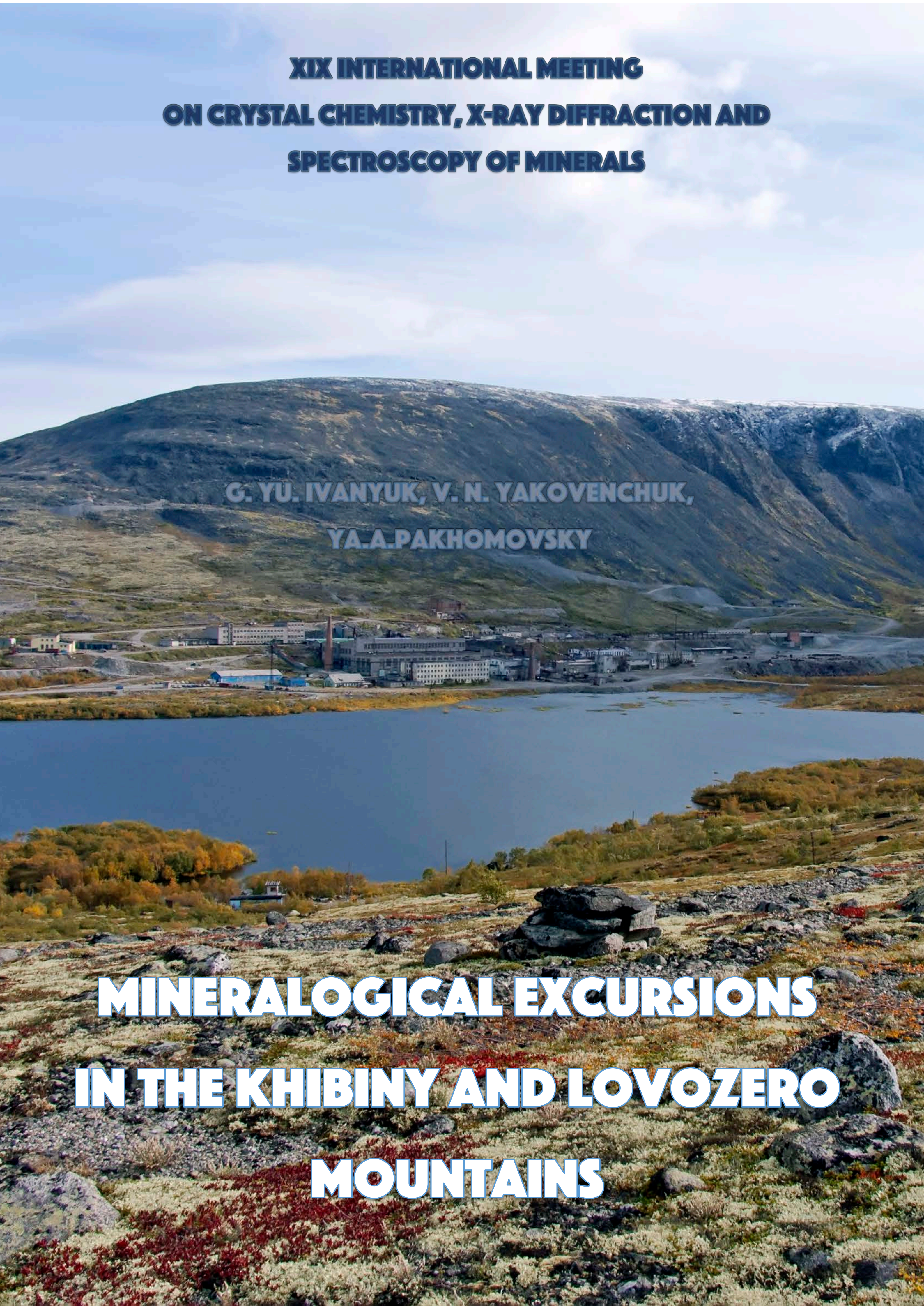

XIX INTERNATIONAL MEETING
ON CRYSTAL CHEMISTRY, X-RAY DIFFRACTION AND
SPECTROSCOPY OF MINERALS

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MINERALOGICAL EXCURSIONS IN THE KHIBINY AND LOVOZERO MOUNTAINS

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Introduction

The Murmansk Region is situated in the north-eastern part of the Fennoscandinavian Shield, the largest outcrop of Precambrian in Europe (Fig. 1). About 90 % of its area is occupied by Archaean ultrametamorphic complexes (Kola-Norvegian, Murmansk, Keivy, Belomorian blocks consisting mostly of biotite, muscovite-biotite and sillimanite-biotite and garnet-biotite gneisses; hornblende and gedrite gneiss–amphibolite; mica, staurolite and kyanite schists; Banded Iron Formations), separated by the Archaean–Early Proterozoic granulite and greenstone belts of komatiites, Banded Iron Formations, hornblende gneiss and amphybolites (the Uraguba-Voronya-Kolmozero belt), chlorite, epidote, actinolite and black shists, dolomite, limestone and sandstone (the Pechenga-Imandra-Varzuga and Salla-Kuolayarvi belts), garnet-quartz-feldspar, garnet-hornblende and diopside-hyperstene granulites and gneisses (the Kandalaksha-Laplandian belt). Narrow belts of Late Proterozoic sedimentary rocks (sandstone, quartzite and aleurolite) lie along the White Sea and Barentz Sea coastlines (Balagansky et al., 1996; Mitrofanov et al., 2000; Kozlov et al., 2006; Ivanyuk et al., 2009).

About 8% of the territory is represented by Late Archaean to Carbon igneous complexes: granite, peralkaline granite, alkaline and alkaline-ultrabasic plutons and basic-ultrabasic complexes. Numerous gabbro-anorthosite massifs (2.7–2.1 Ga) with Fe-Ti, Cu-Ni, Cr and Pt-Pd deposits are widespread within the greenstone and granulite belts. Large granodiorite massifs (1.8 Ga) occur mainly in granite-gneisses of the Kola-Norvegian and Belomorian blocks.

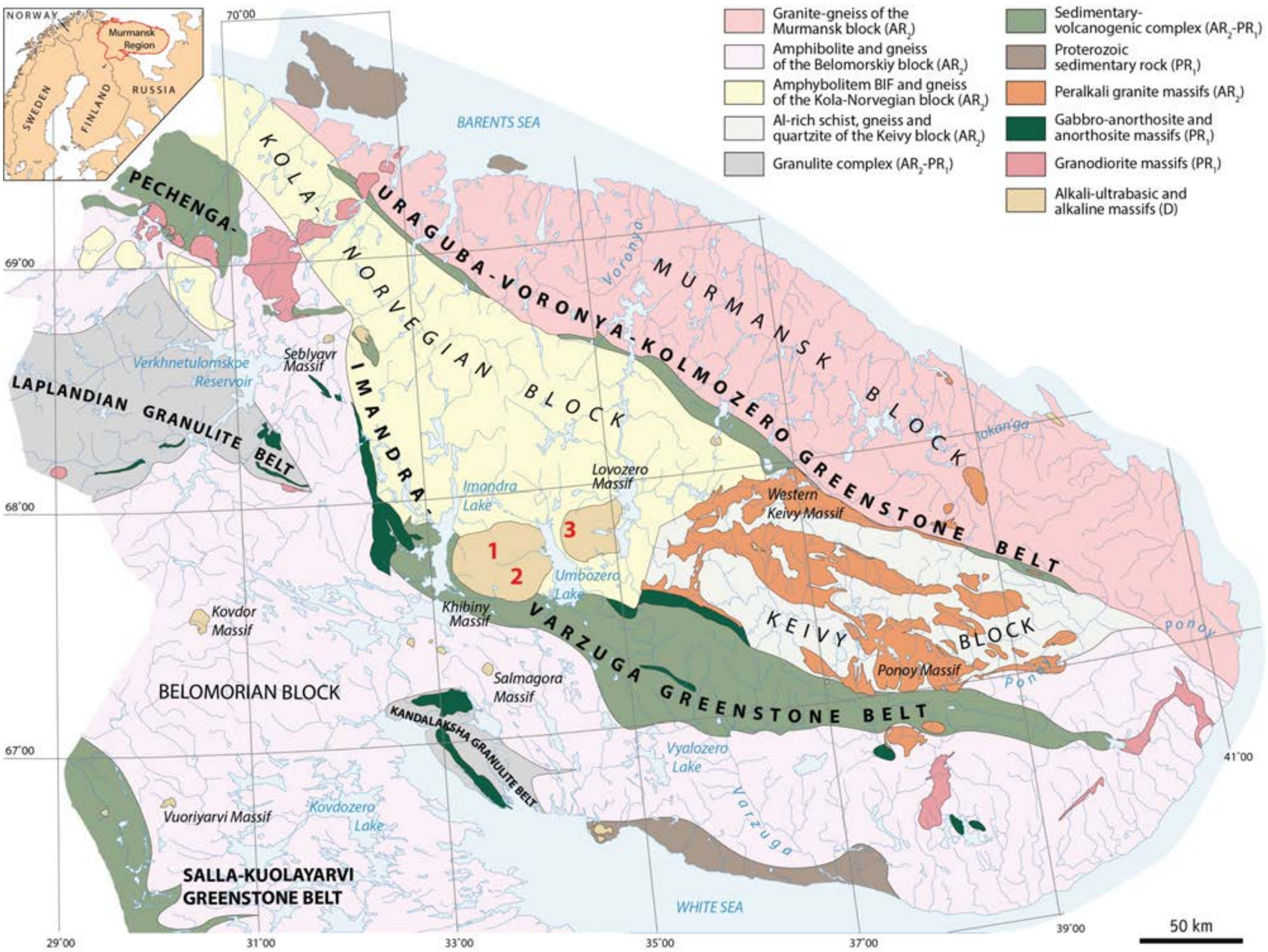


Fig. 1. Simplified geological map of the Murmansk Region.
1–3 – Excursion numbers

Alkaline magmatism has played a crucial role in the Kola Rare Earth metallogenic province. It took place during the formation of the Fennoscandinavian Shield – from Archaean to Paleozoic. The Keivy block was a result of peralkaline granite magmatism in the Archaean stage (2.6 Ga). At the final stage of the Karelian green-stone belts development (2.2–2.6 Ga), alkaline magmatism was expressed by most ancient nepheline syenite of the Sakharyok massif within peralkaline granites of the Keivy block. The Proterozoic stage resulted in the alkaline-ultrabasic rocks of the Soustov and Gremyakha-Vyrmes massifs (1.9 Ga) situated within the Pechenga–Varzuga greenstone belt. The end of the Paleozoic trap effusion epoch was marked by the acme of the alkaline magmatism (350-400 Ma) which generated the world's largest alkaline plutons Khibiny and Lovozero, and a quantity of alkaline-ultrabasic massifs with carbonatites (Korchak et al., 2011; Ivanyuk et al., 2012a; Kalashnikov et al., 2016; Mikhailova et al., 2017).

Alkaline and alkaline-ultrabasic massifs of the Kola Peninsula are unrestrained world's leaders in mineral diversity (Ivanyuk et al., 2012b). More than 700 mineral species have been found here, and more than 200 of them – for the first time in the world (Fig. 2). A lot of minerals discovered in these massifs attract a special attention as prototypes of new functional materials. Synthetic analogues of zorite, chuvruaiite, ivanyukite, sitinakite, strontiofluorite and other minerals are promising materials for a wide range of industrial applications, including gas separation, catalysis, radioactive waste management, pharmacology, optics, laser production etc. (Krivovichev et al., 2008, 2012).

The world's largest Khibiny and Lovozero alkaline massif are the leaders in mineral diversity and quantity of firstly discovered minerals (Ivanyuk et al., 2012b). The trip will provide an opportunity to visit giant Koashva deposit of apatite, nepheline and titanite, as well as the most interesting pegmatites of Mts Marchenko, Eveslogchorr (the Khibiny massif) and Alluaiv (the Lovozero massif) including type localities of ancylite-(La), paraumbite, denisovite, chivruaiite, eliseevite, punkaruaivite and belovite-(La). Also, you can see one of the best landscapes of Russian Laplandia.

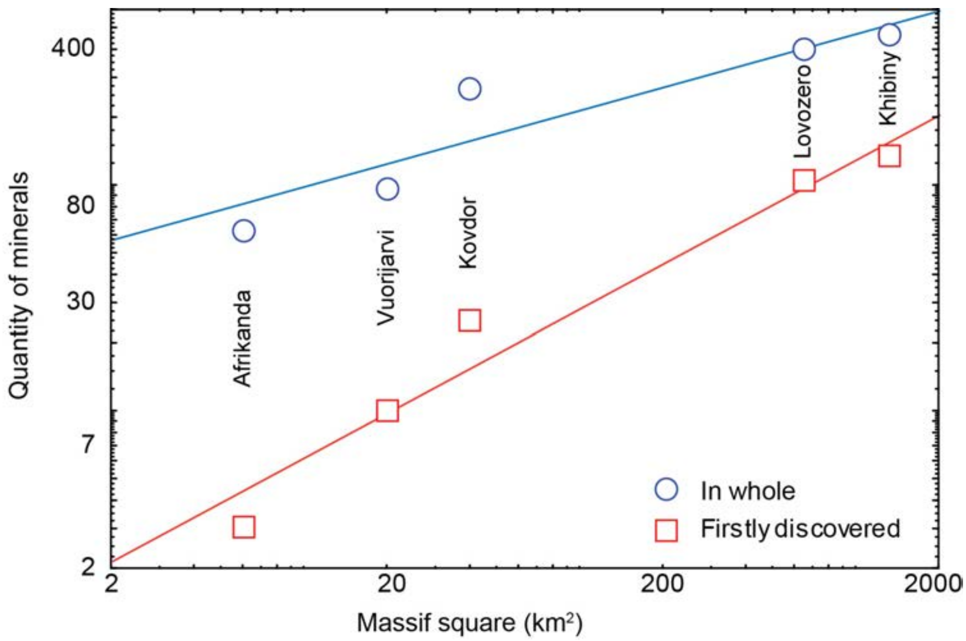


Fig. 2. Quantity of known minerals in alkaline and alkaline-ultrabasic massifs of the Kola province

Geology of the Khibiny massif

The Khibiny massif with area of about 1327 km^2 is the world's largest alkaline complex (Fig. 3). It is situated in the center of the Murmansk Region, at the contact of the Imandra-Varzuga Proterozoic greenstone belt and the the Archaean metamorphic complexes of the Kola-Norwegian megablock (see Fig. 1). The massif represents an oval of 45×35 km in plan while vertically it has a cone-like form with apex pointing downwards (Shablinsky, 1963). Based on Pb-Pb, Rb-Sr and Sm-Nd dating, it formed 380–360 Ma (Kramm and Kogarko, 1994; Arzamastsev et al., 2007). The complex predominantly consists of foyaite (about 70% of total area) and foidolite (8%) intruded into the foyaite massif along the Main Ring fault (Ivanyuk et al., 2012a). Brief characteristics of these and other alkaline rocks are shown in Table 1. High-potassic poikilitic nepheline syenites, "rischorrites" (10%), often lie in between the Main Ring's rocks and foyaite.

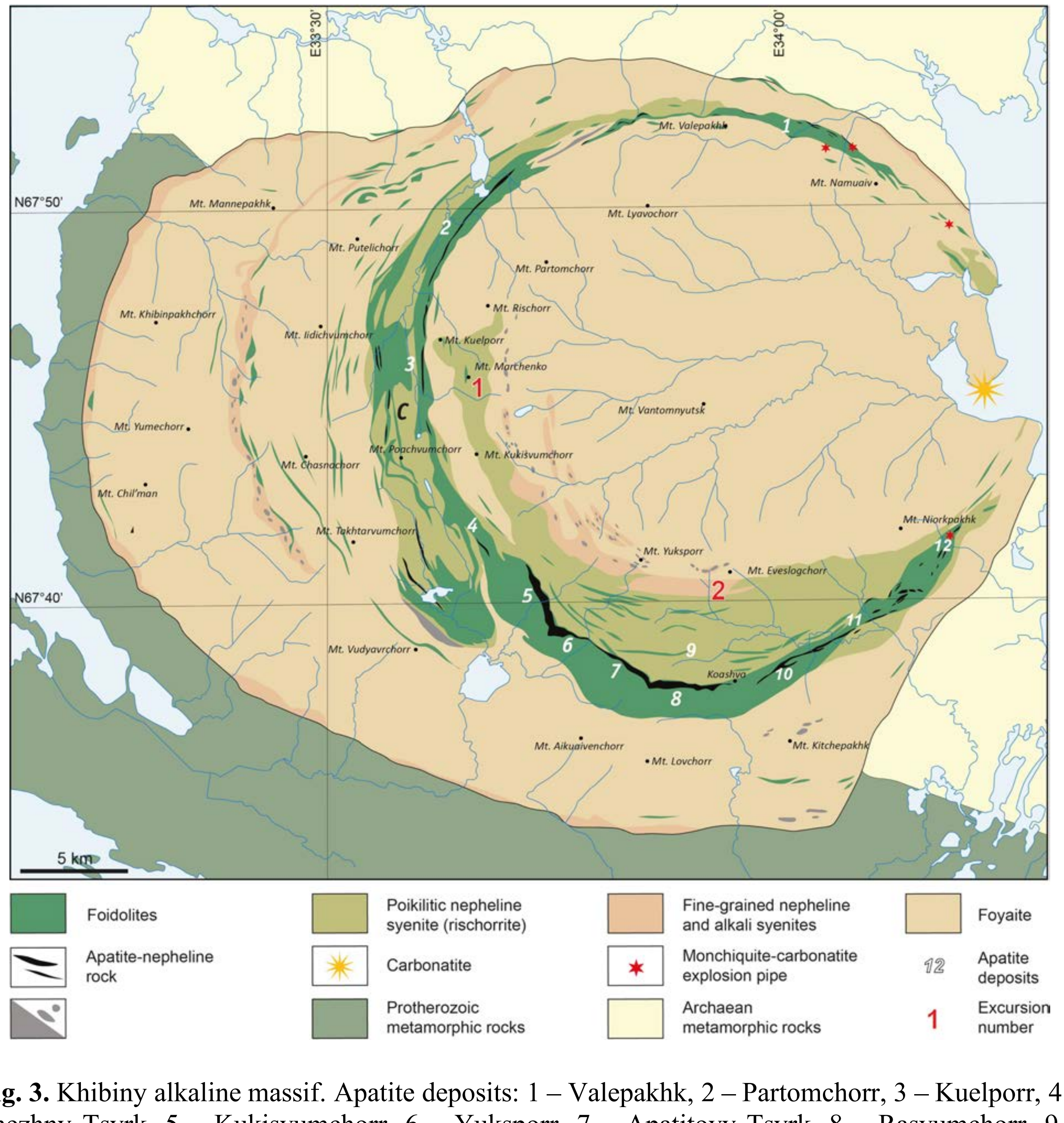
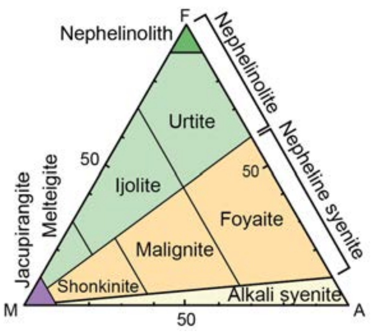


Fig. 3. Khibiny alkaline massif. Apatite deposits: 1 – Valepakhk, 2 – Partomchorr, 3 – Kuelporr, 4 – Snezhny Tsyrk, 5 – Kukisvumchorr, 6 – Yuksporr, 7 – Apatitovy Tsyrk, 8 – Rasvumchorr, 9 – Eveslogchorr, 10 – Koashva, 11 – Nyorkpakhk, 12 – Oleny Ruchey.

Table 1. Rocks hosting REE deposits and occurrences in the Murmansk Region

<table>
<tr><td colspan="2">Rock</td><td colspan="2">Main minerals (modal %), structural features</td><td>Typical minor and accessory minerals</td></tr>
<tr><td rowspan="3">Foidolite (nephelinolite)</td><td>Urtite</td><td rowspan="6">
</td><td rowspan="6">F – nepheline (±sodalite, kalsilite, natrolite);

A – potassic feldspar and albite (An_{0-5});

M – aegirin–diopside, K-Na-Ca amphyboles, fluorapatite, titanite, loparite-(Ce), biotite, eudialyte, etc.</td><td rowspan="8">Astrophyllite, (baryto)lamprophyllite, (mangano)eudialyte, rinkite, wadeite, labuntsovite group minerals, lomonosovite, murmanite, lovozerite, titanomagnetite, ilmenite, perovskite, loparite-(Ce), pyrrhotite, (chlor)bartonite</td></tr>
<tr><td>Ijolite</td></tr>
<tr><td>Melteigite</td></tr>
<tr><td rowspan="5">Nepheline syenite</td><td>Foyaite</td></tr>
<tr><td>Malignite</td></tr>
<tr><td>Shonkinite</td></tr>
<tr><td>Rischorrite</td><td colspan="2">Poikilitic nepheline syenite</td></tr>
<tr><td>Lujavrite</td><td colspan="2">Trachitoid nepheline syenite</td></tr>
</table>

The foidolite Main Ring accommodates all apatite deposits and occurrences. The apatite-nepheline and titanite-apatite-nepheline ores (apatite- and titanite-rich ijolite–melteigite with 7.5–16.2% of P_2O_5) form ore stockworks in apical parts of the melteigite-ijolite-urtite complex, and the rocks as such represent titanite-fluorapatite stockworks in foidolites. Thickness of the apatite-rich foidolites ranges from 200 m in the south-eastern part of the Main Ring to a few meters in its north-eastern part (Ivanyuk et al., 2012*a*). The Main Ring incorporates three ore fields – NW, SW, and SE – containing 12 apatite deposits (Kalashnikov et al., 2016).

The NW ore field extends for more than 10 km and includes the Partomchorr and Kuelporr deposits, and the Snezhny Tsyrk occurrence (see Fig. 2). Ore bodies of these deposits have simple layer- or lens-like form with average thickness of 50–70 m (Ivanyuk et al., 2009, 2012*a*).

The SW ore field includes Kukisvumchorr, Yuksporr, Apatitovy Tsyrk, Rasvumchorr, and Eveslogchorr deposits (see Fig. 3). All of these deposits are bulges of continuous 12 km long apatite-bearing body with average thickness of about 100 m (Kamenev, 1987; Yakovenchuk et al., 2005; Ivanyuk et al., 2012*a*). At its upper level, every deposit is a compact lens-like ore body. At its deep levels the body diverges into different lenses. The main ore body is characterized by distinct vertical zonation and gradual decrease in thickness and P_2O_5 content at depth, with titanite-bearing ores confined to the top contact of the ore body (Fig. 4).

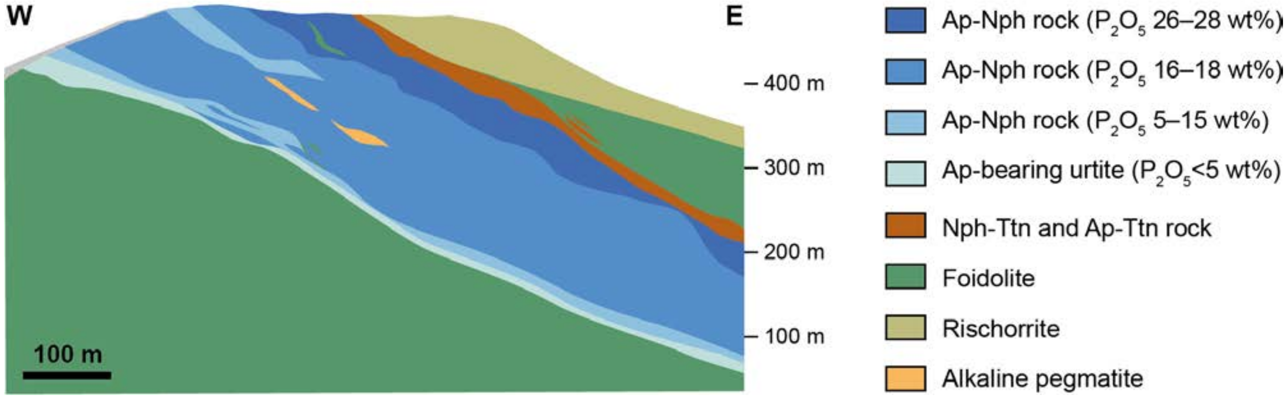


Fig. 4. A vertical section of the Kukisvumchorr titanite-apatite-nepheline ore body

The SE ore field extends for about 15 km and includes the most complicated Koashva, Vuonemyok, Nyorkpakhk, and Oleny Ruchey deposits. Ore zones of the deposits are formed by anisotropic fractal stockworks of (titanite)-apatite-nepheline ores; the titanite-rich ores concentrate within 20-40 m thick zones along the top contact of the ore body (Goryainov et al., 2007; Ivanyuk et al., 2009; Ivanyuk et al., 2012*a*). Block-diagram and a general view of the Koashva deposit are shown in Fig. 5. At present time, seven apatite deposits are being mined: Kukisvumchorr, Yuksporr, Apatitovy Tsyrk, Rasvumchorr, Koashva, and Nyorkpakhk operated by JSC "Apatit" (PhosAgro Corp.), and the Oleny Ruchey apatite deposit mined by JSC "North-Western Phosphorous Company" who also currently explores the Partomchorr deposit.

During the proposed excursions you can visit the Koashva apatite deposit and mostly interesting mineral localities of Mts Marchenko and Eveslogchorr (see Figs 1 and 3).

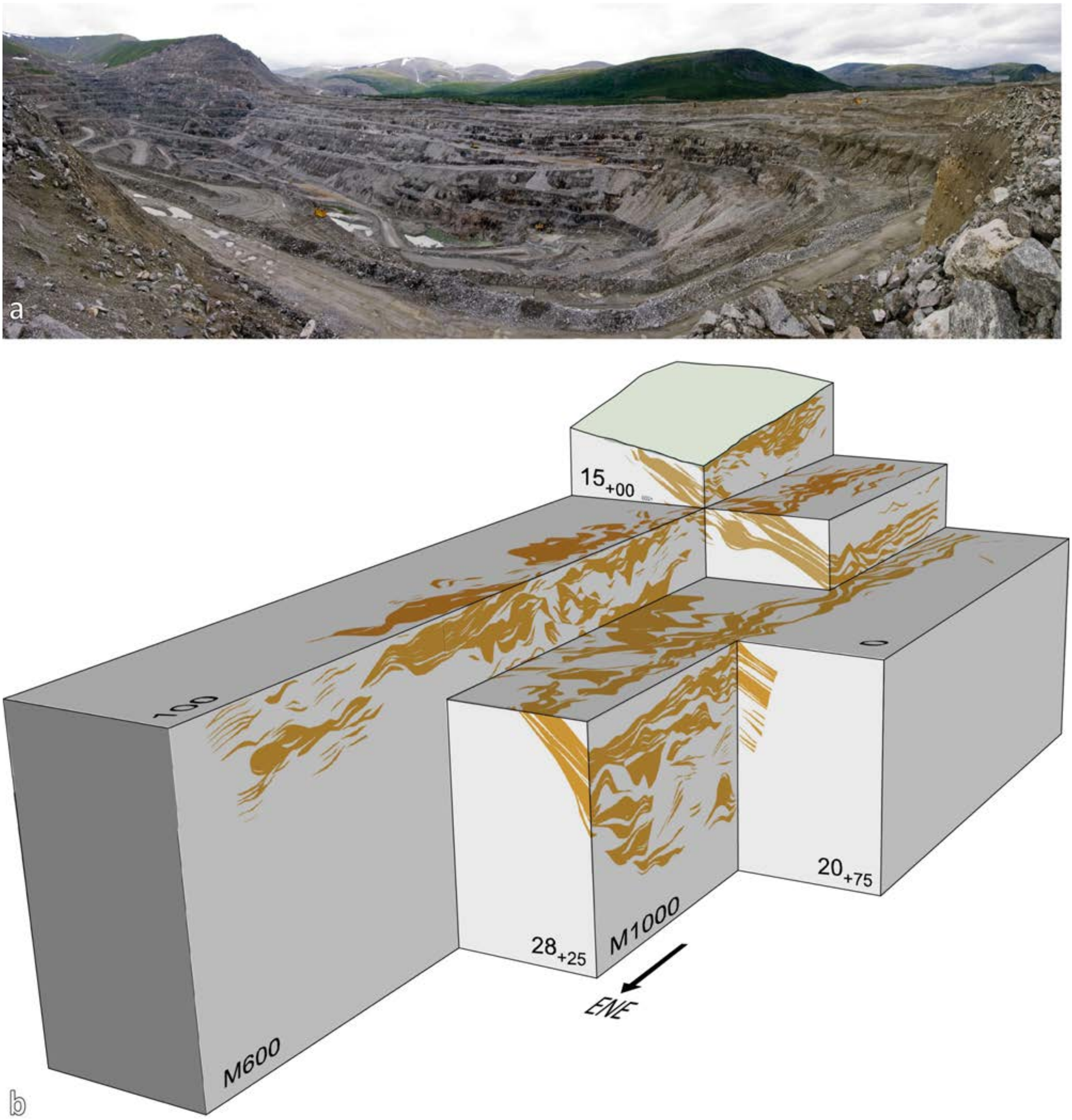


Fig. 5. General view (a) and block-diagram (b) of the Koashva apatite deposit

Mineralogical excursions in the Khibiny massif

Day 1: Pegmatites within rischorrite at the Marchenko Peak

Apatite-titanite veinlets in rischorrite. Pegmatites with ilmenite, zircon, lorenzenite, eudialyte, sodalite, ancylite-(La), etc. Length 1 km, elevation 400 m (Fig. 6).

Stop 1-1A. Sodalite-aegirine-microcline vein in rischorrite, (about 500 m from the vechicle, elevation 100 m). A lens-shaped vein, up to 1 m wide (Fig. 7), which is composed of large light-brown and greenish-brown crystals of microcline (up to 20 cm), with interstitial thin-fibrous green aegirine and sodalite. The lower contact of the vein is sharp and marked by a 5–10 cm wide zone consisting of an aggregate of black elongate-prismatic aegirine (up to 3 cm long) with inclusions of sodalite, light-brown crystals of zircon (up to 1 cm along an edge), elongate-prismatic lorenzenite (up to 2 cm long), and colourless tabular catapleiite (up to 5 mm diameter). The upper contact is indistinct with a gradational transition into rischorrite. In the centre of the vein there are numerous voids. The walls of these voids are encrusted with a dark-green parallel-fibrous aggregate of aegirine, which in turn is overgrown by large rhombic dodecahedral crystals of sodalite (up to 15 cm diameter) partially replaced by natrolite. The remainder of the void space is filled with a friable mixture of dark-green aegirine and phlogopite, amongst which there are separate crystals and aggregates of sodalite. The sodalite has a very bright lilac colour but instantly turns grey when exposed to daylight. In the upper part of the vein, aegirine is less common and sodalite crystals grow directly on microcline. It is necessary to emphasize that the degree of replacement of sodalite by natrolite here is much higher, so relics of sodalite remain only in the central parts of crystals. In voids, there are black crystals of highly altered sphalerite (up to 2 cm), well-shaped transparent crystals of fluorapophyllite (up to 6 mm long) and wadeite (up to 1 mm diameter), elongate-prismatic crystals and aggregates of lorenzenite and also phlogopite (up to 5 cm long). In the main mass of microcline, there are sheaf-like aggregates of semi-transparent light-brown bladed catapleiite (up to 15 cm diameter). These are sometimes exposed in voids and in these cases, sodalite has also grown on the catapleiite. Voids inside large feldspar crystals are often filled with a frame-like aggregate of straw-yellow ancylite-(Ce).

Minerals: aegirine, ancylite-(Ce), catapleiite, fluorapophyllite, lorenzenite, microcline, natrolite, sodalite, sphalerite, phlogopite, wadeite, zircon.

Fig. 6. The Marchenko Peak. It is shown positions of mineral localities 1-1 – 1-5.

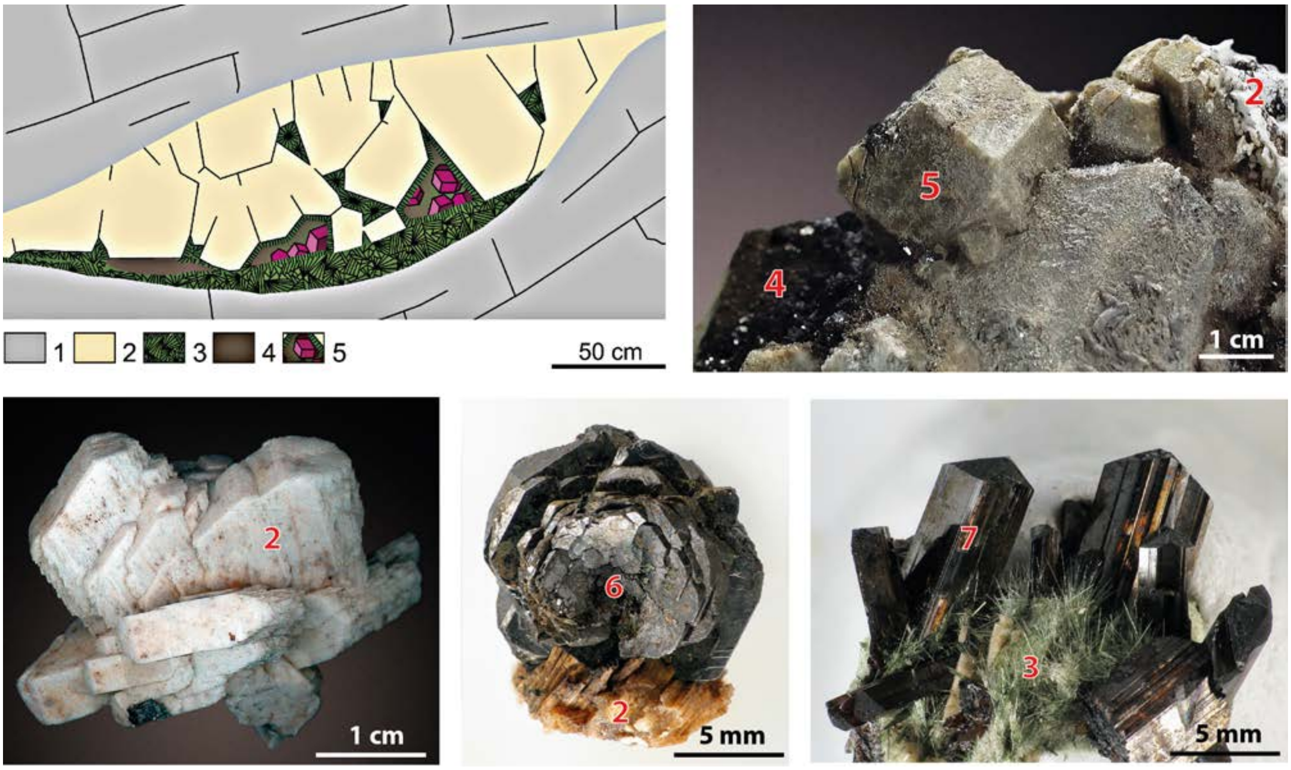


Fig. 7. Aegirine-microcline vein 1-1 in rischorrite, Marchenko Peak. 1 – rischorrite, 2 – microcline, 3 – aegirine, 4 – friable aegirine-phlogopite aggregate, 5 – sodalite, 6 – ilmenite, 7 – lorenzenite

Stop 1-1B. Aegirine-microcline vein in rischorrite, (about 500 m from the vehicle, elevation 100 m). A lens-shaped vein about 1.5 m wide with a distinct symmetric-zoned structure:

1. The selvages are up to 50 cm wide and are composed of fibrous aegirine, amongst which, and at the borders with the microcline core, there are large pale-brown crystals of zircon (up to 1 cm);
2. A zone is made of 20 cm diameter aggregates of microcline. Voids in this zone contain pseudomorphs of natrolite after sodalite (rhombic dodecahedra up to 6 cm diameter) and after nepheline (prismatic six-faced crystals up to 4 cm long and 2 cm diameter), as well as black elongate-prismatic crystals of phlogopite (up to 5 cm long). Large clusters (up to 10 cm diameter) of dipyramidal ancylite-(Ce) (up to 1 mm long) occur in interstices and inside hollow crystals of microcline. Pale-brown dipyramidal crystals of zircon (up to 1.5 cm) are included in microcline or grow on its crystal faces within voids;
3. The axial zone is composed of druses of green, thick-tabular microcline, up to 8 cm diameter. Within numerous voids (up to 40 × 40 × 10 cm) there are regular crystals and aggregates of microcline and phlogopite, and also tabular ilmenite crystals (up to 11 cm diameter, Fig. 13), pale-brown dipyramidal zircon crystals (up to 3 cm along an edge), semi-transparent dark-brown elongate-prismatic lorenzenite crystals (up to 4 cm long), and fine-crystalline segregations (up to 7 cm diameter) of ancylite-(Ce).

<u>Minerals</u>: aegirine, ancylite-(Ce), ilmenite, lorenzenite, microcline, natrolite, sodalite, phlogopite, zircon.

Stop 1-2. Microcline vein in rischorrite (about 700 m from the vehicle, elevation 200 m). A large vein up to 1 m wide and 20 m along strike (Fig. 8), with a symmetric-zoned structure:

1. The selvages are 5–10 cm wide and composed of an entangled-fibrous aggregate of light-green aegirine;
2. Thin cancrinite-nepheline zones (1–10 cm wide) are composed of semi-transparent, yellowish-grey nodules of nepheline (up to 10 cm) replaced by parallel-columnar or radiating aggregates of yellow, fibrous cancrinite or, less often, by colourless radiating natrolite with small inclusions of goethite;

Fig. 8. Microcline vein 1-2 in rischorrite, Marchenko Peak. 1 – zircon, 2 – microcline, 3 – ilmenite

3. The axial zone, 60–80 cm wide, is formed by 20 cm diameter, greenish-grey, tabular crystals of microcline, with interstitial radiating aggregates of green, thin-fibrous aegirine, and aggregates of elongate-prismatic crystals of annite (up to 6 cm long). In the mass of microcline and also in voids, there are numerous thin-tabular crystals of ilmenite (up to 4 cm diameter and 5 mm wide). These are often entirely replaced by an aggregate of anatase, hisingerite and manganese oxides. In the same zone, there are unique, brilliant semitransparent dipyramidal crystals of zircon (up to 6 cm along each edge, Fig. 15). They vary in colour from pale-brown, almost colourless, to dark-reddish-brown. Zircon crystals in the mass of microcline or grown on microcline within voids are often zoned, with a dark-brown core and pale-yellow marginal rim. Some interstices within the microcline aggregate are filled with small pale-yellow crystals of ancylite-(Ce), strong dark-blue tabular anatase (up to 0.3 mm) or colourless crystals of natrolite (up to 3 cm long).

Ten metres below the vein, further along the slope, there are clusters of natrolite-microcline blocks, apparently also the remnants of the disintegrated natrolite core of the vein. Microcline occurs here as greenish-grey, tabular crystals (up to 7 cm diameter), natrolite as porous aggregates of elongate-prismatic crystals (up to 5 cm long) and fine-grained pseudomorphs after six-faced cancrinite(?), up to 4 cm long and 1 cm diameter. Large light-brown dipyramidal crystals of zircon (up to 4 cm diameter) grow on microcline crystals.

<u>Minerals</u>: aegirine, anatase, ancylite-(Ce), annite, cancrinite, goethite, hisingerite, ilmenite, microcline, natrolite, nepheline, zircon.

Stop 1-3. Microcline-aegirine-natrolite vein in rischorrite (about 700 m from the vehicle, elevation 350 m). A vein with three large swellings (1–1.5 m wide, Fig. 9). Each swelling has a similar structure but their zones vary in size:

1. The selvages are composed of coarse-grained, cavernous microcline with druses of mosaic microcline within voids. Within the mass of microcline, there are black acicular aegirine crystals (up to 5 cm long), tabular ilmenite crystals (up to 8 cm diameter and 1 cm wide, Fig. 17) and dipyramidal zircon crystals (up to 1 cm diameter). In voids, aegirine occurs as spherulites of grassy-green acicular crystals, and zircon and ilmenite occur as perfect crystals;
2. An intermediate zone is dominant within the lower swelling but practically absent within the upper one. It is composed of thin-acicular green aegirine, microcline crystals (up to 15 cm diameter), ilmenite (up to 6 cm diameter), zircon (up to 1 cm), natrolite (up to 10 cm long) and ancylite-(Ce);

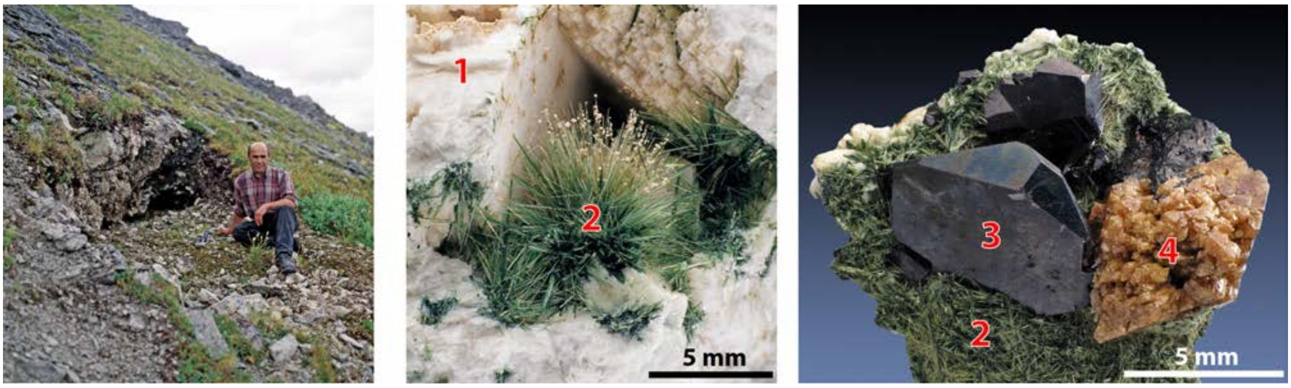


Fig. 9. Microcline-aegirine-natrolite vein 1-3 in rischorrite, Marchenko Peak. 1 – microcline, 2 – aegirine, 3 – ilmenite, 4 – zircon

3. The core can difficult be distinguish within the lower swelling but comprises about 80 vol.% of the upper one. The core is formed by porous, radiating aggregates (up to 30 cm diameter) of milk-white or pale-brown, elongate-prismatic and acicular natrolite with inclusions of euhedral tabular ilmenite (up to 8 cm diameter), zircon (up to 1.5 cm diameter), phlogopite (up to 1 cm) and yellow frame-like segregations (up to 15 cm diameter) of ancylite-(Ce).

Minerals: aegirine, ancylite-(Ce/La), ilmenite, microcline, natrolite, phlogopite, zircon.

Stop 1-4. Aegirine-nepheline-natrolite-microcline vein in rischorrite (about 700 m from the vehicle, elevation 400 m, Fig. 10). It has an irregular shape, is up to 50 cm wide, has a north-south strike, and a dip which is vertical in the top part and almost horizontal in the bottom part. Contacts with host rocks are distinct. The bottom part of the vein (5–10 cm wide) is composed of equant grains of nepheline (up to 3 cm diameter), thin-acicular, dark-green aegirine (up to 4 cm long) and orange-red spherulites of thin-acicular astrophyllite (up to 4 cm diameter). The top, thickest part of the vein has a symmetric-zoned structure:

1. The selvages (5–7 cm wide) are composed of nepheline, microcline and aegirine with inclusions of loparite-(Ce) (up to 1.5 mm), spherulites of astrophyllite (up to 3 cm) and phlogopite (up to 1.5 cm diameter). Thin veinlets (up to 2 mm wide) filled with white gonnardite have also been observed;

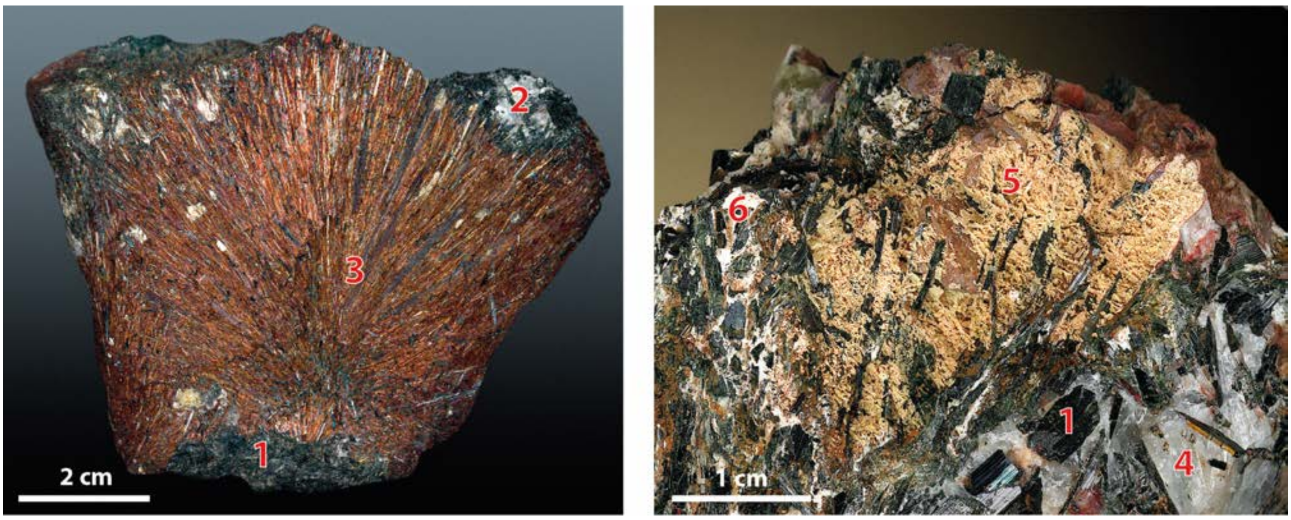


Fig. 10. Minerals of aegirine-nepheline-natrolite-microcline vein 1-4 in rischorrite, Marchenko Peak. 1 – aegirine, 2 – microcline, 3 – astrophyllite, 4 – natrolite, 5 – ancylite-(La), 6 – gonnardite

2. The core is formed by colourless and milk-white, elongate-prismatic crystals of natrolite (up to 7 cm long and 1 cm wide) and columnar aggregates of natrolite with inclusions of dark-green aegirine crystals (up to 4 cm long), black spherulites of phlogopite (up to 2 cm diameter), single, pale-green prismatic fluorapatite crystals (up to 1.5 cm long) and dark-brown acicular lorenzenite (up to 1 cm long). The lorenzenite crystal heads are frequently covered with a parallel-columnar aggregate of vinogradovite up to 0.4 mm wide. Amongst natrolite, there are voids (up to 8 cm diameter) filled with a porous aggregate of small light-yellow crystals (up to 0.8 mm, Fig. 18) of ancylite-(La) (TL), in association with clusters of small cubic purple fluorite crystals, thin-tabular ilmenite crystals (up to 0.1 mm diameter) and small spear-shaped gonnardite crystals. In the natrolite mass there are large galena aggregates (up to 5 cm diameter).

Throughout the vein there are clusters of light-pink, lamellar, six-faced crystals of catapleiite (up to 5 mm diameter and 0.3–0.5 mm wide).

Minerals: aegirine, ancylite-(La), astrophyllite, catapleiite, fluorapatite, fluorite, galena, gonnardite, ilmenite, loparite-(Ce), lorenzenite, microcline, natrolite, nepheline, phlogopite, vinogradovite.

Stop 1-5. Apatite-titanite veinlets in rischorrite (about 700 m from the vehicle, elevation 350 m). There are numerous thin veinlets (up to 15 cm thick) and lens-like segregations of fluorapatite in rischorrite at the Marchenko Peak. Fluorapatite forms granular aggregates with inclusions of well-shaped lens-like titanite crystals (up to 1.5 cm long). Other associated minerals are nepheline, aegirine-augite, eudialyte and ilmenite.

Minerals: aegirine-augite, eudialyte, fluorapatite, ilmenite, microcline, nepheline, titanite

Day 2: Pegmatites within rischorrite and foyaite at the Eveslogchorr Mountain

The main rock types of the Khibiny massif. Koashva deposit of apatite, nepheline and titanite. Eveslogchorr astrofillite deposit. Pegmatites with chivruaiite, punkaruaivite, belovite-(La), paraumbite, denisovite, wadeite, labuntsovite group minerals, etc. Length 4 km, elevation 400 m. (Fig. 11).

Fig. 11. Mt. Eveslogchorr. It is shown positions of mineral localities 2-2 – 2-5.

Stop 2-1. The Koashva Deposit, discovered in 1959 and now richest in the Khibiny massif (near the vehicle). The ore zone of the deposit is made of a series of closely related lens-shaped bodies, spread over more than 3 km (see Fig. 5). Its strike is north-east, 330–340°, and the dip is 30–40°. The thickness of the ore zone as a whole decreases as the depth increases, from 200–300 m up to several metres. The host rocks are orthoclase-bearing ijolite-urtite. Brecciated rocks are most common and all of the other textural types are of secondary importance. Within the overlying rocks, lens-shaped bodies of apatite-titanite rock, up to 20 m thick, are predominant. The deposit has been mined since 1978 by means of an open cast mine.

Stop 2-2. Natrolite-microcline vein in gneissose rischorrite, Mt. Eveslogchorr (about 700 m from the vehicle, elevation 100 m). An irregularly-shaped vein up to 1 m wide with a concentric zoned structure (Fig. 12):

1. The selvages (10–15 cm) are composed of an aggregate- of microcline and aegirine, with scarce rounded clusters of golden-brown lamprophyllite (up to 2 cm diameter);
2. A microcline zone (up to 50 cm) contains- radiating aggregates (up to 3 cm diameter-) of brownish-purple, bladed crystals and lamellar segregations of altered murmanite- (Fig. 21), black sword-shaped crystals of altered pectolite, greenish-yellow belovite-(La) (grains up to 5 mm diameter-), small (up to 1 mm) bright-crimson manganoeudialyte and silvery-white prismatic safflorite (up to 5 mm long and 1 × 0.5 mm diameter). In the interstices of the thickest part of the zone, there are irregularly-shaped crimson grains of tugtupite (up to 2 cm diameter-), partially replaced by white fine-grained epididymite. The interstices also contain aggregates- (up to 1.5 cm diameter) of yellow bladed sphalerite and small flattened-prismatic lampro-phyllite. In places within microcline, there is a 1 cm zone of parallel-fibrous aegirine orien-ted- perpendicular to the contact at the border with the selvages, and at the border- with the inner zone there are scarce small clusters of pink albite. Kuzmenkoite-Mn forms small brown spherulites (up to 0.5 mm diameter) on microcline and aegirine crystals, in association with white disk-like crystals of epididymite (up to 0.1 mm diameter) and brown radiating aggregates of needle-like crystals of Mn-rich palygorskite (up to 0.2 mm long), spherulites (up to 3 mm diameter) of colourless long-prismatic crystals of chivruaiite and sheaf-like aggregates (up to 4 mm diameter) of colorless flattened prismatic crystals of punkaruaivite. Monazite-(La) also occurs here as brown, fine-grained segregations- (up to 8 mm diameter) in microcline;

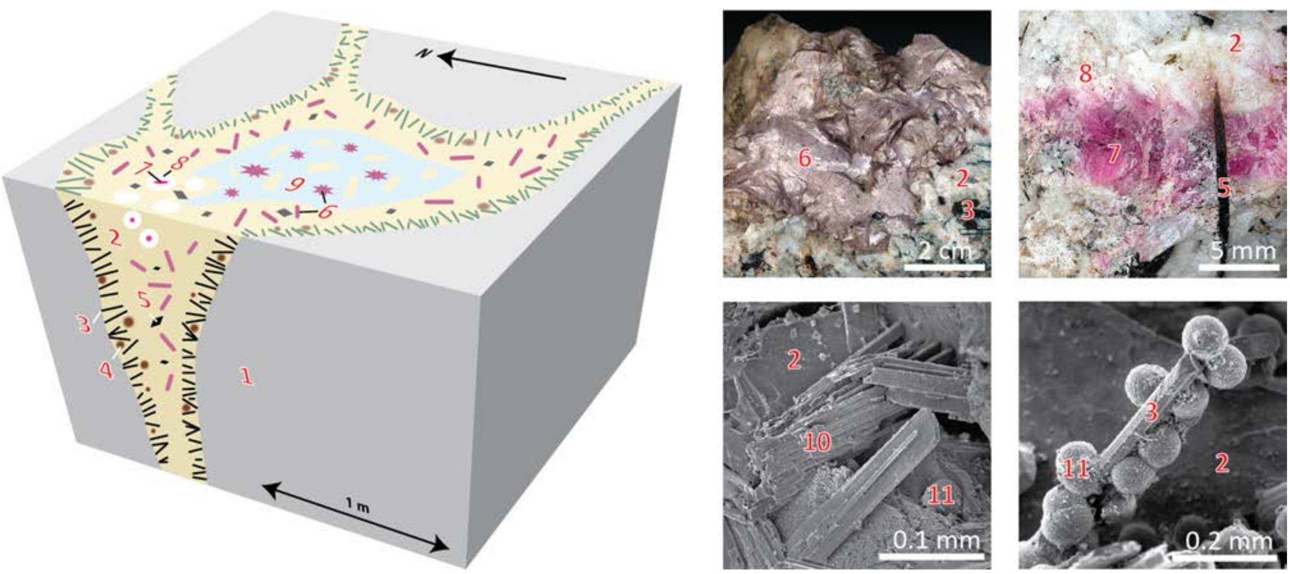


Fig. 12. Nastrolite-microcline pegmatite 2-2 in foyaite, Mt. Eveslogchorr. 1 – foyaite; 2 – microcline; 3 – aegirine; 4 – lamprophyllite; 5 – altered pectolite; 6 – altered murmanite; 7 – tugtupite; 8 – epididymite; 9 – natrolite; 10 – chivruaiite; 11 – kuzmenkoite-Mn.

3. A microcline-natrolite zone (1 × 0.7 × 0.15 m) is formed by cavernous fine-grained white natrolite, amongst which there are scarce tabular microcline crystals, black sword-shaped crystals of altered pectolite, greyish-brown bladed crystals (up to 10 cm diameter and 5 mm wide) and spherulites of murmanite (up to 7 mm diameter).

Minerals: aegirine, albite, belovite-(La), chivruaiite, epididymite, manganoeudialyte, kuzmenkoite-Mn, lamprophyllite, microcline, monazite-(La), murmanite, natrolite, palygorskite, pectolite, punkaruaivite, safflorite, sphalerite, tugtupite.

Stop 2-3. Astrophyllite deposit (about 2 km from the vechicle, elevation 400 m). This 300 × 400 m deposit is located on the southern slope of Mt. Eveslogchorr at an altitude of 700–800 m. It is related to zones of albitization of gneissose foyaite and aegirine-nepheline-microcline veins of sub-latitudinal strike cutting foyaite. The astrophyllite content of the veins and albitites is very variable, from 10 up to 80 vol.%. The veins are 0.5 cm to 7 m wide and are observed for 10–150 m along strike. They are composite, with a pinch and swell structure and abundant apophyses and satellites. The astrophyllite is often found in the central parts of the veins, as radiating (Fig. 13), parallel-columnar, sheaf-like and large-lamellar aggregates of bronze-brown, golden-yellow, greenish-brown and dark-brown flattened-prismatic crystals. It occurs in a characteristic association with aegirine, eudialyte, rinkite, sodalite, cancrinite, loparite-(Ce) and pyrochlore. Monomineralic lamellar segregations and radiating impregnations of astrophyllite frequently cover areas of several square metres. Within microcline veins, sheaf-like aggregates of astrophyllite fill the interstices in aggregates of euhedral feldspar (up to 15 cm diameter). Large segregations of radiating aegirine and astrophyllite are also common. The interior of these spherulites is made of bronze-brown astrophyllite and the margin is green fibrous aegirine. Rather rarely there are segregations of resinous-black, coarse-grained arfvedsonite, within which there are abundant “stars” of golden-yellow astrophyllite. In the albitite rocks, there are regular bar-shaped astrophyllite crystals (up to 5 cm long, 6 mm diameter), resinous-black, flattened-prismatic aenigmatite crystals (up to 15 cm long, 0.5 × 1.8 cm diameter), yellowish-brown, semi-transparent titanite crystals (up to 3 cm diameter), brownish-black, barrel-shaped crystals of annite (up to 4 cm long, 6 mm diameter), pale-green, elongate-prismatic fluorapatite crystals (up to 5 cm long), pseudo-octahedral, purple-red to black crystals of eudialyte (1–40 mm diameter), yellowish-brown prismatic lorenzenite crystals, and small purple grains of fluorite.

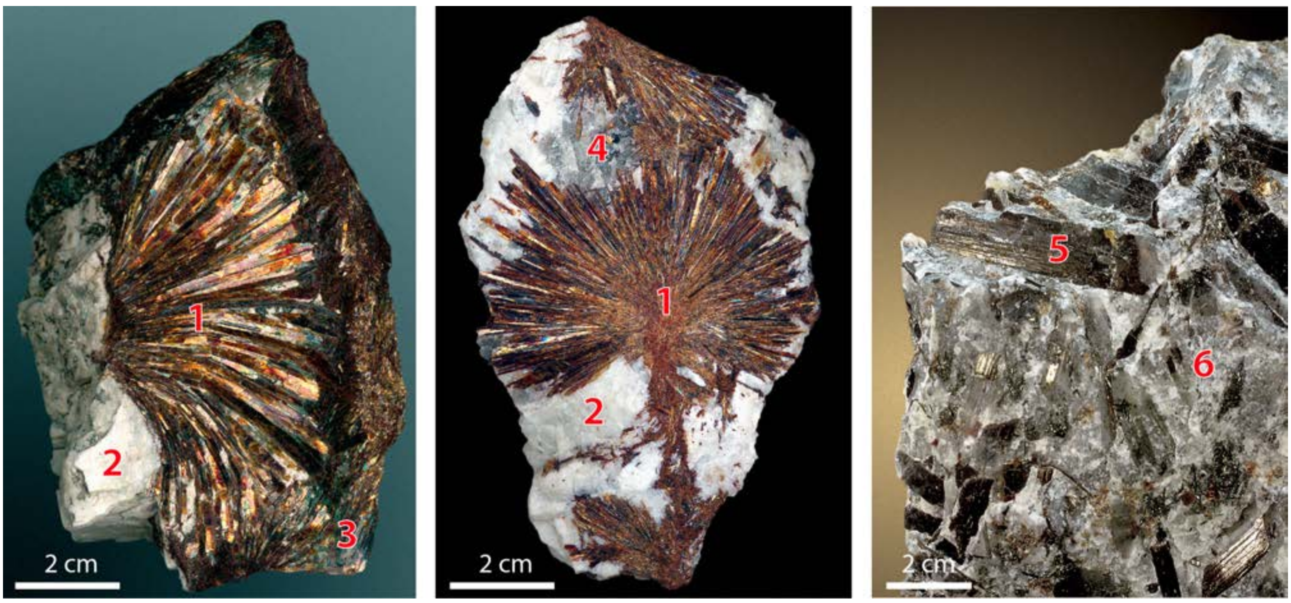


Fig. 13. Minerals of the Eveslogchorr astrophyllite deposit. 1 – astrophyllite, 2 – microcline, 3 – aegirine, 4 – nepheline, 5 – aenigmatite, 6 – albite

Minerals: aegirine, aegirine-augite, aenigmatite, albite, annite, arfvedsonite, astrophyllite, cancrinite, eudialyte, fluorapatite, fluorite, loparite-(Ce), lorenzenite, microcline, nepheline, pyrochlore, rinkite, sodalite, titanite.

Stop 2-4. Eudialyte-nepheline-aegirine-microcline vein in gneissose rischorrite (about 1 km from the vehicle, elevation 350 m). The width of the vein is about 80 cm, the strike is more than 20 m (Fig. 14) and the vein has a symmetrically zoned structure:

1. Margins up to 20 cm wide are composed of large-blocky aggregates of nepheline and microcline, with scarce, large crystals of aegirine (up to 10 cm long and 1 cm wide) and pinacoidal-rhombohedral crystals of eudialyte (up to 4 cm diameter) along the grain boundaries;
2. The central zone, also generally composed of nepheline and microcline, is distinguished by abundant sheaf-like and radiating aggregates of elongate-prismatic crystals of aegirine (up to 15 cm long and 6 mm diameter). Eudialyte/ferrokentbrooksite forms regular crystals (up to 3 cm diameter), mostly replaced to some degree by wadeite. The crystallization of the wadeite started from the eudialyte crystal margins and along fissures, and gradually covered the rest of the crystal. Eudialyte is also replaced by thin-fibrous aggregates of paraumbite causing a characteristic silky lustre on the faces of these crystals. Some pseudomorphs after eudialyte are zoned, with margins of wadeite and cores consisting of a mixture of gaidonnayite, shcherbakovite, paraumbite (TL) and umbite.

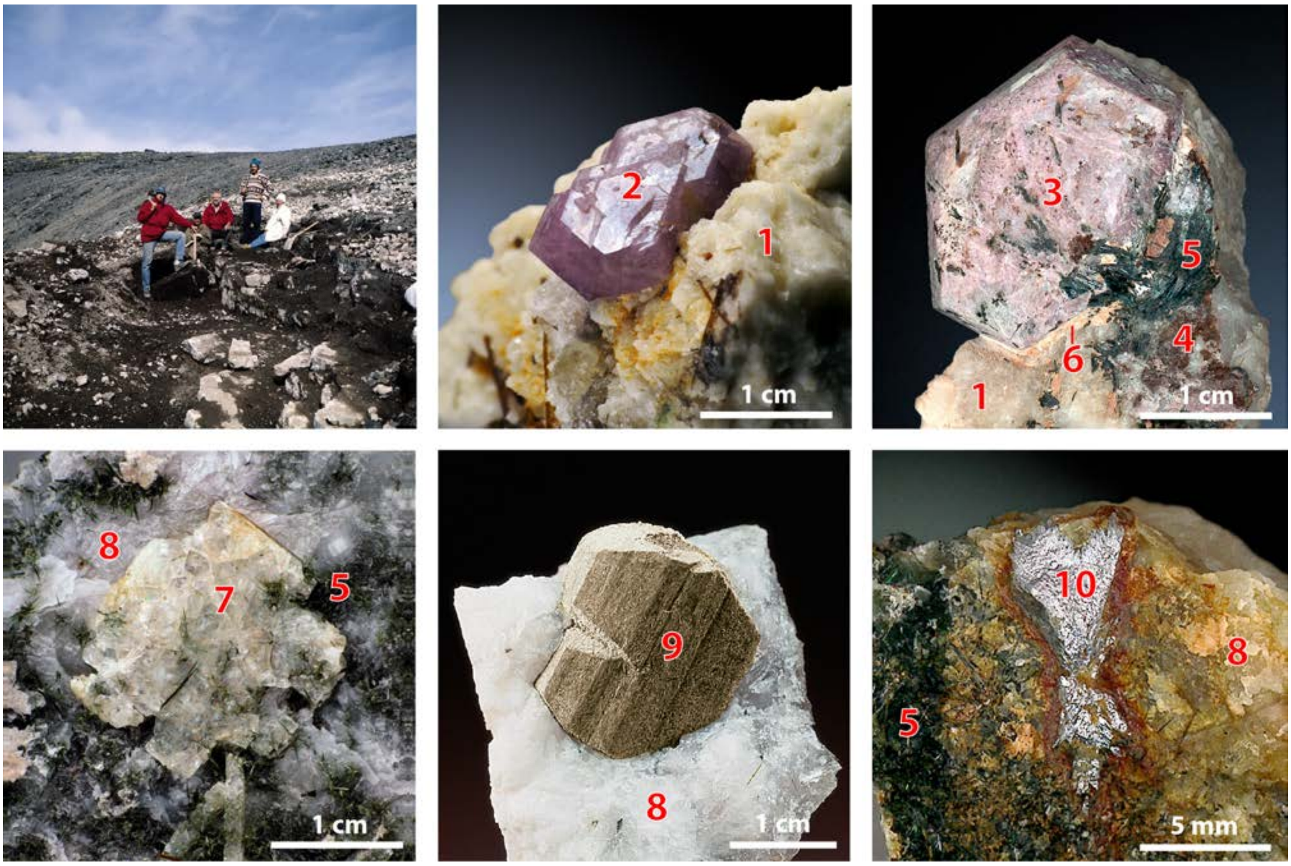


Fig. 14. Eudialyte-nepheline-aegirine-microcline vein 2-4 in gneissose rischorrite, Mt. Eveslogchorr. 1 – microcline, 2 – wadeite, 3 – wadeite pseudomorph after eudialyte, 4 – eudialyte, 5 – aegirine, 6 – rinkite, 7 – leucophanite, 8 – natrolite, 9 – pectolite, 10 – löllingite.

In areas between the central and marginal zones (and less often in the central zone itself), there are characteristic lens-shaped segregations composed of a bright yellow, fine-grained aggregate of rinkite, within which there are acicular aegirine crystals and wadeite pseudo-morphous after eudialyte. Interstices between crystals of nepheline and feldspar contain snow-white fibrous, down-like aggregates of perlialite (up to 8 mm) and small light-pink prismatic crystals of vuorijarvite-K (up to 1.5 mm). The amount of natrolite varies but occasionally is sufficiently high to produce monomineralic natrolite segregations up to 20 cm wide and 50–80 m long. These natrolite aggregates are always penetrated by flattened-prismatic pectolite (up to 7 cm long) and needles of rinkite, aegirine and astrophyllite (up to 8 cm long). Sometimes within the natrolite, there are also some yellowish-green, transparent, tabular fluorapatite crystals (up to 2 cm diameter), colourless tabular leucophanite (up to 1.5 cm diameter), greenish-yellow sphalerite grains (up to 1.5 cm), colourless radiating aggregates of barylite (up to 4 mm diameter), fine-grained aggregates of chabazite-Ca and ancylite-(La), silvery-white lцllingite crystals (up to 1 cm long), dark-red, octahedral thorite (up to 2 mm diameter) and equant galena grains (up to 2 cm diameter). When natrolite mineralization is superimposed on rinkite-eudialyte, wadeite also occurs within natrolite, as bright pink semi-transparent dipyramidal-pinacoidal hexagonal crystals (up to 2 cm diameter, Fig. 24) grown on microcline or, less commonly, embedded in the natrolite groundmass.

<u>Minerals</u>: aegirine, analcime, ancylite-(La), astrophyllite, barylite, chabazite-Ca, eudialyte, ferrokentbrooksite, fluorapatite, fluorite, gaidonnayite, galena, leucophanite, löllingite, lovozerite, microcline, natrolite, nepheline, paraumbite, pectolite, perlialite, rinkite, shcherbakovite, sphalerite, thorite, umbite, vuorijarvite-K, wadeite.

Stop 2-5. Nepheline-aegirine-microcline vein in rischorrite (Near the vehicle, Fig. 15). The 0.9–1.4 m wide vein with the symmetrically zoned structure:

1. The marginal zones, 10–40 cm wide, are composed of compact, dark-green entangled-fibrous aegirine (70–80 vol.%), microcline and nepheline, with inclusions of brownish-black annite (up to 3 cm diameter) and red eudialyte (up to 8 mm diameter). Small cavities, filled by altered greyish-brown pectolite, contain aggregates of fluorapatite and small (1–4 mm) yellowish-brown grains of fersmanite (TL). Lamprophyllite laths (up to 2 cm long), grains of galena (up to 1 cm diameter) and black sphalerite (up to 8 mm) are included in the mass of microcline and aegirine. White, friable rinds of hydrocerussite have developed along the edge of galena grains.
2. The central porous zone, 20–60 cm wide, is composed of greenish-grey microcline and brownish-grey nepheline. Numerous voids are filled with a brown earthy mixture of hydroxides of iron and manganese, apparently an alteration product of pectolite, of which relics have been observed. In these voids, and also within nepheline, there are tabular dark-brown crystals of fersmanite (0.5–6 cm diameter, Fig. 26) and equant grains of fluorapatite, up to 1 cm diameter.

<u>Minerals</u>: aegirine, ancylite-(Ce), annite, eudialyte, fersmanite, fluorapatite, galena, goethite, hydrocerussite, lamprophyllite, microcline, nepheline, pectolite, sodalite, sphalerite.

Fig. 15. Nepheline-aegirine-microcline vein 2-5 in rischorrite, Mt. Eveslogchorr.
1 – fersmanite, 2 – pectolite

Geology of the Lovozero massif

The Lovozero alkaline massif, second largest massif in the world, intruded in the Archaean granite-gneiss and the Devonian tuff-basalt strata 362 Ma (Fig. 16). It comprises regularly alternating subhorizontal layers of foyaite-malignite ("lujavrite") and ijolite-urtite rock series (Fig. 17). All these strata are divided into two complexes – Differentiated (bottom) and Eudyalite (top) that differ in eudyalite content, nepheline-syenite-foidolite proportion and thickness of individual sublayers forming the complexes (Gerasimovsky et al., 1966; Bussen and Sakharov, 1972; Pekov, 2000; Pakhomovsky et al., 2014). The Lovozero massif houses the Lovozero Loparite deposit that has been developed by Lovozerskiy GOK since 1941.

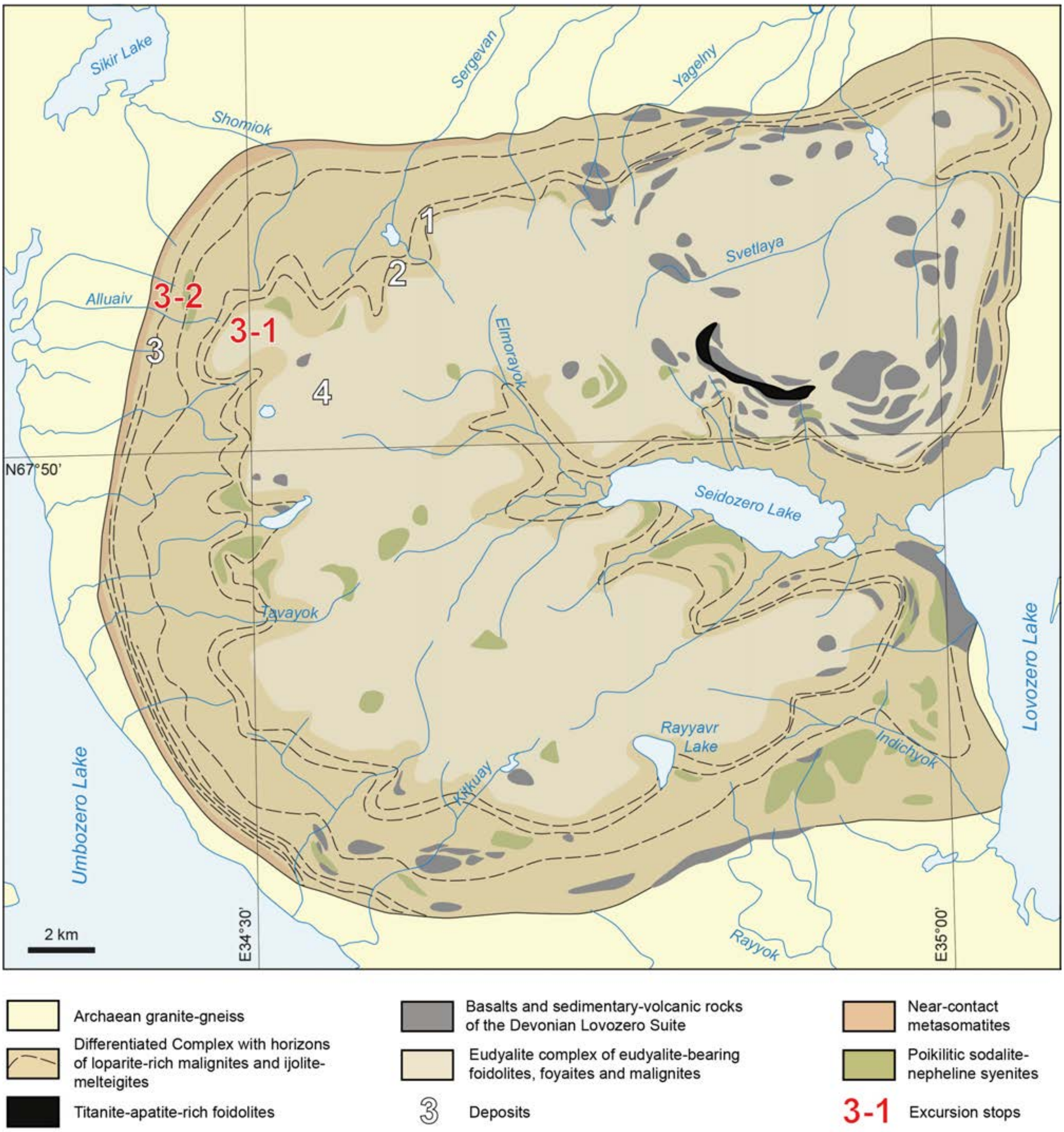


Fig. 16. Lovozero alkaline massif. Deposits: 1 – Karnasurt loparite, 2 – Kedykvyrpakhk loparite, 3 – Umbozero loparite, 4 – Alluaiv eudialyte.

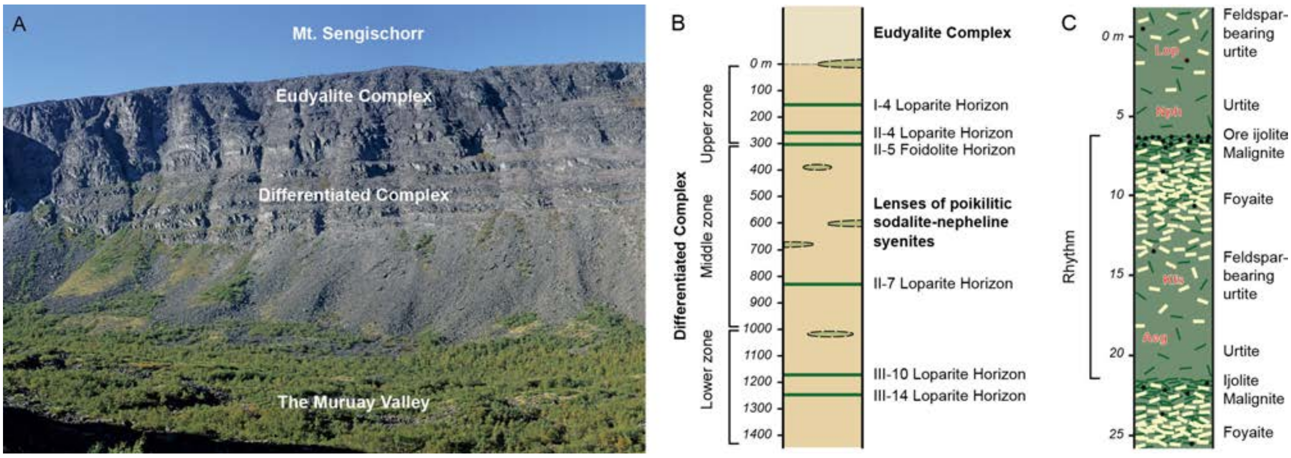


Fig. 17. A general view of the Lovozero massif stratification (A), magmato-stratigraphic column of the Lovozero massif (B; after Gerasimovsky et al., 1966), and principal schema of rhythmic layered units of the Differentiated complex (C; after Arzamastsev, 1994).

The most relevant loparite sources are the Karnasurt, Kedykvyrpakhk, and Umbozero sites (mines) of the Lovozero Loparite deposit. These sites comprise subhorizontal layers of sodalite-kalsilite-nepheline malignite and foidolites rich in loparite-(Ce), but within the first two sites the upper I-4 and II-4 loparite horizons are explored, and the third houses the deeper III-10 and III-14 horizons. At the explored Karnasurt and Kedykvyrpakhk sites, about 90% of loparite-(Ce) is concentrated in narrow (0.1-0.4 m) ore malignite-ijolite layers, although the overlying urtite hosts 1-3 thin layers of loparite-bearing ijolite (Pakhomovsky et al., 2014). The overlying urtite and the underlying foyaite contain a negligible amount of loparite (0.2–2 % of volume). Within the ore horizons, loparite-(Ce) forms twinned pseudocubic metacrysts with numerous (up to 80 % of the crystal volume) inclusions of natrolite, lomonosovite, rhabdophane-(Ce), labuntsovite group and other low-temperature minerals.

The Lovozero Eudyalite Complex covers more than 50% of the area of the Lovozero massif and reaches 500 km^2. Its huge volume and considerable eudyalite percentage makes the Eudyalite Complex the largest zirconium reservoir in the world. Besides Zr, it seems to host the large amounts of REE_2O_3. The Eudyalite Complex is a non-rhythmical coarse-layered stratum-like body with thickness ranging from tens of meters in the NW part to 400 m in SE and NE parts of the massif. The base of the Eudyalite Complex has wave-like form and general south-eastward inclination of 5-30°. The Eudyalite Complex comprises eudyalite malignite and shonkinite ("lujavrite") with varying eudyalite content (up to 95 % of volume). The Lovozero Eudyalite Deposit incorporates Karnasurt, Kedykvyrpakhk, Alluaiv, Angvundaschorr, Sengischorr, Parguaiv, and other sites. Detailed exploration was carried out for the north-western part of the Eudyalite Complex, at the Alluaiv site.

Day 3: Mineralogical excursion at Mt. Alluaiv

The main rock types of the Lovozero massif. Deposits of loparite and eudialyte. Pegmatites with ussingite, murmanite, steenstrupine-(Ce), chivruaiite, punkaruaivite, eliseevite, etc. Length 2 km, elevation 50 m.

Stop 3-1. The Alluaiv Site of the Lovozero Eudialyte Deposit (Fig. 18) accommodates two main ore types (Kalashnikov et al., 2016) – loparite-eudyalite (on average, 4 and 8 % of volume, respetively) and eudyalite (on average, 12 % of volume) – as well as minor types, comparatively rich in lovozerite group minerals (on average, 6 % of volume) and murmanite–lomonosovite (on average, 2.4 % of volume). The eudyalite ore presented by eudyalite-rich rocks of the foyaite-malignite series is dominant in the Alluaiv locality. Eudyalite content in these rocks is inversely proportional to loparite-(Ce) content, and conformal lenses (up to 6 m in width) of loparite-rich (up to 7 modal %) foyaite-malignite are encountered within the eudyalite malignite. These lenses occur predominantly near the bottom contact of the Eudyalite Complex.

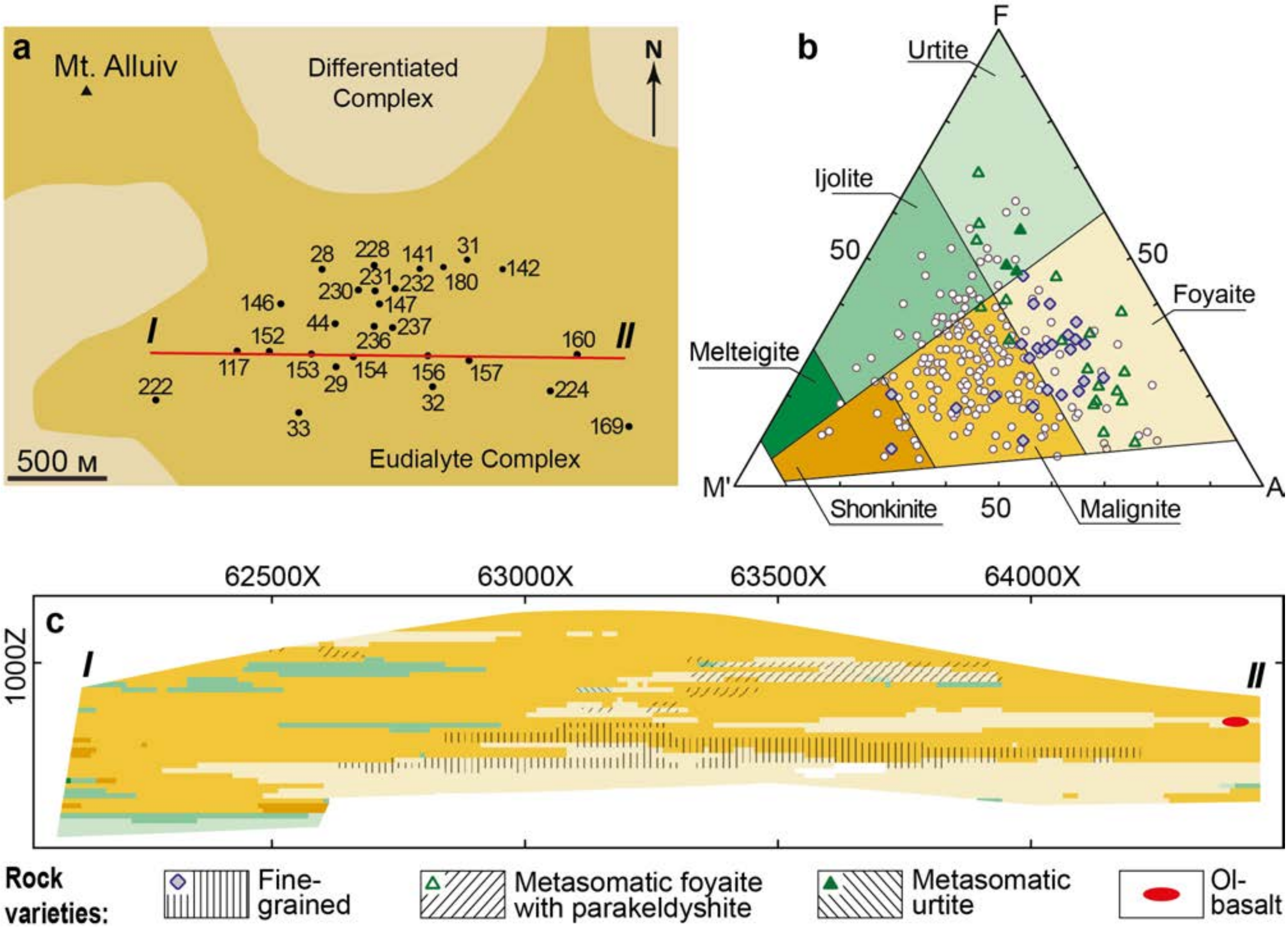


Fig. 18. The Alluaiv Site of the Lovozero Eudialyte Deposit: a – geological map, b – modal compositiuon of rocks, c – vertical section along the I–II line

Minerals: acantite, aegirine-augite, aegirine, albite, alforsite, ancylite-(Ce), arfvedsonite, arsenopyrite, banalsite, barite, bartonite, barytolamprophyllite, bastnäsite-(Ce), bornemanite, britholite-(Ce), burbankite, cafetite, celestine, celsian, cerussite, chalcopyrite, chlorbartonite, cobaltite, costibite, curetonite, djerfisherite, eckermannite, eudialyte, famatinite, ferricnyböite, ferroeckermannite, fluorapatite, fluorcalciopyrochlore, fluorite, fraipontite, galena, georgechaoite, gersdorffite, gittingsite, goethite, hematite, henrymeyerite, hidalgoite, hydroxycalciopyrochlore, khanneshite, labuntsovite (group), lamprophyllite, löllengite, lomonosovite, loparite-(Ce), lorenzenite, lovozerite, lueshite, magnesioriebeckite, manganoeudialyte, manganoneptunite, marcasite, microcline, monazite-(Ce), murmanite, nabaphite, nastrophite, natrolite, nepheline, nickeline, nordite-(Ce), oenite, parakeldyshite, phosinaite, pyrite, pyrophanite, pyrrhotite, rabdophane-(Ce), riebeckite, rinkite, rutile, safflorite, sazhinite-(Ce), selivanovaite, serandite, sodalite, sphalerite, stronadelphite, strontianite, tausonite, tennantite, thorianite, thorite, umbozerite, vuonnemite, willemite, witherite, xenotime-(Y),

Stop 3-2. Microcline-sodalite-ussingite pegmatite in rocks of the Differentiated Complex outcropped in the “Severny” Open Pit (Fig. 19). It is a lens (up to 1 m thick) with a smooth concentric zonation:

1. Marginal zone (up to 80 cm thick) consists of tabular microcline crystals (up to 10 cm in diameter) and long prismatic aegirine crystals (up to 15 cm long), with interstitial nepheline and sodalite (up to 5 cm) partially replaced by natrolite, and inclusions of (mangano)eudialyte (up to 8 cm) partially replaced by catapleiite, lovozerite and zircon, prismatic crystals of (magnesio)arfvedsonite (up to 10 cm long) and lorenzenite (up to 8 cm long), plates of lomonosovite and betalomonosovite (up to 2 cm in diameter), rounded grains of keldyshite (up to 2 cm in diameter) and steenstrupine-(Ce) (up to 1 cm), fluorite-type tweens of loparite-(Ce) and octahedral crystals of pyrochlore (up to 1 mm in diameter). In voids between microcline grains, there are well shaped crystals of aegirine, manganoneptunite (up to 2 cm long), lamprophyllite and barytolamprophyllite (up to 5 mm long), analcime (up to 1 cm in diameter), belovite-(Ce) (up to 1 cm long), plates of murmanite, epistolite and catapleiite (up to 2 mm in diameter), needles of vinogradovite, punkaruaivite and eliseevite (up to 5 mm long), radiated aggregates of punkaruaivite and chivruaiite (up to 1.5 mm in diameter), and druses of natrolite, phillipsite-Ca, chabazite-Ca/K and gmelinite-Ca/K. Besides, the voids can be filled with hydroxycancrinite, epididymite and beryllite.

Fig. 19. The “Severny” Open Pit (Mt. Alluaiv), with the pegmatite 3-2 position. 1 – microcline; 2 – manganoeudialyte; 3 – aegirine; 4 – magnesioarfvedsonite; 5 – nepheline; 6 – sodalite; 7 – hydroxycancrinite; 8 – eliseevite; 9 – albite; 10 – chivruaiite.

2. Core (up to 50 cm) is composed by coarse-grained aggregate of sodalite and ussingite, with inclusions of tabular crystals of nepheline (up to 3 cm in diameter) and murmanite (up to 10 cm in diameter and 2 cm thick), prismatic crystals of aegirine (up to 10 cm long), (magnesio)arfvedsonite (up to 8 cm long) and manganoneptunite (up to 1 cm), short prismatic crystals of lorenzenite (up to 7 cm long), isometric grains of chkalovite (up to 1 cm in diameter) partially replaced by fine-grained crimson tugtupite, radiated aggregates of ferronordite-(Ce) (up to 6 mm in diameter), granular nests of rhabdophane-(Ce), galena, löllengite, arsenopyrite and sphalerite (up to 2 cm).

Minerals: aegirine, analcime, arfvedsonite, arsenopyrite, barytolamprophyllite, belovite-(Ce), beryllite, betalomonosovite, catapleiite, chabazite- K, chabazite-Ca, chivruaiite, chkalovite, eliseevite, epididymite, epistolite, eudialyte, ferronordite-(Ce), fluorapatite, fluorcalciopyrochlore, fluorite, galena, gmelinite- K, gmelinite-Ca, hydroxycancrinite, keldyshite, lamprophyllite, löllingite, lomonosovite, loparite-(Ce), lorenzenite, lovozerite, magnesioarfvedsonite, manganoeudialyte, manganoneptunite, microcline, murmanite, natrolite, nepheline, phillipsite-Ca, punkaruaivite, rhabdophane-(Ce), sodalite, sphalerite, steenstrupine-(Ce), tugtupite, ussingite, vinogradovite, zircon.

References

Arzamastsev, A.A. (1994) *Unique Paleozoic intrusions of the Kola Peninsula*. Kola Science Center press, Apatity

Arzamastsev, A.A., Arzamastseva, L.V., Travin, A.V., Belyatsky, B.V., Shamatrina, A.M., Antonov, A.V., Larionov, A.N., Rodionov, N.V., Sergeev, S.A. (2007) Duration of Formation of Magmatic System of Polyphase Paleozoic Alkaline Complexes of the Central Kola: U–Pb, Rb–Sr, Ar–Ar Data. *Doklady Earth Sciences*, **413A**, 432–436.

Balagansky, V.V., Basalaev, A.A., Belyaev, O.A., Pozhilenko, V.I., Radchenko, A.T., Radchenko, M.K. (1996) *Geological map of Kola region 1:500000*. Apatity, GI KSC RAS.

Bussen, I.V., Sakharov, A.S. (1972) *Petrology of the Lovozero alkaline massif*. Leningrad, Nauka (in Russian)

Gerasmovsky V.I., Volkov V.P., Kogarko L.N., Polyakov A.I., Saprykina T.V., Balashov Yu.A. (1966) *Geochemistry of the Lovozero alkaline massif*. Moskow, Nauka. (in Russian)

Goryainov, P.M., Konopleva, N.G., Ivanyuk, G.Yu., Yakovenchuk, V.N. (2007) Structural organization of an ore zone in the Koashva apatite-nepheline deposit. *Otechestvennaja geologiya*. No. 2. 55–60 (in Russian).

Ivanyuk, G., Yakovenchuk, V., Pakhomovsky, Y., Kalashnikov, A., Mikhailova, J., Goryainov, P. (2012a) Self-Organization of the Khibiny Alkaline Massif (Kola Peninsula, Russia), *in* Dar, I.A. ed., *Earth Sciences*, Rijeka, Croatia, InTech, 131–156.

Ivanyuk, G.Yu., Goryainov, P.M., Pakhomovsky, Ya.A., Konoplyova, N.G., Yakovenchuk, V.N., Bazai, A.V., Kalashnikov, A.O. (2009) *Self-organization of ore-bearing complexes*. Geokart-Geos. Moscow. (in Russian).

Ivanyuk, G.Yu., Yakovenchuk, V.N., Pakhomovsky, Ya.A. (2012b) Where Are New Minerals Hiding? The Main Features of Rare Mineral Localization Within Alkaline Massifs, *in* Krivovichev, S.V., ed., *Minerals as Advanced Materials II*, Berlin-Heidelberg, Springer-Verlag, 13–24

Kalashnikov, A.O., Konopleva, N.G., Pakhomovsky, Ya.A., Ivanyuk, G.Yu. (2016) Rare Earth Deposits of the Murmansk Region, Russia—A Review // *Economic Geology,* **111**, 1529–1559.

Kamenev, Ye.A. (1987) *Prospecting, exploration and geologic-industrial estimation of apatite deposits of Khibiny type*. Leningrad, Nedra (in Russian)

Korchak, Y.A., Men'shikov, Y.P., Pakhomovsky, Y.A., Yakovenchuk, V.N., Ivanyuk, G.Y. (2011) Trap formation of the Kola Peninsula. *Petrology*, **19**, 87–101

Kozlov, N.E., Sorokhtin, N.O., Glaznev, V.N., Kozlova, N.E., Ivanov, A.A., Kudryashov, N.M., Martynov, E.V., Tyuremnov, V.A., Matyushkin, A.V., Osipenko, L.G. (2006) *Geology of Archaean of the Baltic Shield*. Saint-Petersburg, Nauka (in Russian)

Kramm, U., Kogarko, L.N. (1994) Nd and Sr isotope signatures of the Khibina and Lovozero agpaitic centres, Kola Alkaline Province, Russia. *Lithos*, **32**, 225–242.

Krivovichev S.V., ed. (2008) *Minerals as Advanced Materials I*. Springer-Verlag, Berlin Heidelberg

Krivovichev S.V., ed. (2012) *Minerals as Advanced Materials II*. Springer-Verlag, Berlin-Heidelberg

Mikhailova J.A., Pakhomovsky Ya.A., Ivanyuk G.Yu., Bazai A.V., Yakovenchuk V.N., Elizarova I.R., Kalashnikov A.O. (2017) REE mineralogy and geochemistry of the Western Keivy peralkaline granite massif, Kola Peninsula, Russia. *Ore Geology Reviews*, **82**, 181–197

Mitrofanov, F.P., Zozulya, D.R., Bayanova, T.B., Levkovich, N.V. (2000) The World's Oldest Anorogenic Alkaline Granitic Magmatism in the Keivy Structure on the Baltic Shield. *Doklady Earth Science*, **374**, 1145–1148

Pakhomovsky, Ya.A., Ivanyuk, G.Yu., Yakovenchuk, V.N. (2014) Loparite-(Ce) in rocks of the Lovozero layered complex at Mt. Karnasurt and Mt. Kedykvyrpakhk. *Geology of Ore Deposits*, **56**, 685–698

Pekov, I.V. (2000) *Lovozero Massif: History, Pegmatites, Minerals*. Moscow, Ocean Pictures Ltd

Shablinsky, G.N. (1963) To the question on the deep structure of the Khibiny and Lovozero plutons. *Trudy Leningradskogo obshchestva estestvoispytatelei,* **74**, 41–43 (in Russian).

Yakovenchuk, V.N., Ivanyuk, G.Yu., Pakhomovsky, Ya.A. Men'shikov, Yu.P. (Ed. F. Wall) (2005) *Khibiny.* Laplandia Minerals, Apatity