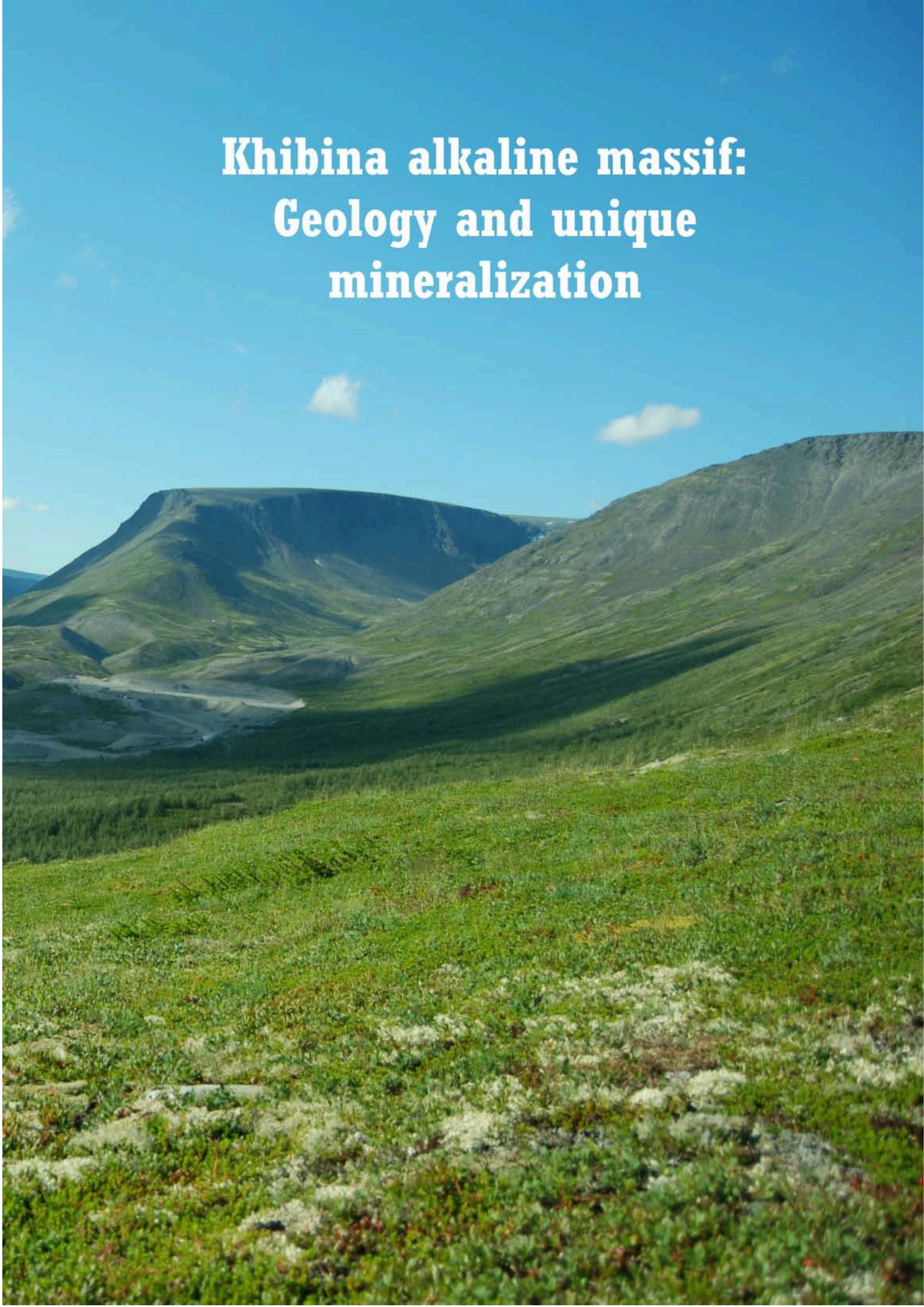
Khibina alkaline massif: Geology and unique mineralization



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KHIBINA ALKALINE MASSIF: GEOLOGY AND UNIQUE MINERALIZATION

Guide Book

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The guidebook highlights the geology, tectonics and stratigraphy of the Khibiny massif (Kola Peninsula, Russia). Provided in detail are the geological structure, occurrence and mineralogy of the rocks.

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GENERAL INTRODUCTION

The world's two biggest agpaitic intrusions are the key magmatic centers of the Paleozoic Kola Alkaline Province of the NE Fennoscandian Shield. In the Khibina massif peralkaline K-Na and K nepheline syenites are intercalated with the members of typical ultrabasic-alkaline and carbonatite series. In the Lovozero massif agpaitic lujavrites (type locality) form a rhythmic layered complex similar to that in Ilimaussaq, Greenland. Geophysical and geological data based on a prospecting drilling program give evidence for significant differences in the internal structure of two giant polyphase magmatic bodies, and commercial mineralization enclosed in these intrusions. Participants will examine the main rock complexes of both massifs. In the Khibina we will visit apatite-nepheline and titanite ore deposits. In the Lovozero field trip we will examine classical outcrops of lujavrite-foyaite-urtite rhythms with loparite (Nb, Ta) and eudialite (Zr, Hf) commercial mineralization. The trip will provide an opportunity for igneous petrologists and geochemists to ponder the role of plume-lithosphere interaction processes responsible for the origin of enormous amounts of agpaitic magmas and deciphering the circuitous routes of alkaline magma evolution. In the open pits of both massifs of small pegmatite bodies with nice alkaline minerals, as well as dykes of alkaline lamprophyres and tinguaite are widespread. The Khibina and Lovozero are famous for their unique mineralogy: over 550 mineral species are presented, more than 100 of them were discovered here first in the world. Most of the rare minerals are sodium Ti-, Nb- and Zr-silicates, which could be found in pegmatites and hydrothermal veins. Alteration of earlier minerals under hydrothermal and supergene conditions produces newly formed mineral phases, and this process continues up to now.

REGIONAL GEOLOGY

The Kola alkaline province occupies the Kola Peninsula, northern Karelia and the adjoining areas of Northern Finland (Fig. 1). Except the Oslo region, the north-eastern part of the Fennoscandian Shield has been the main theatre of intense alkaline magmatism from the Proterozoic to the Paleozoic.

The Palaeozoic magmatism in the Kola Province followed the intense tectonic activity in the surroundings of the Fennoscandian Shield, especially in the North Atlantic belt of the Caledonides. Dallmeyer et al. (1994) dated the collision maximum associated with the closure of the Japetus Ocean within a range of 440-420 Ma. This period was marked by the origin of a

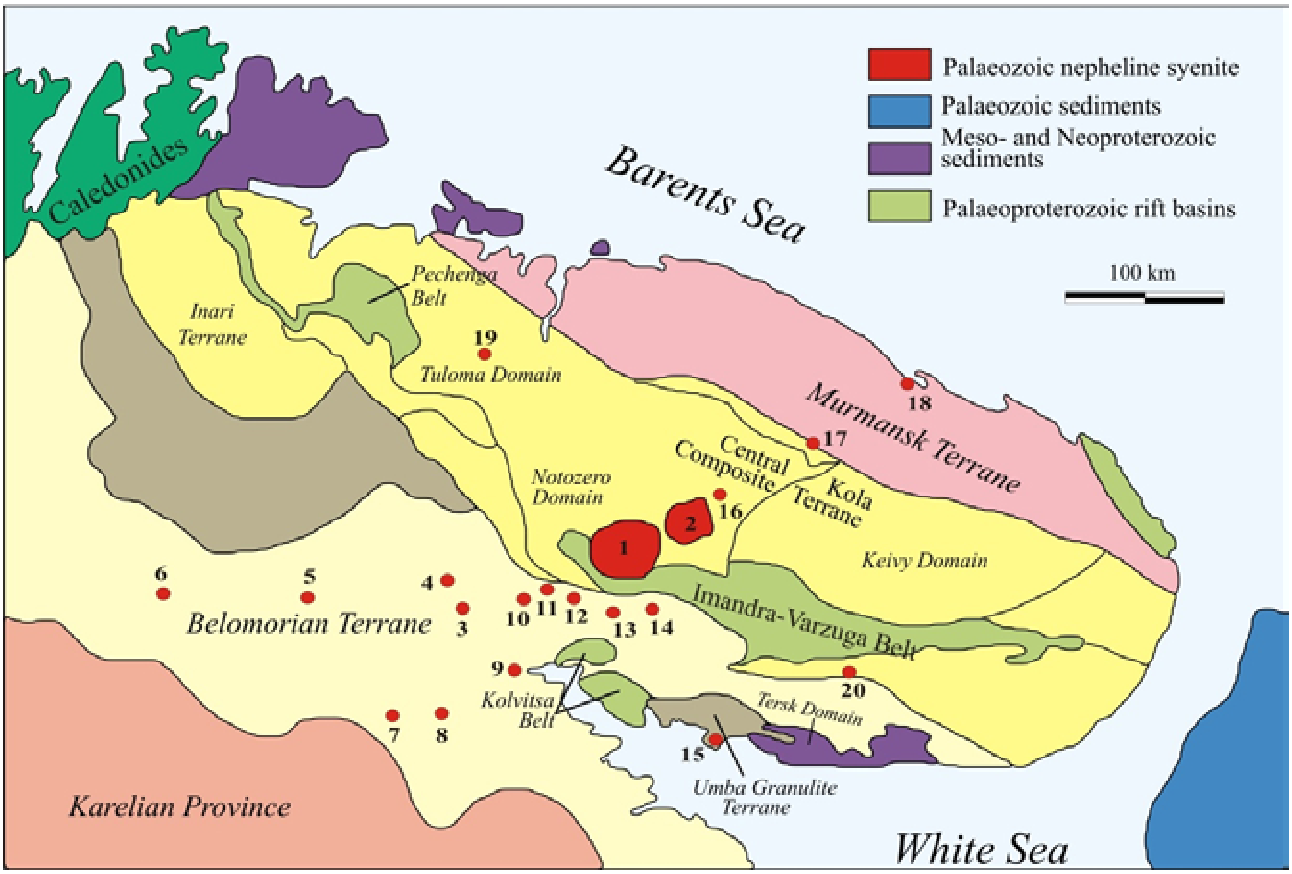

Fig. 1. The locations of various alkaline intrusions in the Kola Peninsula.

The Palaeozoic complexes: 1 – Khibina, 2 – Lovozero, 3 – Niva, 4 – Mavraguba, 5 – Kovdor, 6 – Sokli, 7 – Sallanlatva, 8 – Vuoriyarvi, 9 – Kandaguba, , 10 – Afrikanda, 11 – Ozernaya Varaka, 12 – Lesnaya Varaka, 13 – Salmagora, 14 – Ingozero, 15 – Turiy Mys, 16 – Kurga, 17 – Kontozero, 18 – Ivanovka, 19 – Seblyavr, 20 – Pesochny. Map of Precambrian basement after Balagansky *et al.*, 2006 .

NE-trending zone, parallel to the axis of the Caledonian front, in the east of Fennoscandia in the foreland of the mobile belt (Kukharenko *et at.*, 1965). The tectonic zone was the site where large collapsed calderas filled with sedimentary and volcanic rocks were formed, and numerous alkaline intrusions appeared in Devonian.

Geochronological data supported by geological observations give evidence for three stages of of the Palaeozoic magmatic activity.

The initial stage of igneous activity occurred within the time span of 410-390 Ma. It is represented mainly by subalkaline volcanism which was localized in depressions along the north-east trending fault zone. The only multiphase Kurga intrusion formed during this period comprises both ultrabasic and subalkaline larvikite-lardalite-syenite series. Apart from the alkaline volcanic series localized within the Lovozero and Khibina, Kontozero and Ivanovka there are two other sites of Paleozoic initial volcanism in the Kola. In the Ivanovka Bay remnants of volcanic rocks are represented by tuffs, tuffites, tufflavas, and lava breccias, varying in composition from nepheline basalts to alkaline trachytes. The volcanic-sedimentary rocks of the Kontozero complex fill a caldera 8 km across located in Archean granite-gneisses. The sedimentary-volcanic formation comprises terrigenous-volcanic argillite member, the volcanic melilitite-nephelinite member, and the vechiclebonate-terrigenous carbonatite member. The latter consists of extrusive carbonatite (lavas and tuffs), picrite-carbonatite and also calcareous tuffaceous siltslone and tuffite.

The main stage of igneous activity was marked by the world biggest agpaitic complexes of the Khibina and Lovozero and numerous carbonatite intrusions of Kovdor, Sokli, Afrikanda, Turiy Mys which were formed within the time span of 380-360 Ma (Kramm *et al*., 1993). Whereas the most of carbonatite massifs are known since the beginning of the 20th century, several intrusions were found during the last 15 year period. The Ivanovka volcanic and plutonic foidite complex (Rusanov *et al*., 1993), Niva agpaitic intrusion (Arzamastsev *et al*., 2000) and Kandaguba foidolite massif (Pilipiuk *et al*., 2001) were found during the detailed geological survey of the Kola region. The observed field relations in multiphase carbonatite complexes of the Kola province demonstrate a constant order of their formation and support the general rule of formation, described for carbonatite intrusions elsewhere in the world. Nearly the whole rock sequence is best represented in the Kovdor massif.

The final stage of activity manifested in dyke and pipe magmatism. Numerous dyke swarms dominate throughout the Kola Peninsula and adjacent areas. Most of the dykes occur around or inside the alkaline massifs, but there are also autonomous dyke swarms and pipes. The biggest dyke swarms were found in the coastal zone of the Kandalaksha gulf. The dyke rocks fall into the following groups: (1) Alkali picrite, olivine melanephelinite, alkali lamprophyres, damtjernite; (2) nephelinite; (3) alnöite, nepheline melilitite; (4) phonolite and tinguaite; 5) trachyte; 6) carbonatite; 7) calcite tinguaite porphyre; 8) essexite and theralite. Most of dykes strike in the north-eastern direction that coincides with that of the main fault zone traced by the alkaline massifs. In the Turiy Mys area numerous dykes of all the above named rock types form a «corona», which envelops the vechiclebonatite massif. In the Tersky Coast, 35 km east of the Turiy Mys, a swarm comprises 36 pipes and 15 dykes of micaseous kimberlite, olivine melilitite, and olivine melanephelinite. In two diatremes kimberlite contains sporadic diamonds (Kalinkin *et al*., 1993).

THE KHIBINA MASSIF

The Khibina massif is situated in the central part of the Kola Peninsula, 66°33'-67°55'N, 33°13'-37°16'E. Topographically, it is a dome-shaped mountain massif with the highest point 1200 m above sea level. The massif is intersected by deep canyons and wide river valleys. Some of the mountains are cupped with extensive plateaus, and encircled with cirques and steep slopes. Topographic features bear evidence of glacial activity; moraine ridges are present in the river valleys. The Khibina pluton is located in the

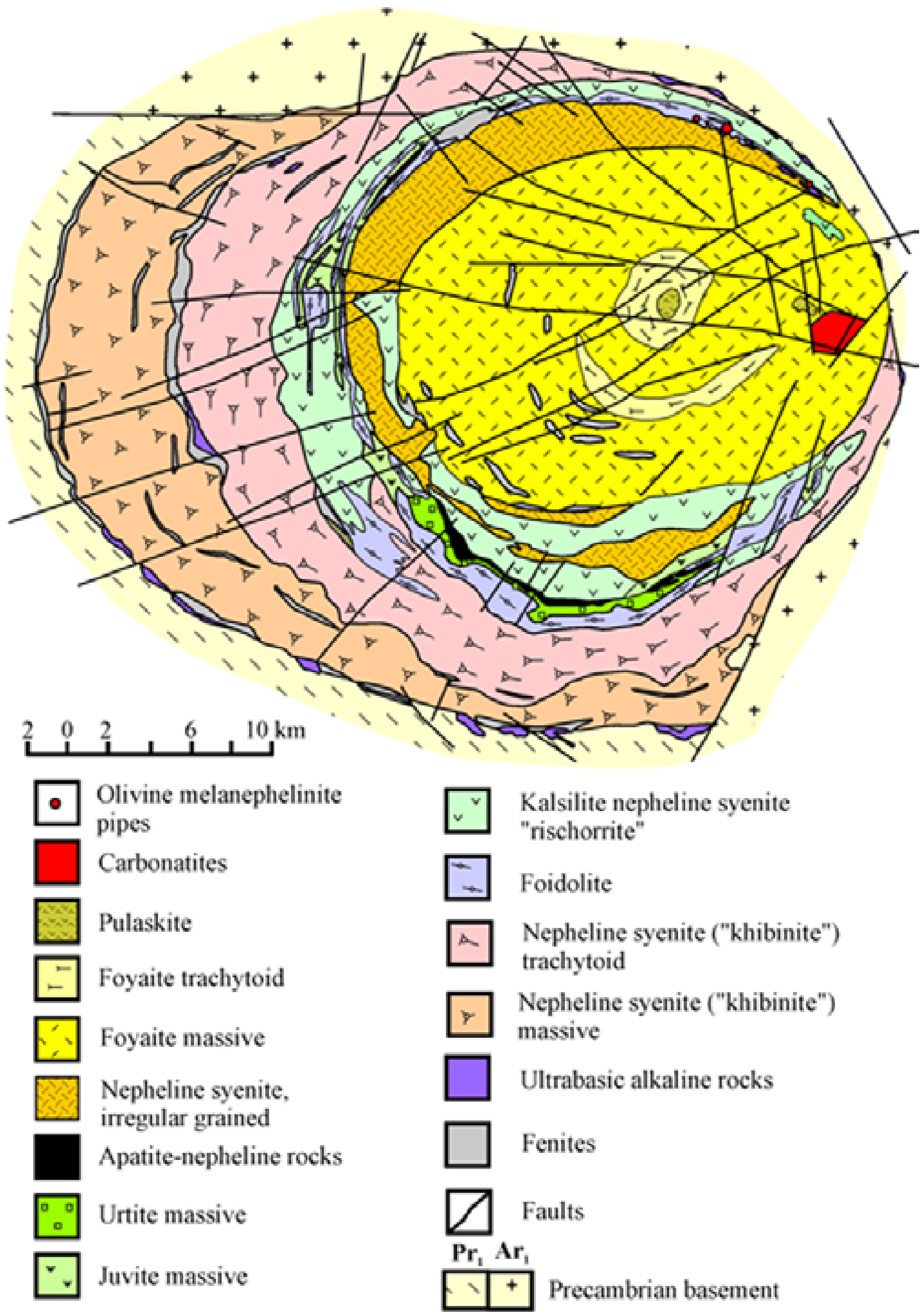

Fig. 2. Geological map of the Khibina massif generalized from the map of MGRE PGO «Sevzapgeologiya» (V.P. Pavlov).

contact of Archaean gneisses and Proterozoic Pechenga-Imandra-Varzuga palaeoriftogenic volcanic-sedimentary complexes, which form the Lapland-Kola-Belomorian collisional structure (Fig. 1).

Main rock complexes forming the Khibina massif. The Khibina massif is a concentrically zoned multiphase intrusion composed of agpaitic nepheline syenites, and in minor amount of ultrabasic alkaline rocks (Fig. 2). From the oldest to the youngest the components are as follows:

1. Remnants of the alkaline volcanic complex.
2. Peridotites, pyroxenites, melilite-bearing rocks.
3. Nepheline syenites of the peripheral zone («khibinites»).
4. Melteigite-ijolite-urtite layered complex.
5. K-nepheline syenites («rischorrites»), juvites, urtites and related apatite-nepheline rocks.
6. Nepheline syenites of the central part of the massif (foyaites) and pulaskites.
7. Dykes of essexite, alkaline picrite, nephelinite, phonolite, trachyte.
8. Carbonatites.

There are few models of the Khibina massif genesis (Fig. 3). According to our data (Arzamastsev *et al.*, 1998), the Khibina massif was formed in the following sequence (Fig. 4)**:**

(a) Collapsed caldera originated at the contact between the Late Archean tonalite trondhjemite-granodiorite complex and the Early Proterozoic Pechenga-Imandra-Varzuga paleoriftogenic complex; volcanic activity began in the peripheral parts of the newly formed structure.

(b) Alkaline-ultrabasic melts were intruded; olivine pyroxenite, melilitolite, and olivine melteigite bodies originated predominantly in the northern peripheral parts of the caldera.

(c) Agpaitic nepheline syenite was intruded along outer conical faults (khibinite intrusion).

(d) Further collapse of the caldera and the development of a layered ijolite-melteigite complex in the central portion of the caldera.

(e) The ijolite-melteigite complex was cut by a series or conical faults, along which phosphate-bearing urtite-juvite-kalsilite syenite intrusion was emplaced.

(f) A new series of conical faults formed in the central part of the ijolite-melteigite series and were emplaced and formed the core of the massif (foyaite intrusion),

(g) The pulaskite and carbonatite stock formed.

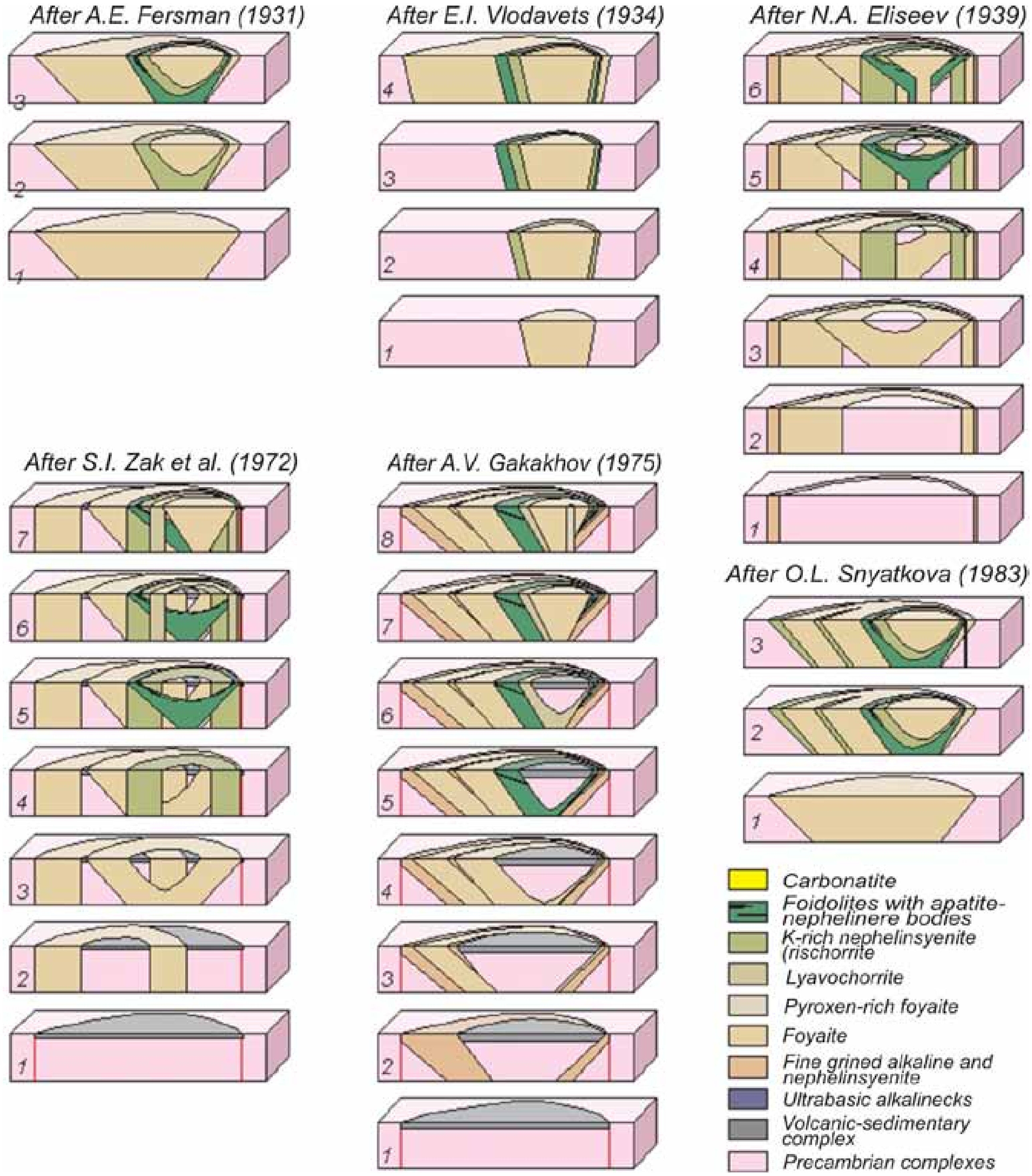

Fig. 3. The main hypothetic schemes of the Khibina massif formation.

Despite the huge size of the Khibina massif, it is surrounded by just a narrow halo of metasomatic alteration. Fenitization of host gneisses rarely exceeds 50 m and the metavolcanic rocks of the Imandra-Varzuga complex have been metamorphosed to hornfels near to the contact without any overall change in composition. In the foyaite, immediately adjacent to the Central Ring, there are many xenoliths of hornfels richest in alumina and their fenitized equivalents, containing sillimanite, andalusite, corundum, hercynite, fayalite, quartz, topaz, cordierite, sekaninaite and pyrrhotite. The size of the xenoliths ranges from several metres up to 3 km, and reaches 600 m wide; their long axes are practically always parallel to the Central Ring.

The Khibina complex is somewhat a Mecca for mineralogists and mineral collectors due to numerous pegmatites comprising unique assemblages of rare minerals. About 80 new minerals were first discovered in the Khibina and most of them occur in pegmatites and late hydrothermal veins (Yakovenchuk *et al.*, 2005). The bulk of the veins is related to rocks of the Central Ring and to adjacent foyaite localities. The most characteristic shapes of veins are equant and stockwork-shaped; their common size is 30-50 m long and 0.5-1 m wide (Tikhonenkov, 1963). The contacts of the host rocks can be gradual or sharp but also in the latter case an exocontact alteration is usually observed (decomposition of nepheline, sodalite and cancrinite to an entangled mass of fibrous natrolite and hydrous micas,

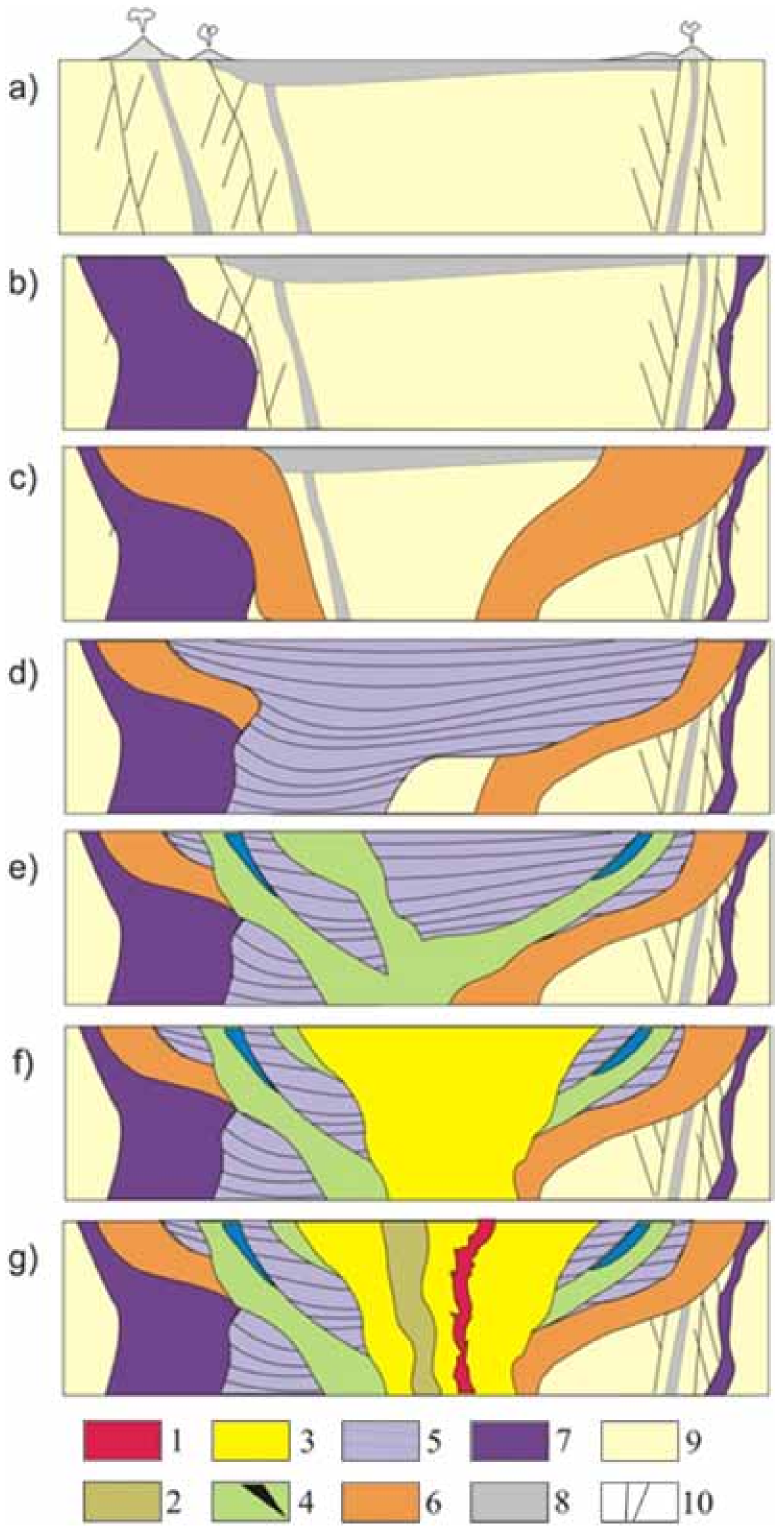

Fig. 4. Hypothetic scheme of formation of the Khibina massif.
Legend: 1 – carbonatites, 2 – pulaskite, 3 – foyaite, 4 – K-nepheline syenite, juvite, urtite and apatite ore (dark), 5 – melteigite-ijolite-urtite layered complex, 6 – nepheline syenites of the peripheral part of the massif («khibinites»), 7 – ultrabasic alkaline rocks, 8 – alkaline volcanics, 9 – Precambrian basement, 10 – dykes of olivine melanephelinite and picrite.

and also eudialytization, aegirinization *etc*.). Many veins are zoned. A mutual relationship between the vein and dyke complexes is also clear (Tikhonenkov, 1963; Kostyleva-Labuntsova *et al*., 1978). In most cases dykes either cut the veins, or penetrate the same weakened zones. The exceptions are the low-temperature carbonate, zeolite and pectolite veinlets which develop in cracks within all types of rocks, including pegmatite veins and dykes. Rather peculiar veins of quartz-syenite, syenite and nepheline-syenite with high concentrations of corundum, hercynite, topaz, almandine, pyrrhotite, pyrite and scarce accessories such as chrysoberyl, gadolinite-(Ce), chevkinite-(Ce), buergerite, native iron, sulphur, crichtonite, alabandite, and akaganйite are associated with xenoliths of hornfels (Yakovenchuk *et al.*, 2005).

DURATION OF THE FORMATION OF SYSTEM AND SUCCESSION OF THE FORMATION OF MASSIFS

The new results obtained and the published isotopic dates (Arzamastsev *et al.*, 2007) indicate multistage evolution of the Khibina–Lovozero volcanic and plutonic system. The emplacement of magma at the oldest stage was accompanied by the formation of the autonomous Kurga intrusion. The subsequent events occurred in both the Khibina and Lovozero plutons and covered a short time span. The sequence of events was as follows.

Premagmatic stage 427±6 Ma ago. Mantle metasomatism that preceeded the vigorous Paleozoic magmatism.

Early magmatic stage 404±6 Ma ago. Faulting in the Neoarchean tonalites, trondhjemites, and granodiorites; emplacement of the Kurga intrusion and eruption of ultramafic and subalkaline volcanics (the Lovozero Formation) in the northeastern area of the future Lovozero ring structure.

Major magmatic stage 388±6 Ma ago. Development of ring faults and initial subsidence of the Khibina caldera at the contact of the Neoarchean complex of tonalites, trondhjemites, and granodiorites and the Paleoproterozoic Pechenga–Imandra–Varzuga Rift Belt; injection of the first portions of melanephelinitic magma as ring dykes of the framework.

388-371 Ma ago. Emplacement of alkaline ultramafic melts in the northern Khibina caldera and in the north-eastern Lovozero caldera; formation of the bodies of olivine pyroxenite, melilitolite, and olivine melteigite.

371-362 Ma ago. Formation of the main Khibina and Lovozero plutonic complexes of peralkaline syenite.

367-366 Ma ago. Intrusion of carbonatitic stock and formation of a stock-like pulaskite body in the eastern Khibina pluton.

363-362 Ma ago. Formation of the late dyke complex of the Khibina and Lovozero. Emplacement of dykes and explosion pipes of alkali picrite, olivine melanephelinite, nephelinite, and phonolite.

Late magmatic stage

359±5 Ma ago. Formation of the late microcline–albite pegmatoids with ilmenite and zircon in the framework of the Lovozero pluton.

347±8 Ma ago. Late magmatic processes in alkali syenite located in the central part of the Lovozero pluton that mark completion of igneous activity in the Khibina and Lovozero calderas.

A cross-section of the massif (Fig. 5): 9 hours, total length 110 km. Short easy hiking, but a hard way on a stony road by an off-road truck.

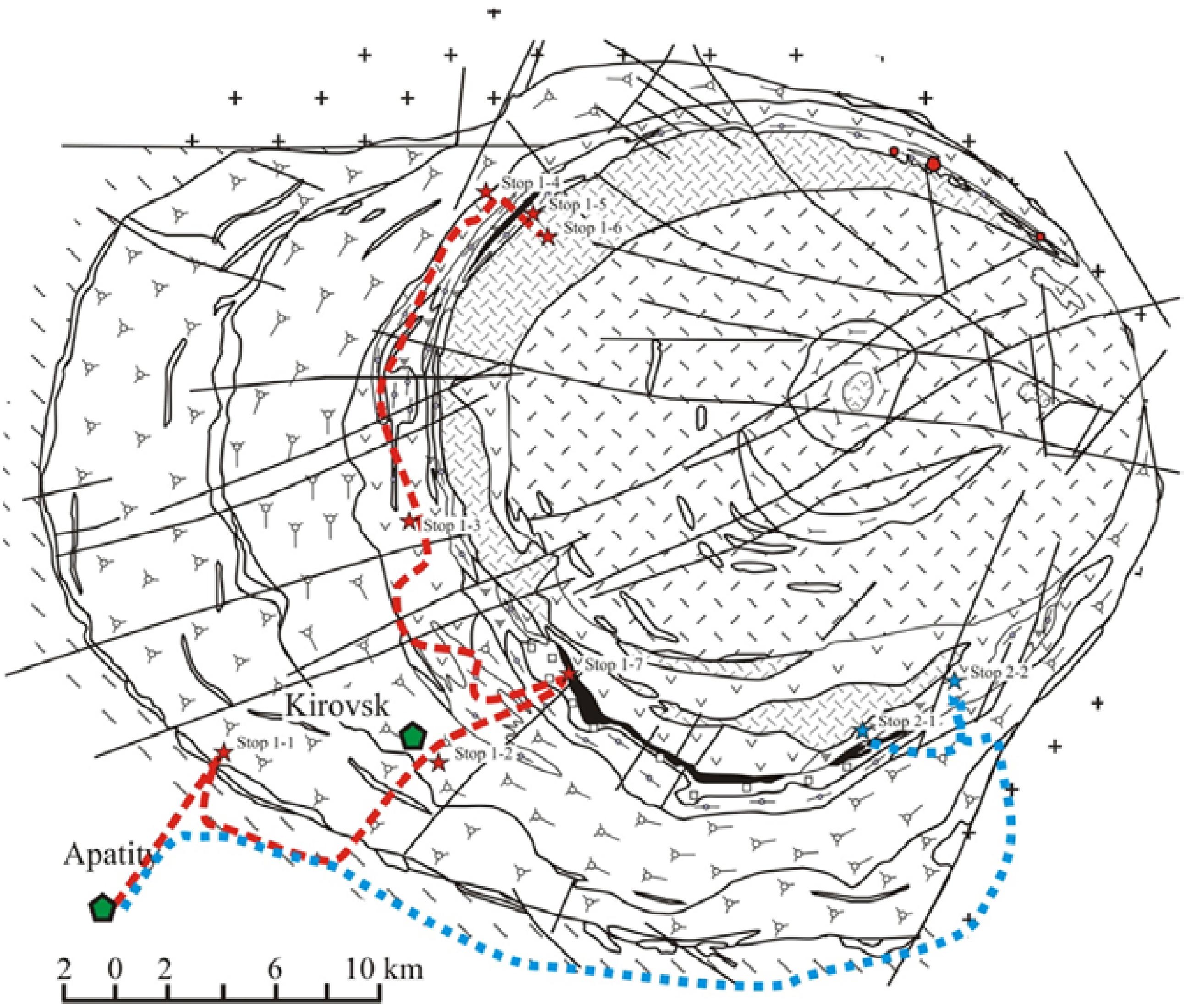

Fig. 5. Excursion routes in the Khibina Massif.

Stop 1-1. The southern slope of Khibina Mountains

Contact zone of intrusion (Easy hiking 350 m). Massive coarse-grained nepheline syenite (massive khibinite) of the peripheral part of the massif (Fig. 6). Contact eudialite-bearing pegmatoid zone (Fig. 7). Xenoliths of Proterozoic green schists in alkaline rocks. Fenites.

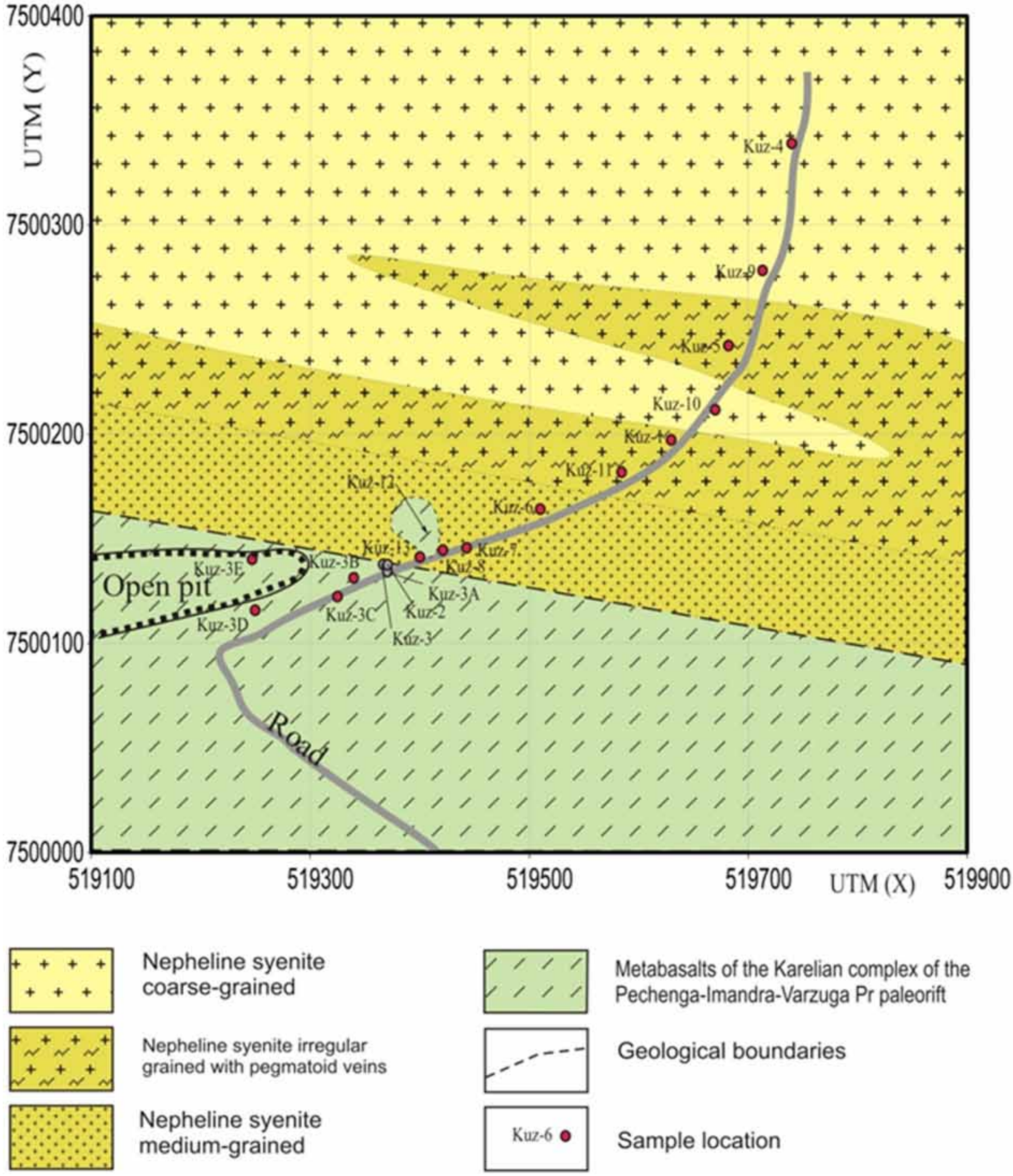

Fig. 6. Geological scheme of the southern contact of the Khibina Massif (Stop 1-1).

Fig. 7. Eudialite pegmatoid in the contact zone of the Khibina Massif (Stop 1-1).

Stop 1-2. The town of Kirovsk. Ski jump lodge

Trachytoid coarse-grained nepheline syenite (trachytoid khibinite) of the peripheral part of the massif. Eudialite-bearing nepheline syenites (*Easy hiking 200 m*).

Nepheline syenites of the peripheral part of the massif were locally named «khibinites» because of their coarse-grained structure and the presence of eudialite in some varieties. The complex consists of two ring bodies of massive and trachytoid nepheline syenites, divided by a narrow zone of titanite bearing varieties and xenoliths of alkalic volcanics and ultrabasic alkaline rocks.

Nepheline syenite series show absence of any signs of modal or cryptic layering. The data from drillholes demonstrate poor and irregular alternation of coarse grained varieties interrupted by irregular zones of fine-grained nepheline syenites which belong to the earliest phase of khibinite intrusion.

Khibinite is a coarse-grained rock with a hypidiomorphic texture. K-Na feldspar is the most abundant mineral represented by the laths of K-Na perthite.

Table 1. Selected analyses of nepheline syenites of the peripheral zone of the massif (oxides in wt. %, trace elements in ppm).

Rock	SFNX	SFNX	SFNX	SFNX
SiO_2	54.24	51.98	53.67	54.07
TiO_2	0.69	0.22	0.50	0.75
Al_2O_3	20.62	23.16	22.41	22.14
Fe_2O_3	3.14	2.66	1.26	1.30
FeO	1.03	2.00	2.07	2.46
MnO	0.18	0.17	0.12	0.15
MgO	0.40	0.14	0.54	0.41
CaO	1.06	0.66	1.16	0.76
Na_2O	11.21	12.20	11.16	10.67
K_2O	5.63	5.03	5.36	5.45
P_2O_5	0.12	0.09	0.11	0.09
CO_2	0.06	0.05	0.01	0.01
$S_{tot.}$	0.18	0.09	0.03	0.04
Cl	0.06	0.012	0.04	0.04
F	0.14	0.08	0.13	0.13
LOI	0.88	1.09	0.80	0.83
Total	99.64	99.63	99.37	99.30
Li	31.3	15.7	17.8	18.8
Rb	162	83.7	68.5	58.4
Cs	1.89	1.94	1.34	1.45
Sr	2711	1005	1318	1209
Ba	1469	570	1029	1033
Y	51.2	18.8	21.7	19.5
Nb	225	184	140	156
Ta	9.49	11.1	9.14	11.8
Zr	638	309	520	621
Hf	15.0	6.13	10.6	13.3
U	8.93	3.84	3.42	2.57
Th	30.7	12.5	10.0	9.07

SFNX – agpaitic syenite («khibinite»).

Textural relationships indicate the following crystallization sequence: apatite - nepheline - K-Na-feldspar - magnetite - titanite - lamprophyllite - aegirine-augite. Nepheline typically includes microliths of aegirine and is partly replaced by sodalite or cancrinite. Pyroxene is corroded by arfvedsonite or/and lepidomelane. Some of pyroxene crystals are zoned and composed of aegirine-augite core rimmed by aegirine. Overgrowths of Ti-magnetite on astrophyllite, titanite on astrophyllite, titanite on aenigmatite are widespread. Chemical analyses of nepheline syenites are listed in Table 1. The agpaicity index $K_{agp.} = (Na_2O + K_2O)/Al_2O_3$ mol. % of nepheline syenites is 1.10.

Stop 1-3. The road to Kuelpor

(No hiking). K-rich m assive nepheline and kalsil ite syenites («rischorrites»). Tinguaite dyke.

K-nepheline syenite. The complex comprising potassium-rich nepheline syenite, and juvite-urtite as subordinate members forms a ring-like body with contacts dipping inward the centre of the massif. The feature of the rischorrite that distinguishes it from the other Khibina nepheline syenites is its extremely high K/Na ratio. This is reflected in the presence of K-feldspar instead of K-Na perthite, modal kalsilite, djerfisherite (potassium-bearing sulfide), wadeite (potassium zircon silicate) and leucite. The latter was recently found in a juvite vein cutting ijolites. Chemical analyses of selected samples of rischorrites, juvites and urtites are listed in Table 2.

Potassium-rich nepheline syenite which was locally named «rischorrite» is a coarse-grained massive nepheline syenite, with varying content of K-feldspar and nepheline. The Khibina juvite is defined as nepheline-rich syenite intermediate between rischorrite and urtite. The complex consists of irregular alternation of potassium-rich nepheline syenite with varying structure and different amounts of major minerals. Large oikocrysts (up to 5 cm in size) of homogeneous orthoclase or microcline include euhedral crystals of nepheline, pyroxene, titanite and apatite to form a poikilitic structure. Graphic intergrowths of nepheline and K-feldspar are widespread. Nepheline is filled with aegirine needles which trace the crystallographic shape of primary crystals. The nepheline composition shows an extremely high K_2O content limited by the solid solution gap between nepheline and kalsilite. Pyroxene compositions range from aegirine-diopside to aegirine. Pyroxene is normally zoned with the acmite component increasing from core to rim. It is partly replaced by

Fig. 8. Phonolite (tinguaite). Stop 1-3.

Table 2. Selected analyses of K-nepheline syenite, juvite, urtite and apatite-nepheline rocks.

Rock	K-nepheline syenite		Juvite		Urtite		Apatite-nepheline rocks	
Drillhole	979	1113	818	360	20	522	1152	466
Depth, m	946	357	786	670	100	500	80	645
SiO_2	48.48	52.55	48.98	46.45	43.09	40.28	12.23	30.33
TiO_2	2.64	0.52	0.64	2.33	3.07	2.09	1.10	10.63
Al_2O_3	19.99	21.53	22.84	20.15	23.46	27.16	6.45	9.52
Fe_2O_3	2.84	2.87	2.98	3.31	2.86	1.96	2.11	4.41
FeO	2.15	1.65	1.57	2.16	2.67	1.37	1.08	3.87
MnO	0.16	0.08	0.12	0.16	0.13	0.04	0.08	0.22
MgO	0.60	0.12	0.92	2.51	1.22	0.20	0.31	1.88
CaO	3.06	0.92	1.26	4.63	4.61	4.52	38.18	20.54
Na_2O	6.55	7.30	9.83	0.01	12.40	15.10	3.36	5.42
K_2O	12.08	11.72	9.98	6.88	5.74	4.98	1.35	2.14
P_2O_5	0.27	0.07	0.20	0.50	0.60	1.65	29.81	9.03
CO_2	0.18	0.21	0.05	0.14	0.09	–	0.10	0.10
Cl	0.04	–	–	–	0.04	–	–	–
F	0.10	0.04	0.13	0.12	0.16	0.23	2.35	0.95
H_2O^+	0.78	0.69	0.62	0.26	0.47	0.76	0.19	0.28
H_2O^-	0.04	0.26	0.08	0.38	0.11	0.01	0.07	0.05
Total	99.92	100.53	100.20	99.99	100.68	100.37	100.62	100.73
Nb	168	98	28	35	43	24	42	412
Sr	1520	1690	1450	1776	846	2114	15559	10993
Rb	357	347	485	219	119	11	18	46
Li	9	20	19	13	11	15	5	9
Cs	17	4	6	3	2	3	1	1

arfvedsonite or/and biotite. Lamprophyllite, aenigmatite, pectolite, eudialite, mosandrite are accessory minerals.

Phonolite dykes cut all rocks of the Khibina massif (Fig. 8). Most of them are radial, except few, which are concentrical.

Stop 1-4. The left bank of the Southern Lyavoiok river

(Hiking 300 m). Apatite-titanite mineralization zone (Fig. 9). A small-scale outcrop model of the Khibina apatite deposits. In the outcrop participants can see massive coarse-grained urtite, which gradually changes into apatite-titanite urtite and apatite-titanite ores.

Fig. 9. Outcrops of the stop 1-4.

Stop 1-5. The left bank of the Southern Lyavoiok river

(Easy hiking 100 m). Layering in the foidolite complex.

Foidolites trend as a continuous stripe throughout the massif and form two units below and above the ore zone. Geological observations testify to the origin of these rocks immediately after the emplacement of the nepheline syenite (khibinite) in the peripheral zone of the massif. The complex is represented by a differentiated body with elements of rhythmic layering (Fig. 10). The regular sequence of alternation of rocks in the vertical section is preserved through several kilometers. In each rhythm melteigite in the bottom grades into leucocratic ijolite, or urtite in the top. The contact between melteigite and urtite of the underlying rhythm is commonly sharp. All layers are lying concordantly and dip to the centre of the massif at an angles of 10-30 °.

Melteigite, ijolite and urtite forming a layered complex are represented by medium-grained varieties with strong planar lamination formed by oriented elongated grains of mafic minerals. The assemblage of accessory aenigmatite, lamprophyllite, eudialite, mosandrite and sodalite in Khibina ijolites and melteigites reflects a high alkali content in these rocks. Near the contacts with nepheline syenites minor K-feldspar is present. In contrast to typical ijolites and melteigites from Fen, Iivara, Kovdor and the Turiy Mys, the Khibina foidolites never contain wollastonite and garnet; perovskite occurs sporadically. Olivine phenocrysts in some of the Khibina melteigites are commonly rimmed by mica-amphibole-magnetite aggregate. Olivine has forsterite content of 68-77, however varieties with Fo_{81-84} are also present. Clinopyroxene which is universally present in all rock types, belongs to Ca-Mg-Fe group with the transition to Na-Ca group, thus forming aegirine-diopside and aegirine-augite series. Two generations of amphibole are present in the Khibina foidolites. The first one forms interstitial or poikilitic unzoned grains that exhibit a dark brownish to light brownish pleochroism. This amphibole belongs to richterite-magnesio-

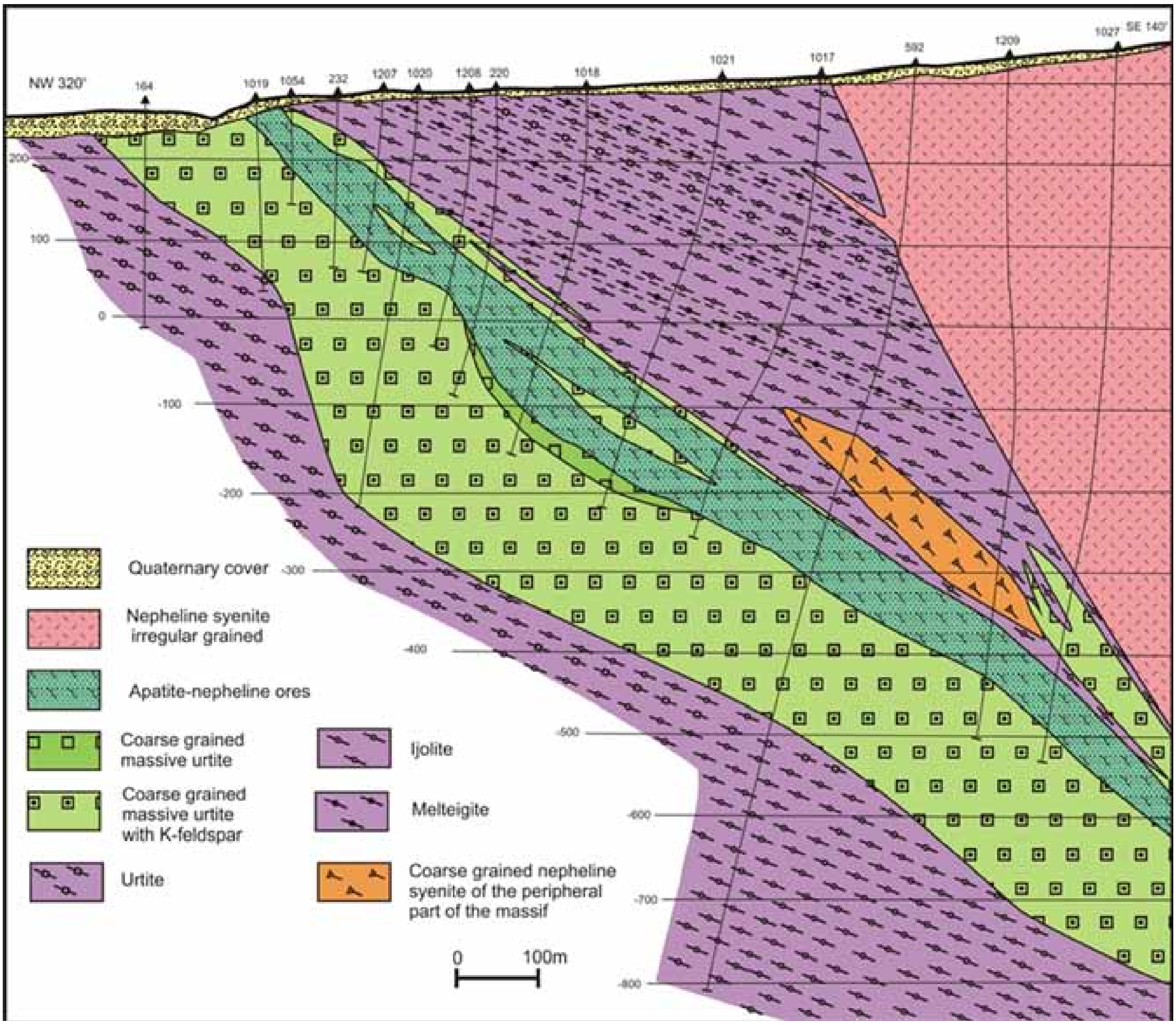

Fig. 10. Cross-section along the Southern Lyavoiok river (Stops 1-4 – 1-6).

katophorite series of Na-Ca group. The richterite richest in magnesium was found in the rims surrounding olivine phenocrysts. Whereas amphibole and pyroxene appear to be in equilibrium in some samples, the replacement relationship is observed in others. Arfvedsonite and magnesio-arfvedsonite, which represent the second generation, form intergrowths in pyroxene crystals or rims around primary richterite grains. It exhibits brownish-green to bluish-green pleochroism.Nepheline is a dominant mineral in foidolites. The form of nepheline crystals depends on its content in the rocks: ijolites contain mainly euhedral nepheline crystals, while in melteigites nepheline forms anhedral interstitial grains. Many of euhedral grains are overcrowded by aegirine needles settled in the interior zones. The content of Fe in nepheline is extremely high (up to 3.3% Fe_2O_3); its distribution inside the crystal is irregular. The electron-microprobe scanning indicates the presence of enormous dots up to 5 m in size with high Fe content, which may have been the result of the exsolution

Table 3. Selective analyses of foidolites (oxides in wt. %, trace elements in ppm).

Number	7	8	9
Rock	MLG*	IJL*	URT*
SiO_2	38.27	43.34	42.01
TiO_2	5.33	3.09	2.51
Al_2O_3	7.78	17.97	22.13
Fe_2O_3	9.65	5.08	4.41
FeO	8.61	3.83	3.26
MnO	0.45	0.25	0.17
MgO	5.47	2.71	1.80
CaO	13.31	6.92	5.52
Na_2O	5.51	10.48	11.86
K_2O	1.77	4.21	4.61
P_2O_5	2.37	0.74	0.60
CO_2	0.10	0.11	0.09
F	0.28	0.17	0.10
H_2O^+	0.51	0.58	0.58
H_2O^-	0.08	0.13	0.12
Total	99.49	99.61	99.77
Ni	81	58	53
Co	65	55	66
Cr	205	50	34
V	586	352	206
Zr	780	672	339
Y	35	37	22
Nb	114	228	136
Sr	2569	2123	1466
Ba	227	387	39
Rb	37	77	88

MLG – melteigite, IJL – ijolite, URT – urtite. * – average composition.

Table 4. Selected analyses of nepheline syenites of the central part of the massif (oxides in wt. %, trace elements in ppm).

Rock	SFNF	SFNF	SFNF	SAP
SiO_2	53.03	55.22	56.98	60.59
TiO_2	0.75	0.66	0.17	0.40
Al_2O_3	20.60	20.85	21.14	18.28
Fe_2O_3	2.01	1.28	1.30	0.41
FeO	2.19	2.87	2.07	2.67
MnO	0.17	0.21	0.10	0.09
MgO	0.71	0.84	0.23	0.32
CaO	2.76	0.63	0.39	1.38
Na_2O	9.52	9.68	7.31	7.20
K_2O	5.98	5.44	8.28	5.63
P_2O_5	0.16	0.20	0.02	0.09
CO_2	0.20	0.78	0.14	0.84
$S_{tot.}$	0.02	0.13	0.07	0.14
Cl	0.41	0.01	0.03	0.04
F	0.11	0.23	0.05	0.05
LOI	1.05	0.51	1.15	1.22
Total	99.67	99.54	99.43	99.35
Li	15.6	57.1	8.03	26.3
Rb	66.1	388	156	92.0
Cs	1.45	3.79	1.15	1.69
Sr	1500	450	907	309
Ba	1316	572	366	485
Y	15.8	21.2	6.02	8.19
Nb	150	103	55.1	79.9
Ta	9.94	5.52	1.24	6.74
Zr	238	251	204	223
Hf	4.55	5.46	3.55	4.64
U	2.18	1.51	1.06	3.66
Th	14.4	9.37	7.32	18.1

SFNF – foyaite, SAP – pulaskite.

process. On the Nepheline-Kalsilite-SiO_2 diagram the nepheline compositions lie within the Morozevich-Buerger convergence field of plutonic nephelines. Representative analyses of various rock types of ijolite-melteigite complex are listed in Table 3.

Stop 1-6. The Southern Lyavoiok river

(Easy hiking 300 m). Nepheline syenites of the central part of the massif. Medium-grained nepheline syenites, foyaites, pulaskites.

The nepheline syenites forming the central part of the massif are the youngest, except carbonatites and dyke rocks. It is proved by numerous foyaite veins in K-nepheline syenites and juvites, steep contacts, cutting the layered ijolite-melteigite series and by the presence of ijolite xenoliths in foyaites. Nepheline syenites of the Khibina core are traditionally subdivided into foyaite and the so-called medium-grained nepheline syenite («lyavochorrite» – local name) (Zak *et al.*, 1972). The latter forms a marginal zone of the foyaite intrusion, and between the two varieties there is a gradual transitional zone, rather than sharp contacts.

Foyaite and «medium-grained nepheline syenite» are texturally and modally similar to nepheline syenites of the peripheral part of the massif. Irregular lenses of massive and trachytoid varieties ranging in composition from amphibole-lepidomelane to aegirine-amphibole foyaites form a heterogeneous intrusive body. No evidence of modal or cryptic layering have yet been found.

Foyaite consists of K-Na feldspar perthite (50-60 % vol.), nepheline (30-35 %), pyroxene (5-10 %), amphibole (1-5 %), biotite (1-5 %), titanite, Ti-magnetite, eudialite, astrophyllite, aenigmatite, apatite, rinkolite, sodalite, cancrinite and natrolite.

In addition to perthite intergrowths, albite forms twinned laths and rims around nepheline crystals. Zoned grains of pyroxene with an aegirine-augite core rimmed by aegirine are widespread. Amphibole in foyaites is more abundant than in nepheline syenites of the peripheral part of the massif where pyroxene dominates. Large zoned amphibole grains (5-20 mm) consist of a hastingsite core and an arfvedsonite rim. Titanite is commonly present in minor amount and forms honey-colored euhedral crystals or fibrillar segregations together with aegirine, astrophyllite and biotite. Eudialite is less abundant and was found as an accessory phase only in the marginal zone of the foyaite complex.

Pulaskites have been recently found in the core samples from the bore holes cutting a negative gravity anomaly in the central part of the foyaite complex (Arzamastsev *et al.*, 1998). Pulaskite recovered by many holes from below Quaternary deposits, occurs, as follows from geophysical data, as a round body (2 by 3 km in a map view) in foyaite (Fig. 2). The rock is medium- to coarse-grained and consists of microperthite feldspar laths (80-95 %), nepheline (1-5 %), amphibole (Mg-arfvedsonite and arfvedsonite), clinopyroxene, and biotite (the sum of mafic minerals amounts to 1-15 %). The rock contains minor titanite, calcite, sodalite, cancrinite, fluorite, sulfides, titanomagnetite. Chemical analyses of the miaskites are listed in Table 4.The agpaitic coefficient of these rocks ranges between 0.91 and 0.98. In contrast to the agpaitic syenite, their CIPW norms include 1-5 % anorthite but no acrmite, which is a typical component of the Khibina nepheline syenites. Agpaicity index varies from 1.09 in foyaite to 0.91-0.98 in pulaskite.

DAY 2: MINERAL DEPOSITS OF THE KHIBINA MASSIF

Visit to the Eastern group of apatite-nepheline deposits (Vostochny mine) (8 hours, 50 km of the Apatity town).

Stop 2-1. Koashva open pit

Main types of apatite-nepheline ores, titanite-apatite ore, magmatic apatite breccia, massive juvite, pegmatite zones.

Apatite-nepheline rocks are spatially related to urtite and juvite. Rasvumchorr, Kukisvumchorr, Yukspor, Koashva, Niorkpahk are the biggest deposits of apatite ores located within a narrow zone in the southern part of the massif. A typical cross section of the ore body from top to bottom is as follows (Fig. 11):

a) titanite-apatite uppermost contact zone, titanite mineralization is spread in the upper zone of juvites and ijolites;

b) breccia of apatite ores, xenoliths of different ore types are settled fine-grained apatite, apatite-titanite or apatite-nepheline matrix;

c) rich mottled and banded apatite ores (10-20 wt % P_2O_5);

c) poor lenticular, taxitic, and block apatite ore types (5-10 wt % P_2O_5);

Table 5. Average modal composition of industrial types of apatite ores, vol. % (After Kamenev, 1987).

	Apatite	Nepheline	Pyroxene	Titanite	Titano-magnetite	Ilmenite	Feldspar	Others
Titanite-apatite	21.9	30.92	17.73	18.21	4.23	1.19	2.20	3.62
Mottled	74.62	14.85	5.89	1.35	0.39	0.20	1.55	1.15
«Blocked»	44.04	39.75	8.68	3.00	1.21	0.35	1.22	1.74
Lens-banded	43.33	42.09	7.69	2.21	2.02	0.28	0.68	1.70
Massive	40.11	38.74	11.11	3.12	1.12	0.38	3.26	2.16
Net-like	31.71	51.84	9.25	2.64	2.55	0.65	0.45	1.51
Urtite with apatite	10.10	63.50	16.18	4.16	0.75	0.37	2.30	2.64

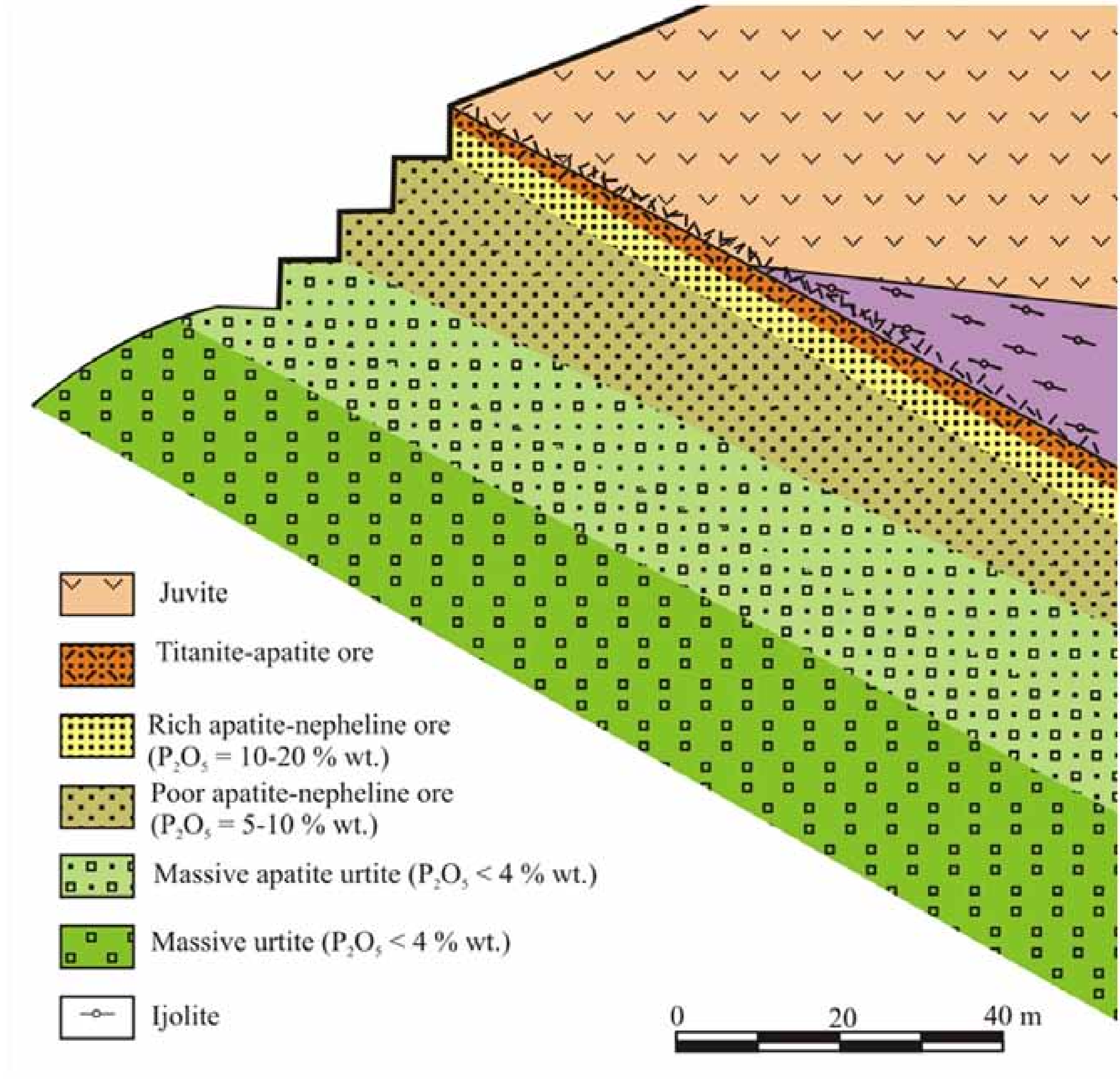

Fig. 11. Schematic cross section of the apatite-nepheline ore zone in the northwestern part of the massif.

d) apatite-bearing massive coarse-grained urtite;

e) apatite-free massive coarse-grained urtite.

There is no distinct boundary between the ore zone and the underlying urtite, and with the decrease in the amount of apatite the ore grades into urtite. This structure of ore bodies is typical of western group of deposits, whereas in south-eastern part of the massif the ore zone is brecciated.

Apatite $Ca_5(PO_4)_3F$, being the main component of the ore, contains 40-41 wt. % P_2O_5, 1.8-3.5 wt. % SrO, 9000-11000 ppm REE, and 500-900 ppm Y. It is represented by several generations of different shape and colour. Light green fine-grained varieties dominate, needle-like light yellow crystals and recrystallized smoky-coloured coarse-grained aggregates are also abundant. Nepheline (Fig. 12), the second main rock component used now as by-product, consists of 33 wt.% Al_2O_3, 15 wt.% Na_2O, 7 wt.% K_2O, 150 ppm Rb and 40 ppm Ga. High content of Fe and presence of numerous microneedles of aegirine is a factor which limits the use of nepheline as a crude ore for ceramics. Chemical analyses of apatite-nepheline ores are listed in Table 2, modal composition of commercial ore types are presented in Table 5.

Given the high content of P, Sr, REE, Y, Ti, Al, Na, K, Li, Rb and Ga, the Khibina apatite-nepheline ores are of great commercial importance. However, apatite deposits are now the only object of commercial importance for phosphorus.

There are eleven apatite-nepheline ore deposits in the Khibina massif: Partomchorr, Kuelporr, Kukisvumchorr, Yuksporr, Apatite Circus, Rasvumchorr, Koashva, Niorkpakhk, the Oleny Ruchei River and Vuonnemiok River. All are located along the Central Ring of the massif. A company, fittingly called «APATIT», was set up in 1929 and in the 1930s industrial production of the Khibina apatite from the Kukisvumchorr Deposit enabled Russia to stop importing Moroccan phosphorites and become the largest supplier of apatite concentrate in the international market. In the mid 1950s, the «APATIT» company began production of apatite ore using underground mines at Mts Yuksporr and Rasvumchorr, and then, in 1964, the «Tsentralny» (Central) Open Cast Mine on the Rasvumchorr Plateau was put into operation.

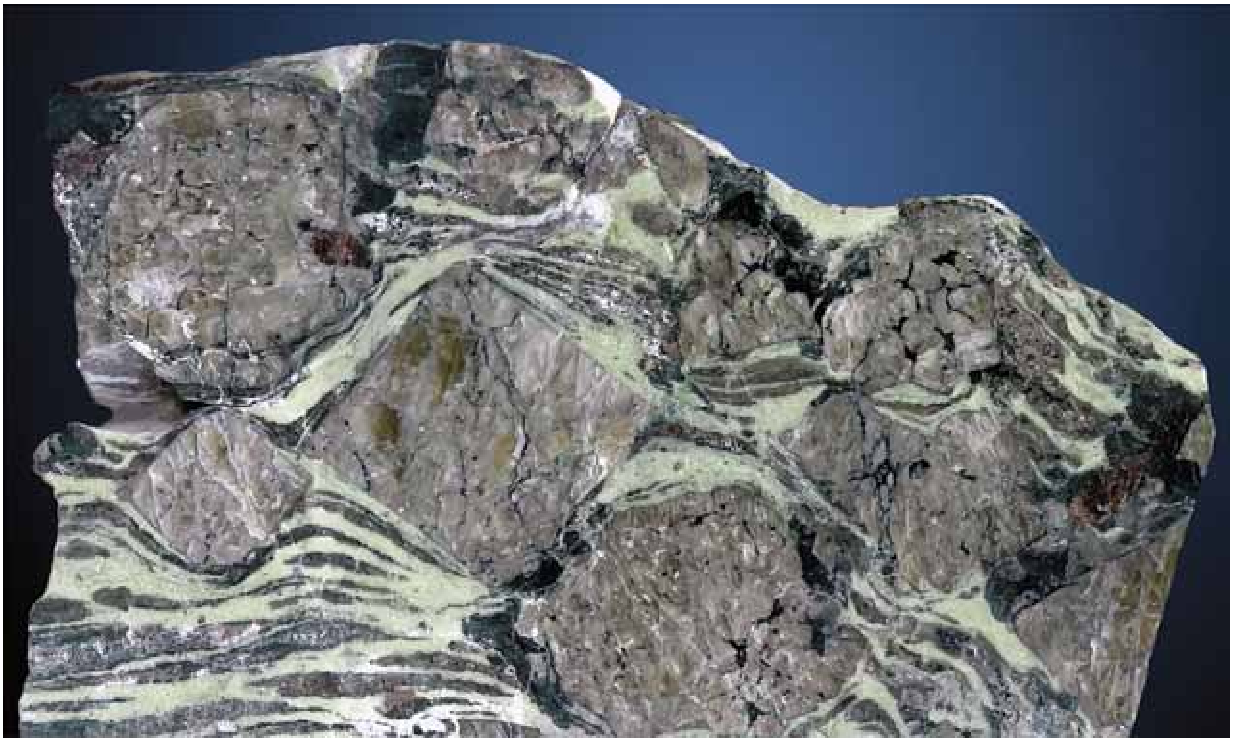

Fig. 12. 4 cm size nepheline crystals in apatite-nepheline ore.

Later, in 1981, the «Vostochny» (East) Open Cast Mine was set up to work the Koashva and Niorkpakhk Deposits. In 2007, a new open cast mine was opened to work the Oleny Ruchei River Deposit. Today the «APATIT» company is unique, it is one of the world's biggest manufacturers of phosphate raw material. Total reserves of apatite at the Khibina are estimated at 3 billion tons. Production reached a maximum of 20.04 million tons per year in 1981 but has now fallen and levelled off at 9 million tons per year in 2000. The total registered reserves of apatite-nepheline ores of the Khibina deposits are estimated as almost 4 bln.t., which corresponds to 600 mln.t. of P_2O_5, i.e. the enterprise is provided with prospected reserves for 50 years.

The Koashva Deposit, richest in the Khibina massif, was discovered in 1959. The ore zone of the deposit is made of a series of closely related lens-shaped bodies, spread over more than 3 km (Fig. 13). 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. Typical characteristics of the deep part of the ore zone are the compact arrangement of the ore bodies and consistent layered form. The ore body is practically uniform up to 200 m

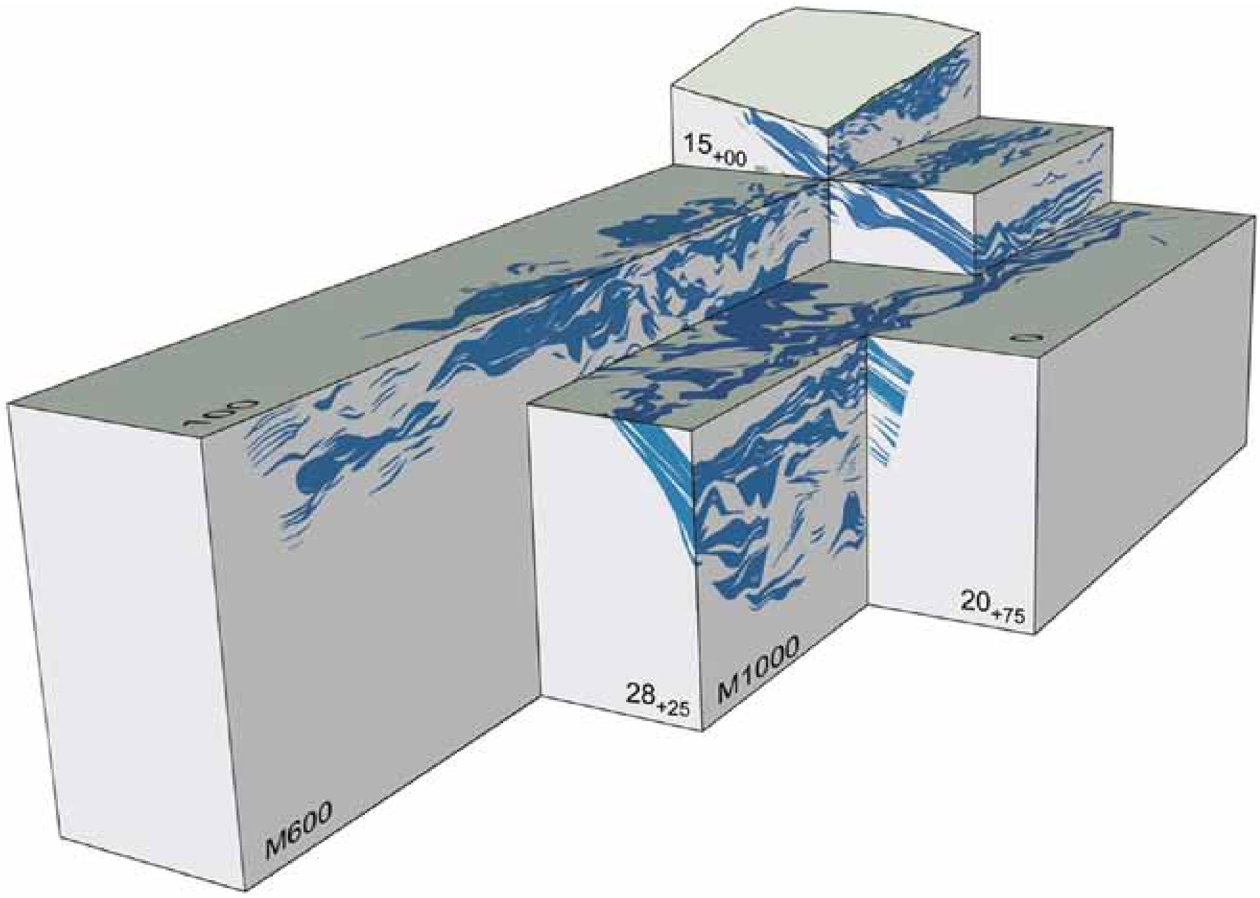

Fig. 13. Block-diagram of the Koashva deposit (Goryainov *et al.*, 2007). Grey – ijolite-urtite, blue – apatite-nepheline rock.

Fig. 14. Open cast mine, the Koashva Deposit. 2002.

thick and for the purposes of mining, the structure is very similar to the Kukisvumchorr or Rasvumchorr Deposits. In the top part of the ore zone the ore body is divided into series of separate lenses. Brecciated rocks are most common and all the rest 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 (the «Vostochny» Mine): Fig. 14.

Stop 2-2. Mt. Koashva

(Near the vechicle) Sodalite-microcline-aegirine vein in urtite. A large irregularly-shaped vein (2×3 m), consisting of three indistinct zones (Fig. 15).

1. A marginal zone up to 50 cm wide, composed of dark green spherulites (up to 10 cm) of fibrous aegirine with impregnations of large, light green, tabular microcline crystals (up to 12 cm), prismatic arfvedsonite (up to 5 cm long), laths and spherulites of lamprophyllite (up to 2 cm), bright purple crystals of sodalite (greying quickly when exposed to light), greenish-grey nepheline (up to 3 cm) and straw-yellow rinkite (up to 5 cm long).

2. An intermediate zone formed by massive medium-grained lilac-grey

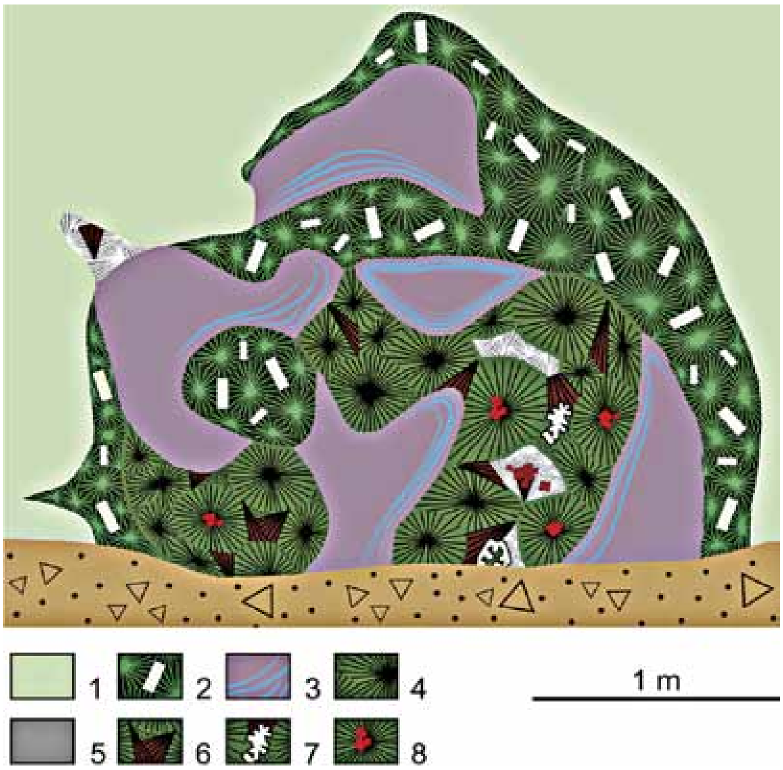

Fig. 15. Sodalite-microcline-aegirine vein in urtite, Mt. Koashva (Stop 2-2): 1 – urtite; 2 – microcline-aegirine zone; 3 – massive sodalite with layers of fluorapatite; 4 – radiating aegirine; 5 – pectolite; 6 – lomonosovite; 7 – microcline; 8 – villiaumite.

Fig. 16. Bladed umbite crystals in voids (up to 1.5 cm diameter) of leached eudialyte from sodalite-microcline-aegirine vein in urtite, Mt. Koashva.

sodalite with inclusions of dark green aegirine and light green, medium-grained fluorapatite. The fluorapatite occurs near to the contact with the aegirine core and forms a few (3-4) gradually thinning layers up to 1.5 cm wide. Voids within sodalite are encrusted by small transparent bright lilac crystals of sodalite (up to 5 mm).

3. The axial zone composed of large, dark-green spherulites (up to 20 cm) of fibrous aegirine with separate green crystals (coloured by aegirine inclusions) and druses of microcline, porous nodules of radiating snow-white pectolite, lamprophyllite laths (up to 5 cm long) and sodalite crystals (up to 4 cm). There are also numerous dark brown, tabular crystals of lomonosovite (up to 12 cm long). At the centre of the aegirine spherulites there are often inclusions of cubic villiaumite up to 3 cm edge-length. Villiaumite is a common mineral in pectolite-aegirine aggregates, where it forms segregations up to 15 cm diameter in association with colourless crystals of chkalovite (up to 10 cm diameter) and druses of small colourless crystals of umbite (up to 1 mm, Fig. 16). Peculiar funnel-shaped, zoned crystals of sphalerite with yellow cores and brown margins (up to 5 mm) and druses of small pale-cream crystals (up to 1 mm) of vitusite-(Ce), intergrown with 1–2 mm reddish-brown nacaphite crystals, also occur here. Vitusite-(Ce) is partially replaced

by a yellow, finely-crystalline aggregate of petersenite-(Ce). The rims of the aegirine spherulites have numerous voids up to 4 cm wide, within which, in addition to relics of natrophosphate and poorly-developed crystals of partially dissolved natrolite, there are often druses of 1 mm colourless crystals of umbite, cruciform twins of kostylevite and 1-5 mm brown crystals of sazykinaite-(Y) and sidorenkite.

Minerals: aegirine, arfvedsonite, chkalovite, fluorapatite, kostylevite, lamprophyllite, lomonosovite, microcline, nacaphite, natrophosphate, nepheline, pectolite, petersenite-(Ce), rinkite, sazykinaite-(Y), sidorenkite, sodalite, sphalerite, umbite, villiaumite, vitusite-(Ce).

Stop 2-3. Mt. Koashva

Nepheline-sodalite-microcline-aegirine vein in urtite, *(Near the vechicle)*. A large equant vein, about 5 m diameter, with a distinct concentric zonation (Fig. 17):

1. The marginal zone is 0.2-1 m wide and composed of light green microcline.
2. An intermediate zone, 0.5-1.5 m wide, is composed of 50 cm aggregates of dark cherry-coloured sodalite and greenish-grey nepheline, with

Fig. 17. Nepheline-sodalite-microcline-aegirine vein in urtite, Mt. Koashva. Stop 2-3.

irregularly shaped inclusions (up to 15 cm) of white, acicular pectolite and clusters of brown, semi-transparent grains of titanite (up to 7 cm diameter).

3. A core zone, about 3 m wide, is made of dark green entangled- and radiating-fibrous aegirine, containing separate aegirine "spheres" up to 50 cm diameter. In a rather friable top part of the core zone, there are heterogeneously-distributed, irregularly-shaped nodules of pectolite, natrolite-pectolite and natrolite up 80 cm in size. Pectolite forms white radiating aggregates composed of flattened-prismatic crystals (up to 5 cm long). Natrolite commonly occurs as irregularly-shaped nodules, composed of grains full of inclusions of acicular aegirine so that the colour of the mineral becomes green and even black. Inside the nodules there are many voids, and the walls of these are covered with aggregates of water-transparent prismatic natrolite. Pectolite and natrolite nodules are penetrated by black elongate-prismaticsix-faced crystals of aegirine (up to 20 cm long with a diameter of about 5 mm). Sheaf-like and radiating aggregates of lamprophyllite (15 cm maximum) composed of flattened-prismatic dark brown crystals are also widespread within aegirine. Massive natrolite contains yellow, elongate-prismatic crystals of belovite-(Ce) up to 1.5 cm long, water-transparent scalenohedral arctite (up to 1.5 mm long), and amongst the pectolite it is possible to find coal-black balls of solid organics (up to 3 mm diameter).

4. A lower section of the core zone is distinct from the rest in that the aegirine is more compact and fine-grained. Within the aegirine, there are numerous voids, up to 3 cm diameter, matching the morphology of negative crystals of eudialyte. Commonly the voids are encrusted by an aggregate of small, colourless, bladed crystals of fluorapatite (up to 0.7 mm), pectolite and/or catapleiite. Separate crystals of lamprophyllite, spherulites of late black aegirine and druses of colourless wedge-shaped albite occur on the fluorapatite and pectolite. Much less often there are small groups of colourless short-prismatic sitinakite crystals, up to 0.5 mm, bright orange spherulites of rhabdophane-(Ce) (up to 0.6 mm) and separate ochre-yellow rhombohedra of sazykinaite-(Y) up to 4 mm (Fig. 18). The sitinakite crystals contain small, rounded inclusions of lemmleinite-K. The rare minerals listed above are found in zones that contain radiating black aegirine as well as in the voids. In the aegirine zones, rhabdophane-(Ce), associated with natrolite, shcherbakovite and catapleiite, occurs mainly in areas enriched in pectolite. Sazykinaite-(Y) and sitinakite occur in large-porous masses of dark-green, extremely fine-grained aegirine filling interstices in aggregates

Fig. 18. Sazykinaite-(Y) crystal (2 mm diameter) in void of nepheline-sodalite microcline-aegirine vein in urtite, Mt. Koashva.

of large spherulites of black, coarsely-crystalline aegirine. Small brilliant cube-octahedral crystals of cobaltite (up to 0.7 mm) are also found here.

Minerals: aegirine, arctite, belovite-(Ce), carbonate-fluorapatite, catapleiite, cobaltite, fluorapatite, fluorite, lamprophyllite, lemmleinite-K, lorenzenite, microcline, natrolite, pectolite, rhabdophane-(Ce), sazykinaite-(Y), shcherbakovite, sitinakite, sodalite, titanite.

Stop 2-4. Mt. Koashva

Sodalite-microcline-aegirine vein in the contact zone of urtite and fine-grained nepheline syenite, *(Near the vechicle)*. A stockwork of what are essentially aegirine veinlets envelopes lens-shaped segments of nepheline syenite and forms two large swellings (2×4 m, Fig. 19). Three zones can be distinguished within the swellings.

1. The margins of the swellings (as well as thin veinlets) are composed of compact, dark green, radiating aggregates of aegirine with inclusions of white tabular microcline (up to 10 cm diameter), brown crystals of altered eudialyte (up to 1 cm), black elongate-prismatic aegirine (up to 12 cm long, 0.5 cm diameter), bladed crystals of lamprophyllite (up to 7 cm long) and large segregations (up to 4 cm diameter) of pink fenaksite plates.

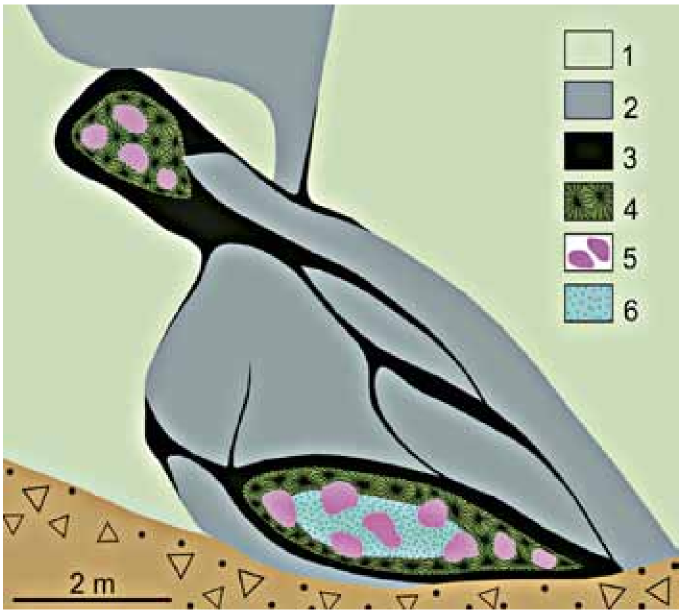

Fig. 19. Sodalite-microcline-aegirine vein in the contact zone of urtite and fine-grained nepheline syenite, Mt. Koashva (Stop 2-4): 1 – urtite; 2 – fine-grained nepheline syenite; 3 – eudialyte-microcline-aegirine rock; 4 – radiating aegirine; 5 – sodalite; 6 – felt-like bluish-green aegirine.

Fig. 20. Shcherbakovite crystal (3 cm long) from sodalite-microcline-aegirine vein within the contact zone of urtite and fine-grained nepheline syenite, Mt. Koashva.

2. The main volume of the swellings is composed of 5-10 cm light green spherulites of thin-fibrous aegirine, between which, and less often, inside of which, there are rhombic dodecahedral crystals (up to 3 cm diameter) and irregular-shaped segregations (up to 20 cm diameter) of bright pink sodalite with inclusions of altered pectolite spherulites (up to 5 cm), aggregates of 1-6 cm coffee-brown prismatic shcherbakovite (Fig. 20), and bronze-brown flattened-prismatic lamprophyllite (up to 4 cm long). Amongst the black altered pectolite, there are numerous light pink lamellae of fenaksite (up to 1 cm).

3. The internal part of the lower swelling is composed of extremely soft, felt-like, blue-green aegirine, containing heterogeneously distributed segregations of friable, fine-lamellar lamprophyllite and scarce sodalite-pectolite nodules with inclusions of shcherbakovite and lamprophyllite.

Minerals: aegirine, eudialyte, fenaksite, lamprophyllite, microcline, pectolite, shcherbakovite, sodalite.

DAY 3: THE KHIBINA MASSIF. VISIT TO THE NIORKPAHK OPEN PIT

(8 hours, 50 km from Apatity town).

Stop 3-1. Mt. Niorkpakhk

Brecciated apatite ores of the Niorkpakhk deposit *(Near the vechicle)*. Apatite-rich rocks at Mts Niorkpakhk and Suoluaiv were found by P.I. Prokofiev in 1932. For a long time the deposit was not considered to be of any industrial interest because most of the rocks were brecciated. However, in 1972 work was started on the deposit under the management of E.A. Kamenev and mining started at the Niorkpakhk Deposit in 1981 (Fig. 21).

Fig. 21. Open cast mines, the Niorkpakhk (at the front) and Koashva (in the background) deposits.

The ore zone of the deposit is spatially related to a layer of trachytoid ijolite, and consists of four horizons of separate lens-shaped bodies, ranging from several metres to 2 km long and 0.5 to 130 m thick. As a whole, the zone, 280-350 m thick, dips to the north-west at an angle of 10-25°. Within the deposit, brecciated ore rocks are dominant. The breccia is made of fragments of apatite-nepheline rocks and massive urtite enriched by apatite. The size of the ore xenoliths ranges from 3 cm up to several tens of metres. The distribution of xenoliths is heterogeneous.

Brecciated apatite-nepheline ore consists of fragments of banded apatite-nepheline rock cemented by foidolite ore pegmatite (Fig. 22). The fragment sizes are distributed as power law with coefficient -0.6. It means that the breccia is a fractal, organized like broken sea ice. Probably, its origin is caused by non-linear (explosion-like) fragmentation of ore-bodies near the surface.

Fig. 22. Stop 3-1. Brecciated apatite ores, Mt. Niorkpakhk.

Stop 3-2. Mt. Niorkpakhk

Dumps of the open pit: pegmatite and hydrothermal veins of the ore complex *(Near the vechicle)*. In the dumps, there are numerous fragments of pegmatite and hydrothermal veins within the dumps. Aegirine-pectolite-

Fig. 23. Eudialyte crystals (up to 2.5 cm diameter) in pectolite, from an aegirine-microcline vein in rischorrite, dumps of the Niorkpakhk deposit.

microcline pegmatites are most common. They often include giant crystals of rare minerals: lamprophyllite (radiated aggregates up to 20 cm diameter), fenaksite (tabular crystals up to 10 см diameter), eudialyte (crystals up to 15 cm diameter, Fig. 23), delhayelite (crystals up to 10 cm long), grains of beta-lomonosovite (up to 4 cm diameter) etc. The monomineral aggregates of dark-crimson eudialyte (up to 80 cm diameter) and monomineral veinlets of brioght yellow cancrinite are especially attractive for mineral amateurs.

Stop 3-3. Mt. Niorkpakhk

Stockwork of natrolite-albite and natrolite-pectolite-sodalite veins in urtite, Mt. Niorkpakhk *(Near the vechicle)*. A good example of one of these natrolite-pectolite-sodalite veins is provided by a 1 to 5 cm-wide veinlet that contains fersmanite and has a clear symmetrical zonation (Fig. 24).

1. The selvages comprise druses of slender acicular crystals of brown altered pectolite and black aegirine (up to 1 cm long) with scarce thick, tabular crystals of semi-transparent yellowish brown fersmanite (up to 1.2 cm diameter) and brownish black elongate, prismatic annite (up to 4 cm long).

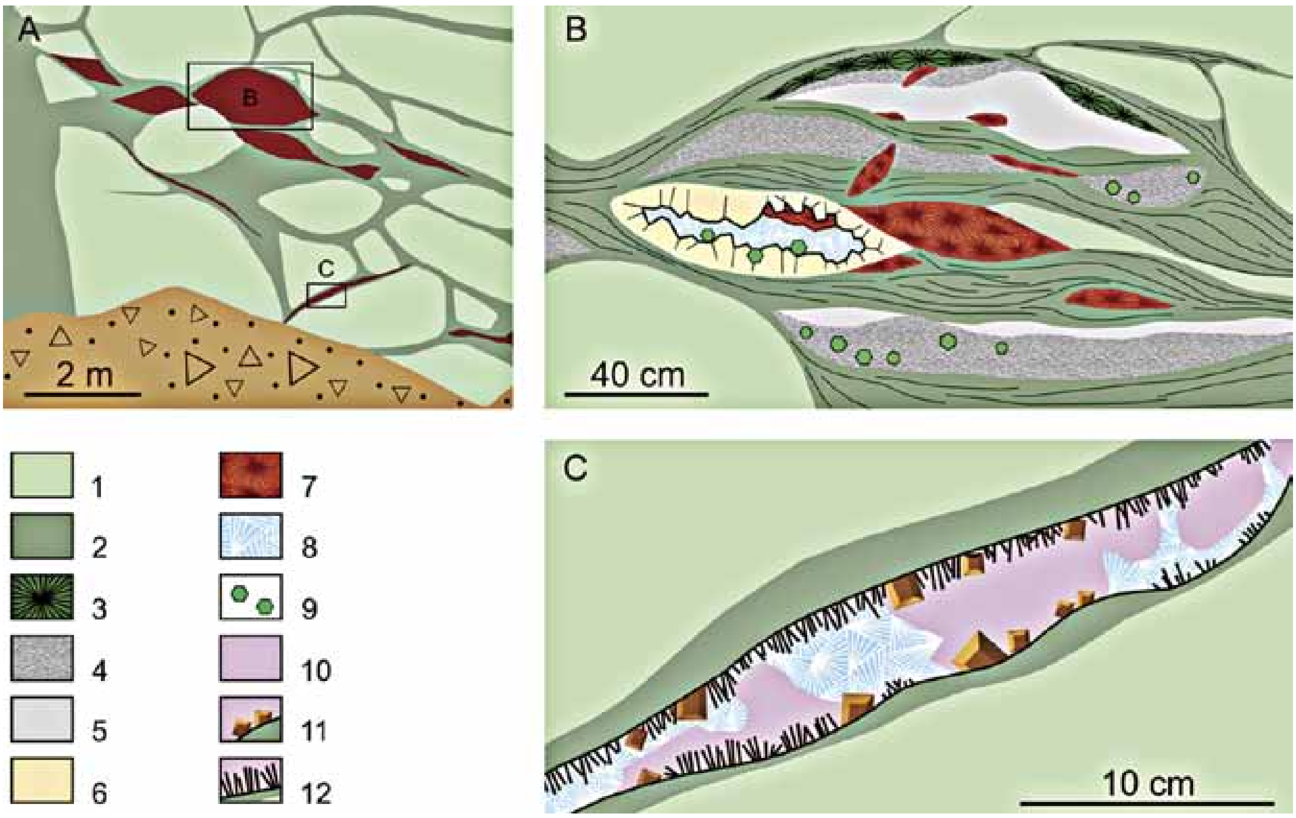

Fig. 24. Stockwork of natrolite-albite and natrolite-pectolite-sodalite veins, Mt. Niorkpakhk (Stop 3-3): 1 – massive urtite, 2 – layered phlogopitised urtite, 3 – radiating aegirine, 4 – coarse-grained albite, 5 – fine-grained albite, 6 – microcline; 7 – lemmleinite-K-Ba–labuntsovite-Mn, 8 – natrolite, 9 – fluorapatite, 10 – sodalite, 11 – fersmanite, 12 – pectolite.

2. The central part of the veinlet is filled by a columnar or fine-grained aggregate of semi-transparent white natrolite with relics of bright pink sodalite (that grey quickly under light).

An example of a natrolite-albite vein is provided by a lemmleinite and fluorapatite-bearing vein with a strike of about 3 m, and a width of about 1 m. The top contact with massive urtite is marked by a 5-20 cm rim of black radiating aegirine. The core of the vein is composed of several lenses of porous aggregates of albite, separated by 10-30 cm layers of foliated and phlogopitised urtite. Brownish-green sphalerite grains (up to 5 mm), small elongate-prismatic lorenzenite (up to 2-3 mm) and pale yellow spherulites of titanite (up to 2 mm diameter) are embedded in a mass of white compact albite. Spherulites of orange lemmleinite-K–lemmleinite-Ba–labuntsovite-Mn (Fig. 25) grow on cavity walls encrusted by wedge-shaped albite. In the axial part of the vein there is a large cluster (0.3×1 m) of reddish-orange radiating aggregates of lemmleinite-K (each up to 10 cm diameter), and also a lens of microcline-natrolite-albite composition, where, within a mass of semi-transparent compact natrolite, there are sheaf-like aggregates of lemmleinite-K (up to 5 cm long), galena cubes (up to 5 mm), aggregates of lilac sodalite (up to 10 cm) and yellowish-green sphalerite (up to 2 cm). Sphalerite is quite frequently heavily altered, resorbed by goethite and penetrated by a dense network of slender stringers of white hemimorphite.

Fig. 25. Radiating aggregates of lemmleinite-K from natrolite-albite vein in urtite, Mt. Niorkpakhk. Field of view 16×14 cm.

Small (up to 2 mm) cubic crystals of pyrite, replaced by goethite, are found on druses of tabular albite encrusting the walls of voids filled by natrolite. Near the lower contact there is a zone of cavernous albititite, where the walls of cavities are encrusted by apple-green elongate-prismatic or tabular fluorapatite, up to 1.5 cm diameter, and by spherulites or separate elongate-prismatic crystals of orange, yellow or colourless lemmleinite-K.

Minerals: aegirine, albite, annite, fersmanite, fluorapatite, galena, goethite, hemimorphite, lemmleinite-K, lorenzenite, microcline, natrolite, pectolite, sodalite, sphalerite, titanite.

Stop 3-4. Mt. Niorkpakhk

The eudialyte deposit (*Near the vechicle*). The eudialyte deposit is related to the north-southern zone of foyaite eudialytization that contains numerous eudialyte-sodalite-aegirine veins (Fig. 26). The veins have strikes of 50 to 250 m and widths between 1 and 20 m. In the main mass of foyaite, veinlets can be so rich in eudialyte that they form 0.5-1.0 m lenses of almost monomineralic eudialytite. Foyaite adjacent to such veinlets is aegirinised, so that short-prismatic eudialyte crystals are frequently included in compact aggregates of elongate-prismatic, black aegirine. The eudialyte crystals are zoned, with a yellowish-brown core and pink marginal rim.

Lenses (up to 5 cm long and 1 cm wide) of fine-grained bronze-brown lorenzenite are sometimes associated with these eudialyte localities. Crimson eudialyte-Mn crystals (up to 4 cm diameter, Fig. 27) and black acicular aegirine fill interstices in aggregates of large (up to 10 cm) brownish-white, semi-transparent, tabular crystals of microcline within albitised microcline-sodalite-aegirine veins. There are also impregnations of smaller brilliant eudialyte-Mn crystals (up to 1 cm) in compact white albite. In addition to these minerals there are also bronze-yellow lamprophyllite segregations up to 4 cm diameter, black columnar arfvedsonite (up to 6 cm long and 1 cm diameter) and small black twinned crystals (up to 0.5 mm) of loparite-(Ce), embedded in masses of green aegirine or grown on the faces of microcline crystals. Such veins frequently contain zones of aegirinization, to which large dark-crimson semi-transparent rhombohedral eudialyte-Mn crystals (up to 7 cm) are related. These are enveloped by stream-like aggregates of acicular green aegirine, as well as large brilliant dark brown prismatic crystals of lorenzenite (up to 2 cm long). Occasionallythere are voids (up to 5 cm diameter) with pink eudialyte-Mn crystals covered by a rind (up to 5 mm wide) of parallel-columnar or compact white natrolite.

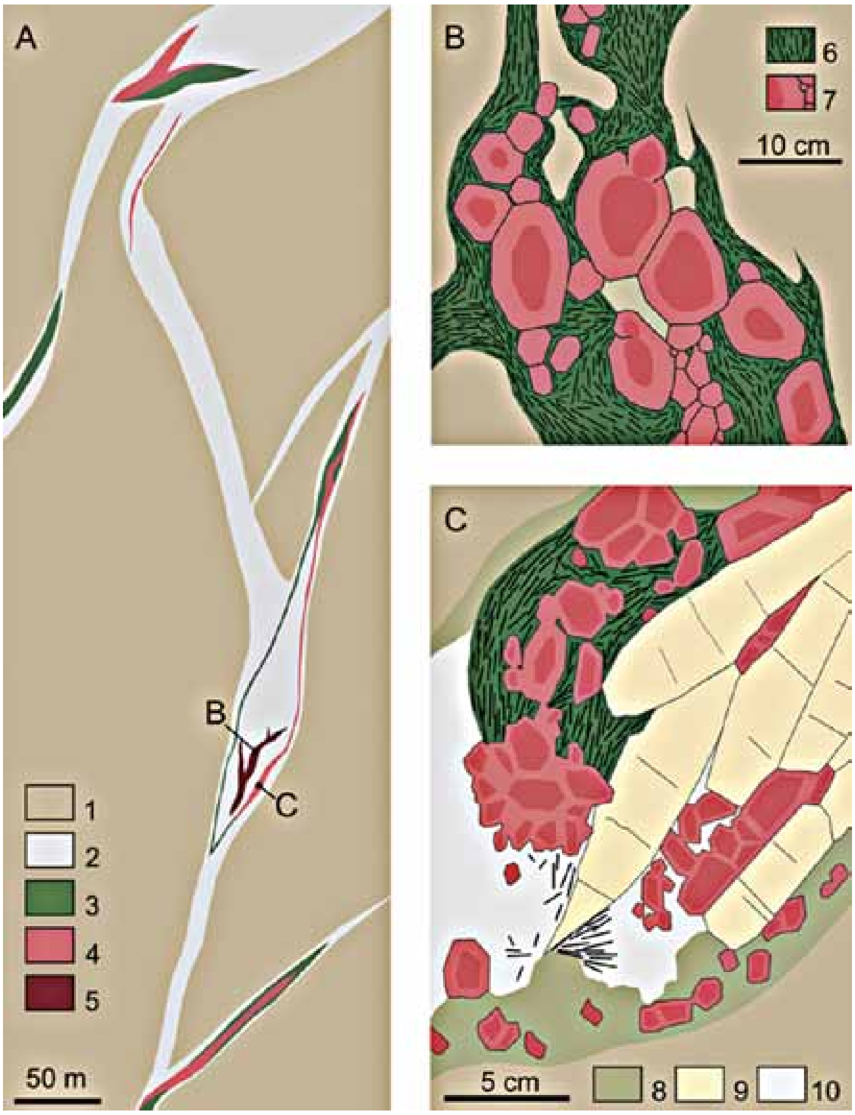

Fig. 26. Stockwork of veins, locality no. 2 within foyaite, Mt. Niorkpakhk (after Yu. O. Lipovsky): 1 – foyaite, 2 – albitised foyaite with an impregnation of eudialyte-Mn, 3 – aegirine-microcline and sodalite-aegirine-microcline veins, 4 – aegirine-eudialyte veins, 5 – eudialytite-Mn (30-80 vol. % eudialyte), 6 – aegirine, 7 – eudialyte, 8 – nepheline, 9 – microcline, 10 – albite.

Fig. 27. Crystals of lorenzenite (up to 2.5 cm long) and eudialyte (up to 1 cm diameter) from eudialyte deposit at Mt. Niorkpakhk.

Minerals: aegirine, albite, arfvedsonite, eudialyte, lamprophyllite, loparite-(Ce), lorenzenite, microcline, natrolite, nepheline, sodalite.

DAY 4: THE KHIBINA MASSIF. PEGMATITES AND HYDROTHERMALITES WITHIN IJOLITE, RISCHORRITE AND FOYAITE AT MT. EVESLOGCHORR

(Length 4 km, elevation 400 m).

Stop 4-1. Mt. Eveslogchorr

Nepheline-aegirine-microcline vein in rischorrite *(Near the vechicle, Fig. 28*). The 0.9-1.4 m-wide vein with the symmetrically zoned structure.

Fig. 28. Mt. Eveslogchorr. It is shown positions of the numbered mineral localities (Stops 4-1 – 4-5).

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

Fig. 29. Stop 4-1: type locality of fersmanite.

fersmanite (0.5-6 cm diameter, Fig. 29) and equant grains of fluorapatite, up to 1 cm diameter.

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

Stop 4-2. Mt. Eveslogchorr

Natrolite-albite-aegirine-microcline vein in gneissose foyaite, *(about 1 km from the vechicle, elevation 150 m)***.** A 2 m-wide vein with a concentric-zoned structure composed of eight zones.

1. The selvages are about 20 cm wide and composed of an aggregate of dark green acicular aegirine with an impregnation of crimson eudialyte (up to 2 cm diameter). Slickensides are observed along the contact with foyaite (Fig. 30).
2. A microcline-eudialyte-aegirine zone (up to 15 cm) is formed by green radiating aggregates of aegirine with interstitial microcline and eudia-

lyte. Numerous voids are encrusted by short-prismatic natrolite. Nodules, up to 3 cm diameter, of snow-white porcelaneous epididymite are also found.

3. A microcline-eudialyte-natrolite zone (up to 15 cm) contains clusters of white porcelaneous epididymite (up to 5 cm diameter).

4. A catapleiite-microcline zone (up to 30 cm) has lens-shaped segregations of black thin-prismatic aegirine. Catapleiite occurs as beige, fine-grained aggregates, pseudomorphous after eudialyte (up to 3 cm) and heterogeneously distributed within the zone. Aegirine also occurrs as light green spherulites in the interstices in an aggregate of light grey tabular microcline (up to 3 cm). In voids close to the borders of segregations of black aegirine, there are white flattened-prismatic crystals and radiating intergrowths of vuorijarvite-K.

5. A microcline zone (up to 50 cm) is composed of coarse-grained microcline (up to 30 cm diameter). Microcline within voids occurrs as regular prismatic crystals up to 10 cm long and 5 cm diameter.

6. An albite zone (up to 15 cm) is composed of water-transparent tabular albite (up to 3 cm diameter and 3 mm wide) with interstitial pale pink fine-grained albite. The walls of numerous voids are also encrusted by wedge-shaped albite, on which there are snow-white crystals of analcime (up to 3 cm diameter), black altered pectolite (up to 7 cm long and 2 × 0.3 cm diameter), and white prismatic crystals and sheaf-like aggregates of leifite (up to 8 mm long).

Fig. 30. Fersmanite crystal (2.2 cm edge-length) from nepheline-aegirine-microcline vein in rischorrite, Mt. Eveslogchorr.

Fig. 31. Leifite spherulites (up to 6 mm diameter) in pink albite from natrolite-albite-aegirine-microcline vein in gneissose foyait Mt. Eveslogchorr.

7. A natrolite-albite lens (15×50 cm) consists of a fine-grained aggregate of albite with clusters (up to 6 cm) of natrolite. Voids contain colourless regular natrolite crystals. Leifite occurs in voids within albite, frequently at the contact with natrolite, forming 5 mm diameter, radiating aggregates of acicular crystals (Fig. 31). The main mass of albite also contains separate dark-green aegirine crystals (up to 4 cm long) and pale cream vuorijarvite-K crystals (up to 2 cm long).

8. A cavernous natrolite-microcline lens (0.5×1 m) is composed of large blocks of feldspar with interstices encrusted by natrolite. Most of the other minerals in the vein occur within the masses of natrolite. Black flattened-prismatic crystals of aegirine (up to 4 cm long) are dispersed heterogeneously throughout. There are also light-green nodules of aegirine with a thin-fibrous structure, separate dark red mangan-neptunite crystals (up to 8 mm long) and their intergrowths (up to 2 cm diameter), and white porcelaneous nodules (up to 20 cm diameter) of epididymite. The epididymite nodules are composed of flattened-prismatic crystals (up to 2 mm long) and spherulites (up to 1.5 cm diameter). Rarely there are also pale-green prismatic belovite-(Ce) crystals (up to 2 mm long) and separate light-brown, thin crystals of astrophyllite. Near to aegirine clusters there are thin-prismatic lorenzenite crystals and in voids within natrolite there are yellow crystals of ancylite-(Ce), shaped like envelopes, and yellowish-brown kidney-shaped aggregates (up to 4 mm) of thorite.

Minerals: aegirine, albite, analcime, ancylite-(Ce), astrophyllite, belovite-(Ce), catapleiite, epididymite, eudialyte, leifite, lorenzenite, mangan-neptunite, microcline, natrolite, pectolite, thorite, vinogradovite, vuorijarvite-K.

Stop 4-3. Mt. Eveslogchorr

Xenolith of aluminous hornfels in foyaite, *(about 2 km from the vec hicle, elevation 200 m)***.** It is a small xenolith (20×9 m, Fig. 32) composed of fine-grained massive heterogeneous hornfels, containing the following mineral assemblages: corundum-muscovite-albite-sillimanite-andalusite-quartz, muscovite-albite-sillimanite-andalusite-quartz, albite-andalusite-sillimanite-quartz, albite-sillimanite-andalusite-quartz, andalusite-albite-sillimanite-quartz, albite-sillimanite-quartz, muscovite-topaz-albite-sillimanite-quartz, andalusite-muscovite-sillimanite-albite -quartz, topaz-muscovite-albite-quartz, sillimanite-andalusite-albite-quartz, albite-quartz, muscovite-andalusite-sillimanite-quartz-albite, corundum-orthoclase-muscovite-quartz-albite, muscovite-quartz-albite,

Fig. 32. Stop 4-3: xenolith of aluminous hornfels in foyaite, Mt. Eveslogchorr.

Fig. 33. Corundum crystals (up to 1 cm) in nepheline.

orthoclase-muscovite-corundum-quartz-albite, hercynite-muscovite-albite, quartz-hercynite-corundum-muscovite-albite, topaz-quartz-muscovite-andalusite-sillimanite-albite, sillimanite-corundum-albite, corundum-albite, quartz-muscovite-andalusite-albite-sillimanite, albite-andalusite-quartz-topaz-sillimanite, andalusite-albite-sillimanite and corundum-muscovite-quartz-albite-orthoclase. Besides these minerals, pyrrhotite, pyrite, marcasite, zircon, monazite-(Ce) and rutile are always present. Pegmatoid orthoclase-anorthoclase veinlets with dark blue corundum (up to 3 cm diameter, Fig. 33), colourless to brown iron-stained topaz (coarse-grained segregations up to 4 cm diameter), colourless thin-fibrous sillimanite, pink andalusite (grains up to 1 mm diameter), black and dark green hercynite (crystals up to 8 mm diameter), monazite-(Ce) and rutile (crystals less than 1 mm long) are also widespread. The hornfels xenolith is surrounded by a 6 m-wide rim of fine-grained troilite-bearing nepheline syenite.

Minerals: aegirine, albite, andalusite, anorthoclase, arfvedsonite, corundum, hercynite, marcasite, monazite-(Ce), muscovite, nepheline, orthoclase, pyrite, pyrrhotite, quartz, rutile, sillimanite, topaz, troilite, zircon.

Stop 4-4. Mt. Eveslogchorr

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. 34), 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

Fig. 34. Astrophyllite «stars» (10 cm diameter) from the Astrophyllite deposit at Mt. Eveslogchorr.

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.

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

Stop 4-5. Mt. Eveslogchorr

Eudialyte-nepheline-aegirine-microcline vein in gneissose rischorrite *(about 1 km from the vechicle, elevation 350 m)*. The width of the vein is about 80 cm, the strike is more than 20 m and the vein has a symmetrically zoned structure (Fig. 35).

Fig. 35. Stop 4-5: eudialyte-nepheline-aegirine-microcline vein in gneissose rischorrite, Mt. Eveslogchorr.

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.

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 pseudomorphous 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 cm 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),

Fig. 36. Wadeite crystal (1.5 cm long) on microcline from eudialyte-nepheline-aegirine-microcline vein within rischorrite, Mt. Eveslogchorr.

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. 36) grown on microcline or, less commonly, embedded in the natrolite groundmass.

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

DAY 5: THE KHIBINA MASSIF. PEGMATITES AND HYDROTHERMALITES WITHIN RISCHORRITE AT THE MARCHENKO PEAK

Apatite-titanite veinlets in rischorrite. Veins with ilmenite, zircon, lorenzenite, eudialyte, sodalite, ancylite-(La) etc. Length 1 km, elevation 400 m. (Fig. 37).

Fig. 37. Marchenko Peak. It is shown positions of mineral localities (Stops 5-1 – 5-5).

Stop 5-1 A. The Marchenko Peak

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. 38), 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

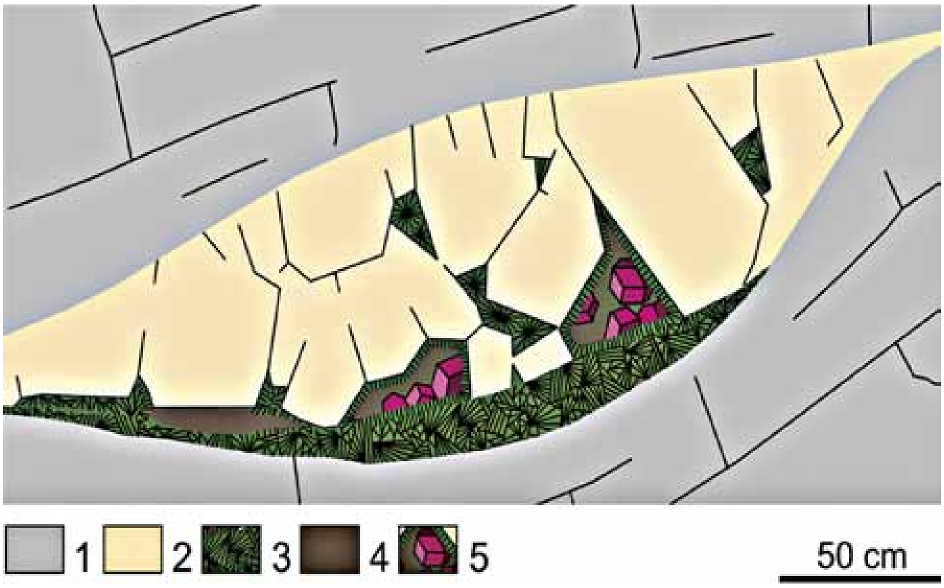

Fig. 38. Stop 5-1A: sodalite-aegirine-microcline vein no. 57 in rischorrite, Marchenko¬ Peak: 1 – rischorrite, 2 – microcline, 3 – aegirine, 4 – friable aegirine-phlogopite aggregate, 5 – sodalite.

(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

Fig. 39. Sodalite crystals (up to 6 cm diameter) from sodalite-aegirine-microcline vein in rischorrite, Marchenko Peak.

Fig. 40. Rosette of split ilmenite crystals (1 cm diameter) from aegirine-microcline vein in rischorrite, Marchenko Peak.

which there are separate crystals and aggregates of sodalite (Fig. 39). 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.

Stop 5-1 B. The Marchenko Peak

Aegirine-microcline vein in rischorrite, *(about 500 m from the vechicle, 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. 40), 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).

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

Stop 5-2. The Marchenko Peak

Microcline vein in rischorrite *(about 700 m from the vechicle, elevation 200 m)***.** A large vein up to 1 m wide and 20 m along strike, with a symmetric-zoned structure (Fig. 41).

Fig. 41. Stop 5-2: microcline vein in rischorrite, the Marchenko Peak.

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. 42. Zircon crystal (3 cm edge-length) from microcline vein in rischorrite, the Marchenko Peak.

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. 42). 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 meters 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.

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

Stop 5-3. The Marchenko Peak

Microcline-aegirine-natrolite vein in rischorrite *(about 700 m from the vechicle, elevation 350 m)***.** A vein with three large swellings (1-1.5 m wide, Fig. 43). Each swelling has a similar structure but their zones vary in size.

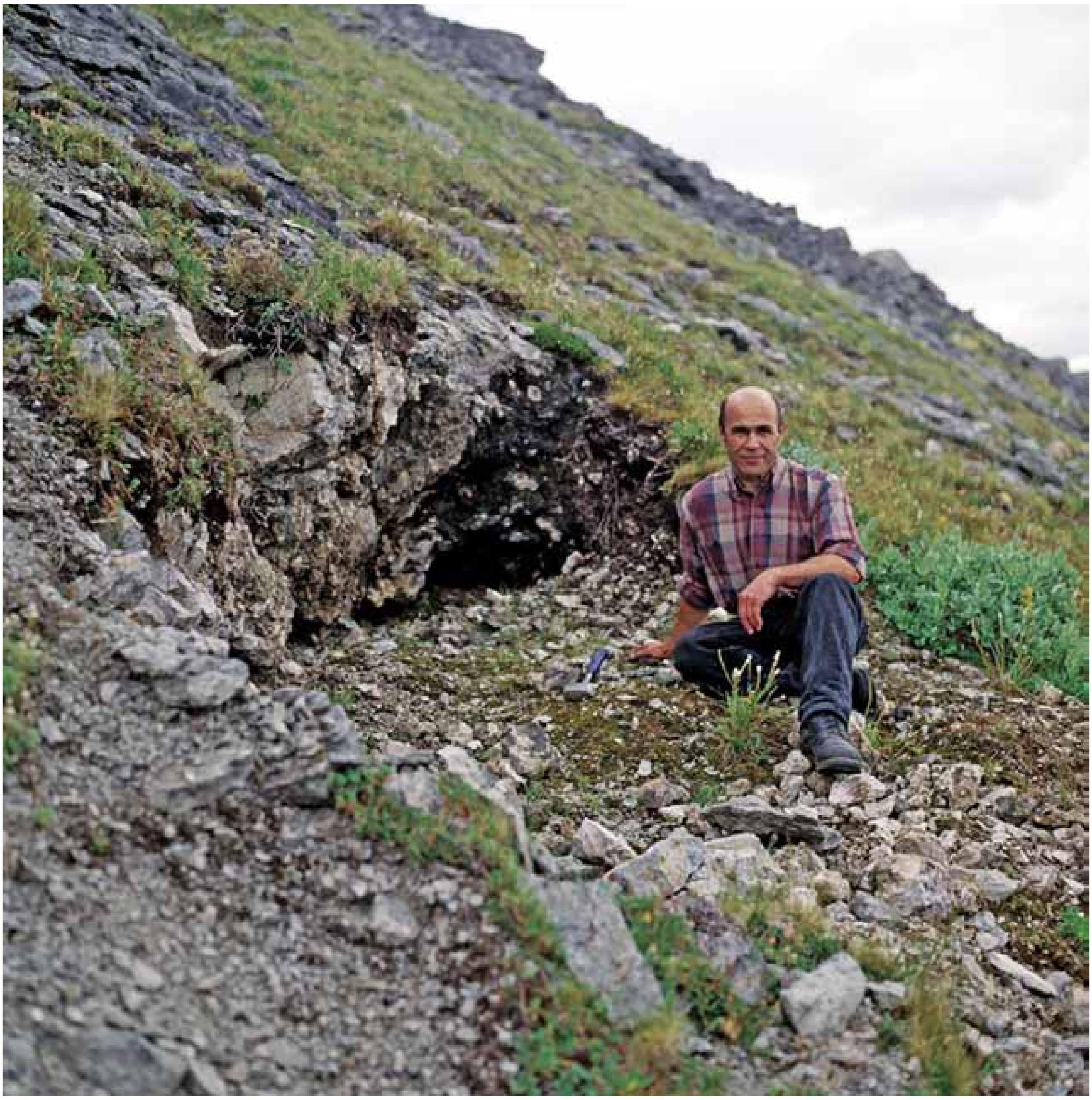

Fig. 43. Stop 5-3: microcline-aegirine-natrolite vein in rischorrite, the Marchenko Peak.

Fig. 44. lmenite crystal (1.5 cm edge-length) from microcline-aegirine-natrolite vein in rischorrite, the Marchenko Peak.

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. 44) 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).

3. The core is difficult to 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), ilmenite, microcline, natrolite, phlogopite, zircon.

Stop 5-4. The Marchenko Peak

Aegirine-nepheline-natrolite-microcline vein in rischorrite *(about 700 m from the vechicle, elevation 400 m)*.

This vein was described in detail by L. V. Kozyreva and Yu. P. Men'shikov (1974). 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. 45. Aggregate (3 cm diameter) of ancylite-(La) crystals in natrolite from aegirine-microcline vein in rischorrite, Marchenko Peak.

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. 45) 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 5-5. The Marchenko Peak

Apatite-titanite veinlets in rischorrite *(about 700 m from the vechicle, 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.

DAY 6: THE KHIBINA MASSIF. PHONOLITE DYKES, ALKALINE PEGMATITES AND ALBITITES OF MT. TAKHTARVUMCHORR

(Fig. 46). Length 2 km, elevation 100 m.

Stop 6-1. Mt. Takhtarvumchorr

Phonolite dykes in foyaite of Mt. Takhtarvumchorr (about 500 m from the vechicle, elevation 100 m).

There are a lot of vertical phonolite dykes (up to 1 m thick) at the slopes of this mountain (Fig. 47). Phonolite is a fine-grained green rock consisting of euhedral crystals of nepheline, thin-bladed orthoclase,

Fig. 46. Mt. Takhtarvumchorr. It shows positions of the numbered mineral localities.

Fig. 47. Stop 6-1: phonolite dyke in foyaite, Mt. Takhtarvumchorr.

entangled-fibrous and radiating aegirine, lamellae of phlogopite and grains of sodalite, analcime, natrolite, cancrinite and fluorite. Tinguaite is also

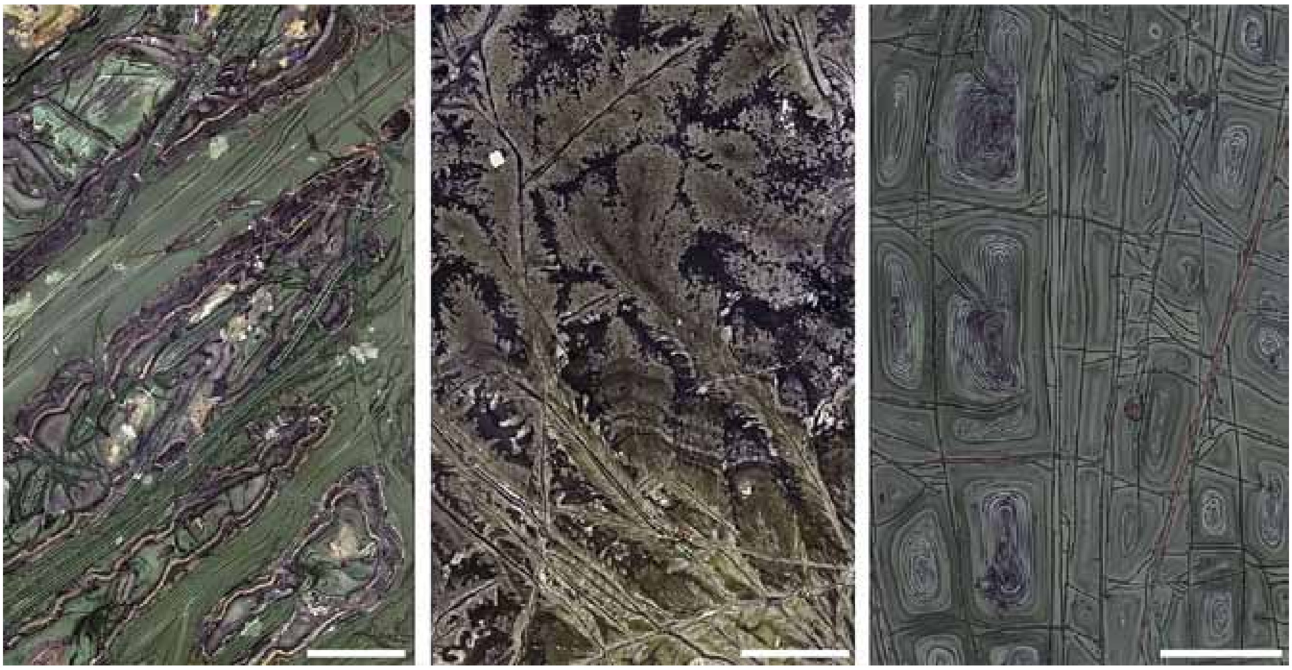

Fig. 48. Patterned phonolites, Mt. Takhtarvumchorr. The scale is 2 cm long.

found in the axial zones of the largest phonolite dykes and is distinguished from other varieties of phonolite by its microstructure, in which there are large impregnations of nepheline and orthoclase into the trachytic structure of the main orthoclase-aegirine-nepheline mass. The marginal parts of the phonolite dykes frequently display an unusual cellular-zoned, rhythmically-banded, dendrite-like, breccia or «ruin» texture (Fig. 48), imparting a rather attractive appearance. Abundant bladed crystals of troilite are located in the central parts of cells.

Minerals: aegirine, analcime, cancrinite, fluorite, natrolite, nepheline, orthoclase, phlogopite, sodalite, troilite.

Stop 6-2. Mt. Takhtarvumchorr

Albitites, Mt. Takhtarvumchorr. Albitites are widespread on the eastern slope of Mt. Takhtarvumchorr, forming a stockwork of veins from 0.1 up to 4 m wide, between which the foyaite is variably albitised. Albitites are usually easy to distinguish because of their rusty-brown colouring caused by the widespread development of goethite after pyrrhotite. Contacts with the host rocks are usually indistinct; in places, the eudialyte content increases appreciably in foyaite up to 30 cm from the albite veins. The veins are composed of compact, fine-grained albite with relics of altered light-brown eudialyte (up to 1 cm diameter), microcline laths up to 3 cm long and nodules and stream-like aggregates of black fine-crystalline aegirine. Sometimes albitization has developed within separate parts of the aenigmatite-eudialyte-aegirine-microcline veins widespread in this area. Lens-shaped clusters (up

Fig. 49. Molybdenite rosettes (up to 2.5 mm) in an apatite-albite rock, Mt. Takhtarvumchorr.

Fig. 50. Radiating intergrowths of graphite-(2H) and aegirine from aegirine-albite vein in foyaite, Mt. Takhtarvumchorr. (7×10 cm).

to 50 cm wide and up to 1 m diameter) of light green sugar-like fluorapatite and molybdenite (Fig. 49) are found in the axial zones of these veins. Molybdenite occurrs as groups (up to 2 cm diameter) and spherulites (up to 5 mm diameter) of lamellar crystals within the groundmass of albite and fluorapatite and can reach proportions as high as 20 vol. %. Bladed ilmenite crystals (up to 7 mm diameter) occur in association with the molybdenite. Titanite is widespread as lemon-yellow prismatic crystals (up to1.5 cm long) and spherulites of thin-acicular crystals (up to 4 cm diameter, Fig. 50). Graphite is characteristic of the aegirine-rich parts of the veins. It forms parallel-fibrous (areas up to 100 cm^2) or radiating (up to 5 cm diameter) aggregates when intergrown with aegirine, and occurrs together with molybdenite impregnating albite and fluorapatite. In some of the albite veins there is an abundant impregnation of semi-transparent brown, prismatic zircon (up to 6 mm) surrounded by a 1-3 mm fringe of snow-white parakeldyshite (TL), keldyshite, sodalite and cancrinite. Parakeldyshite and keldyshite also often develop after eudialyte. Reddish-orange prismatic levenite (up to 3 mm long) is common. Bladed grains of pyrrhotite, up to 1 cm, are always, to a greater or lesser degree, replaced by pyrite, marcasite and goethite. Grains of galena (up to 5 mm) and black sphalerite (up to 1 cm) are also found.

Minerals: aegirine, aegirine-augite, aenigmatite, albite, astrophyllite, cancrinite, eudialyte, fluorapatite, galena, goethite, graphite, ilmenite, keldyshite, låvenite, marcasite, microcline, molybdenite, parakeldyshite, pyrite, pyrrhotite, sodalite, sphalerite, titanite, zircon.

Stop 6-3. Mt. Takhtarvumchorr (Fig. 51, 52, 53)

Microcline-aegirine vein in foyaite, Mt. Takhtarvumchorr. The vein is up to 1.5 m wide with a symmetric-zoned structure.

1. The selvages (30-50 cm wide) are composed of large, greenish-grey, equant microcline crystals (up to 20 cm diameter) with radiating aegirine and brown-red crystals of eudialyte (up to 1 cm) in the microcline interstices.

The axial zone is up to 80 cm wide and composed of about 70 vol. % large greenish-black spherulites of thin-fibrous aegirine (up to 15 cm diameter) plus about 10 vol. % large, resinous-black, short-prismatic aenigmatite (up to 10 cm diameter) with a 1-5 mm astrophyllite corona and (about 15 vol.%) red rhombohedral eudialyte, elongate along the three-fold axis and up to 7 cm long and 4 cm diameter. There are also bronze-brown, «square» (up to 4×5 cm) laths of lamprophyllite, radiating aggregates of straw-yellow, elongate-prismatic rinkite (up to 3 cm long), nodules of natrolitised nepheline (up to 5 cm diameter) with water-transparent tabular gibbsite (up to 8 mm, Fig. 51) in voids, blood-red aggregates of fine-grained hematite (rinds, veinlets up to 3 mm wide in radiating aegirine), grains of galena (up to 1 cm diameter) and dark brown sphalerite (up to 3 mm). Within the eudialyte grains there are scarce, small (up to 1 mm), cube-octahedral crystals of loparite-(Ce). Chalcopyrite grains (1.5 cm diameter) surrounded by a wide rim of blueish-green brochantite are found in the thin-fibrous aegirine spherulites.

Fig. 51. Gibbsite crystals from microcline-aegirine vein no. 54 in foyaite, Mt. Takhtarvumchorr. Field of view 17×13 mm.

Fig. 52. Stop 8-1: loparite open-pit at Mt. Karnasurt.

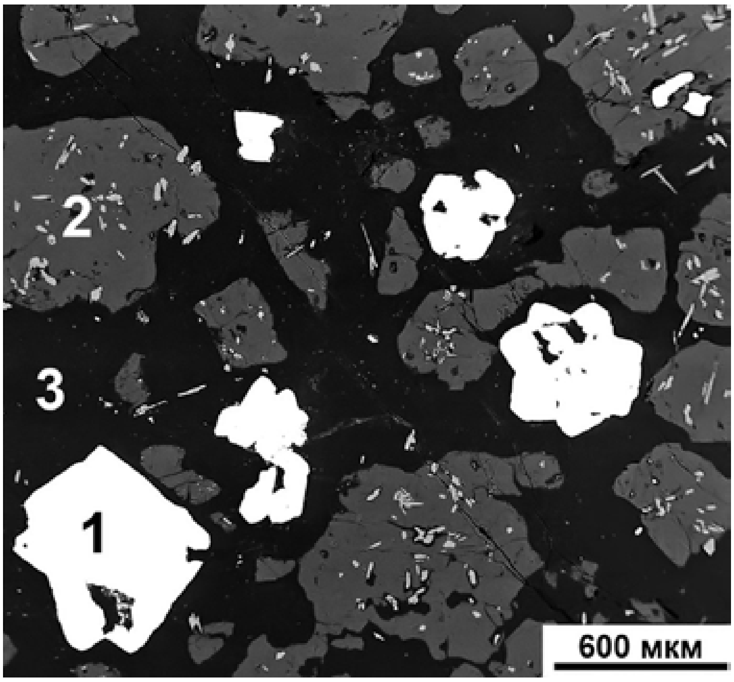

Fig. 53. Loparite-(Ce) (1) metacryst and relics of nepheline with aegirine inclusions (2) in natrolite (3), from malignite.

Minerals: aegirine, aenigmatite, albite, astrophyllite, brochantite, chalcopyrite, eudialyte, galena, gibbsite, hematite, lamprophyllite, loparite-(Ce), microcline, natrolite, rinkite, sodalite, sphalerite.

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