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Rb–Sr Isotopic Systematic of Hydrothermal Minerals, Age, and Matter Sources of the Nezhdaninskoe Gold Deposit (Yakutia)

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The problem of the relationship between orogenic (mesothermal) gold deposits and magmatic and metamorphic processes is the most debatable [1, 2]. The Nezhdaninskoe deposit is a typical and large object of such type, that is why the age of hydrothermal mineralization and sources of metals are the key points in the study of this concrete deposit and working out of the abovementioned problem as a whole. Direct dating of hydrothermal formations of the Nezhdaninskoe deposit is currently the central problem. Such isotope geochronological data are absent, so that the age correlation of ore-forming and magmatic processes on this deposit is still an open question.

The Nezhdaninskoe gold deposit (Fig. 1) with explored Au resources of 311 t [3] including estimated reserves of 478 t Au is located in the Southern Verkhoyan synclinorium within the Verkhoyan folded mobile belt activated during the accretion of the Okhotsk–Chukotsk volcanic–plutonic belt [2]. The Nezhdaninskoe ore field is situated at the boundary of two structural–material zones of the Southern Verkhoyan synclinorium: Prisettedaban and Central. The area of the ore field is composed of Lower and Upper Permian sand–schist deposits forming an anticline flexurelike fold and has a length of 15 km at a width of ~4 km (Fig. 1). The Kurum granite–granodiorite massif (6.5 km^2) is outcropped in the northeastern part, and the Gel'din group of diorite stocks and Yaman granitoid stock are in the southwestern part. The isotopic age of these rocks ranges from 126 to 70 Ma. The ore field is located at the juncture of four fault systems including the regional deep submeridional (Kiderikin), latitudinal (Tyrin), and two diagonal (Suntar and Khalyin) ones, dividing the crown of the fold into a number of horstlike blocks and controlling the location of gold mineralization.

A nontraditional approach based on hydrothermal quartz as a Rb–Sr geochronometer was applied for Rb–Sr dating of vein mineralization of the Nezhdaninskoe deposit. The study of the Rb–Sr isotopic system of this mineral allows us to solve geochronological, as well as isotope–geochemical, tasks successfully [4–8]. The Rb–Sr isotopic system of quartz is characterized by some peculiarities preventing wide application of this mineral in isotopic geology. The main peculiarities are, first, the low level of the concentration of studied elements (<100 ppb), which requires a specific methodological approach to the study of this mineral, and, second, the diversity of forms of Rb and Sr existence in quartz and, consequently, the complex behavior of the Rb–Sr isotopic system under the influence of superposed processes. The Rb–Sr study of quartz is desirable to combine with the study of ^{87}Sr/^{86}Sr variations in other hydrothermal minerals characterized by low ^{87}Sr/^{86}Sr values [9]. We studied scheelite and carbonates.

Due to their crystallochemical peculiarities, scheelite and carbonates predominantly accumulate Sr rather than Rb. Consequently, the Sr isotopic composition in carbonates does not change in time after their crystallization. Thus, the data on the Rb–Sr study of these minerals allow us to ascertain the ^{87}Sr/^{86}Sr value directly in the fluid from which their crystallization occurred.

All measurements of the Sr isotopic composition and Rb and Sr concentrations were performed by the method of isotopic dilution on a seven-collector mass-spectrometer Micromass Sector 54. The study of the Rb–Sr isotopic system of quartz was carried out using specially developed methodologies [8], which in complex provided a low background level on all stages of the analyses (the total background level for Rb and Sr is 0.06 and 0.11 ng, respectively) and the high sensitivity of mass-spectrometric measurements. The average error of the ^{87}Sr/^{86}Sr ratio measurement during the analysis of quartz was ±0.003% (2σ). Correctness of the results was controlled by systematic analyses of the Sr isotopic composition in the standard sample SRM-987. The errors of the final results (values of isotopic ratios ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr of the analyses of individual samples) are given in the table.

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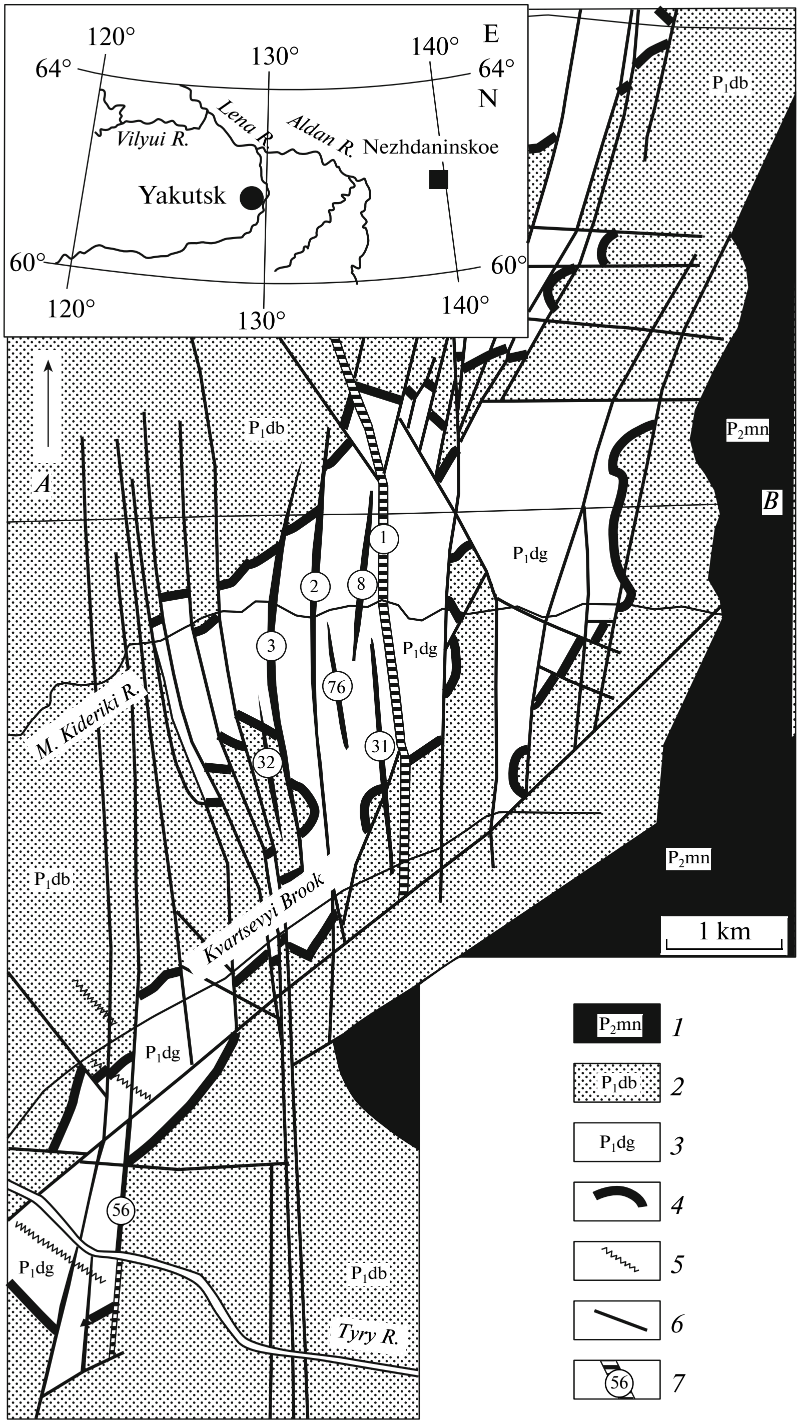

Fig. 1. Scheme of geological structure of the Nezhdaninskoe deposit [2]. (*1*) Sandstone, aleurolite (P_2mn); (*2*) sandstone, aleurolite, argillite (P_1db); (*3*) aleurolite, sandstone (P_1dg); (*4*) reference sandstone layer (P_1dg); (*5*) dykes of lamprophyre and porphyry diorite; (*6*) dislocations; (*7*) ore zones and their numbers.

Three generations of quartz are distinguished in ores of the Nezhdaninskoe deposit [2]. Quartz of the second generation composing most of the ore bodies and containing gold mineralization prevails. Eight samples of quartz of the second generation were selected for the analysis. Seven samples represented various levels of ore zone no. 1 and one sample was from ore zone no. 3. The microscopic texture of quartz from the studied samples demonstrates isometric or poorly elongated grains with a size ranging from a few millimeters to a few centimeters. A significant content of predominantly primary two-phase (gas–liquid) and

Results of the Rb–Sr study of scheelite and carbonates from ore zones of the Nezhdaninskoe deposit

No.	Sample	Place of sampling	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$, ±2σ	$^{87}Sr/^{86}Sr$, ±2σ
Scheelite from the ore zone no. 1						
1	2/28-1	+800 m, southern part	0.1	5850	0.0001 ± 3	0.713578 ± 15
2	2/27	+1000 m, southern part	0.3	3865	0.0002 ± 3	0.713871 ± 15
3	149-Gr-78	+700 m, central part	0.1	10600	0.0001 ± 3	0.712558 ± 15
4	189-Gr-78	+1200 m, central part	0.4	8300	0.0001 ± 2	0.712345 ± 15
5	85/2	+800 m, northern part	0.5	7380	0.0002 ± 2	0.713052 ± 15
6	13-10	+1100 m, northern part	0.4	3970	0.0003 ± 4	0.713364 ± 15
Metamorphogenetic carbonate (preore stage)						
7	5L-G-9		0.55	11740	0.0001 ± 2	0.711268 ± 15
8	392-8 ShT		0.78	2400	0.0009 ± 1	0.708117 ± 15
Metasomatic and hydrothermal carbonate (ore stage)						
9	13-709	Ore zone no. 1	8.57	1700	0.015 ± 2	0.713168 ± 15
10	15-730	“	5.03	10126	0.0015 ± 6	0.713073 ± 15
11	42-Gr-78	“	2.1	14600	0.0004 ± 1	0.712875 ± 14
12	206-Gr-77	“	1.03	1430	0.003 ± 2	0.712810 ± 20
13	860-147	Ore zone no. 2	1.1	53	0.061 ± 6	0.713276 ± 15
14	860-148	“	6.4	3600	0.006 ± 1	0.713412 ± 15
15	159-128	Ore zone no. 32	1.2	1960	0.0018 ± 2	0.713046 ± 10
16	160-158	“	4.2	880	0.014 ± 1	0.713074 ± 10
17	560-307	Ore zone no. 56	0.9	506	0.005 ± 8	0.712994 ± 30
18	296-135	Ore zone no. 76	6.2	3870	0.005 ± 1	0.713259 ± 15
Regenerated carbonate (postore stage)						
19	ShT-27 reg 3	Ore zone no. 1	0.4	1810	0.001 ± 1	0.713668 ± 15
20	ShT-8 reg 6	Ore zone no. 8	25	3100	0.023 ± 1	0.712818 ± 15
21	165-350	Ore zone no. 32	0.03	17	0.01 ± 1	0.713537 ± 14
22	159-208	Ore zone no. 56	3.6	271	0.038 ± 1	0.713023 ± 15
23	4/6-29-1	“	2.7	6610	0.001 ± 2	0.713616 ± 16
24	15/6-29	“	1.6	306	0.015 ± 2	0.713524 ± 15
25	ShT-16	Ore zone no. 76	0.05	2470	0.0001 ± 1	0.713278 ± 15

Note: The given errors are related to the last significant digits.

gaseous inclusions is observed in all samples. Quartz contains rare microinclusions of carbonates and muscovite. The signs of late recrystallization of vein quartz are not found, which is the main mineralogical criterion of violation of the Rb–Sr isotopic system in the selected quartz samples determining their applicability for isotopic dating.

Scheelite in the deposit is represented by two generations (early and late). The studied scheelite of the early generation is widely abundant and occurs in ore bodies as impregnation or nests [2]. Segregations of this mineral are often observed in selvages of quartz veins and veinlets, where scheelite is closely associated with sulfides. Six monomineral scheelite fractions from different hypsometric levels of ore zone no. 1 were prepared. The vertical sampling range was 500 m.

Carbonates in ore bodies of the Nezhdaninskoe deposit are less abundant than quartz alone. The precipitation of carbonates occurred at different stages of the hydrothermal process. Preore carbonates comprise calcite from metamorphogenetic hydrothermal quartz–carbonate–chlorite veins, as well as dolomite, ankerite, and siderite from early sericite–carbonate metasomatite. Carbonates of the ore stage (magnesite–ferromagnesite and ankerite–dolomite) occur in ore metasomatite and vein bodies. Post-ore carbonates of the siderite–magnesite group compose late veins together with quartz. We studied 19 carbonate samples. Two samples were collected in metamorphogenetic quartz–carbonate veins; ten samples, from metasomatites and vein formations of different ore

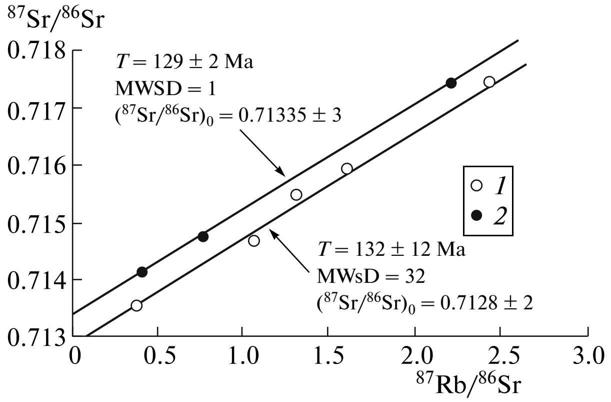

Fig. 2. Rb–Sr isotopic diagram for vein quartz from ore bodies of the Nezhdaninskoe deposit. Quartz samples from the upper (*1*) and lower (*2*) horizons of the deposit.

zones; and seven samples were represented by postore carbonate.

The results of Rb–Sr study of minerals are given in the table. The concentrations of Rb and Sr in quartz range in relatively wide limits from 0.025 to 1.17 ppm and from 0.12 to 1.28 ppm, respectively, but as a whole are quite typical of quartz of hydrothermal origin. The isotopic ratio ^{87}Rb/^{86}Sr in quartz of the Nezhdaninskoe deposit varies from 0.4 to 2.4. It differs strongly from the ^{87}Rb/^{86}Sr ratio in hydrothermal quartz formed by fluids of magmatic origin [4, 8], in which this ratio may reach values of ~40 and higher, but is comparable with the ^{87}Rb/^{86}Sr ratio in quartz from mesothermal gold deposits of various types. The values of the ^{87}Sr/^{86}Sr ratio vary in narrow limits from 0.714 to 0.717, which is controlled by low ^{87}Rb/^{86}Sr ratio values in the studied samples and a relatively young age of the Nezhdaninskoe deposit.

Experimental points of quartz do not follow a single regression line on the Rb–Sr diagram (Fig. 2). The observed scatter may be explained in principle by two geochemical reasons: on the one side, violation of the quartz Rb–Sr isotopic system closure in the course of its late transformation; on the other side, heterogeneity of mineral-forming fluid with respect to the (^{87}Sr/^{86}Sr)$_0$ value. The microscopic study of quartz demonstrated the absence of its recrystallization signs and allowed us to exclude the influence of violation of the quartz Rb–Sr isotopic system closure from consideration. Heterogeneity of the (^{87}Sr/^{86}Sr)$_0$ value is the most probable reason of point scatter that is confirmed by the results of the Rb–Sr study of scheelite and carbonates discussed below. The analysis of point distribution on the Rb–Sr diagram demonstrates that the points lie on two parallel lines with close angles. The upper regression line on the diagram is formed by three points corresponding to the samples of vein quartz from the deepest horizons of ore zone no. 1 (–100 to +150 m). Points of samples from ore zones nos. 1 and 3 collected in the depth range from +350 to +1450 m plot onto the lower line. Rb–Sr datings calculated by these two groups of points are the same within the error and are 129 ± 2 Ma at (^{87}Sr/^{86}Sr)$_0$ = 0.71335 ± 3 and MSWD = 1 (three points) and 132 ± 12 at (^{87}Sr/^{86}Sr)$_0$ = 0.7128 ± 2 and MSWD = 32 (five points).

These results are not contradictory to the geological data on the Early Cretaceous age of the deposit. The Rb–Sr system of quartz allows us to establish only the time of mineral crystallization that is explained by peculiarities of Rb and Sr forms of existence, which controls significant differences in the migration ability of these elements during the secondary transformation [8]. It is impossible to date the processes of the secondary transformation of this mineral, since quartz recrystallization is not accompanied by homogenization of the Sr isotopic composition. The reliability of the datings obtained is also confirmed by the consistence of (^{87}Sr/^{86}Sr)$_0$ values calculated by regression lines (Fig. 2) and ^{87}Sr/^{86}Sr values in scheelite and carbonates associating with quartz (table). Thus, the ^{87}Sr/^{86}Sr values in carbonate samples nos. 11 and 12 collected in the same depth range of ore zone no. 1 as quartz are 0.712875 ± 14 and 0.712810 ± 20 at a calculated value of (^{87}Sr/^{86}Sr)$_0$ = 0.7128 ± 2. However, some heterogeneity of the (^{87}Sr/^{86}Sr)$_0$ value undoubtedly occurred in the ore-forming fluid that results in the higher MSWD = 32 for the lower isochrone and quite high error of the measured age (132 ± 12 Ma). Note also that the Rb–Sr dating of quartz is the same as the K–Ar age (119 ± 4 Ma) obtained for sericite from metasomatite of the deposit (measurements were performed in SVKNII, Magadan, by the sample from the collection of G.N. Gamyanin) within the error limits.

As a whole, scheelite of the Nezhdaninskoe deposit has very high (thousands of ppm) Sr concentrations, which is typical for this mineral. The ^{87}Sr/^{86}Sr ratio ranges from 0.7123 to 0.7139 (table). The lowest values of ^{87}Sr/^{86}Sr were registered in scheelite from the central part of ore zone no. 1 (nos. 3 and 4), whereas this mineral from the marginal part of this zone is characterized by higher values. Such variations cannot be explained by variable addition of radiogenic ^{87}Sr because of the extremely low ^{87}Rb/^{86}Sr ratio (<0.0003) and, thus, provide evidence for heterogeneity of this ratio in the mineral-forming fluid in the ore formation zone.

A wide range of Sr concentrations from 17 to 14 600 ppm is a characteristic feature of carbonates from the Nezhdaninskoe deposit. Most likely this results from significant variability of the chemical composition of these minerals in the deposit. The values of the ^{87}Rb/^{86}Sr ratio are low, ranging from 0.0001 to 0.061 and being typical for carbonates of hydrothermal genesis as a whole. The change in the ^{87}Sr/^{86}Sr ratio in carbonates at the expense of radiogenic addition of the ^{87}Sr isotope at established ^{87}Rb/^{86}Sr values over 130 Ma is definitely lower than 0.00001, which is close to the error of the ^{87}Sr/^{86}Sr ratio measurement.

Consequently, the measured values of the $^{87}Sr/^{86}Sr$ ratio in carbonates may be accepted as the initial ones. They vary in a wide range with the minimal values (0.708 and 0.711) typical for preore carbonates from metamorphogenetic quartz–carbonate veins, whereas carbonates of ore and postore stages have higher values of the $^{87}Sr/^{86}Sr$ ratio. The range of the $^{87}Sr/^{86}Sr$ ratio change in carbonates of the ore stage is smaller (0.7128–0.7134) than in postore carbonates (0.7128–0.7137). There is no correlation between the value of the $^{87}Sr/^{86}Sr$ ratio and the Sr concentration, as well as the depth of sampling for carbonates.

The discussed Rb–Sr isotopic data allow us to make the following conclusion. Datings of the hydrothermal process on the Nezhdaninskoe deposit confirm the time relationships between the ore formation and Cretaceous magmatism in the region. By virtue of the abovementioned reasons, the datings obtained bear a significant error reaching 12 Ma. Because of this, the most precise time correlation of the ore origin and the formation of concrete intrusive bodies requires additional confirmation of isotopic datings. The massif of Rb–Sr data obtained for scheelite and carbonate provides unambiguous evidence for the crustal nature of source of Sr coming to the ore deposition zone. Magmatic melts controlling the formation of Cretaceous granitoid intrusions in the region and (or) host Permian terrigenous–sedimentary rock could be potential sources of Sr. The value of the initial $^{87}Sr/^{86}Sr$ ratio in intrusive rocks of the Nezhdaninskoe ore field (~0.707 [10]) is significantly lower than the values of 0.7123–0.7139 registered in scheelite and carbonates of the ore stage and characterizing mineral-forming fluid. The data obtained allow us to limit the role of the magmatic source of strontium, but its receipt from magma cannot be excluded. Strontium was most likely extracted by fluid from terrigenous–sedimentary rocks. The $^{87}Sr/^{86}Sr$ isotopic ratio in these rocks at the moment of the formation of metamorphogenetic carbonates in them was 0.708–0.711. At $^{87}Rb/^{86}Sr$ values typical for black schist (a few units), this value could reach 0.7123–0.7139, which is typical for fluid to the moment of hydrothermal ore formation development at the expense of radiogenic ^{87}Sr accumulation.

Thus, according to the data obtained, the underlying Permian terrigenous–carbonate rocks were the predominant source of Sr; the revealed heterogeneity of the Sr isotopic composition in fluid was most likely controlled by the initial heterogeneity of the Rb–Sr ratio in these rocks. As a whole, these conclusions are consistent with the available information that Sr came to the orogenic gold-forming systems from underlying rocks occurring in the area of deposits and heterogeneity of $^{87}Sr/^{86}Sr$ ratios that resulted from mixing of Sr extracted from different rocks [11]. As is evident from the previously published data on the isotopic composition of O, C, S, as well as on the distribution of rare elements in minerals of metasomatic, intrusive, and terrigenous–sedimentary rocks [1, 2], some other mineral-forming components could come to the ore-forming system from the magmatic source.

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