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Rare Earth Deposits of the Murmansk Region, Russia—A Review

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Abstract

This paper reviews the available information on the geology, mineralogy, and resources of the significant rare earth element (REE) deposits and occurrences in the Murmansk Region, northwest Russia. The region has one of the largest endowments of REE in the world, primarily the light REE (LREE); however, most of the deposits are of potential economic interest for the REE, only as by-products of other mining activity, because of the relatively low REE grade. The measured and indicated REE_2O_3 resources of all deposits in the region total 22.4, and 36.2 million tonnes, respectively. The most important resources occur in (1) the currently mined Khibiny titanite-apatite deposits, and (2) the Lovozero loparite-eudialyte deposit. The Kovdor baddeleyite-apatite-magnetite deposit is a potentially important resource of scandium. These deposits all have polymetallic ores, i.e., REE would be a by-product of P, Ti, and Al mining at Khibiny, Fe, Zr, Ta, and Nb mining at Lovozero, and Fe and Ti mining at Afrikanda. The Keivy block has potential for heavy REE exploitation in the peralkaline granite-hosted Yumperuaiv and Large Pedestal Zr-REE deposits and the nepheline syenite-hosted Sakharyok Zr-REE deposit. With the exception of the Afrikanda perovskite-magnetite deposit (LREE in perovskite) and the Kovdor baddeleyite-apatite-magnetite deposit (scandium in baddelyite), carbonatite-bearing complexes of the Murmansk Region appear to have limited potential for REE by-products. The sound transport, energy, and mining infrastructure of the region are important factors that will help ensure future production of the REE.

Introduction

Russia is host to some of the largest REE resources in the world. As of January 1, 2014, Russia's measured resources of REE_2O_3, primarily the light REE (LREE) totaled 17.7 million tonnes (Mt), and indicated resources totaled 9.6 Mt (Khramov, 2014). However, only 29,000 t of REE_2O_3 were produced in Russia in 2013, by the mining company Lovozersky GOK, located in the Murmansk Region (Khramov, 2014).

Most Russian REE resources (about 70%) are situated in the Murmansk Region (NW Russia, NE part of Fennoscandinavian Shield), mainly in the Khibiny and Lovozero alkaline massifs. In addition to the Russian part of the Fennoscandinavian Shield, some potentially economic REE deposits and occurrences are known in Finland, Sweden, and Norway. Other Russian REE deposits and occurrences are found in the Sakha (Yakutia) Republic, the Irkutsk Region, the Komi Republic, and the Krasnoyarsky Krai, Zabaykalsky Krai, and Tyva Republics. The Seligdar P-REE and Tomtor Nb-REE deposits in Yakutia, the Belaya Zima P-Nb-REE deposit in the Irkutsk Region, and the Chuktukon Nb-REE deposit in the Krasnoyarsky Krai are hosted by carbonatites and/or the residual soils above carbonatites. The Ulug-Tanzek Ta-Nb-REE deposit in Tyva and the Katugino Ta-Nb-REE deposit in Zabaykalsky Krai are stockworks of quartz-albite-microcline in alkaline granite (Bykov and Arkhangel'skaya, 1995; Tolstov and Gunin, 2001; Khramov, 2014; Andreas and Lepeshkin, 2014). A potentially exotic source of titanium and REE is the Yarega petroleum-Ti-REE deposit of the Komi Republic, which is hosted by sandstone (Khramov, 2014). The REE_2O_3 resources and grades of the deposits referred to above are summarized in Table 1.

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Between 2012 and 2014, we reevaluated the known REE occurrences of the Murmansk Region based on published and unpublished information in Russian, and our own investigations of the most important deposits. This paper incorporates the main findings of that research, and presents an up-to-date review of the rare earth deposits, occurrences and prospects of the region.

Geology Overview of the Murmansk Region

The Murmansk Region is situated in the northeastern part of the Fennoscandinavian Shield, the largest exposure of Precambrian rocks in Europe (Fig. 1). About 90% of its area is occupied by Archean ultrametamorphic complexes—the Kola-Norvegian, Murmansk, Keivy, and Belomorian blocks, consisting mostly of biotite, muscovite-biotite, sillimanite-biotite, and garnet-biotite gneisses; hornblende and gedrite gneiss/amphibolite; mica, staurolite and kyanite schists; and banded iron formation (BIF)—separated by the Archean to Early Proterozoic granulite and greenstone belts of komatiites, BIF, hornblende gneiss, and amphibolites (the Uraguba-Voronya-Kolmozero belt), chlorite, epidote, actinolite schists, dolomites, limestones, and sandstones (the Pechenga-Imandra-Varzuga and Salla-Kuolayarvi belts), garnet-quartz-feldspar, garnet-hornblende, and diopside-hypersthene granulites and gneisses (the Kandalaksha-Laplandian belt). Narrow belts of Late Proterozoic sedimentary rocks (sandstones, quartzites, and aleurolites) lie along the White Sea and Barentz Sea.

About 8% of the territory is represented by Late Archean to Carboniferous igneous complexes comprising granites, peralkaline granites, alkaline-ultrabasic plutons, and basic to ultrabasic complexes. Numerous gabbro-anorthosite massifs (2.7–2.1 Ga) containing Fe-Ti, Cu-Ni, Cr, and Pt-Pd deposits occur within the greenstone and granulite belts. Large

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Table 1. Russian REE-bearing Deposits Outside the Murmansk Region (Bykov and Arkhangel'skaya, 1995; Tolstov and Gunin, 2001; Khramov, 2014; Andreas and Lepeshkin, 2014)

				REE_2O_3 resources, Mt @ grade, wt. %	
Deposit	Economic component	Location	Host in	Measured	Indicated
Tomtor	Nb-Sc-REE	Yakutia	Carbonatite and residual soil	0.1 @ 9.53	
Seligdar	P-REE		Carbonatite	4.4 @ 0.35	
Belaya Zima	P-Nb-REE	Irkutsk Region			1.6 @ 0.9
Chuktukon	Nb-REE	Krasnoyarsky Krai			0.5 @ 7.32
Ulug-Tanzek	Ta-Nb-REE	Tyva	Quartz-albite-microcline metasomatite after alkali granitoid	0.5 @ 0.06	
Katugino	Ta-Nb-REE	Zabaykalsky Krai		0.8 @ 0.4	
Yarega	petroleum-Ti-REE	Komi	Sandstone	1 @ 0.039	

granodiorite massifs (1.8 Ga) occur mainly in granite-gneisses of the Kola-Norvegian and Belomorian blocks.

Alkaline magmatism played an essential role in the Kola rare metal metallogenic province. It took place during the formation of the Fennoscandinavian Shield, which occurred between the Archean and Paleozoic. The Keivy block was a result of Archean peralkaline granite magmatism (2.6 Ga). During the final stage in the development of the Karelian green-stone belts (2.2–2.6 Ga), alkaline magmatism was expressed by the emplacement of nepheline syenite in the Sakharyok massif within peralkaline granites of the Keivy block. Alkaline-ultrabasic rocks produced the Soustov and Gremyakha-Vyrmes massifs in the Pechenga-Varzuga green-stone belt during the Proterozoic (1.9 Ga). The acme of the alkaline magmatism activity, however, took place during the Paleozoic (350–400 Ma), and gave rise to the world's largest alkaline plutons, Khibiny and Lovozero, and a number of other alkaline-ultrabasic massifs, all containing carbonatites (Balagansky et al., 1996; Mitrofanov et al., 2000; Kozlov et al., 2006; Korchak et al., 2011).

Materials and Methods

In preparing this paper, the authors reviewed most of the published and unpublished literature on REE deposits and prospects in the Murmansk Region. Based on this review, most promising deposits/prospects were identified. In order of priority, these are as follows:

1. Apatite deposits and occurrences of the Khibiny alkaline massif, namely Kukisvumchorr, Yuksporr, Apatitovy Tsyrc, Rasvumchorr, Koashva, Nyorkpakhk (mined by JSC "Apatit"); Oleny Ruchey, Partomchorr (mined by JSC "NWPC"); Kuelporr, Poachvumchorr, and Putelichorr;
2. The Yuksporr Lovchorrite (rinkite) deposit of the Khibiny massif;
3. The entire Khibiny alkaline massif, including minor rinkite, titanite, and even apatite occurrences not previously recognized as potential sources of REE;
4. The Lovozero loparite deposit, including the Ta-Nb-REE Karnasurt-Kedykvyrpakhk mine;
5. The eudialyte complex of the Lovozero massif;
6. Alkaline-ultrabasic massifs containing carbonatites, namely Afrikanda, Kovdor, Vuoriyarvi, Sallanlatva, and Seblyavr;
7. Keivy block peralkaline granite REE occurrences (Large Pedestal and Yumperuaiv), and amazonite pegmatite-hosted REE occurrences (Vyuntspakhk, Rovgora, and Serpovidny Ridge);
8. The Sakharyok Zr-REE deposit, which is hosted by a nepheline and alkali feldspar syenite massif of the same name (Fig. 1).

The authors sampled the deposits of the Khibiny alkaline massif, the Keivy peralkaline granites, and loparite deposits of the Lovozero massif. The Khibiny massif was sampled along three profiles at 50-m intervals from its center to the west, northeast, and southeast contacts with metamorphic host rocks that intersected the Koashva, Partomchorr, Poachvumchorr, and Marchenko apatite deposits. Samples were also taken from the Kukisvumchorr, Yuksporr, Rasvumchorr, and Oleny Ruchey apatite deposits and the Yuksporr rinkite deposit. The Kedykvyrpakhk-Karnasurt loparite deposit was sampled along 21 vertical profiles at 10-cm intervals across the I-4 and II-4 loparite layers. The Kovdor phoscorite-carbonatite complex was sampled on a dense grid that covered the entire expanse of the Kovdor baddeleyite-apatite-magnetite deposit. Sampling of the Keivy areas was guided by results of a radiometric survey using a field radiometer SRP-200; highly radioactive areas were mapped and sampled. Each of the samples referred to above was divided into two portions. One portion was milled and prepared for chemical analysis. Major element concentrations were determined by "wet" chemical analysis (Geological Institute of the Kola Science Centre, Russian Academy of Sciences, Apatity, Russia) and REE concentrations by ICP-MS analysis (PerkinElmer ELAN 9000 DRC-e, Institute of Chemistry and Technology of Rare Elements and Mineral Raw Materials, Apatity, Murmansk Region, Russia; analyst I.R. Yelizarova). The other portion was prepared as a thin section for optical and electron microscope studies and electron microprobe analysis. All minerals were identified using an LEO-1450 scanning electron microscope equipped with a Quantax EDS microanalyzer. Chemical analyses of the minerals were carried out with a Cameca MS-46 electron microprobe WDS analyzer. Where necessary, minerals were identified using X-ray diffractometry (STOE IPDS II, St. Petersburg State University). A geostatistical analysis and spatial modeling of the Kovdor phoscorite-carbonatite pipe was performed using GEOMIX (VIOGEM, Belgorod, Russia, http://www.geomix.ru).

Resources of the deposits examined (except for the Oleny Ruchey apatite deposit) were estimated in accordance with

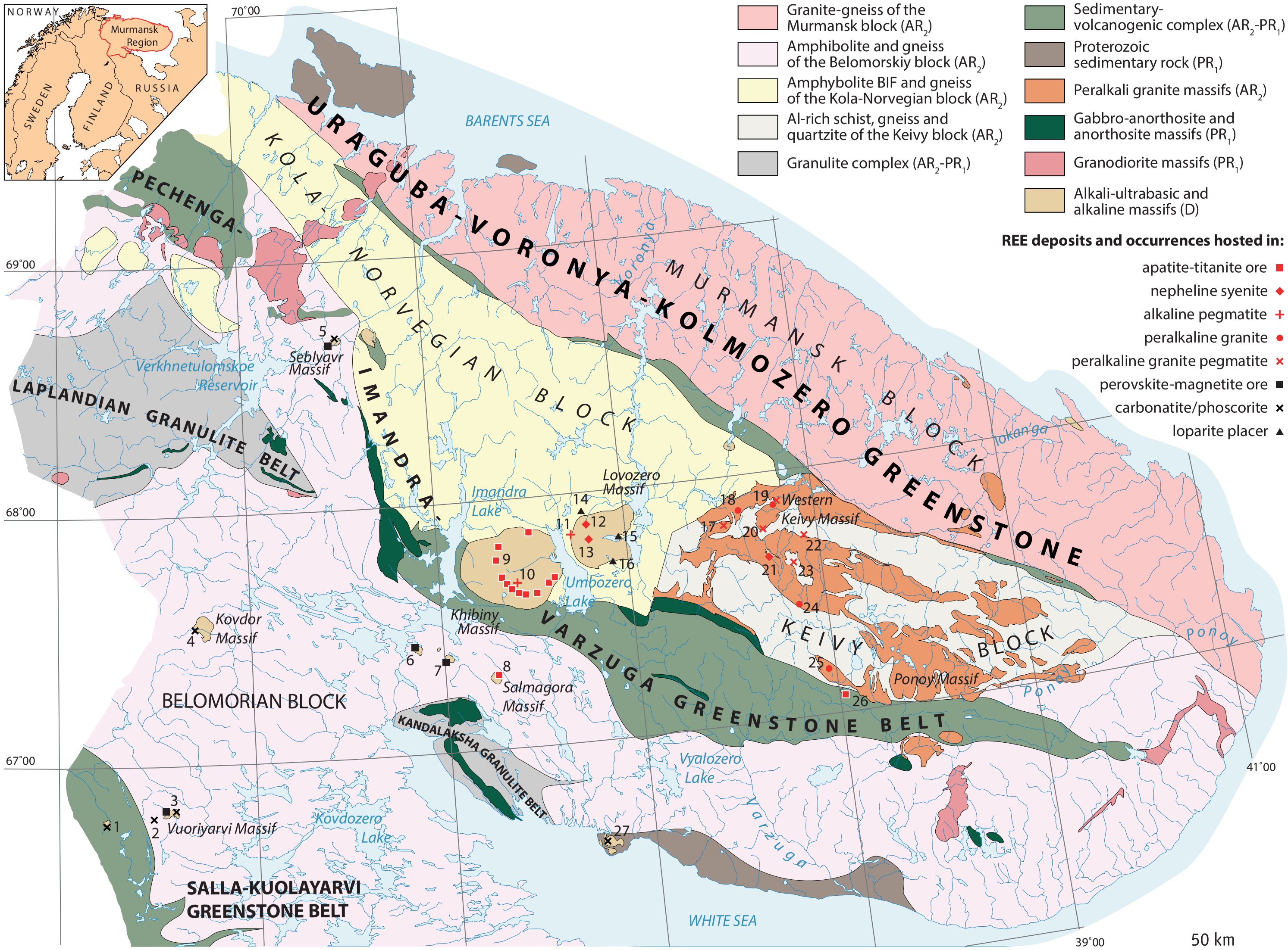


Fig. 1. Simplified geological map of the Murmansk Region and location of REE deposits and occurrences (after Gaskelberg et al., 1978; Balagansky et al., 1996; Ivanyuk et al., 2002; Afanasyev, 2011; Bazai et al., 2014). The numbers indicate REE deposits and occurrences: 1 = Sallanlatva Ta-Nb deposit in carbonatite, 2 = Nama-Vara REE carbonatite field, 3 = Vuoriyarvi massif: Western (apatite)-perovskite-magnetite deposit, Neske-Vara and Tukhta-Vara (P-Fe)-Ta-Nb deposits in carbonatite and phoscorite, 4 = Kovdor baddeleyite-apatite-magnetite deposit, 5 = Seblyavr massif, 6 = Arikanda perovskite-magnetite deposit, 7 = Lesnaya Varaka perovskite-magnetite deposit, 8 = Salmagora apatite deposit, 9 = Khibiny apatite deposits (see detailed Fig. 2), 10 = Yuksporr Lovchorrite mine, 11 = Shomiokitovoye hydrothermal-pegmatite body, 12 = Lovozero Loparite deposit, 13 = Lovozero Loparite-Eudialyte deposit, 14–16 = loparite placers: 14 = Revda, 15 = Seidozero, 16 = Rayyavr, 17 = Southern Tapperyok-Pessariok REE pegmatite field, 18 = Yumperuaiv Zr-REE deposit in peralkaline granite, 19 = Large Pedestal Zr-REE deposit in peralkaline granite and Small Pedestal REE pegmatite field, 20 = Rovgora REE pegmatite field, 21 = Sakharyok REE-Zr deposit in nepheline syenite, 22 = Southern Serpovidny REE pegmatite field, 23 = Vyuntspakhk REE pegmatite field, 24 = Yel'skiye Lakes REE deposits in peralkaline granite and granite-aplite veins, 25 = Lavrentyevskaya Mt. REE occurrences in alkali feldspar granite, 26 = Pesochny apatite occurrence, 27 = Tury Mys carbonatites.

Fig. 2. The geology of the Khibiny alkaline massif modified after Ivanyuk et al. (2009, 2012) using data from Gutkova (1933), Ozhinsky (1935), and Snyatkova et al. (1983). See Figure 5 for explanation of points A-F.

the Classification of Mineral Resources and Reserves protocol established by the Russian State Reserves Committee (GKZ). To introduce international readers to this classification scheme and make it easier to understand, the authors have translated the categories of the Russian GKZ classification into the categories of the Combined Reserves International Reporting Standards Committee (CRIRSCO) using the "Guidelines on Alignment of Russian Minerals Reporting Standards and the CRIRSCO Template" (Table 2), approved by both GKZ and CRIRSCO (Guidelines, 2010). This study mainly focused on the exploration potential. Thus, the resource categories do not constitute an estimate of economic potential and the translation of the resource categories is not a report of the Competent Person in terms of the Guidelines (2010).

Table 2. Guidelines on Alignment of Russian GKZ and CRIRSCO Categories (Guidelines, 2010)

Categories of the Russian GKZ classification	Categories in the CRIRSCO template
Prognostic resources of categories P3 and P2	Exploration results (only actual data are reported: not estimated resources tonnages and grades)
Prognostic resources of category P1	Inferred resources
Russian resources of category C2 in deposits of all complexity groups, and Russian resources of category C1 in deposits of the 4th complexity group	Indicated resources
Russian resources of category C1 in deposits of 1st, 2nd, and 3rd complexity groups with Russian resources of category A and B in areas of detailed study	Measured resources

REE Deposits and Occurrences of the Murmansk Region

Most of the REE resources of the Murmansk Region are concentrated in two large nepheline syenite and foidolite (an intrusive rock containing >60 vol % feldspathid minerals) plutons, Khibiny and Lovozero. A potentially economic deposit (the Sakharyok REE-Ta-Nb deposit in an alkaline pluton with the same name) and several subeconomic deposits and occurrences are situated in the Keivy block. These latter deposits are associated with peralkaline granites (locally altered) and amazonite-bearing pegmatites (Gaskelberg et al., 1978). Alkaline-ultrabasic complexes containing carbonatites are another potential REE source (Afanasyev, 2011; Chakhmouradian and Zaitsev, 2012; Zaitsev et al., 2014). There are 14 such complexes in the region (Bulakh et al., 2004). The most promising in terms of REE mineralization are Afrikanda, Kovdor, Vuoriyarvi, and Seblyavr.

The resources of some REE deposits and occurrences in the Murmansk Region have been previously evaluated. Data on the size and grade of these deposits are presented in Table 3 and their locations shown in Figure 1. Brief descriptions of the REE- and rare metal-bearing minerals discussed in this paper are presented in Table 4 and the rocks hosting the REE deposits and occurrences of the region are briefly described in Table 5.

Khibiny alkaline massif

Although the Khibiny massif has been investigated since the 19th century (Ramsay and Hackman, 1894), and the apatite deposits were discovered as far back as 1921 (Fersman et al., 1928), apatite was not recognized as an important REE source until the second half of the 20th century. As the Khibiny pluton represents one of the world's largest REE reservoirs (Chakhmoradian and Zaitsev, 2012; Khramov, 2014), we have placed particular emphasis on this complex.

The Khibiny massif, with an area of about 1,327 km^2, is the world's largest alkaline complex (Fig. 2). It is situated in the center of the Murmansk Region, at the contact of the Imandra-Varzuga Proterozoic greenstone belt with the Archaean metamorphic complexes of the Kola-Norwegian megablock (Fig. 1). In plan view, the massif is elliptical (45 × 35 km) and vertically it is cone-like, with its apex pointing downward (Shablinsky, 1963). Based on results of Pb-Pb, Rb-Sr and Sm-Nd dating, it formed between 380 and 360 Ma (Kramm and Kogarko, 1994; Arzamastsev et al., 2007). The massif consists dominantly of foyaite/khibinite (a nepheline syenite with predominant K-feldspar; about 70% of the outcrop area) and foidolite (8% of the outcrop area) that intruded into the foyaite massif along the Main Ring fault (Ivanyuk et al., 2012a). Highly potassic poikilitic nepheline syenites, "rischorrites" (10%), commonly occur between the rocks of the Main Ring and the foyaite. The foidolite of the Main Ring accommodates all the apatite deposits and occurrences. The apatite-nepheline and titanite-apatite-nepheline ores (apatite- and titanite-rich ijolites [composed mainly of nepheline and aegirine-augite] and melteigites [nepheline plus 70–90 vol % alkali ferromagnesian minerals]), with a P_2O_5 cutoff grade of 4 wt % and grades generally between 7.5 and 16.2% of P_2O_5 (Khramov, 2014), form stockworks in the apical parts of the melteigite-ijolite-urtite (10–90 vol % nepheline plus mafic minerals; classification of the nepheline-bearing rocks is shown in Table 5) complex, which for simplicity we refer to as foidolite (Fig. 3). The thickness of the apatite-rich foidolite ranges from 200 m in the southeastern part of the Main Ring to a few meters in its northeastern part (Ivanyuk et al., 2012a).

Titanite-apatite deposits of the Khibiny alkaline massif

The foidolite Main Ring incorporates three ore fields, NW, SW, and SE, containing 11 (titanite)-apatite deposits (Kamenev and Mineev, 1982). The NW ore field extends for more than 10 km and includes the Partomchorr and Kuelporr deposits, and the Snezhny Tsyrk occurrence (Fig. 2). Orebodies of these deposits have simple layer- or lenslike forms with average thicknesses of 50 to 70 m (Perekrest et al., 1978; Ivanyuk et al., 2009, 2012a). The SW ore field includes the Kukisvumchorr, Yuksporr, Apatitovy Tsyrk, Rasvumchorr, and Eveslogchorr deposits (Fig. 2). All these deposits are sections of a continuous, 12-km-long, apatite-bearing body with an average thickness of about 100 m (Kamenev, 1987; Ivanyuk et al., 2012a). Their upper parts comprise a single compact lens, whereas at depth the mineralization is distributed among a number of lenses. There is a distinct vertical zonation marked by a gradual increase in P_2O_5 content upward; titanite-bearing rocks are concenrated near the upper contact (Onokhin, 1967). The SE ore field extends for about 15 km and includes the Koashva, Vuonemyok, Nyorkpakhk, and Oleny Ruchey deposits (Fig. 2). In contrast to the SW ore field, the mineralization occurs in the form of complex (titanite)-apatite-nepheline stockworks (Fig. 3). The titanite-rich ores concentrate in 20- to 40-m-thick zones along the top contact of the orebodies (Goryainov et al., 2007; Ivanyuk et al., 2009; Ivanyuk et al., 2012a). A general view of the principal deposits, Koashva and Rasvumchorr, and typical mineralization are shown in Figure 4. At present, seven apatite deposits are being mined, i.e., 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," which currently is also exploring the Partomchorr deposit.

Table 3. Resources and Average Content of Main REE Deposits in the Murmansk Region

Deposit	REE_2O_3 resources, kt Measured (A+B+C1)	Indicated (C2)	Inferred (P1)	Average REE_2O_3 content in ore, %	Host rock	Main REE minerals	Other economic components	References
Khibiny alkaline massif								
Partomchorr	1,497	258		0.20	Ijolite, urtite, melteigite	Apatite, titanite	P, Ti, Al	Khramov, 2014; IMC, 2011a,b; PhosAgro, 2013; Kamenev and Mineev, 1982; this study
Kukisvumchorr	1,040			0.25				
Yuksporr	2,100			0.39				
Apatitovy Tsyrk	431			0.37				
Rasvumchorr	1,189			0.35				
Koashva	2,600	700		0.41				
Nyorkpakhk	213			0.37				
Oleny Ruchey	1,236	229		0.38				
Kuelporr			65	0.34				
Eveslogchorr			2,275	0.44				
Vuonemjok			351	0.17				
Khibiny apatite deposits, total	11,493		2,685	0.36				
Yuksporr Lovchorrite deposit	2.5	14.5		0.7	Pegmatite field in rischorrite	Rinkite		Krasotkin et al., 2008
Lovozero massif								
Lovozero loparite deposit (Differentiated suite)	7,290	3,000	19,200	0.78	Ijolite-melteigite and malignite	Loparite, eudialyte	Ta, Nb	FODD, 2011; Khramov, 2014; this study
Lovozero loparite-eudialyte deposit (Eudialyte suite)	350		7,500[1]	0.42	Eudialyte-rich malignite and foyaite	Eudialyte, loparite, lovozerite, murmanite	Zr, Ta, Nb	Samonov, 2008; Melent'ev, 2013; this study
Kuivchorr			3,190	0.58	Ijolite-melteigite, foyaite	Apatite, titanite	P, Ti, Al	Saprykina et al., 1978
Loparite placers (Revda, Seidozero, Rayyavr)			80	2.7 (kg/m^3)	Sand and turf	Loparite	Ta, Nb, sand, kaolin	This study
Afrikanda	230			0.67	Pyroxenite and alkaline pegmatites	Perovskite	Ti, Fe	Afanasyev, 2011; Afanasyev et al., 1950; this study
Seblyavr			2,587	0.24	Pyroxenite	Perovskite	Ti, Fe	Afanasyev, 2011
Western Vuoriyarvi			829	0.29	Pyroxenite	Perovskite, apatite	Ti, Fe, P	Afanasyev, 2011
Keivy block								
Sakharyok		22	10	0.34[2]	Nepheline and alkaline syenite	Britholite, zircon, pyrochlore	Zr, Ta, Nb	Pasternok, 2000; Zozulya et al., 2012
Yumperuaiv			60	0.55[2]	Peralkaline granite	Bastnäsite, allanite, monazite	Zr	Chukhina et al., 1963
Large Pedestal			36	0.33[2]		Chevkinite, monazite	Zr	This study
Yel'skiye Lakes deposit group			3	1.57[2]	Veins of peralkaline granite and granite-aplite	Gadolinite, pyrochlore, fergusonite, bastnäsite	U, Zr	Bogatyrev et al., 1967

[1] Plus, 60,000 kt of hypothetical resources of REE_2O_3 @ 0.4 % (Samonov, 2008)
[2] Heavy REE constitute a significant part in total REE

Fluorapatite and titanite are the main REE-bearing minerals in the Khibiny massif. The REE content of both of these minerals, however, is relatively low (Tables 6–8), although the resources they host are huge (see Table 3). The total measured and indicated resources of REE_2O_3 in the Khibiny titanite-apatite-nepheline deposits are 11.5 Mt, at an average grade of 0.35 wt % REE_2O_3. There are also 2.7 Mt of inferred resources grading 0.40 wt % REE_2O_3 (Kamenev and Mineev, 1982; IMC Montan IEEC, 2011a, b; PhosAgro, 2013; Khramov, 2014; the present study).

Table 4. Rare Earth- and Rare Metal-Bearing Minerals of the Murmansk Region, Mentioned in the Text

Mineral	General formula [1]	Principal location[2]	Geological or economic role[2]
Apatite[3] (mostly fluor- and hydroxylapatite)	$Ca_5(PO_4)_3(F,OH,Cl)$	Khibiny and Kovdor massifs	Major recovered mineral
Allanite-(Ce)	$(CaCe)(Al_2Fe^{2+})(Si_2O_7)(SiO_4)O(OH)$	Keivy's peralkaline granite	Accessory
Ancylite-(Ce)	$SrCe(CO_3)_2(OH) \cdot H_2O$	Kovdor, Afrikanda	Accessory
Baddeleyite	ZrO_2	Kovdor	Recovered mineral
Bastnäsite-(Ce)	$(Ce,La)(CO_3)F$	Keivy's peralkaline granite	Major REE concentrator
Britholite-(Y)	$Ca_2(Y,Ca)_3(SiO_4,PO_4)_3(OH,F)$	Sakharyok, Keivy's peralkaline granite	Major REE concentrator or accessory
Calzirtite	$Ca_2Zr_5Ti_2O_{16}$	Carbonatite complexes	Accessory
Cerite-(Ce)	$(Ce,La,Ca)_9(Fe^{3+},Mg)[SiO_4]_6[SiO_3(OH)](OH)_3$	Afrikanda	Accessory
Chevkinite-(Ce)	$(Ce,La,Ca)_4 Fe^{2+} (Ti,Fe)_4[Si_2O_7]_2O_8$	Keivy's peralkaline granite	Major REE concentrator
Eudialyte[3] (mostly eudialyte and manganoeudialyte)	$Na_{15}(Ca,Ce)_6(Mn^{2+},Fe^{2+}, Y)_3(Zr,Nb)_3[Si_{25}O_{73}](O,OH,H_2O)_3(OH,Cl)_2$	Lovozero eudialyte complex	Major ore mineral
Euxenite-(Y)	$(Y,Ca,Ce,U,Th)(Nb,Ti,Ta)_2O_6$	Keivy's peralkaline granite and pegmatites	Accessory
Fergusonite-(Y)	$YNbO_4$	Keivy's peralkaline granite and pegmatites	Major HREE concentrator
Fluorite	$(Ca,Y)F_2$	Ploskaya Mt. pegmatite (Keivy)	Major REE concentrator
Gadolinite-(Y)	$Y_2Fe^{2+}Be_2Si_2O_{10}$	Keivy's peralkaline granite and pegmatites	Accessory and sometimes major REE concentrator
Labuntsovite[3]	$(K,Ba,Na)(Ti,Nb)(Si,Al)_2 (O,OH)_7 \cdot nH_2 O$	Lovozero loparite deposit	Accessory
Lomonosovite	$Na_5Ti_2(Si_2O_7)(PO_4)O_2$	Lovozero massif	Minor ore mineral or accessory
Loparite-(Ce)	$(Na,Ce,Ca)(Ti,Nb)O_3$	Lovozero loparite deposit	Major recovered mineral
Lovozerite	$(Na,Ca)_3(Zr,Ti)[Si_6O_{12}(O,OH)_6] \cdot H_2O$	Lovozero eudialyte suite	Minor ore mineral or accessory
Monazite-(Ce)	$Ce(PO_4)$	Keivy's peralkaline REE-rich granite	Major REE concentrator
Murmanite	$Na_2Ti_2(Si_2O_7)O_2 \cdot 2H_2O$	Lovozero massif	Minor ore mineral or accessory
Perovskite	$CaTiO_3$	Afrikanda, Vuoriyarvi, Seblyavr	Major REE concentrator
Pyrochlore[3]	$(Na,Ca,Mn,Sr,Pb,REE,Y,U,H_2O,\square)_2(Nb,Ti)_2(O,OH)_6(OH,F,O,H_2O,\square)$	Carbonatite complexes, Keivy's peralkaline granite	Accessory
Rhabdophane-(Ce)	$(Ce,La)(PO_4) \cdot H_2O$	Lovozero loparite deposit	Accessory
Rinkite	$(Na,Ca)_3(Ca,Ce)_4Ti(Si_2O_7)_2OF_3$	Yuksporr lovchorrite deposit (Khibiny massif)	Major ore mineral
Shomiokite-(Y)	$Na_3Y[CO_3]_3 \cdot 3H_2O$	Shomiokitovoye pegmatite (Lovozero)	Major mineral
Thalénite-(Y)	$Y_3Si_3O_{10}F$	Keivy's peralkaline granite and pegmatites	Accessory
Thorite	$(Th,U)SiO_4$	Keivy's peralkaline granite	Accessory
Titanite	$CaTi(SiO_4)O$	Khibiny titanite-apaitie deposits	Recovered mineral
Xenotime-(Y)	$Y(PO_4)$	Keivy's peralkaline granite and pegmatites	Accessory
Yttrialite-(Y)	$(Y,Th)_2Si_2O_7$	Keivy's peralkaline granite and pegmatites	Accessory
Zircon	$ZrSiO_4$	Sakharyok massif, Keivy's peralkaline granite	Ore mineral
Zirconolite	$CaZrTi_2O_7$	Carbonatite complexes	Accessory

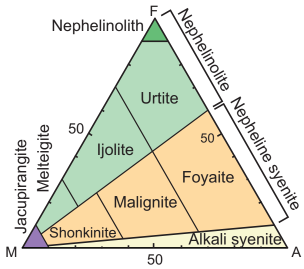
[1] Strunz and Nickel, 2001; Mindat, 2015
[2] Gaskelberg, 1978; Pekov, 2000; Ivanyuk et al., 2002; Yakovenchuk et al., 2005; Afanasyev, 2011; this study
[3]Group name

Minor titanite-apatite deposits and occurrences in the Khibiny massif

Ivanyuk et al. (2009, 2012a) and Konopleva and colleagues (2014a) showed that the fluorapatite becomes richer in Ca, Sr, and P and carries less Na, lanthanoids (Ln), and Si from the center and margins of the massif toward the Main Ring (points C and E; Fig. 5). This can be explained by the coupled substitutions: $Ln^{3+} + Si^{4+} \Leftrightarrow (Ca, Sr)^{2+} + P^{5+}$ and $Na^{+} + Ln^{3+} \Leftrightarrow 2(Ca, Sr)^{2+}$. Within the foidolite Main Ring, these substitutions are expressed by an increase in Ca content at point E in Figure 2 (Koashva deposit), and Sr content at point C (Poachvumchorr occurrence). Importantly, these elements display similar behavior within the (titanite)-apatite deposits, i.e., the higher the P_2O_5 content of the fluorapatite, the lower are the contents of Sr and REE (Ivanov, 1987; Ivanyuk et al., 2012a; Konopleva et al., 2014a).

The content of titanite is highest in the foidolites of the SE and NW sectors of the Main Ring, with some deposits (e.g., Vuonnemyok and Partomchorr) hosting only titanite-apatite ores (up to 80 vol % of titanite). The REE content of the titanite changes in the same way as it does in the fluorapatite (Fig. 5), i.e., the REE content gradually decreases from the margins of the massif to its center. Locally, however, the titanite is enriched in REE within the rischorrites (35–40 km in Fig. 5) and depleted within the foidolites (points C and E). The average content of REE_2O_3 in the titanite of the (titanite)-apatite-nepheline ores is 0.51 wt %, although

Table 5. Rocks Hosting REE Deposits and Occurrences in the Murmansk Region

Rock	Main minerals (vol %), structural features	Typical minor and accessory minerals	Principal localities (massifs)
Foidolites (nephelinolites)			
Urtite Ijolite Melteigite	 F – nepheline (±sodalite, kalsilite, natrolite); A – potassic feldspar and albite (An_{0-5}); M – aegirine–diopside, K-Na-Ca amphyboles, fluorapatite, titanite, loparite-(Ce), biotite, eudialyte, etc.	Astrophyllite, ilmenite, labuntsovite (baryto) lamprophyllite, lomonosovite, lovozerite, magnetite, murmanite, perovskite, pyrrhotite, rinkite	Khibiny, Lovozero
Nepheline syenites Foyaite Malignite Shonkinite			Khibiny, Lovozero, Sakharyok
Rischorrite	Poikilitic nepheline syenite		Khibiny
"Lujavrite"	Trachitoid nepheline syenite		Lovozero
Phoscorite	Forsterite+apatite+magnetite >50, carbonates (0-50)	Spinel, ilmenite-geikielite, baddeleyite, pyrochlore, zirconolite	Kovdor, Vuoriyarvi, Seblyavr
Carbonatite	Igneous rock with carbonates >50		
"Ore pyroxenite"	Pyroxene (>60), titanomagnetite (up to 30), perovskite (up to 25)	Amphiboles, phlogopite, fluor-hydroxylapatite	Afrikanda, Vuoriyarvi, Seblyavr
Peralkaline granite	Quartz (20-60), alkali feldspar+albite An_{0-5} (40-80), aegirine-augite+alkali amphiboles (up to 20)	Phlogopite, aenigmatite, magnetite, zircon	Western Keivy

References: Le Maitre, 2002; Ivanyuk et al., 2009; Afanasyev, 2011; Mikhailova et al., 2016

locally it reaches 4 wt %. Titanite contains roughly 10% of the REE_2O_3 resources of the Khibiny massif, or >1 Mt. At present, the REE in titanite are not regarded as reserves or resources, although processes are available for recovering the REE as a by-product (Nikolaev et al., 2009).

Rinkite mineralization of the Khibiny massif—Yuksporr Lovchorrite deposit

Rinkite is an accessory mineral in all rocks of the Khibiny massif and is an essential rock-forming mineral in some rischorrites and pegmatites. Commonly, the host rischorrite and

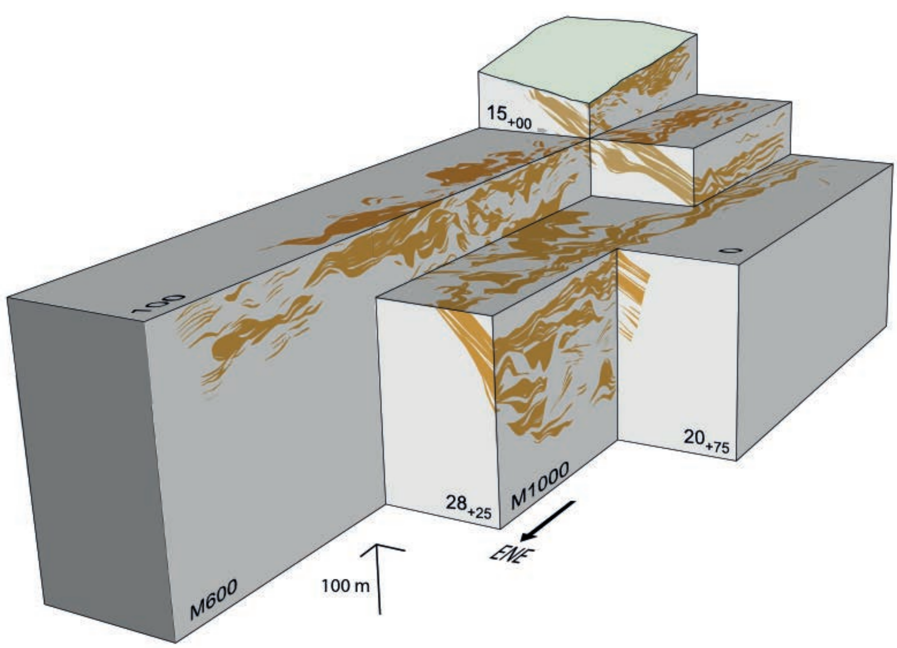


Fig. 3. Block diagram of the Koashva titanite-apatite deposit. The titanite-apatite ores are shown in brown (cutoff grade of 4 wt % P_2O_5), and the host foidolites in gray (Goryainov et al., 2007). The mine levels and drilling profiles are in meters.

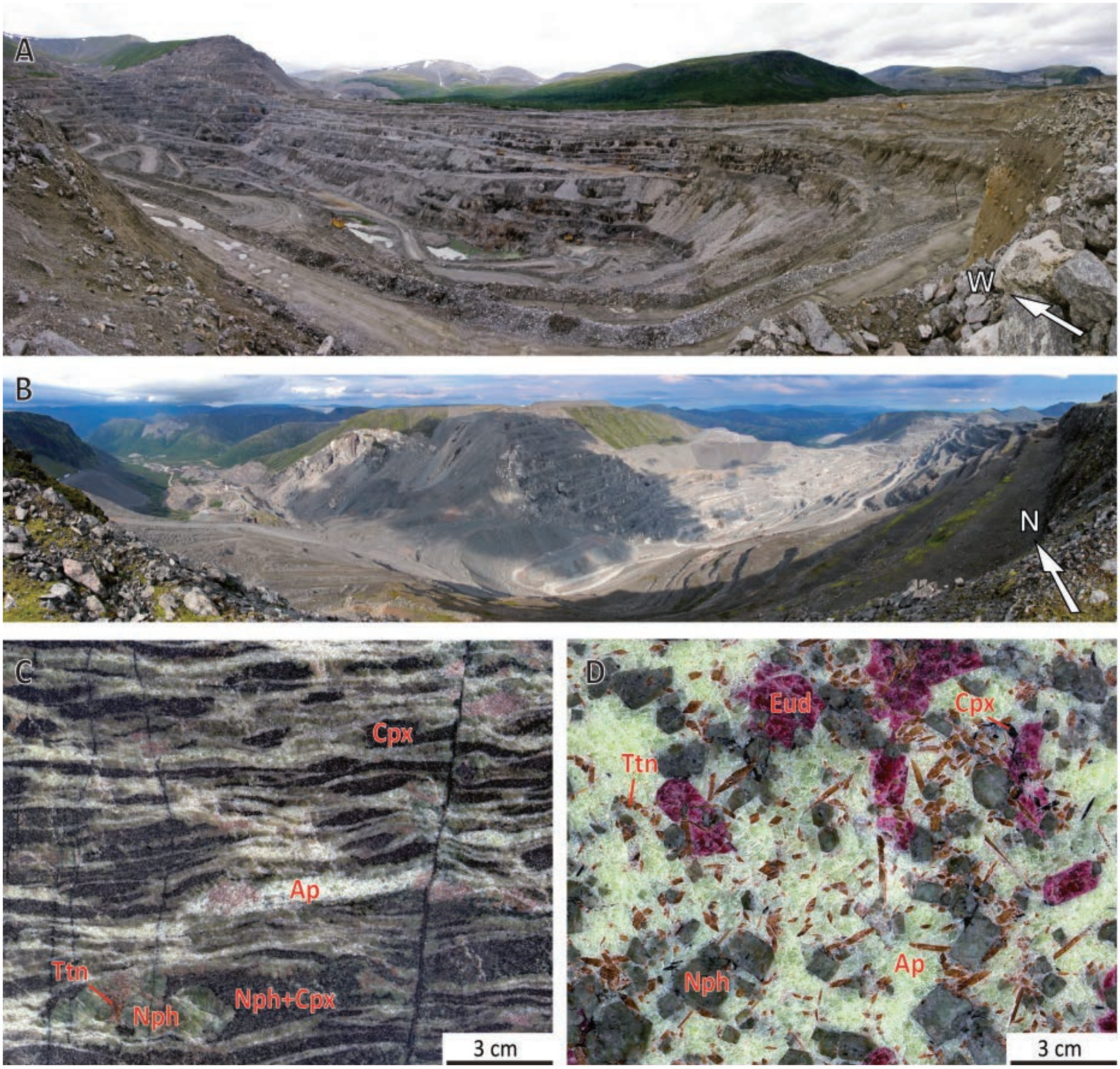


Fig. 4. Views of the Koashva (A) and Rasvumchorr (B) titanite-apatite deposits and photographs of polished slabs of lenticular-striped (C) and spotted (D) ores typical of the Khibiny titanite-apatite deposits. Ap = fluorapatite, Cpx = clinopyroxene of the aegirine-diopside series, Eud = eudialyte, Nph = nepheline, Ttn = titanite.

foyaite rich in rinkite forms crescent-shaped ore zones along the foidolite Main Ring (Fig. 2).The REE_2O_3 content of the rinkite is highest at point A and, apart from a peak at point C, decreases to a minimum at point D and then increases gradually to point F (Fig. 5). On the whole, the average REE content of the rinkite decreases gradually from foyaite to foidolite, rischorrite and (titanite)-apatite-nepheline rock, and then increases steeply in the pegmatites (up to 24 wt % REE_2O_3). This is important because the heavy REE (HREE) content of rinkite hosted by pegmatites and hydrothermal veins is much higher than that of rinkite in the other rock types.

The only rinkite deposit that hosts potentially economic resources in the Khibiny massif is the Yuksporr Lovchorrite deposit located near the Yuksporr titanite-apatite deposit (Fig. 2). It occurs as a belt of rinkite-nepheline-aegirine-feldspar pegmatites confined to a fault zone (1,900 m long and 100–400 m wide) within rischorrite (Fig. 6). The rinkite content of these pegmatites ranges from 1 to 80 vol % (Afanasyev and Salye, 1933; Ozhinsky, 1935). Rinkite from this deposit is distinguished by a comparatively high content of HREE (up to 3.2 wt % or 13% of REE sum) (Table 8) and is therefore of particular interest. The deposit was mined and the ore processing plant operated from 1934 to 1939, when about 19 kt of ore was extracted and about 1 kt of rinkite concentrate produced. On January 1, 1939, the measured REE_2O_3 reserves of the deposit were estimated to be 2.5 kt, the indicated reserves to be 14.5 kt, and the average REE_2O_3 content to be 0.7 wt % (Afanasyev and Salye, 1933; Krasotkin et al., 2008).

Although the Yuksporr Lovchorrite deposit was abandoned in 1939, it deserves re-evaluation because of the demand for HREE, state-of-the-art hydrometallurgical technologies that now allow more effective concentration of rinkite, and the

Table 6. Average Content and Composition of Fluorapatite and Titanite in (Titanite)-Apatite-Nepheline Ores of the Khibiny Massif

	Ore field/deposit									
	NW		SW					SE		
Component	Partomchorr (Belyakov et al., 1983)	Kuelporr (Zhilko et al., 1994; this study)	Kukisvumchorr (Perekrest et al., 1978)	Yuksporr (Pan'shin et al., 1980)	Apatitovy Tsyrk (Kamenev et al, 1984)	Rasvumchorr (Mineev et al., 1975)	Eveslogchorr (Kamenev et al., 1979)	Koashva (Perekrest et al., 1985)	Nyorkpakhk (Kamenev et al., 1975; this study)	Oleny Ruchey (Fanygin et al., 1985)
Average mineral content in ore (wt %) (Ivanov, 1987)										
Apatite	18.4	23.0	37.1	36.4	36.6	37.6	30.0	40.1	36.7	38.3
Titanite	6.9	6.1	4.2	4.4	2.9	4.0	8.9	6.0	2.3	3.2
Average REE content (wt %)										
Apatite	1.13	1.12	0.71	1.04	0.90	0.99	1.02	1.02	0.95	1.02
Titanite	0.52		0.40	0.49	0.58	0.60		0.56	0.34	0.56
REE distribution in minerals (relative %)										
Apatite	88.72	94.08	89.38	94.65	85.0	93.5	80.7	91.1	96.5	87.5
Titanite	7.45	3.34	9.06		4.6	4.3	17.0	6.7	1.75	3.7
Others	3.83	2.58	1.56		10.4	2.2	2.3	2.2	1.75	8.8

Table 7. REE Balance in Ores of the Khibiny Massif, Relative Percent (Samonov, 2008; Belyakov et al., 1983; Mineev et al., 1975; Melent'ev, 2013; this study)

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
Koashva	27.8	42.4	4.4	14.8	2.0	0.6	2.3	0.2	1.0	0.2	0.3	–	0.2	–	3.7
Nyorkpakhk	28.4	46.3	4.0	14.8	1.8	0.6	1.7	0.3	0.9	0.2	0.4	0.1	0.4	0.1	–
Oleny Ruchey	26.5	46.6	4.0	15.7	2.5	0.8	2.0	0.2	0.9	0.1	0.3	0.1	0.2	–	0.1
Partomchorr	26.2	47.0	4.2	14.8	2.5	0.7	2.0	0.3	1.1	0.2	0.4	0.1	0.4	0.1	
Average	27.1	46.2	4.1	15.1	2.3	0.7	1.9	0.3	0.9	0.2	0.4	0.3	0.4	0.1	–

location of the deposit close to a center of mining and mineral processing (it is situated ~3 km from the Yuksporr apatite mine and about 20 km from the JSC "Apatit" beneficiation plant).

The Lovozero alkaline massif

One of Russia's major REE reservoirs is the Lovozero alkaline massif, the second largest layered igneous complex in the world after the Bushveld Complex, South Africa. The Lovozero massif intruded Archean granite-gneiss and Devonian tuff-basalt strata at ~362 Ma (Korchak et al., 2011). It comprises regularly alternating subhorizontal layers of foyaite-malignite (a nepheline syenite containing ~50 vol % aegirine; "lujavrite") and ijolite-urtite (Fig. 8). These strata have been broadly subdivided into differentiated (bottom) and eudialyte (top) suites that differ in their eudialyte content (on average, <1 and 6 vol %, respectively), proportions of nepheline-syenite and foidolite (about 8:1 and 15:1), the thickness of the individual layers (5–30 m and 5–100 m) and the sharpness of the layers boundaries (sharp in differentiated suite and gradual in eudialyte suite) (Vlasov et al., 1959; Gerasimovsky et al., 1966; Bussen and Sakharov, 1972; Pekov, 2000; Pakhomovsky et al., 2014; present study). The Lovozero massif houses the Lovozero loparite deposit that has been exploited by Lovozerskiy GOK since 1941. It is the largest Ti, Nb, Ta, and REE deposit in Russia and currently the country's only source of REE.

The Lovozero massif comprises seven types of REE-bearing mineralization:

1. "Loparite horizons" in the differentiated suite forming the huge Lovozero loparite (REE-Ti-Ta-Nb) deposit. These "horizons" are thin, subhorizontal (0.1–1.5 m) layers of loparite-rich malignite and ijolite-melteigite. The layers extend throughout the Lovozero differentiated suite and constitute resources at the following sites (Fig. 7): Umbozero (including the Northern Flank, Mine Fields

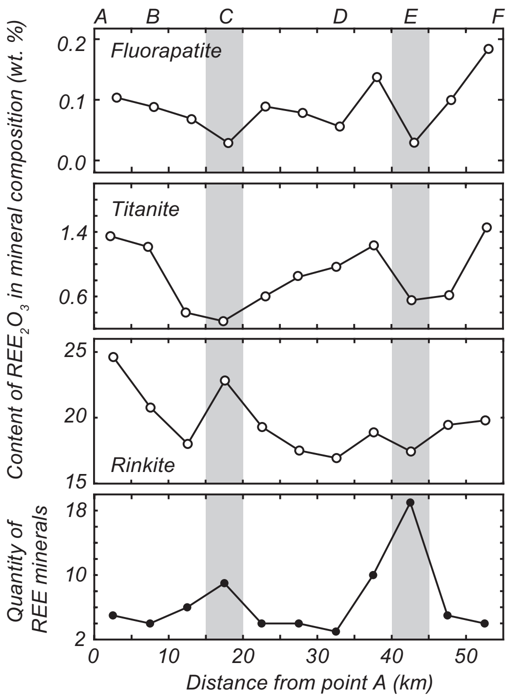


Fig. 5. The REE_2O_3 content of fluorapatite, titanite, and rinkite and quantity of REE minerals as a function of the distance from point A along the A-B-C-D-E-F profile shown in Figure 2 (from Ivanyuk et al., 2013a; Konopleva et al., 2014a,b).

I and II, and the Southern Flank), Karnasurt, Kedykvyrpakhk, Alluaiv, Angvundaschorr, Sengischorr, Parganyun, Kuftnyun, Strashempakhk, Ninchurt, and Kuamdespakhk (Sukharev et al., 1990). The only sites currently being exploited are Karnasurt and Kedykvyrpakhk; the Umbozero Mine Field I was exploited between 1983 and 2003;

2. (Loparite)-eudialyte ores of the eudialyte suite. This suite has potentially economic resources at the following sites: Karnasurt, Kedykvyrpakhk, Alluaiv, Angvundaschorr–Sengischorr, and Parguaiv (Utkin et al., 1995; Danilov et al., 1997);
3. (Loparite)-murmanite-lovozerite mineralization in murmanite-bearing porphyritic malignite (Bussen and Sakharov, 1972). The rocks usually form lenses (up to 300 m in diameter and 150 m in thickness). An aureole of this type of mineralization is developed around the (loparite)-eudialyte deposits (Utkin et al., 1995);
4. Titanite-apatite mineralization in ijolite: Kuivchorr occurrence and Horizon II-7 (Saprykina et al., 1977).
5. Rare metal mineralization in aegirine-albite metasomatic rocks of the exocontact ring of the massif. Pyrochlore, zircon, lorenzenite {$Na_2Ti_2(Si_2O_6)O_3$}, murmanite, loparite, mosandrite {$(\square,Ca,Na)_3(Ca,REE)_4Ti(Si_2O_7)_2[H_2O,OH,F]_4 \cdot H_2O$}, apatite, titanite, and eudialyte concentrate Nb, Ta, Th, U, Zr, Ti, and REE. This mineralization is encountered at Mts. Flora, Vavnbed, Appuaiv, Punkaruaiv, and Kitknyun (Danilov et al., 1997).

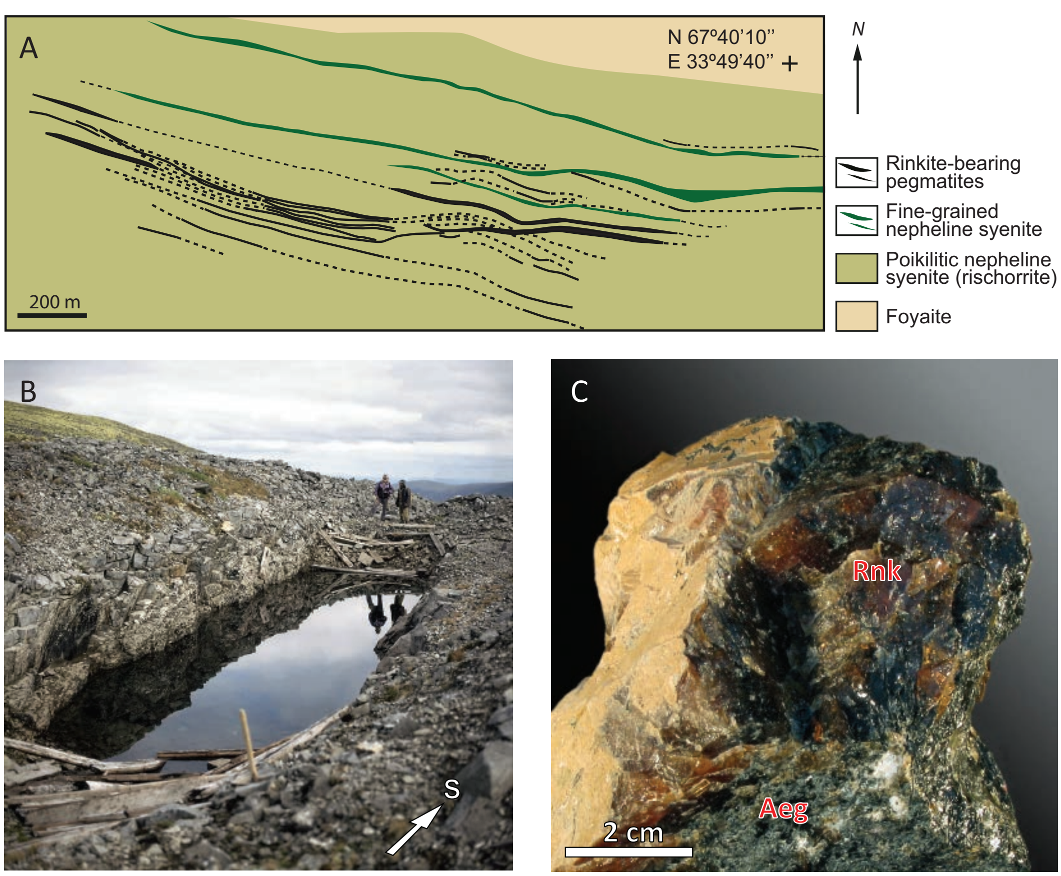


Fig. 6. A geologic map of the Yukspor lovchorrite deposit (A; Mikhalev, 1937), a photograph of an abandoned open pit (B), and a typical rinkite ore (C). Aeg = aegirine, Rnk = cryptocrystalline rinkite.

Table 8. Content of REE_2O_3 in REE-rich Minerals of Different Deposits of the Murmansk

Mineral	*n*	La_2O_3	Ce_2O_3	Pr_2O_3	Nd_2O_3	Sm_2O_3	Eu_2O_3
Fluorapatite[1]	*69*	0.01±0.01 0.00–0.07	0.01±0.01 0.00–0.12	0.00 0.00–0.02	0.00±0.01 0.00–0.05	–	–
Titanite[1]	*15*	0.05±0.07 0.00–0.17	0.3±0.2 0.00–0.68	–	0.04±0.08 0.00–0.26	–	–
Rinkite[2]	*6*	3±1 2.17–4.88	8±2 6.15–11.13	1.2±0.3 0.69–1.48	3.1±0.8 2.03–4.09	0.4±0.3 0.00–0.70	–
Zirkonolite[3]	*9*	0.79±0.55 0.22–1.82	5.51±2.23 1.96–9.47	1.07±0.47 0.48–2.01	4.31±3.02 1.49–10.14	0.91±0.61 0–2.19	0.22±0.49 0–1.50
Eudialyte[4]	*83*	0.04±0.05 0.00–0.19	0.09±0.07 0.00–0.38	0.00±0.02 0.00–0.09	0.02±0.03 0.00–0.14	–	–
Eudialyte[5]	*63*	0.5±0.3 0.00–1.25	1.4±0.7 0.00–3.22	0.1±0.1 0.00–0.52	0.6±0.2 0.00–1.10	0.02±0.07 0.00–0.42	–
Loparite-(Ce)[5]	*83*	8.8±0.4 7.67–9.65	18.0±0.6 15.18–19.56	1.4±0.3 0.58–2.02	4.1±0.2 3.78–4.61	0.1±0.2 0.00–0.73	–
Eudialyte[6]	*8*	0.2±0.2 0.00–0.39	0.7±0.3 0.17–0.97	–	0.3±0.1 0.00–0.37	–	–
Shomiokite-(Y)[7]	*5*	–	0.08±0.05 0.04–0.16	0.00±0.01 0.00–0.02	0.2±0.4 0.03–0.88	0.7±0.6 0.02–1.59	0.2±0.4 0.03–0.88
Loparite-(Ce)[8]	*5*	6±3 3.63–11.17	15±5 10.05–23.44	1.3±0.3 1.11–1.78	5±1 3.53–5.98	–	–
Perovskite[8]	*4*	1.3±0.9 0.34–2.49	5±4 1.43–9.93	0.7±0.6 0.00–1.36	2±2 0.00–3.90	–	–
Ancylite-(Ce)[9]	*17*	17±4 6.11–23.47	24±3 15.92–27.53	2±2 0.00–6.06	6±3 0.00–10.61	–	–
Hydroxyl-apatite[9]	*538*	0.00±0.03 0.00–0.45	0.1±0.2 0.00–2.90	–	0.00±0.02 0.00–0.23	–	–
Pyrochlore[9]	*271*	1±1 0.00–10.52	3±3 0.00–16.67	0.00±0.05 0.00–0.51	0±1 0.00–9.38	–	–
Zirconolite[9]	*155*	1±1 0.00–4.85	4±3 0.00–14.30	0.02±0.09 0.00–0.65	1±2 0.00–8.50	0.0±0.2 0.00–1.96	–
Allanite-(Ce) [10]	*15*	7±1 5.09–9.60	12±2 7.03–14.02	1.4±0.5 0.68–2.14	4±1 1.39–5.47	0.6±0.7 0.00–2.25	–
Bastnäsite[10]	*113*	19±6 0.00–36.19	30±9 0.51–52.65	4±1 0.00–10.18	11±4 0.83–27.81	2±1 0.00–5.18	0.0±0.2 0.00–2.06
Chevkinite-(Ce)[10]	*43*	10±3 0.00–14.81	19±5 2.56–23.15	1.9±0.9 0.00–2.93	7±2 0.00–10.17	1±1 0.00–2.79	0.1±0.3 0.00–2.19
Fergusonite-(Y)[10]	*29*	0.03±0.08 0.00–0.33	0.5±0.8 0.00–0.50	0.02±0.09 0.00–0.50	1±1 0.00–4.75	1.2±0.7 0.00–2.62	0.01±0.04 0.00–0.19
Xenotime-(Y)[10]	*39*	0.01±0.03 0.00–0.18	0.1±0.2 0.00–0.90	0.01±0.07 0.00–0.43	0.1±0.2 0.00–0.82	0.4±0.5 0.00–1.54	0.01±0.04 0.00–0.24
Xenotime-(Y/Yb) [11]	*13*	–	–	–	–	0.1±0.1 0.00–0.26	0.1±0.3 0.00–1.00
Bastnäsite-(Ce)[11]	*6*	19±2 16.78–20.99	39±2 37.37–41.93	3.3±0.2 3.02–3.64	7.4±0.8 6.87–8.87	1.6±0.4 1.28–2.31	0.2±0.2 0.00–0.45
Monazite-(Ce/La/Nd)[11]	*92*	16±4 8.05–34.32	26±9 2.31–35.62	4±1 1.97–7.93	13±4 7.86–26.64	2±1 0.00–5.34	0.0±0.3 0.00–3.30
Monazite-(Ce)[11]	*4*	14.8±0.5 14.39–15.51	37±2 34.89–39.87	2±2 0.00–3.47	6.6±0.7 5.90–7.31	0.7±0.5 0.00–1.32	–
Fergusonite-(Y)[11]	*9*	–	–	–	–	0.1±0.1 0.00–0.30	0.1±0.1 0.00–0.35
Fluorite[11]	*13*	–	–	–	–	0.02±0.07 0.00–0.26	–

n – the number of investigated specimens (1–8 analyses per specimen)

Notes: Khibiny massif: [1](titanite)-apatite deposits, [2]pegmatites of the Yuksporr Lovchorrite deposit, [3]fenitized volcano-sedimentary rocks, [4]foyaite; Lovozero massif: [5]Loparite deposit, [6]loparite-eudialyte deposit; [7]pegmatite (Pekov, 2000); Afrikanda massif: [8]calcite-amphibole-clinopyroxene rock (Chakhmouradian and Zaitsev, 1999); Kovdor massif: [9]phoscorite-carbonatite complex; Western Keivy massif: [10]peralkaline granite; [11]amazonite pegmatite (Voloshin and Pakhomovsky, 1986)

Region Determined by Electron-Microprobe Analyses (mean ± SD / min-max, wt %)

Gd_2O_3	Tb_2O_3	Dy_2O_3	Ho_2O_3	Er_2O_3	Tm_2O_3	Yb_2O_3	Lu_2O_3	Y_2O_3
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
0.2±0.2 0.00–0.52	–	0.1±0.1 0.00–0.27	–	–	–	–	–	1.3±0.7 0.52–2.38
0.80±0.65 0–1.97	0.08±0.1 0–0.23	0.86±0.58 0–1.70	0.07±0.11 0–0.27	0.34±0.30 0–0.96	0.03±0.08 0–0.23	0.22±0.24 0–0.62	–	3.15±1.71 0.94–5.37
–	–	–	–	–	–	–	–	0.01±0.05 0.00–0.23
–	–	–	–	–	–	–	–	0.00±0.03 0.00–0.27
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	0.1±0.2 0.00–0.49
1.7±0.5 1.01–2.30	0.3±0.3 0.00–0.51	3±1 1.67–5.03	0.7±0.7 0.00–1.67	2.1±0.7 1.24–3.11	0.1±0.2 0.00–0.34	1.0±0.7 0.02–1.75	0.06±0.08 0.00–0.17	23±2 20.72–24.50
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	0±1 0.00–5.77
0.00±0.00 0.00–0.00	–	–	–	–	–	–	–	0.00±0.00 0.00–0.00
–	–	0.1±0.3 0.00–1.18	–	–	–	–	–	0.3±0.9 0.00–3.32
1±1 0.00–4.14	0.0±0.1 0.00–0.89	1±1 0.00–4.06	0.00±0.03 0.00–0.33	0.1±0.3 0.00–2.08	0.00±0.01 0.00–0.15	0.0±0.3 0.00–2.58	–	3±4 0.00–15.66
0.4±0.7 0.00–2.75	–	0.3±0.7 0.00–4.32	–	0.01±0.04 0.00–0.23	–	0.01±0.05 0.00–0.23	–	1±2 0.00–9.28
3±1 0.00–4.98	0.2±0.3 0.00–0.79	4±1 1.12–7.07	0.4±0.6 0.00–1.91	3±1 0.83–5.02	0.1±0.2 0.00–0.65	3±1 0.43–5.90	0.1±0.4 0.00–1.95	26±4 3.87–31.72
3±1 0.00–5.45	0.2±0.4 0.00–1.61	7±2 2.95–10.17	0.9±0.8 0.00–3.19	5±1 3.23–7.81	0.2±0.3 0.00–1.11	4±1 1.64–7.20	0.1±0.3 0.00–0.98	42±4 32.25–48.93
0.8±0.3 0.39–1.36	0.1±0.1 0.00–0.40	4±1 2.40–5.53	1.4±0.7 0.06–2.33	6±2 0.71–9.23	1.5±0.3 1.00–1.95	15±5 8.16–24.69	1.9±0.6 0.78–2.61	31±5 22.78–36.98
0.4±0.5 0.00–1.25	–	0.1±0.2 0.00–0.46	0.1±0.1 0.00–0.26	–	–	–	–	0.7±0.8 0.00–1.80
1±1 0.00–3.57	0.0±0.2 0.00–1.58	0.3±0.6 0.00–3.24	–	0.00±0.01 0.00–0.13	–	0.00±0.02 0.00–0.15		2±3 0.00–19.93
0.1±0.1 0.00–0.23	–	0.02±0.04 0.00–0.07	0.02±0.05 0.00–0.09	–	–	–	–	1.2±0.8 0.53–2.21
0.4±0.3 0.00–0.77	–	1.8±0.5 1.23–2.48	0.4±0.4 0.00–0.90	2.6±0.7 2.09–4.00	0.4±0.5 0.00–1.49	4±2 1.81–8.78	0.5±0.7 0.00–2.00	25±7 13.32–32.00
–	–	0.2±0.3 0.00–0.96	0.04±0.09 0.00–0.30	0.3±0.5 0.00–1.51	0.1±0.1 0.00–0.35	1±1 0.00–3.92	–	3±3 0.43–11.62

Fig. 7. A geologic map of the of the Lovozero massif showing REE deposits and occurrences after Bussen and Sakharov (1972), based on the data of Kalinkin et al. (1972), Saprykina et al. (1977), Utkin et al. (1995), and Danilov et al. (1997), and observations made during the current study.

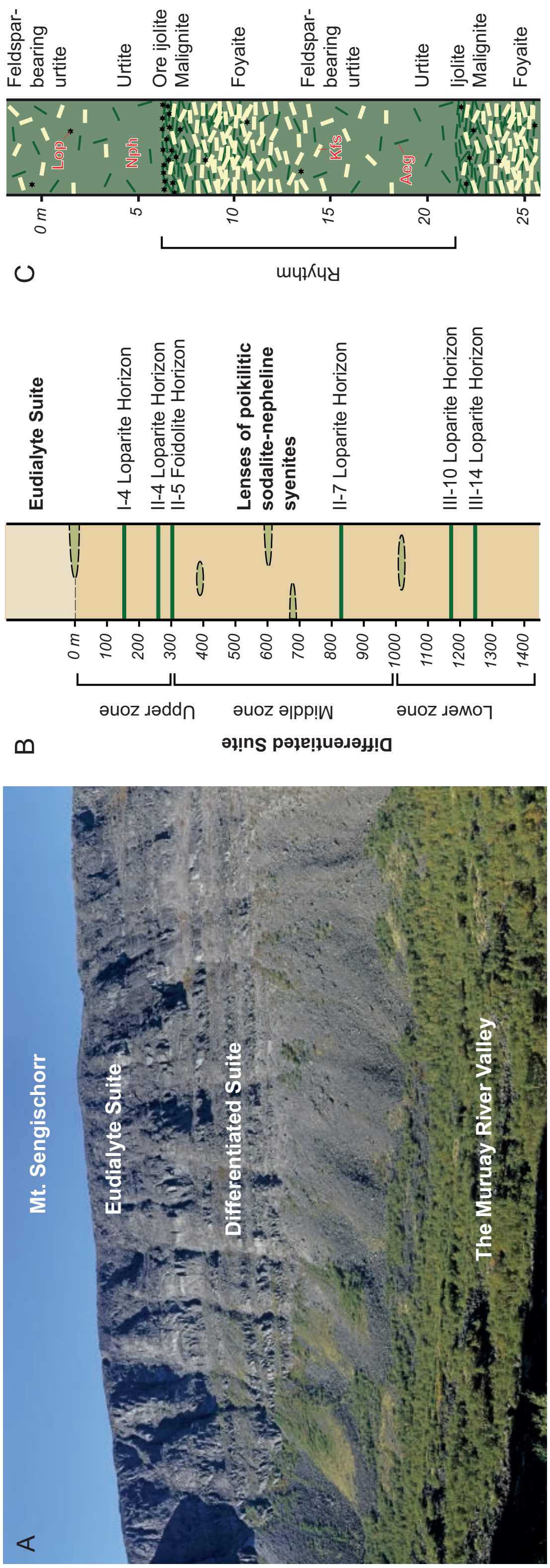


Fig. 8. A general view of the stratification in the Lovozero massif along the Muruay River Valley near Mt. Sengischorr (A), a stratigraphic column of the Lovozero massif (B; after Gerasimovsky et al., 1966), and schematic stratigraphic column illustrating the rhythmic layering of the Differentiated layered suite (C; after Arzamastsev, 1994).

6. Numerous REE-bearing alkaline pegmatites. The largest is the Shomiokitovoe pegmatite body at the Umbozero mine (Pekov, 1998, 2000).
7. Loparite placers (Yevzerov, 1978).

The deposits and occurrences of greatest importance are described below.

The Lovozero loparite deposit

The most important sources of REE in the massif 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). The first two sites exploit the upper I-4 and II-4 loparite horizons, and the third exploited the deeper III-10 and III-14 horizons. At the Karnasurt and Kedykvyrpakhk sites, ~ 90% of the loparite-(Ce) is concentrated in narrow (0.1–0.4 m) malignite-ijolite layers (Pakhomovsky et al., 2014). The overlying urtite and the underlying foyaite contain negligible proportions of loparite (0.2–2 vol %). A typical exposure of a loparite horizon and photomicrograph of the loparite ore in transmitted light are shown in Figure 9.

Within the ore horizons, loparite-(Ce) forms twinned pseudocubic poikilitic crystals with numerous (up to 80% of the crystal volume) inclusions of natrolite ($Na_2Al_2Si_3O_{10} \cdot 2H_2O$), lomonosovite, rhabdophane-(Ce), labuntsovite group and other low-temperature minerals. The chemical composition of the loparite-(Ce) varies within comparatively narrow limits: $(Na_{0.43–0.54}Ca_{0.12–0.18}Sr_{0.04–0.07}K_{0.00–0.05}La_{0.08–0.10}Ce_{0.18–0.21}Pr_{0.01–0.02}Nd_{0.04–0.05}Sm_{0.00–0.01}Th_{0.00–0.01})_{\Sigma 1.01–1.11}(Ti_{0.85–0.91}Nb_{0.07–0.12}Ta_{0.00–0.01}Fe_{0.01}Al_{0.00–0.01})_{\Sigma 0.97–1.01}O_3$. There is no evident variation in the proportions of La, Ce, Pr, Nd (Table 8) either within individual loparite layers or on the scale of the deposit (Pakhomovsky et al., 2014).

A small portion of the resource is hosted by eudialyte group minerals. In both the nepheline syenite and the foidolite, the “eudialyte” fills interstices in aggregates of nepheline, sodalite, and microcline-perthite. Within the interstices, the “eudialyte” replaced parakeldyshite ($Na_2ZrSi_2O_7$), dalyite ($K_2ZrSi_6O_{15}$), and other anhydrous zirconosilicates, and, in turn, was replaced by georgechaoite $\{NaKZr(Si_3O_9) \cdot 2H_2O\}$ and lovozerite group minerals. The chemical composition of the eudialyte group minerals varies widely, from that of manganoeudialyte (predominant) to eudialyte, kentbrooksite, and alluaivite (Ivanyuk et al., 2014), and the REE content varies from negligible to 6 wt %; the average REE content is 3 ± 1 wt % (Table 8).

Another potential source of REE in the deposit is apatite. In the foidolite loparite-bearing horizons, the apatite is relatively rich in REE (avg 7.6 wt %), although the proportion of apatite in these rocks is relatively low (avg 1.5 to 3 vol %), except for Horizon II-7, which contains 11.5 wt % apatite. Horizon II-7 extends throughout the Lovozero massif, and has a thickness ranging from 0.7 to 4 m (Saprykina et al., 1978).

The measured and indicated REE_2O_3 resources of the Karnasurt-Kedykvyrpakhk site are 453 kt grading 1.4 wt. % (FODD, 2011), whereas the total measured REE_2O_3 resources of the Lovozero loparite deposit are 7.3 Mt grading 1.08 wt %, the indicated resources are ~3 Mt grading 1.2 wt %, and the inferred resources are ~19.2 Mt grading 0.6 wt %. The

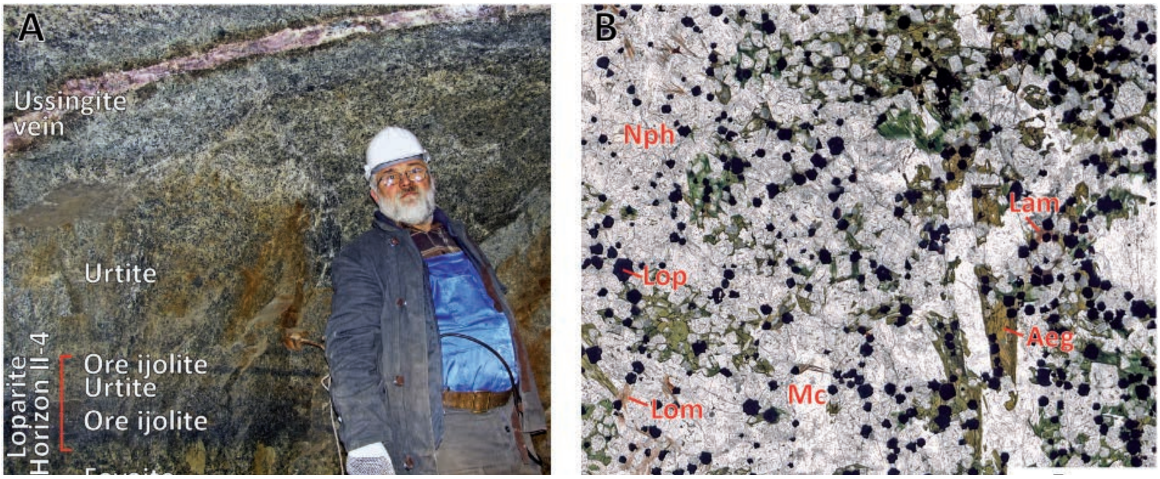


Fig. 9. An underground view of Loparite Horizon II-4 in Kedykvyrpakhk mine (A), and a photomicrograph of a thin section of loparite-bearing ijolite (B). Aeg = aegirine, Mc = microcline-perthite, Lam = lamprophillite, Lom = lomonosovite, Lop = loparite-(Ce), Nph = nepheline.

weighted average REE_2O_3 content of all resource categories for the deposit is 0.78 wt %. Approximately 2.5 kt of REE_2O_3 are being mined annually (FODD, 2011; Khramov, 2014; this study).

The Lovozero loparite-eudialyte deposit

The Lovozero eudialyte layered suite covers more than 50% of the area of the Lovozero massif and reaches 500 km^2. Its extremely large volume and high proportion of eudialyte (on avg, 8 vol %, and locally up to 90 vol %) make the eudialyte layered suite the largest zirconium reservoir in the world. In addition to Zr, the suite hosts a large resource of REE_2O_3. The thickness of the suite ranges from tens of meters to 400 m. The base of the suite undulates and the dip varies between 5° and 30° to the SE. Eudialyte malignite and shonkinite ("lujavrite") with variable eudialyte contents (up to 95% of volume) are the dominant rock types. In addition to eudialyte, the ore minerals include loparite-(Ce), members of the lomonosovite-murmanite, and lovozerite group minerals (Bussen and Sakharov, 1972). Their contents are inversely proportional to that of eudialyte.

The Lovozero loparite-eudialyte (Ta-Nb-REE-Zr) deposit incorporates Karnasurt, Kedykvyrpakhk, Alluaiv, Angvundaschorr, Sengischorr, Parguaiv, and other sites. The best explored is the Alluaiv site (Fig. 10). Two main ore types are present at this site, namely loparite-eudialyte (representing, on avg, 4 and 8 vol % of the rock, respectively) and eudialyte (avg, 12 vol %). There are also small proportions of ore comparatively rich in lovozerite group minerals (avg, 6 vol %) and murmanite-lomonosovite (avg, 2.4 vol %) (Utkin et al., 1995). The eudialyte content of these rocks is inversely proportional to the loparite-(Ce) content. Near the base of the eudialyte suite, the proportion of loparite-(Ce) increases with the occurrence of conformal lenses (up to 6 m thick) of loparite-(Ce)-rich (up to 7 modal %) foyaite-malignite within the eudialyte malignite.

The total measured and indicated REE_2O_3 resources of the eudialyte layered suite are 350 kt grading 0.42 wt %, and inferred resources are 7,500 kt grading 0.43 wt % (Samonov, 2008; Melent'ev, 2013; this study). It should be noted that the REE resources of the southern, northern, and central parts of the eudialyte layered suite have neither been explored nor estimated. However, by analogy with other parts of the eudialyte layered suite, it is reasonable to speculate that these parts contain at least 60 Mt of REE_2O_3 in loparite-eudialyte ores at an average grade of 0.4 to 0.45 wt % (hypothetical resources category; Samonov, 2008).

REE-bearing pegmatites

Pegmatites enriched in REE minerals occur widely in both the differentiated and eudialyte layered suites (Semenov, 1972; Pekov, 2000; Ivanyuk et al., 2006), but are mostly uneconomic. This type of REE mineralization is exemplified by the Shomiokitovoye hydrothermal-pegmatite body in the northern part of the Umbozero mine. The body, which is almost mined out, contained ~10 t of shomiokite-(Y) (Table 8), or ~5 t of yttrium (Pekov, 1998, 2000).

Loparite placers

Three loparite placer deposits rest on and near the Lovozero massif, namely the Seidozero, Rayyavr, and Revda deposits. These are Quaternary alluvial, deluvial, marsh, fluvioglacial sediments, and moraine deposits (Yevzerov, 1978). Their inferred REE_2O_3 resources are 80 kt and the grade is 2.7 kg/m^3.

Alkaline-ultrabasic massifs with carbonatites

Numerous alkaline ultrabasic carbonatite-bearing plutons are encountered in the Murmansk Region, with the most important from the perspective of the REE being Afrikanda, Kovdor, Vuoriyarvi, Seblyavr, Salmagora, Lesnaya Varaka, Ozernaya Varaka, Sallanlatva, Kandaguba, Pesochniy, Turiy Mys, and Gremyakha-Vyrmes (Fig. 1). REE resources, however, have only been estimated for the Afrikanda olivinite-melteigite-pyroxenite massif. In this paper, we mainly limit our descriptions to the most promising occurrences (Afrikanda, Kovdor, Vuoriyarvi).

The Afrikanda perovskite-titanomagnetite deposit

The 380 Ma Afrikanda melteigite-pyroxenite-olivinite massif (Wu et al., 2013) is situated in the center of the Murmansk

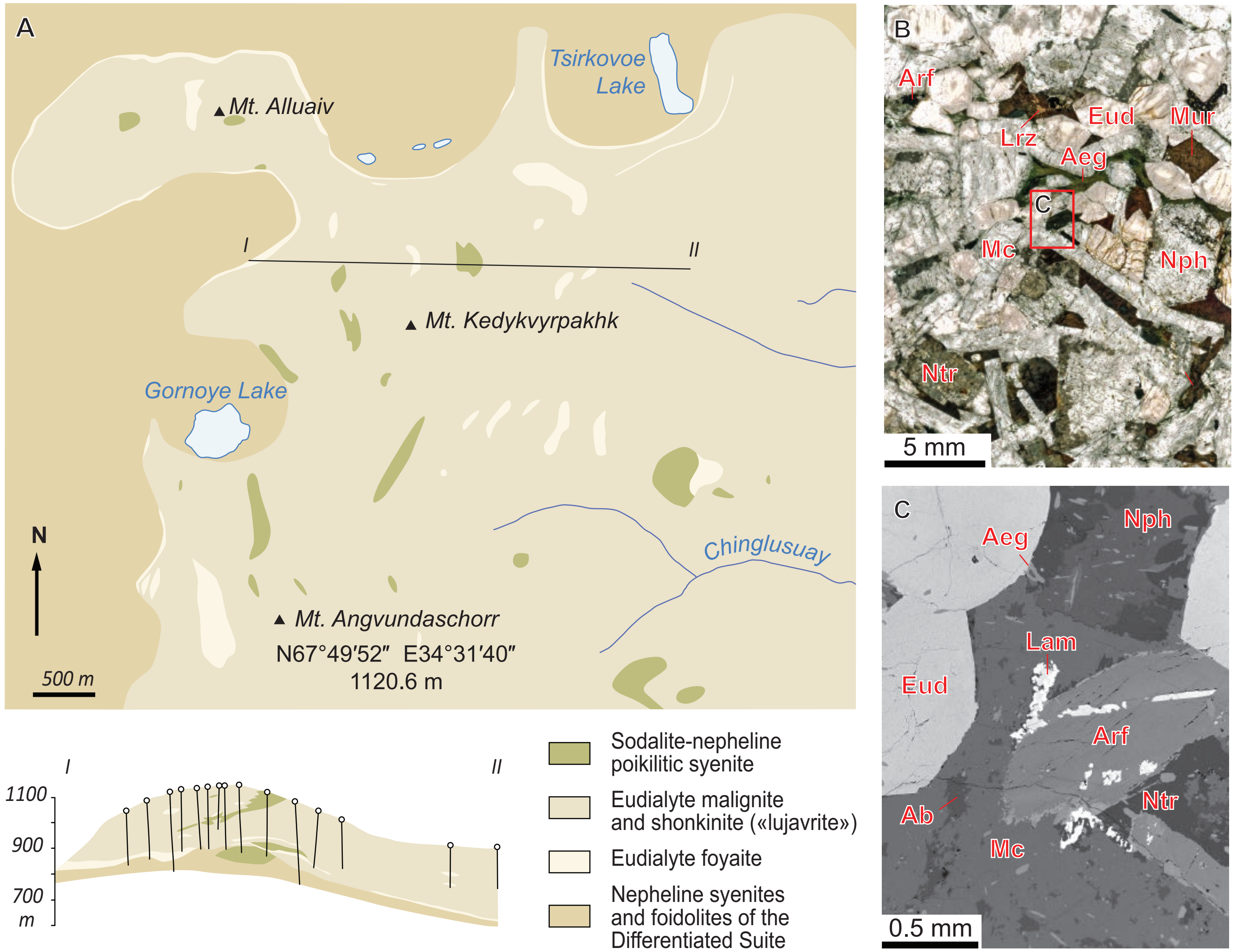


Fig. 10. (A) A geologic map of the Alluaiv site of the Lovozero loparite-eudialyte deposit (simplified from Utkin et al., 1995), (B) a photomicrograph of eudialyte-rich nepheline syenite in transmitted light and (C) a BSE image of the area marked (C) in (B). Ab = albite, Aeg = aegirine, Arf = arfvedsonite, Eud = manganoeudialyte, Lam = lamprophyllite, Lrz = lorenzenite, Mc = microcline, Mur = murmanite, Nph = nepheline, Ntr = natrolite.

Region near Khabozero Bay of Imandra Lake, where it intruded Archean biotite-plagioclase gneiss. It is zoned into a central perovskite-titanomagnetite-bearing pyroxenite and a marginal facies of ijolite-melteigite and nepheline-bearing pyroxenite, and is surrounded by an extensive zone of fenitization (Fig. 11a). The core contains veins and nests of calcite-magnesio-hastingsite-diopside rocks as well as alkaline pegmatites that locally are rich in both titanomagnetite and perovskite (Eliseev and Afanasyev, 1958; Kukharenko et al., 1965; Chakhmouradian and Zaitsev, 1999).

The main ore minerals are titanomagnetite and perovskite, which are abundant in the core of the pluton. Four ore types have been recognized, namely peridotite (about 9 vol % of the deposit), pyroxenite (>50 vol % of the deposit), calcite-magnesio-hastingsite-diopside rock (21 vol % of the deposit), and alkaline pegmatite (12 vol % of the deposit). The REE are concentrated mainly in minerals of the perovskite-loparite group, as well as apatite, titanite, pyrochlore, zirconolite, loparite-(Ce), cerite-(Ce) and ancylite-(Ce) (Chakhmouradian and Zaitsev, 1999). However, most of these minerals (except perovskite-loparite) occur in small proportions. The REE content of the perovskite is lowest in the marginal peridotite facies, and generally increases in rocks of the pluton core. Compositional data for the perovskite are reported in Table 8 and these show it to be LREE dominant.

The Afrikanda deposit was mined as an open pit between 1956 and 1958. A general view of the open pit and perovskite from the calcite-magnesiohastingsite-diopside rock are shown in Figure 11b, c. The measured resources of REE_2O_3 to a depth of 300 m are 230 kt; the grade of the ores is 0.67 wt % (Afanasyev et al., 1950; Afanasyev, 2011).

The Kovdor baddeleyite-apatite-magnetite deposit

The Kovdor massif, which intruded Archean granite-gneiss at 376 to 380 Ma (Rodionov et al., 2012), consists of peridotite, foidolite, phoscorite, carbonatite, and related metasomatic

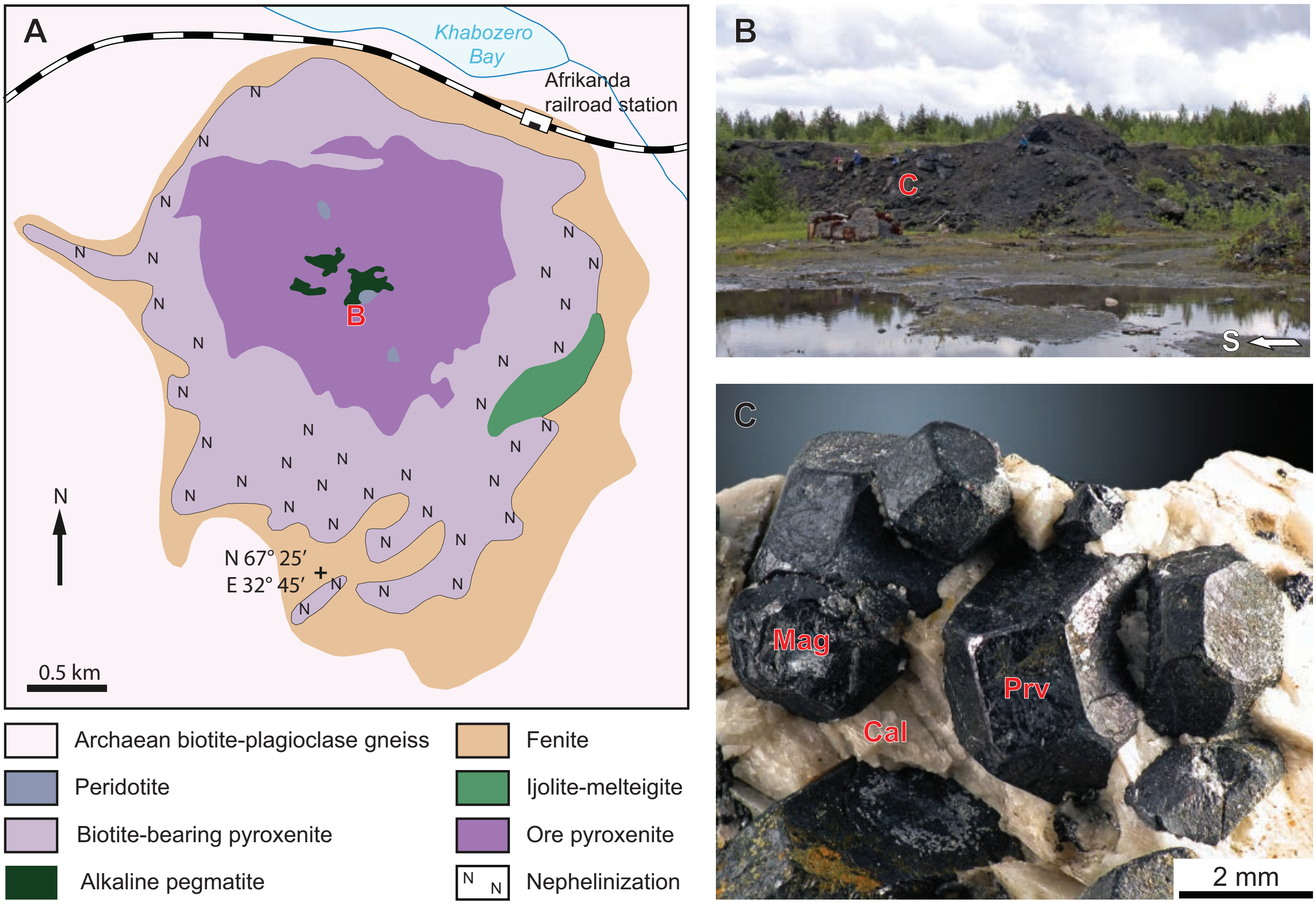
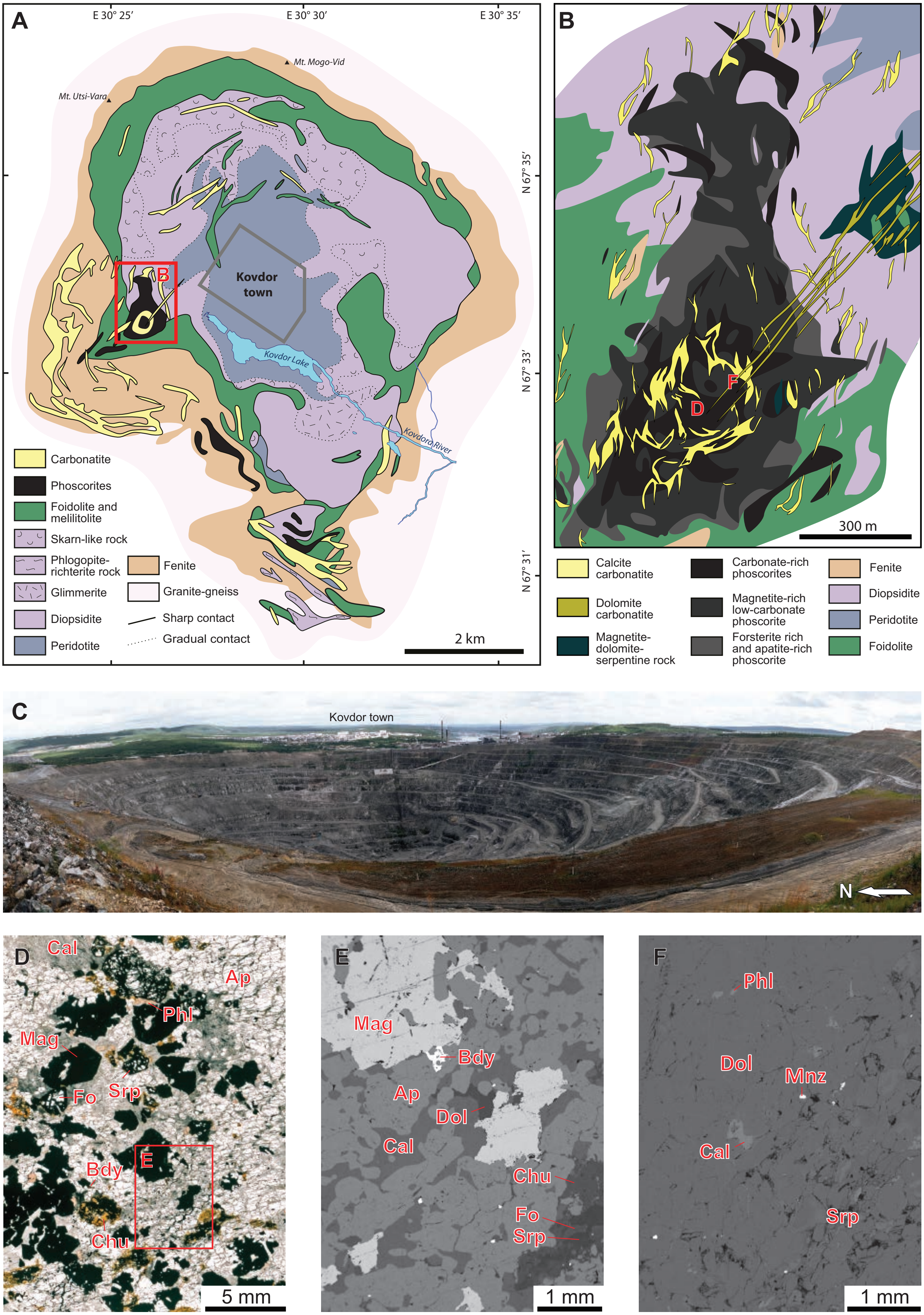


Fig. 11. (A) A geologic map of the Afrikanda foidolite-pyroxenite massif (simplified from Afanasyev, 2011), (B) a general view of the Afrikanda perovskite-titanomagnetite open pit and (C) perovskite crystals from calcite-magnesiohastingsite-diopside rock. Cal = calcite, Mag = magnetite, Prv = perovskite.

rocks (e.g., diopsidite, phlogopitite, and fenite) and lies in the SW part of the Murmansk Region (Fig. 1). In plan, the massif is concentrically zoned (Fig. 12A), with the earliest peridotite occurring in the central part of the massif, surrounded by ring-shaped zones of foidolite and related metasomatic rocks, i.e., diopsidite and phlogopitite, as well as melilite-, monticellite-, vesuvianite-, and andradite-rich skarns (after peridotite), fenitized gneiss, and fenite (after gneisses). Both the major rocks and the host fenitized gneiss contain veinlets and dikes of nepheline and cancrinite syenites, (micro)ijolite, phonolite, alnöites, shonkinite, and calcite and dolomite-calcite carbonatites (Ivanyuk et al., 2002; Krasnova et al., 2004). At the western contact of the peridotite with foidolite, a concentrically zoned pipe of phoscorite (an igneous rock consisting of forsterite, apatite, magnetite, and carbonates, in variable proportions) and carbonatite intrudes the massif (Mikhailova et al., 2016). The pipe is generally coincident with the Kovdor baddeleyite-apatite-magnetite deposit (Fig. 12B), which has been mined as an open pit since 1962 by the company "Kovdorskiy GOK" (Eurochem Corporation, Russia). A general view of the deposit is shown in Figure 12C.

The Kovdor deposit is an important potential source of scandium, an element that has been included in the rare earth group by the International Union of Pure and Applied Chemistry (Connelly et al., 2005), but is often overlooked as one of the REE by geochemists. The main scandium mineral in the deposit is baddeleyite, which is being mined for its Zr content; scandium is not currently being recovered. The average Sc_2O_3 content of the baddeleyite is 0.08 wt %, and within the inner zone of the Kovdor phoscorite-carbonatite pipe the content increases to >0.3 wt % (Fig. 13A). Based on the average annual production of baddeleyite concentrate (~10 kt)

Fig. 12. (A) A geologic map of the Kovdor massif (Ivanyuk et al., 2002), (B) a geological map of the Kovdor baddeleyite-apatite-magnetite deposit at level –100 m (Ivanyuk et al., 2013b), (C) a view of the "Zhelezniy" (iron ore) open pit, (D) a photomicrograph in transmitted light of the forsterite-apatite-magnetite-calcite phoscorite, and (E, F) BSE images of of the area marked (E) in (D) and of dolomite carbonatite, respectively. Ap = hydroxylapatite, Bdy = baddeleyite, Cal = calcite, Chu = clinohumite, Dol = dolomite, Fo = forsterite, Mag = magnetite, Mnz = monazite-(Ce), Phl = (tetraferri)phlogopite, Srp = serpentine.


A
E 30° 25′
E 30° 30′
E 30° 35′
Mt. Mogo-Vid
Mt. Utsi-Vara
N 67° 35′
N 67° 33′
N 67° 31′
Kovdor town
Kovdor Lake
Kovdora River
B
Carbonatite
Phoscorites
Foidolite and melilitolite
Skarn-like rock
Phlogopite-richterite rock
Fenite
Glimmerite
Granite-gneiss
Diopsidite
Sharp contact
Peridotite
Gradual contact
2 km
B
D
F
300 m
Calcite carbonatite
Carbonate-rich phoscorites
Fenite
Dolomite carbonatite
Magnetite-rich low-carbonate phoscorite
Diopsidite
Magnetite-dolomite-serpentine rock
Forsterite rich and apatite-rich phoscorite
Peridotite
Foidolite
C
Kovdor town
N
D
Cal
Ap
Phl
Mag
Fo
Srp
Bdy
E
Chu
5 mm
E
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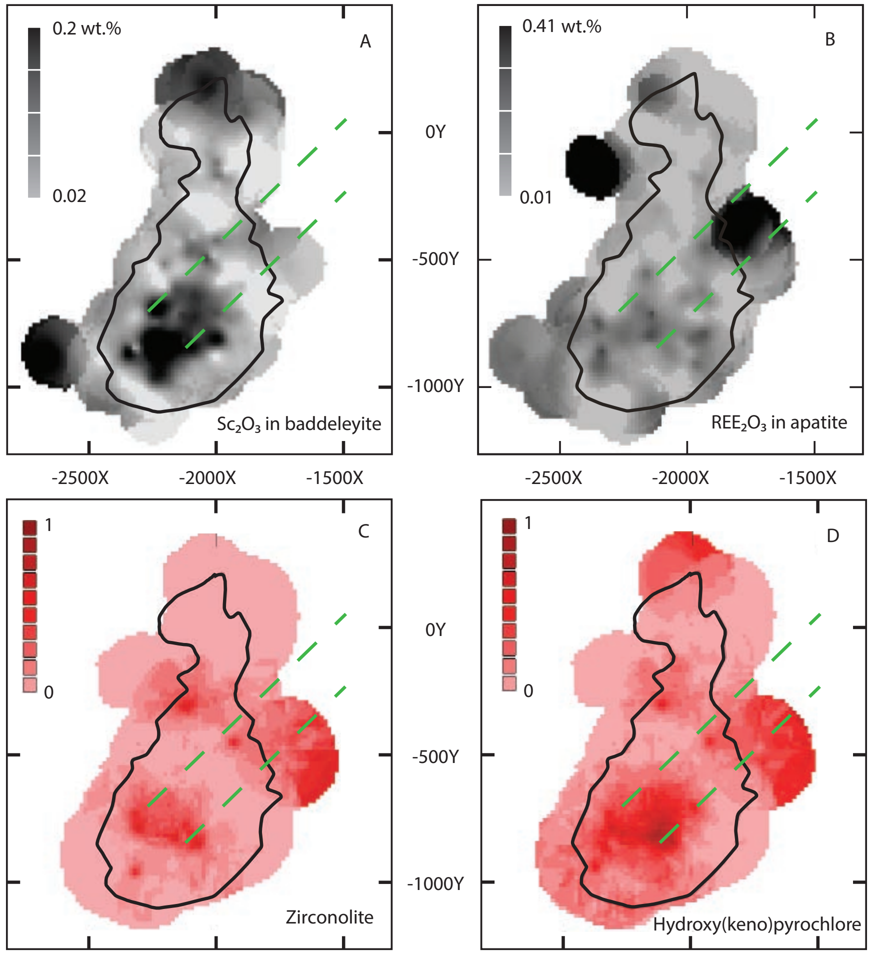

Fig. 13. The spatial distribution of REE within the Kovdor phoscorite-carbonatite pipe (black contour), level –170 ml. (A) Sc_2O_3 concentration in baddeleyite; (B) REE_2O_3 concentration in apatite; (C, D) the probability (on a scale of 1 to 0) of finding zirconolite and pyrochlore, respectively, in thin section. The data were interpolated by ordinary kriging of the drill core sample grid. The green dashed line indicates the dolomite carbonatite zone (from Ivanyuk et al., 2013b, 2016; Kalashnikov et al., 2016; Mikhailova et al., 2016).

and measured + indicated ZrO_2 resources from this mineral (504.5 kt), we estimate that the Kovdor deposit contains 420 t of Sc_2O_3, and that the potential annual production of Sc_2O_3 is 8 t (Kalashnikov et al., 2016).

The average content of other REE (lanthanoids and yttrium) in the different types of phoscorite varies from 0.001 to 0.05 wt %, and, in calcite carbonatite, from 0.019 to 0.09 wt % (Afanasyev, 2011; Zaitsev et al., 2014). The main minerals concentrating lanthanoids within the Kovdor deposit are hydroxylapatite, pyrochlore, zirconolite, and ancylite-(Ce) (Table 8). The probability of finding the REE-bearing minerals and maximal REE content in hydroxylapatite is confined to the linear zone of dolomite carbonatite veins (marked by the green dashed lines in Fig. 13A-D).

Hydroxylapatite is a rock-forming mineral in the phoscorite and although its chemical composition is relatively uniform, the content of P_2O_5 is highest in hydroxylapatite from apatite-forsterite and carbonate-rich phoscorites. In contrast, hydroxylapatite in the host rocks (foidolites and diopsidites) and carbonatites is enriched in Si and REE (Fig. 13B) as a result of the coupled substitution: $Ca^{2+} + P^{5+} \Leftrightarrow Ln^{3+} + Si^{4+}$ (Ivanyuk et al., 2016).

Zirconolite is a common secondary mineral in the baddeleyite-bearing rocks and usually forms pseudomorphs after baddeleyite (commonly together with pyrochlore) and spatial distribution of its content in the phoscorite-carbonatite pipe therefore follows that of baddeleyite (Fig. 13C). The U and REE contents of zirconolite are highest in the carbonate-rich phoscorite and carbonatites in the core of the pipe (Table 8).

Like zirconolite, pyrochlore is a common secondary mineral in the baddeleyite-bearing rocks. It is especially abundant in the carbonatites where, together with zirconolite, it replaced baddeleyite. The spatial distribution of pyrochlore within the phoscorite-carbonatite pipe follows that of baddeleyite and zirconolite (Fig. 13D); its REE content is highest in the dolomite carbonatites and apatite-forsterite marginal phoscorites (Table 8).

Ancylite-(Ce) is a common secondary mineral of the phoscorites and carbonatites, especially in the linear zone of dolomite carbonatite veins, in which hydroxylapatite is also characterized by a higher REE content (Table 8). A similar correlation between REE mineralization and dolomite carbonatites is observed in the Vuoriyarvi massif and the Nama-Vara carbonatite field.

Vuoriyarvi

The Vuoriyarvi massif lies in the west of the Murmansk Region (point 3 in Fig. 1), and intruded Archean granite-gneiss of the Belomorskiy block. In plan, the massif has a pear-like shape (Fig. 14) and an area of about 20 km². The massif is concentrically zoned, with a core of pyroxenite (most of the massif) containing peridotite xenoliths, and a marginal zone composed of foidolites (ijolite, and rarely, melteigite and urtite) and exocontact fenite. The E-SE part of the massif was cut by stockworks and pipes of carbonatite and phoscorite veins. Phlogopite, perovskite, and titanomagnetite are essential accessory minerals of the pyroxenite. Locally, the concentration of the latter two minerals rises to a level sufficient for the rocks to be considered ores. These ores form bodies in the western and eastern parts of the massif, and along a latitudinal fault coinciding with the long axis of the massif. Along the outer contact, the pyroxenite is enriched in fluorapatite and/or nepheline. Both calcite and dolomite carbonatites are observed. The calcite carbonatites carry apatite, magnetite, and baddeleyite, and locally are rare-metal rich owing to the presence of abundant baddeleyite, pyrochlore, and zirconolite. The dolomite carbonatites are rich in REE in the NE part of the massif; REE minerals are pyrochlore, zirconolite, ancylite-(Ce), burbankite $\{(Na,Ca)_3(Sr,Ba,Ce)_3(CO_3)_5\}$, and monazite-(Ce).

The massif contains four different deposits, the most promising of which is the Western Vuoriyarvi (REE-Nb)-Ti-Fe deposit (point A in Fig. 14). This deposit comprises pyroxenite rich in titanomagnetite (about 26 wt %) and perovskite (about 10 wt %). The cutoff grade for the deposit, Fe_{total} =

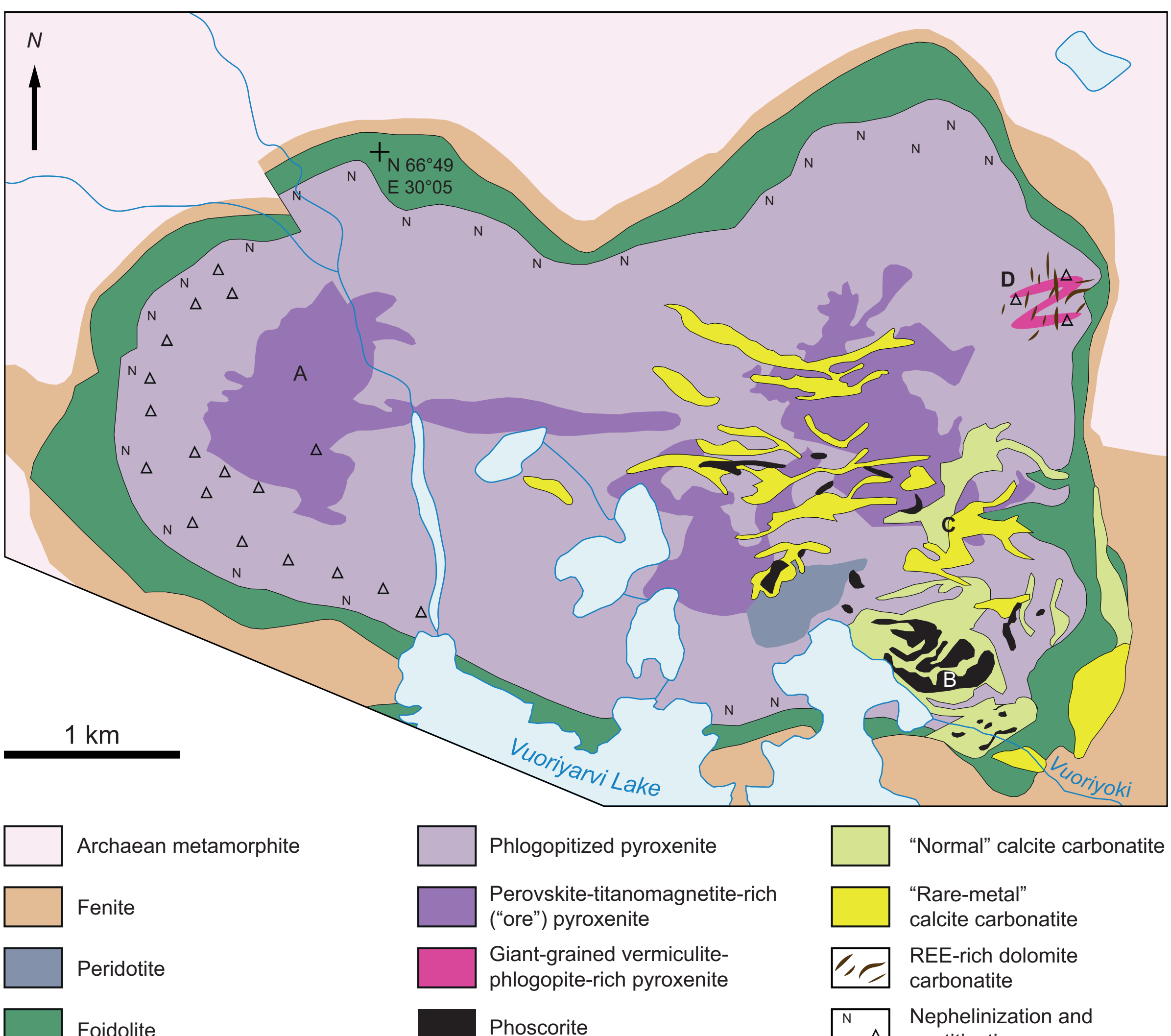

Fig. 14. Geologic map of the Vuoriyarvi foidolite-pyroxenite massif (Afanasyev, 2011). (A) the Western Vuoriyarvi perovskite-titanomagnetite (REE-Ti-Fe) deposit in pyroxenite ore; (B) the Tukhta-Vara baddeleyite-pyrochlore-magnetite-apatite (Zr-Ta-Nb-Fe-P) deposit in carbonatite and phoscorite; (C) the Neske-Vara apatite-magnetite-pyrochlore (P-Fe-Th-U-Ta-Nb) deposit in “rare-metal” carbonatite; and (D) the Petyayan-Vara vermiculite-phlogopite-Zr-REE deposit.

15 wt %, yields an inferred resource of 288 000 kt to a depth of 300 m (Afanasyev, 2011). Perovskite is the main REE mineral (Table 8); the corresponding REE_2O_3 resource is estimated to be 829.4 kt for a grade of 0.29 wt %. Some REE mineralization is associated with apatitized pyroxenite that borders the western and southern parts of the Western Vuoriyarvi deposit. The inferred resources for this apatite-perovskite-magnetite mineralization are estimated to be 336 Mt.

Seblyavr

The Seblyavr carbonatite-ijolite-pyroxenite massif is located in the NW part of the Murmansk Region, approximately 80 km SW of the city of Murmansk (point 5 in Fig. 1). The massif comprises pyroxenite, rich in phlogopite, perovskite, and magnetite, as well as phoscorites, carbonatites, and metasomatic apatite-phlogopite-diopside rocks with calzirtite and perovskite. There is potential for economic resources of P, Ta, Nb, Zr, and probably REE. The perovskite-magnetite-rich pyroxenite is similar to that occurring in the Afrikanda massif, so this could potentially be an economic source of REE. On average, the perovskite makes up about 12 wt % of the rock and has a mean REE_2O_3 content of 1.96 wt %. The inferred resource to a depth of 300 m is 1.1 Mt at a grade of 14.85 wt % Fe_{tot} and 8.18 wt % TiO_2 (Afanasyev, 2011). Thus, the corresponding REE_2O_3 resource would be 2.6 kt, assuming a grade of 0.24 wt %. Other REE resources of the Seblyavr massif occur potentially in the phoscorite-carbonatite complex (with apatite, calzirtite, zirconolite, perovskite, and pyrochlore), apatite-phlogopite-diopside metasomatitic rocks (with calzirtite and perovskite), and apatite-vermiculite–altered rocks (with apatite and REE-bearing clay) (Afanasyev, 2011).

Salmagora

The Salmagora massif is located in the central part of the Murmansk Region, about 35 km south of the Khibiny massif (point 8 in Fig. 1). It comprises (melilitic) melteigite-urtite (more than 80% of the outcrop area) and peridotite-pyroxenite rocks. The melteigite and urtite occur in the central part and contain apatite (about 4 vol %) and sulfide minerals (the copper content of the rock reaches 0.5 wt %), whereas the peridotite and pyroxenite contain perovskite and magnetite (about 9 and 19 vol %, respectively) (Kukharenko et al., 1965; Afanasyev, 2011). Currently (2013–2015), the Murmanskaya Geological Survey Expedition (JSC "MGRE," Apatity, Russia) is carrying out exploration at the massif.

Other massifs

All other alkaline-ultrabasic massifs and dolomite carbonatites in the region contain apatite and/or perovskite mineralization (Afanasyev, 2011). However, they vary considerably in the amount of mineralization and the extent to which they have been explored. Some massifs (e.g., Sallanlatva, Pesochny, and the Nama-Vara carbonatite field) are relatvely unexplored, and other massifs (Lesnaya Varaka, Ozyornaya Varaka, and Tury Mys) have been shown to contain insignificant REE resources.

REE mineralization of the Keivy block

The Keivy block is situated in the central part of the Kola Peninsula. It borders Archean granite-gneisses of the Kola-Norwegian (to the west), Murmanskiy (to the north) and Belomorkskiy (to the east) blocks, and to the south, the Proterozoic Imandra-Varzuga greenstone belt. The metamorphic rocks of the Keivy block comprise the following, from north to south: (1) the terrigenous Kolovay-Kinemur suite of amphibole and biotite gneiss, quartzites, and a basal metaconglomerate; (2) the Padcherva suite composed of amphibolites, amphibole, and sericitized plagioclase schists; (3) the Lebyazhya (also spelled as Lebyazhka, Lebyazhinskaya) suite comprising (garnet)-biotite gneiss and plagioclase gneiss; (4) the Keivy series, consisting of schists with kyanite, staurolite, garnet, muscovite, biotite, and graphite in varying proportions, as well as metamorphosed tuff-conglomerates and volcanic rocks (Kozlov et al., 2006). One of the main features of the Keivy block is the widespread occurrence of peralkaline granites emplaced at 2674 ± 6 Ma (Mitrofanov et al., 2000). These are the main source of REE in the block. The Keivy REE-bearing occurrences were investigated between the 1950s and 1970s (Gavrilov et al., 1957; Khineyko et al., 1958; Porotova et al., 1959; Tavastshern et al., 1960; Belolipetsky and Pletneva, 1966; Sotnikova et al., 1966; Bogatyrev et al., 1967; and Gaskelberg et al., 1978) and again during the current study.

Five types of REE mineralization have been recognized in the Keivy block (Fig. 1): (1) peralkaline granite rich in REE (e.g., Yumperuaiv, Large Pedestal, Mt. Marya, Belaya Golovka, and Lebedinoye Lake); (2) nepheline syenite (the Sakharyok massif); (3) veins of peralkaline granite and granite-aplite (the Yel'skiye Lakes deposit group); (4) REE-bearing amazonite pegmatites (e.g., Vyuntspakhk, Southern Tapperyok, Pessaryok, Small Pedestal, Rovgora, and the Serpovidny pegmatite fields); (5) metamorphic complexes (e.g., Shuururta, Nussa, and the Romanovo Lake occurrence). More than 90% of the REE resources of the Keivy block occur within REE-rich peralkaline granite. These include the veins of peralkaline granite and granite-aplite of the Yel'skye Lakes deposits. Many of the amazonite pegmatites are distinguished by high-grade REE mineralization, but the amounts of this mineralization are low. Occurrences in the metasomatized gneiss are insignificant. A summary on some REE deposits and occurrences within the Keivy block is given in Tables 3 and 9.

Peralkaline granites

There are six large alkali feldspar granite massifs (Western Keivy, Beliye Tundry, Ponoy, Lavrentyevskiy, Pacha, and Purnach) and numerous smaller bodies. Most of the REE deposits and prospects occur witin the Western Keivy massif. The exposed area of this massif, 1,300 km², makes it the largest granite massif in the Murmansk Region. The peralkaline granite is a fine- to coarse-grained, light-brown to orange rock made up of microcline, albite, quartz, aegirine-augite, alkaline amphibole (mainly ferro-richterite, arfvedsonite, and riebeckite), aenigmatite, and phlogopite (Batieva, 1976). Accessory minerals include ilmenite, magnetite, titanite, pyrrhotite, zircon, fluorapatite, and monazite-(Ce). The REE-bearing minerals are (in order of importance) chevkinite-(Ce), bastnäsite-(Ce), allanite-(Ce), fergusonite-(Y), monazite-(Ce), britholite-(Y), fluorapatite, titanite, pyrochlore, and xenotime-(Y). The REE-rich granites (3,000–5,000 ppm REE) differ from the other granites (50–200 ppm REE, Table 10) in having a higher quartz content (about 40 vs. 30 vol %) a

Table 9. REE Resources and Average Content in Deposits and Occurrences of the Keivy Block

Occurrence	REE_2O_3 inferred resources (kt)	REE_2O_3 average content (wt %)	Host rock	Main REE minerals	Other components	References
Yumperuaiv	60	0.55	Peralkaline granite rich in REE	Bastnäsite-(Ce), allanite-(Ce), monazite-(Ce)	Nb, U, Th, Zr	Chukhina et al., 1963
Large Pedestal	36	0.33		Chevkinite-(Ce), monazite-(Ce), bastnäsite-(Ce) fergusonite-(Y)	Zr	This study
Mt. Lavrentyevskaya deposit group	6	0.3		Allanite-(Ce), pyrochlore, chevkinite-(Ce), thorite, fergusonite-(Y)	Zr, Nb, Ta, Th, U	Bogatyrev et al., 1967
Yel'skye Lakes deposit group	3	1.57	Veins of leucocratic peralkaline granite in amphibolite	Gadolinite-(Y), pyrochlore, fergusonite-(Y), bastnäsite-(Ce)	Zr, Nb, Ta, Th, U	Bogatyrev et al., 1967
Pessaryok pegmatite field	0.4	0.23	Peralkaline granite pegmatite	Fergusonite-(Y), allanite-(Ce), xenotime-(Y), monazite-(Ce)	Be	Tavastshern et al., 1960
Southern Tapperyok field	0.1	0.3		Fergusonite-(Y), allanite-(Ce)	Th, U	Tavastshern et al., 1960
Vyuntspakhk pegmatite field	0.1	0.1-1		Allanite-(Ce), gadolinite-(Y), fergusonite-(Y), fluorite, plumbomicrolite	Amazonite, U, Th, Nb	Gavrilov et al., 1957; Voloshin and Pakhomovsky, 1986
North Rovozerskoe	Not estimated	0.95		Aeschynite-(Y), gadolinite-(Y), monazite-(Ce)	Nb	Khineyko et al., 1958
Serpovidny pegmatite field	Not estimated	0.25 [1]		Gadolinite-(Y), fergusonite-(Y), allanite-(Ce)	Be	Khineyko et al., 1958
Rova I	Not estimated	0.25 [1]		Gadolinite-(Y)		Khineyko et al., 1958
Platongora	Not estimated	4.5		Euxenite-(Y)	Zr, Nb, Ta, Th, U	Gaskelberg et al., 1978
Sakharyok massif	22+10[2]	0.34	Nepheline and alkaline syenite	Britholite-(Ce), zircon, pyrochlore	Zr, Ta, Nb	Pasternok, 2000; Zozulya et al., 2012

[1] Y_2O_3 average content, wt %
[2] Indicated + inferred resources

lower content of feldspar (50 vs. 60 vol %), aegirine instead of aegirine-augite, and a higher proportion of zircon and the above-mentioned REE-minerals. The contact of REE-rich peralkaline granites with peralkaline granite not enriched in the REE is gradational, and texturally, the two types of granite are indistinguishable.

The Western Keivy massif contains two large peralkaline granite-hosted REE deposits, Yumperuaiv (point 18 in Fig. 1) and Large Pedestal (point 19 in Fig. 1), as well as eight small occurrences. The Large Pedestal deposit (Fig. 15A, B) is confined to an apical prominence of the Western Keivy massif jutting out into Archean (garnet-muscovite)-biotite gneiss of the Lebyazhya suite. The REE content reaches 2 wt %, mainly as chevkinite-(Ce), and bastnäsite-(Ce) (Fig. 15D; Table 8). There are also small proportions of fergusonite-(Y), monazite-(Ce), titanite, allanite-(Ce), fluorapatite, britholite-(Y), fluorite, and thorite. We estimate the REE resource (down to the depth of 20 m) to be 36 kt for a grade of 0.33 wt % REE_2O_3; 25% are heavy (HREE) (Table 10). The Yumperuaiv deposit (Fig. 15A) is confined to a 3-km-wide granite prominence that intruded gneiss of the Lebyazhya suite. It contains abundant zircon, together with bastnäsite-(Ce/La/Y), allanite-(Ce), titanite, thorite (Fig. 15C; Table 8), and rare monazite-(Ce), fergusonite-(Y), britholite-(Y), pyrochlore, and xenotime-(Y). The inferred REE resource is 60 kt for a grade of 0.55 wt % REE_2O_3; 25% of the REE are HREE (Chukhina et al., 1963).

REE-bearing pegmatites

The Keivy block contains over 250 pegmatite lenses and veins (10s of meters in length with widths of 0.5–5 m) that form fields and clusters in peralkaline granite or biotite gneiss (points 17, 19, 20, 22, 23 in Fig. 1; Gaskelberg et al., 1978). There are 14 fields of REE-bearing amazonite pegmatites, namely Lenyavr, Southern Tapperyok, Pessaryok, Small Pedestal, Tuorvyd, Rovgora, Mt. Slyudyanaya, Rova I, Rova II, Serpovidny Ridge, Vyuntspakhk, Dal'niy (Topkiy Ruchey), Parusnaya, and Kanevka, and numerous isolated veins (the

Table 10. REE Content in Peralkaline Granites of the Western Keivy Massif (ppm, mean ± SD/min-max).

	Normal granite (103 samples)	REE-rich granite: Yumperuaiv deposit (6 samples)	REE-rich granite: Large Pedestal deposit (8 samples)
La	33±25 2–210	1,073±834 89–2,317	489±356 59–1,119
Ce	83±37 4–201	2,331±1,778 92–4,971	1,112±672 309–2,146
Pr	9±6 0–44	256±199 19–549	122±84 15–236
Nd	35±21 1–150	879±688 72–1,848	461±320 61–895
Sm	7±4 0–22	206±163 14–428	88±57 14–179
Eu	1±1 0–3	15±12 1–30	7±4 1–14
Gd	8±4 0–20	235±190 16–494	95±56 17–187
Tb	1±1 0–3	33±26 2–67	15±9 3–32
Dy	8±4 0–16	215±169 15–437	91±56 21–203
Ho	2±1 0–3	39±30 3–76	18±11 4–42
Er	5±2 0–11	118±90 6–235	55±34 15–125
Tm	1±0 0–2	16±12 1–31	8±5 3–18
Yb	5±2 0–11	107±77 6–206	54±31 21–121
Lu	1±0 0–2	14±10 1–26	8±4 3–17
Y	36±20 1–131	969±796 74–2,005	386±212 86–787
ΣREE	232±109 10–655	6,503±5,047 411–13,717	3,008±1,697 632–5,236

largest is situated at Mt. Ploskaya). Compositionally, the REE-bearing pegmatites are similar to the peralkaline granite, and consist of quartz, microcline (usually amazonite), albite, biotite, alkali amphibole, and locally muscovite. The accessory minerals include aegirine, astrophyllite, magnetite, fluorite, zircon, and the REE-bearing minerals, gadolinite-(Y), fergusonite-(Y), chevkinite-(Ce), and allanite-(Ce). The largest and most promising pegmatite fields from the perspective of REE mineralization are the Vyuntspakhk, Southern Tapperyok, Pessaryok, Small Pedestal, and Serpovidny Ridge pegmatite fields. In addition, the Vyuntspakhk, Rovgora, and Serpovidny Ridge fields have economic deposits of ornamental amazonite, some of which were exploited between the 1960s and 1980s (e.g., the Ploskaya and Rovgora amazonite deposits).

The Vyuntspakhk field hosts 23 separate pegmatite veins (Gaskelberg et al., 1978), including the large amazonite REE-bearing pegmatite hosted in biotite gneiss at Mt. Ploskaya (Fig. 16) near its contact with peralkaline granite. The vein is ~210 m in length, and has an average thickness of 25 m. The vein is zoned, with an outer part composed of medium-grained quartz and albite, an intermediate zone of very coarse grained amazonite, and a core of quartz and albite, including large monomineralic blocks of smoky quartz. The Ploskaya deposit was exploited for ornamental amazonite in the1970s and 1980s.

The Ploskaya pegmatite contains an abundance of REE minerals, including Y-rich fluorite, vyuntspakhkite-(Y) {$(Y,Yb)_4Al_{2.5-1.5}(Si,Al)_{1.5-2.5}(SiO_4)_4O(OH)_7$}, hingganite-(Y) {$(Y,REE,Ca)_2(\square,Fe^{2+})Be_2[SiO_4]_2(OH)_2$}, hingganite-(Yb) {$(Yb,Y,REE)_2\square Be_2[SiO_4]_2(OH)_2$}, keiviite-(Y) {$(Y,Yb)_2[Si_2O_7]$}, keiviite-(Yb) {$(Yb,Y)_2Si_2O_7$}, kuliokite-(Y) {$Y_4Al(SiO_4)_2(OH)_2F_5$}, fluorthalénite-(Y) {$Y_3Si_3O_{10}F$}, monazite-(Ce), bastnäsite-(Ce), xenotime-(Y), churchite-(Y) {$Y(PO_4)\cdot 2H_2O$}, zircon, pyrochlore, fergusonite-(Y), euxenite-(Y), and aeschynite-(Ce) {$(Ce,Ca,Fe,Th)(Ti,Nb)_2(O,OH)_6$}. The main REE minerals, however, are Y-rich fluorite and fergusonite-(Y) (Table 8), followed by much smaller proportions of xenotime-(Y), monazite-(Ce), and bastnäsite-(Ce) (Voloshin and Pakhomovsky, 1986). The REE resource contained by this and other pegmatites in the Keivy block has not been evaluated, although it has been noted that the pegmatites are particularly enriched in the HREE (~70% of the total REE concentration).

The Yel'skie Lakes deposits

The Yel'skie Lakes group of deposits differs from other deposits in the Keivy block in comprising REE-Zr-Nb-Ta-U ores hosted by veins of peralkaline granite or granite-aplite (and locally quartz veins) lying at the contact of amphibolitized gabbro-anorthosite of the Shchucheozersky massif with peralkaline granite of the Western Keivy massif (Bogatyrev et al., 1967) (Fig. 17). The REE mineralization is associated with silicification, albitization, and cataclasis. More than 300 veins (up to 150 m in length and 12 m in width) have been identified that are composed of 25 to 50 vol % quartz, 20 to 50 vol % microcline, 5 to 30 vol % albite, up to 5 vol % biotite, up to 7 vol % magnetite, and up to 5 vol % aegirine and riebeckite. In the REE-rich veins, allanite-(Y), gadolinite-(Y), fergusonite-(Y), chevkinite-(Ce), Y-rich pyrochlore, zircon, thorite, and titanite make up about 50% of the rock by volume. There are also minor proportions of monazite-(Ce/Y), bastnäsite-(Ce/Y), REE-rich fluorite, euxenite-(Y), and traces of britholite-(Y), thalénite-(Y), and yttrialite-(Y) (Kostin et al., 1964; Belolipetsky and Pletneva, 1966; Bogatyrev et al., 1967). The inferred REE_2O_3 resource of the Yel'skiye Lakes deposit group is 3 kt, of which the HREE comprise >50% (Bogatyrev et al., 1967).

Sakharyok alkaline massif

The Sakharyok alkaline massif is situated in the southern part of the Western Keivy massif (point 21 in Fig. 1) and comprises alkali feldspar syenites and nepheline syenites that form a fault-type body >5 km in length and 2 km in width (Fig. 18) (Batieva and Bel'kov, 1984; Zozulya et al., 2007, 2012). The nepheline syenite is composed of albite (30–40 vol %), microcline (20–30 vol %), nepheline (5–25 vol %), aegirine-hedenbergite and ferrohastingsite (30 vol %), and biotite (up to 10 vol %). Accessory minerals include zircon, fluorite, fluorapatite, titanite, pyrochlore, magnetite, and calcite. The

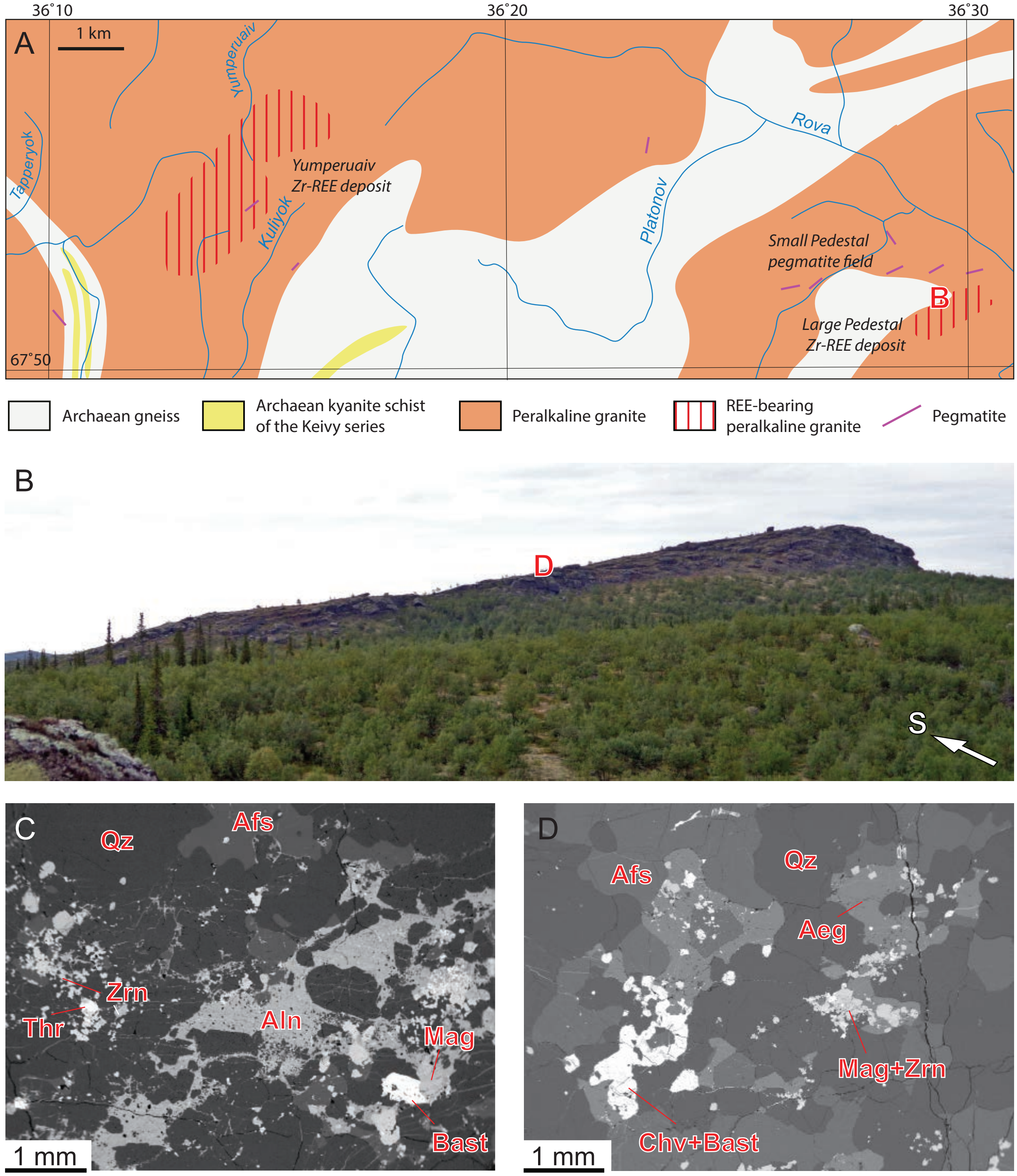

Fig. 15. Geologic map of the Yumperuaiv and Large Pedestal Zr-REE deposits and Small Pedestal pegmatite field (A; modified after Gaskelberg et al., 1978; Bazai et al., 2014); a view of the Large Pedestal Mt. (B), and BSE images of REE-bearing peralkaline granite from the Yumperuaiv (C) and the Large Pedestal (D) deposits. Minerals abbreviations: Aeg = aegirine, Afs = alkali feldspar, Aln = allanite-(Ce), Bast = bastnäsite, Chv = chevkinite, Mag = magnetite, Qz = quartz, Thr = thorite, Zrn = zircon.

potential orebodies, which are concentrated in the northern part of the massif, consist of nepheline syenite rich in zircon (0.5–2.5 vol %), britholite-(Y) (0.2–1.0 vol %), and pyrochlore (0.1–0.2 vol %). The deposit consists of eight lens-like orebodies (200–1,350 m in length and 3–30 m in width), having an average content (based on 11 samples) of 363 ppm Y, 528 ppm La, 934 ppm Ce, 60 ppm Pr, 310 ppm Nd, 45 ppm Sm, 4 ppm Eu, 47 ppm Gd, 8 ppm Tb, ~40 ppm Dy, ~18 ppm Ho, ~50 ppm Er, 6 ppm Tm, 41 ppm Yb, and 6 ppm Lu (Zozulya et al., 2015). The indicated and inferred REE_2O_3 resources are 22.4 and 10 kt, respectively, and the the average REE_2O_3 content is 0.34 wt % (Pasternok, 2000).

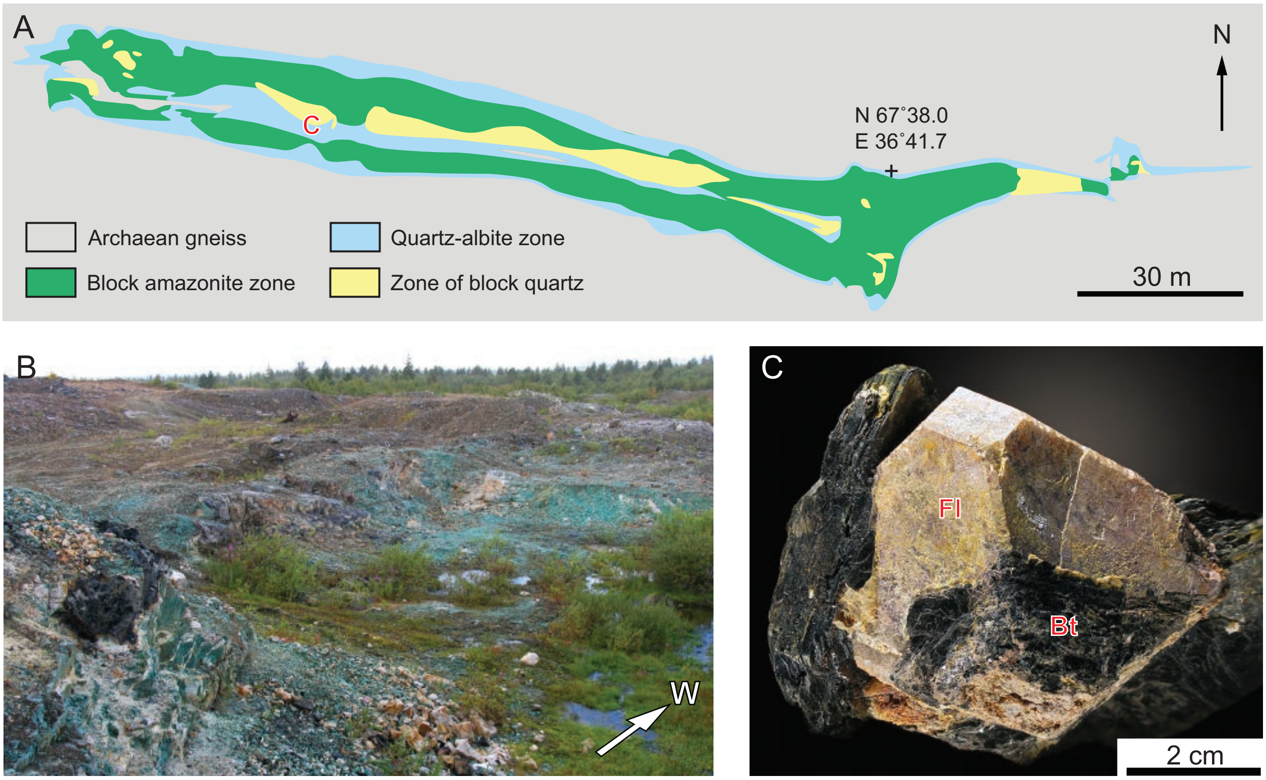

Fig. 16. (A) Geologic map of the Mt. Ploskaya amazonite pegmatite body (Voloshin and Pakhomovsky, 1986), (B) a view of the pegmatite; and (C) Y-rich fluorite from the pegmatite. Bt = biotite, Fl = Y-rich fluorite.

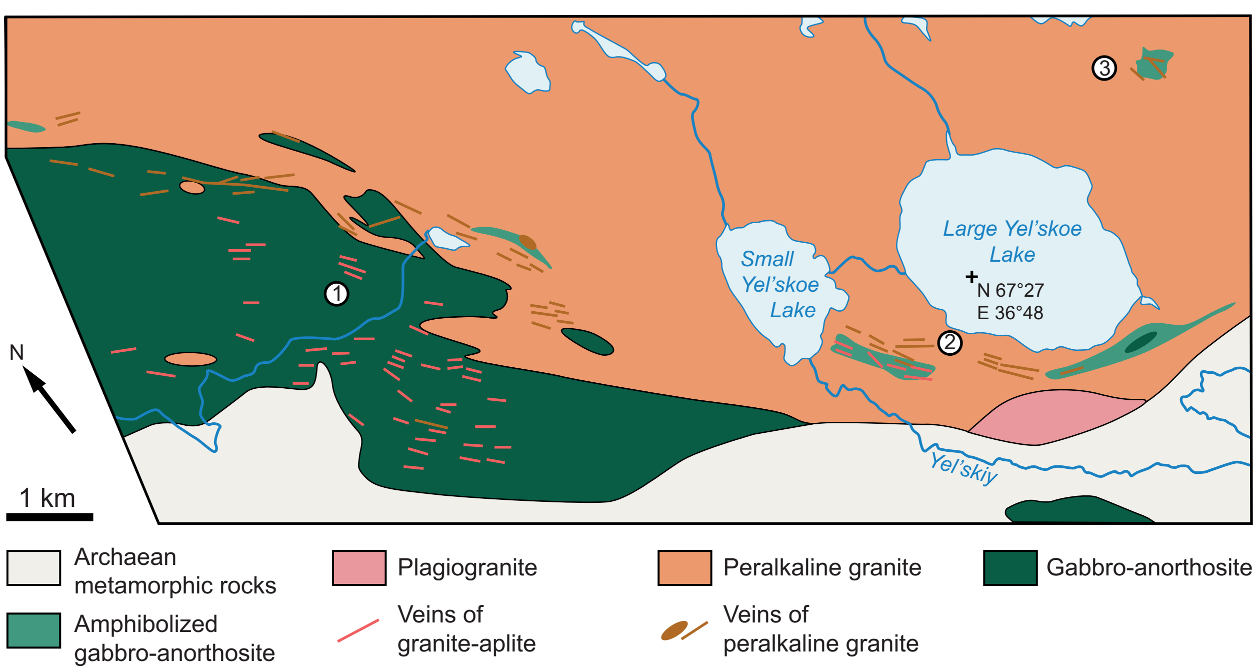

Fig. 17. A geologic map showing the Yel'skie Lakes U-Ta-Nb-Zr-REE deposit group (Bogatyrev et al., 1967). The circled numbers indicate deposits.

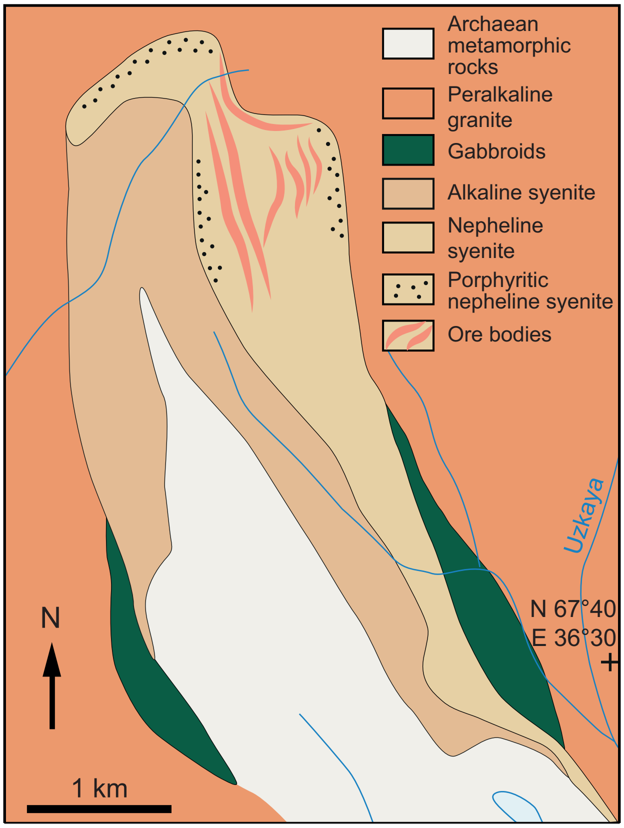

Fig. 18. A geologic map of the Sakharyok massif, modified from Batieva and Bel'kov (1984) and Zozulya et al. (2012).

Discussion

The Murmansk Region is a major REE metallogenic province, containing 22.4 Mt measured and indicated REE_2O_3 resources, 36.2 Mt inferred resources, and more than 60 Mt hypothetical resources (category P2 in GKZ classification). Most of these resources are hosted by peralkaline igneous rocks, most were developed by igneous processes, some owe their origin to postmagmatic hydrothermal processes, and a very small proportion were the result of weathering.

The Khibiny apatite deposits have the greatest potential for REE production in the Murmansk Region and, indeed, in Russia, because of the extremely large size of the resource, ongoing production of phosphorus, existence of a well-developed mining infrastructure, and the availability of sulfuric acid (a waste product of the Monchegorsk metallurgical complex), which is essential for the hydrometallugical recovery of the REE. Rare earth elements are conventionally mined as a by-product or co-product of other elements (Long et al., 2012). Indeed, this is the case for the world's largest REE deposit, Bayan Obo (China), where the REE are produced together with iron (Drew et al., 1990). In Russia, REE are also produced by Lovozerskiy GOK as a by-product of Nb and Ta. Only the North-Western Phosphorous Company, which exploits minor apatite deposits at Oleny Ruchey and Partomchorr, has shown an interest in recovering the REE from apatite (Pyatakova and Kalinnikov, 2012). In contrast, the world's leading apatite concentrate producer, JSC Apatit, a branch of PhosAgro Corp., has indicated no intention of producing the REE as by-products, despite the fact that the REE are extracted from its apatite concentrate by other companies (e.g., Sarapää et al. 2013). Thus, about 85 kt of REE_2O_3 available from Khibiny apatite as a by-product of phosphorus production are rejected as waste.

The second most important resources having potential for significant REE production are the deposits of the Lovozero massif, especially the eudialyte layered suite (and particularly the Alluaiv site). The huge size of the resource, the absence of overburden, proximity to infrastructure (transport and energy, and a developed mineral processing complex), are all factors that will help facilitate economic exploitation of these deposits.

The Kovdor baddeleyite-apatite-magnetite deposit is a promising source of scandium, as baddeleyite, in which the scandium is concentrated, is exploited for its zirconium (Kalashnikov et al., 2016). The deposit could yield up to 8 t of Sc_2O_3 as a by-product of the current mining operation. The deposit is currently not being considered for yttrium and lanthanoid as by-products owing to the low concentrations of these elements.

Because of the much higher demand for the HREE relative to the LREE, other than neodymium, the deposits of the Western Keivy massif may be an important REE source in the future. We estimate that these deposits contain at least 120 kt of REE in ores grading between 0.3 and 0.55 wt % REE_2O_3, of which 25% are HREE. The potential economic mineralization is concentrated mainly in the Yumperuaiv and Large Pedestal deposits. All the significant occurrences of this massif occur within a radius of 5 to 10 km, which would permit their exploitation in a single mining operation. One impediment to their exploitation, however, is the remoteness from a source of energy and the lack of roads in the area; the nearest industrial centers are Koashva and Revda, about 100 and 80 km, respectively, from the deposits. However, the pegmatites of the Vyuntspakhk pegmatite field, including the abandoned Ploskaya amazonite mine, may be another significant source of HREE.

The enormous volume of peralkaline silicate and carbonatite magma that was emplaced in the Murmansk Region between 380 and 360 Ma (20 large plutons, including the Lovozero, Khibiny Kovdor, and Afrikanda massifs) make it compelling to argue that much of the endowment of the region in rare metals, including the REE, was due to a large mantle plume (Tolstikhin et al., 2002). However, it is also clear that appreciable REE resources, of which an elevated proportion are HREE, were introduced during an episode of Archean anorogenic magmatism that produced peralkaline granitic intrusions in the Keivy block (Vetrin and Rodionov, 2009).

Very low degrees of partial melting at the head of the Devonian mantle plume ensured enrichment of the magmas in alkalis, incompatible rare metals—notably Zr, Ti, Nb and the REE—and elements like fluorine. The high content of alkalis and fluorine, in turn, promoted dissolution of the rare metals in the magmas (Balashov, 1976; Ponader and Brown, 1989; Keppler, 1993). In the case of the Archean anorogenic event, the silicic peralkaline magmas likely originated by melting of a lower crust that had been enriched in the REE, F, and other incompatible elements by metasomatic fluids of mantle origin

(Zozulya et al., 2005; Bonin, 2007; Zozulya and Eby, 2009). Saturation of the magmas in REE-bearing minerals and their concentration to potentially ore-forming levels was facilitated by extreme fractional crystallization, as illustrated by the layering of the Lovozero massif, although other processes, including liquid immiscibility, may have played a role. Hydrothermal fluids exsolved from the crystallizing magma further concentrated the rare metals (Zr^{4+}, Ti^{4+}, Nb^{5+}, REE^{3+}) by forming stable complexes with ligands such as F^-, OH^-, CO_3^{2-} and SO_4^{2-} (Balashov, 1976; Migdisov et al., 2011; Williams-Jones et al., 2012; Timofeev et al., 2015). Destabilization of the rare metal complexes due to changes in temperature, pH, oxygen fugacity, or ligand activity induced by boiling, fluid-rock interaction, or fluid mixing led to the deposition of REE-bearing minerals. Conditions that were essential for REE concentration within the massifs of the Murmansk Region include the following: (1) the large size and longevity of the massifs; (2) their unusual enrichment in F; (3) their richness in Zr and Ti; and (4) postmagmatic hydrothermal activity. All these conditions were realized in the giant Khibiny and Lovozero alkaline massifs, producing giant deposits of REE-Ti-P (apatite-titanite and rinkite deposits), REE-Ti-Nb (loparite deposit), and REE-Zr (eudialyte deposit), and in the somewhat smaller Kovdor massif. The peralkaline granite massifs of the Keivy block also satisfied some of these conditions, e.g., they are rich in F and Zr, but they were comparatively dry, precluding the formation of large zones of hydrothermally enriched REE mineralization.

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