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Sulfur isotope signatures of sulfides from the Khibina and Lovozero massifs (Kola Alkaline Province, Fennoscandian Shield)

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Abstract

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The sulfur isotope geochemistry of the Khibina and Lovozero apatitic massifs provides an opportunity to understand the role of plume-lithosphere interaction processes responsible for the Paleozoic alkaline igneous activity in the north-eastern part of the Fennoscandian Shield. The stable sulfur isotope $\delta^{34}\text{S}$ analysis using triple collector isotope ratio mass spectrometer (IRMS) has been carried out on the pentlandite, chalcopyrite and pyrite from nepheline syenites. The $\delta^{34}\text{S}$ values for pentlandite from Khibina rocks range from +0.69 to +2.06 ‰ relative to the Vienna Canyon Diablo Troilite standard (VCDT), and the pyrite has significantly higher $\delta^{34}\text{S}$ values up to +4.92 ‰ VCDT. The pentlandite from the Lovozero samples has value +1.48 ‰ VCDT, $\delta^{34}\text{S}$ values of chalcopyrite is +2.85 ‰ VCDT. The maximum positive $\delta^{34}\text{S}$ values are obtained for Lovozero pyrite, which vary from +5.41 to +6.30 ‰ VCDT. Comparison of sulfur-geochemical features of Khibina and Lovozero nepheline syenite with $\delta^{34}\text{S}$ data for the carbonatites from the Khibina, Sallanlatvi, Seblyavr, Vuoriarvi, Salmagora and Kovdor massifs show later carbonatite formation relatively to associated alkaline rocks. Geochemical sulfur isotope $\delta^{34}\text{S}$ investigations emphasizes that parental magmas of the Khibina and Lovozero alkaline massifs were derived from a metasomatized subcontinental lithospheric mantle (SCLM). We suggest that high- $\delta^{34}\text{S}$ signature on the SCLM ($\delta^{34}\text{S}$ of +1 to +6 ‰ VCDT) can be explained by subduction of the high- $\delta^{34}\text{S}$ Archaean crust.

Key words:

geochemistry,
sulfur stable isotope,
Khibina,
Lovozero,
Kola Alkaline Province,
Arctic zone of RF

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Изотопные характеристики серы сульфидов Хибинского и Ловозерского массивов (Кольская щелочная провинция, Фенноскандинавский щит)

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Геохимия изотопов серы Хибинского и Ловозерского апатитовых массивов дает возможность понять роль плюм-литосферных процессов, ответственных за палеозойскую щелочную магматическую активность в северо-восточной части Фенноскандинавского щита. Изотопный состав серы ($\delta^{34}\text{S}$) получен для пентландита, халькопирита и пирита из нефелиновых сиенитов с использованием масс-спектрометра с тройным коллектором (IRMS). Значения $\delta^{34}\text{S}$ пентландита из пород Хибинского массива варьируют от +0,69 до +2,06 ‰ относительно стандарта Вена-Каньон-Дьябло-Троилит (VCDT); значительно выше значения для пирита (+ 4,92 ‰ VCDT). Ловозерский пентландит имеет значение $\delta^{34}\text{S}$, равное +1,48 ‰ VCDT; $\delta^{34}\text{S}$ для халькопирита составляет +2,85 ‰ VCDT. Максимально положительные значения $\delta^{34}\text{S}$ для сульфидов Ловозерского массива получены для пирита (от +5,41 до +6,30 ‰ VCDT). Сравнение полученных данных с данными по изотопии серы для карбонатитов Хибин, Салланлатви, Себлявра, Вуориярви, Салмагоры и Ковдора указывает на более позднее образование карбонатитов относительно связанных с ними щелочных пород. Геохимические исследования изотопов серы показывают, что первичным магматическим источником Хибинского и Ловозерского щелочных массивов является метасоматизированная субконтинентальная литосферная мантия (SCLM). Сделано предположение, что высокие значения $\delta^{34}\text{S}$ для SCLM (от +1 до +6 ‰ VCDT) обусловлены субдукцией архейской коры, обогащенной тяжелым ^{34}S изотопом серы.

Ключевые слова:

геохимия,
стабильные изотопы
серы,
Хибинны,
Ловозеро,
Кольская щелочная
провинция,
Арктическая зона РФ

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Introduction

The Kola Alkaline Province (KAP) is one of the largest alkaline-carbonatite associations with more than 30 massifs occupying the Kola region, northern Karelia and Finland (Fig. 1). The main stage of alkaline igneous activity in the north-eastern part of the Fennoscandian Shield was marked by the biggest agpaite complexes of Khibina and Lovozero with numerous carbonatite intrusions of Kovdor, Sokli, Afrikanda, Turiy Mys which were formed in Late Devonian, at 365–370 Ma. The Khibina apatite-nepheline deposits with Lovozero REE commercial mineralization make a great contribution to the mineral resource base of the Arctic zone of the Russian Federation. Geophysical and geological data based on a prospecting drilling program give evidence for significant differences in the internal structure of two giant polyphase magmatic bodies, and commercial mineralization enclosed in these intrusions (Kramm *et al.*, 1993; Kogarko *et al.*, 2019).

The Khibina massif is a dome-shaped mountain massif, situated in the central part of the Kola Peninsula. It's located within Archaean gneisses and Proterozoic Pechenga-Imandra-Varzuga palaeoriftogenic volcanic-sedimentary complexes (Fig. 1). In the Khibina massif, peralkaline K-Na and K nepheline syenites are intercalated with the members of the typical ultrabasic-alkaline and carbonatite series. The Khibina massif is a concentrically zoned multiphase intrusion composed of agpaite nepheline syenites and in a minor amount of ultrabasic alkaline rocks. The zone of fenitized rocks extends for 50–200 m. Numerous nepheline syenite veins and alkaline pegmatites penetrated the country rocks at a distance of more than 100 m from the contact (Arzamastsev *et al.*, 2008).

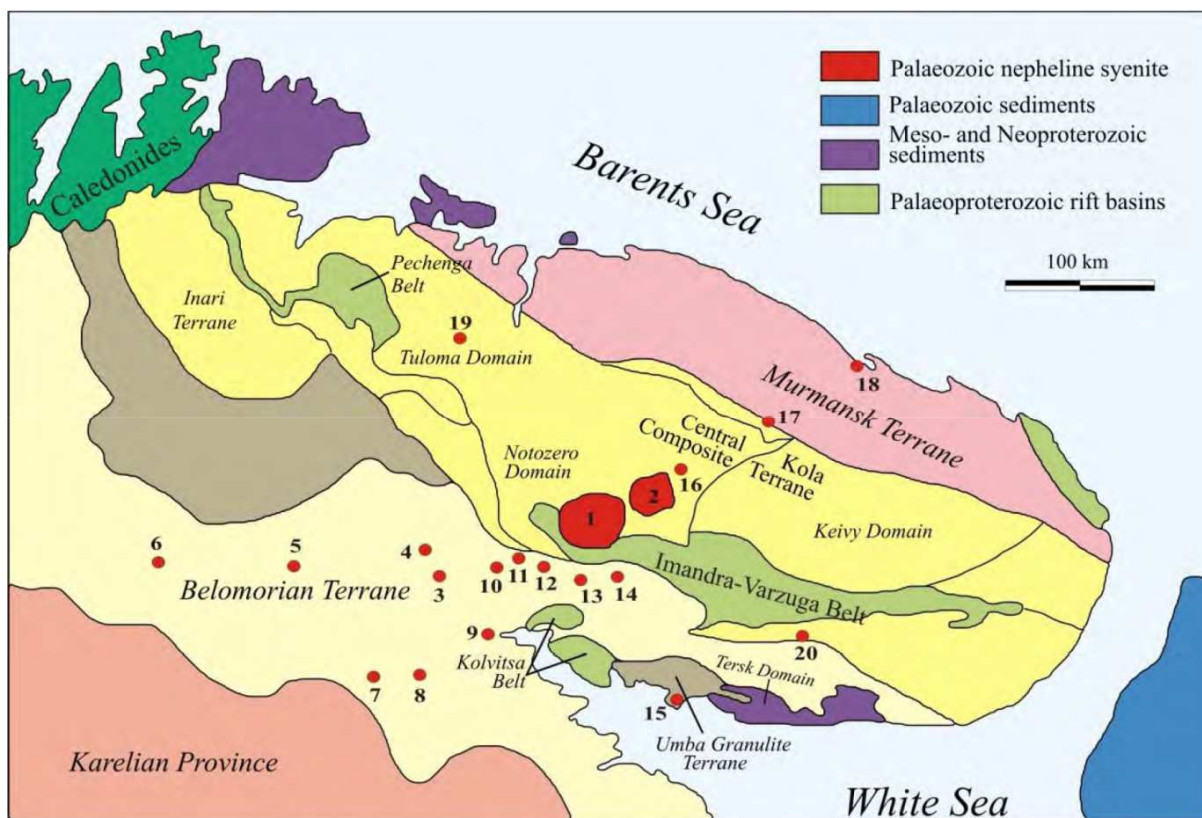


Fig. 1. Scheme of the locations of Kola Alkaline Province intrusions (Arzamastsev *et al.*, 2008):

- 1 – Khibina; 2 – Lovozero; 3 – Niva; 4 – Mavraguba; 5 – Kovdor; 6 – Sokli; 7 – Sallanlatva;
- 8 – Vuoriyarvi; 9 – Kandaguba; 10 – Afrikanda; 11 – Ozernaya Varaka; 12 – Lesnaya Varaka;
- 13 – Salmagora; 14 – Ingozero; 15 – Turiy Mys; 16 – Kurga; 17 – Kontozero; 18 – Ivanovka;
- 19 – Seblyavr; 20 – Pesochny

Рис. 1. Схема расположения интрузий Кольской щелочной провинции (Arzamastsev *et al.*, 2008):

- 1 – Хибины; 2 – Ловозеро; 3 – Нива; 4 – Маврагуба; 5 – Ковдор; 6 – Сокли; 7 – Салланлатва;
- 8 – Вуориярви; 9 – Кандагуба; 10 – Африканда; 11 – Озерная варака; 12 – Лесная варака;
- 13 – Салмагора; 14 – Ингозеро; 15 – Турий Мыс; 16 – Курга; 17 – Контозеро; 18 – Ивановка;
- 19 – Себлявр; 20 – Песочный

The Lovozero intrusive complex has the form of a laccolith with a broad base. The drilling program combined with three-dimensional modeling of gravity data made it possible to decipher the internal structure of the massif down to the depth of 10 km. According to these data, the Lovozero massif consists of two zones principally different in density. In the Lovozero massif, agpaitic lujavrites (type locality) form a rhythmic layered complex similar to that in Ilimaussaq, Greenland. A south-western zone, composed of agpaitic syenite to a depth of at least 10 km, is the most probable locus of the magma conduit. In the central part of the massif, at the Seidjavr Lake, a local negative gravity anomaly was detected, which corresponds to a body of alkaline and analcime syenite. A north-eastern zone is suggested to be composed of ultrabasic alkaline rocks similar to that of the adjacent Kurga alkaline-ultramafic massif. The south-eastern, southern, and western contacts of the massif are almost vertical to a depth of 4 km within the nepheline syenite zone but become sloping more gently at depths below 8–10 km. The northern and north-western contacts dip at smaller angles, which vary from 50–60° at the surface to 30–40° at depths of 4–5 km but become nearly vertical from this level to depths of 9–10 km. The alkaline rocks forming the Lovozero massif are represented by plutonic, subvolcanic, and volcanic magma products (Arzamastsev *et al.*, 2008).

Alkaline rocks are a powerful data set for understanding connections between surface and mantle sulfur reservoirs over geological timescales. Alkaline magmas (silicate rocks and carbonatites) are associated with mantle plumes (Sasada *et al.*, 1997; Marty *et al.*, 1998; Ernst *et al.*, 2010) and/or sub-continental lithospheric mantle (Goodenough *et al.*, 2002; Downes *et al.*, 2005) that has been metasomatised by fluids and melts derived from previously subducted slabs. Evolved alkaline rocks are also rich in sulfur-bearing minerals, which reflect the high solubility of sulfur in carbonatitic and alkaline silicate melts (Babiel *et al.*, 2018). There have been a large number of sulfur isotope investigations of alkaline complexes, few have thoroughly investigated how crustal contamination, degassing and fluid evolution (i. e. changes in temperature-pH-fO₂) altered the primary mantle signature. Understanding these processes is critical to unlocking the alkaline record of magma sources. Global data compilation reveals that $\delta^{34}\text{S}$ of alkaline magma sources fall between –5 and +5 ‰ VCDT. The igneous $\delta^{34}\text{S}$ time-series shows a temporal trend with Proterozoic alkaline magmas largely restricted to positive $\delta^{34}\text{S}$ values (0 – +5 ‰ VCDT) and Phanerozoic suites showing greater $\delta^{34}\text{S}$ diversity from –5 to +4 ‰ VCDT (Hutchison *et al.*, 2019). Here, we present a study of sulfur isotope signatures of the Khibina and Lovozero massifs and demonstrate that an enriched subduction-influenced source ($\delta^{34}\text{S}$ of +1 to +6 ‰ VCDT) can be reconstructed for the Kola alkaline province of the Fennoscandian Shield.

Materials and methods

The Khibina rock samples (01CH, 04CH and 10CH) were taken from massive nepheline syenite from Mt. Rasvumchorr outcrops. The Lovozero eudialyte-bearing nepheline syenites (01LV, 03LV, 04LV and 05 LV) were collected from the classical outcrops of lujavrite-foyaite-urtite rhythms, exposed at the foot of the western slope of Mt. Alluaiv (Fig. 2). These samples were described by petrography investigation in transmitted and reflected light with the polarized optical microscope Leica DM2500P (Fig. 3) and examined on the scanning electron microscope Hitachi SU6600 with the energy dispersion spectroscope (EDS) mode. The sulfide minerals have been chemically characterized by electron microprobe analysis. For the sulfur isotopes analysis the sulfide grains were hand-picked using a binocular magnifying glass, so the contamination of the accompanying sulfide phases was not excluded. These studies were implemented at the Department of Geology and Soil Science at the Faculty of Earth Sciences and Spatial Management of the Maria Curie-Skłodowska University (UMCS, Lublin, Poland).

The stable sulfur isotopes $\delta^{34}\text{S}$ study was carried out on the pentlandite ((Fe, Ni)₉S₈, samples 01CH, 10CH) and pyrite (FeS₂, sample 04CH) from Khibina nepheline syenite and on the pentlandite ((Fe, Ni)₉S₈, sample 04LV), chalcopyrite (CuFeS₂, sample 03LV) and pyrite (FeS₂, samples 01LV, 05LV) from Lovozero eudialyte-bearing nepheline syenite. Sulfur isotope analysis was undertaken at the Mass Spectrometry Laboratory of the Institute of Physics of the Maria Curie-Skłodowska University (UMCS, Lublin, Poland) by triple collector isotope ratio mass spectrometer (IRMS), using SO₂ as the analyzed gas. The sulfide mineral specimens were quantitatively converted to SO₂ in a vacuum line by their oxidation with analytical grade CuO reagent at temperatures between 800 and 900 °C. Along with the analyzed specimens, an aliquot of 20 mg of the IAEA-S1 standard (Ag₂S) was converted to SO₂ and analyzed using the mass spectrometer. All results are reported here in standard delta notation as per mil deviations from the Vienna-defined Canyon Diablo Troilite (VCDT). The precision of $\delta^{34}\text{S}$ values was 0.05 ‰.

Results and discussion

The Khibina massive nepheline syenites have coarse-grained structure and poikilitic texture (Fig. 3, *a, b*). The main minerals are automorphic orthoclase, plagioclases, and apatite, among which can be found crystals of aegirine-acmite and xenomorphic crystals of eudialyte. There are also present ilmenite, titanite, magnetite, arfvedsonite, riebeckite, astrophyllite, aenigmatite and lorenzenite. Among the ore minerals it can be found the vast majority of ilmenite, titanite and magnetite. In addition there are relatively often encountered sulfide phases such as pyrite (about 4 %) and in an amount of less than 1 % – chalcopyrite, pentlandite, and arsenopyrite. Chalcocine and sphalerite are also noticed in some samples. The sulfide phases from Khibina samples – pentlandite ((Fe, Ni)₉S₈, samples 01CH, 10CH) and pyrite (FeS₂, sample 04CH) – show a large spread in $\delta^{34}\text{S}$ values from +0.69 to +4.92 ‰ VCDT. The $\delta^{34}\text{S}$ values for two analysis of pentlandite range from +0.69 to +2.06 ‰, and the pyrite has significantly higher $\delta^{34}\text{S}$ values up to +4.92 ‰ VCDT (Table).

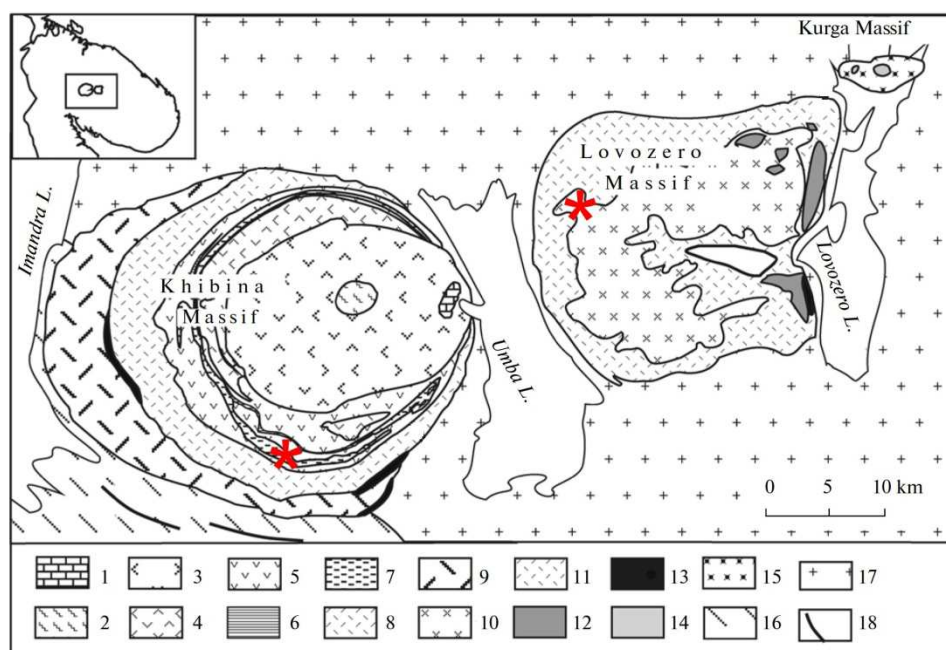


Fig. 2. Schematic geological map of the Khibina and Lovozero massifs (Arzamastsev et al., 2011).

Khibina massif: 1 – carbonatite; 2 – pulaskite; 3 – foyaite; 4 – nepheline syenite; 5 – massive rischorrite, jovite and urtite; 6 – apatite-nepheline rock; 7 – ijolite and melteigite; 8 – coarse-grained trachytoid nepheline syenite; 9 – coarse-grained massive nepheline syenite (khibinite). Lovozero massif: 10 – eudialyte lujavrite; 11 – lujavrite, foyaite and urtite of the differentiated complex; 12 – volcanic rocks of the Lovozero Formation; 13 – alkaline-ultramafic rocks. Kurga massif: 14 – nepheline syenite; 15 – peridotite. Host rocks: 16 – basaltic porphyry and dolerite (Late Proterozoic); 17 – granodiorite, tonalite, and trondhjemite (Archean); 18 – dikes of alkaline rocks. The stars indicate the sampling locations

Рис. 2. Схематическая геологическая карта Хибинского и Ловозерского массивов (Arzamastsev et al., 2011).

Хибинский массив: 1 – карбонатит; 2 – пуласкит; 3 – фойяит; 4 – нефелиновый сиенит; 5 – массивные рисчоррит, ювит и уртит; 6 – апатит-нефелиновая порода; 7 – ийолит и мельтейгит; 8 – крупнозернистый трахитоидный нефелиновый сиенит; 9 – крупнозернистый массивный нефелиновый сиенит (хибинит). Ловозерский массив: 10 – эвдиалитовый лувяврит; 11 – лувяврит, фойяит и уртит дифференцированного комплекса; 12 – вулканические породы ловозерской свиты; 13 – щелочно-ультраосновные породы. Кургинский массив: 14 – нефелиновый сиенит; 15 – перидотит.

Вмещающие породы: 16 – базальтовые порфиры и долериты (поздний протерозой);

17 – гранодиорит, тоналит и тронджемит (архей); 18 – дайки щелочных пород.

Звездами показаны места отбора образцов

The Lovozero eudialyte-bearing nepheline syenites are gray-green color rocks with visible red-blood crystals of eudialyte and fine-crystalline feldspars and aegirine (Fig. 3, *c, d*). These rocks have a coarse-grained structure and a porphyritic, linear texture. The orthoclase crystals, twinned according to the Carlsbad law, often have a very elongated form giving the rocks a linear and pseudo-ophitic structure. Between these crystals there are also albite tablets. When an interaction between the minerals occurs, one meets the needles of aegirine in the company of ilmenite and titanomagnetite, as well as individual rutile and titanite grains. The stable sulfur isotopes analyses have been carried out on the three sulfide phases from the Lovozero samples: pentlandite ((Fe,

Ni)₉S₈, sample 04LV), chalcopyrite (CuFeS₂, sample 03LV), and pyrite (FeS₂, samples 01LV, 05LV). The results of the sulfur isotopes study $\delta^{34}\text{S}$ vary widely from +1.48 to +6.30 ‰ VCDT (Table). The pentlandite in the Lovozero samples has value +1.48 ‰ VCDT, $\delta^{34}\text{S}$ values of chalcopyrite is +2.85 ‰ VCDT. The maximum positive $\delta^{34}\text{S}$ values are obtained for pyrite, which vary from +5.41 to +6.30 ‰ VCDT (Table).

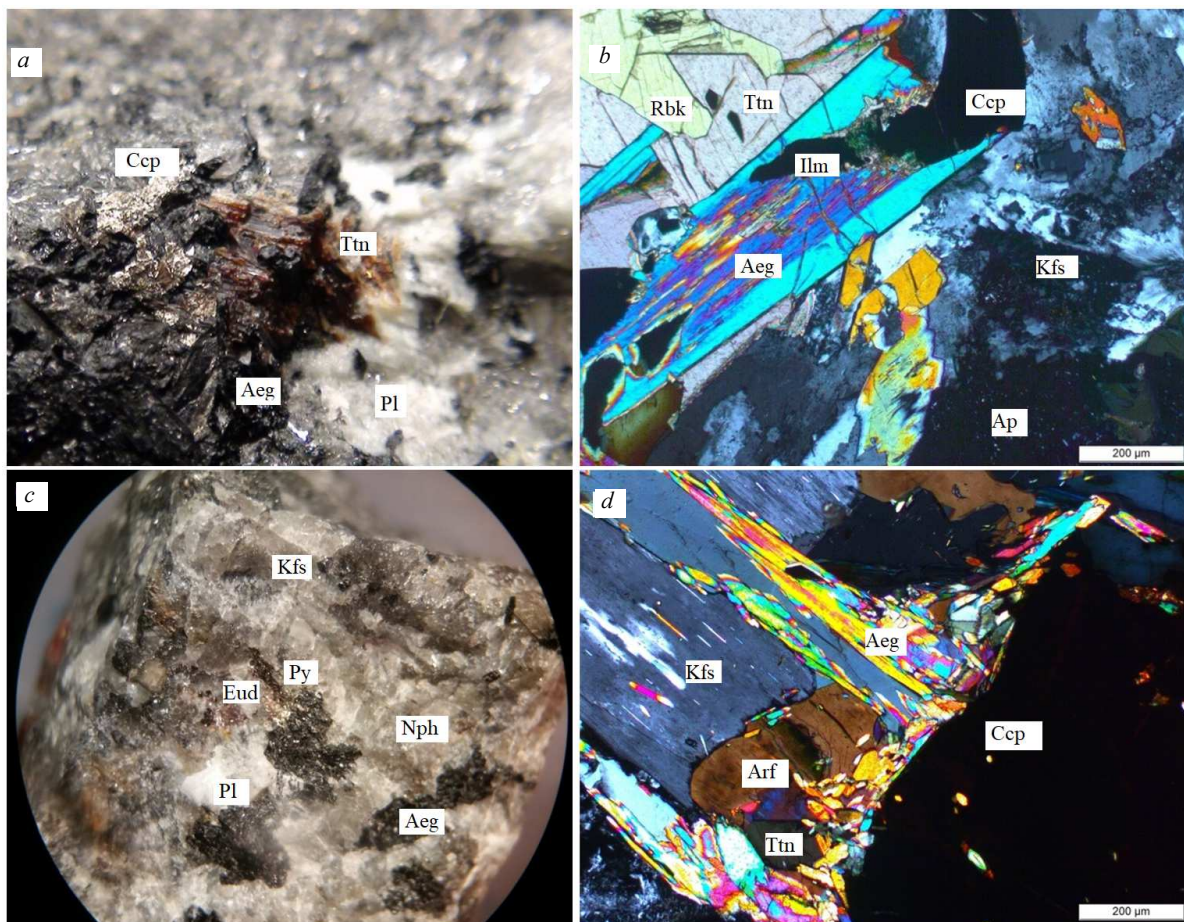


Fig. 3. Photos of the Khibina (*a, b* – sample 01CH) and Lovozero (*c, d* – sample 04LV) samples of sulfide-bearing nepheline syenite. *b, d* – photo of the polished thin section in transmitted light. Mineral symbols: Py – pyrite; Ccp – chalcopyrite; Kfs – orthoclase; Pl – plagioclase; Rbk – riebeckite; Aeg – aegirine; Nph – nepheline; Ap – apatite; Arf – arfvedsonite; Eud – eudialyte; Ttn – titanite; Ilm – ilmenite

Рис. 3. Фотографии образцов сульфидсодержащих нефелиновых сиенитов Хибинского (*a, b*) и Ловозерского массивов (*c, d*). *b, d* – фотография полированного шлифа в проходящем свете. Символы минералов: Py – пирит; Ccp – халькопирит; Kfs – ортоклаз; Pl – плагиоклаз; Rbk – рибекит; Aeg – эгирин; Ne – нефелин; Ap – апатит; Arf – арфведсонит; Eud – эвдиалит; Ttn – титанит; Ilm – ильменит

Table. $\delta^{34}\text{S}$ isotope data for sulfides from nepheline syenite of the Khibina and Lovozero massifs
Таблица. Изотопные $\delta^{34}\text{S}$ данные для сульфидов из нефелиновых сиенитов Хибинского и Ловозерского массивов

Massif	Khibina			Lovozero			
	01CH	10CH	04CH	04LV	03LV	01LV	05LV
Sample	Pn	Pn	Py	Pn	Ccp	Py	Py
$\delta^{34}\text{S}_{\text{VCDT}}$ (‰)	0.69	1.90–2.06	4.80–4.92	1.48	2.85	5.41	5.45–6.30

Variation in the $\delta^{34}\text{S}$ signature can be explained by changes in the redox conditions, fluid sources, and/or the temperature of the hydrothermal fluid. The ranges in $\delta^{34}\text{S}$ values are generally large but vary according to the isotopic fractionation between the sulfide phase and the melt or fluid. This is evidenced by mineral associations, including numerous sulfide minerals such as pentlandite, chalcopyrite and pyrite, which are accompanied by

arsenopyrite, sphalerite and barite. The admixture of these minerals among the analyzed sulfides contributed to the isotopic contamination of sulfur and changes in $\delta^{34}\text{S}$. Almost invariably, there is a decrease in $\delta^{34}\text{S}$ between early and later formed sulfides within a given system (Hutchison et al., 2019). For example, the sulfur isotopic composition ($\delta^{34}\text{S}$) of galena (PbS) from the carbonatites (Khibina, Sallanlatvi, Seblyavr, Vuoriyarvi and Kovdor), as well as from hydrothermal veins of the Khibina massif is significantly lighter than the mantle value of 0 ‰ VCDT (Bell et al., 2015; Hutchison et al., 2019). Conversely, the nepheline syenites which belong to the early magmatic rocks of Khibina and Lovozero massifs contain sulphides with positive $\delta^{34}\text{S}$ values (Table, Fig. 4).

Geochemical sulfur isotope $\delta^{34}\text{S}$ investigations emphasize that parental magmas of the Khibina and Lovozero alkaline massifs were derived from a metasomatized sub-continental lithospheric mantle (Fig. 4). These results correlate with the previous studies, which have shown that the isotopic composition of the carbonatites, alkaline rocks, and rare-metal ores estimated indicates that many of them have mantle sources. It was recently confirmed by the work on the Pb-isotopic composition of the alkaline rocks from the KAP (Kogarko et al., 2019). Earlier, the noble gas isotopic data of carbonatites also confirm that the KAP was likely related to a lower mantle plume (Tolstikhin et al., 2002; Marty et al., 1998), and radiogenic isotopes also support ancient (potentially Archaean) sources (Bell et al., 2015). The published isotopic data indicate multistage evolution of the Khibina – Lovozero volcanic and plutonic system. First of all, at the premagmatic stage 427 ± 6 Ma ago the plume triggered mantle metasomatism that preceded the vigorous Paleozoic magmatism (Arzamastsev et al., 2011). The impact of the plume on the upper mantle metasomatically altered under subduction conditions entailed the interaction of the plume and subduction sulfur-enriched component ($\delta^{34}\text{S}$ of +1 to +6 ‰ VCDT) in the magma source. Since subduction exerts an important control on SCLM composition, this would suggest that high- $\delta^{34}\text{S}$ Archaean crust were subducted and imprinted a high- $\delta^{34}\text{S}$ signature on the SCLM. There is hypothesis argues that a missing Archaean sulphur pool, injected into the mantle at ancient subduction zones and stored in the deep mantle, occasionally recycled back to the near surface in mantle plumes (Farquhar et al., 2016). Thus, our favored hypothesis is that parental magmas of the Khibina and Lovozero alkaline massifs are associated with subcontinental lithospheric mantle that has been metasomatised by fluids and melts derived from previously subducted slabs.

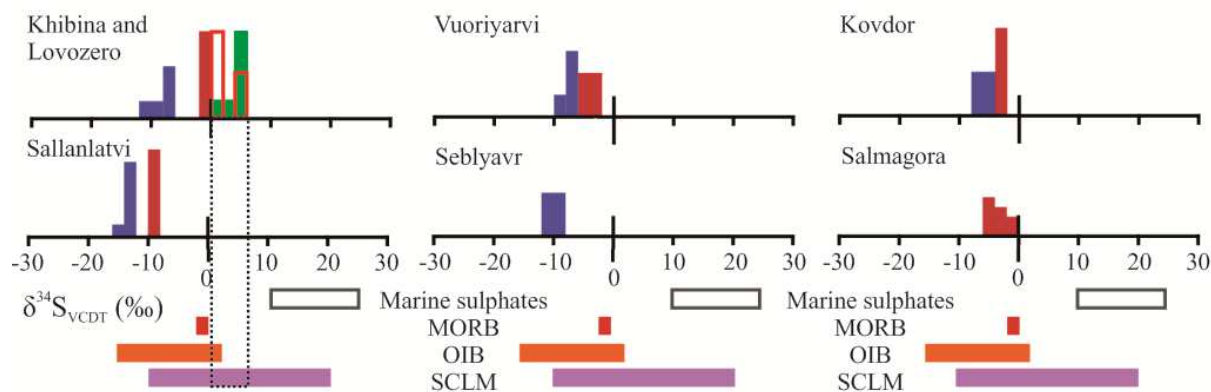


Fig. 4. Compilation of stable sulfur isotopes $\delta^{34}\text{S}$ data for sulfides from the Khibina nepheline syenite (red outlined bars) and Lovozero nepheline syenite (green filled bars) with $\delta^{34}\text{S}$ data for galena (PbS) from the carbonatites (red and blue filled bars) from the Khibina, Sallanlatvi, Seblyavr, Vuoriyarvi, Salmagora, and Kovdor massifs. Normalized histograms show early- (red) and late-stage (blue) $\delta^{34}\text{S}$ for galena from the carbonatites (Bell et al., 2015; Hutchison et al., 2019). The $\delta^{34}\text{S}$ values of potential sulfur sources are shown by the bars at the base of the plot and include marine sulfates (Farquhar et al., 2010); MORB – mid-ocean ridge basalt (Labidi et al., 2012); OIB – ocean island basalt (Labidi et al., 2015; Cabral et al., 2013; Delavault et al., 2016); SCLM – sub-continental lithospheric mantle (Giuliani et al., 2016)

Рис. 4. Обобщение данных по стабильным изотопам серы $\delta^{34}\text{S}$ для сульфидов из нефелиновых сиенитов Хибинского (красные, не залитые блоки) и Ловозерского (зеленые блоки) массивов и для галенита (PbS) из карбонатитов (красные и синие блоки) Хибинского, Салланлатви, Себлявр, Vuoriyarvi, Салмагора и Ковдорского массивов. Нормализованные гистограммы показывают раннюю (красный) и позднюю стадии (синий) $\delta^{34}\text{S}$ для галенита из карбонатитов (Bell et al., 2015; Hutchison et al., 2019). Значения $\delta^{34}\text{S}$ потенциальных источников серы показаны интервалами в основании графика и включают: морские сульфаты (Farquhar et al., 2010); MORB – базальты срединно-океанического хребта (Labidi et al., 2012); OIB – базальты океанических островов (Labidi et al., 2015; Cabral et al., 2013; Delavault et al., 2016); SCLM – субконтинентальная литосферная мантия (Giuliani et al., 2016)

Conclusion

The sulfur isotope geochemistry of the two world biggest agpaitic complexes of the Khibina and Lovozero, which are the key magmatic centers of the Paleozoic KAP, provides an opportunity to understand the role of plume-lithosphere interaction processes responsible for the alkaline igneous activity in the north-eastern part of the Fennoscandian Shield. The stable sulfur isotope $\delta^{34}\text{S}$ study has been carried out on the pentlandite $(\text{Fe, Ni})_9\text{S}_8$ and pyrite (FeS_2) from Khibina nepheline syenite and on the pentlandite $(\text{Fe, Ni})_9\text{S}_8$, chalcopyrite (CuFeS_2) and pyrite (FeS_2) from Lovozero eudialyte-bearing nepheline syenite. The ranges in $\delta^{34}\text{S}$ values are generally large (from +0.69 to +6.30 ‰ VCDT), but vary according to the isotopic fractionation between the sulfide phase and the melt or fluid. Comparison of sulfur-geochemical features of Khibina and Lovozero nepheline syenite with $\delta^{34}\text{S}$ data for the carbonatites from the Khibina, Sallanlatvi, Seblyavr, Vuoriarvi, Salmagora and Kovdor massifs show later carbonatite formation relatively to associated alkaline rocks. Geochemical sulfur isotope $\delta^{34}\text{S}$ investigations emphasize that parental magmas of the Khibina and Lovozero alkaline massifs were derived from a metasomatized sulfur-enriched ($\delta^{34}\text{S}$ of +1 to +6 ‰ VCDT) subcontinental lithospheric mantle (SCLM). We suggest that high- $\delta^{34}\text{S}$ signature on the SCLM can be explained by high- $\delta^{34}\text{S}$ Archaean crust subduction.

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Conflict of interest

The authors declare no conflict of interest.

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