Sm-Nd System of Rare-Metal Pegmatites of the World-Class Kolmozero Lithium Deposit and Shongui Beryllium Deposit, NW Russia: Geochemical Causes of Disturbance and Nd Mobility

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Abstract: The Sm-Nd geochronological study was performed to investigate rare-metal pegmatites from the two unique deposits, i.e., the Kolmozero lithium deposit and Shongui deposit with beryllium mineralization (Kola Peninsula, Russia). For Kolmozero lithium deposit was obtained the Sm-Nd isochrone, corresponding to an age of 1705 ± 60 Ma with high $\varepsilon Nd(T) = +9.1$. For Shongui beryllium deposit was obtained the Sm-Nd age, corresponding to an age of 1747 ± 33 Ma with high $\varepsilon Nd(T) = +9.7$. This age values are close to the ages of metamorphism obtained earlier by Rb-Sr, K-Ca, and K-Ar methods. Pegmatites are characterized by a wide range of $\varepsilon Nd(T)$ values from +2 to +16 and $^{147}Sm/^{144}Nd$ ratios up to 0.3. Possible reasons for disturbance of the Sm-Nd isotope system of pegmatites are analyzed, including multicomponent mixing, fluid influence and metamorphic overprinting. The highly radiogenic signatures of rare metal pegmatites of the Shongui and Kolmozero deposits were found to appear by fractionation of Nd and Sm and their different redistribution with the change of the Sm/Nd ratio. High $\varepsilon Nd(T)$ values and changes in Sm/Nd ratios indicate the role of REE (rare-earth element) fractionation, while narrow $\varepsilon Nd(T)$ ranges suggest interaction with fluids during pegmatite formation. These findings emphasize the need for further research into the composition of fluids and their influence on isotope systems.

Keywords: Kolmozero lithium deposit, Shongui beryllium deposit, rare-metal pegmatites, LCT-type, spodumene, beryl, Sm-Nd age, REE.

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1. Introduction

Analytical methods which allow highly precise dating of geological events, are not always applicable to pegmatite systems. This problem is due to the disturbance of the isotope systems during the formation of rare-metal pegmatites. Also, zircon within pegmatite system often metamict because of high content of U and Th, and hydrothermal processes may cause dilution and recrystallization of zircon and disturbance of the U-Pb system in a mineral. Due to these reasons it is not always possible to determine a geologically relevant U-Pb age of the rare-metal pegmatites.

A heightened interest in the strategic critical elements (Li, Be) provokes a wide range of necessary and urgent studies. They should expand our knowledge regarding the fundamentals of formation of large rare-metal deposits and substantiate assessment and exploration criteria for the mineral resource base development. Thus, isotope-geochronological and isotope-geochemical studies play an important role in our understanding of pegmatite systems. They provide the necessary background to define the key stages of pegmatite formation and identify ore sources.

This paper presents the Sm-Nd isotope-geochronological research of rare-metal pegmatites from the Kolmozero and Shongui deposits located in the north-eastern part of the Kola Peninsula (Russia). The available geochronological data on the pegmatite age cover a time interval from 2.7 to 1.6 Ga, i.e., from the magmatic stage to suggested ages of metamorphic or metasomatic events, and hydrothermal processes [*Kudryashov et al.*, 2022; *Pushkarev et al.*, 1978]. However, reliable evidence regarding the age of the pegmatites is still insufficient. The obtained results were analyzed and discussed in the light of contemporary ideas of the isotope system disturbance and "survival" during the post-magmatic processes and elemental REE (rare-earth element) fractioning in granite-pegmatite systems [*Janots et al.*, 2018; *Li et al.*, 2021; *Petersson et al.*, 2023; *Vezinet et al.*, 2021; *Zhang et al.*, 2023]. Pegmatites from the Shongui deposit are known to have only one geochronological age estimation. Having been made by the K-Ar method for micas, this estimation showed an age value of 2.35–2.10 Ga [*Polkanov and Gerling*, 1961]. The U-Pb age of columbite from the albite-spodumene pegmatites of the Kolmozero lithium deposit is determined to be 2315 ± 10 Ma [*Morozova et al.*, 2017]. The choice of the Sm-Nd isotopic system was made to use the "unpopular" isotopic approach for pegmatites in order to obtain new isotopic and geochemical data, as well as valuable information about the behavior of the Sm-Nd system and Nd in particular at the whole-rock (WR) level within rare metal pegmatites.

2. Geological Settings

The Kola rare-metal pegmatite belt is located in the north-western Fennoscandian Shield (Kola Peninsula, Russia). It stretches northwestward from the central part of the peninsula almost to the Norwegian border [*Morozova et al.*, 2020, 2024]. The Kola rare-metal pegmatite belt is more than 300 km long with a width of 20–45 km. It includes the world-class Kolmozero lithium deposit [*Morozova*, 2018; *Morozova et al.*, 2022] and Shongui beryllium deposit [*Morozova et al.*, 2023]. The Kolmozero deposit is situated in the south-eastern part of the Kola rare-metal pegmatite belt within the Murmansk province. The Shongui deposit is situated in the north-western part of the Kola rare-metal pegmatite belt within the Kola province (Figure 1).

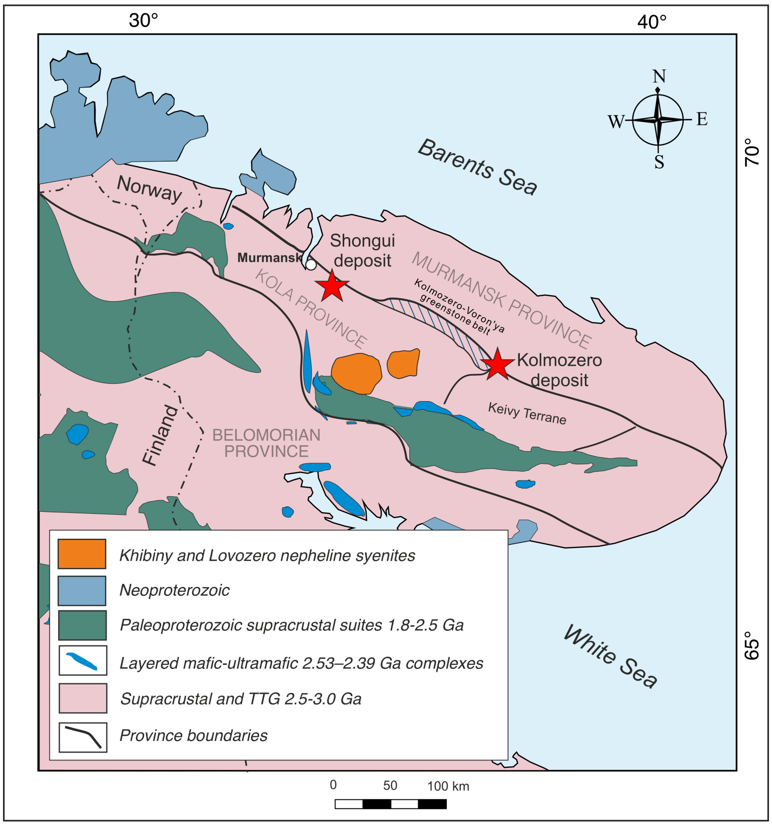

Figure 1. Schematic geological map of the northeastern part of the Fennoscandian Shield (red asterisks indicate sampling locations).

The Murmansk province is composed of Mesoarchean and Neoarchean granites, enderbites, charnockites, and tonalite–trondhjemite gneisses (TTG) with relics of supracrustal rocks. Basing on the Sm-Nd model age, formation time of the migmatite-granite complex is estimated at 2.68–2.94 Ga [*Mints et al.*, 2015; *Timmerman and Daly*, 1995]. These rocks have undergone a high-temperature amphibolite facies metamorphism [*Mints et al.*, 2015].

The Kola-Norwegian and Keivy terranes and Kolmozero-Voron'ya greenstone belt are the main tectonic units of the Archean Kola province [*Daly et al.*, 2006]. The Kola-Norwegian and Keivy terranes are mainly composed of TTG, charnockites and enderbites, meta-sediments and amphibolites. The Kolmozero-Voron'ya greenstone belt with an age of 2.92–2.79 Ga comprises rocks metamorphosed within the amphibolite facies. The volcano-sedimentary rocks have undergone an amphibolite facies metamorphism [*Glebovitsky*, 2005].

The main tectonic boundaries of the northern Fennoscandia finally formed in the Paleoproterozoic during the Lapland-Kola collisional orogeny [*Daly et al.*, 2006; *Hölttä et al.*, 2008; *Lahtinen and Huhma*, 2019]. The history of the Lapland-Kola collisional orogeny includes intracontinental rifting of Archean crust (2.5–2.1 Ga), Red-Sea-type oceanic separation (2.1–2.0 Ga), subduction and crustal growth (2.0–1.9 Ga), collision (1.94–1.86 Ga), and orogenic collapse and exhumation (1.90–1.86 Ga) [*Daly et al.*, 2006].

2.1. Kolmozero Lithium Deposit

The Kolmozero lithium deposit includes 12 big veins of rare-metal albite-spodumene pegmatites (2315 ± 10 Ma) [*Morozova et al.*, 2020], occurring in metagabbro-anorthosites of the Potchemvarek massif (2661.8 ± 7.1 Ma) [*Vrevsky and Lvov*, 2016] (Figure 2).

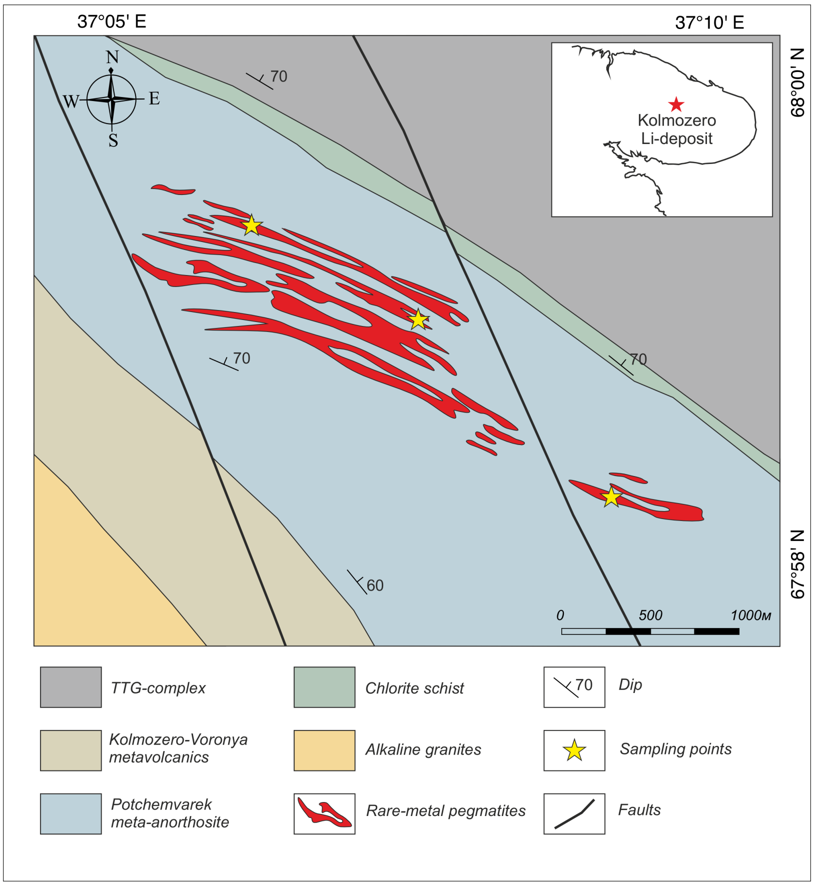

Figure 2. Sketch map of geological structure of the Kolmozero lithium deposit area.

Pegmatite dikes have a length of 480–1700 m, thickness of up to 70 m, and can be traced to a depth of 500 m. According to the classification given in [*Černý and Ercit*, 2005], the Kolmozero deposit pegmatites belong to the lithium-cesium-tantalum (LCT-type) pegmatite family of albite-spodumene type [*Morozova*, 2018].

The Kolmozero deposit pegmatites are essentially leucocratic rocks with non-uniform structure, which regularly changes from a fine-grained one in the margin zone to a pegmatoid and blocky ones in the central zone. The main rock-forming minerals are as follows: quartz (30–35%), plagioclase (30–35%), microcline (10–25%), spodumene (~20%), and muscovite (5–7%). Ore minerals are as follows: spodumene, columbite, tantalite, and beryl. Accessory minerals are as follows: apatite, spessartine, sphalerite, pyrite. Secondary minerals are represented by phosphates and zeolites. Albite-spodumene pegmatites of the Kolmozero deposit feature a mildly differentiated REE distribution spectrum with $(La/Yb)_n$ = 6.86–27.69. Total REE contents in pegmatites of the Kolmozero deposit vary from 20 to 1.4 ppm [*Morozova*, 2018]. These pegmatites feature a negative europium anomaly with Eu/Eu* = 0.39–0.65 (Figure 3); a negative Ce anomaly is slightly manifested or absent (Ce/Ce* = 0.49–1.07) [*Morozova*, 2018]. Negative Ce anomaly indicates oxidizing conditions during the process of rare-metal mineralization formation [*Garba*, 2003].

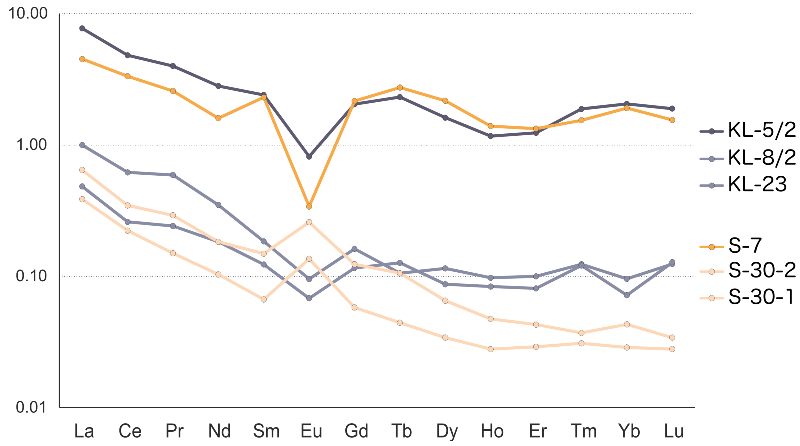

Figure 3. Chondrite-normalized REE distribution in the rare-metal pegmatites of the Shongui and Kolmozero deposits (data for the Shongui deposit from [*Morozova et al.*, 2023]; data for the Kolmozero deposit from [*Morozova*, 2018].

2.2. Shongui Beryllium Deposit

The Shongui deposit consists of several pegmatite veins which occur within amphibolites of the Kola Province (Figure 4). But only three dikes contain a beryllium mineralization.

Pegmatite veins have a length of up to 1000 m, thickness of up to 80 m, and can be traced to a depth of 180 m. Pegmatites consist of quartz (30–35%), plagioclase (30–35%), and microcline (20–25%). Veins have zonal structure and include border, intermediate, and central zones. The border zone comprises fine-grained quartz-plagioclase aggregate and medium-grained quartz-albite-microcline aggregate. The intermediate zone comprises quartz-albite-microcline, quartz-microcline, and quartz-cleavelandite aggregates. The central zone is composed of a quartz core. Beryl is the main source of beryllium in the Shongui deposit pegmatites. It is located in the intermediate and central zones of the dikes [*Morozova et al.*, 2023]. The barren pegmatites intrude the amphibolites and amphibole-biotite gneisses (Figure 4). They have a simple mineral composition, consisting of quartz (35–45 vol. %), K-feldspar (45–60%), and plagioclase (25–30%) [*Ponomareva et al.*, 2005].

According to the classification Černý and Ercit given in [*Černý and Ercit*, 2005], the Shongui deposit pegmatites belong to the lithium-cesium-tantalum (LCT) family of moderately fractioned beryl-type pegmatites of beryl-columbite subtype [*Morozova et al.*, 2023]. The Shongui deposit pegmatites are enriched with Cs, Be, Mn, Ti, Li, Ta,

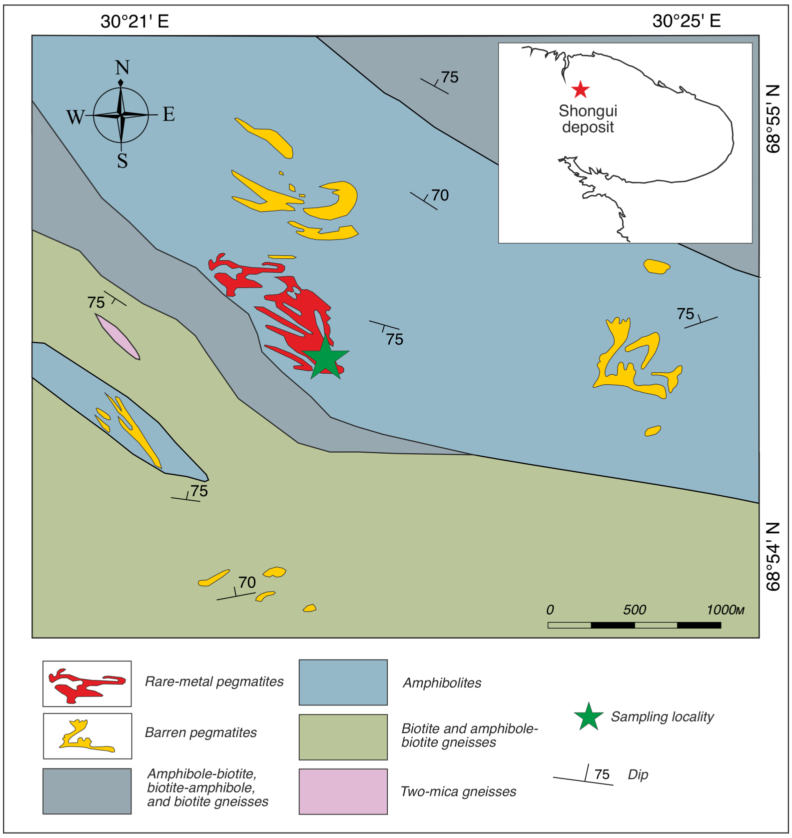

Figure 4. Sketch map of geological structure of the Shongui beryllium deposit area.

and Nb, and depleted in REE, Ba Sr, Y. The REE spectra feature negative slope with $(La/Lu)_n$ = 2.60–33.47, which indicates a depletion in HREE (0.04–3.87 ppm) and enrichment in LREE (0.40–11.85 ppm). The LREE/HREE ratio value varies from 3.07 to 12.64. Quartz-microcline aggregates have a positive Eu anomaly (Eu/Eu* = 1.29–2.19, Figure 3), which is associated with the high abundance of microcline [*Morozova et al.*, 2023]. Negative Eu anomalies (Eu/Eu* = 0.17–0.81) are typical of the quartz-microcline-albite, microcline-quartz-cleavelandite, and albite-muscovite-quartz aggregates. Fractioning degree of the heavy rare-earth elements $(Gd/Lu)_n$ varies from 0.78 to 4.92, and that of the light rare-earth elements $(La/Sm)_n$ varies from 1.95 to 6.76 [*Morozova et al.*, 2023].

3. Samples and Methods

Samples from pegmatite veins were collected from the Kolmozero lithium (Kl-23, Kl-8/2 and Kl-5/2) and Shongui beryllium (S-30-1, S-30-2 and S-7) deposits. The weight of samples varied from 10 to 20 kg in dependence on the size of rock-forming minerals.

Samples from the Kolmozero deposit (Kl-8/2 and Kl-23) were collected from a quartz-albite-spodumene aggregate with (± microcline). The samples contain (wt. %): SiO_2 – 72.22 and 72.46; Al_2O_3 – 15.90 and 17.36; TiO_2 – 0.01 and 0.03; Fe_2O_3 – 0.18 and 0.10; FeO – 1.33 and 1.61; MnO – 0.09 and 0.11; MgO – 0.04 and 0.11; Na_2O – 3.29 and 2.87; CaO – 0.09 and 0.11; K_2O – 4.22 and 0.73; Li_2O – 0.95 and 3.23 [*Morozova*, 2018]. Secondary and accessory minerals include garnet, apatite, magnetite, and ilmenite. The sample (Kl-5/2) was collected from a quartz-plagioclase-microcline aggregate of feldspar pegmatites and has the following rock-forming oxide content (wt. %): SiO_2 – 72.6; Al_2O_3 – 15.03; TiO_2 – 0.01; FeO – 0.88; MnO – 0.11; MgO – 0.04; Na_2O – 3.56; CaO – 0.15; K_2O – 7.0; Li_2O – 0.02. Secondary and accessory minerals include beryl, pyrochlore, garnet, magnetite and ilmenite.

Samples of the Shongui deposit were collected from an intermediate zone that contains beryl mineralization. Sample S-7 was collected from a quartz-microcline-albite aggregate, with the following content of rock-forming oxides (wt. %): SiO_2 – 85.33; Al_2O_3 – 7.33; TiO_2 – 0.02; Fe_2O_3 – 0.09; FeO – 1.67; MnO – 0.18; MgO – 0.24; Na_2O – 4.15; CaO – 0.20; K_2O – 0.17; Li_2O – 0.005 [*Zozulya et al.*, 2024]. Samples S-30-1 and S-30-2 were collected from a quartz-microcline aggregate, with a content of SiO_2 at 66.63% and 66.1%, respectively. Other rock-forming oxide contents were: Al_2O_3 at 17.61%; TiO_2 between 0.04 and 0.03%; FeO at 0.67 to 0.63%; MnO at 0.11%; MgO at 0.5%; Na_2O at 3.0 to 2.27%; CaO below 0.1%; K_2O between 10.98% and 12.34%; and Li_2O at 0.014 to 0.054%. Secondary and accessory minerals include beryl, columbite-group minerals, tourmaline, apatite, garnet, magnetite, and pyrochlore.

The REE in minerals from the pegmatites of both deposits are predominantly concentrated in garnet, pyrochlore, and ilmenite [*Morozova*, 2018; *Morozova et al.*, 2022, 2023].

Sm-Nd isotopic whole-rock analysis was performed for ore-bearing rare-metal pegmatites. Three whole-rock samples of the Shongui deposit rare-metal pegmatites and three whole-rock samples of the Kolmozero deposit rare-metal pegmatites were analyzed using the thermal ionization mass spectrometry (TIMS). The concentrations of Sm, Nd, and neodymium isotope composition were determined with a multicollector mass-spectrometer Finnigan-MAT-262 in the Collective Resource Center of the Kola Science Centre, Russian Academy of Sciences (Apatity, Russia).

In order to define concentrations of samarium and neodymium, the sample (about 200 mg) was mixed with a ^{149}Sm-^{150}Nd spike prior to dissolution. It was then diluted with a mixture of HF + HNO_3 (or $^{+}HClO_4$) in teflon vials at a temperature of 100 °C until complete dissolution. Further extraction of Sm and Nd was carried out using two-stage ion-exchange and extraction-chromatographic separation in chromatographic columns employing 2.3 N and 4.5 N HCl as an eluent. Further extraction of Sm and Nd was carried out with two-stage ion-exchange and extraction–chromatographic separation using ion-exchange tar "Dowex" 50 × 8 in chromatographic columns, employing 2.3 N and 4.5 N HCl as an eluent. The separated REE fraction was evaporated dry, dissolved in 0.1 N HCl, and loaded into the second column with Eichrom LN resin solid ion-exchange resin HDEHP. The resin was used to separate Sm and Nd. The separated Sm and Nd fractions were converted into a nitrate form. The neodymium isotope composition and samarium and neodymium contents were measured in a static double-filament mode, using Re and Ta filaments. The quality of isotopic analysis was monitored by repeated measurements of JNdi-1 standard reference material and the BCR-2 rock sample. A mean value of $^{143}Nd/^{144}Nd$ ratio in a JNdi-1 standard was 0.512083 ± 15 (2σ, $n = 11$); for BCR-2 $^{143}Nd/^{144}Nd = 0.512625 \pm 12$ (2σ, $n = 7$), $^{147}Sm/^{144}Nd = 0.1379$ with good agreement to the reference values [*Raczek et al.*, 2003; *Tanaka et al.*, 2000]. An error in $^{147}Sm/^{144}Nd$ in ratios was 0.3% (2σ), which is a mean value for 7 measurements in a BCR-2 rock standard. An error in estimation of isotope Nd composition in an individual analysis was up to 0.1% for samples with low Sm and Nd contents. The blank laboratory contamination was 0.3 ng in Nd and 0.06 ng in Sm. The accuracy of estimation of Sm and Nd contents was ±0.5%. Isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$, and then recalculated for the $^{143}Nd/^{144}Nd$ reference value for JNdi-1=0.512115 [*Tanaka et al.*, 2000]. Values of $\varepsilon Nd(T)$ were estimated using present-day values of CHUR as described in [*Bouvier et al.*, 2008] at ($^{143}Nd/^{144}Nd = 0.512630$, $^{147}Sm/^{144}Nd = 0.1960$). Isochron parameters were calculated using the IsoplotR online software [*Vermeesch*, 2018].

4. Results

The Nd concentrations in studied samples vary from 0.072 ppm to 1.634 ppm; the Sm concentrations range from 0.015 ppm to 0.535 ppm (Table 1). The concentrations of Nd and Sm are consistent with those obtained previously using the ICP-MS method [*Morozova*, 2018; *Morozova et al.*, 2022, 2023]. The $\varepsilon Nd(T)$ values were calculated for an age of 2315 Ma (this corresponds to the previously reported U-Pb age of the Kolmozero pegmatites [*Morozova et al.*, 2017] and K-Ar age of micas from the Shongui pegmatites [*Polkanov and Gerling*, 1961] and showed significant dispersion, i.e., $\varepsilon_{Nd}(T = 2315)$ values varied from +2.2 to +16.0.

For Kolmozero lithium deposit was obtained the Sm-Nd isochrone from three whole-rock rare-metal pegmatite samples, corresponding to an age of 1705 ± 60 Ma with high positive εNd(T) = +9.1 (Figure 5a). For Shongui beryllium deposit was obtained the Sm-Nd age from three whole-rock pegmatite samples, corresponding to an age of 1747 ± 33 Ma with high positive εNd(T) = +9.7 (Figure 5b). The slightly younger calculated age from the Kolmozero deposit, within the uncertainties, is close to the age obtained for the Shongui deposit. The high uncertainty of the calculated age for the Kolmozero deposit is mainly due to the insufficient precision of the ^{143}Nd/^{144}Nd ratios and the small number of analyzed fractions. In addition to the observed isotopic disequilibrium, a disturbance of the Sm/Nd ratio in pegmatites is also detected by individual REE spectra. Pegmatites with higher Sm/Nd ratios (samples KL-5/2 and S-7) have higher Σ_{REE} and more significant Eu-minimum, while samples with lower Sm/Nd ratios are characterized by low Σ_{REE} (Figure 3). Also, the $\varepsilon_{Nd}(T = 2315)$ values for samples KL-5/2 and S-7 have the lowest values, but this difference is practically eliminated when calculated on isochron ages (Table 1).

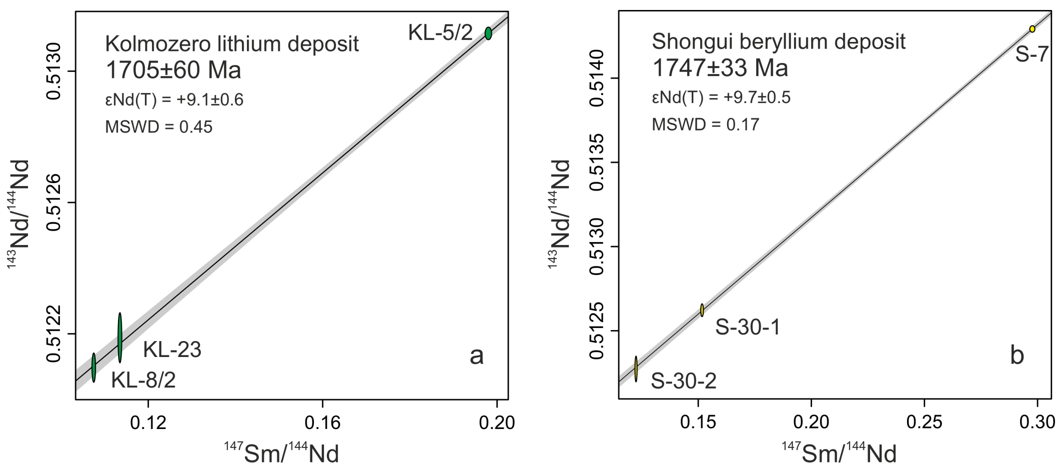

Figure 5. Sm-Nd whole-rock isochrones for rare-metal pegmatites from the and Kolmozero lithium deposit (a) and Shongui beryllium deposit (b).

Table 1. Results of Sm-Nd whole-rock analysis of rare-metal pegmatites of the Shongui and Kolmozero deposits

Sample	Concentrations, ppm		Isotopic Ratios		εNd(T) (2315 Ma)	εNd(T) (1705 Ma)	εNd(T) (1747 Ma)
	Sm	Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd			
Shongui deposit							
S-7	0.235	0.478	0.2977	0.514292 ± 14	+2.2		+9.7
S-30-1	0.032	0.126	0.1517	0.512622 ± 32	+13.2		+9.8
S-30-2	0.015	0.072	0.1225	0.512273 ± 60	+15.0		+9.6
Kolmozero deposit							
Kl-5/2	0.535	1.634	0.1980	0.513115 ± 16	+8.9	+9.1	
Kl-23	0.024	0.126	0.1135	0.512188 ± 59	+16.0	+9.5	
Kl-8/2	0.035	0.195	0.1075	0.512097 ± 34	+16.0	+9.0	

5. Discussion

The obtained ages are close to the previously made Rb-Sr, K-Ca, and K-Ar dating of microclines and micas from rare-metal pegmatites of the Shongui and Kolmozero deposits, i.e., ca. 1.75 Ga metamorphism [*Pushkarev*, 1990]. The stage of 1.75 Ga also corresponds to the final "Nordic" stage of orogeny, which completed almost 200 million years lasting Svecofennian orogeny [*Lahtinen et al.*, 2008]. The available data on the rare-metal pegmatites (Rb-Sr, K-Ca, and K-Ar age values of ca. 1.75 Ga, including the U-Pb age of about 1.7 Ga of the zircon outer rims from the Okhmylk deposit pegmatites [*Kudryashov et al.*, 2022] provide a reliable substantiation for the later events to have taken place within the belt in a time span of 1.8–1.6 Ga. Contemporary data, for example [*Yan et al.*, 2023], show that episodes of regional tectonic and hydrothermal events in the north of the Fennoscandian Shield may have probably happened in the past repeatedly at the edges of ca. 1.8 Ga, ca. 1.73 Ga, ca. 1.63 Ga, and ca. 1.5 Ga [*Antonyuk*, 1962; *Cliff and Rickard*, 1992; *Romer*, 1996; *Westhues et al.*, 2017; *Yan et al.*, 2023]. Despite the abundance of age values around 1.75 Ga in different isotope systems, these data suggest some geological events that are only confirmed in the North Norway area and are related to a local deformation during the waning stage of the Svecofennian orogeny [*Lahtinen et al.*, 2008]. However, the obtaining of close ages that correspond to overprinting processes in different isotope systems clearly suggests the effect of a real process, which probably had a significant impact on the pegmatite isotope systems. Absence of direct evidence of metamorphic process in the studied pegmatites does not give us reasons to declare that the obtained age is a metamorphic or crystallization age. Nevertheless, we consider the similarity of ages in different isotope systems to be not accidental and this fact is of high interest for further investigations.

There are two possible interpretations of the regression line that gives a younger age: 1) the result of multi-component mixing; 2) an isochrone that records the age of the superimposed (overprinting) event. The hypothesis of the mixing line is supported by the detected dependence of the Nd isotopic composition on neodymium concentrations.

The hypothesis of multi-component mixing of Nd from several sources cannot be supported. In this instance there must exist an end-member with even more radiogenic Nd isotope composition than that of rare-metal pegmatites. The existence of such a highly radiogenic source is near to improbable.

The second hypothesis is that the obtained isochrones yields the age of the isotope system reset due to a late superimposed event. An argument in favor of reset of the rare-metal pegmatites isotope system is a high and non-realistic values $\varepsilon\text{Nd}(T) = +9.1 - +9.7$ (relative to CHUR), which implies the ultra-depleted source for pegmatites. Higher Nd mobility during the metamorphic and metasomatic processes may lead to a neodymium redistribution between the rocks, which would be indicated by an incomplete homogenization of isotope system and rejuvenated ages or mixing lines (errochrons). As shown above, the mixing hypothesis collapses in this case, so the rejuvenated age is more likely to correspond with metamorphic manifestation, whereas the appearance of highly radiogenic rock marks is caused by the REE fractioning and irregular Nd redistribution (the latter was accompanied by disturbance of the Sm/Nd ratios). A similar REE behavior was observed at some other rare-metal pegmatites composing world-class deposits. For example, the Sm-Nd data were earlier obtained for the pegmatite fields of Zimbabwe (Bikita) and Western Australia (Cattlin Creek, Wodgina, Mount Deans, and Londonderry), which also indicated extremely high $^{147}\text{Sm}/^{144}\text{Nd}$ values up to 0.8–0.9 [*Dittrich et al.*, 2019]. The authors explained such values by a high degree of the REE fractioning and by later substitution processes, which led to the REE redistribution [*Dittrich*, 2017; *Dittrich et al.*, 2019]. A wide spread of calculated initial $\varepsilon\text{Nd}(T)$ values and Sm-Nd model ages of these pegmatites is also observed, which allowed the authors to conclude that rare-metal pegmatites were influenced by later substitution processes and associated redistribution of elements [*Dittrich et al.*, 2019]. A similar trend was demonstrated in the result of our research of the rare-metal pegmatites from the studied deposits. The pegmatites are characterized by the Sm/Nd ratios of up to 0.3. One possible explanation for the occurrence of high εNd(T) values could be the mobilization of neodymium from an ancient source with a high Sm/Nd ratio, resulting from a superimposed process. While this hypothesis is interesting, it requires further investigation.

Generally, the Sm-Nd isotope system may be sensitive to later stages of alteration process [*Salerno et al.*, 2021], while the presence of chlorine-containing fluids promotes high REE mobility, with Nd being more mobile than Sm [*Li et al.*, 2021, 2022b; *Migdisov et al.*, 2016, 2009]. This leads to Nd migration and change in Sm/Nd ratios, and consequently to the corruption of geochronological data. Current information on composition of fluids in rare-metal pegmatites of the Kolmozero and Shongui deposits is absent. Basing upon available preliminary data on Cl contents in these pegmatites, we may only assume a possible interaction exactly with a Cl-containing fluid. It is important to note that the εNd(T) values for rare metal pegmatites calculated for isochron ages (1705 Ma for Kolmozero and 1747 Ma for Shongui) show a fairly narrow range of variation, ranging from +9.6 to +9.8 for Kolmozero and from +9.0 to +9.5 for Shongui (Table 1). This may suggest the interaction with a fluid, which could have caused neodymium to become more homogeneous after the isotopic system of the pegmatites was reset. The isotopic homogenization induced by fluids is likely a common process in granite-pegmatite systems [*Li et al.*, 2022a, 2024].

In most cases the Sm-Nd geochronological system remains sufficiently stable. The reasons of this stability are as follows: metamorphically redistributed Sm and Nd have the same origin (source) as the primary minerals; the P-T conditions may be inappropriate to counterbalance the Sm-Nd system between minerals and rocks during the low and medium grade metamorphism [*Li et al.*, 2021; *Wang et al.*, 2022]. At the same time the Sm-Nd isotope system may be disturbed by outer fluid impact [*Barker et al.*, 2009; *Janots et al.*, 2018; *Poitrasson et al.*, 1998]. During these processes, caused by incomplete equilibration of the Sm-Nd system between the rock and fluid, the Sm-Nd ages are potentially distorted [*Barker et al.*, 2009; *Zhang et al.*, 2023].

6. Conclusions

1. The analysis of isotope systems in rare-metal pegmatites from the Kolmozero and Shongui deposits confirms their sensitivity to late-stage processes, including metamorphism and interaction with fluids. The yielded isochron ages (1705 Ma for Kolmozero deposit and 1747 Ma for Shongui deposit) and consistent εNd(T) values (+9.0–+9.8) indicate Nd redistribution and partial homogenization of the isotope system after its reset. This process probably involved REE fractionation and a change in the Sm/Nd ratio, resulting in the young ages obtained.
2. The hypothesis of multicomponent mixing from several sources is not supported by the lack of evidence for an ultraradiogenic source, which could explain the observed high values of εNd(T).
3. The similarity of ages in different isotope systems (Rb-Sr, K-Ca, K-Ar, U-Pb, and Sm-Nd) indicates late geological processes affecting the pegmatites within the 1.8–1.6 Ga stage. High εNd(T) values and changes in Sm/Nd ratios indicate the role of REE fractionation, while narrow εNd(T) ranges suggest interaction with fluids during pegmatite formation. These findings emphasize the need for further research into the composition of fluids and their influence on isotope systems.

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References

Antonyuk, E. S. (1962), Structural-mineral associations of granite pegmatite veins, in *Materials on Mineralogy of the Kola Peninsula*, pp. 134–142, Kola Branch of the USSR Academy of Sciences, Apatity, USSR (in Russian).

Barker, S. L. L., V. C. Bennett, S. F. Cox, et al. (2009), Sm-Nd, Sr, C and O isotope systematics in hydrothermal calcite-fluorite veins: Implications for fluid-rock reaction and geochronology, *Chemical Geology*, *268*(1–2), 58–66, https://doi.org/10.1016/j.chemgeo.2009.07.009.

Bouvier, A., J. D. Vervoort, and P. J. Patchett (2008), The Lu-Hf and Sm-Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets, *Earth and Planetary Science Letters*, *273*(1–2), 48–57, https://doi.org/10.1016/j.epsl.2008.06.010.

Černý, P., and T. S. Ercit (2005), The classification of granitic pegmatites revisited, *The Canadian Mineralogist*, *43*(6), 2005–2026, https://doi.org/10.2113/gscanmin.43.6.2005.

Cliff, R. A., and D. Rickard (1992), Isotope systematics of the Kiruna magnetite ores, Sweden; Part 2, Evidence for a secondary event 400 m.y. after ore formation, *Economic Geology*, *87*(4), 1121–1129, https://doi.org/10.2113/gsecongeo.87.4.1121.

Daly, J. S., V. V. Balagansky, M. J. Timmerman, et al. (2006), The Lapland-Kola orogen: Palaeoproterozoic collision and accretion of the northern Fennoscandian lithosphere, *Geological Society, London, Memoirs*, *32*(1), 579–598, https://doi.org/10.1144/gsl.mem.2006.032.01.35.

Dittrich, T. (2017), Meso- to Neoarchean Pegmatites (Western Australia, Zimbabwe) and a Genetic Model for the Formation of Massive Pollucite Mineralisations, phdthesis, Technischen Universität Bergakademie, Freiberg.

Dittrich, T., T. Seifert, B. Schulz, et al. (2019), *Archean Rare-Metal Pegmatites in Zimbabwe and Western Australia: Geology and Metallogeny of Pollucite Mineralisations*, Springer International Publishing, https://doi.org/10.1007/978-3-030-10943-1.

Garba, I. (2003), Geochemical discrimination of newly discovered rare-metal bearing and barren pegmatites in the Pan-African (600 ± 150 Ma) basement of northern Nigeria, *Applied Earth Science*, *112*(3), 287–292, https://doi.org/10.1179/037174503225011270.

Glebovitsky, V. A. (Ed.) (2005), *Early Precambrian of the Baltic shield*, 711 pp., Nauka, Saint-Petersburg (in Russian).

Hölttä, P., V. Balagansky, A. A. Garde, et al. (2008), Archean of Greenland and Fennoscandia, *Episodes*, *31*(1), 13–19, https://doi.org/10.18814/epiiugs/2008/v31i1/003.

Janots, E., H. Austrheim, C. Spandler, et al. (2018), Rare earth elements and Sm-Nd isotope redistribution in apatite and accessory minerals in retrogressed lower crust material (Bergen Arcs, Norway), *Chemical Geology*, *484*, 120–135, https://doi.org/10.1016/j.chemgeo.2017.10.007.

Kudryashov, N., O. Udoratina, A. Kalinin, et al. (2022), U-Pb (SHRIMP-RG) age of zircon from rare-metal (Li, Cs) pegmatites of the Okhmylk deposit of the Kolmozero-Voron'ya greenstone belt (northeast of the Fennoscandian shield), *Journal of Mining Institute*, *255*, 448–454, https://doi.org/10.31897/pmi.2022.41.

Lahtinen, R., and H. Huhma (2019), A revised geodynamic model for the Lapland-Kola Orogen, *Precambrian Research*, *330*, 1–19, https://doi.org/10.1016/j.precamres.2019.04.022.

Lahtinen, R., A. A. Garde, and V. A. Melezhik (2008), Paleoproterozoic evolution of Fennoscandia and Greenland, *Episodes*, *31*(1), 20–28, https://doi.org/10.18814/epiiugs/2008/v31i1/004.

Li, X.-C., K.-F. Yang, C. Spandler, et al. (2021), The effect of fluid-aided modification on the Sm-Nd and Th-Pb geochronology of monazite and bastnäsite: Implication for resolving complex isotopic age data in REE ore systems, *Geochimica et Cosmochimica Acta*, *300*, 1–24, https://doi.org/10.1016/j.gca.2021.02.028.

Li, X.-C., D. E. Harlov, M.-F. Zhou, et al. (2022a), Experimental investigation into the disturbance of the Sm-Nd isotopic system during metasomatic alteration of apatite, *Geochimica et Cosmochimica Acta*, *330*, 191–208, https://doi.org/10.1016/j.gca.2021.04.036.

Li, Z.-X., S.-B. Zhang, Y.-F. Zheng, et al. (2022b), Mobilization and fractionation of HFSE and REE by high fluorine fluid of magmatic origin during the alteration of amphibolite, *Lithos*, *420–421*, 106,701, https://doi.org/10.1016/j.lithos.2022.106701.

Li, Z.-X., S.-B. Zhang, Y.-F. Zheng, et al. (2024), Homogenization of Hf-Nd isotopes induced by hydrothermal fluids during the differentiation of granitic magmas into pegmatites, *Chemical Geology*, *670*, 122,455, https://doi.org/10.1016/j.chemgeo.2024.122455.

Migdisov, A., A. E. Williams-Jones, J. Brugger, et al. (2016), Hydrothermal transport, deposition, and fractionation of the REE: Experimental data and thermodynamic calculations, *Chemical Geology*, *439*, 13–42, https://doi.org/10.1016/j.chemgeo.2016.06.005.

Migdisov, A. A., A. E. Williams-Jones, and T. Wagner (2009), An experimental study of the solubility and speciation of the Rare Earth Elements (III) in fluoride- and chloride-bearing aqueous solutions at temperatures up to 300°C, *Geochimica et Cosmochimica Acta*, *73*(23), 7087–7109, https://doi.org/10.1016/j.gca.2009.08.023.

Mints, M. V., K. A. Dokukina, A. N. Konilov, et al. (2015), 2. Mesoarchean Kola-Karelia continent, in *East European Craton: Early Precambrian History and 3D Models of Deep Crustal Structure*, pp. 15–88, Geological Society of America, Boulder, Colorado, https://doi.org/10.1130/2015.2510(02).

Morozova, L. N. (2018), Lithium Kolmozero deposit of rare metal pegmatites: New data on rare element composition (Kola Peninsula), *Lithosfera*, *18*(1), 82–98, https://doi.org/10.24930/1681-9004-2018-18-1-082-098 (in Russian).

Morozova, L. N., T. B. Bayanova, A. V. Bazay, et al. (2017), Rare metal pegmatites of the Kolmozero lithium deposit of the Arctic region of the Baltic shield: New geochronological data, *Vestnik KSC RAS*, *9*(1), 43–52 (in Russian), EDN: YKJYGL.

Morozova, L. N., E. N. Sokolova, S. Z. Smirnov, et al. (2020), Spodumene from rare-metal pegmatites of the Kolmozero lithium world-class deposit on the Fennoscandian shield: trace elements and crystal-rich fluid inclusions, *Mineralogical Magazine*, *85*(2), 149–160, https://doi.org/10.1180/mgm.2020.104.

Morozova, L. N., D. R. Zozulya, E. Selivanova, et al. (2022), Distribution of Trace Elements in K-Feldspar with Implications for Tracing Ore-Forming Processes in Pegmatites: Examples from the World-Class Kolmozero Lithium Deposit, NW Russia, *Minerals*, *12*(11), 1448, https://doi.org/10.3390/min12111448.

Morozova, L. N., S. G. Skublov, D. R. Zozulya, et al. (2023), Li-Cs-Na-Rich Beryl from Beryl-Bearing Pegmatite Dike No. 7 of the Shongui Deposit, Kola Province, Russia, *Geosciences*, *13*(10), 309, https://doi.org/10.3390/geosciences13100309.

Morozova, L. N., D. R. Zozulya, and S. G. Skublov (2024), Kola rare-metal pegmatite belt - the most important source of strategic mineral raw materials (Li, Be, Nb, Ta, Cs) in Russia, *Prospect & protection of mineral resources*, (2), 36–40, https://doi.org/10.53085/0034-026x_2024_2_36.

Petersson, A., U. Söderlund, A. Scherstén, et al. (2023), The robustness of the Lu-Hf and Sm-Nd isotopic systems during metamorphism - A case study of the Åker metabasite in southern Sweden, *Precambrian Research*, *394*, 107,122, https://doi.org/10.1016/j.precamres.2023.107122.

Poitrasson, F., J.-L. Paquette, J.-M. Montel, et al. (1998), Importance of late-magmatic and hydrothermal fluids on the Sm-Nd isotope mineral systematics of hypersolvus granites, *Chemical Geology*, *146*(3–4), 187–203, https://doi.org/10.1016/S0009-2541(98)00010-2.

Polkanov, A. A., and E. K. Gerling (1961), Geochronology and geological evolution of the Baltic Shield and its folded framing, *Trudy Laboratory of Precambrian Geology, Academy of Sciences of the USSR*, *12*, 101–102 (in Russian).

Ponomareva, N. I., V. V. Gordienko, and R. S. Shurekova (2005), Physicochemical Circumstances of Beryl Generation in "Bol'Shoy Lapot" Deposit (Kola Peninsula), *Bulletin of the Saint Petersburg State Institute of Technology*, (3), 4–20 (in Russian), EDN: UXOJDP.

Pushkarev, Y. D. (1990), *Megacycles in evolution of crust-mantle system*, 217 pp., Nauka, St. Petersburg (in Russian).

Pushkarev, Y. D., E. V. Kravchenko, and G. I. Shestakov (1978), *Geochronologic repertoires in the Precambrian of the Baltic Shield*, 136 pp., Nauka, Leningrad (in Russian).

Raczek, I., K. P. Jochum, and A. W. Hofmann (2003), Neodymium and Strontium Isotope Data for USGS Reference Materials BCR-1, BCR-2, BHVO-1, BHVO-2, AGV-1, AGV-2, GSP-1, GSP-2 and Eight MPI-DING Reference Glasses, *Geostandards Newsletter*, *27*(2), 173–179, https://doi.org/10.1111/j.1751-908x.2003.tb00644.x.

Romer, R. L. (1996), U-Pb systematics of stilbite-bearing low-temperature mineral assemblages from the Malmberget iron ore, northern Sweden, *Geochimica et Cosmochimica Acta*, *60*(11), 1951–1961, https://doi.org/10.1016/0016-7037(96)00066-x.

Salerno, R., J. Vervoort, C. Fisher, et al. (2021), The coupled Hf-Nd isotope record of the early Earth in the Pilbara Craton, *Earth and Planetary Science Letters*, *572*, 117,139, https://doi.org/10.1016/j.epsl.2021.117139.

Tanaka, T., S. Togashi, H. Kamioka, et al. (2000), JNdi-1: a neodymium isotopic reference in consistency with LaJolla neodymium, *Chemical Geology*, *168*(3–4), 279–281, https://doi.org/10.1016/s0009-2541(00)00198-4.

Timmerman, M. J., and J. S. Daly (1995), Sm-Nd evidence for late Archaean crust formation in the Lapland-Kola Mobile Belt, Kola Peninsula, Russia and Norway, *Precambrian Research*, *72*(1–2), 97–107, https://doi.org/10.1016/0301-9268(94)00045-s.

Vermeesch, P. (2018), IsoplotR: A free and open toolbox for geochronology, *Geoscience Frontiers*, *9*(5), 1479–1493, https://doi.org/10.1016/j.gsf.2018.04.001.

Vezinet, A., D. G. Pearson, and E. Thomassot (2021), Effects of contamination on whole-rock isochrons in ancient rocks: A numerical modelling approach, *Lithos*, *386–387*, 106,040, https://doi.org/10.1016/j.lithos.2021.106040.

Vrevsky, A. B., and A. P. Lvov (2016), Isotopic age and heterogeneous sources of gabbro-anorthosites from the Patchemvarek massif, Kola Peninsula, *Doklady Earth Sciences*, *469*(1), 716–721, https://doi.org/10.1134/s1028334x16070163.

Wang, D., S. B. Shirey, R. W. Carlson, et al. (2022), Comparative Sm-Nd isotope behavior of accessory minerals: Reconstructing the Sm-Nd isotope evolution of early Archean rocks, *Geochimica et Cosmochimica Acta*, *318*, 190–212, https://doi.org/10.1016/j.gca.2021.11.031.

Westhues, A., J. M. Hanchar, C. R. Voisey, et al. (2017), Tracing the fluid evolution of the Kiruna iron oxide apatite deposits using zircon, monazite, and whole rock trace elements and isotopic studies, *Chemical Geology*, *466*, 303–322, https://doi.org/10.1016/j.chemgeo.2017.06.020.

Yan, S., B. Wan, and U. B. Andersson (2023), Hydrothermal circulation at 1.8 Ga in the Kiruna area, northern Sweden, as revealed by apatite geochemical systematics, *Precambrian Research*, *395*, 107,151, https://doi.org/10.1016/j.precamres.2023.107151.

Zhang, H.-X., S.-Y. Jiang, S.-Q. Liu, et al. (2023), Sm-Nd and U-Pb isotope behavior of REE-rich accessory minerals in pegmatite during overprinted metamorphic and hydrothermal events: Evidence from the Paleoproterozoic rare-earth pegmatite in the lesser Qinling district of China, *Precambrian Research*, *389*, 107,020, https://doi.org/10.1016/j.precamres.2023.107020.

Zozulya, D., L. N. Morozova, K. Kullerud, et al. (2024), Nb-Ta-Sn Oxides from Lithium-Beryllium-Tantalum Pegmatite Deposits of the Kolmozero-Voronja Belt, NW Russia: Implications for Tracing Ore-Forming Processes and Mineralization Signatures, *Geosciences*, *14*(1), https://doi.org/10.3390/geosciences14010009.