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Research paper

Gold mineralisation and orogenic metamorphism in the Lena province of Siberia as assessed from Chertovo Koryto and Sukhoi Log deposits

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ABSTRACT

The Chertovo Koryto gold deposit (80 t Au at 1.84 g/t) in the Lena world-class province, Siberia, is hosted in a metamorphosed sequence of the Paleoproterozoic Mikhailovsk Formation that comprises the oldest black shale strata of the Baikal-Patom region. The mineralisation is confined to the thrust zone complicated with a conjugate anticline fold, zones of shearing and dislocation. The structural position of the mineralisation is similar to that at the giant Sukhoi Log deposit in the neighbouring Mama-Bodaibo zone. In the latter, the isotope age data suggest that Khomolkho black shales, hosts to Sukhoi Log mineralisation, are of Ediacaran age and underwent prograde metamorphism during early Paleozoic. The geochemical composition of the terrigenous rocks that host Sukhoi Log, Chertovo Koryto, and a number of other deposits at the various stratigraphic levels throughout the Proterozoic sequence have much in common. They do not show elevated metal contents above the common black shale abundances, except for Au and As, which is at variance with the accepted view on diagenetic enrichment of black shales in the Lena province. The occurrence of sagenitic rutile in quartz and chlorite pseudomorphs after biotite and other petrographic observations provide evidence on a retrograde nature of the metamorphic mineral assemblages in the Mikhailovsk rocks. The sulphides are pyrrhotite and arsenopyrite with very minor pyrite at Chertovo Koryto, whereas pyrite is the predominant sulphide in the Sukhoi Log ore. Fluid inclusion data on both deposits emphasise a high-temperature nature of the mineralisation albeit revealing great contrast in the fluid composition. Sukhoi Log mineralisation was formed at mixing between low-salinity aqueous solutions and dense gaseous carbonic fluids, which facilitated effective gold scavenging and precipitation, as demonstrated by thermodynamic simulation. The precursory devolatilisation of the Mikhailovsk sediments at the prograde stage results in the paucity of gaseous carbonic fluid during retrograde metamorphism and mineralisation. The similarity in the styles and chemical parameters of mineralisation, and the predominant structural control of ore localisation within the same Precambrian regional tectonic unit support an idea that orogenic gold mineralisation in the Lena province was produced during a single early Paleozoic event.

1. Introduction

The Lena gold province is known for richness of its gold placers, which have been exploited since the mid-19th century to endow more than 2000 tons Au (Buryak and Khmelevskaya, 1997). The unique placer wealth corresponds to a high potential of lode deposits that include the giant Sukhoi Log deposit along with three large (Vysochaishee, Verninskoe and Chertovo Koryto) and a few dozen smaller deposits and occurrences. Most of these lode resources remain unexploited as of yet, with the only three mines currently operating in the region. The Vysochaishee Mine developed by the GV Gold Company, the Pervenets-Verninskoe Mine by Polyus Gold, and the Nevskoe Mine by Druza Company produced 5.2, 4.7 and 0.62 t Au, respectively, in 2014 according to the

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company's records, whereas the total annual production in the province reached 22 t Au, with half of this amount provided by the placer gold fields.

New economic conditions with a lower cutoff led to the substantial reappraisal of proved and probable reserves at the Sukhoi Log deposit, which are currently estimated at 2956 t Au and 1541 t Ag (Migachev et al., 2008). The reserve was increased twice with respect to previous evaluation that totaled 1040 t at an average grade of 2.73 g/t Au approved by the USSR State Reserves Committee in 1977. According to a Polyus Gold press release, the proved and probable reserves of the Verninskoe deposit are close to 179 t at an average 2.7 g/t Au or within 240 t Au of measured and indicated resources, i.e. three times higher than the previous estimation during the Soviet period. The proved and probable reserves of the Chertovo Koryto deposit appeared to be close to 80 t Au at an average 1.84 g/t, which is slightly lower than the previous Soviet assessment. The reserves of the Vysochaishee deposit were estimated at around 90 t Au, although these reserves are now almost depleted. In addition, recent exploration works were targeted at and confirmed several medium-sized deposits whose resources range between 10 and 50 t Au, such as the Nevskoe, Ugakhan, Khodokan, Krasnoe and Kopylovskoe deposits.

The genesis of the gold lodes and relationships between mineralisation, metamorphism and granitoid magmatic events are debatable since the discovery of the Sukhoi Log gold-quartz-sulphide disseminated ore in 1961 (Buryak, 1982). The metamorphic–hydrothermal–sedimentary model suggests a Precambrian age of the gold mineralisation, assuming that ore zones were formed through metamorphic redistribution of metal, which was primarily accumulated at sedimentary or exhalative-sedimentary processes (Nemerov, 1989; Buryak and Khmelevskaya, 1997; Large et al., 2007). According to this model, the mineralisation and metamorphism predate the Paleozoic granite intrusions. The distribution of the gold deposits is believed to be controlled by their confinement to weakly metamorphosed rocks, as the model envisages gold migration from anatectic and high-grade metamorphic zones on the periphery of the province towards the central parts metamorphosed under greenschist facies conditions. An alternative model relates mineralisation to the Paleozoic granitoids and orogenic metamorphism (Sher, 1972; Rundqvist et al., 1992; Distler et al., 1996; Kucherenko et al., 2011). Both of these extreme views have their weak and strong points that give rise to a number of intermediate hypotheses, which try to account for the complex multi-stage geological history of the region (Meffre et al., 2008; Kryazhev et al., 2009). An ultimate source of gold, whether it was primarily deposited together with other black shale components or derived by high-temperature fluids from a depth, is one of the keystones to elucidate the gold provenance. The timing of mineralisation relative to the metamorphic events, whether it predates or postdates the metamorphic peaks, is another key evidence for the genetic type of gold mineralisation in the province.

Two outstanding monographs summarized geological knowledge on the Lena province in due course. The two-volume review *Lena Gold-bearing Region* (Kazakevich et al., 1971) is based on the research output obtained at TSNIGRI in 1952–1964. *The Precambrian of the Patom Highlands* (Ivanov et al., 1995) compiled and interpreted data of geological mapping and geochronological dating under the leadership of Irkutskgeologia in the 1980s and early 1990s. Both books extensively referred to the published and unpublished results of the other research teams, such as the Institute of Precambrian Geology, VSEGEI, Geological Institute (GIN) and Lenzoloto. New data were obtained during the past two decades under the Program of State Geological Mapping or academic studies (Mitrofanov, 2006) and also involved the results obtained in exploration, prospecting and reassessment projects of various mining companies (Migachev et al., 2008; Ivanov, 2014).

Here we report newly obtained data on the geological setting, metamorphism and mineralisation of the little known and unexploited Chertovo Koryto deposit in the north of the Patom Highlands in comparison to the Sukhoi Log giant deposit. The Chertovo Koryto deposit is hosted in the lower Proterozoic black shale strata of the Mikhailovsk Formation that are intruded by 1.85–1.95 Ga Chuya-Nechera granite in the vicinity of the deposit. The age of the mineralisation is not constrained because its host rocks are the oldest black shale succession in the region, but mineralisation was believed to be confined to a thrust zone of supposedly late Riphean age (Ivanov et al., 1995). It should be admitted that the age of Sukhoi Log mineralisation hosted by ca. 1 Ga younger Ediacaran (Russian Vendian) black shales is still also highly disputable (Meffre et al., 2008; Yudovskaya et al., 2011; Yakubchuk et al., 2014).

Our fluid inclusion data indicate that Sukhoi Log and Chertovo Koryto gold ores were formed under high-temperature conditions, while modeling shows that physical mixing of gaseous and aqueous fluids could be an important factor controlling effective gold deposition. Similarity of the styles and chemical parameters of the mineralisation, the predominant structural control of emplacement as well as the localization within the same Precambrian regional structure (Fig. 1) allows speculating upon a common endogenous event that triggered gold mineralisation throughout the province.

We use the subdivisions of the International Stratigraphic Scale through the paper whereas the equivalents of the Russian stratigraphic scales are given in Fig. 2 and shown in brackets when relevant.

2. Geological setting of the Lena gold province

2.1. Sedimentation and regional metamorphism

The Lena province is located in the Patom Highlands of the Baikal orogen separated from the Angara block of the Siberian Platform by the Akitkan-Zherba Suture (Mitrofanov, 2006). The Archean basement of the craton extends beneath the Baikal orogen for 80–100 km according to geophysical data (Ivanov et al., 1995). The Baikal orogen together with the Enisei and the Eastern Sayan Ranges form the complex Sayan-Baikal Fold Belt which rims the southern margins of the platform (Fig. 1). The Sayan-Baikal fold belt was initially founded on the reworked basement of the Siberian craton, although its later evolution was related to the higher-level Central Asian Orogenic Belt, one of the Earth's largest accretionary orogens, existing from about 1000 Ma (Kröner et al., 2014). The voluminous Neoproterozoic terranes adjacent to the Siberian craton were generated during an early phase of CAOB evolution through continuous subduction–accretion within the long-lived Palaeo-Asian Ocean (e.g., Yarmolyuk et al., 2006; Rytsk et al., 2011). The upper Proterozoic carbonate terrigenous sequences of the Baikal orogen were recognised as a regional stratigraphic standard of so-called Baikalides in Siberia although their stratigraphic age is currently appeared to be revisited (Kuznetsov et al., 2013).

The Baikal orogen is subdivided into two structural megazones: the outer Baikal-Patom and inner Baikal-Vitim-Barguzin (Mitrofanov, 2006). The Proterozoic black shale deposition spreads over the whole Baikal-Patom megazone and margins of the adjacent Aldan Shield (Fig. 1). The Patom and Mama-Bodaibo synclinoriums separated by the Tonoda-Chuya-Nechera Uplift are the major structural units of the Baikal-Patom megazone (Fig. 3).

The basement of the Baikal-Patom megazone is composed of metaterrigenous rocks of the Kevakta Group (Figs. 2 and 3), which