CORUNDUM–BEARING PEGMATITES OF CROSSING TREND OF EVOLUTION OF THE KHIBINY MASSIF AND THEIR ROLE IN RECONSTRUCTION OF PARENTAL ROCKS OF HOST PRE–PROTEROZOIC HORNFELS

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Corundum-bearing pegmatoids located within the Svintsovy (Lead) Creek, Mount Kukisvumchorr are studied. Mineralogy of these pegmatoid bodies and its changes in the direction from nepheline syenite to xenolith of hornfels are described in detail. Microinclusions in corundum, sodalite, and nepheline are investigated. Formation process of the pegmatoids and initial composition of annite-feldspar hornfels are proposed.

2 tables, 6 photos, 13 references.
Keywords: corundum, corundum-bearing pegmatoids, pegmatites of crossing trend of evolution, Khibiny massif, peraluminous hornfels, melt inclusions.

Inroduction

In the central Khibiny massif there are various xenoliths of hornfelses of pre-Proterozoic host rocks. Most of them are aluminous (cordierite, sillimanite, corundum-bearing or corundum-free cordierite-andalusite, annite-feldspar, and annite-feldspar-chlorite), clay slate, carbonaceous shale, phyllite, and pyrrhotite-bearing hornfels (Kupletsky, 1932; Simon and Shlyukova, 1972; Men'shikov, 1978; Shlyukova, 1986; Men'shikov *et al.*, 2000). Probably, these are metamorphosed and metasomatically altered sedimentary-volcanic rocks of several formations in the Imandra-Varzuga structure (phyllite, clay slate, chlorite-sericite schist, two-mica schist, siltstone, and carbonate rocks). Xenoliths of pre-Proterozoic rocks mainly occur at the contact between nepheline syenite (foyaite, khibinite, and lyavochorrite) and rischorrite and/or ijolite-urtite of the Central arc of the massif within paleoboundary of Proterozoic rocks. (Simon and Shlyukova, 1972; Shlyukova and Borutsky, 1976; Shlyukova, 1986). Heterogeneity of xenolith rocks interacted with nepheline-syenite magma resulted in the formation of distinctive pegmatites with peraluminous mineral assemblages atypical of nepheline syenite and pegmatite of the massif both in the xenoliths and at the contact with nepheline syenite. Such mineralogy is characteristic of granite and non-granite pegmatites, whose solution-melt was contaminated by components of chemical contrasting host rocks. Similar pegmatites were repeatedly described as pegmatites of crossing trend of evolution including alkaline massifs (Fersman, 1940; Uspensky, 1968; Shlyukova *et al.*, 2003; Chukanov *et al.*, 2003).

Geological and mineralogical characteristics of corundum–bearing pegmatites of crossing trend of evolution

According to Men'shikov (1978), two major types of corundum-bearing pegmatites are recognized in the Khibiny massif: nepheline [major minerals are nepheline, orthoclase, and lepidomelane (annite); sodalite, hercynite, and corundum are minor] and nepheline-free [major minerals are orthoclase, and lepidomelane (annite); sodalite, hercynite, and corundum are minor].

We have studied a number of the first type corundum-bearing pegmatites found

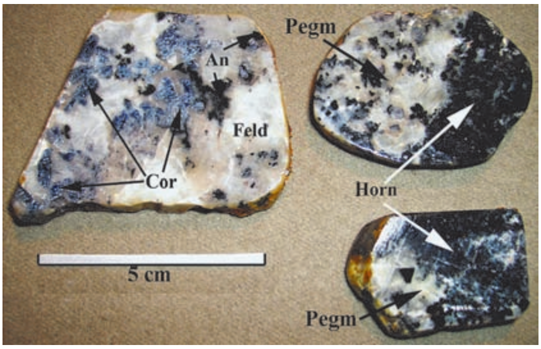

Fig. 1. Samples of corundum-bearing pegmatite, Mount Kukisvumchorr; contact of pegmatite and feldspar-annite hornfels. Cor — corundum, Feld — feldspar, An — annite; Pegm — pegmatite, Horn — hornfels.

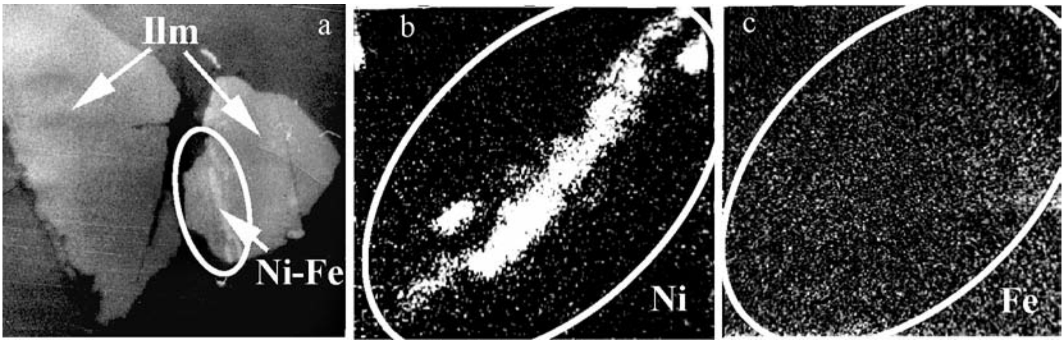

Fig. 2. Natural nickel-iron (Ni-Fe) alloy in ilmenite (Ilm) from corundum-bearing pegmatite.

at both the surface at Mts. Rischorr, Kukisvumchorr, Yuksporr, and Aeveslogchorr and great depth (observed in cores of holes drilled through hornfelses after relicts of ancient rocks in the Maly Vudyavr Lake area and at the Partomchorr apatite deposit). The pegmatites occur at the contact between nepheline syenite and aluminous hornfels. These are schliere-shaped irregular bodies frequently divided into several apophysises. Veins are few meters to 200 m long along striking and 0.2 to 1.5 m thick. In the pegmatites, minerals are irregularly distributed. Arfvedsonite, aegirine, nepheline, biotite (annite), and feldspar are major minerals. In addition, blue corundum (sapphire), hercynite as crystals and rims around corundum, lepidomelane, ilmenite, monazite, graphite, eskolaite, and Co-bearing lцllingite were identified in apophysises of nepheline-feldspar pegmatite hosted in hornfels. Most pegmatites are highly sodalitized. Apatite, gadolinite, zircon and titanoniobates occur in sodalite areas (Shluykova, 1996; Shlyukova *et al.*, 2003).

Corundum-bearing pegmatoids located within the Svitsovy Creek, Mount Kukisvumchorr hosted in peraluminous (52.10 wt. % Al_2O_3) annite-feldspar hornfels are studied in most detail. Corundum-bearing annite-nepheline-feldspar apophysises (Fig. 1) of nepheline-feldspar-aegirine pegmatite with lamprophyllite cut hornfels xenolith, which is surrounded by foyaite hosting pegmatite body. Contacts of the pegmatoids with hornfels are fuzzy due to phenitization. Change of mineralogy of apophysises outward major pegmatite body is clearly documented: aluminous mineral assemblage, corundum, hercynite, annite, and cordierite, is formed instead of arfvedsonite, aegirine, and lamprophyllite (Bukanov and Lipovsky, 1980).

Rock-forming minerals in the apophysises are K-Na-feldspar, nepheline, and mica whose composition according to (Rieder *et al.*, 1998) corresponds to annite depleted in phlogopite (magnesium) component. Extremely high Al content (17 wt. % Al_2O_3 instead of usual 7—10 wt. %) is a feature of

Table 1. **Chemical compositions of rock-forming minerals and accessories from corundum-bearing pegmatite, Svintsovy Creek, Mt. Kukisvumchorr**

	Rock-forming mineral					Accessory				
	Annite		Nepheline	Feldspar		Hercynite	Muscovite	Monazite	Bornite	Chalcopyrite
Component, wt. %	1	2	3	4	5	6	7	8	9	10
Na_2O	0.36	0.00	17.50	1.94	9.85	–	2.37	–	–	–
K_2O	9.97	14.35	5.88	14.82	0.27	–	6.88	–	–	–
CaO	0.06	0.00	–	0.18	0.62	–	–	–	–	–
MnO	–	0.68	–	–	–	1.29	–	–	–	–
FeO/Fe*	31.01	36.59	0.07	n.a.	n.a.	53.00	–	–	59.35	38.19
CuO/Cu*	–	–	–	–	–	–	–	–	18.57	28.37
Ce_2O_3	–	–	–	–	–	–	–	34.18	–	–
La_2O_3	–	–	–	–	–	–	–	24.91	–	–
Pr_2O_3	–	–	–	–	–	–	–	2.18	–	–
Nd_2O_3	–	–	–	–	–	–	–	5.85	–	–
Al_2O_3	17.42	14.16	32.62	18.58	19.85	42.44	34.81	–	–	–
SiO_2	31.58	25.66	43.43	63.08	66.97	–	42.22	0.68	–	–
TiO_2	4.73	2.94	–	–	–	0.27	–	–	–	–
ThO_2	–	–	–	–	–	–	–	1.12	–	–
P_2O_5	–		–	–	–	–	–	29.46	–	–
S	–	–	–	–	–	–	–	–	24.32	30.22
O=F	0.50	–	–	–	–		–	–	–	–
Total	95.86**	94.38	99.50	98.60	97.56	97.00	86.28	98.46	102.24	96.78
Minals, %)	-	-	Nef – 78 Ks – 17 Q – 5	Ort – 83 Ab – 16 An – 1	Ort – 1 Ab – 96 An – 3	-	-	-	-	-

*Notes: * – content of elements are given for sulfides. ** – 0.73% MgO was detected in annite. (1) wet chemical analysis, analyst G.F. Egorova. (2) JSM-5300 scanning electron microscope equipped with energy dispersion system, analyst N.V. Trubkin. (3–9) Cameca MS-46 electron microprobe: (3–6, 8, 9) analyst T.I. Golovanova; (7) analyst A.I. Tsepin.*
n.a. is not analysed. Dash denotes that content is below detection limit.

this annite; its composition corresponds to the formula: $(K_{1.04}Na_{0.05})_{1.09}(Fe^{2+}_{1.95}\,Ti_{0.29}Al_{0.28}Fe^{3+}_{0.16}\,Mg_{0.09}Mn_{0.06})_{2.83}\,Al(Si_{2.60}Al_{0.40})_{3.00}O_{10}(OH)_2$ (Table 1, anal. 1). It is interesting that we identified annite of similar composition in host hornfels. The composition of Al-rich annite from hornfels is as follows: $K_{1.07}(Fe_{1.91}Mg_{0.54}Al_{0.19}Ti_{0.18})_{2.82}[Al(Si_{2.66}Al_{0.34})_3O_{10}](OH)_2$ (Table 1, anal. 2). Fe^{2+} and Fe^{3+} are calculated by charge balance. Sufficiently low sums of analyses of annite in Table 1 are probably caused by its partial hydration. Similar annite is characteristic rock-forming mineral of hornfels in Vudyavr block (Menshikov *et al.*, 2000; our data).

Feldspar occurs as block-crystals with macroperthites. Electron-microprobe analysis revealed two phases in these block-crystals: K-rich (Table 1, anal. 4) and Na-rich (Table 1, anal. 5). The composition of nepheline (Table 1, anal. 3) is typical of nepheline syenite from the Khibiny massif.

The following minerals were found in the pegmatoid: spheric segregations of graphite; natural nickel-cobalt alloy (Fig. 2); Co-bearing löllingite; chalcopyrite and bornite (Table 1, anal. 9, 10); corundum (sapphire reaches 1.5 cm across, Fig. 1); hercynite of two generations: large isometric crystals of 1–2 mm to 1 cm in size (Table 1, anal. 6) and rims overgrown crystals of corundum (Shlyukova, 1986; Borisova *et al.*, 2001); zirkelite and other titanoniobates; Al-rich mica of the muscovite-paragonite series (table 1, anal. 7; low sum of analysis is probably caused by partial hydration of the mineral and bad polishing quality); andalusite, schorlomite, zircon, gadolinite, analcime,

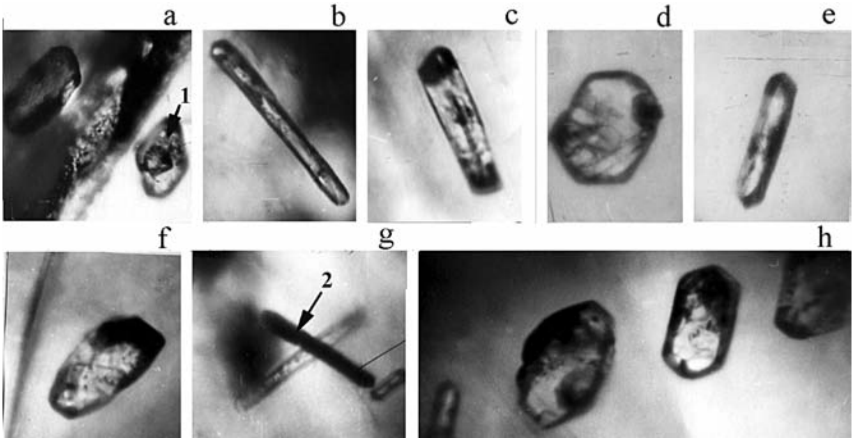

Fig. 3. Primary inclusions in corundum.

sodalite, monazite (Table 1, anal. 8), and apatite. Microinclusions in minerals from this type pegmatite were studied in samples of the corundum-bearing pegmatite (Shlyukova *et al.*, 2003).

Petrography and microthermometry of inclusions

Microinclusions in minerals of the studied pegmatite were examined by A.R. Groshenko.

Few types of inclusions of mineral-forming media differed in arrangement in crystal, composition, shape, and size were recognized in **corundum (dark blue sapphire)**:

(1) The largest elongated inclusions up to few hundreds microns in size as negative crystals are arranged singly, as small clusters, and locally, along growth zones. Most inclusions are glass devitrified to variable degree with numerous solid phases and few gas (3 – 8%) occurred in interstices (Fig. 3a – h). These inclusions are reliably identified as primary.

(2) Melt inclusions of 2 to 3 μm in size (locally, 10 – 20 μm long) healing thin fractures within crystal are pseudosecondary.

(3) Secondary gas-dominated rounded and tubular inclusions were trapped along long thin fractures, which cut crystal.

Melt inclusions are also observed in **nepheline** but they are vitreous and contain great gas (up to 40 – 80%). Primary inclusions are very rare; pseudosecondary inclusions are observable more abundant; yellowish and dark brown secondary inclusions are dominant. They are spherical, oval, and less frequent elongated. Nepheline crystals are troubled and opaque. Size of inclusions ranges from few to tens microns (Fig. 4).

Primary inclusions were not identified in **sodalite**. Yellowish and dark brown spherical, oval or elongated secondary inclusions are liquid-gas and gas-dominated with size ranging from few to hundreds microns (Fig. 5).

Microthermometry of inclusions was performed with a T-1400 heating-freezing stage designed by A.R. Groshenko. No any changes were documented during heating primary inclusions in corundum up to 700 – 800°C; clarification of content at softening solid phases, individualization of gas bubble (occasionally, two or three bubbles), and gradual dissolution of solids were observed at 980 – 1030°C. Only secondary inclusions homogenized into gas at 380 – 520°C were studied in sodalite.

Compositions of some solid phases of devitrified melt inclusions in corundum (Fig. 6; Table 2) correspond to albite (Fig. 6a, phase 1; Fig. 6b, phase 1) and mica of the paragonite-muscovite series (Fig. 6a, phase 2; Fig. 6b, phase 2; Figs. 6c, 6d, 6e).

Discussion

Mineral assemblages of corundum-bearing pegmatite described in this paper and melt inclusions in minerals provide certain assumptions of the formation of

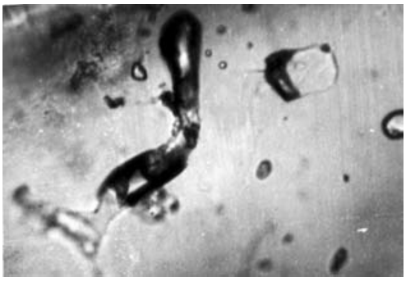

Fig. 4. Secondary inclusions in nepheline.

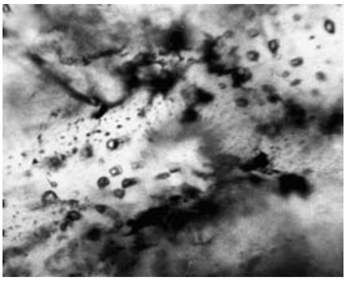

Fig. 5. Secondary inclusions in sodalite.

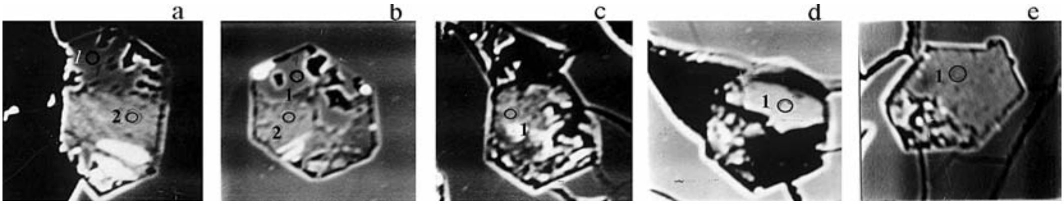

Fig. 6. Solid inclusions in corundum: (1) albite; (2) muscovite.

corundum-bearing pegmatites and composition of source rocks for host annite-feldspar hornfels.

Firstly, according to microthemometric measurements, temperature of formation did not exceed 700 — 1030°C that is consistent with crystallization temperature of nepheline estimated from geothermometer by Hamilton 800 — 850°C. On the basis of the data obtained, the pegmatite was formed from residual melt-solution at final stage of crystallization of syenite magma. It may be suggested that earlier, relics of Proterozoic Imandra-Varguza rocks (shale and/or chlorite-sericite schist) were metamorphosed to annite-feldspar hornfels under effect of nepheline-syenite melt. Probably, high-temperature aluminous minerals (cordierite, andalusite, and sillimanite) were formed at this time. Pegmatite-forming melt-solution was intruded along fractures in the previously formed hornfels.

Secondly, high Al content in the hornfels determined unusual pegmatite mineral assemblage found in the area of Svitsovy Creek and differed from assemblages of standard nepheline-syenite pegmatites. As aforementioned, mineralogy of pegmatite apophysises changes moving away major pegmatite body. Aluminous mineral assemblage, corundum, hercynite, unusual Al-rich annite, cordierite, andalusite, and sillimanite, is formed instead of arfvedsonite, aegirine, and lamprophyllite of nepheline-syenite pegmatite. It is most probably that annite, cordierite, sillimanite, andalusite, and hercynite were captured by pegmatite-forming melt-solution together with xenolith rocks. Most likely, corundum crystallized as a result of fixation of excess alumina formed

Table 2. **Chemical compositions of phases in melt inclusions in sapphire**

Component, wt. %	Albite 6a (1)*	Muscovite 6a (2)	Albite 6b (1)	Muscovite 6b (2)	Muscovite 6c	Muscovite 6d	Muscovite 6e
Na_2O	11.71	1.67	11.26	1.19	3.38	0.98	2.86
K_2O	0.02	9.38	0.04	9.60	6.65	9.68	6.94
FeO	0.07	0.91	0.04	1.26	0.97	1.04	0.99
Al_2O_3	21.53	39.36	21.62	38.52	38.01	39.33	37.14
SiO_2	67.67	48.95	63.87	45.58	41.45	45.26	43.02
TiO_2	0.03	0.39	0.02	0.47	0.47	0.40	0.17
Total	101.03	100.66	96.85	96.62	90.93	96.69	91.12

Notes: * — number corresponds to the number of the points in Fig. 6.

during interaction of nepheline-syenite melt-solution and aluminous hornfels. Absence of corundum in both hornfels and pegmatite supports this suggestion. In addition, excess alumina can be resulted from removal of alkalis from Al-rich nepheline, when pegmatoid veins intruded hornfels.

Nepheline, rare metal and REE minerals probably crystallized from melt-solution during formation of the major nepheline-syenite pegmatite and were not modified by the interaction with hornfels.

Thirdly, secondary hydrocarbon inclusions and graphite in nepheline and sodalite indicate the effect of "dry" reducing fluids during late stage of pegmatite formation. Homogenization temperature of secondary liquid-gas and gas-dominated inclusions in sodalite is relatively low and ranges from 380 to 520°C. It may be suggested that this late reworking corresponds to the late hydrothermal transformation of nepheline syenite and its pegmatites. Sodalitization and zeolitization, which are characteristic of alkaline massifs including Khibiny, are related to this stage.

Fourthly, muscovite was trapped in primary inclusions in corundum formed in pegmatoid bodies hosted in hornfels. Muscovite is not typical of both nepheline-syenite pegmatite and nepheline syenite; micas are only minor minerals as products of transformation of amphiboles and pyroxenes. According to this, muscovite is suggested to be characteristic of hornlfels protolith (rocks of the Imandra-Varzuga Formations). Muscovite was conversed into Al-rich annite under effect of nepheline-syenite magma at high activity of alkalis (uppermost K) and mafic elements (uppermost Fe).

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