. 30.4% Ir), platinian (max. 10% Pt), gold with 4.4% Fe, etc. The commonest isomorphic admixtures in gold are silver, copper, and mercury (Spiridonov, 2010). They form solid solutions and intermetallic compounds. These impurities are generally more evenly distributed, in contrast to mechanical inclusions, which occur locally and irregularly in a gold grain. However, their concentrations vary broadly among different mineragenic deposit types and among products of various ore formation stages.

Major isomorphic impurities in gold

The crystallochemical features of gold determine merely its ability to include isomorphic impurities (Ag, Cu, and Hg) into its lattice. The actual prevalence of these impurities depends on many physicochemical indices of hydrothermal solutions: temperature, pressure, quantitative composition, pH, Eh, etc. (Amuzinskii et al., 1992b; Borisenko et al., 2006; Gas'kov et al., 2001; Moiseenko, 1977; Murzin, 2010; Murzin et al., 1981; Pal'yanova, 2008; Petrovskaya, 1973; Samusikov, 1981, 2010). Many scientists associate elevated concentrations of impurity elements in gold with the confinement of gold ore deposits to certain rock associations (Nikolaeva et al., 2013; Samusikov, 2003; Yablokova et al., 2001), starting concentrations of impurity elements in ore-forming solutions (Murzin et al., 1981), and degrees of solution supersaturation (dsup) with various impurity elements (Samusikov, 2010). The contents of isomorphic elements in native gold vary widely.

Silver is the commonest impurity in gold (Gammons and Williams-Jones, 1995; Gas'kov et al., 2001; Knight and Leitch, 2001; Kovalev et al., 2004; Murzin, 2010; Pal'yanova, 2008; Spiridonov, 2010; Vikent'eva and Tyukova, 2007). Petrovskaya (1973) proposed the following gradation of native gold with regard to Ag content: very fine gold (1000–951‰), fine gold (950–900‰), medium fine gold (899–800‰), lower-fineness gold (799–700‰), low fineness gold, electrum (699–400‰), and kustelite (399–100‰). At present, data of thousands of precise analyses have shown that Au and Ag form a continuous series (Spiridonov, 2010). Petrovskaya (1973) analyzed regularities of silver contents in gold and indicated that small silver contents and higher gold fineness (>900‰) were typical of ores formed at greater depths, whereas higher silver contents and lower gold fineness (<750‰) tended to occur in near-surface deposits. She also noted that gold fineness did not depend directly on formation temperature and that high Ag concentrations in the deposit little affected its content in gold.

Mercury is the second most abundant impurity element in native gold. Petrovskaya (1973) assessed Hg content in native gold to be thousandths to tenths of percent. However, later studies showed that mercury contents could be much higher, up to the formation of mercurian gold (Amuzinskii et al., 1992b; Borisenko et al., 2006; Gas'kov et al., 2001, 2006;