

Corundum-Group Minerals in Rocks of the Khibiny Alkaline Pluton, Kola Peninsula

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Abstract—Five minerals of the corundum group have been identified in the Khibiny pluton with certainty. Corundum proper and karelianite occur only in hornfels after volcanic and sedimentary rocks. Xenoliths of hornfels mark the ring faults that bound foidalite within the field of foyaite. Hematite occurs in hydrothermally altered nepheline syenite and crosscutting hydrothermal veins related to the ring faults. Minerals of the ilmenite–pyrophanite series are present in all rocks of the pluton, including veins. Accessory ilmenite in foyaite varies from the manganese variety and pyrophanite in the inner and outer parts of the pluton to manganese-free ilmenite in zone of the Main Ring Fault. In xenoliths of volcanic rocks and alkaline ultramafic rocks, ilmenite is enriched in magnesium. The zoning in distribution of the above-mentioned minerals and the character of variation in their compositions from margins of the pluton to its center are consistent with the petrochemical zoning formed as a result of foyaite alteration of near ring faults.

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INTRODUCTION

The corundum group comprises trigonal oxides with crystal structure formed by the hexagonal close packing of oxygen atoms, while two-thirds of octahedral interstices are occupied by trivalent cations (corundum subgroup, $R\bar{3}c$: corundum, hematite, karelianite, and eskolaite) or by combination of di- and tetravalent or uni- and pentavalent cations (ilmenite subgroup, $R\bar{3}$: ilmenite, pyrophanite, brizziite etc.).

Five minerals of the corundum group—corundum proper, hematite, karelianite, ilmenite, and pyrophanite—have been identified in the Khibiny pluton (Yakovenchuk et al., 2005). In addition, Shlyukova (1986) noted the presence of eskolaite as minute (up to 0.3 μm) oval inclusions in nepheline from corundum-bearing hybrid pegmatite hosted in hornfels at Mount Kukisvumchorr, but this finding requires further investigation. This paper presents the characteristics of all reliably identified minerals of the corundum group; the consideration is based on the original data. The minerals have been identified with EPMA and XRD. The chemical composition was determined on an MS-46 Cameca microprobe at the Geological Institute, Kola Scientific Center, Russian Academy of Sciences. The SE and BSE images were obtained on a LEO-1450 SEM.

GEOLOGICAL SETTING

The Khibiny alkaline pluton is located in the westernmost part of the Kola Peninsula at the contact of the

Archean granite gneisses of the Kola Block and the Proterozoic Imandra–Varzuga volcanic–sedimentary complex. Foyaite, the major rock of the pluton, occupies more than 70% of its volume (Fig. 1). The foyaite body is divided into two equal parts by the Main Ring Zone, 50–500 m wide in the north and 1500–2000 m wide in the south. The Main Ring Zone, composed of melteigite–urtite and apatite–nepheline rocks, is surrounded by 0.1–2-km-wide zones of nepheline syenite of the lavochorrite–rischorrite series, which grades into foyaite.

The Main Ring Zone is characterized by symmetrical zonal structure over most of its extent: foyaite $\rightarrow$ rischorite (lavochorrite) $\rightarrow$ foidolite $\rightarrow$ apatite–nepheline rock and then in reverse order. This zoning is underscored by an almost continuous ring of xenoliths of volcanic and sedimentary rocks of the Lovozero Formation transformed into hornfels and afterward fenitized at the rischorrite–foyaite boundary. The young dikes of alkaline and alkaline ultramafic rocks, volcanic pipes, pegmatite and hydrothermal veins are also related to the Main Ring (Arzamastsev et al., 1988; Ivanyuk et al., 2002). The Minor Semiring Zone (up to 500 m wide) of foidolites and hornfels after volcanic and sedimentary rocks is traced outward of the Main Ring Zone.

Ilmenite is a ubiquitous mineral of the corundum group, which occurs in hornfel xenoliths, fenite, nepheline syenite, foidolites, apatite and apatite–titanite ores, alkaline ultrabasic rocks, pegmatite, carbonatite, and hydrothermal veins, whereas pyrophanite as its manganese analogue is noted rarely in foyaite from

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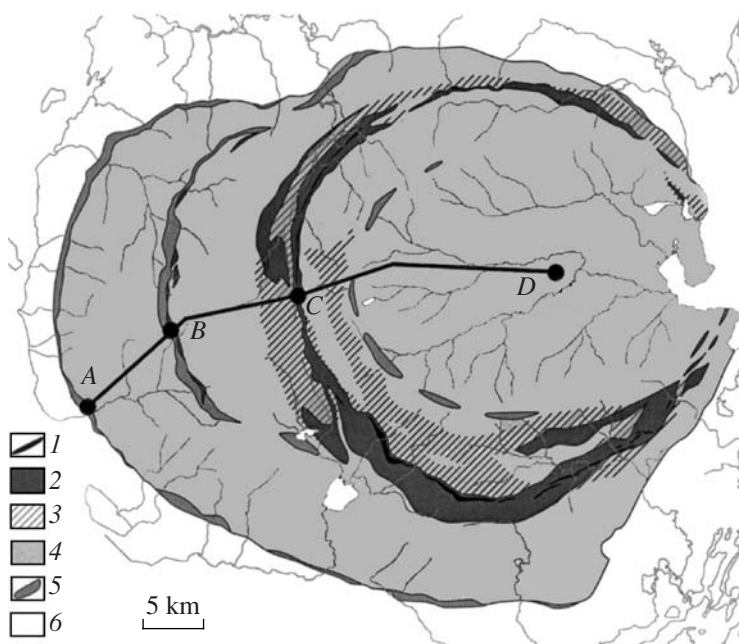


Fig. 1. Geological sketch map of the Khibiny pluton, simplified after O.L. Snyatkova and N.K. Mikhnyak. (1) apatite–nepheline rock, (2) melteigite–urtite, (3) rischorrite, (4) foyaite, (5) xenolith of hornfels after volcanic and sedimentary rocks, (6) Archaean and Proterozoic metamorphic complexes. A–B–C–D is the profile of sampling; 75 samples were taken at a distance 200–500 m from one another.

the marginal zone of the pluton and in some hydrothermal veins that cross rischorrite. Corundum and karelianite are known only from volcanic and sedimentary rocks of the Lovozero Formation that have transformed into hornfels, while hematite is a scarce mineral of hydrothermally altered nepheline syenite, pegmatite and hydrothermal veins, and carbonatites.

DESCRIPTION OF THE MINERALS

Corundum Al_2O_3 is characteristic of orthoclase–sillimanite–corundum, hercynite–orthoclase–corundum, corundum–orthoclase–albite–sillimanite, hercynite–phlogopite–corundum–orthoclase–albite, corundum–muscovite–albite–sillimanite–andalusite–quartz, corundum–orthoclase–muscovite–albite–quartz, quartz–hercynite–corundum–muscovite–albite, sillimanite–corundum–albite, and other hornfel varieties formed as a result of contact metamorphism of the volcanic and sedimentary rocks of the Lovozero Formation. The composition of corundum-bearing hornfels is determined by quantitative proportions of orthoclase (anorthoclase), albite, phlogopite–annite, hercynite, ilmenite, rutile, and pyrrhotite. Baddeleyite, tausonite, ankangite, vuorelainenite, karelianite, shrilankite, alabandite, chrysoberyl, boehmite, spessartine, muscovite, topaz, andalusite, sillimanite, zircon, zirconolite, stromolite, monazite-(Ce), xenotime, pyrite, sphalerite, loellingite, galena, and fluorite are accessory minerals. Finitization of the hornfels results in the formation of alkali pyroxenes and amphiboles, nepheline and sodalite–nosean replaced by

natrolite and analcite, apoilmenite titanite, renegeite, fluorapatite, and other minerals. Bluish gray to colorless platy grains (up to 1 mm in diameter and 0.1 mm thick) of corundum are uniformly scattered in the silicate matrix or grouped together into lenticular, striated, and banded aggregates.

Corundum occurs in a specific assemblage together with sodalite, hercynite, annite, chrysoberyl, and hochelagaite in nepheline–orthoclase and orthoclase veins that crosscut hornfels and are formed due to gradual variation in composition of alkaline pegmatites propagating into xenoliths. In the selvages of large veins and throughout thin veinlets, corundum composes aggregates of tabular crystals (up to 5 cm across and 1 cm thick) with the faces of dominant basal plane and hexagonal prism $\{11\bar{2}0\}$ and additional faces of rhombohedron $\{01\bar{1}2\}$ and hexagonal dipyrmaid $\{11\bar{2}3\}$ (Fig. 2). Corundum crystals are characterized by polysynthetic twins on (0001) and $\{01\bar{1}2\}$ and vary in color from dark blue and blue to bluish green, gray, pink, and colorless (Men'shikov, 1978). Crystals are usually nonuniformly colored, zonal, and sectorial; some fragments of such crystals are of gem quality.

In the process of hydrothermal alteration of the corundum-bearing rocks and veins, this mineral remains sufficiently stable, although in samples of fenitized hornfels from a xenolith in foyaite at Mount Eveslogchorr, corundum is replaced with sillimanite.

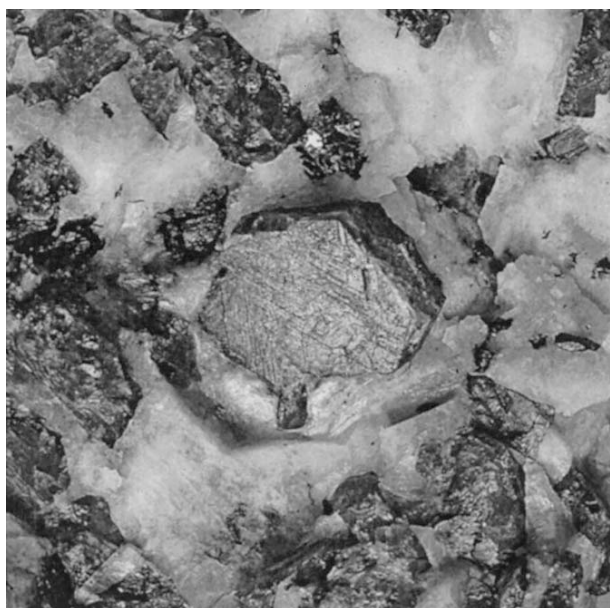


Fig. 2. Corundum crystals (up to 1 cm across) from corundum–orthoclase vein in hornfels, Mount Kukisvumchorr.

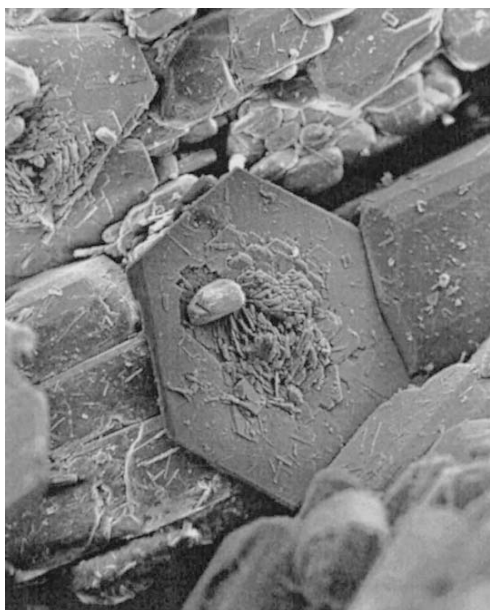


Fig. 3. Rosette of tabular hematite crystals (up to 0.15 mm across) in a vug of natrolite vein in rischorrite, Mount Rasvumchorr. SE image.

Hematite Fe_2O_3 is a rather rare mineral from different low-temperature hydrothermal rocks, both background and veined, that occur in nepheline syenite close to its contact with melteigite–urtite. In hydrothermally altered foyaite from Mount Yumjehchorr at a distance of 500 m from the contact with the foidolite–fenite unit of the Minor Arc, hematite occurs as subhedral tabular crystals (up to 0.5 mm across) and veins (up to

0.2 mm thick) of parallel-columnar structure in association with lamprophyllite, rosenbuschite, and minerals of the ilmenite–pyrophanite series. In apatite–calcite veins, in foidolites of mounts Yukspor and Rasvumchorr, the tabular hematite crystals make up fine-cellular aggregates (cells are up to 0.2 mm in size) in calcite (Kostyleva-Labuntsova et al., 1978). Intergrowths (up to 5 mm across) of tabular hematite crystals and its latticed pseudomorphs after magnetite have been detected in carbonate veins of the easternmost part of the pluton (Dudkin et al., 1984). Thin (up to 3 mm) monomineralic veinlets composed of parallel-columnar aggregate of dark red hematite variety occur in a microcline–aegirine vein that contains albite, sodalite, natrolite, astrophyllite, lamprophyllite, eudialyte, aenigmatite, rinkite, gibbsite, loparite-(Ce), galena, sphalerite, chalcopryite, and brochantite; the vein is hosted in foyaite at Mount Tahtarvumchorr (Yakovenchuk et al., 1999). Tabular hexagonal hematite crystals (up to 1.5 mm across) are associated with priderite–henrymeyerite crystals in vugs of a natrolite vein hosted in rischorrite at Mount Eveslogchorr, while discrete dark red compact spherulites (up to 1.5 mm in diameter) are nonuniformly distributed in the mass of columnar natrolite. Rosettes of split tabular hematite crystals up to 1 mm in diameter (Fig. 3) in association with aegirine, microcline, nepheline, annite, astrophyllite, lorenzenite, shcherbakovite, titanite, wadeite, leucophane, morimotoite, banalsite, cafetite, chabasite-Ca, chabasite-K, thomsonite-Ca, fluorapatite, fluorite, magnetite, rutile, pyrophanite, henrymeyerite, pyrochlore, chalcopryite, and pyrrhotite were observed in the natrolite vein that cuts rischorrite at Mount Rasvumchorr (Yakovenchuk et al., 2005).

Karelianite V_2O_5 has been found in fenitized phlogopite–nepheline–albite hornfels from a large xenolith in foyaite at Mount Kaskasnyunchorr (Yakovenchuk et al., 2005). Karelianite occurs as tiny (up to 20 μm in diameter) isometric grains in polyminerale rims around rutile in pyrrhotite inclusions (Fig. 4). In addition to karelianite, the rims contain vuorelainenite, vanadium crichtonite and unknown Fe–V–Cr sulfide. Baddeleyite, britholite-(Ce), calcite, crichtonite, monazite-(Ce), natrolite, pyrite, rengerite, rhodochrosite, titanite, fluorapatite, zircon, zirconolite, and shrilankite have been identified in the rims.

Ilmenite FeTiO_3 is the most abundant mineral throughout the Khibiny pluton. Maximum concentrations of ilmenite have been detected in hornfel xenoliths, fenite, apofoyaite albitite, aegirinite, and low-temperature hydrothermal albite and natrolite veins. In albitites, fenites, and hornfels, ilmenite occurs as isometric or flattened grains and subhedral thin tabular crystals (up to 5 mm across) incorporated into fine-grained orthoclase, albite, alkali amphiboles and pyroxenes, nepheline, cordierite–sekaninaite, quartz, fayalite, and biotite in association with pyrrhotite, native gold, magnetite, gahnite, hercynite, corundum, chrysoberyl, (ilmeno)rutile, freudenbergite, crichto-

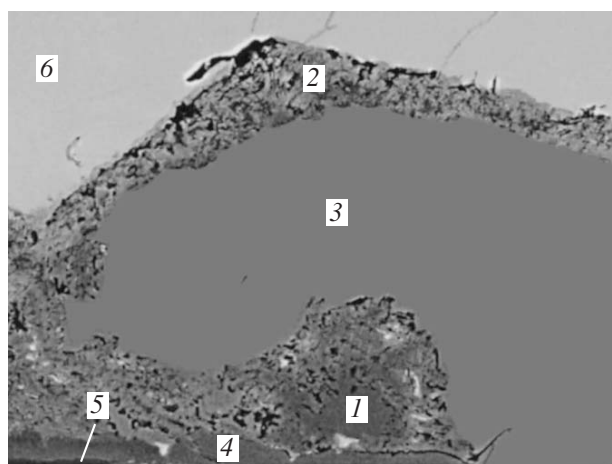


Fig. 4. Segregation of karelianite (1), 20 μm across, within a rim of unidentified Fe-V-Cr sulfide (2); vuorelainite (3) and chrichtonite (4) at the boundary between rutile (5) and pyrrhotite (6) from phlogopite-nepheline-albite hornfels, Mount Kaskasnyunchorr. BSE image.

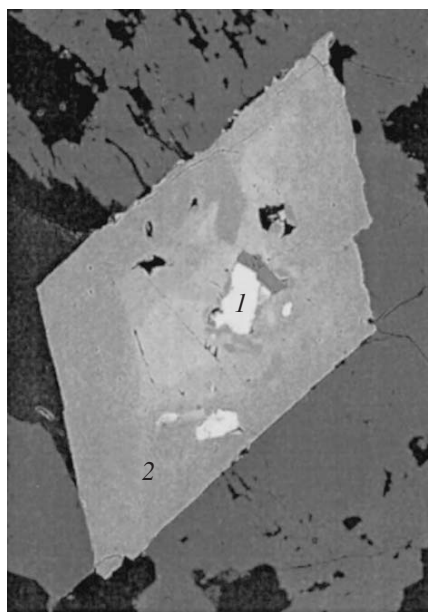


Fig. 5. Ilmenite inclusions (1) in titanite crystal (2) from foyaite, Mount Kukisvumchorr. BSE image $0.8 \times 0.6 \mu\text{m}$ in size.



Fig. 6. Rosette of tabular ilmenite crystals (1 cm in diameter) from aegirine-microcline vein in rischorrite, Peak Marchenko.



Fig. 7. Rosette of pyrophanite (0.8 mm in diameter) on astrophyllite from natrolite-aegirine-microcline vein in foyaite, Mount Yukspor. SE image.

nite-loveringite, sillimanite-andalusite, muscovite, almandine-spessartine, titanite, seidozerite, fluorite, monazite-(Ce), and other less abundant minerals.

Ilmenite usually occurs as separate platy grains (up to 1 cm across) in foyaite, rischorrite, melteigite-urtite, and apatite-nepheline rock. Only an insignificant percentage of ilmenite falls on exsolution lamellas, streaky, dendritic, and droplike inclusions in magnetite

(Bonshtedt et al., 1937; Kostyleva-Labuntsova et al., 1978). In the majority of foyaite and foidolite samples, ilmenite is closely associated with titanite (Kozyreva, 1990; Yakovenchuk et al., 2005), which often encloses a small ilmenite crystal, which probably was a seed (Fig. 5). Annite, aenigmatite, albite, natrolite, lorenzenite, magnetite, hematite, pyrrhotite, and fluorite also occur in association with ilmenite.

Table 1. Microprobe analyses of minerals of the corundum subgroup, wt %

Analysis	MgO	Al ₂ O ₃	SiO ₂	CaO	TiO ₂	V ₂ O ₃	Cr ₂ O ₃	MnO	Fe ₂ O ₃	Σ
Corundum										
1	–	98.03	–	–	0.33	–	–	–	0.26	98.62
2	–	98.42	0.45	–	–	–	–	–	0.96	99.83
3	–	99.80	–	–	0.29	–	–	–	0.38	100.47
4	–	100.20	–	–	–	–	–	–	0.16	100.36
5	–	100.07	–	–	–	–	–	–	0.25	100.31
6	–	98.99	0.30	–	–	–	–	–	0.08	99.38
7	–	100.14	–	–	0.05	–	–	–	–	100.19
8	–	99.70	0.41	–	0.36	–	–	–	–	100.47
9	–	99.32	0.17	–	–	–	–	–	0.69	100.18
10	–	98.55	0.22	–	0.17	–	–	–	0.15	99.09
11	–	99.24	0.72	–	0.22	–	–	–	–	100.17
12	0.03	98.98	0.27	0.03	–	–	–	–	0.43	99.74
13	–	99.00	–	–	–	–	–	–	0.16	99.16
14	–	97.52	0.18	–	–	–	–	–	0.68	98.38
Karelianite										
15	–	–	–	–	1.56	84.74	11.23	0.10	1.89	99.52
Hematite										
16	–	0.18	1.75	0.04	0.02	0.05	–	0.32	94.12	96.69
17	–	0.09	1.49	0.03	0.12	–	–	0.30	97.74	99.77
18	–	0.00	0.35	–	0.09	–	–	0.09	97.78	98.50
19	–	0.00	0.12	–	1.32	0.77	–	0.24	97.48	99.92
20	–	0.20	0.49	–	1.88	–	–	0.54	96.84	99.95
21	–	0.18	0.55	–	1.14	–	–	0.09	97.91	99.86

Note: (1–15) Xenoliths of hornfels after volcanic and sedimentary rocks in foyaite: (1–9) Mount Eveslogchorr, (10–12, 15) Mount Kaskasnyunchorr, (13, 14) Mount Kukisvumchorr; (16–19) foyaite, Mount Yumjechorr; (20, 21) natrolite vein in rischorrite, Mount Eveslogchorr.

The largest ilmenite inclusions have been found in pegmatite and hydrothermal veins. In a microcline–aegirine–natrolite vein in rischorrite at Peak Marchenko, ilmenite forms tabular crystals (up to 3 cm across) with the faces of the {0001} basal plane and {10 $\bar{1}$ 4} rhombohedron that grew in vugs over green acicular aegirine or microcline in association with zircon, phlogopite, and ancylite-(Ce). Ilmenite crystals embedded in columnar natrolite in the axial part of a vein are additionally characterized by the faces of the {01 $\bar{1}$ 4}, {11 $\bar{2}$ 3} rhombohedrons and {11 $\bar{2}$ 0} hexagonal prism. The complexly built ilmenite crystals with faces of negative rhombohedron {01 $\bar{1}$ 2} in addition to the above-mentioned forms have been described in natrolite–albite–aegirine–microcline veins in rischorrite at Mount Kukisvumchorr (Bonshtedt et al., 1937). These veins are characterized by rosette-shaped intergrowths (up to 5 cm in diameter) of lustrous tabular ilmenite crystals (Dorfman, 1973; Yakovenchuk et al.,

2005), encrusting microcline crystals in the vugs (Fig. 6). Zircon, sodalite, phlogopite, lorenzenite, cancrinite, catapleite, fluorapophyllite, ancylite-(Ce/La), sphalerite, and pyrrhotite are typical minerals of this assemblage.

Anatase, goethite, and manganese hydroxides are common products of ilmenite alteration (Kostyleva-Labuntsova et al., 1978; Yakovenchuk et al., 2005). In the albite–aegirine–microcline vein hosted in rischorrite at Mount Poachvumchorr, ilmenite was replaced by lorenzenite and astrophyllite (Semenov and Tikhonov, 1961). In aegirine–feldspar veins that cross lavochorrite–rischorrite at Mount Namuaiv, ilmenite was replaced by hematite, and in hornfels of the Lesser Vudjavr lake valley, ilmenite was transformed into graphic aggregate of rutile and pyrite (Shlyukova, 1986).

Pyrophanite MnTiO₃ is a rare accessory mineral of hydrothermally altered foyaite at Mount Yumjechorr at the contact with the fenite–foiolite unit of the Minor ring, where this mineral occurs as platy grains (up to

Table 2. Microprobe analyses of minerals of the ilmenite–pyrophanite series, wt %

Analys- is	MgO	Al ₂ O ₃	SiO ₂	CaO	TiO ₂	V ₂ O ₃	Cr ₂ O ₃	MnO	FeO	ZnO	ZrO ₂	Nb ₂ O ₅	Ta ₂ O ₅	Σ
Ilmenite														
1	0.17	–	0.38	0.09	53.04	–	–	17.25	28.06	0.31	0.18	0.35	–	99.83
2	–	0.35	1.10	0.05	48.71	0.10	–	2.81	38.44	–	0.82	1.61	–	93.99
3	0.16	0.06	0.24	0.15	53.79	–	–	7.27	36.48	0.10	–	0.33	–	98.56
4	–	0.19	0.48	0.00	51.38	0.05	–	14.50	32.22	–	–	–	–	98.82
5	–	0.19	0.24	0.03	51.03	–	–	2.94	43.17	–	–	0.73	–	98.32
6	0.08	0.13	0.24	–	51.86	–	–	21.00	25.38	–	–	0.33	–	99.02
7	–	0.27	0.44	–	52.13	–	–	12.15	33.70	0.12	0.22	–	–	99.02
8	–	–	0.16	0.10	53.52	–	–	5.94	37.55	–	–	–	–	97.26
9	–	0.06	0.18	0.19	53.46	–	–	16.92	29.05	–	–	–	–	99.86
10	–	0.06	0.00	–	51.87	–	–	4.55	41.99	–	–	0.10	–	98.57
11	0.14	–	0.30	–	53.22	–	–	13.87	33.01	–	–	–	–	100.54
12	–	–	0.26	–	52.43	–	–	7.72	39.57	–	–	0.16	–	100.14
13	0.45	–	0.18	0.03	53.30	–	–	4.76	41.98	–	–	–	–	100.69
14	–	–	–	–	53.54	–	–	15.24	30.57	–	–	–	–	99.35
15	0.09	–	–	–	52.05	0.04	–	3.30	43.81	–	–	–	–	99.29
16	0.09	–	–	–	51.56	–	–	1.45	43.50	–	–	2.64	0.19	99.43
17	–	–	–	–	53.81	–	–	8.57	37.26	–	–	0.32	–	99.95
18	–	0.02	–	–	51.62	–	–	10.96	35.77	–	–	0.49	0.27	99.13
19	–	–	–	–	52.75	–	–	5.25	40.13	–	–	1.25	–	99.38
20	0.06	–	0.44	–	52.61	–	–	21.02	25.41	–	–	–	–	99.54
21	3.87	0.07	0.25	–	53.26	0.15	–	4.29	37.36	–	–	–	–	99.25
22	0.09	–	–	–	52.46	–	0.02	4.62	42.25	–	–	–	–	99.44
23	–	–	–	–	50.41	–	–	1.17	45.35	0.08	–	2.04	–	99.05
24	0.13	0.15	0.28	0.02	52.43	–	–	18.63	26.84	–	–	0.61	–	99.08
25	–	0.48	0.33	–	51.22	0.05	–	0.51	46.05	–	–	0.56	–	99.18
26	0.48	–	–	0.13	54.09	–	0.05	5.84	38.64	–	0.15	–	–	99.39
27	0.78	–	–	–	52.57	0.17	–	1.64	43.46	–	–	0.68	–	99.29
28	–	–	–	–	51.85	–	–	0.56	45.37	–	–	0.93	–	98.72
29	0.16	0.16	0.13	0.02	50.94	0.22	–	4.71	41.11	0.17	–	1.68	–	99.30
30	0.09	0.23	0.28	–	50.93	–	–	6.44	40.27	1.27	–	0.88	–	100.37
31	–	–	0.23	–	51.43	0.44	–	0.40	46.33	–	–	0.85	–	99.68
32	–	0.32	–	–	54.09	0.25	–	1.97	43.16	–	–	–	–	99.80
33	0.44	–	0.05	–	51.49	0.05	–	4.34	41.53	–	–	1.50	–	99.40
34	0.09	–	–	–	49.24	0.06	–	5.44	43.17	–	–	2.19	–	100.19
35	3.28	0.26	0.54	0.10	50.71	0.09	–	2.97	40.79	–	–	–	–	98.74
36	0.55	0.34	0.69	0.02	49.54	–	–	4.93	39.97	–	–	0.60	–	96.63
Pyrophanite														
37	–	–	0.22	–	51.95	0.03	–	22.62	22.87	–	–	–	–	97.69
38	–	0.09	0.82	0.02	51.09	–	–	42.23	5.08	0.21	–	0.34	–	99.88
39	–	–	–	–	49.05	–	–	44.17	1.21	–	–	4.91	–	99.33
40	–	–	–	–	49.04	–	–	41.56	5.15	–	–	3.98	–	99.72
41	–	–	–	–	46.94	–	–	40.13	4.18	–	–	8.17	–	99.41
42	–	–	–	–	51.05	–	–	39.24	7.73	–	–	1.59	–	99.61

Note: (1–11, 37, 38) Foyaite: (1, 2) Mount Kukisvumchorr, (3–5) Peak Marchenko, (6, 7) Mount Vantomnyutsk, (8, 9) Mount Yudydchumchorr, (10, 11, 37, 38) Mount Yumjehorr; (12) rischorrite, Peak Marchenko; (13) melteigite, Mount Poachvumchorr; (14) aegirine–microcline vein hosted in foyaite, Mount Khibinpakhchorr; (15) aegirine–microcline vein in apatite–nepheline rock, Mount Kukisvumchorr; (16) natrolite–microcline vein in urtite, Mount Kukisvumchorr; (17) natrolite–aegirine–microcline vein in rischorrite, Peak Marchenko; (18) aegirine–feldspar vein in rischorrite, Mount Namuaiv (Kozyreva, 1990); (19) natrolite–aegirine–microcline vein in rischorrite, Mount Njorkpahk; (20) aegirine–microcline vein in rischorrite, Mount Valepakhk; (21) picrite from volcanic pipe in urtite, Mount Namuaiv; (22) alkali picrite from dike in ijolite–urtite, the Olenii Creek (Arzamastsev et al., 1988); (23–36) xenoliths of hornfels after volcanic and sedimentary rocks in foyaite: (23, 24) Mount Eveslogchorr, (25, 26) Mount Kaskasnyunchorr, (27) Mount Khibinpakhchorr, (28, 29) Mount Kukisvumchorr, (30, 31) Peak Marchenko, (32) Mount Partomchorr, (33) Mount Poachvumchorr, (34) Mount Yuksporr, (35, 36) Mount Yumjehorr; (39, 40) natrolite vein hosted in rischorrite, Mount Eveslogchorr; (41, 42) natrolite–microcline vein in rischorrite, Mount Yuksporr.

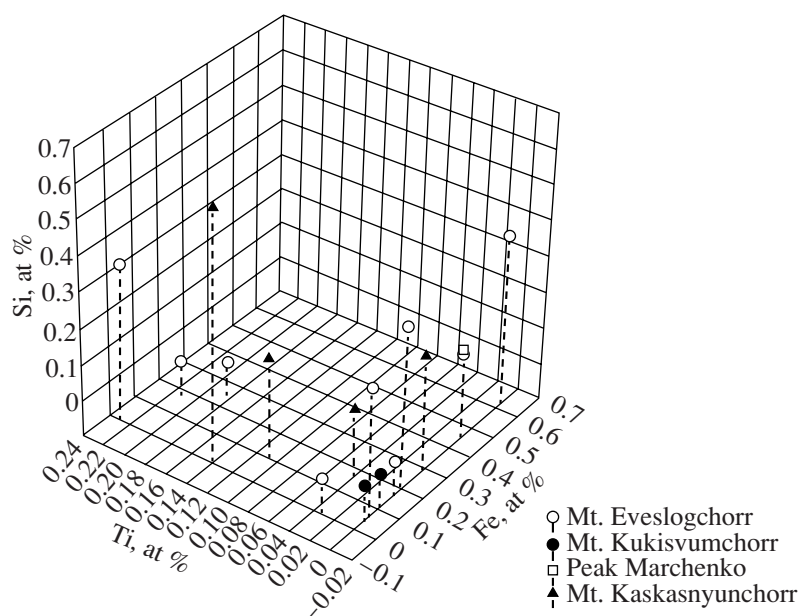


Fig. 8. Correlation of trace elements in corundum, at %.

0.2 mm across) in nepheline and aegirine crystals. Pyrophanite is commonly associated with magnetite, hematite, rosenbuschite, lamprophyllite, annite, and kochite. Pyrophanite forms thin platy grains in association with kupletskite, zircon, and eudialyte in an albitized aegirine–feldspar vein in metavolcanic rocks exposed close to the Khibiny railway station (Shlyukova, 1986). Tabular to isometric pyrophanite crystals (up to 2 mm across) with faces of rhombohedron $\{10\bar{1}1\}$ and the basal plane have been detected in association with kukharenkoite-(La), boehmite, amesite, pyrite, and hematite in the natrolitized aegirine–nepheline–microcline vein hosted in ijolite–urtite at Mount Kukisvumchorr (Pekov and Podlesny, 2004). In a natrolite–microcline vein hosted in gneissose foyaite

at Mount Yuksporr, rosettes up to 1 mm in diameter of lustrous tabular pyrophanite crystals (Fig. 7) are associated with aegirine, barylite, labuntsovite-Mn, astrophyllite, titanite, and fluorite. Similar large rosettes up to 1 cm in diameter have been found in the natrolite vein in rischorrite at Mount Rasvumchorr in association with hematite, henrymeyerite, cafetite, and morimotoite, as well as in association with hematite, henrymeyerite, and priderite in the natrolite vein hosted in gneissose rischorrite at Mount Eveslogchorr (Yakovenchuk et al., 2005).

CHEMICAL COMPOSITION OF MINERALS

Representative microprobe analyses of corundum, hematite, karelianite, and minerals of the ilmenite–pyrophanite series are shown in Tables 1 and 2. As follows from Table 1, Khibiny corundum contains Fe or Ti impurity regardless of its belonging to any certain xenolith or type of hornfels (Fig. 8). The decrease in Ti or Fe content in corundum correlates with the decrease in Si. Therefore, two isovalent substitutions Al^{3+} for Fe^{3+} and Al^{3+} for Ti^{3+} instead of the seemingly more probable scheme $2Al^{3+} \rightleftharpoons Fe^{2+} + Ti^{4+}$ may be suggested. The enrichment of corundum in Ti and Fe was likely caused by the specific composition and metamorphic evolution of hornfels.

The chemical composition of hematite from hydrothermally altered foyaite and hydrothermal veins of the Khibiny pluton (Table 1) is controlled by isomorphic replacement of $2Fe^{3+} \rightleftharpoons Mn^{2+} + Ti^{4+}$ (Fig. 9) characteristic of Khibiny magnetite as well. The chemical composition of karelianite (Table 1) differs from the theoretical composition in a high chromium content,

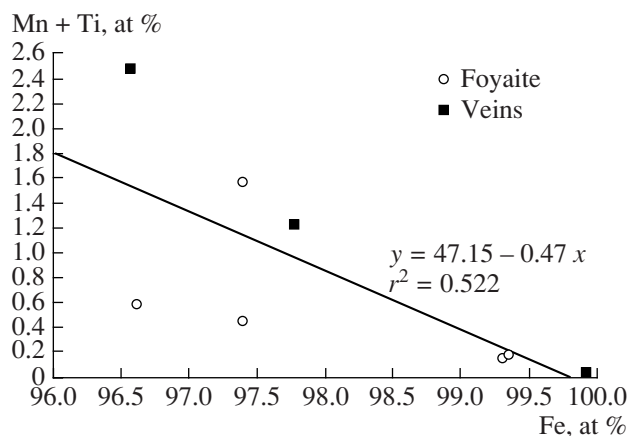


Fig. 9. Correlations of Fe, Ti, and Mn in hematite.

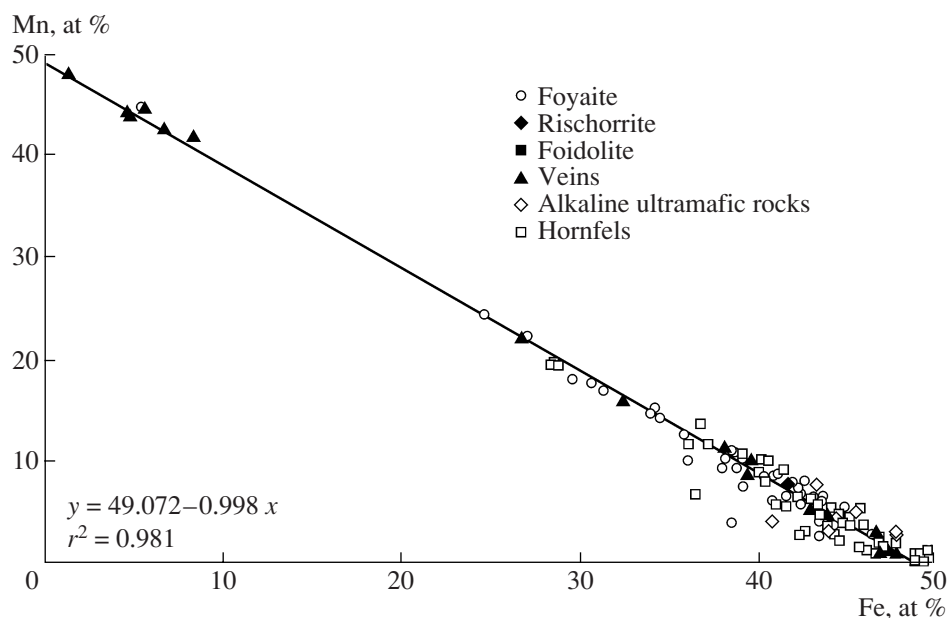


Fig. 10. Correlation of Fe and Mn in minerals of the ilmenite-pyrophanite series.

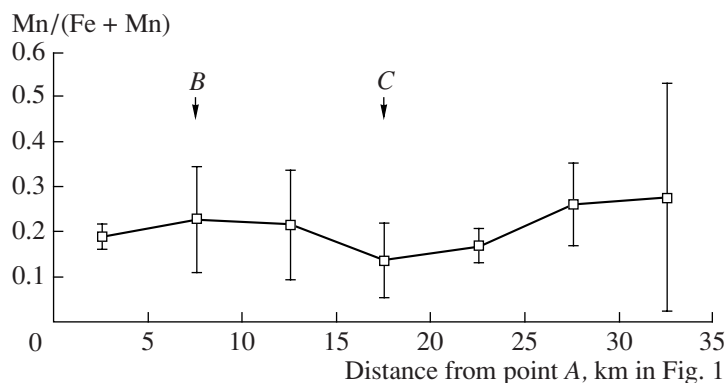


Fig. 11. Variation of average ilmenite composition along profile A-B-C-D; arrows show position of the Minor semiring (B) and Main ring (C), see Fig. 1.

which indicates the probable presence of eskolaite in hornfel xenoliths.

The chemical composition of minerals from the pyrophanite-ilmenite series (Table 2) varies widely, and correlation between Fe and Mn (Fig. 10) testifies to the almost complete absence of other variants of isomorphism in the first site. In our case, the variable composition of the studied minerals from hydrothermally altered rocks covers the entire interval of possible values. The composition of these minerals from other rocks varies from ideal ilmenite composition to an ilmenite-pyrophanite boundary. In addition, ilmenite from alkaline ultramafic rocks of the dike suite and from some hornfels after basaltic rocks is enriched in magnesium.

DISCUSSION

The corundum-bearing interbeds intercalating with orthoclase-sillimanite, annite-orthoclase-secaninaite, albite-orthoclase-sillimanite-quartz, muscovite-albite, fayalite-annite-orthoclase, and other hornfels layers (Yakovenchuk et al., 2005) were formed as products of contact metamorphism of banded volcanic and sedimentary rocks of the Lovozero Formation. These rocks are composed of basalts (including olivine-bearing varieties) and sedimentary material transformed into biotite glimmerite and almost monomineralic quartzite (Pakhomovsky et al., 2005). Corundum occurred in those rocks as a product of high-temperature metamorphic reactions similar to those typical of pelitic rocks under conditions of pyroxene and sanidine facies: $\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 \rightleftharpoons \text{KAlSi}_3\text{O}_8 + \text{Al}_2\text{O}_3, 2\text{FeAl}_2\text{O}_4 +$

$5\text{Al}_2\text{SiO}_5 \rightleftharpoons \text{Fe}_2\text{Al}_4\text{Si}_5\text{O}_{18} + 5\text{Al}_2\text{O}_3$, etc. Corundum-bearing hybrid pegmatites were formed due to removal of Na from nepheline syenite pegmatites into host hornfels, which caused nepheline alteration and transformation of alkaline pegmatite into corundum-orthoclase vein: $3\text{KNa}_3\text{Al}_4\text{Si}_4\text{O}_{16} - 4\text{Na}_2\text{O} = \text{NaAlSi}_3\text{O}_8 + 3\text{KAlSi}_3\text{O}_8 + 4\text{Al}_2\text{O}_3$. This process could have resulted in the formation of both veins and apofyaite corundum-feldspar metasomatic rocks, which are similar to hornfels in composition (Levin et al., 1975). Aluminum released from nepheline in the course of fenitization of xenoliths partly entered into magnetite, amphibole, and other minerals, contributing to symmetrical zoning of the Khibiny pluton relative to the Main Ring of the melt-eigite-urtite and apatite-nepheline rocks (Goryainov et al., 2005; Yakovenchuk et al., 2005).

The study of compositional variation of accessory ilmenite from foyaite along profile A–B–C–D (Fig. 1) has showed that the Fe content appreciably increases near the Main Ring (Fig. 11) due to alteration of nepheline syenite under the influence of the foidolite melt-fluid that intruded through the ring fracture. In the course of this process, manganese was removed from ilmenite and amphibole and gained in magnetite, eudialyte, and younger hydrothermal minerals, including pyrophanite (Yakovenchuk et al., 2005).

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