Rare-metal pegmatites of the Soldat-Myl’k pegmatite field: geology, geochemistry of rare elements

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Abstract. Rare-metal pegmatites, in which spodumene is a major mineral of lithium, form vein series, or occur as individual veins in pegmatite fields. One such example is the Soldat-Myl’k pegmatite field located in the south-eastern Kola rare-metal pegmatite belt of the Baltic Shield (Kola Peninsula, Russia). Geologically the pegmatite field is situated on the Kolmozero-Voronya greenstone belt, and includes a vein of albite-spodumene pegmatites, veins of Ta-Nb feldspar pegmatites, and veins of ore-free pegmatites. The new data on a rare element content in rare-metal pegmatites determined using the ICP-MS method have been obtained. The study results have indicated that albite-spodumene pegmatites correspond to LCT rare-metal pegmatites by their mineralogical and geochemical features. Compared to a granite clarkite, albite-spodumene pegmatites are enriched in Li, Nb, Ta, Be, Cs, Rb, Hf, U, depleted in Ba, Sr, Y, Th, REE, and have low values of indicators of ratios, i.e. Mg/Li (0.43), Nb/Ta (1.29), Zr/Hf (8.3), Ba/Rb (0.01), Sr/Rb (0.02). Ore minerals in pegmatites occur as spodumene, beryl, and minerals of the columbite group. Spodumene content in pegmatites is ~20% of the total volume of veins. Albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field differ from rare-metal pegmatites of the Kolmozero lithium deposit by higher contents of boron (29-fold enrichment), phosphorus, medium (Gd, Tb, Dy) and heavy lanthanoids, lower contents of lithium (17-fold depliation), and a weakly differentiated spectrum of lanthanoid dissemination. Feldspar pegmatites with the Ta-Nb mineralisation have high contents of Ta, Nb, Rb, Hf, U, B, and are depleted in Ba, Sr, Y, Th, REE. There is a lowering (ppm) of LREE (1.91 and 1.07, respectively), MREE (2.11 and 0.61, respectively), LREE (0.29 and 0.19, respectively) from Ta-Nb feldspar pegmatites to albite-spodumene pegmatites. Mean values of indicators of ratios, i.e. Mg/Li, Nb/Ta, Zr/Hf, Ba/Rb, Sr/Rb, also indicate a characteristic lowering from feldspar pegmatites with the Ta-Nb mineralisation (9.74, 1.70, 10.9, 0.05, 0.06, respectively) to albite-spodumene pegmatites with the Be-Nb-Ta mineralisation (0.43, 1.29, 8.3, 0.01, 0.02, respectively). Results of geochemical studies taking into account the mineralogical data indicate that rare-metal pegmatites of the Soldat-Myl’k pegmatite field can be of practical interest in relation to the rare-metal mineralisation.

1. Introduction
Around the world, there is a growing interest in albite-spodumene pegmatites, which are a significant source of lithium. In addition to lithium, these pegmatites contain Nb, Ta, Sn, Cs, Be, and other rare elements. Large deposits of albite-spodumene pegmatites are located in Canada, the USA, China, Australia, Russia, Brazil, Zimbabwe, and other countries throughout the world [1], [2], [3], [4], [5], [6], [7], [8]. Lithium reserves can reach one million tons in such deposits [9]. Apart from famous...
deposits, individual veins of albite-spodumene pegmatites are of interest. They can be also prospective with regard to lithium.

The Kola rare-metal pegmatite belt located on the Baltic Shield includes large lithium deposits of albite-spodumene pegmatites, i.e. Polmos-Tundra and Kolmozero (Kola Peninsula, Russia) [10]. In addition to these lithium deposits, there are individual veins of albite-spodumene pegmatites within the Kola pegmatite belt. One such example is a vein of albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field. This paper presents new data on contents of rare and ore elements in rare-metal pegmatites of the Soldat-Myl’k pegmatite field. They have been compared to rare-metal pegmatites of the Kolmozero lithium deposit. The study material has been collected during geological field works on the Soldat-Myl’k pegmatite field.

2. Research methods

Samples from a central part of the albite-spodumene pegmatites (CM-101-1; CM-102-GX) and central parts of feldspar pegmatite veins (CM-87-2; CM-87-3) of the Soldat-Myl’k pegmatite field have been collected in order to attain the envisaged objectives. The content of rare elements in pegmatites has been determined for the first time using the mass-spectroscopy with inductively coupled plasma (ICP-MS) in the Analytical Centre of the Trofimuk United Institute of Geology, Geophysics, and Mineralogy SB RAS (Novosibirsk). Contents of Li, Be, and B have been determined for the first time using the ICP-MS method on the ELAN-9000 DRC-e mass-spectrometer (Perkin Elmer, USA) in the laboratory of chemical and optic methods of analysis of the I.V. Tanaev Institute of Chemistry and Technology of Rare Minerals and Raw Materials (Apatity). Accuracy of the conducted measurements has been confirmed by analysing the SSS 812-75, SSS 8670-2005, and SSS 519-84II state standard reference samples of composition. The studies of the petrographic composition have been carried out on the Axioplan-2 optical microscope.

3. Main part

Geologically, the Soldat-Myl’k pegmatite field is located in the southeastern of the Archaean Kolmozero-Voron’ya Greenstone Belt (Figure 1).

![Figure 1](image-url)
The Soldat-Myl’k pegmatite field is located on the Kola rare-metal pegmatite belt 32 km north-west of the Kolmozero lithium deposit (Kola Peninsula, Russia). The pegmatite field includes a vein of albite-spodumene pegmatites, veins of Ta-Nb feldspar pegmatites, and veins of feldspar ore-free pegmatites. Veins of various pegmatites are deposited in amphibolites, biotites, and amphibolite-biotite gneisses of the Kolmozero-Voron’ya greenstone belt [12]. Albite-spodumene pegmatites and the Ta-Nb feldspar pegmatites are the subjects of studies. The study of ore-free pegmatites has not been carried out.

The vein of albite-spodumene pegmatites occurs in a central part of the Soldat-Myl’k pegmatite field. It is ~ 400 m long and 45 to 85 m thick. The vein stretches out to the north-east, dips to the south-west at 70–80°. The vein is plate-like and has intersecting contacts with amphibolites of the Kolmozero-Voronya greenstone belt. The vein is weakly differentiated. A fine-to-medium grained quartz-feldspar aggregate is fragmentarily developed in the vein selvage. A major part of the vein is composed of coarse-to-megagraned quartz-spodumene-feldspar pegmatite. Major rock-forming minerals of rare-metal pegmatites are quartz (25–30%), plagioclase (35–40%), potassium feldspar (10–15%), spodumene (~20%). Ore minerals are spodumene, beryl, minerals of the columbite group. Accessory minerals are black tourmaline, garnet, and muscovite.

Spodumene from albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field, unlike greenish spodumene from the Kolmozero deposit rare-metal pegmatites, is white, grayish-white (Figure 2).

![Figure 2. Spodumene (Spd) in albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field.](image)

Compared to rare-metal pegmatites of the Kolmozero deposit, black tourmaline in the Soldat-Myl’k albite-spodumene pegmatites is widely developed as small grains and (or) crystals of up to 9×2 cm.

In the Soldat-Myl’k pegmatite field, veins of Nb-Ta feldspar pegmatites are deposited in biotite and amphibolite-biotites of the Kolmozero-Voronya greenstone belt. The veins are 50 to 150 m long and 10 to 20 m thick. Major rock-forming minerals are quartz (25–30%), plagioclase (45–50%), and potassium feldspar (25–30%).

Table 1 shows the content of rare and ore elements in pegmatites of the Soldat-Myl’k pegmatite field.

The study results indicate that albite-spodumene pegmatites are significantly enriched in Li (17-fold enrichment), Be (19-fold enrichment), Nb (~3-fold enrichment), Ta (~13-fold enrichment), Cs (7.5-fold enrichment), Rb (5-fold enrichment), B (12-fold enrichment), U (1.6-fold enrichment), and Hf (1.3-fold enrichment) compared to the granite clarke. In relation to Sr, Y, Zr, Ba, REE, and Th, there is reverse trend. Compared to the granite clarke, albite-spodumene pegmatites are depleted in Sr, Ba, Y, Zr, REE, Th (Figure 3).
Table 1. Content of rare elements (ppm) in albite-spodumene pegmatites (1–2) and Nb-Ta feldspar pegmatites (3–4) of the Soldat-Myl’k pegmatite field and a granite clarke (5)

| Elements | CM-101-1 | CM-102-FX | CM-87-2 | CM-87-3 | Granite clarke 5 |
|----------|----------|-----------|---------|---------|-----------------|
| Rb       | 860      | 1261      | 442.06  | 433.47  | 200             |
| Li       | 743.2    | 603.85    | 26.94   | 65.03   | 40              |
| Be       | 103.4    | -         | 2.39    | 3.24    | 5.5             |
| Sr       | 13.1     | 29        | 3.83    | 48.38   | 300             |
| Y        | 1.16     | 0.86      | 3.59    | 1.34    | 34              |
| Zr       | 11.8     | 10.1      | 15.38   | 15.80   | 200             |
| Nb       | 66       | 50        | 93.28   | 56.15   | 20              |
| Ta       | 46       | 44        | 37.87   | 50.10   | 3.5             |
| Cs       | 34       | 41        | 1.89    | 22.96   | 5               |
| Ba       | ≤5.00    | ≤5.0      | ≤5.00   | 35.28   | 830             |
| La       | 0.25     | 0.15      | 0.75    | 0.31    | 60              |
| Ce       | 0.47     | 1.19      | 1.82    | 0.64    | 100             |
| Pr       | 0.042    | 0.044     | 0.23    | 0.08    | 12              |
| Nd       | 0.12     | 0.11      | 0.59    | 0.25    | 46              |
| Sm       | 0.14     | 0.099     | 0.67    | 0.26    | 9               |
| Eu       | 0.01     | 0.005     | 0.02    | 0.01    | 1.5             |
| Gd       | 0.16     | 0.12      | 0.84    | 0.27    | 9               |
| Tb       | 0.052    | 0.025     | 0.21    | 0.08    | 2.5             |
| Dy       | 0.25     | 0.15      | 0.76    | 0.26    | 6.7             |
| Ho       | 0.028    | 0.023     | 0.08    | 0.03    | 2               |
| Er       | 0.060    | 0.055     | 0.14    | 0.07    | 4               |
| Tm       | 0.012    | 0.010     | 0.02    | 0.01    | 0.3             |
| Yb       | 0.072    | 0.068     | 0.13    | 0.07    | 4               |
| Lu       | 0.011    | 0.008     | 0.02    | 0.01    | 1               |
| Hf       | 1.29     | 1.37      | 1.54    | 1.33    | 1               |
| Th       | 0.72     | 0.57      | 0.45    | 0.90    | 18              |
| U        | 6.1      | 5.3       | 6.01    | 8.76    | 3.5             |
| B        | 190.7    | -         | 331.70  | 626.00  | 15              |

Note. Dash – element content is not determined.

Graphs of dissemination of REE normalised to chondrite for albite-spodumene pegmatites typically have a weakly differentiated spectrum of lanthanoid dissemination \((\text{La/Yb})_N = 1.47\text{–}2.31\) with a clearly defined negative Eu-anomaly \((\text{Eu/Eu}^* = 0.10\text{–}0.14\) (Figure 4). The negative Eu-anomaly at low Sr contents indicates that plagioclase is fractionated during enrichment of the melt incompatible components [15]. These geochemical features determined in albite-spodumene pegmatites of the Soldat-Myl’k pegmatites field are typical for LCT-pegmatites [16–25]. Compared to the granite clarke, feldspar pegmatites with the Ta-Nb mineralisation are also enriched in Nb (3.7-fold enrichment), Ta (~13-fold enrichment), Cs (~4-fold enrichment), Rb (2-fold enrichment), U (2-fold enrichment), B (32-fold enrichment), and Hf (1.4-fold enrichment). The content of Be, Sr, Ba, Y, Zr, REE, Th in feldspar pegmatites with the Ta-Nb mineralisation is lower than in the granite clarke.
Figure 3. Distribution of rare elements in pegmatites of the Soldier-Myl’k pegmatite field and Kolmozero deposit. Normalized to a clark granite, after [13].

Figure 4. Chondrite-normalized REEs in pegmatites of the Soldier-Myl’k pegmatite field. Normalizing values after [14]

Graphs of dissemination of REE normalised to chondrite for Ta-Nb feldspar pegmatites typically have a weakly fractionated spectrum of lanthanoid dissemination ((La/Yb)$_N$ = 4.04–2.82) with a well-defined negative Eu-anomaly (Eu/Eu* = 0.09–0.06) (Figure 4).
There is a lowering (ppm) of LREE (1.91 and 1.07, respectively), MREE (2.11 and 0.61, respectively), LREE (0.29 and 0.19, respectively) from Ta-Nb feldspar pegmatites to albite-spodumene pegmatites. Mean values of indicators of ratios, i.e. Mg/Li, Nb/Ta, Zr/Hf, Ba/Rb, Sr/Rb, also indicate a characteristic lowering from feldspar pegmatites with the Ta-Nb mineralisation (9.74, 1.70, 10.9, 0.05, 0.06, respectively) to albite-spodumene pegmatites with the Be-Nb-Ta mineralisation (0.43, 1.29, 8.3, 0.01, 0.02, respectively). A significant positive correlation relationship between Sr/Rb‒Sr (r = 0.92) and Ba/Rb-Ba (r = 0.99) has been determined for all types of pegmatites.

A characteristic lowering of contents of LREE, MREE, HREE and mean values of indicators of ratios, i.e. Mg/Li, Nb/Ta, Zr/Hf, Ba/Rb, Sr/Rb, from feldspar pegmatites to albite-spodumene pegmatites, if there is a negative Eu-anomaly, can be related to formation of various types of pegmatites from one granite source during plagioclase fractionation.

Albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field have been compared to albite-spodumene pegmatites of the Kolmozero deposit [27, 28]. It has been found that the Soldat-Myl’k albite-spodumene pegmatites, as well as Kolmozero deposit albite-spodumene pegmatites, are enriched in Li, Nb, Ta, Be, Cs, Rb, Hf, U, depleted in Ba, Sr, Y, Th, REE and have low values of indicators of ratios, i.e. Mg/Li, Nb/Ta, Zr/Hf, Ba/Rb, Sr/Rb. As ore minerals, albite-spodumene pegmatites contain spodumene, beryl, and minerals of the columbite group. The spodumene content in pegmatites is ~20% of the total volume of veins, so albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field can be considered as prospective in relation to lithium.

Albite-spodumene pegmatites of the Soldat-Myl’k pegmatite field differ from rare-metal pegmatites of the Kolmozero lithium deposit by higher contents of boron (29-fold enrichment), phosphorus, medium (Gd, Tb, Dy) and heavy lanthanoids, lower Li contents (17-fold depletion), and a weakly differentiated spectrum of lanthanoid dissemination (La/Yb)N (Figure 5). Various degrees of enrichment of rare-metal pegmatite sources in boron, fluorine, lithium, and REE is one possible explanations for these differences.

![Figure 5](image_url) Chondrite-normalized REEs in rare-metal pegmatites of the Soldat-Myl’k pegmatite field and pegmatites of the Kolmozero deposit. Normalizing values after [14]

The following conclusions can be made based on the conducted studies:
1. The Soldat-Myl’k albite-spodumene pegmatites correspond to rare-metal LCT pegmatites by its mineralogical and geochemical characteristics. Compared to the granite clarke, albite-spodumene pegmatites are markedly enriched in Li, Nb, Ta, Be, Cs, Rb, Hf, U and depleted in Ba, Sr, Y, Th, REE.


Albite-spodumene pegmatites have low values of indicators of ratios, i.e. Mg/Li (0.43), Nb/Ta (1.29), Zr/Hf (8.3), Ba/Rb (0.01), Sr/Rb (0.02), and are highly differentiated varieties of the residual granite melt. Ore minerals in pegmatites occur as spodumene, beryl, and minerals of the columbite group. The spodumene content in pegmatites is ~20% of the total volume of veins.

2. Results of geochemical studies taking into account the mineralogical data indicate that rare-metal pegmatites of the Soldat-Myl’k pegmatite field can be of practical interest in relation to the rare-metal mineralisation.

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