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Formation Conditions of Au–Mo(W)–Pb–Zn Ores of the Bugdain Atypical Porphyry Deposit, Eastern Transbaikalia, Russia

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Porphyry copper–molybdenum deposits lead in the world with respect to reserves and mining of copper and molybdenum. However, unlike porphyry molybdenum–tungsten deposits, many deposits of the first type also contain significant amounts of Au and Ag. They are typically formed in geodynamic settings of the continental margin and island-arc volcanic arcs. Their geology and formation conditions were studied in detail and considered elsewhere [1 and others].

In contrast to typical auriferous porphyry Cu–Mo deposits, the large Bugdain porphyry Mo(W) deposit in the eastern Transbaikal region was formed in a within-plate rift setting and has elevated gold potential [2]. The Bugdain deposit is characterized by the significant predominance of Mo over Cu (Cu/Mo ~ 0.1). However, in terms of the Au (g/t)/Mo(%) ratio (~4), this deposit is plotted within the range typical of porphyry Cu–Au–Mo deposits (3–30), but differs from presently distinguished auriferous porphyry deposits of Cu–Au (>30) and Cu–Mo (<3) subtypes [3].

Based on these data, the Bugdain deposit should be ascribed to the specific Cu-poor auriferous porphyry systems. Elucidation of the specifics of the formation of these deposits is important in light of their high gold potential and low abundance. However, data on the composition and formation conditions of the Bugdain deposit were mainly obtained in the 1960s and 1970s [4, 5]. In this work, we studied fluid inclusions (FI) and the sulfur isotopic composition to determine the *PT* parameters and composition of fluids during formation of the ores of the Bugdain deposit.

The Bugdain deposit is confined to the central part of the volcanic dome in the southeastern part of the large granitoid pluton, which was crosscut by Late Jurassic subvolcanic rhyolite porphyry intrusions [2]. The stockwork Mo–W ores as a network of randomly oriented sulfide–quartz veins and stringers are clustered around a stock of silicified rhyolite porphyries. The Au content varies from 0.*n* to *n* g/t. The higher gold contents (from few to 100–150 g/t) were found in the steep (75°–80°) sulfide–quartz veins (250–300 m long and up to 3–4 m thick), which host the main reserves of the Pb–Zn deposit [2].

The ores have a more complex and diverse composition than suggested by previous works. The list of minerals determined in these ores comprises 60 minerals, including native metals, sulfides, sulfosalts, tellurides, oxides, carbonates, silicates, sulfates, wolframates, fluorides, and prevailing quartz. Four ore stages are distinctly distinguished at the deposit. Mineralization of the preore stage (K-feldspathization and silicification) was manifested after emplacement of the subvolcanic rhyolite porphyry stock. This was followed by the Mo–W stockwork mineralization (quartz–molybdenite stage) and the formation of quartz–sulfide veins (gold–base metal stage) associated with sericitization and pyritization of wall rocks. The postore stage produced veins and veinlets of chalcedony, quartz, and carbonate.

The mineral formation conditions, evolution of *PT* parameters, and composition of hydrothermal solutions were determined by studying individual FIs in the minerals of the preore, quartz–molybdenite, and gold–base metal stages. Microthermometric data were obtained using the Lincam THMSG-600 thermostage with a measurement accuracy of ±0.2°C (for the interval from –60 to +60°C) and ±1.5°C (for values beyond the above range). Eutectic melting temperatures ($T_{\text{eut. melt.}}$) ranging from –20.8 to –35°C correspond to the Na^+-dominating chloride solutions; temperatures below –52°C characterize calcium chloride solutions [6]; and temperatures between –35 and –49°C indicate

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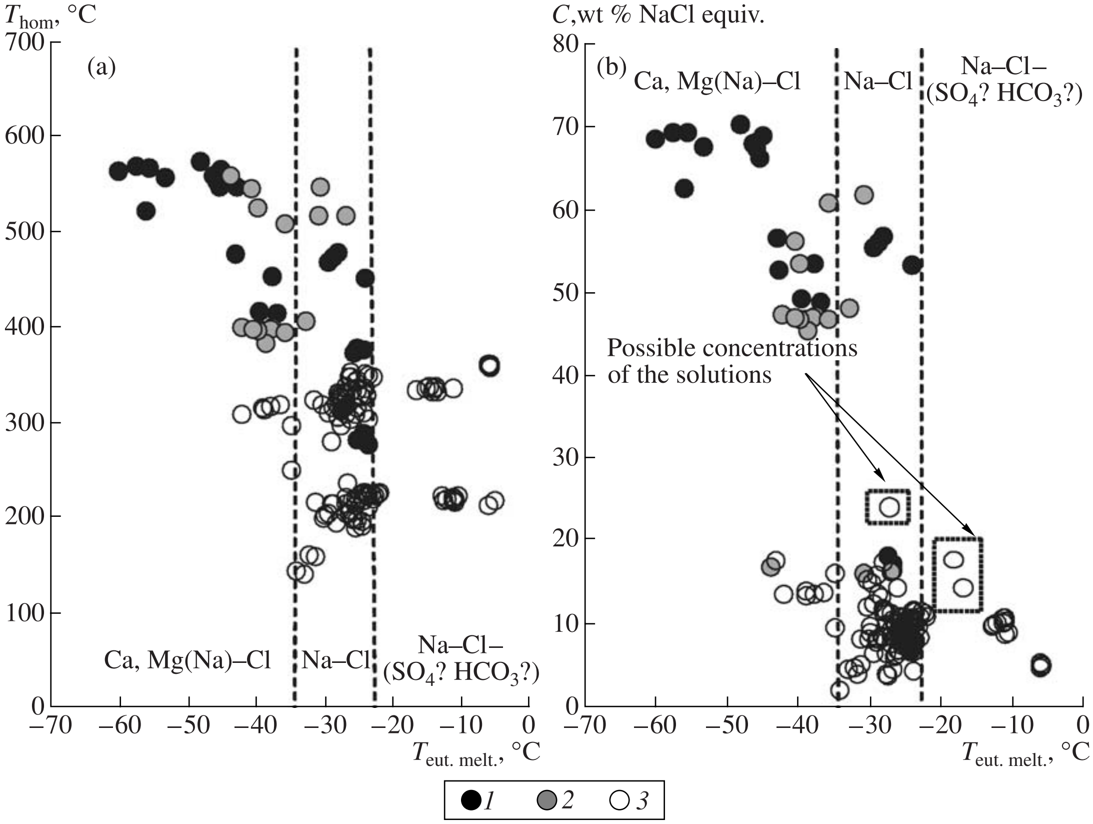

Fig. 1. Diagrams showing relationships for fluid inclusions in minerals of different stages of the Bugdain deposit. (a) Homogenization temperature vs. fluid composition; (b) salt content vs. fluid composition. (*1*) Quartz of the preore stage; (*2*) quartz of the quartz–molybdenite stage; (*3*) minerals of the gold–base metal stage.

Mg–Na chloride solutions [7]. Values of the salt content and fluid density were calculated using the FLINCOR program [8]. The data obtained are summarized in the diagrams (Figs. 1a, 1b) and discussed below.

In quartz of the preore stage, melt inclusions (MIs) coexist with FIs. The FIs are dominated by monophase gas (occasionally with a thin solution rim), with rare two-phase (gas–liquid) and multiphase (gas + solution + solid phase) FIs. The coexistence of MIs and FIs with variable phase proportions suggests the simultaneous entrainment of the melt, as well as gas and water–salt fluids, during heterogenization and unmixing of fluid exsolved from crystallization magma [9]. The melt inclusions contain variable volume (5–50%) of the gas phase. Changes of phase relations in FIs were not noted, except for rare CO_2 freezing within an interval from –97 to –115°C. This fact testifies that the inclusions were filled with low-density water and water–CO_2 fluid. In the multiphase FI, solid phases are dominated by NaCl and ore minerals are rare. The vacuoles of these FIs are filled with high-salinity (70.5–49.1 wt % NaCl equiv.) Na–Mg–Ca chloride brines ($T_{eut. melt.}$ from –55.9 to –35.5°C), which are homogenized into liquid at 576–415°C (Fig. 1). The density of the homogenous fluid is 1.49–1.16 g/cm^3. As is evident from Fig. 1, two-phase FIs homogenize at 379–277°C and contain sodium chloride solutions with high density (0.9–0.8 g/cm^3) and moderate salinity (18.6–6.9 wt % NaCl equiv.).

Quartz from stringers of stockwork Mo–W mineralization of the quartz–molybdenite stage also contains mainly monophase vapor (gas)-rich FIs, while two-phase (gas + solution) and multiphase (gas + solution + solid) inclusions are less abundant, indicating that the mineral-forming medium was entrained from boiling heterogeneous fluid [10]. All FI types of this stage contain opaque ore mineral (supposedly, molybdenite). Figure 1 shows that the multiphase FIs contained chloride solutions with variable proportions of Mg and Na ($T_{eut. melt.}$ from –40.4 to –30.5°C), which homogenized at 549–384°C. Salt hydrates in these FIs yield a melting temperature from 15 to 6°C, which indicates the presence of significant amounts of aqueous species of sodium sulfate and/or bicarbonate [11]. The salt content in the solutions also demonstrates a decrease from very high (62–53.8 wt % NaCl equiv.) in high-temperature FIs (T_{hom} from 549 to 510°C) to moderate ones (48.3–45.7 wt % NaCl equiv.) in relatively low-temperature (408–384°C) FIs (Fig. 1). The fluid density is 1.32–1.11 g/cm^3. Two-phase FIs containing Mg–Na chloride solutions ($T_{\text{eut. melt.}}$ from –43.6 to –26.7°C) with relatively low density (0.52–0.51 g/cm^3) and moderate salinity (17–16 wt % NaCl equiv.) are homogenized into gas at 561–518°C (Fig. 1).

Gangue quartz of the gold–base metal stage contains only two-phase (gas + solution) FIs with T_{hom} from 362 to 205°C (Fig. 1). They can be divided into two types. FI 1 occurs in quartz with base metal mineralization and contains Na–K chloride solutions ($T_{\text{eut. melt.}}$ from –27.4 to –22.0°C) with a salt content of 26.0–23.2 wt %. FI 2, typically hosted in auriferous quartz, contains not only chlorides, but also SO_4^{2-} and HCO_3^- anions. This follows from the high $T_{\text{eut. melt.}}$ (from –16.3 to –5.3°C) and melting temperature of salt hydrates (from +9.9 to +2.0°C) [11]. The ionic and gas-chromatographic study showed that quartz of this stage contains the following components (g/kg H_2O): Na^+ 2.27, K^+ 9.52, Ca^{2+} 0.83, Mg^{2+} 1.33, Cl^- 5.55, SO_4^{2-} 2.7, HCO_3^- 17.3, CO_2 16.75, CH_4 0.16 ($CO_2/CH_4 > 100$). Such a composition confirms the significant role of sulfates and, especially, bicarbonates in the composition of the mineral-forming solution of the gold–base metal stage and indicates the high oxidation state of the fluid. Based on the ICP-MS analyses of aqueous extract from quartz of the same sample, K/Rb = 89. This value is consistent with the concept of fluid derivation from the granitic melt.

The magmatic origin of the mineral-forming solutions is also supported by the sulfur isotopic composition determined for the first time in the major sulfide minerals (23 samples) from quartz–molybdenite and gold–base metal stages of the Bugdain deposit. The variations in $\delta^{34}S$ are within a narrow range (‰): from –1.72 to +3.07 (average +0.37) in pyrite (n = 10 samples), from +0.78 to +0.98 in chalcopyrite (n = 2), from +0.78 to + 4.97 (average +3.21) in sphalerite (n = 5), from 2.60 to + 3.15 (average +1.22) in galena (n = 5), and +1.08 in molybdenite (n = 1). Based on these data, known equations [12], and accepted average temperatures of the mineral-forming fluid, the $\delta^{34}S$ H_2S_{aq} value varies from +0.1 to +0.4‰ for the quartz–molybdenite stage (400°C) and from –2.1 to –3.1‰ for the gold–base metal stage (300°C). These values correspond to the magmatic sulfur source [12].

Thus, the obtained data indicate that the auriferous porphyry Mo–W mineralization of the Bugdain deposit was controlled by several factors. Fluids exsolved from the crystallizing magmatic melt were enriched in volatiles. Owing to pressure decrease in the course of exhumation to the surface, the fluids were fractionated into low-density vapor and highly saline (water–salt brine–melt) liquid phases. The finding of molybdenite crystals in the vacuoles, as well as gas and water–salt FIs, confirms the experimentally based suggestion [13, 14] that Mo could be fractionated into the vapor phase during unmixing of the magmatic melt and then be precipitated as molybdenite in the presence of sulfur if the temperature is 100–150°C below the temperature of the magma chamber. At the same time, the variation trends of temperature, salinity, and composition of mineral-forming fluid during the evolution of the hydrothermal process (Fig. 1) were governed by the temperature decrease in the course of ascent of the fluid to the surface, interaction with wall rocks, and mixing with the oxidized near-surface sulfate–hydrocarbonate waters.

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REFERENCES

1. E. Seedorf, J. H. Dilles, J. M. Proffett, et al., Econ. Geol. **100**, 251 (2005).
2. V. I. Krasnikov, A. Kh. Shafikov, V. V. Ershov, et al., in *Gold of the Transbaikal Region* (Chita, 2003), pp. 23–28 [in Russian].
3. D. A. Singer, V. I. Berger, W. D. Menzie, and B. R. Berger, Econ. Geol. **100**, 491 (2005).
4. V. G. Kruglova, B. S. Chernov, A. G. Evdokhin, and E. S. Pastukhova, Sov. Geol., No. 3, 118 (1965).
5. L. I. Koltun and A. V. Piznyur, Mineral. Sb. L'vov. Univ., **24**, 274 (1970).
6. M. L. Crawford, Mineral. Assoc. Canada Short Course **6**, 75 (1981).
7. D. V. Davis, T. K. Lowenstern, and R. J. Spenser, Geochim. Cosmochim. Acta **54**, 591 (1990).
8. P. E. Brown, Am. Mineral. **74**, 101 (1989).
9. A. C. Harris, V. S. Kamenetsky, N. C. White, et al., Science **302**, 2109 (2003).
10. R. J. Bodnar, T. J. Reynolds, and C. A. Keuhn, Rev. Econ. Geol. **2**, 73 (1985).
11. A. S. Borisenko, Dokl. Akad. Nauk SSSR **214**, 917 (1974).
12. C. W. Field and R. H. Fifarek, Rev. Econ. Geol. **2**, 99 (1985).
13. T. N. Tingle and F. M. Fenn, Geology **12**, 156 (1984).
14. A. Bernard, R. B. Symonds, and W. I. Rose, Jr., Appl. Geochem. **5**, 317 (1990).