

Metal Sources of the Large Nezhdaninsky Orogenic Gold Deposit, Yakutia, Russia: Results of High-Precision MC-ICP-MS Analysis of Lead Isotopic Composition Supplemented by Data on Strontium Isotopes

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Abstract—A collection of galena from the Nezhdaninsky gold deposit (62 samples), as well as galena from the Menkeche silver–base-metal deposit and the Sentyabr occurrence and K-feldspar from intrusive rocks of the Tyry–Dyby ore cluster have been studied using the high-precision ($\pm 0.02\%$) MC-ICP-MS method. Particular ore zones are characterized by relatively narrow variations of isotope ratios (no wider than $\sigma_{6/4} = 0.26\%$). Vertical zoning of Pb isotopic composition is not detected. Variation in Pb isotope ratios mainly depends on the type of mineral assemblage. Galena of the gold–sulfide assemblage dominating at the Nezhdaninsky deposit is characterized by the following average isotope ratios: $^{206}\text{Pb}/^{204}\text{Pb} = 18.472$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.586$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.605$. Galena from the regenerated silver–base-metal assemblage is distinguished by less radiogenic lead isotope ratios: 18.420, 15.575, and 38.518, respectively. In lead from the Nezhdaninsky deposit, the component, whose source is identified as Permian host terrigenous rocks, is predominant. The data points of isotopic composition of lode lead make up a linear trend within the range of $\mu_2 = 9.5$ – 9.6 . K-feldspar of granitic rocks has less radiogenic and widely varying lead isotopic composition compared to that of galena. The isotopic data on Pb and Sr constrain the contribution of Late Cretaceous granitic rocks as a source of gold mineralization at the Nezhdaninsky deposit. The matter from the Early Cretaceous fluid-generating magma chamber participated in the ore-forming system of the Nezhdaninsky deposit. The existence of such a chamber is confirmed by the occurrence of Early Cretaceous granitoid intrusions on the flanks of the Nezhdaninsky ore field. The greatest contribution of magmatic lead ($\sim 30\%$) is noted in galena from the silver–base-metal mineral assemblage. This component has isotopic marks characteristic of lower crustal lead: the elevated $^{208}\text{Pb}/^{206}\text{Pb}$ ratio relative to the mean crustal value and the lower $^{207}\text{Pb}/^{204}\text{Pb}$ ratio. Taken together, they determine a high Th/U ~ 4.0 in the source and $\mu_2 = 9.37$ – 9.50 . This conclusion is consistent with the contemporary tectonic model describing evolution of the South Verkhoyansk sector of the Verkhoyansk Foldbelt and the Okhotsk Terrane.

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INTRODUCTION

The attention that has recently been paid to the wide class of orogenic gold deposits (Groves et al., 1998) hosted in carbonaceous metasedimentary rocks of the continental crust is related, on the one hand, to their increasing economic importance, and on the other hand, to their insufficiently clear origin.

Gold deposits localized in carbonaceous metasedimentary sequences contain considerable resources of this metal. In Russia, more than half of lode gold resources consist of large, unique deposits of this type: Sukhoi Log, Natalka, Maisky, Olimpiada, and Nezhdaninsky. Deposits hosted in carbonaceous terrigenous rocks are also the basis of gold mining in other

countries, e.g., Muruntau, Daugyztau, Kokpatas, and Charmitan in Uzbekistan; Bakyrchik in Kazakhstan; and Kumtor in Kyrgyzstan. The mined, explored, and forecasted gold resources of specific deposits are estimated at 300–1000 t, and no less than 3400 t at the Muruntau deposit (Kempe et al., 2001).

Sources of mineral-forming fluid and metals at the deposits of this type are a matter of debate. Hypotheses of sedimentary–metamorphic and hydrothermal–metamorphic origin were put forward as early as the first years of the study of Muruntau and Sukhoi Log deposits (Gar'kovets, 1973; Buryak, 1975). It was suggested that gold was partly taken from host rocks or removed from zones of high-grade metamorphism. This hypothesis was supported by subsequent studies of the Sukhoi Log deposit (Chernyshev et al., 2009).

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As concerns the Mutuntau deposit, various concepts were discussed: the involvement of fluid and gain of gold from evaporite sequence (Wilde et al., 2001); extraction of gold from host rocks by the fluids formed as products of dehydration and decarbonation during regional metamorphism or emplacement of granites; a mantle source of fluid is not ruled out (Kempe et al., 2001; Graupner et al., 2006; Morelli et al., 2007). It is assumed that the fluids and their components released from granites during crystallization or from country rock undergone dehydration and decarbonation were supplied to the ore-forming systems of the Charmitan, Maisky, Natalka, and Nezhdaninsky deposits (Bortnikov et al., 2004, 2008).

The Nezhdaninsky gold deposit is a typical example of stringer–disseminated and gold–quartz deposits localized in carbonaceous terrigenous rocks. It is the third in reserves in Russia. As a result of geological exploration completed by the Polyus Gold Company, the gold reserves in category $C_1 + C_2$ (indicated + inferred) are estimated at 628.6 t (20.2 million oz) Au suitable for combined mining (<http://www.polyus-gold.com>). The Nezhdaninsky deposit is distinguished by close spatial association of orebodies with various igneous complexes. Therefore, its formation was referred to the evolution of the Kurum–Gel'dy ore–magmatic system (Gamyagin et al., 1985; Gamyagin, Bortnikov, and Alpatov, 2000) with involvement of fluids and their components derived from a magma chamber and taken from host rocks (Bortnikov et al., 2007; Chugaev et al., 2010b).

In most publications, the origin of gold mineralization at the Nezhdaninsky deposit is considered with allowance for variation in radiogenic and stable isotope contents. The lead isotopic composition is the most important indicator of sources participating in hydrothermal ore formation. The available data on the Precambrian and Phanerozoic orogenic gold deposits show that lead from different reservoirs, including granitic rocks coeval with gold mineralization participated in ore formation (Carr et al., 1995; Ho et al., 1995; McNaughton and Groves, 1996; Bierlein and McNaughton, 1998; Qiu and McNaughton, 1999).

The use of multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) for high-precision isotopic analysis of lead (a version of this method with measurement from solution and correction of mass discrimination effect by standard $^{205}\text{Tl}/^{203}\text{Tl}$ ratio) increased the comprehension and widened the capability of the Pb/Pb method in its geochemical applications (Rehkämper and Halliday, 1998; Collerson, Kamber, and Schoenberg, 2002; Kamenov et al., 2005; Chernyshev, Chugaev, and Shatagin, 2007a, 2007b). The use of this method for the study of common lead has increased the accuracy of measurement of isotopic ratios by almost an order of magnitude (up to $\pm 0.02\%$) in comparison with traditional TIMS¹. The accuracy of determination of evolutionary lead characteristics (μ , ω , t_m) has also

increased for both single samples and their series. The method makes it possible to detect minor difference in isotope ratios, to reliably reveal evolutionary trends of lead isotopic composition, which are obliterated or strongly distorted by analytical uncertainties, when other techniques of lead isotopic analysis (TIMS, LA-ICP-MS) are used.

The experience in application of high-precision MC-ICP-MS method (Chernyshev, Chugaev, and Shatagin, 2007b; Chernyshev et al., 2008, 2009; Chugaev et al., 2010a) allowed us to carry out a detailed study of lead isotopes for large-scale ore mineralization at the Nezhdaninsky deposit, to identify its sources, and to specify previously proposed model of its formation. In addition to the data on lead isotopes, the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios in hydrothermal minerals were taken into account. This study is based on the collection of samples taken with allowance for the previous geological and mineralogical study of the Nezhdaninsky deposit, the Menkeche deposit, and Sentyabr occurrence, as well as intrusive rocks of the Tyry–Dyby ore cluster (Gamyagin, Bortnikov, and Alpatov, 2000).

THE NEZHDANINSKY DEPOSIT

Regional Geological Setting

The Nezhdaninsky gold deposit is situated in the South Verkhoyansk Synclinorium at the southern end of the Verkhoyansk Foldbelt of the Mesozoides. The foldbelt was formed at the subsided margin of the North Asian Craton and is regarded as a marginal zone of the Mesozoic–Cenozoic orogenic belt.

Folding in the South Verkhoyansk Synclinorium was related to the westward docking of the Okhotsk Terrane to the Siberian Craton (Gamyagin, Bortnikov, and Alpatov, 2000). Three structural zones are distinguished in the South Verkhoyansk Synclinorium from west to east: the Sette–Daban and Central zones with tight folds and the Okhotsk Zone, where linear folds alternate with areas characterized by gentle dip of rocks. The near-meridional magma-controlling Kideriki Fault comprises a series of left-lateral reverse–strike-slip dislocations. This repeatedly reactivated fault controls localization of the Early Cretaceous granitoid plutons (Uemlyakh, Tarbaganakh, Vetka, Dyby), the Late Cretaceous plutons (Yaman, Kurum, Sup), and related dikes. At the Nezhdaninsky deposit, the Kideriki Fault is the major ore-controlling tectonic line.

The present-day geological appearance of the South Verkhoyansk Synclinorium was formed in a complex geodynamic setting. The northern part of this synclinorium was affected by the recurrent Uda sub-

¹ Standard uncertainty of isotope ratio measurements of the common lead using thermal ionization mass spectrometry (TIMS) is 0.1–0.2% and increases to 0.5–1.5% for LA-ICP-MS.

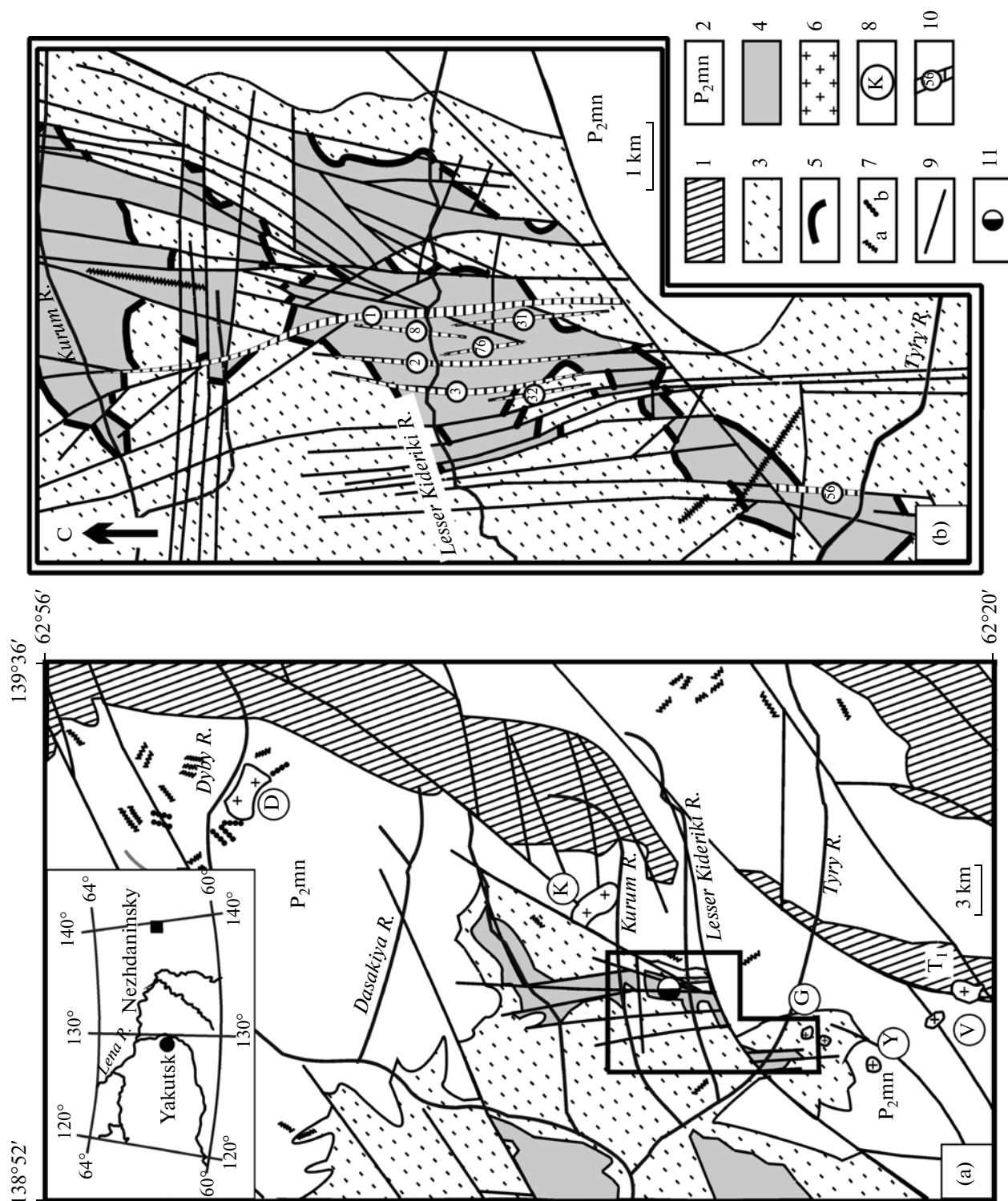


Fig. 1. Geological schemes: (a) Tyry–Dyby ore cluster and (b) Nezhdaninsky ore field. (1–4) Upper Paleozoic–Lower Mesozoic metasedimentary rocks: (1) Lower Triassic claystone and siltstone, (2) Upper Permian siltstone and sandstone of the Menkeche Formation, (3) Lower Permian siltstone with claystone interlayers of the Dyby Formation, (4) Lower Permian siltstone and sandstone of the Dzhuhtana Formation; (5) key sandstone unit; (6) postaccretionary Cretaceous granitoids; (7) dikes: (a) intermedite and (b) felsic; (8) granitic intrusions (letters in circles): D, Dyby; K, Kurum; G, Gel'dy; Y, Yaman; V, Vetka; (9) fault; (10) ore zone; (11) Nezhdaninsky deposit.

duction resulted in reactivation of the near-meridional Kideriki Fault and increase in thickness of the crust, which reaches 45 km at the Nezhdaninsky deposit and nearby (Gamyarin, Bortnikov, and Alpatov, 2000). The deposit (Fig. 1) is a part of the Tyry–Dyby ore cluster that includes the Kurum and Dyby granitoid plutons. The Au–Bi deposits and a number of minor felsic stocks are localized close to the contacts of these plutons. Numerous silver–base-metal occurrences and medium-size Menkeche deposit are located in the north and northeast of the ore cluster.

Geology of the Nezhdaninsky Deposit

The Nezhdaninsky deposit is related to the Dyby asymmetric box anticline. In intensity and character of folding and faulting, the crest of the Dyby Anticline is a structural anomaly standing out against the background of the adjacent areas. The Nezhdaninsky deposit is localized at the intersection of the near-meridional Nezhdaninsky, near-latitudinal Kurum, NE-trending Suntar, and NW-trending Setan'ya systems of regional faults. The deposit is bounded by the Main Fault in the east, the Boundary Fault in the west, and fracture zones of the Kurum System at the headwater of Kvartsevy Brook and at the drainage divide of the Zimov'e and Kurum brooks (Fig. 1).

The Lower Permian terrigenous rocks exposed at the deposit are subdivided into the Dzhuhtanga (lower) and the Dyby (upper) formations. The lithology of rocks is monotonous and differs only in relative amounts of pelitic, silty, and psammitic fractions; content of carbonaceous and carbonate materials.

The Kurum granitoid pluton is located on the northern flank of the Nezhdaninsky ore field, while the Yaman pluton and the Gel'dy group of stocks are situated at the southern flank. Their geology, petrography, age, and origin have been characterized by Gamyarin, Bortnikov, and Alpatov (2000) and Gamyarin et al. (2003). In the area of deposit proper, only dikes controlled by N–S-, NNE- and NW-trending faults are known. They vary from 0.5 to 8 m in thickness and extend for a few hundred meters to 10 km. Gabbrodiorite and lamprophyre dikes are distinguished. The latter comprise malchite, kersantite, and spessartite. Malchite dikes contain only 10–17% (occasionally, up to 26%) dark-colored minerals and differ in this respect from younger kersantite and spessartite. The Nadezhdinsky-type mineralization is superimposed on these dikes.

Early, productive, and late stages of deformation of host rocks are recognized. Normal tension cracks of the Setan'ya System were formed at anticline crests synchronously with the main phase of Mesozoic folding. At the productive stage, the displacements along the Kideriki Fault resulted in the formation of the main ore-bearing faults of the Nezhdaninsky system; the basement was also involved in these displacements. This stage is marked by emplacement of intermediate

dikes under extension of the crest of the Dyby Anticline. The late stage was characterized by left-lateral offsets along the faults of the Nezhdaninsky System, which host the main orebodies. The pinnate veins are localized in splays, including NW-trending tension cracks and NE-trending shear fractures. The emplacement of the Kurum and Yaman granitoid plutons and the Gel'dy minor stocks was related to the late stage of tectonomagmatic reactivation of the Kideriki Fault, which took place in the Late Cretaceous. These intrusions produced Au–Bi mineralization. The right-lateral strike-slip and normal displacements along the faults of the Nezhdaninsky System took place during the late stage. The silver–base-metal mineralization related to the Cretaceous–Paleogene reactivation of this province is superimposed on gold orebodies along this fault system.

Metasomatic Alteration of Host Rocks and Morphology of Orebodies

Multistage transformations of host rocks predated deposition of gold ore: (1) dislocation metamorphism of terrigenous rocks; (2) preore metasomatism related to the supply of CO₂, Ca, and Mg and development of high-Fe metasomatic alteration, (3) ore-forming infiltration beresitization and diffusion replacement of wall rocks with arsenopyrite. Zonal metasomatic rocks with disseminated Au-bearing pyrite and arsenopyrite have been formed as a result of beresitization. The aureole of sulfidation consists of the outer pyrite and the inner pyrite–arsenopyrite zones. The outer boundary of the pyrite zone serves as a boundary of beresitized rocks. Pyrite and arsenopyrite disseminations contain 40 and 120 ppm Au, respectively (on average). The Au grade of metasomatic rocks containing >5% sulfides is about 2 gpt.

More than 50 orebodies varying in economic importance, thickness, and extent are known at the deposit. These are mineralized crush zones, simple veins, and stockwork zones. The Kideriki Fault hosts the largest ore zone 1 and nearly parallel zones 2, 3, 8, 56, etc. Ore zone 1 is a typical mineralized crush zone, which crosses the crest of the Dyby Horst-Anticline at an angle of 25°, striking at an azimuth of 350° NNW, and is traced for 10 km along the strike and 2 km down the dip without signs of pinching out. The average thickness of ore zone is 14 m with variations from 2 to 40 m. Other ore zones are much smaller. The pinnate veins 6, 7, 14, etc. are steeply dipping splays of ore zone 1. They are traced along the strike in the N–S, NE and NW directions for 80–340 m and for 100–450 m to the depth; their thickness vary from 0.8 to 3.3 m.

Formation Stages and Mineralogy of the Deposit

Three stages of mineral formation are distinguished: hydrothermal–metamorphic, and two hydrothermal postmagmatic: the main productive

low-sulfide gold–quartz and the silver–base-metal (Gamyanin et al., 1985, 2000). The first stage developed on the regional scale and was expressed in the formation of low-grade gold-bearing quartz–ankerite veins and veinlets with sporadic pyrite disseminations often localized above granite–gneiss domes. The second stage of mineral formation is a product of the origination and evolution of the Au-bearing ore–magmatic system. At this stage, ore-bearing metasomatic rocks and productive mineralized ore zones and veins were formed, owing to generation and infiltration of the fluid derived from a transitional magma chamber at a depth of 15–18 km. Orebodies are composed of several mineral assemblages. The earliest scheelite–pyrite–arsenopyrite–dolomite–quartz assemblage forms the main gangue matrix of orebodies and is progressively followed by gold–chalcopyrite–galena–sphalerite; gold–sulfoantimonite–ankerite with Ag–tetrahedrite, bournonite, bulangerite; and chalcostibite–stibnite assemblages. During the third stage, the Late Cretaceous Ag–Sb-bearing ore–magmatic systems functioned in the region. The silver–base-metal mineralization at the Nadezhdinsky deposit is related to such a system. During this stage, the fissures formed as a result of right-lateral offsets along the NE- and N–S-trending faults were filled with scheelite–pyrite–arsenopyrite–quartz; gold–base-metal–Ag–sulfosalt–magnosiderite with freibergite, miargyrite, pyargyrite, stephanite; and hydromica–dickite assemblages composed of both regenerated and newly formed minerals. The minerals pertaining to earlier assemblages are disintegrated, cemented, and metasomatically replaced with minerals of later assemblages. The hydrothermal solutions forming these assemblages differed in physicochemical parameters, and similar minerals related to different stages are distinguished by typomorphic properties (Gamyanin, Bortnikov, and Alpatov, 2000).

All ore zones reveal direct vertical mineralogical zoning. From top to bottom, a contribution of Pb, Fe, and Cu sulfoantimonites decreases at the expense of increasing abundance of galena, sphalerite, and chalcopyrite. Arsenopyrite and pyrite dominate at the lowermost levels. The cryptic zoning of mineralization is expressed in variation of typomorphic features of quartz, gold, and sulfides, as well as in temperature regime, salinity, and pressure of fluid.

Age of Intrusive Rocks and Gold Mineralization

The formation of the Nezhdaninsky deposit is described by a model of functioning of heterogeneous and multistage ore–magmatic system (Gamyanin, Bortnikov, and Alpatov, 2000; Bortnikov et al., 2007). According to this model, the ore elements (Au, As, Sb, Ag, Pb, Cu) were supplied to the ore–magmatic system from the granodiorite melt filling a transitional magma chamber, which was also parental for the Kurum granodioritic pluton situated in the north of the Nezhdaninsky ore field and the Au–Bi mineralization

related to this pluton. Plutonic rocks cutting through the Permian terrigenous rocks plunge to the southwest toward ore zone 1 of the Nezhdaninsky deposit, however, the genetic link of the Kurum granodioritic pluton and quartz dioritic Gel'dy stocks to the gold ore–magmatic system came into conflict with new isotopic dating obtained after publication of the model. These geochronological data concern both the age of gold mineralization at the Nezhdaninsky deposit and intrusive rocks localized within the ore field.

The ^{39}Ar – ^{40}Ar age of dislocation metamorphism of the Paleozoic sedimentary rocks, which was apparently coeval with formation of Au-bearing beresites and quartz–sulfide veins, is 119 ± 0.5 Ma (Prokopiev et al., 2009). The age was determined for biotite formed along cleavage planes in Carboniferous metasandstone in the Allakh-Yun Zone. The K–Ar age of sericite from metasomatic rocks of the Nezhdaninsky deposit estimated at 119 ± 4 Ma was measured at the Northeastern Multidisciplinary Research Institute (SVKNII), Far East Branch, Russian Academy of Sciences in Magadan. The direct determination of Rb–Sr isochron age of quartz veins related to the hydrothermal gold mineralization of the Nezhdaninsky deposit yielded 132 ± 12 Ma (Ghugaev et al., 2010b). This estimate does not contradict the aforementioned indirect ^{39}Ar – ^{40}Ar date within uncertainty limits.

New isotopic geochronological data allowed us to specify temporal relationships between intrusive rocks in the studied region established in the 1970s–1980s on the basis of numerous K–Ar determinations (Zagruzina, 1977; Nenashev and Zaitsev, 1980) and to constrain the stages of Late Mesozoic granitoid magmatism in the Verkhoyansk Foldbelt and the adjacent tectonic units. The Early Cretaceous magmatism (130–120 Ma) widespread in this vast territory is exemplified in the South Verkhoyansk sector by the Tarbaganakh pluton (123 ± 1 Ma, U–Pb method, Prokopiev et al., 2009) and the Uemlyakh pluton (129 Ma, ^{39}Ar – ^{40}Ar , Layer et al., 2001), which are exposed to the south of the Nezhdaninsky deposit. Within the Nezhdaninsky ore field, malchite dikes only are igneous rocks reliably dated at the Early Cretaceous. The Rb–Sr mineral isochron age of 120 ± 4 Ma was obtained at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (IGEM RAS) (rock-forming minerals were used for isochron calculation). The U–Pb zircon age of 121 ± 1 Ma was estimated with ID-TIMS method at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences (IPGG RAS).

The time interval of the Late Cretaceous magmatism in the South Verkhoyansk sector of the Verkhoyansk Foldbelt estimated from the prevalent ^{39}Ar – ^{40}Ar ages of biotite is 106–92 Ma (Layer et al., 2001). The isotopic data on the intrusive rocks exposed in the Tyry–Dyby ore cluster show that the Kurum granodiorite pluton, Gel'dy quartz diorite stocks, and the

Sup intrusion of quartz monzodiorite undoubtedly are Late Cretaceous in age (Layer et al., 2001). The Rb–Sr isochron based on rock-forming minerals of the Kurum pluton and corresponding to 91 ± 2 Ma was obtained at the IGM RAS; the U–Pb zircon age of 94 ± 1 Ma was estimated at the IPGG RAS (ID-TIMS method). The Rb–Sr age of 92 ± 2 Ma was established for the Gel'dy stocks.

Thus, the Nezhadinsky deposit was formed contemporarily with Early Cretaceous magmatic activity. The Late Cretaceous magmatism widely developed in the Tyry–Dyby is more than 25 Ma younger and thus cannot be regarded as responsible for the formation of gold mineralization but could have been a cause of superimposed processes with possible gain and redistribution of ore matter, including lead, within the deposit.

RESEARCH METHODS

The high-precision MC-ICP-MS method applied to this study is based on the isotopic analysis of Pb from solution on the multicollector mass spectrometer with inductively coupled plasma and external correction of all measured intensities of Pb ion currents for mass discrimination effect by standard $^{205}\text{Tl}/^{203}\text{Tl}$ ratio. This method, which provides the accuracy of isotopic analysis of common lead by almost an order of magnitude higher than has been achieved by traditional thermal ionization mass spectrometry (TIMS), was elaborated in the last decade by Rehkämper and Halliday (1998), Collerson, Kamber, and Schoenberg (2002), and Kamenov et al. (2005). The detailed substantiation and description of the version of high-precision MC-ICP-MS analysis of Pb used in this study was given by Chernyshev, Chugaev, and Shatagin (2007a).

The analysis on a MC-ICP-MS NEPTUNE mass spectrometer comprised measurement of intensities of ion currents of four Pb isotopes, ^{205}Tl , ^{203}Tl , and ^{202}Hg with the aid of seven collectors. The measurements were conducted at the power of RF-generator of 950 W; the rate of solution delivery into spray chamber is 0.4 ml/min; the Pb concentration in working solution (3% HNO_3) is 150–400 ng/ml. The amount of Tl input into the analyzed Pb solutions corresponded to concentration of 20 ng/ml. Intensity of $^{208}\text{Pb}^+$ ion current was $2.5\text{--}8.0 \times 10^{-11}$ A (or 2.5–8.0 V at output voltage of electrometric amplifier); intensity of $^{205}\text{Tl}^+$ ion current was 0.6×10^{-11} A. Analysis of the samples consisted of the recording of 27 mass spectra including peaks of ion current of the aforementioned Pb, Tl, and Hg isotopes. On the basis of $^{202}\text{Hg}^+$ peak intensity, a correction for isobaric interference of $^{204}\text{Hg}^+$ was introduced into intensity of $^{204}\text{Pb}^+$ peak. The standard $^{205}\text{Tl}/^{203}\text{Tl}$ ratio = 2.3889 ± 1 was used for correction of Pb isotope ratios (Chernyshev, Chuguev, and Shatagin, 2007).

Uncertainty of the MC-ICP-MS mass spectrometric method proper estimated as $\pm 2\text{SD}$ from systematic parallel measurements of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ in metallic Pb SRM-981 standard and galena samples is not higher than $\pm 0.02\%$ and characterizes accuracy of measurements of Pb isotopic composition in galena. When Pb isotopic composition is measured in the minerals containing Pb as an admixture (commonly 10–100 $\mu\text{g/g}$), the uncertainty increases to $\pm 0.03\%$. Such analytical uncertainty is characteristic of the results of Pb isotopic analysis in K-feldspar from igneous rocks.

The chemical preparation of galena included dissolution of the selected grain of this mineral and preparation of working solution in 3% HNO_3 . When Pb isotopic composition was studied in rocks and rock-forming minerals (K-feldspar in the given case) containing 13–75 $\mu\text{g/g}$ Pb, chromatographic separation of Pb (Manhes, Allegre, and Provost, 1984) was used. Samples 20–50 mg in mass and 0.50–0.25 mm in grain size were preliminarily treated by 2M HNO_3 to remove readily soluble Pb from the sample surface. The chemical decomposition was carried out with concentrated $\text{HF} + \text{HNO}_3$ in teflon vessels at atmospheric pressure and temperature of $\sim 90^\circ\text{C}$ up to the complete dissolution of charge. One aliquot of solution was used for separation of common lead and another aliquot (smaller in volume) was used after addition of ^{208}Pb spike for separation of Pb to determine its content with isotope dilution. Chromatographic separation of Pb from elements of matrix was implemented in HBr medium on teflon microcolumns filled with Bio-Rad AG-1X8 anionite 200–400 mesh and 100 μl in volume. The total procedure blank did not exceed 0.15 ng Pb.

All measurements of Sr isotopic composition of scheelite and carbonates and Rb and Sr contents therein were carried out with isotope dilution on a Micromass Sector 54 seven-collector thermal ionization mass spectrometer. The mixed $^{85}\text{Rb} + ^{84}\text{Sr}$ spike was used in isotope dilution. Rb and Sr were separated from solutions for isotopic analysis using chromatographic technique on the columns with Dowex 50 $\times$ 8 cationite, 200–400 mesh. Uncertainty of $^{87}\text{Sr}/^{86}\text{Sr}$ measurements was about $\pm 0.002\%$. Precision of results was controlled by systematic analyses of SRM-987 standard. Uncertainty of final $^{87}\text{Sr}/^{86}\text{Sr}$ values of individual samples was below $\pm 0.003\%$.

DISCUSSION

The Pb isotopic composition of galena from the Nezhadaninsky deposit and the spatially associated Menkeche deposit and Sentyabr occurrence (66 samples in total), as well as of K-feldspar from some igneous rocks (9 samples) from the Tyry–Dyby ore cluster are presented in Tables 1 and 2. Table 3 demonstrates the results of Rb–Sr study of scheelite and carbonates

Table 1. Lead isotopic composition of galena from the Nezhdaninsky deposit and silver–base-metal deposit and occurrence in the Tyry–Dyby ore cluster measured with high-precision MC-ICP-MS method

No.	Sample location	Height, masl	Mineral assemblage	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
<i>Ore zone 1</i>						
1	Dug hole 22	1450	Galena + freibergite + pyrrargyrite + stephanite	18.3797	15.5711	38.4938
2	"19	1420	Galena + sphalerite + bournonite	18.4427	15.5787	38.5528
3	Ad. 6a, in. 5	1300	Galena + tetrahedrite	18.4585	15.5839	38.5920
4	"	1300	Galena + sphalerite + bournonite	18.4466	15.5835	38.5637
5	Ad. 5, in. 1	1200	Galena + sphalerite + freibergite	18.4212	15.5807	38.5843
6	"	1200	Galena + freibergite + pyrrargyrite	18.4191	15.5772	38.5825
7	Ad. 5, in. 19	1200	Galena + sphalerite + freibergite + pyrrargyrite	18.4184	15.5798	38.5779
8	Ad. 3, in. 2	900	Galena + Fe-sphalerite	18.4577	15.5837	38.5876
9	Ad. 2, in. 18	800	Galena + Fe-sphalerite + bournonite	18.4647	15.5843	38.5914
10	Ad. 1, dr. 2, in. 1	700	Galena + Fe-sphalerite + tetrahedrite	18.4783	15.5822	38.5919
11	Ad. 1, dr. 2, in. 13	700	Galena + Fe-sphalerite	18.4649	15.5834	38.5883
12	Ad. 1, in. 26	700	Galena + sphalerite	18.4531	15.5824	38.5857
13	Ad. 1, in. 34	700	Galena	18.4997	15.5899	38.6491
14	Ad. 1, in. 39	700	Galena + Fe-sphalerite	18.4598	15.5839	38.5768
15	Ad. 1, in. 41	700	Galena + freibergite	18.4368	15.5779	38.5263
16	Ad. 1, in. 51	700	Galena + sphalerite	18.4582	15.5816	38.6017
17	Ad. 1, in. 66	700	Galena + sphalerite + tetrahedrite	18.4282	15.5802	38.5729
18	Sh. 3, dr. 5, in. 7	600	Galena + sphalerite + bournonite	18.4402	15.5794	38.5459
19	Hole 409, 168 m	300	Galena	18.5026	15.5876	38.6230
20	Hole 250, 950 m	0	Galena + Fe-sphalerite	18.4553	15.5799	38.5851
21	Hole 644, 1037 m	–100	Galena + Fe-sphalerite	18.4834	15.5884	38.6169
<i>Ore zone 8</i>						
22	Ad. 28, in. 389, fc. 2	900	Galena + bournonite	18.4439	15.5811	38.5607
23	Ad. 28, in. 389, fc. 13	900	Galena + sphalerite + freibergite	18.4393	15.5801	38.5451
24	Ad. 28, in. 6	800	Galena	18.4624	15.5842	38.5831
25	Ad. 28, in. 11	800	Galena + bournonite	18.4835	15.5855	38.6350
26	Ad. 28, in. 21	800	Galena + bournonite	18.4841	15.5872	38.6360
27	Ad. 28, in. 39	800	Galena + Fe-sphalerite	18.4724	15.5828	38.5717
28	Ad. 28, in. 94	800	Galena	18.4689	15.5860	38.5891
29	Ad. 26	700	Galena + sphalerite	18.4514	15.5853	38.5750
30	Ad. 26, in. 30	700	Galena + Fe-sphalerite	18.4789	15.5903	38.6366
31	Hole 155, 270 m	450	Galena + sphalerite + tetrahedrite	18.4447	15.5800	38.5451
32	Hole 411, 633 m	400	Galena	18.4549	15.5871	38.6133
33	Sh. 3, dr. 5, in. 7	600	Galena + tetrahedrite + bournonite	18.4654	15.5899	38.6002
34	Sh. 3, dr. 7, in. 15	600	Galena + sphalerite + bournonite	18.4516	15.5875	38.5952
35	"	600	Galena + tetrahedrite	18.4459	15.5838	38.5833
<i>Ore zone 21</i>						
36	Ad. 8, dr. 2, rs. 1	800	Galena + tetrahedrite + bournonite	18.4539	15.5831	38.5685
37	"	800	Galena + Fe-sphalerite + bournonite	18.4749	15.5856	38.6011
<i>Ore zone 32</i>						
38	Hole 158, 101 m	980	Galena + tetrahedrite + bournonite	18.5339	15.5957	38.7028

Table 1. (Contd.)

No.	Sample location	Height, masl	Mineral assemblage	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
<i>Ore zone 55</i>						
39	Trench 927	600	Galena + freibergite + pyrrargyrite	18.4337	15.5764	38.5290
<i>Ore zone 56</i>						
40	Trench 1110	980	Galena + freibergite + miargyrite	18.4188	15.5705	38.4928
41	Ad. 412, in. 1	820	Galena + tetrahedrite + bournonite	18.4421	15.5761	38.5415
42	Ad. 31, in. 4	720	Galena + sphalerite	18.4508	15.5775	38.5534
43	Ad. 31, in. 6	720	Galena + Fe-sphalerite	18.5320	15.5977	38.7000
45	" in. 10	720	Galena + Fe-sphalerite	18.5269	15.5945	38.6901
46	" in. 11	720	Galena + sphalerite + Ag-tetrahedrite	18.4424	15.5789	38.5615
47	" in. 13	720	Galena + Fe-sphalerite + bournonite	18.5192	15.5941	38.6760
48	Ad. 29, dr. 6	620	Galena + tetrahedrite + bournonite	18.5264	15.5943	38.6859
49	" in. 26	620	Galena + freibergite	18.4466	15.5818	38.5561
50	" dr. 3, in. 4	620	Galena + freibergite + miargyrite	18.4354	15.5776	38.5171
51	" dr. 6, in. 20	620	Galena + tetrahedrite + bournonite	18.5156	15.5942	38.6817
52	Hole 547A, 290 m	550	Galena + pyrrargyrite + miargyrite	18.4134	15.5731	38.4774
<i>Ore zone 59</i>						
53	Trench 721	600	Galena + freibergite + pyrrargyrite	18.4051	15.5702	38.4689
<i>Ore zone 60</i>						
54	Trench 722	600	"	18.4267	15.5718	38.4955
55	Trench 726	600	"	18.4045	15.5695	38.4630
56	In. 732	600	"	18.4046	15.5676	38.4553
<i>Ore zone 76</i>						
57	Ad. 17, in. 7	1100	Galena + sphalerite + tetrahedrite	18.5006	15.5903	38.6447
58	Ad. 376, in. 22	1000	Galena + tetrahedrite + bournonite	18.4675	15.5822	38.5808
59	Ad. 22, in. 11	800	"	18.4747	15.5851	38.5945
60	Ad. 22, dr. 4, in. 3	800	Galena + Fe-sphalerite + bournonite	18.4942	15.5856	38.6003
61	Ad. 16, dr. 6, in. 2	700	Galena + sphalerite + bournonite	18.4481	15.5825	38.5772
62	Hole no. 299, 253 m	300	Galena + Fe-sphalerite + bournonite	18.4704	15.5887	38.6186
<i>Menkeche deposit</i>						
63	Orebody 2-5		Galena + freibergite	18.1827	15.5402	38.3010
64	"		Galena + freibergite + pyrrargyrite	18.2214	15.5422	38.3587
65	"		Galena + freibergite + pyrrargyrite + stephanite	18.1971	15.5421	38.3205
<i>Sentyabr occurrence</i>						
66	Wall of the Sentyabr Cr.	650	Galena + sphalerite + chalcopryrite + freibergite	18.3398	15.5597	38.3498

Notes: According to the measuring program, an error of average result ($\pm 2\text{SE}$) reflecting intrinsic (in the given analysis) convergence of mea-

surements was calculated; $2\text{SE} = 2 \sqrt{\frac{\sum (x_j - \bar{x})^2}{n(n-1)}}$, x_j and $\bar{x}$ are individual and average values of isotopic ratios in analysis; n is number

of measurements (mass spectra). In all analyses, $\pm 2\text{SE}$ value for the presented $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios did not exceed ± 0.0037 , ± 0.0032 , and ± 0.0078 , respectively (absolute units); i.e., $\pm 2\text{SE}$ was lower than $\pm 0.02\%$. This limit is accepted as an estimate of the total uncertainty of isotopic analysis of Pb in galena and corresponds to the level of independently estimated uncertainty of long-term reproducibility of independent parallel analyses $\pm 2\text{SD}$. The accepted abbreviations: Ad., adit; in., inset; dr., drift; Sh., shaft; Hole, borehole; fc., face; rs., raise.

Table 2. Lead isotopic composition of K-feldspar from igneous rocks of the Tyry–Dyby ore cluster measured with high-precision MC-ICP-MS method

No.	Sample	Sample location	Rock	Total Pb content, µg/g	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
1	1266 BB-89	Kurum pluton, central part	Granite	49.3	18.2754	15.5257	38.4268
2	1266 1BB-89	Kurum pluton, vein in granite	Aplite	50.0	18.2998	15.5264	38.4244
3	1267 B-89	Kurum pluton, main phase	Granodiorite	45.5	18.2614	15.5219	38.4024
4	1267 1B-89	Kurum pluton, dike in contact zone	Aplite-like granite	13.4	18.2355	15.5239	38.2971
5	1274 B-89	Gel'dy stock, main phase	Quartz diorite	15.0	18.3119	15.5272	38.3248
6	1279 2B-89	Dyby pluton, main phase	Granodiorite	46.1	18.1652	15.5330	38.5088
7	1300 B-91	Yaman stock, main phase	Quartz diorite	37.6	18.3906	15.5430	38.4474
8	1307 B-89	Sup pluton, main phase	Quartz monzodiorite	75.3	18.3927	15.5322	38.4664
9	1321 B-92	Vetka pluton, main phase	Granodiorite	29.9	18.4141	15.5586	38.5118

Note: As for the analysis of Pb isotopic composition of galena (Table 1), errors $\pm 2\text{SE}$ were calculated for individual Pb analyses of K-feldspar. For isotopic ratios $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratio, they ranged from ± 0.005 to $\pm 0.02\%$ and did not exceed $\pm 0.03\%$ in all cases. This value corresponds to the $\pm 2\text{SD}$ uncertainty of long-term reproducibility independent parallel analyses of lead extracted from rocks and was accepted as an estimate of the total uncertainty of isotopic analysis of Pb in the studied K-feldspars.

from the Nezhdaninsky deposit, including their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios.

Lead Isotopic Composition of the Nezhdaninsky Deposit and Silver–Base-Metal Deposit and Occurrence in the Tyry–Dyby Ore Cluster

Consider the Pb/Pb data on galena from the Nezhdaninsky deposit (Table 1). Sixty-two galena samples were analyzed from nine ore zones, including the most extended zone 1, the largest in gold reserves. The detailed Pb/Pb data characterizing different ore zones of the large deposit in combination with high-precision measurements allowed us to estimate the real range of variable Pb isotopic composition, to point out a difference in Pb/Pb isotopic parameters characteristic of separate ore zones and to assess spatial distribution of isotopic Pb composition of ore.

The variations in Pb isotope ratios at the deposit as a whole are as follows: $^{206}\text{Pb}/^{204}\text{Pb} = 18.3797\text{--}18.5339$ (0.8%), $^{207}\text{Pb}/^{204}\text{Pb} = 15.5676\text{--}15.5977$ (0.2%), and $^{208}\text{Pb}/^{204}\text{Pb} = 38.4553\text{--}38.7028$ (0.6%). The variation of Pb/Pb data recently obtained with MC-ICP-MS for the Sukhoi Log and Chertovo Koryto gold deposits (Chernyshev et al., 2009; Chugaev et al, 2010a) are 3–5 times wider. Thus, variations of Pb isotopic composition at the Nezhdaninsky deposit are generally not great. On the one hand, this indicates geochemical (U, Th, Pb) similarity in sources of ore-forming solutions, and on the other hand, specific conditions of the ore-forming system evolution, which made it possible to reach a sufficiently high averaging of Pb isotopic composition of solutions. It should be noted that in contrast to the hydrothermal–metamorphic Sukhoi Log deposit, which does not show a direct link to mag-

matic bodies, the Nezhdaninsky deposit, as inferred (Gamyanin, Bortnikov, and Alpatov, 2000; Bortnikov et al., 2007), was formed as a result of the functioning of the ore-magmatic system.

The available data on the Nezhdaninsky deposit allowed us to estimate variations in Pb isotopic composition within particular ore zones. The most representative data have been obtained for ore zone 1 (21 samples), 8 (14 samples), 56 (13 samples), and 76 (6 samples). The analyzed galena samples cover significant vertical intervals of gold mineralization: in zone 1 the interval of sampling is 1550 m; in zone 8, 500 m; in zone 76, 800 m; and in zone 56, 430 m. Owing to minor analytical uncertainty of the MC-ICP-MS method ($\pm 0.02\%$), geochemically significant variations in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios can be detected. As was proposed by Gulson (1986), these variations are expressed in values of standard deviation scattering (σ , %) of isotopic ratios for individual samples (Table 4). They are the most appreciable for the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio: in ore zones 1, 8, 56, and 76, the σ value varies from 0.08 to 0.26% and thus is 4–10 times greater than possible analytical uncertainty. For the $^{208}\text{Pb}/^{204}\text{Pb}$ ratio, the range of variations is somewhat narrower (0.07–0.22%); for the $^{207}\text{Pb}/^{204}\text{Pb}$ ratio, it is minimal and corresponds to the analytical uncertainty in ore zones 1, 8, and 76. Only in zone 56, when galena is characterized by maximal variations in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, the σ value for $^{207}\text{Pb}/^{204}\text{Pb}$ attains 0.06%.

Comparison of the average Pb isotopic ratios in different ore zones allows us to estimate the degree of homogeneity in the distribution of Pb isotopic composition throughout the Nezhdaninsky deposit (Table 4). Comparison of ore zones 1, 8, 56, and 76, which are

Table 3. Rb–Sr isotopic characteristics of scheelite and carbonates from ore zones of the Nezhdaninsky deposit

No.	Sample	Sample location	Rb, µg/g	Sr, µg/g	$^{87}\text{Rb}/^{86}\text{Sr}, \pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}, \pm 2\sigma$
<i>Scheelite from ore zone 1</i>						
1	2/28-1	Level +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
<i>Metamorphic carbonate (preore stage)</i>						
7	5L-G-9		0.55	11740	0.0001 ± 2	0.711268 ± 15
8	AD-392-8		0.78	2400	0.0009 ± 1	0.708117 ± 15
<i>Hydrothermal metasomatic carbonate (ore stage)</i>						
9	13-709	Ore zone 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 2	1.1	53	0.061 ± 6	0.713276 ± 15
14	860-147	"	6.4	3600	0.006 ± 1	0.713412 ± 15
15	159-128	Ore zone 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 56	0.9	506	0.005 ± 8	0.712994 ± 30
18	296-135	Ore zone 76	6.2	3870	0.005 ± 1	0.713259 ± 15
<i>Regenerated carbonate (postore stage)</i>						
19	AD-27 reg 3	Ore zone 1	0.4	1810	0.001 ± 1	0.713668 ± 15
20	AD-8 reg 6	Ore zone 8	25	3100	0.023 ± 1	0.712818 ± 15
21	165-350	Ore zone 32	0.03	17	0.01 ± 1	0.713537 ± 14
22	159-208	Ore zone 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	AD-16	Ore zone 76	0.05	2470	0.0001 ± 1	0.713278 ± 15

Note: Uncertainties are related to the last significant figures.

characterized by the greatest number of analyses, is especially indicative. As follows from the σ values mentioned above, the $^{207}\text{Pb}/^{204}\text{Pb}$ ratio, being the most homogeneous within particular ore zones, is almost the same in all four zones: 15.582 (zone 1), 15.585 (zone 8), 15.585 (zone 56), and 15.586 (zone 76). The average $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios differ from one zone to another more conspicuous, however, this difference also lies within the limits of statistical scattering estimated as $2\sigma_{\text{aver}}$.

The correlation between Pb isotopic composition and depth of sampling within the ore zones is not detected or remains very weak: in almost all ore zones,

correlation coefficient (R^2) does not exceed 0.2. Only in ore zone 1, a weak negative correlation of $^{206}\text{Pb}/^{204}\text{Pb}$ versus depth is established (Fig. 2); $R^2 = 0.4$.

Against the background of small variations in Pb isotopic composition, the following tendency is clearly seen for particular ore zones and the Nezhdaninsky deposit as a whole: galena in association with silver minerals (pyrargyrite, freibergite, stephanite, miargyrite) shows the lowest (least radiogenic) isotope ratios for the given ore zone (Table 1). In ore zone 1, this is established in samples 1, 5–7, 15; in ore zone 8, in sample 23; in ore zone 56, in samples 40, 49, 50, and 52. This tendency is expressed not only in variation of

Table 4. Average values and variations of Pb isotopic composition of galena in ore zones of the Nezhdaninsky deposit

Ore zone	Number of samples	$^{206}\text{Pb}/^{204}\text{Pb}$, $\pm 2\sigma_{\text{aver}}$	$^{207}\text{Pb}/^{204}\text{Pb}$, $\pm 2\sigma_{\text{aver}}$	$^{208}\text{Pb}/^{204}\text{Pb}$, $\pm 2\sigma_{\text{aver}}$
1	21	18.451 ± 0.013 $\sigma = 0.15\%$	15.582 ± 0.002 $\sigma = 0.03\%$	38.579 ± 0.014 $\sigma = 0.09\%$
8	14	18.461 ± 0.008 $\sigma = 0.08\%$	15.585 ± 0.002 $\sigma = 0.02\%$	38.591 ± 0.017 $\sigma = 0.08\%$
56	13	18.477 ± 0.026 $\sigma = 0.26\%$	15.585 ± 0.006 $\sigma = 0.06\%$	38.602 ± 0.048 $\sigma = 0.22\%$
76	6	18.476 ± 0.016 $\sigma = 0.10\%$	15.586 ± 0.003 $\sigma = 0.02\%$	38.603 ± 0.021 $\sigma = 0.07\%$

Note: The calculated confidence interval $\pm 2\sigma_{\text{aver}}$ —double standard deviation of average value is indicated for average Pb isotope ratios; σ is the standard deviation, % of single value.

$^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 3), but also of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, though not so contrastingly. Ore zones 55, 59, and 60 are characterized by five galena samples in association with pyrargyrite and freibergite. Lead in galena of all these zones is the least radiogenic in comparison with galena of gold–sulfide assemblage represented by samples from zones 1, 8, 21, 32, 56, and 76.

The relationship between Pb isotopic composition of galena and type of mineral assemblage determines ver-

tical zoning of $^{206}\text{Pb}/^{204}\text{Pb}$ ratio in ore zone 1 (Fig. 2). The increase in $^{206}\text{Pb}/^{204}\text{Pb}$ value with depth is mainly determined by the data points in the upper left part of the plot, which correspond to the galena samples from the Ag-bearing mineral assemblage.

Thus, two generations of galena distinctly differing in Pb isotopic composition occur at the Nezhdaninsky deposit (Table 5). In our collection of samples, as at the deposit as a whole, galena from gold–sulfide association dominates. Therefore, the main mass of lead at

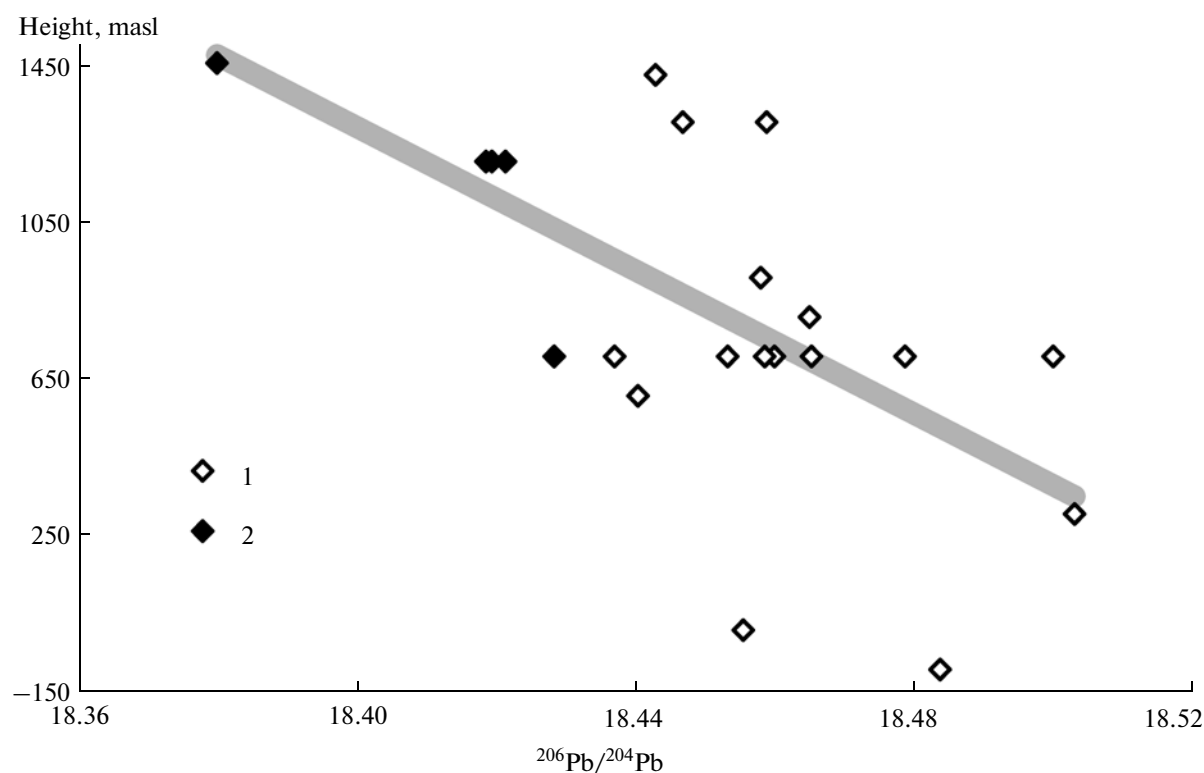


Fig. 2. Distribution of $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of galena in the vertical section of ore zone 1 at the Nezhdaninsky deposit. (1) Gold–sulfide and (2) silver–base-metal assemblages. Linear trend of Pb isotopic composition is gray.

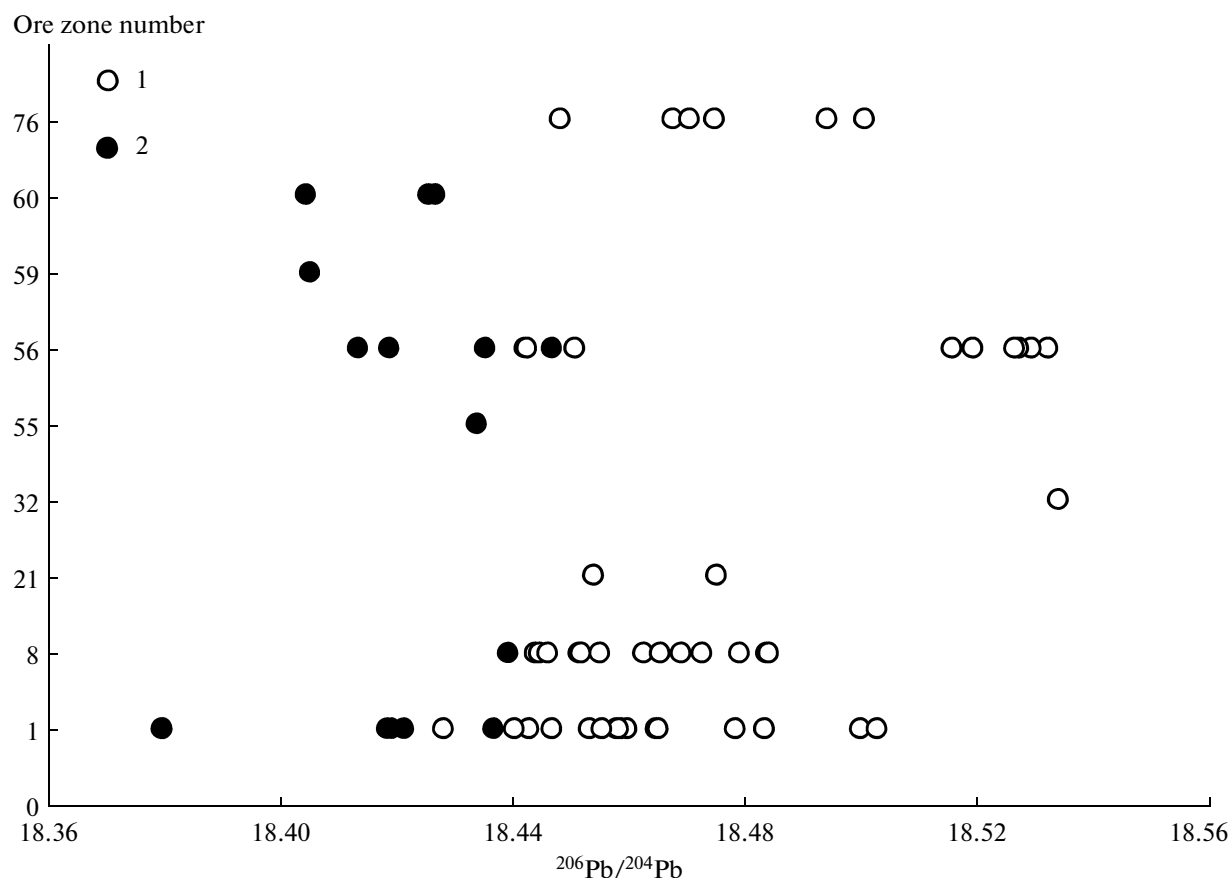


Fig. 3. Distribution of $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of galena from (1) gold-sulfide and (2) silver-base-metal assemblages in ore zones of the Nezhdaninsky deposit.

the deposit is characterized by average $^{206}\text{Pb}/^{204}\text{Pb} = 18.472$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.586$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.605$. Galena associated with Ag-bearing minerals enters into the regenerated or newly formed silver-base-metal assemblage and is characterized less radiogenic lead isotopic composition in all three isotope ratios: $^{206}\text{Pb}/^{204}\text{Pb} = 18.420$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.575$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.518$. According to Gamyagin, Bortnikov, and Alpatov (2000), this regenerated mineral assemblage is superimposed on the earlier gold-bearing assemblages. The formation of regenerated assemblage was accompanied by recrystallization of gangue and ore minerals, including galena, and quite probably, by gain of ore matter and lead in particular. The aforesaid gives grounds to suggest that at least two different sources of ore matter participated in the formation of the Nezhdaninsky deposit, so that Pb isotopic composition of galena is, in general case, a two-component mixture. The average Pb isotope ratios in galena from different mineral assemblages formed with a lag in time are not end members of such a mixture, but taken together, demonstrate a minimal difference in the Pb isotopic composition of two distinct sources.

Galena from the Menkeche silver-base-metal deposit and Sentyabr occurrence of the same type in the Tyry-Dyby ore cluster show even lower $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios than galena from the silver-base-metal assemblage of the Nezhdaninsky deposit. Moreover, lead in galena from the Menkeche deposit (Table 1) is distinguished by the lowest contents of ^{206}Pb and ^{207}Pb .

The data points of 62 galena samples from the Nezhdaninsky deposit make up linear trends in both plots (Figs. 4a, 4b). The points of Pb isotopic composition pertaining to the silver-base-metal mineral assemblage are localized in the lower segments of these trends. In coordinates $^{206}\text{Pb}/^{204}\text{Pb}$ — $^{207}\text{Pb}/^{204}\text{Pb}$, the data points of Pb isotopic composition characterizing four galena samples from the Menkeche deposit and Sentyabr occurrence lie at the lower continuation of the trend (Fig. 4b). At the same time, only one point related to the Sentyabr occurrence is aligned with trend of the Nezhdaninsky deposit in coordinates $^{208}\text{Pb}/^{204}\text{Pb}$ — $^{207}\text{Pb}/^{204}\text{Pb}$, whereas the data points of the Pb isotopic composition of galena from the Menkeche deposit are shifted upward along the $^{208}\text{Pb}/^{204}\text{Pb}$ axis, due to the higher Th/U ratio in the Pb source of

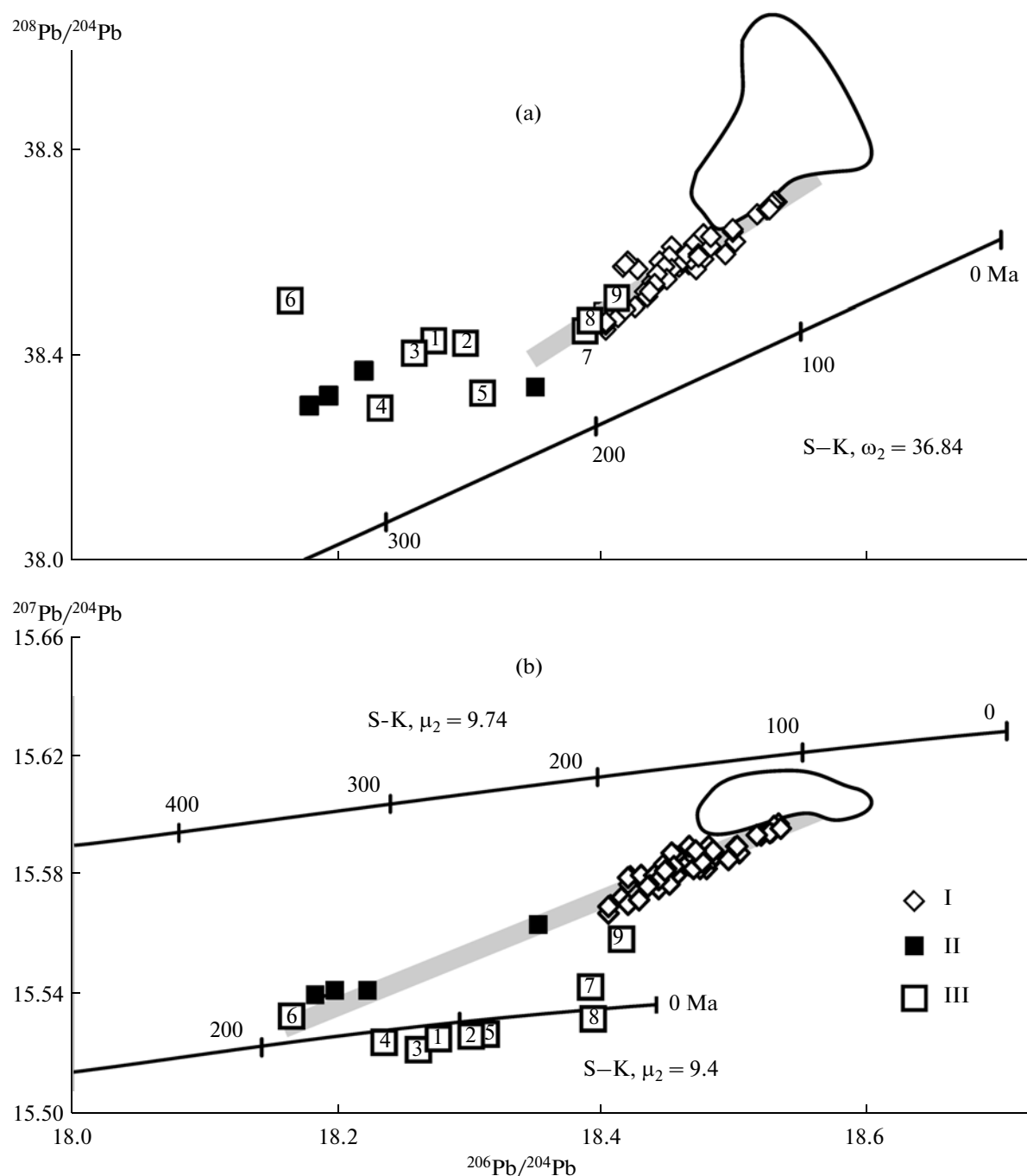


Fig. 4. Lead isotope ratios plotted on the Pb/Pb diagrams. (I) Galena from ore zones of the Nezhdaninsky deposit, (II) galena from silver–base-metal Menkeche deposit and Sentyabr occurrence, (III) K-feldspar from intrusive rocks of the Kurum pluton: 1, granite; 2, aplite; 3, granodiorite; 4, aplite-like granite; Gel'dy stock: 5, quartz diorite; Dyby pluton: 6, granodiorite; Yaman stock, 7, quartz diorite; Sup pluton: 8, quartz monzodiorite; Vetka pluton: 9, granodiorite. Numbers in boxes designate numbers in Table 2. Solid evolutionary lines of the Stacey–Kramers model (S–K) are shown, as well as contours of the fields of Pb isotope ratios in hydrothermal–metamorphic gold deposits of the Verkhoyansk Foldbelt and linear trends of Pb isotopic compositions (gray).

the Menkeche deposit in comparison with the Pb source of the Nezhdaninsky deposit.

A narrow range of the calculated parameter $\mu_2 = ^{238}\text{U}/^{204}\text{Pb}$ and model Pb/Pb age (t_m) attracts attention. In coordinates $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 4b),

the data points of Pb isotopic compositions are located below the mean evolutionary curve of the Stacey–Kramers model ($\mu_2 = 9.74$). For the overwhelming majority of galena samples from the Nezhdaninsky deposit, μ_2 values are within a range of 9.5–9.6. The

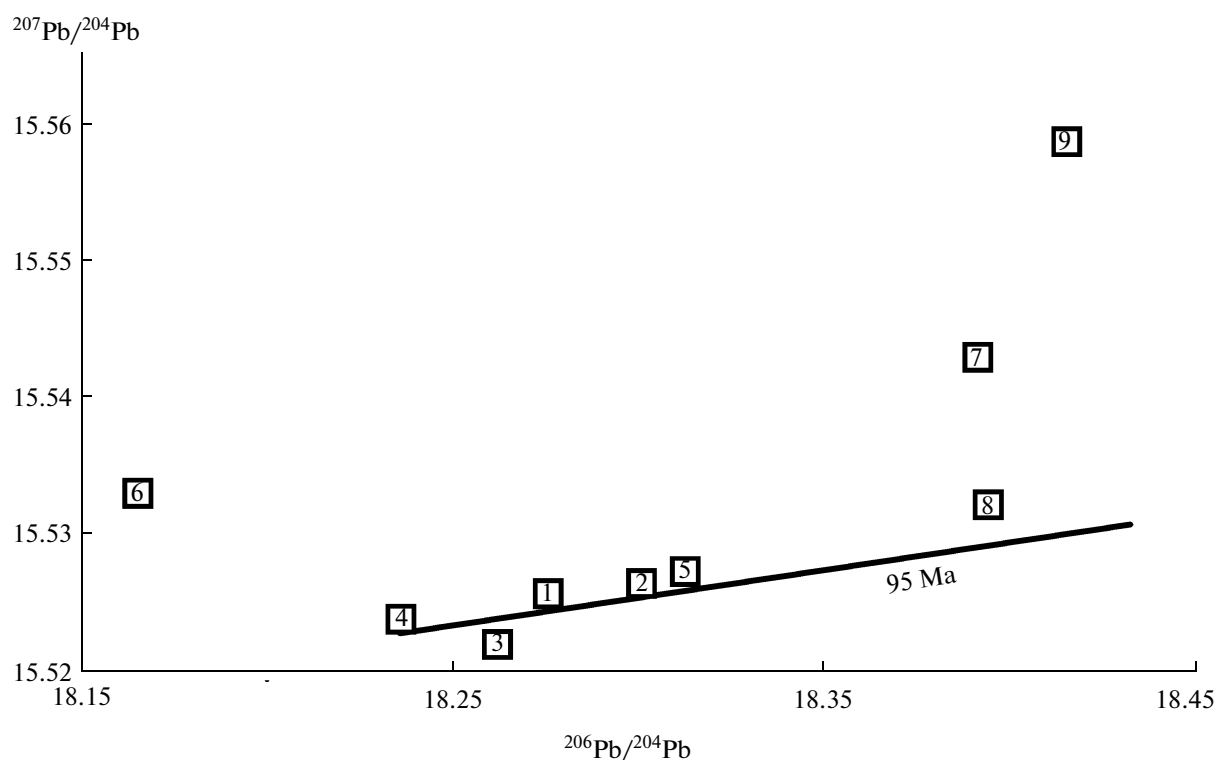


Fig. 5. Data points of Pb isotopic composition of K-feldspar from igneous rocks in the Tyry–Dyby ore cluster plotted on the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram. Point numbers correspond to sample numbers in Table 2 and Fig. 4.

model age t_m of lead is consistent with the true age of ore formation. Note that owing to the application of high-precision MC-ICP-MS method of analysis of Pb isotopic composition, the analytical uncertainty of t_m calculation is only $\pm 4 \text{ Ma}$ ². The t_m values for lead of the Nezhdaninsky deposit ranges from 122 to 57 Ma. The maximal values (122–111 Ma) are close to the age of mineralization at the Nezhdaninsky deposit dated with Rb–Sr method for gangue quartz (Chugaev et al., 2010b) and K–Ar method for sericite of metasomatic rock ($119 \pm 4 \text{ Ma}$) (data obtained at the SVKNII). The μ_2 and t_m values show that a source of lode lead that operated during the formation of the Nezhdaninsky deposit had a moderate U/Pb ratio characteristic of the terrigenous rocks in the zone of ocean–continent transition, which containing material of oceanic crust with a short residence time.

Lead Isotopic Composition of Igneous Rocks

To identify a possible magmatic source of lead in the Nezhdaninsky deposit, it is necessary to take into account the Pb isotopic composition of intrusive rocks

localized in the Tyry–Dyby ore cluster (Kurum pluton in its northern part, Gel'dy and Yaman stocks and Vetka intrusion in its southern part), as well as of the Dyby and Sup plutons localized in the South Verkhoyansk Tectonic Zone to the north of the Kurum Pluton (Table 2). Monomineralic fractions of K-feldspar have been picked out for isotopic analysis. The Lower Cretaceous age has been determined with confidence only for the Dyby pluton (Layer et al., 2001). As was mentioned above, the Kurum pluton, stocks of the Gel'dy group, and the Sup pluton were formed in the Late Cretaceous. The K–Ar age of the Yaman stock is 101–96 Ma (Gamyranin et al., 2003).

The Pb isotopic compositions of K-feldspar from intrusive rocks are plotted on the Pb/Pb diagrams together with the data obtained for galena (Figs. 4a, 4b). The ranges of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios (~ 1.4 , ~ 0.3 , and $\sim 0.5\%$) are close to those of Pb in ore of the Nezhdaninsky deposit. A small percentage of the observed variations (only with respect to $^{206}\text{Pb}/^{204}\text{Pb}$) can be referred to the radiogenic Pb gained in K-feldspar over $\sim 100 \text{ Ma}$ elapsed after rock crystallization. This possibility is confirmed by a short trend of data points of Pb isotopic composition of K-feldspar from the Kurum pluton and Gel'dy stocks (Fig. 5). The slope of this trend is close to that of the isochron corresponding to 95 Ma. K-feldspars from other intrusive rocks of the Tyry–Dyby ore cluster differ appreciably from the feldspar of the Kurum

² Because of this, when lead from young deposits is measured using MC-ICP-MS, the calculated model age of lode lead t_m becomes a self-dependent geochemical parameter. Analytical uncertainty of t_m calculated using traditional TIMS method is $\pm 35 \text{ Ma}$.

pluton and Gel'dy stocks in all three Pb isotopic ratios. The variations of Pb isotopic compositions of the studied intrusive rocks provide evidence for isotopic heterogeneity and thus compositionally contrasting quartz diorite–granodiorite magma sources. In comparison with lead in the Nezhdaninsky deposit and silver–base-metal Menkeche deposit and Sentyabr occurrence, the Pb of intrusive rocks is less radiogenic as concerns ^{206}Pb , ^{207}Pb , and ^{208}Pb , and the corresponding data points plotted on Pb/Pb diagrams lie below the overwhelming majority of Pb data points of galena.

It should be noted that the Pb data point of K-feldspar from the Early Cretaceous Dyby pluton falls on the aforementioned trend of Pb isotopic composition of galena from the Nezhdaninsky deposit and from silver–base-metal ore from the Menkeche deposit and Sentyabr occurrence (Fig. 4b). The data points of Pb isotopic composition from other Late Cretaceous intrusive rocks lie beyond this trend. Lead from the Kurum pluton and the Gel'dy stocks is distinguished by the lowest $^{207}\text{Pb}/^{204}\text{Pb}$ ratio among other rocks and ores of the Tyry–Dyby ore cluster.

The isotopic age of granodiorite and quartz diorite of the Kurum pluton and the Gel'dy stocks, respectively, is approximately 25 Ma younger than the Nezhdaninsky deposit and thus did not participate in the formation of ore-generating system of this deposit, as all other Late Cretaceous igneous rocks. This statement is in agreement with substantial difference in the Pb isotopic composition between ore and Late Cretaceous intrusive rocks, restricting the role of the later as sources of lead at the Nezhdaninsky deposit.

As concerns the Early Cretaceous igneous rocks in the Tyry–Dyby ore cluster, which are presented in the studied collection of samples by granodiorite of the Dyby pluton, then lead from these rocks drastically differs from lead of the Late Cretaceous rocks. Furthermore, localization of the data point of lead from the Dyby granodiorite at the continuation of the linear trend of lead from the Nezhdaninsky deposit (Fig. 4b) gives grounds to suggest that the Early Cretaceous magma chamber was a source of the lead, which participated in the formation of the Nezhdaninsky deposit. The isotopic composition of this lead corresponds to the least radiogenic end member of mixing in ^{206}Pb and ^{207}Pb contents.

Assuming that the linear trend in coordinates $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ is a mixing line (Fig. 4b), it may be concluded that lead from the Menkeche silver–base-metal deposit consists largely of lead from the magmatic source, which also makes an appreciable contribution to the balance of Pb isotopic composition in galena from the Sentyabr occurrence and the silver–base-metal assemblage at the Nezhdaninsky deposit.

Sr Isotopic Composition of Rocks and Minerals at the Nezhdaninsky Deposit

To ascertain a source of gold mineralization at the Nezhdaninsky deposit, the comparison of initial Sr isotopic composition of hydrothermal minerals and intrusive rocks of the Kurum pluton and the Gel'dy stocks is important (Table 3).

The Rb–Sr study of carbonates and scheelite from various ore zones of the Nezhdaninsky deposit has shown that because of widely variable but always low Rb contents and high Sr contents in these minerals, the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of these minerals varies from 0.0001 to 0.6 in carbonates and from 0.0001 to 0.0003 in scheelite (Chugaev et al., 2006). At such a low $^{87}\text{Rb}/^{86}\text{Sr}$ value, the variation of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of carbonate and scheelite owing to the gain of radiogenic ^{87}Sr over 130 Ma is wittingly lower than 0.00001 and is close to the analytical uncertainty. Thus, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios measured in carbonates and scheelite actually remained initial in these minerals and in the hydrothermal fluid. In carbonates from ore zones 1, 2, 8, 32, 56, and 76 (17 samples), the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio varies within a narrow range of 0.7128 to 0.7137. The Sr isotopic composition of scheelite from ore zone 1 (6 samples) is as homogeneous as of carbonates and ranges from 0.7123 to 0.7139.

Much lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios close to 0.707 are characteristic of intrusive rocks in the Tyry–Dyby ore cluster (Gamyanin, Bortnikov and Alpatov, 2000). According to our specified data, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ values are 0.7067 ± 2 , and 0.70637 ± 3 of granitic rocks of the Kurum pluton, quartz diorite of the Gel'dy stock, and malchite-type lamprophyre dike, respectively. These values rule out these igneous rocks as a single source of gold mineralization at the Nezhdaninsky deposit.

Returning to the subject of the Permian terrigenous rocks of the Nezhdaninsky ore field as a possible source of Sr and other components contained in the hydrothermal fluid, in the framework of this study, we failed to obtain Rb–Sr isotopic characteristics of the terrigenous rocks, which would allow estimation of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio at the moment of ore formation. The results of direct measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of pre-ore metamorphic carbonates indicate, however, a $^{87}\text{Sr}/^{86}\text{Sr}$ value in the Lower Permian host terrigenous rocks at the moment of their metamorphism (Table 3). This value is within a range of 0.708–0.711 and thus much closer to the Sr isotope ratio in the ore-forming fluid. It must be remembered that over the time span that separated regional metamorphism and ore deposition, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in the host metamorphic rocks should increase due to the gain of radiogenic ^{87}Sr . Thus, the host and underlying Permian terrigenous rocks were a preferred source of Sr in gold mineralization of the Nezhdaninsky deposit. Inhomogeneous Sr isotopic composition of fluid apparently was caused by initial variations in Rb/Sr ratio of these

Table 5. Average Pb isotopic compositions of galena from two mineral assemblages at the Nezhdaninsky deposit

Mineral assemblage	Number of samples	$^{206}\text{Pb}/^{204}\text{Pb}$ $\pm 2\sigma_{\text{aver}}$	$^{207}\text{Pb}/^{204}\text{Pb}$ $\pm 2\sigma_{\text{aver}}$	$^{208}\text{Pb}/^{204}\text{Pb}$ $\pm 2\sigma_{\text{aver}}$
Gold–sulfide	47	18.472 ± 0.008	15.586 ± 0.002	38.605 ± 0.013
Silver–base-metal	15	18.420 ± 0.009	15.575 ± 0.002	38.518 ± 0.023

Note: $\pm 2\sigma_{\text{aver}}$ is the double standard deviation of average value.

rocks. In general, this conclusion is consistent with the available information on supply of Sr from underlying rocks to the orogenic gold ore-forming systems (Ridley and Diamond, 2000).

ORE MATTER SOURCES OF THE NEZHDANINSKY DEPOSIT

The data on Pb isotopic composition of 62 galena samples taken from the main ore zones of the Nezhdaninsky deposit extending for ~5 km in the horizontal direction and for 1500 m in the vertical direction allow us to draw a conclusion that lead in the Nezhdaninsky deposit is a mixture of two components derived from different sources.

The Pb and Sr isotopic compositions and the results of isotopic dating definitely show that the Late Cretaceous magma chamber and granitoid rocks did not participate in the formation of the Nezhdaninsky deposit. At the same time, the difference between Early and Late Cretaceous granitoid intrusions in Pb/Pb isotopic characteristic and compatibility of the former with the regional trend of Pb isotopic composition in coordinates $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ (Fig. 4b) suggest that lead from a magmatic source was involved into the Nezhdaninsky ore-forming system. In this connection, the origin of the Early Cretaceous granitoids attracts attention.

According to the tectonic model of evolution of the South Verkhoyansk Foldbelt and the Okhotsk Terrane elaborated by L.M. Parfenov and A.V. Prokopyev (Gamyanin, Bortnikov, and Alpatov, 2000; Prokopyev et al., 2009), granitoid batholiths were emplaced in the late Neocomian 129–123 Ma ago in the Allakh-Yun Zone of the South Verkhoyansk region after termination of metamorphism and deformation proceeded in the Early Cretaceous. The plutonic activity resumed here in the Cenomanian 95–91 Ma ago. Magma formation was related to the subduction of the Okhotsk Terrane beneath the North Asian continent (Fig. 6). On the basis of this model, it can be inferred that the magmatic melts that formed granitoid intrusions in the Early and Late Cretaceous were generated by melting of the lower crust composed of the rocks pertaining to the North Asian Craton.

The evolution of Pb isotopic composition in the lower crust is mostly determined by elemental fractionation in the U–Th–Pb system and corresponding decrease in U/Pb and increase in Th/U ratios in the lower crust relative to the initial mantle material and the upper crust in the process of cratonization (Zartman and Doe, 1981; Wedepohl, 1995; Kramers and Tolstikhin, 1997). The isotopic composition of Pb that resides in the lower crust under conditions of the hindered gain of the isotopes produced by uranium decay differs from Pb of other geochemical reservoirs of the mantle and the crust by lower $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and elevated $^{208}\text{Pb}/^{204}\text{Pb}$ ratio. Their specific numerical values depend on regional factors: parameters of U–Th–Pb system of crustal protoliths, their age, residence time of lead in the lower crust before the moment of its mobilization. From this standpoint, let us again address to the Pb isotopic compositions plotted on the diagrams shown in Figs. 4a and 4b.

As was noted above, lead from all studied intrusive rocks and silver–base-metal Menkeche deposit and Sentyabr occurrence are the least radiogenic in ^{206}Pb and ^{207}Pb contents. The data points of these rocks and ores are widely scattered in Fig. 4b but all of them are close to the line with $\mu_2 = 9.4$ describing evolution of lead in the sources with low U/Pb ratio. The arrangement of data points of Pb isotopic composition in Fig. 4a differs from that in the plot shown in Fig. 4b, because the location and correlation of data points in coordinates $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{208}\text{Pb}/^{204}\text{Pb}$ depend on Th/U ratio in the source of lead. In this case, it is important that the points corresponding to lead in intrusive rocks of the Tyry–Dyby ore cluster and in galena from the Mekenche silver–base-metal deposit are shifted toward elevated $^{208}\text{Pb}/^{204}\text{Pb}$ values, which characterize a source of lead as fractionated and depleted in U relative to Th. The Th/U ratio that corresponds to the mean crustal evolutionary curve in the Stacey–Kramers model is 3.78 (Fig. 4a). The Th/U ratios of a source calculated from the measured Pb isotopic compositions are 4.04 for granitoids of the Dyby pluton, 3.92, for the Mekenche deposit, 3.87–3.92 for granitoids of the Kurum pluton, and 3.84–3.88 for other intrusive rocks of the Tyry–Dyby ore cluster. It also is noteworthy that the lode lead in the Nezhdaninsky deposit has

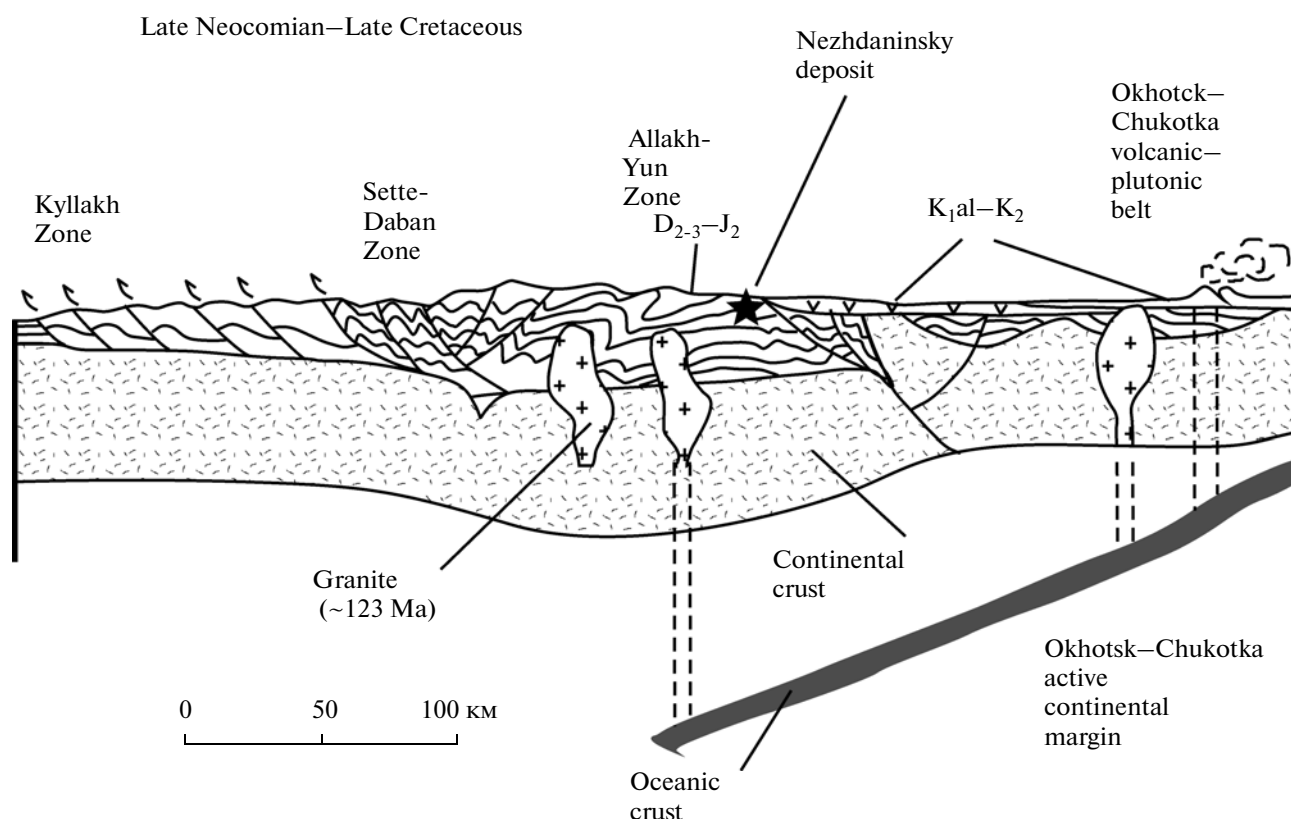


Fig. 6. Tectonic scheme of the South Verkhoyansk Foldbelt and the Okhotsk Terrane, after Prokopyev et al. (2009).

a Th/U ratio of 3.86–3.92, which is higher than the mean crustal value.

Thus, the suggestion of the lower crustal source of intrusive rocks in the Tyry–Dyby ore cluster, including both Early and Late Cretaceous granitoids, and the Allakh-Yun Zone of the South Verkhoyansk region as a whole is supported by the data on Pb isotopes. Judging from the contents of ^{206}Pb and ^{207}Pb , the contribution of the lower crustal magmatic source to the silver–base-metal mineralization on the flanks of the Nezhdaninsky ore field is significant (about 50% to the Sentyabr occurrence) or crucial (to the Menkeche deposit). At the Nezhdaninsky deposit itself, an appreciable role of lower crustal magmatic source is recorded in galena from the silver–base-metal assemblage superimposed on the earlier gold–sulfide mineralization.

The Pb isotopic composition and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio allow us to identify the second component involved in mixing and dominating in galena of gold–sulfide assemblage at the Nezhdaninsky deposit as the lead derived from host terrigenous rocks. The position of Pb isotopic compositions of galena from hydrothermal–metamorphic gold deposits in the southern sector of the South Verkhoyansk Foldbelt in Pb–Pb plots (Figs. 4a, 4b) provides substantial evidence in favor of such interpretation. These are the

Bular, Kuzminichna, Yur, Duet, and Finn deposits and occurrences localized in metasedimentary rocks without spatial relations to magmatic bodies. The averaged Pb isotopic composition of this group of deposits apparently corresponds to the Pb isotopic composition of the Upper Paleozoic terrigenous sequences at the moment of ore formation. The Pb isotopic composition of galena from hydrothermal–metamorphic gold deposits is the most radiogenic (up to the $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ values reaching 18.59, 15.61, and 39.05, respectively) in comparison with lead from the Nezhdaninsky deposit and deposits of other types in the southern sector of the South Verkhoyansk Foldbelt. The data points of Pb isotopic compositions of galena from the above-listed hydrothermal–metamorphic gold deposits are not strictly confined to the trends of the Nezhdaninsky deposit but adjoins their upper ends in both plots (Figs. 4a, 4b).

The lead predominant at the Nezhdaninsky deposit and close in isotopic composition lead of the hydrothermal–metamorphic gold deposits in the South Verkhoyansk Foldbelt correspond in all isotopic attributes (isotopic composition, μ , t_m) to the lead of island-arc igneous rocks (Zartman and Doe, 1981). The retention of such isotopic marks by terrigenous sediments of the Carboniferous–Permian basin at the

Verkhoyansk margin of the North Asian Craton is probably related to the short residence time of the oceanic crustal material in these sediments.

Having accepted two-component model of lead mixing and taking into account the arrangement of data points characterizing Pb isotopic composition of galena from older and younger mineral assemblages of the Nezhdaninsky deposit along the mixing line, a conclusion can be drawn that Pb from magmatic source was supplied to the ore-forming system at the late stage of its evolution. This explains the observed disequilibrium of Pb isotopic compositions of galena within the deposit.

The two-component Pb isotopic composition has been substantiated for the Precambrian (2.64–2.63 Ga) gold deposits of the Yilgarn Craton in southwestern Australia (Qiu and McNaughton, 1999), where lode lead is a mixture of lead from granitoids and greenstone host rocks. The most attractive, however, is comparison of Pb isotopic composition of galena from the Nezhdaninsky deposit with gold deposits of the Lachlan Foldbelt in southeastern Australia (Ho et al., 1995; Bierlein and McNaughton, 1998) characterized by the same geological setting.

The mesothermal gold–sulfide deposits of southeastern Australia are hosted in the Ordovician metasedimentary rocks intruded by granitoids and dikes; some of them are close in age to hydrothermal mineralization, whereas others are as younger as 25 Ma (Bierlein et al., 1999). The deposits occurring in the vast territory of New South Wales (Dargues, Cowarra, etc.) and Victoria (Ballarat West, Tarnagulla, Maldon), taken together, make up a world-class gold mining district. Only the Cowarra deposit reveals a small range of variations, approximately similar to the Nezhdaninsky deposit range of variations of $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios of lode lead (0.4, 0.15, and 0.3%, respectively). At other deposits in southeastern Australia, a range of variations is several times wider, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratio reaches anomalous values up to 27.7. Owing to higher $^{207}\text{Pb}/^{204}\text{Pb}$ values, the deposits of southeastern Australia are distinguished by parameter μ_2 in the Stacey–Kramers evolutionary model: 9.7 and higher against 9.5–9.6 at the Nezhdaninsky deposit. In contrast to the Tyry–Dyby ore cluster, where Pb isotopic composition is less radiogenic in comparison with lode lead, inverse relationships are established in the deposits of southeastern Australia. According to geological and geochemical data, most of these deposits reveal spatial and genetic links of gold mineralization to associated granitoids. Variations and anomalies in isotopic composition of lode ore in the deposits of southeastern Australia are mainly caused by inhomogeneity of Pb isotopic composition of granitic rocks, although according to isotopic data, a significant part of lode lead, as at the Nezhdaninsky deposit, has been mobilized from host metasedimentary rocks. The

MORB-type mantle-derived basalts and boninites are incorporated into Ordovician host rocks, but they are mostly composed of terrigenous material resided in the crust for a long time. As a result of leaching of lead from large volumes of these rocks in combination with Pb supply by magmatic fluids, the lead with mean crustal (~ 9.7) and even higher μ_2 values is contained in the deposits of southeastern Australia.

In contrast, lead of the Nezhdaninsky deposit evolved in a relatively low-U reservoir of Permian terrigenous rocks composed of the material that resided in the continental crust for a short geological time. Another distinguishing feature of lead at the Nezhdaninsky deposit and other gold deposits of the South Verkhoyansk Foldbelt is its enrichment in ^{208}Pb . Together with low $\mu_2 = 9.5$ – 9.6 , this feature indicates an elevated Th/U ratio relative to the mean crustal level. The regional character of such specificity allows us to suggest that the lower crustal material with its U–Th–Pb isotopic and elemental marks participated in the formation not only of Cretaceous granitic rocks but also of pre-Mesozoic protoliths, which were a source of terrigenous material for the Carbonaceous–Jurassic Verkhoyansk Complex, in particular, for the Lower Permian Dzhuptanga Formation in the Nezhdaninsky ore field. The Devonian volcanic rocks of the Okhotsk Terrane adjoining the eastern margin of the South Verkhoyansk Synclinorium and granitic rocks of the same age could have been such lower crustal protoliths. The Late Devonian age of these rocks related to the subduction zone of the Okhotsk continental margin is confirmed by ^{39}Ar – ^{40}Ar - and U–Pb datings of the Maastakh granodioritic pluton (375 ± 2 Ma) (Prokoviev et al., 2009). The Devonian and Early Carboniferous basalts buried in thick sedimentary sequences of the Verkhoyansk Complex could have been another source of clastic material of the lower crustal magmatic origin. It is noteworthy that specificity of isotopic composition of Pb of the Nezhdaninsky deposit and Early Cretaceous granitoids in the South Verkhoyansk region are also inherent to Au–Ag, Pb–Zn–Ag, Cu–Pb–Zn, and other deposits of the Verkhoyansk–Chukotka region, e.g., the large Dukat Au–Ag deposit, small deposits and occurrences of the Omolon Cratonic Block, and the Yana–Kolyma Fold System (Chernyshev and Shpikerman, 2001; Chernyshev et al., 2005).

CONCLUSIONS

The Nezhdaninsky deposit is a complicated object for the study of Pb isotopes, because of the relatively narrow range of their variations. The use of a high-precision ($\pm 0.02\%$) MC-ICP-MS method of isotopic analysis allowed us to overcome this difficulty and establish systematic isotopic trends within the deposit. Comparison of the data on particular ore zones characterized by many samples shows sufficiently uniform

distribution of Pb isotopic composition throughout the deposit. Owing to the high precision of the MC-ICP-MS analysis, relatively small but significant variations of isotopic ratios in galena within separate zones are established, largely with respect to $^{206}\text{Pb}/^{204}\text{Pb}$ (up to $\sigma_{6/4} = 0.26\%$). At the same time, a difference in three isotope ratios is within statistical scattering. No vertical zoning of Pb isotopic composition is noted.

The main factor that controls the observed variations is the relationship between Pb isotopic composition of galena and the type of mineral assemblage. Galena associated with silver minerals is distinguished by the lowest (least radiogenic) isotope ratios. Galena of the gold–sulfide assemblage, which dominates at the Nezhdaninsky deposit, is characterized by $^{206}\text{Pb}/^{204}\text{Pb} = 18.472$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.586$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.605$. Galena of the regenerated silver–base-metal mineral assemblage has significantly lower Pb isotope ratios: $^{206}\text{Pb}/^{204}\text{Pb} = 18.420$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.575$, and $^{208}\text{Pb}/^{204}\text{Pb} = 38.518$.

The data on Pb isotopes and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios restricts the role of Upper Cretaceous granitoids of the Kurum massif and quartz diorite of the Gel'dy stocks as sources of lead for gold mineralization at the Nezhdaninsky deposit, and thus, make it necessary to specify an existing model of its formation. Isotopic parameters of the Late Cretaceous intrusive rocks differ from those of the Early Cretaceous granitoids represented in the Tyry–Dyby ore cluster by the Dyby pluton and give grounds to conclude that lead of the gold mineralization at the Nezhdaninsky deposit is a mixture of two sources.

Making allowance for the available isotopic data, the main correction of the previously proposed model (Gamyranin, Bortnikov, and Alpatov, 2000) consists in the elimination of the Kurum pluton and the Gel'dy stocks belonging to the younger tectonomagmatic cycle from the elements of the Nezhdaninsky gold magmatic–ore system. Owing to the existence of the long-living deep Kideriki Fault, the Early Cretaceous fluid-generating magma chamber participated in the evolution of the magmatic–ore system. The reality of this chamber is confirmed by the occurrence of Early Cretaceous granitoid plutons on the flanks of the Nezhdaninsky ore field.

A source of lead prevailing in the Nezhdaninsky deposit is identified as host Permian terrigenous rocks. This conclusion supported by the isotopic composition of Pb at the hydrothermal–metamorphic gold deposits in the South Verkhoyansk region is consistent with high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7123–0.7139) of hydrothermal minerals at the Nezhdaninsky deposit. The terrigenous rocks are one component of the mixed source of Pb. Another component is identified as a magmatic lead delivered to the ore-forming system by magma-derived fluids in connection with granite formation in the Early Cretaceous. This lead component has isotopic marks characteristic of the lower crust: elevated $^{208}\text{Pb}/^{206}\text{Pb}$ and relatively low $^{207}\text{Pb}/^{204}\text{Pb}$

ratios, which taken together, determine a high Th/U ~ 4.0 in the source and $\mu_2 = ^{238}\text{U}/^{204}\text{Pb} = 9.37\text{--}9.50$. This conclusion is consistent with the modern tectonic model of evolution of the South Verkhoyansk sector of the Verkhoyansk Foldbelt and the Okhotsk Terrane.

Magmatic lead prevails (50–80%) in silver–base-metal deposits and occurrences of the Tyry–Dyby ore cluster localized on the flanks of the Nezhdaninsky ore field. Within the Nezhdaninsky deposit proper, the lead mobilized from terrigenous rocks dominates. This is indicated by both Pb and Sr isotopic data. The greatest contribution ($\sim 30\%$) of magmatic lead is characteristic of galena from the silver–base-metal mineral assemblage. The mixed origin of metals (Au, Ag, Zn, Cu, Ni, Co, Sb) with participation of magmatic and crustal sources is not an extraordinary phenomenon unique to the gold mineralization at the Nezhdaninsky deposit. Isotopic and geochemical data indicate a similar genesis for other gold deposits, for example, from southeastern and southwestern Australia.

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