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GEOCHEMISTRY

Formation Stages of the Large-Scale Noble Metal Mineralization in the Sukhoi Log Deposit, East Siberia: Results of Isotope–Geochronological Study

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This paper presents results of the Rb–Sr and K–Ar isotope–geochronological study of the Sukhoi Log deposit, one of the world's largest noble metal deposits localized among metasedimentary black shales. The deposits of this type (Muruntau, Uzbekistan; Nezhdaninskoe, Russia; Ashanti, Gana; and others) account for a considerable part in the balance of mined gold and its potential reserves. The significance of these deposits and, primarily, the Sukhoi Log deposit became even higher with the discovery of Pt mineralization in some of them [1–3]. However, the origin and especially age of the noble metal mineralization in the Sukhoi Log deposit remain controversial.

The Sukhoi Log deposit is located within the Baikal–Patom highland and confined to the Sukhoi Log syncline, part of the Bodaibo synclinorium (Fig. 1). The area is composed mainly of Upper Proterozoic terrigenous–carbonate rocks, which are metamorphosed at greenschist facies and deformed into linear folds. The host rocks of the Khomolkho Formation (Nygrin Group) were metasomatically altered. The metasomatites accompany ore bodies and occur along narrow tectonic zones. In plan view, they extend over a few kilometers as zones tens to hundreds of meters thick. Detailed characteristics of metasomatic minerals and their chemical compositions are reported in [4].

The Sukhoi Log deposit is a NW-trending sheetlike lode. The largest Sukhoi Log orebody (~4 km^2 in area) consists of stringer-disseminated ores and low-sulfide gold–quartz ores spatially confined to quartz veins. Gold occurs mainly as native gold in pyrite and quartz. PGE mineralization at the deposit is restricted to stringer-disseminated mineralization. Platinum occurs mainly in the native form and as Pt–Fe–Cu alloys [2].

Until recently, the Precambrian–Early Paleozoic age of the Sukhoi Log mineralization was constrained from geological data and resulted from generally accepted metamorphic–hydrothermal genetic model [5]. Isotope–geochronological data published prior to the present communication are only related to the age of magmatic rocks of the Sukhoi Log ore field and adjacent areas. Several datings of magmatic rocks intruding the Riphean

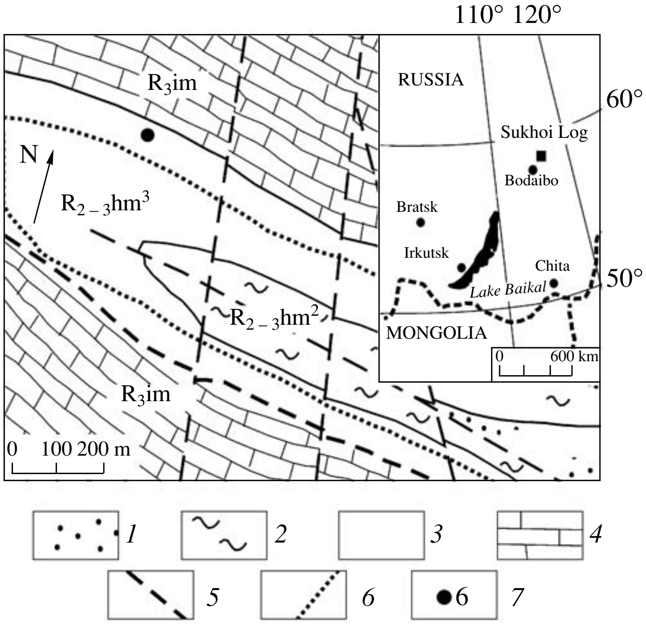

Fig. 1. Geological scheme of the Sukhoi Log deposit [2]. (*1–3*) Units of the Khomolkho Formation ($R_{2–3}$hm): (*1*) lower, (*2*) middle, (*3*) upper; (*4*) limestones of the Imnyakh Formation (R_3im); (*5*) faults; (*6*) boundary of the ore zone; (*7*) borehole 6.

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sedimentary sequences are reported in [6, 7]. The age of different basic rocks developed beyond the ore field varies from 1050 to 620 Ma. The Konstantinovsky granite stock exposed 6 km southwest of the deposit is estimated at ~300 Ma.

We believe that dating of ore material is the main task in the isotope investigation of the Sukhoi Log deposit, because the results of this investigation can elucidate the key issues of the age of Au–Pt mineralization and its temporal relation with processes of the formation and metamorphism of black shales.

Among mineral geochronometers traditionally studied by different isotope methods, only hydrothermal–metasomatic sericite is present in ores of the Sukhoi Log deposit. However, the small size (less than 0.1 mm) and close intergrowths of sericite with other minerals (chlorite, carbonate, and quartz) make it impossible to extract its monofraction of the required purity. Therefore, our Rb–Sr datings are based on two geochronometers (bulk ore samples and gangue quartz) that are nontraditional for hydrothermal rocks.

The use of whole-rock samples as geochronometers in the Rb–Sr isotope dating of hydrothermal–metasomatic processes is based on the following assumption: the transformation of the host rocks (black shales, in the Sukhoi Log deposit) and different gangue and other newly formed minerals is accompanied by the homogenization of the Sr isotopic composition over the entire volume of the studied geological body. The equilibration of the Sr isotopic composition between mineral components of the rocks, as was mentioned in [8], is fostered by the high mobility of Sr in processes involving the fluid phase.

The application of quartz in geochronological study is a promising aspect for many reasons, in particular, the abundance of different generations and morphologies of this mineral at gold-bearing and other deposits. The problems of Rb–Sr dating of hydrothermal quartz are discussed in [9–11]. The scarcity of isotope data on quartz is primarily related to the complexity of the analytical technique. The present application of quartz as the Rb–Sr geochronometer is based on our previous research [11], in which we developed the technique of isotope analysis of extremely small amounts of Sr and Rb contained in quartz and estimated modes of occurrences and geochemical behavior of the Rb–Sr system in quartz.

Samples for isotope–geochronological study of ore mineralization in the Sukhoi Log deposit were taken from the core of borehole 6, which entered the Khomolkho Formation and recovered ore zone of the deposit within the depth range from 171 to 251 m (Fig. 1). The ore zone has no visible boundaries. Its roof and bottom are identified only by the gold content.

Whole-rock samples. Among 12 samples of metasomatized black shales taken for Rb–Sr isotope dating, 10 samples were taken within the ore zone. They are sufficiently regularly spaced along the vertical section. They contain stringer-disseminated gold–sulfide mineralization. Two samples are black shales developed beyond the ore zone. Sericite-rich fractions were separated from three whole-rock samples. One fraction was obtained from sample 6/49[1] located above the ore zone, while two fractions were taken from samples within the ore zone (samples 6/220.15 and 6/248). These fractions were also analyzed by the K–Ar method. In addition, Rb–Sr dating was used to analyze four samples of metasedimentary rocks of the Valyukhta Formation, which is widespread in the Bodaibo synclinorium and represents a stratigraphic analogue of the Khomolkho Formation.

The XRF study showed that the metasomatized black shales recovered by the borehole have a steady chemical composition, which is typical of greenschist metapelites. No significant differences are observed between major element compositions of ore and barren intervals.

The black shales of the ore zone are characterized by a microgranular texture and thin-banded structure. The main rock-forming minerals are sericite (35–50 vol %), quartz (20–35 vol %), and carbonate (10–50 vol %). Feldspars, chlorite, sulfides, and scattered carbonaceous matter are subordinate. The banded structure of shales is caused by alternation of sericite–quartz layers and layers enriched in carbonaceous matter and chlorite. The samples prepared for Rb–Sr isotope measurements and chemical analysis weighed 200–300 g.

Quartz. The Rb–Sr parameters were obtained for hydrothermal quartz from vein bodies with low-sulfide gold–quartz mineralization, which is superimposed on the stringer-disseminated gold–sulfide mineralization. Four monomineral fractions of quartz were prepared from samples taken from vein bodies: samples 6/197.3, 6/198.8, and 6/237 were recovered within the ore zone by borehole 6; sample 2/198, by borehole 2 drilled 800 m west of borehole 6. The vein bodies are filled with milky white coarse-grained massive quartz accounting for up to 90–95 vol % of the samples. Quartz contains isometric or slightly extended aggregates of coarse-grained ankerite. Ore minerals in these samples occur as single grains (up to 2–3 mm) of pyrite and less common chalcopyrite. The quartz contains solid microinclusions of ankerite, sericite, apatite, pyrite, and monazite. The fluid inclusions are dominated by two-phase primary inclusions. Quartz in the studied samples does not bear evidence of late recrystallization of vein matter.

All measurements of the Sr isotope composition and Rb and Sr contents were performed on a Micromass Sector 54 7-collector mass spectrometer. Whole-rock samples were using isotope analysis and sample preparation techniques developed by authors of the present paper [12, 13]. Quartz with Rb and Sr contents two orders of magnitude lower (up to 0.1 μg/g) were analyzed using specially developed techniques [11]. Com-

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[1] Hereinafter, the numerator and denominator designate the borehole number and depth, respectively.

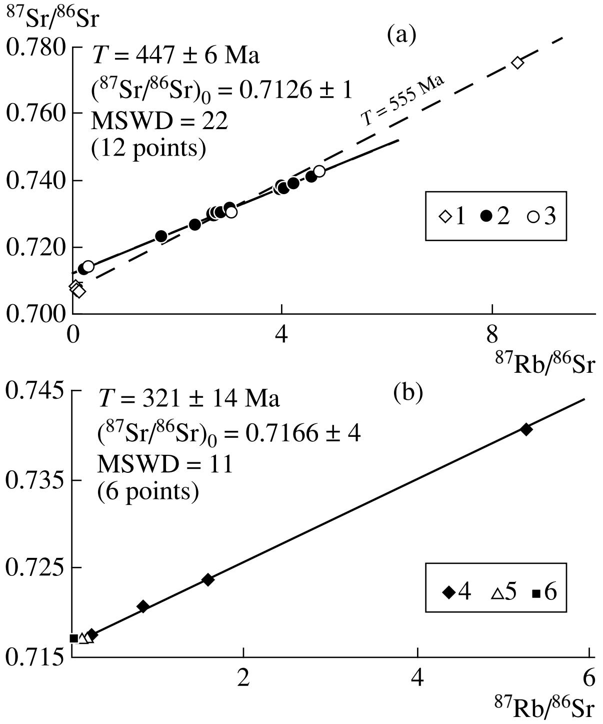

Fig. 2. Rb–Sr diagram for the rocks and minerals of the Sukhoi Log deposit: (a) whole-rock samples of the metasedimentary rocks of the Valyukhta and Khomolkho formations; (b) minerals from quartz veins. (*1*) Rocks of the Valyukhta Formation beyond the ore field; (*2*) ore-hosting black shales of the Khomolkho Formation; (*3*) sericite-rich fractions of the rocks of the Khomolkho Formation; (*4*) quartz from the late gold-bearing veins; (*5*) acid leachate from quartz; (*6*) ankerite from late gold-bearing veins

bination of these analytical techniques provided a low background at all stages (the total blank for Rb and Sr was 0.06 and 0.11 ng, respectively) and high sensitivity of mass-spectrometric measurements. The standard error of the ^{87}Sr/^{86}Sr ratio measurement in the whole-rock samples was accurate to 0.003 (2σ). The results were controlled by systematic analyses of the SRM-987 Sr standard. The table shows measurement errors for specified samples. The K–Ar age of three sericite-rich fractions were measured in our laboratory by V.A. Lebedev. The decay constants recommended by the International Geochronological Subcommision in 1977 were used for geochronological calculations.

Let us consider first the results of Rb–Sr measurements presented in the table. The Rb and Sr contents in the samples from borehole 6 vary within 39–180 and 62–610 μg/g, respectively. The consequent significant dispersion of ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios is favorable for isochron dating of the sample series.

In the Rb–Sr diagram (Fig. 2), the data points of the shales from borehole 6 define a regression line with T = 447 ± 6 Ma (^{87}Sr/^{86}Sr)$_0$ = 0.7126 ± 1, MSWD = 22). The linear correlation obtained is close to the isochron. This is suggested by small errors in the calculated age (±6 Ma or 1.3 rel %) and initial ratio ^{87}Sr/^{86}Sr (±0.0001 or 0.015%) at a relatively low MSWD value. Three data points corresponding to sericite-rich fractions are also plotted at this regression line. Incorporation of these data points in calculations does not affect significantly the isochron parameters: MSWD = 31, T = 446 ± 6 Ma, (^{87}Sr/^{86}Sr)$_0$ = 0.7126 ± 1. The data points of the ore and barren samples in the total isochron define an event at 447 ± 6 Ma, which led to the homogenization of Sr isotopic composition in all minerals of black shales. This homogenization spanned a significant volume, at least the volume of rocks intersected by borehole 6. The high MSWD value owing to a relatively small geochemical dispersion of data points in the isochron diagram is presumably caused by the close association of newly formed hydrothermal–metasomatic minerals with relicts of metamorphic minerals in the host rocks of the Sukhoi Log deposit.

In the Rb–Sr diagram, the data points of the unaltered rocks of the Valyukhta Formation deviate from the isochron (Fig. 2) and are approximated by the line with a slope corresponding to an age of 555 Ma. This dating is rough, but consistent with the age of 513 ± 22 Ma [14], which is considered as the metamorphic age of the Riphean terrigenous–sedimentary rocks of the Ura Uplift (northern part of the Baikal–Patom highland), whose stratigraphic section comprises the rocks of the Valyukhta Formation.

Figure 2 shows that the Rb–Sr isotope characteristics obtained for four quartz samples and two acid leachates define an isochron dependence with T = 321 ± 14 Ma, (^{87}Sr/^{86}Sr)$_0$ = 0.7166 ± 4 and MSWD = 11). The elevated MSWD value is presumably explained by some heterogeneity of the initial ^{87}Sr/^{86}Sr ratio in the samples taken from spatially unrelated veins.

The values of K–Ar age obtained for sericite-rich fractions taken from three spatially unrelated whole-rock samples are similar within the analytical error: 329 ± 13 Ma (sample 6/49A), 328 ± 6 Ma (sample 6/220.15A), and 313 ± 10 Ma (sample 6/248A). Rb–Sr data on quartz (321 ± 14 Ma) together with the aforementioned K–Ar data indicate the age of the repeated pulse of hydrothermal activity at the deposit and disturbance of closure of the K–Ar isotope system of fine-dispersed sericite in the metasomatized black shales. Thus, the isotope–geochronological study conducted for the first time for the ore matter of the Sukhoi Log deposit recorded two events with ages of 447 ± 6 Ma and 321 ± 14 Ma, which mark two major stages of the deposit formation separated by an interval of 120 Ma. The first stage involved the hydrothermal–metasomatic alteration of the rocks of the Khomolkho Formation and the formation of stringer-disseminated mineralization. The second stage was marked by the formation of gold-bearing quartz veins of the Sukhoi Log deposit.

The reliability of the two Rb–Sr datings considered above is confirmed by consistent initial ^{87}Sr/^{86}Sr ratios calculated from isochrons. The calculations show that

Results of Rb–Sr study of the rocks and minerals of the Sukhoi Log deposit

Sample no.	Analyzed material	Rb	Sr	$^{87}Rb/^{86}Sr$ (±2σ)	$^{87}Sr/^{86}Sr$ (±2σ)
		µg/g			
Metasedimentary rocks beyond the ore field (Valyukhta Formation)					
685-13	Aleuritic shales	125	43	8.49 ± 4	0.77548 ± 2
6105-19	Dolomitolites	0.9	830	0.0031 ± 2	0.70825 ± 2
691-29	Black limestones	0.9	590	0.0044 ± 5	0.70828 ± 2
6105-42	Aleuritic shales	3.3	770	0.0124 ± 5	0.70819 ± 2
Ore-hosting black shales (Khomolkho Formation)					
6/49	Shales beyond the ore zone	110	135	2.32 ± 2	0.72720 ± 2
6/49-A	The same, sericite-rich fraction	145	140	3.03 ± 2	0.73111 ± 2
6/171	Shales from the ore zone	115	110	2.99 ± 2	0.73209 ± 2
6/178	The same	110	120	2.71 ± 2	0.73017 ± 2
6/192	″	140	100	4.02 ± 3	0.73776 ± 2
6/198.1	″	59	62	2.79 ± 2	0.73067 ± 2
6/210.8	″	150	98	4.56 ± 2	0.74155 ± 2
6/220.15	″	150	110	4.01 ± 2	0.73849 ± 2
6/220.15-A	Sericite-rich fraction	180	110	4.71 ± 3	0.74270 ± 2
6/221	Shales from ore the zone	120	88	3.96 ± 2	0.73734 ± 2
6/231.2	The same	130	89	4.25 ± 3	0.73980 ± 2
6/247.4	″	97	170	1.69 ± 4	0.72341 ± 2
6/248	Carbonatized shales from the ore zone	39	500	0.227 ± 2	0.71408 ± 2
6/248-A	The same, sericite-rich fraction	58	610	0.275 ± 2	0.71430 ± 2
6/254.4	Shales beyond the ore zone	87	88	2.85 ± 2	0.73050 ± 2
Late quartz veins					
6/237	Quartz	0.106	0.059	5.26 ± 3	0.74060 ± 12
	Acid leachate	0.0005	0.004	0.20 ± 15	0.7174 ± 9
6/198.8	Quartz	0.021	0.0865	0.820 ± 7	0.72072 ± 14
	Acid leachate	0.0002	0.011	0.092 ± 4	0.7171 ± 3
6/197.3	Quartz	0.060	0.1097	1.57 ± 1	0.72360 ± 13
2/198	Quartz	0.0055	0.0860	0.186 ± 2	0.71722 ± 14
6/237	Ankerite	0.0001	1430	0.001 ± 1	0.71710 ± 2

the $(^{87}Sr/^{86}Sr)_0$ in metasomatic rocks should increase by 0.005, on average, over the period of 126 Ma between dated events and reach ~0.718 at an initial value of 0.7126 ± 1 (whole-rock samples of metasomatized shale). A similar value was obtained from the isochron for quartz $(^{87}Sr/^{86}Sr)_0 = 0.7166 \pm 4$) and measured in quartz-associated ankerite (0.71710 ± 2).

Obtained datings indicate that the large-scale noble metal mineralization at the deposit is related to the Paleozoic tectonomagmatic activation. They do not suggest that the formation of stringer–disseminated ores 447 ± 5 Ma ago was related to emplacement of an intrusive body. The magmatic rocks of this age are not exposed at the deposit. However, they could occur at depths. In particular, geophysical data indicate a local gravity minimum at the deposit, indicating the presence of a granite pluton beneath the deposit [15]. Rejuvenation of hydrothermal activity at the Sukhoi Log deposit, which produced the low-sulfide gold–quartz veins (321 ± 14 Ma), coincides with the emplacement of acid intrusions of the Konkuder–Mamakan and Aglan–Yan complexes dated by K–Ar and U–Pb methods in [7].

The age of regional metamorphism of the Riphean black shales at the Sukhoi Log deposit has not yet been established reliably. Available age estimates of this process vary from 570 to 510 Ma [6, 14, and present paper]. These data together with the datings considered above indicate that noble metal mineralization significantly postdated the regional metamorphism of black shales.

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