

## Physicochemical conditions of ore formation in the Samolazovskoe gold deposit (*Central Aldan*)

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### Abstract

Using modern thermobarogeochemical methods (thermo- and cryometry, Raman spectroscopy, and LA–ICP–MS), we studied fluid inclusions in quartz from ores formed at the quartz–fluorite, pyrite–chalcopyrite, pyrite–molybdenite, and polysulfide stages of evolution of the Samolazovskoe gold deposit. We have established the fluid regime of the ore formation processes, the gas and liquid composition, main solid phases (metal sulfates, carbonates, and chlorides), homogenization temperatures of the inclusions, and the eutectic temperatures of their solutions. The obtained data helped to estimate the fluid temperatures during the formation of ores at each stage and to determine the contents of major salt components. Based on the substance solubility values given in the reference-book by V.B. Kogan, we have first constructed a phase diagram of the system  $\text{Na}_2\text{SO}_4\text{--NaHCO}_3\text{--H}_2\text{O}$  ( $\text{Na}_2\text{SO}_4 < 35$  wt.%) at temperatures below 40 °C. The metal contents and geochemical specifics of solutions at each stage of the ore formation were determined by LA–ICP–MS. At the quartz–fluorite stage, the solutions were enriched in B, V, Co, Ni, Zn, As, Te, Cs, Ba, and Mg; at the pyrite–molybdenite stage, they had high concentrations of Ti, Ni, Nb, and Mo; and at the polysulfide stage, the solutions were rich in Ca, As, Pb, Sb, Te, Ag, Rb, Ba, and Sr. Native sulfur found along with sulfate and sulfide sulfur in the inclusions impelled us to study the sulfur isotope composition. The research has shown a light sulfur isotope composition ( $\delta^{34}\text{S} = -2.5$  to  $-13.4\text{‰}$ ). We believe that sulfide sulfur in the Samolazovskoe deposit formed from a fluid during high-temperature (>500–700 °C) sulfate reduction.

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**Keywords:** thermobarogeochemistry; alkaline magmatism; oxidized fluids; LA–ICP–MS; fluid inclusions; metal contents in solutions

### Introduction

Central Aldan is one of the largest gold ore districts in Russia, where large primary gold deposits and gold placers were discovered: Kuranakhskoe (>400 tons Au), Ryabinovoe (>100 tons Au), Lebedinoe (>100 tons Au), Samolazovskoe, etc. The Central Aldan ore district is characterized by the wide development of gold, copper–molybdenum, uranium, platinum, and fluorite mineralization associated with the Mesozoic alkaline magmatism of the Aldan complex (Fig. 1). This region is a typical example of a large highly productive ore-magmatic system associated with a particular local area of differentiated alkaline magmatism (Kochetkov, 2006). Its geologic structure, magmatism, and mineralization are considered in detail elsewhere (Boitsov et al., 2002; Kochetkov,

2006; Maksimov, 1991, 2003; Maximov et al., 2010; Vetluzhskikh et al., 2002). Besides Precambrian metamorphic rocks and overlying Vendian–Cambrian carbonate and Jurassic terrigenous deposits, there is a large area (12,500 km<sup>2</sup>) of Mesozoic alkaline magmatism within the region.

Thermobarogeochemical methods were used to study the physicochemical formation conditions of the ores of the Samolazovskoe gold deposit located in the Central Aldan ore (Au–U) district of southern Yakutia. This deposit is confined to the Yukhta alkaline massif of Late Mesozoic age (K<sub>1</sub>). The Yukhta alkaline massif is composed of alkali and calc-alkalic syenites, nordmarkites, syenite- and granosyenite-porphry, kersantite dikes, and alkali basite stocks (Fig. 2). The latest magmatic bodies are explosive breccias with syenite-porphry cement (127 Ma, U–Pb dating). Ores formed in two stages: (1) early—formation of low-Au skarns with pyrite–chalcopyrite ( $\pm$  carrollyte) ores (130–135 Ma) and (2) main productive—genesis of Au–Mo–polymetallic ores (<127 Ma), proceeding after the appearance of explosive breccias. The

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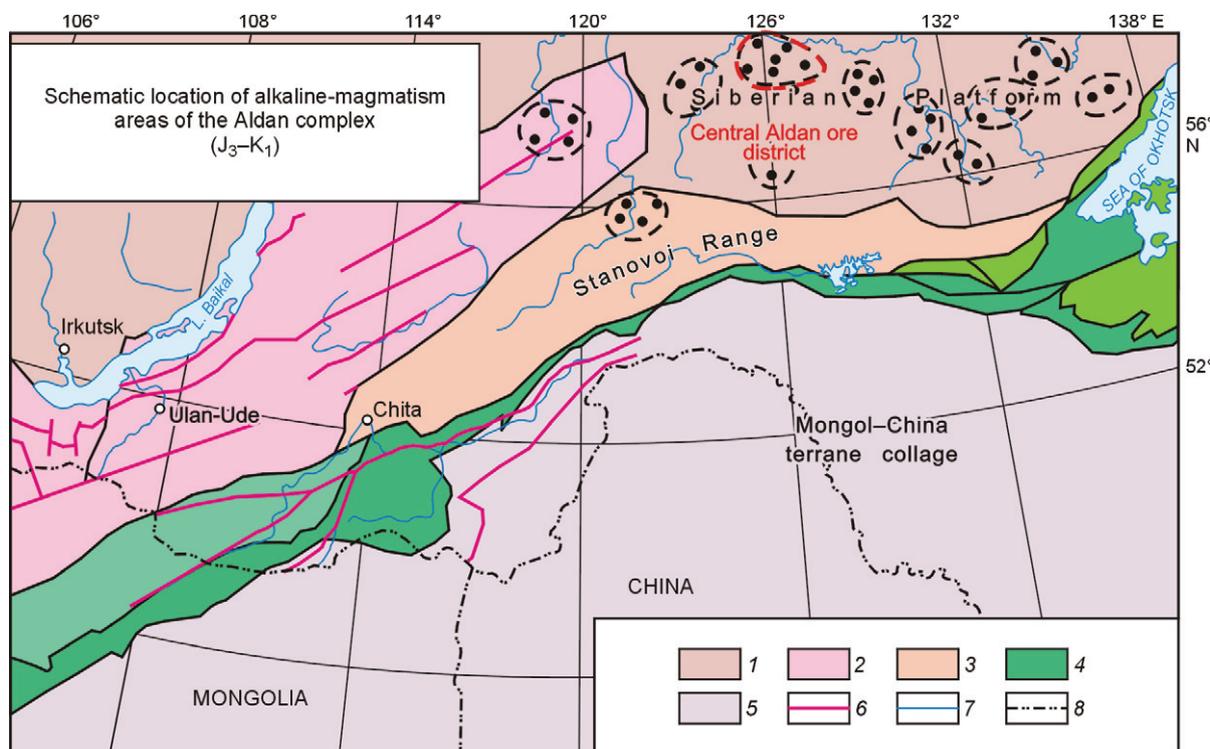


Fig. 1. Schematic geologic location of the Central Aldan ore district in the area of the Aldan alkaline complex (after A.S. Borisenko and G.S. Fedoseev). 1, Siberian Platform; 2, Baikalsk–Patom belt; 3, Stanovoi area; 4, Mongol–Okhotsk belt; 5, Mongol–China terrane collage; 6, faults, 7, water reservoirs, 8, state borders. Red dashed contour marks the Central Aldan ore district, and black contours show local areas of the Late Mesozoic alkaline magmatism.

second stage is divided into four substages of development of vein-disseminated mineralization: (1) quartz–fluorite (Q + Fl), (2) pyrite–chalcopryrite (Py–Chp), (3) pyrite–molybdenite (Py–Mo), and (4) polysulfide (Au–Pb–Zn) (pyrite, fahlore, galena, sphalerite, chalcopryrite, bornite, sylvanite, vanadinite, roscelite, Hg–gold, silver, etc.) (Borisenko, 2016). Uranium mineralization is represented by uraninite and coffinite with quartz, carbonates, and fluorite.

## Methods

To study fluid inclusions, we used common and new instrumental thermobarogeochemistry methods. The homogenization temperatures of inclusions, salt composition and concentration of solutions, and density of CO<sub>2</sub> in the gas phase of the inclusions were determined by thermometry and cryometry, using a Linkam THMSG-600 heating/freezing stage with a measurement range from –196 °C to +600 °C. To estimate the eutectic temperatures of mineral-forming solutions in the inclusions, dissolution temperatures of crystalline hydrate phases, homogenization temperatures of the gas bubble, and total homogenization temperatures, we cooled the inclusions to –100 °C to freeze their solutions to a fine-grained aggregate of ice and crystalline hydrates. Then, the inclusion was gradually heated (at a rate of ~15 °C/min) until the ice began melting. During the beginning of the ice melting, the heating rate was decreased to 3–5 °C/min, and when the last ice crystals remained on the stage, the inclusion was again

slowly cooled to freeze water over these ice crystals. The above procedure was repeated three times in order to turn the maximum amount of water into one or two ice crystals. The residual solution crystallized into a fine-grained aggregate. Then, the inclusion was gradually heated, and the temperature at which the fine-grained aggregate incrementally melted together with the ice crystals (eutectic temperature  $T_{eut}$ ) was measured. Heating of the inclusion was continued, and after the disappearance of the ice crystals, a small amount of solid phases (probably, crystalline hydrates) remained in the inclusion, which also dissolved at the corresponding temperature ( $T_{dissol cr.hydr.}$ ). On further heating of the inclusion, the dissolution temperatures of the gas bubble ( $T_{dissol gas b.}$ ) and solid salt phases ( $T_{dissol sol.ph.}$ ) were measured.

The concentrations of Na<sub>2</sub>SO<sub>4</sub> and NaHCO<sub>3</sub> in fluid inclusions were calculated based on the system Na<sub>2</sub>SO<sub>4</sub>–NaHCO<sub>3</sub>–H<sub>2</sub>O, which was also used to interpret the results of cryometric analysis of Na<sub>2</sub>SO<sub>4</sub>–NaHCO<sub>3</sub> solutions of two-phase (L + G) inclusions. For this purpose, we constructed a phase diagram of this system for temperatures below 40 °C and concentration of Na<sub>2</sub>SO<sub>4</sub> lower than 35 wt.%, using the data from the “Solubility Reference-Book” (Kogan, 1963). The results of cryometric analysis were corrected with regard to the data of LA–ICP–MS analysis of the inclusions.

To determine the composition and metal content of the ore-forming fluids from gold ores of the Samolazovskoe ore field, we examined the inclusions by LA–ICP–MS on a ThermoScientific XSERIES2 mass spectrometer combined with a New Wave Research Nd:YAG laser system at the

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