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Rock-Forming Feldspars of the Khibiny Alkaline Pluton, Kola Peninsula, Russia

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Abstract—This paper describes the structural–compositional zoning of the well-known Khibiny pluton in regard to rock-forming feldspars. The content of K–Na-feldspars increases inward and outward from the Main foidolite ring. The degree of coorientation of tabular K–Na-feldspar crystals sharply increases in the Main ring zone, and microcline-dominant foyaite turns into orthoclase-dominant foyaite. The composition of K–Na-feldspars in the center of the pluton and the Main ring zone is characterized by an enrichment in Al. This shift is compensated by a substitution of some K and Na with Ba (the Main ring zone) or by an addition of K and Na cations to the initially cation-deficient microcline (the central part of the pluton). Feldspars of volcanosedimentary rocks occurring as xenoliths in foyaite primarily corresponded to plagioclase An_{15-40}, but high-temperature fenitization and formation of hornfels in the Main ring zone gave rise to the crystallization of anorthoclase subsequently transformed into orthoclase and albite due to cooling and further fenitization. Such a zoning is the result of filling the Main ring fault zone within the homogeneous foyaite pluton with a foidolite melt, which provided the heating and potassium metasomatism of foyaite and xenoliths of volcanosedimentary rocks therein. The process eventually led to the transformation of foyaite into rischorrite–lyavochorrite, while xenoliths were transformed into aluminum hornfels with anorthoclase, annite, andalusite, topaz, and sekaninaite.

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INTRODUCTION

The world's largest Khibiny alkaline pluton (about 1327 km^2 in area) is located in the westernmost part of the Kola Peninsula at the contact of the Proterozoic rocks of the Imandra–Varzuga greenstone belt with Archean metamorphic complexes of the Kola–Norwegian Megablock (Fig. 1). As follows from the Pb–Pb, Rb–Sr, and Sm–Nd dating, the age of the main rock types of the Khibiny pluton varies from 380 to 360 Ma (Bayanova et al., 2002; Arzamastsev et al., 2007). The oval-shaped (in the plan view) pluton is 45 km long in the W–E direction and 35 km wide in the N–S direction. The seismic, gravity, and magnetic exploration (Shablinsky et al., 1963) showed that the contact of nepheline syenite with country rocks almost vertical at the surface levels out with depth (especially in the south and west and less significantly in the north and east). As a result, at a depth of 10 km the horizontal section of the pluton is reduced by more than 50% in comparison to its area at the surface.

Homogeneous nepheline syenite (foyaite) occupies about 70% of the pluton area and is commonly subdivided into foyaite proper in the center of the pluton and khibinite in its outer part separated by the zonal rock complex of the Main ring. The concentric zones of massive foyaite and khibinite at the margin and in the center and trachytoid rocks of the same composition on both sides of the Main ring are depicted in most geological maps, although such a textural zoning cannot be regarded as absolutely proved (see below).

Foidolite (melteigite–ijolite–urtite), high potassium (leucite-normative) poikilitic (kalsilite)–nepheline syenite (rischorrite) and less abundant malignite, titanite–nepheline, titanite–apatite, and apatite–nepheline rocks are predominant within the Main ring. Inequigranular nepheline syenite (lyavochorrite) transitional to rischorrite in its composition, textural–structural features, and geological position belongs to the same rock complex (Fig. 1).

Fersman (1941) suggested that the rock complex of the Main ring fills up the conical fracture zone, where the angle between the axis and the generatrix varies from 50°–70° near the surface to 10°–40° at a depth greater than 1 km. At the surface the area occupied by the rocks of this complex covers 27% of the total area of the pluton, and the contributions of foidolite, rischorrite, and lyavochorrite are almost equal. Apatite–nepheline and titanite–apatite–nepheline rocks form lenticular bodies in the apical parts of the foidolite sequence and grade into it. The thickness of these bodies estimated from the contour lines of apatite content varies from 200 m in the southwestern part of the Main ring to a few meters in its northeastern part.

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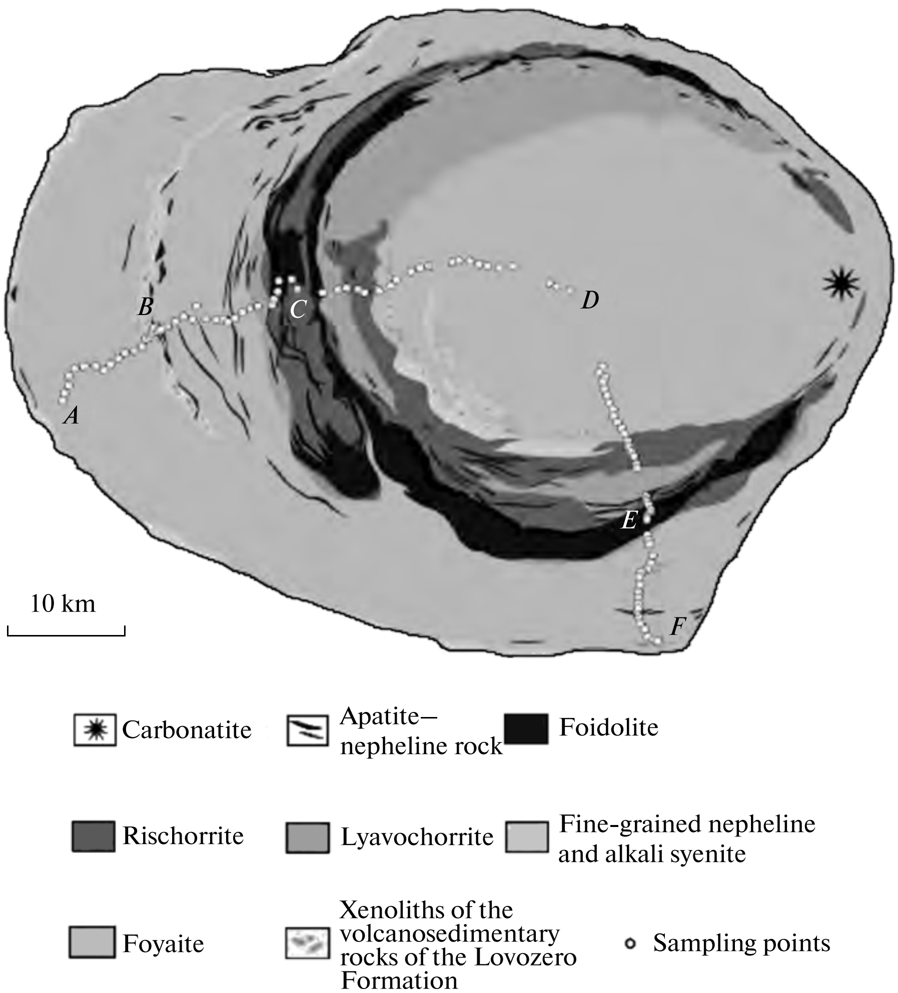

Fig. 1. Geological scheme of the Khibiny pluton (after Snyatkova et al.,1983). *A–B–C–D–E–F* is a profile line with sampling points.

Many xenoliths, which vary in their size from half a meter to several kilometers across and are composed of hornfels after volcanosedimentary rocks of the Lovozero Formation with a normative composition widely ranging from quartzite and granite to olivine basalt and alkaline ultrabasic rocks, occur within the Main ring and in the adjacent nepheline syenite on both its sides. The total area of xenoliths is less than 1% of the entire pluton, but their close association with fine-grained alkali and nepheline syenites (Fig. 1), which are the products of fenitization of the volcanosedimentary rocks, indicates that initially they were more abundant.

Fine-grained alkali and nepheline syenites, which occupy 3% of the pluton's area, are localized within three (semi)circular zones: at the pluton margin, at the periphery of the Main ring, and within the so-called Small semiring (Fig. 1). The latter reaches 500 m in thickness and located in the outer part of the pluton relative to the Main ring, is composed of fine-grained alkali and nepheline syenites (fenites?) with xenoliths of volcanosedimentary rocks pertaining to the Lovozero Formation, ijolite–urtite, and malignite. Fine-grained alkali and nepheline syenites of the marginal zone occur as separate lenses and strips up to 200 m thick, usually have gradual contacts with foyaite, and are often contained as xenoliths in the latter. Fine-grained syenite, in turn, hosts xenoliths of alkaline ultramafic rocks (peridotite, pyroxenite, and melilitolite) and metavolcanic rocks of the Imandra–Varzuga Zone and/or the Lovozero Formation. In addition to the fenite rims around xenoliths of the metamorphozed volcanosedimenatry rocks, fine-grained gneissose nepheline syenite with many xenoliths of fenitized hornfels is abundant in the Main ring zone.

The dike suite comprises veined bodies of the main rock complexes (microfoyaite, microijolite, and others) spatially related to the corresponding intrusive complexes, as well as phonolite, (mela)nephelinite, and alkali-feldspar trachyte dikes, explosion breccia pipes with monchiquite–carbonatite cement, and

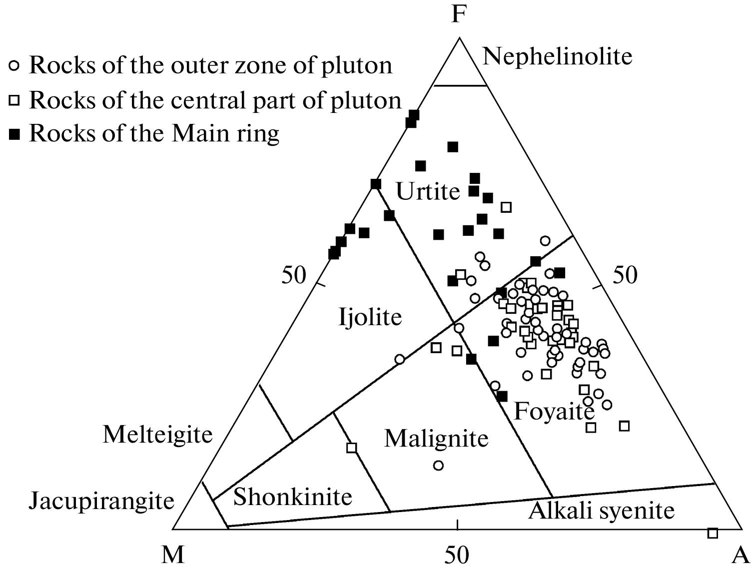

Fig. 2. Mineral composition of rocks from the Khibiny pluton along the *A–B–C–D–E–F* profile line estimated from counting of the areas occupied by minerals in the polished sections of the hand specimens. (M) dark-colored minerals, (A) K–Na-feldspars, (F) nepheline, kalsilite, sodalite, nosean, cancrinite, analcime, and natrolite.

finally the stockwork of carbonatite veins localized in the Main ring zone (Fig. 1).

Most of these rocks are composed of alkali feldspars, nepheline, and clinopyroxene with striking typomorphism (Borutsky, 1988, 2005; Yakovenchuk et al., 2005, 2008). Microcline- and orthoclase-perthite are the major minerals of foyaite and alkali syenite of the Khibiny pluton; perthite-free granular albite is sporadic. Perthite-free orthoclase grading into hyalophane is the major mineral of rischorrite, feldspatized ijolite–urtite, and hornfels after the volcanosedimentary rocks of the Lovozero Formation. Anorthoclase often replaces orthoclase in the latter rocks. Perthite-free albite is the major mineral of fenite, albitite, phonolite, and alkali-feldspar trachyte. Rock-forming feldspars with An > 5% were identified in slightly metamorphosed basalts from xenoliths of the Lovozero Formation rocks in foyaite at Mount Kitchepakh.

The object of this paper is to present new data on typomorphism of feldspars obtained during the study of the structural–compositional zoning of the Khibiny pluton from its western boundary in the area of the Khibiny Railway Station (point *A* in Fig. 1) via the Small semiring (*B*) and the Marchenko Peak ore occurrence (*C*) to its center at Mount Vantomnyutsk (*D*) and further across the Koashva deposit (*E*) to the southern margin at the base of Mount Kitchepakh (*F*). The BSE images of the polished sections were obtained on a LEO 1450 SEM. The identification of minerals coexisting with feldspars was carried out using X-ray diffraction and microprobe.

ABUNDANCE AND MORPHOLOGY OF FELDSPARS

Feldspars of foyaite. Foyaite is a medium- to coarse-grained leucocratic rock of greenish-gray color composed of tabular to isometric crystals of a potassium feldspar (usually with perthite ingrowths of albite), interstitial euhedral nepheline grains, prismatic clinopyroxene crystals of the aegirine–augite series, and alkali and Na–Ca-amphiboles (richterite–ferrorichterite, magnesiokatophorite–katophorite, magnesio-arfvedsonite–arfvedsonite and others). The quantitative ratio of feldspar, nepheline and melanocratic minerals (M) in foyaite along the *A–B–C–D–E–F* profile line varies broadly (Fig. 2) on average corresponding to $Fsp_{44}Ne_{40}M_{16}$.[1] The average mineral composition ($Fsp_{44}Ne_{40}M_{16}$) of foyaite from the outer (khibinite) part of the pluton is almost identical to the composition of these rocks in its central part ($Fsp_{43}Ne_{40}M_{17}$).

Microcline and orthoclase often coexist in the same samples as tabular crystals up to 3 cm across and up to 1 cm in thickness with perthite ingrowths of albite and numerous zonally arranged inclusions of fine-acicular aegirine. Their content in foyaite varies along the *A–B–C–D–E–F* line symmetrically with respect to the Main ring (Fig. 3). The percentage of alkali feldspars in the rock decreases towards the contacts with foidolite proportionally to the thickness of the latter, less distinctly around the Marchenko Peak (point *C*) and more notably in the area of Mount Koashva (point *E*). This variation is compensated by

[1] The volumetric ratio of minerals was calculated by counting the areas occupied by these minerals in the polished sections.

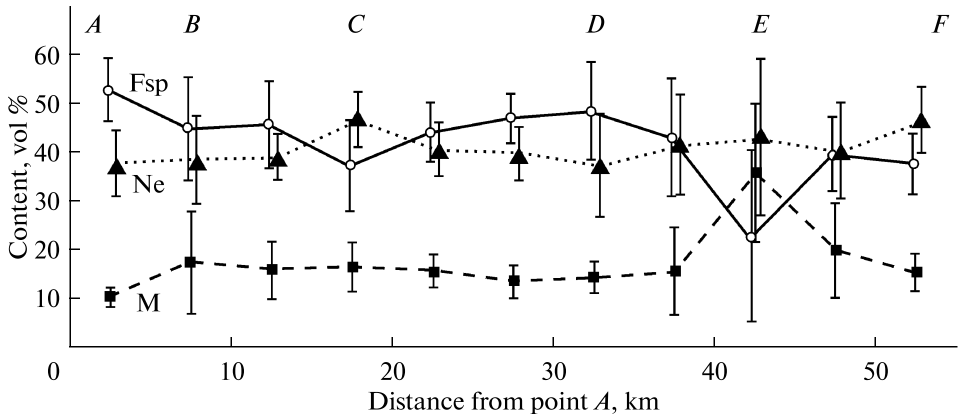

Fig. 3. Variation in the contents of alkali feldspars (Fsp), nepheline and replacing sodalite, natrolite, and analcime (Ne), and dark-colored minerals (M) in nepheline syenite along the *A–B–C–D–E–F* profile line (average values over 5-km intervals plus or minus standard deviation).

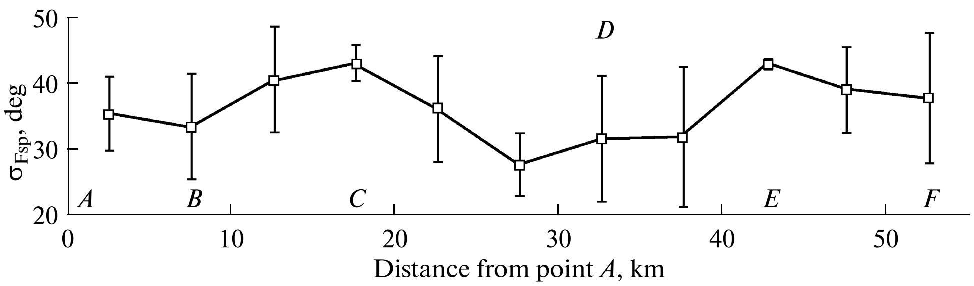

Fig. 4. Variation in σ_{Fsp} along the *A–B–C–D–E–F* profile line (average values over 5-km intervals plus or minus standard deviation).

an increase in the content of nepheline (point *C*) and melanocratic minerals (point *E*). At the point *C*, this leads to the formation of leucocratic foyaite transitional to urtite or even urtite texturally similar to foyaite, and at the point *E*, to mesocratic nepheline syenite and malignite. In addition, progressive enrichment of the feldspar at the expense of nepheline towards the margins and the center of the pluton results in the appearance of nepheline syenite described as umptekite (*A*) and pulaskite (*B*) (Ramsay and Hackman, 1894; Gorstka, 1971; Korobeinikov and Pavlov, 1990).

Foyaite is characterized by both massive and trachytoid structures. Trachytoid foyaite is commonly localized at the contacts with foidolite of the Small and Main rings and at the western and southern contacts of the pluton with country metamorphic rocks (Vlodavets, 1935; Eliseev et al., 1937; Tikhonenkov et al., 1963; Zak et al., 1972; Galakhov et al., 1975). It was also noted that trachytoid foyaite often alternates with its massive varieties (Snyatkova et al., 1983), so herewe deal with the abundance of special trachytoid rocks rather than with the transformation of these massive rocks into their trachytoid variety.

The degree of coorientation of tabular potassium feldspar crystals was estimated in polished sections sampled along the *A–B–C–D–E–F* line shown in Fig. 1 (Kalashnikov et al., 2006). As a measure, we used the standard deviation σ_{Fsp} of the *b* axis orientation of tabular potassium feldspar crystals from their average direction; 72 samples with tabular potassium feldspar crystals were studied. The diagram of the σ_{Fsp} variation (Fig. 4) demonstrates that the degree of foyaite isotropy progressively increases from the marginal and central parts of the pluton to the Main ring, near which foyaite is transformed into absolutely isotropic rischorrite.

The XRD of potassium feldspars revealed (Fig. 5) that the frequency of occurrence of orthoclase-dominant foyaite decreased from the peripheral part of the pluton to its center, and on this background a sharp orthoclase maximum develops near the Main ring. Because orthoclase is a higher temperature modification of potassium feldspar than microcline, when all other contributing factors are equal (Borutsky, 2005), then the decrease in the contribution of orthoclase from the margin of the foyaite complex towards its center allows a suggestion that the temperature of feldspar (re)crystallization consecutively fell in this direc-

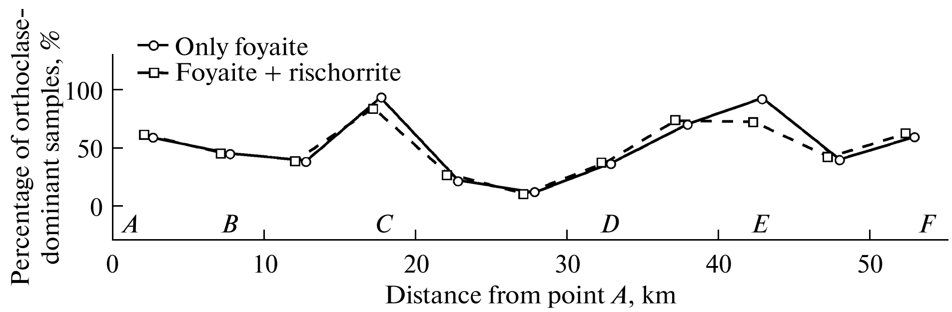

Fig. 5. The occurrence frequency of orthoclase- and microcline-dominant nepheline syenite along the *A*–*B*–*C*–*D*–*E*–*F* profile line.

tion as foyaite intrusion was being consolidated. The transition of microcline foyaite to an orthoclase variety and further to rischorrite near the Main ring accompanying the structural isotropization of these rocks obviously occurred after the tectonic relaxation of fault-line areas of the pluton and their reworking under the influence of a foidolite melt (fluid).

Albite in foyaite mainly occurs as perthite ingrowths in microcline or orthoclase. In addition to common exsolution perthites, perthites of replacement grow inward the potassium feldspar crystals from their contacts with nepheline. The secondary fine-grained sugarlike albite develops at the boundaries of primary mineral grains and along the fractures in the rock up to the formation of the almost monomineral albitite or aegirine–albite metasomatic rock.

Feldspars of foidolite and rischorrite. Ijolite–urtite is a fine- to medium-grained greenish-gray rock of amassive and gneissose structure. The rock consists of euhedral nepheline crystals, interstitial clinopyroxene grains of the aegirine–augite series, K–Na–Ca-amphiboles (potassic richterite, potassic ferrorichterite and others), annite, titanite, magnetite, ilmenite, and eudialite. Nepheline crystals occur as poikilitic inclusions in large orthoclase metacrysts (up to 10 cm across). The relative number of the latter in ijolite–urtite varies from zero to the threshold value determining transition to rischorrite (Fig. 2). Later albite occurs as fine-grained segregations and veins in close association with natrolite and aegirine.

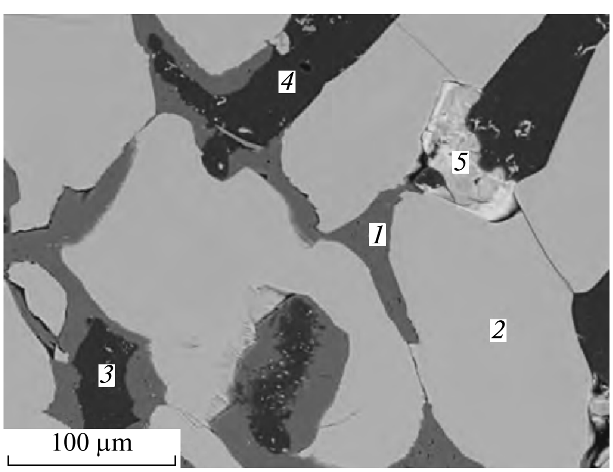

Fig. 6. Orthoclase poikiloblast (*1*) in the apatite–nepheline rock from Mt. Koashva; fluorapatite (*2*), nepheline (*3*), natrolite (*4*), and rinkite (*5*). A BSE image of the polished section.

Apatite–nepheline and apatite–titanite–nepheline rocks are a special foidolite variety of ijolite–urtite significantly enriched in fluorapatite up to almost monomineralic apatitolite. These are spotty greenish-gray rocks often occurring as stockworks of late fluorapatite veinlets in ijolite–urtite. The major minerals of these rocks are the same as in ijolite–urtite: fluorapatite, nepheline, diopside–aegirine–augite, potassic richterite, orthoclase, titanite, magnetite, and ilmenite. Orthoclase poikiloblasts in apatite–nepheline rocks are similar to those in ijolite–urtite and contain both nepheline and fluorapatite ingrowths (Fig. 6).

Rischorrite and poikilitic nepheline syenite are leucocratic massive medium- to coarse-grained rocks easily identified by the unaided eye due to their typical poikilitic texture. This texture is caused by large isometric orthoclase metacrysts (up to 20 cm across) with numerous poikilitic inclusions of nepheline, kalsilite, and dark-colored minerals in a fine- to medium-grained matrix composed of euhedral nepheline grains cemented by aegirine and potassic arvfedsonite. The average composition of rischorrite along the *A*–*B*–*C*–*D*–*E*–*F* line is $Fsp_{36}Ne_{44}M_{26}$. As in the case of foyaite, the boundary between rischorrite and feldspar urtite was drawn arbitrary in compliance with the QAPF classification. Actually, this is a continuous series of rocks genetically related to one another by the orthoclase poikiloblastesis phenomenon, so that even rischorrite and urtite with 20–40 vol % of orthoclase (they are often called yuvite in the literature concerning the Khibiny pluton) are almost indistinguishable.

In addition to the poikilitic texture, some samples of rischorrite and feldspar urtite (not more than 10%

of the samples studied) had micrographic intergrowths of nepheline with aegirine and orthoclase (Fig. 7). In the mid-20th century, the origin of such intergrowths was the subject of some heated discussions. The eutectic crystallization of the nepheline–syenite melt (Galakhov, 1959, 1975), metasomatic replacement of nepheline by orthoclase (Tikhonenkov, 1963), and the exsolution of the primary leucite (Galakhov, 1959) were proposed as possible explanations. Our data confirm the observations made by Tikhonenkov (1963), according to which orthoclase and aegirine usually occur as common skeletal crystals in these intergrowths, whereas nepheline inclusions occur as fragments of several grains traced beyond the skeletal crystals. The adjacent orthoclase and aegirine crystals, in their turn, can enclose fragments of the same nepheline grain.

The micrographic ingrowths of all three minerals can exist independently, but more often they occure as natural constituents of orthoclase clusters (Fig. 7) or even fragments of a single orthoclase poikilocrystal (Galakhov, 1959). Moreover, the skeletal feldspar and clinopyroxene crystals, as a rule, have the same zoning as the neighboring fully faceted crystals: the outer zone of clinopyroxene crystals is enriched in the aegirine component, and the outer zone of orthoclase crystals is enriched in celsian. All this allows us to state that these textures are the result of the nonequilibrium growth of orthoclase and aegirine metacrysts (Ivanyuk and Yakovenchuk, 1996) and cannot be regarded as products of the eutectic crystallization of the nepheline–syenite melt or the exsolution of hypothetical leucite.

The width of the transition zone between foyaite and rischorrite varies from 30 m to a few centimeters (Tikhonenkov, 1963). Even in the latter case, relict tabular crystals of perthite feldspar usually occur in rischorrite, and clusters of newly formed orthoclase poikilocrysts appear in foyaite at a distance of 3 m from the contact. Rischorrite becomes more fine-grained near the contact; it is enriched in dark-colored minerals and nepheline up to the formation of malignite and ijolite interlayers (Galakhov, 1959; Zak et al., 1972; our observations).

Feldspars of alkali syenite. Alkali syenite of the Khibiny pluton is a sharply subordinated rock relative to nepheline syenite with a gradual transition to the latter. Alkali syenite is a white or light-gray fine- to medium-grained massive rock, 75–99 vol % of which is composed of tabular orthoclase-perthite crystals along with interstitial grains of nepheline, aegirine–augite, and magnesioarfvedsonite (Gorstka, 1971; Korobeinikov and Pavlov, 1990; our data). As a rule, dark-colored minerals mainly occur as uniform disseminations in the feldspar matrix and rarely form large segregations (up to 50 cm in size) that impart a taxitic appearance to the rock.

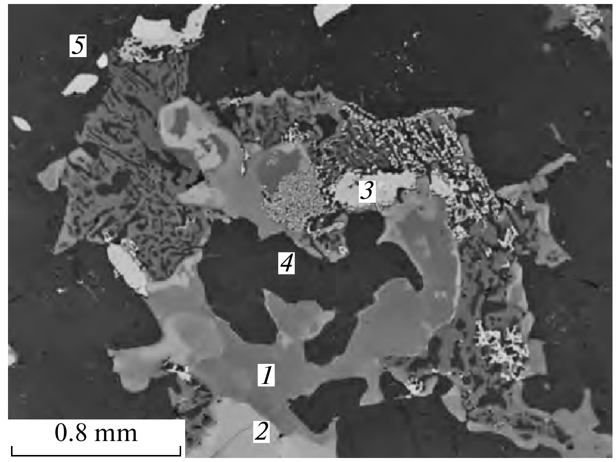

Fig. 7. Micrographic intergrowths of orthoclase (*1*), hyalophane (*2*), and aegirine (*3*) with nepheline (*4*) in feldspathic urtite from Mt. Koashva; fluorapatite (*5*). A BSE image of the polished section.

Feldspars of hornfels and fenite. Hornfels is a fine-grained rock with an average grain size of 0.07 mm; typical conchoidal fracture; and a color varying from white, light-gray, pale-purple, sky-blue, different hues of green and brown to dark gray and black. The rock is characterized by wide variations in the mineral composition in separate xenoliths, samples, or even polished sections (Yakovenchuk et al., 2005). The structure of rocks changes from massive and vaguely banded to contrasting- and lenticular-banded, taxitic, and porphyritic. The microstructure is typically granoblastic and poikiloblastic with large metacrysts of orthoclase, amphibole, corundum, nepheline, aenigmatite, and other minerals.

Plagioclase corresponding to oligoclase–andesine is the major mineral of slightly metamorphosed metabasalt and metatuffite at Mount Kitchepakh. Microphenocrysts of tabular plagioclase crystals (up to 0.1 mm in length) in aphyric hornfels are incorporated into a fine-grained groundmass composed of diopside, augite, phlogopite, and titanomagnetite.

Anorthoclase, which is the major mineral of hornfels and fenite from xenoliths in nepheline syenite of the Khibiny and Lovozero plutons, is the product of high-temperature alkaline metasomatic reactions:

$$\underset{\text{Quartz}}{27SiO_2} + \underset{\text{Annite}}{2KFe_3AlSi_3O_{10}(OH)_2}$$

$$+ \underbrace{K^+ + 3Na^+ + 4AlO_2^- + 8H_2}_{\text{Alkaline fluid}} = \underset{\text{Sekaninaite}}{3Fe_2Al_4Si_5O_{18}}$$

$$+ \underset{\text{Anorthoclase}}{6(K_{0.5}Na_{0.5})AlSi_3O_8} + 10H_2O,$$

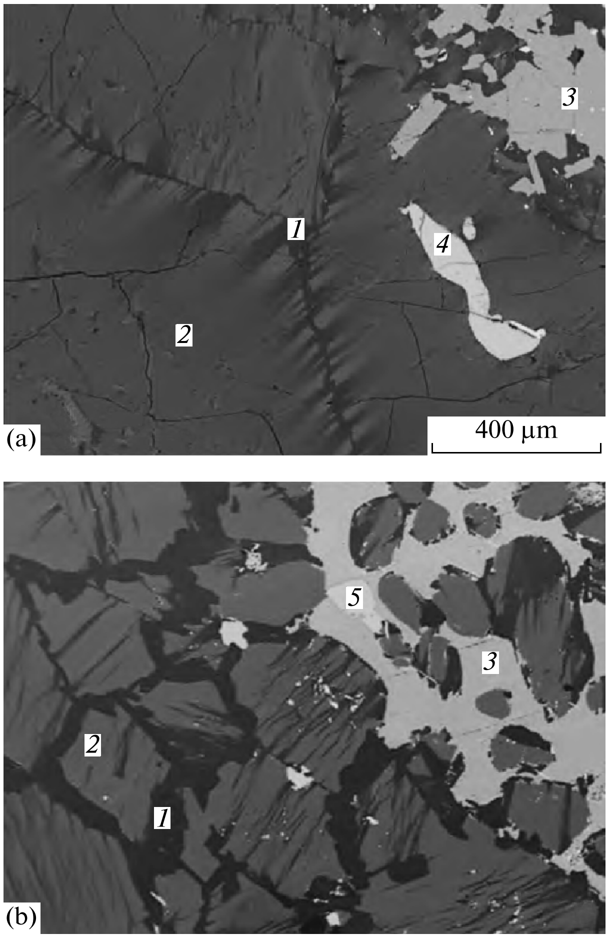

Fig. 8. (a) Initial and (b) final stages of formation of replacement perthites in anorthoclase from annite–anorthoclase hornfels, the Marchenko Peak. Albite (*1*), anorthoclase (*2*), annite (*3*), titanite (*4*), pyrrhotite (*5*). A BSE image of the polished section.

$$\underset{\text{Quartz}}{6SiO_2} + \underbrace{K^+ + Na^+ + 2AlO_2^-}_{\text{Alkaline fluid}} = \underset{\text{Anorthoclase}}{2(Na_{0.5}K_{0.5})AlSi_3O_8},$$

$$\underset{\text{Quartz}}{8SiO_2} + \underbrace{Na^+ + K^+ + 6AlO_2^- + 2HF}_{\text{Alkaline fluid}} = \underset{\text{Topaz}}{Al_2SiO_4F_2} + \underset{\text{Andalusite}}{Al_2SiO_5} + \underset{\text{Anorthoclase}}{2(K_{0.5}Na_{0.5})AlSi_3O_8} + H_2O \text{ etc.}$$

Correspondingly, the minerals closely associated with anorthoclase include andalusite, sillimanite, cordierite–sekaninaite, topaz, fayalite, muscovite, phlogopite–annite, edenite, (magnesio)arfvedsonite, diopside–gedenbergite–aegirine, epidote, corundum, rutile, tausonite, baddeleyite, pyrrhotite, and zircon. Anorthoclase grains (on average 0.01–0.02 mm across) are usually overfilled with numerous round inclusions of ilmenite, pyrrhotite, and flakes of annite imparting a black color to the rocks. The fine-grained matrix of these rocks contains more or less evenly distributed anorthoclase microspherules (up to 1 mm in diameter, but usually 0.1–0.2 mm) consisting of larger grains free from inclusions and formed by collective recrystallization.

"Fresh" anorthoclase is rare, because its fenitization results in its replacement with albite and formation of either pure orthoclase or anorthoclase depleted in sodium:

$$\underset{\text{Anorthoclase}}{2(K_{0.5}Na_{0.5})AlSi_3O_8} + \underbrace{Na^+ + AlO_2^- + 3SiO_2}_{\text{Alkaline fluid}} = \underset{\text{Albite}}{2NaAlSi_3O_8} + \underset{\text{Orthoclase}}{KAlSi_3O_8}.$$

This process commonly begins with the development of perthites replacing anorthoclase grains from their margins (Fig. 8a) and ends by the retention of lamellar anorthoclase relics in albite, which are typical of fenitized hornfels from xenoliths at the Marchenko Peak and Mount Kaskasnyunchorr.

Feldspars of dike suites. In addition to the fine-grained analogues of nepheline and alkali syenite, feldspar-bearing dikes of the Khibiny pluton include phonolite and alkali-feldspar trachyte. These are grayish green to greenish black fine-grained rocks composed of a framework aggregate of tabular orthoclase crystals (20–200 μm) rimmed by needles of aegirine–augite with interstitial nepheline, analcime, cancrinite, and natrolite with aegirine inclusions. Secondary orthoclase occurs locally in alkali-feldspar trachyte dikes, which cut rischorrite and orthoclase-bearing urtite (Arzamastsev et al., 1988). This fact shows that feldspatization of the country rocks accompanying the formation of the Main foidolite ring lasted longer than it was considered earlier and affected both foyaite and dike suites.

CHEMISTRY OF FELDSPARS

The chemical composition of feldspars from the Khibiny pluton was determined on a MS-46 Cameca microprobe at the Geological Institute, Kola Division, Russian Academy of Sciences (RAS). The study was conducted under the following conditions: accelerating voltage 20 kV, current 20 nA, and beam diameter 3 μm. The following standards were used: lorenzenite (for Na), wadeite (K), vollastonite (Ca, Si), pyrope (Al), synthetic $MnCO_3$ (Mn), and hematite (Fe). The selected data illustrating the composition of 15 K–Na-feldspars and 15 albites chosen from more than 200 original analyses are shown in Tables 1 and 2.

The variation in the composition of potassium feldspars and albite in the Khibiny rocks along the *A–B–C–D–E–F* line (Fig. 1) is shown in Fig. 9. It is seen

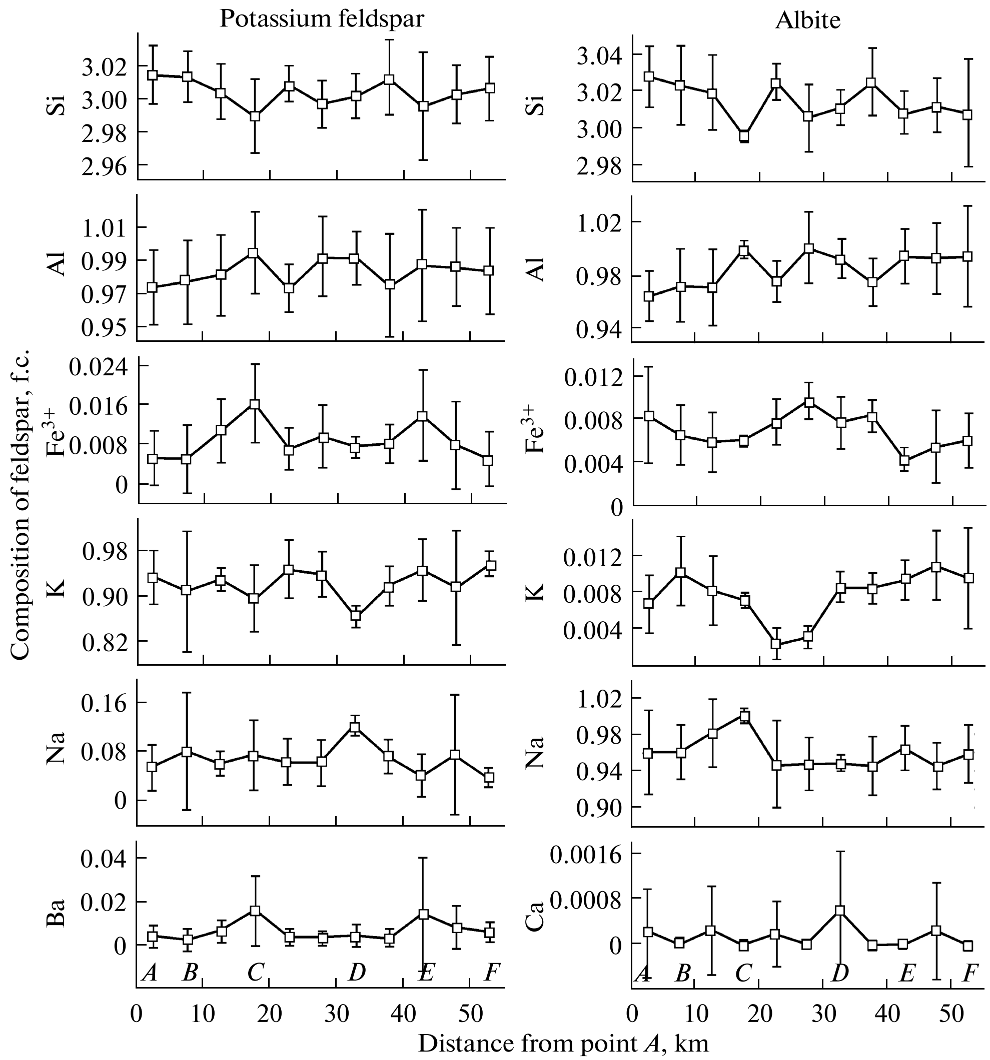

Fig. 9. Variation in the composition of potassium feldspar and albite in the Khibiny rocks along the *A–B–C–D–E–F* profile line (average values over 5-km intervals plus or minus standard deviation).

that this variation is symmetrical in respect to the center of the pluton. The shape of the graphs displaying variations in Si and Al contents in potassium feldspar is almost identical to the shape of the corresponding graphs of albite composition: feldspars in the central part of the pluton (point *D*) and the area of the Main ring (points *C* and *F*) are enriched in Al at the expense of Si. The replacement is compensated by the following schemes:

$$(1)\ (K,Na) + Si \longleftrightarrow (Ba,Ca) + (Al,Fe^{3+})\ \text{and}$$

$$(2)\ \square + Si \longleftrightarrow (Na,K) + Al,$$

which control the principal difference in the composition of the minerals studied in the central Khibiny pluton and its Main foidolite ring. Thus, the potassium feldspar from foyaite from the central part of pluton is characterized by a chemical substitution corresponding to scheme (2) and this from nepheline syenite of the Main ring corresponds to scheme (1) with participation of Ba.[2] On the contrary, the enrichment of albite from foyaite from the central part of the pluton in Al is compensated by scheme (1), whereas this from nepheline syenite of the Main ring is compensated by scheme (2) with Ca instead of Ba.

Feldspars from the ore (point *E*, Koashva deposit) and mineralized rock (point *C*, Marchenko Peak occurrence) of the Main ring primarily differ in the Na/K ratio (Fig. 8). Both orthoclase and albite from large operating deposits are depleted in Na.

In anorthoclase of fenitized hornfels after volcanosedimentary rocks of the Lovozero Formation K is partially replaced by Na. The Na content in most samples is only 0.2–0.3 f.c. (Fig. 10) due to the exsolution

[2] The role of Ba and Fe in rischorrite and ijolite–urtite increased until the final stages of orthoclase poikiloblastesis; therefore, the marginal zones of such poikiloblasts in both rocks often contain ferroan hyalophane (Fig. 7).

Table 1. Chemical composition of K–Na-feldspars from the Khibiny pluton, wt %

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Or	Mc	Mc	Or	Or	Or	Or	Or	Or	Or	Mc	Or	Or	Anor	Anor
SiO_2	65.42	65.20	63.89	64.94	65.13	65.12	64.72	63.25	65.02	60.03	65.00	65.16	65.03	64.90	63.05
Al_2O_3	16.80	17.51	18.12	18.00	18.01	18.17	18.34	16.82	17.63	18.95	18.43	18.36	18.55	18.33	21.58
Fe_2O_3	0.09	0.18	0.13	0.04	0.22	0.07	0.58	0.02	0.71	0.72	0.37	0.24	0.29	–	–
CaO	–	–	–	–	–	–	–	0.43	–	–	–	–	–	–	0.89
Na_2O	0.37	0.39	0.65	0.37	0.47	0.97	–	0.09	0.38	0.47	0.67	0.17	0.87	2.86	8.36
K_2O	16.39	16.03	16.16	16.45	15.97	15.40	16.78	16.05	16.08	13.75	15.92	16.52	15.15	13.20	2.20
Rb_2O	–	–	–	–	–	–	0.24	–	–	–	–	–	–	–	–
SrO	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.46
BaO	0.00	0.56	0.13	0.00	0.40	0.33	–	–	0.62	5.31	0.00	–	–	–	0.58
Total	99.07	99.87	99.08	99.80	100.20	100.06	100.66	96.66	100.43	99.23	100.39	100.45	99.89	99.29	99.29
Formula coefficients (O = 8)															
Si^{4+}	3.05	3.03	2.99	3.01	3.01	3.01	2.99	3.03	3.01	2.90	2.99	3.00	3.00	2.99	2.87
Al^{3+}	0.92	0.96	1.00	0.98	0.98	0.99	1.00	0.96	0.96	1.08	1.00	1.00	1.01	1.00	1.16
Fe^{3+}	–	0.01	–	–	0.01	–	0.02	–	0.02	0.03	0.01	0.01	0.01	–	–
Ca^{2+}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.04
Na^+	0.03	0.04	0.06	0.03	0.04	0.09	0.00	–	0.03	0.04	0.06	0.02	0.08	0.26	0.74
K^+	0.98	0.95	0.96	0.97	0.94	0.91	0.99	0.98	0.95	0.85	0.93	0.97	0.89	0.78	0.13
Rb^+	–	–	–	–	–	–	0.01	–	–	–	–	–	–	–	–
Sr^{2+}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.04
Ba^{2+}	–	0.01	–	–	0.01	0.01	–	–	0.01	0.10	–	–	–	–	0.01
Total	4.99	4.98	5.02	5.00	4.99	5.00	5.01	4.99	4.99	4.99	5.00	5.00	4.99	5.02	4.99
End members															
An	–	–	–	–	–	–	–	0.02	–	–	–	–	–	–	0.05
Ab	0.03	0.04	0.06	0.03	0.04	0.09	–	0.01	0.03	0.04	0.06	0.02	0.08	0.25	0.77
Or	0.96	0.95	0.94	0.97	0.94	0.90	0.97	0.97	0.93	0.83	0.93	0.98	0.91	0.75	0.13
Csn	–	–	–	–	0.01	0.01	–	–	0.01	0.10	–	–	–	–	0.01
Rbc	–	–	–	–	–	–	0.01	–	–	–	–	–	–	–	–
For	–	0.01	–	–	0.01	–	0.02	–	0.02	0.03	0.01	0.01	0.01	0.00	–

Note: Deposits and rocks: (1–4) foyaite: (1) Mt. Yumjechorr, (2) Mt. Yudychvumchorr, (3) Mt. Kukisvumchorr, (4) Mt. Kitchepakh; (5) malignite, Mt. Eveslogchorr; (6, 7) rischorrite: (6) Mt. Eveslogchorr, (7) Mt. Kukisvumchorr; (8) apatite–nepheline rock, Mt. Koashva (Fig. 6); (9, 10) urtite, Mt. Koashva (Fig. 7); (11) pulaskite, Mt. Kukisvumchorr; (12) phonolite, Mt. Kukisvumchorr; (13) edenite–orthoclase hornfels, Mt. Yumjechorr; (14) biotite–anorthoclase hornfels, the Marchenko Peak; (15) corundum–pyrrhotite–anorthoclase hornfels, Mt. Kaskasnyunchorr. Or, Mc, and Anor are orthoclase, microcline, and anortholcase, respectively. End members: An (anorthite), Ab (albite), Or (orthoclase), Csn (celsian), Rbc (rubicline), For (ferriorthoclase $KFe^{3+}Si_3O_8$).

Table 2. Chemical composition of albite from the Khibiny pluton, wt %

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	68.90	69.24	68.12	69.34	68.76	68.45	69.62	68.57	67.11	64.13	55.71	55.98	58.83	66.44	67.70
Al_2O_3	19.13	18.45	18.06	19.11	18.86	18.51	19.36	19.70	18.45	19.02	26.96	26.44	24.46	20.22	18.93
Fe_2O_3	0.19	0.23	0.28	0.18	0.28	0.27	0.11	0.16	0.20	0.17	–	0.07	2.04	–	0.22
CaO	–	0.03	0.04	–	–	–	–	–	–	0.74	9.65	8.50	5.27	0.18	–
Na_2O	12.12	11.72	11.64	11.61	12.17	10.80	10.07	11.26	10.69	11.58	5.78	6.17	8.62	10.23	11.74
K_2O	0.15	0.05	0.03	0.03	0.18	0.13	0.11	0.18	0.16	3.80	0.16	0.16	0.36	0.35	0.08
SrO	–	–	–	–	–	–	–	–	–	–	–	0.57	0.62	1.61	–
BaO	–	–	–	–	–	–	–	–	–	–	–	–	–	0.95	–
Total	100.49	99.72	98.17	100.28	100.24	98.16	99.28	99.86	96.61	99.44	98.26	97.89	100.20	99.98	98.67
Formula coefficients (O = 8)															
Si^{4+}	3.00	3.03	3.03	3.02	3.00	3.03	3.04	2.89	3.02	2.91	2.54	2.57	2.65	2.95	3.00
Al^{3+}	0.98	0.95	0.95	0.98	0.97	0.97	1.00	1.01	0.98	1.02	1.45	1.43	1.30	1.06	0.99
Fe^{3+}	0.01	0.01	0.01	0.01	0.01	0.01	–	0.01	0.01	0.01	–	–	0.07	–	0.01
Ca^{2+}	–	–	–	–	–	–	–	–	–	0.04	0.47	0.42	0.25	0.01	–
Na^+	1.02	0.99	1.00	0.98	1.03	0.93	0.85	0.95	0.93	1.02	0.51	0.55	0.75	0.88	1.01
K^+	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.22	0.01	0.01	0.02	0.02	–
Sr^{2+}	–	–	–	–	–	–	–	–	–	–	–	0.02	0.02	0.04	–
Ba^{2+}	–	–	–	–	–	–	–	–	–	–	–	–	–	0.02	–
Total	5.02	4.99	4.99	4.98	5.03	4.95	4.89	4.98	4.95	5.20	4.99	4.99	5.06	4.97	5.01
End members															
An	–	–	–	–	–	–	–	–	–	0.03	0.48	0.42	0.24	0.01	–
Ab	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.80	0.52	0.55	0.67	0.91	1.00
Or	–	–	–	–	–	–	–	–	–	0.17	0.01	0.01	0.00	0.02	–
Csn	–	–	–	–	–	–	–	–	–	–	–	–	–	0.02	–
Rbc	0.01	–	–	–	0.01	0.01	–	0.01	0.01	–	–	–	0.02	–	–
Fab	–	–	–	–	–	–	–	–	–	–	–	–	0.05	–	–

Note: Deposits and rocks: (1–5) foyaite: (1) Mt. Yumjechorr, (2) Mt. Yudychvumchorr, (3) Marchenko Peak, (4) Mt. Kukisvumchorr, (5) Mt. Kitchepakh; (6) malignite, Mt. Eveslogchorr; (7) rischorrite, the Marchenko Peak; (8, 9) ijolite–urtite: (8) Mt. Eveslogchorr, (9) Mt.Koashva; (10) alkali-feldspar trachyte, Mt. Njorpakhk (Arzamastsev et al., 1988); (11) annite–anortholcalse hornfels, Mt. Kukisvumchorr; (12) annite–hercynite–anorthoclase hornfels, Mt. Kukisvumchorr; (13) metabasalt, Mt. Kitchepakh; (14) phlogopite–nepheline–albite hornfels, Mt. Kaskasnyunchorr; (15) annite–albite–anorthoclase hornfels, the Marchenko Peak. End members: An (anorthite), Ab (albite), Or (orthoclase), Csn (celsian), For (ferriorthoclase $KFe^{3+}Si_3O_8$), Fab (ferri-albite $NaFe^{3+}Si_3O_8$).

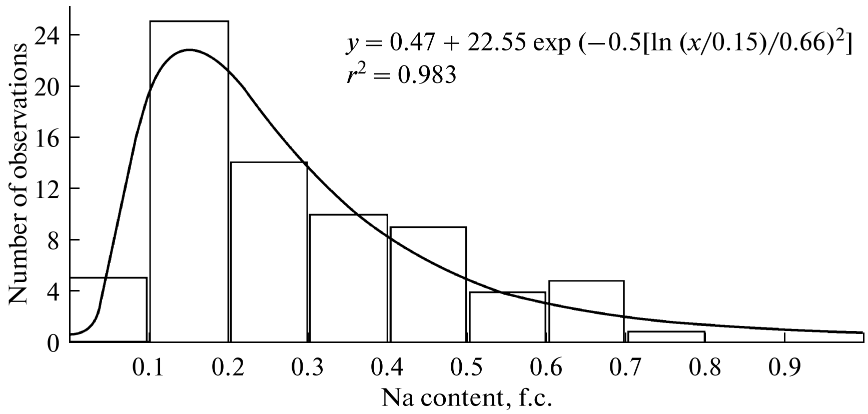

Fig. 10. Occurrence frequency of minerals of the orthoclase–anortholcase series in hornfels from xenoliths of the volcanosedimentary rocks in foyaite of the Khibiny pluton.

of high-Na anorthoclases and replacement by albite (Fig. 8). Furthermore, anorthoclase is characterized by isomorphism according to scheme (1) up to the formation of ferroan hyalophane (the Ba content reaches 0.3 f.c.) in the hornfels of Mount Kaskasnyunchorr.

The Ca content in plagioclases from the volcanosedimentary rocks of the Lovozero Formation diminishes from 0.3 f.c. in metabasalt to zero in metaquartzite. This allows identification of the protolith composition of the slightly fenitized hornfels from the Khibiny pluton using the composition of plagioclase for this purpose.

DISCUSSION

In the light of the original and published data (Ivanyuk et al., 1996, 2006; Goryainov et al., 1998, 2007; Yakovenchuk et al., 2005, 2008; Konopleva et al., 2008), the formation of the Khibiny pluton comprises the following sequence of events:

(1) deposition of shallow-water terrigenous and volcanosedimentary rocks of the Lovozero Formation (quartzites, sandstones, basalts, and basaltic tuffs) with rock-forming andesine–labradorite;

(2) emplacement of the foyaite pluton with its marginal part composed of massive, substantially orthoclase rocks and the central part consisting of trachytoid, largely microcline rocks due to the gradually decreasing crystallization temperature of the melt towards the center of the pluton;

(3) formation of the Main and Small conical fracture zones in a completely consolidated foyaite body sharply expanding near the surface owing to dilation; infill of the fracture zones with the foidolite melt with a notable increase in the K/(K+Na) ratio of its final portion due to the decrease in the crystallization temperature of nepheline; heating of the adjacent (especially covering) foyaite, its feldspatization and structural isotropization; and, finally, transformation of the xenoliths of the volcanosedimentary rocks incorporated into foidolite and the zone of heated foyaite first into anorthoclase hornfels and then into orthoclase–albite fenite;

(4) consolidation and fracturing of ijolite–urtite along the same ring, the position of which is determined by the stress field in the expanding Khibiny pluton; squeezing of the residual melt and related fluids enriched in Ca, K, P, F, Cl, C, and H into the fractures with the formation of fluorapatite stockworks; kalsilite–orthoclase poikiloblastesis in ijolite–urtite, apatite–nepheline rocks, and foyaite owing to the release of excess potassium from nepheline as foidolite cooled and to the formation of rischorrite, lyavochorrite, and orthoclase-bearing ijolite–urtite;

(5) origin of the pegmatite and hydrothermal veins with a sharp prevalence of microcline over orthoclase; dikes of alkaline, ultramafic rocks, and carbonatites; explosion pipes with monchiquite–carbonatite cement and zones of low-temperature hydrothermal reworking of rocks localized at the shallow-seated part of the Main ring.

All these events, including the lowest-temperature processes, were recorded in the composition and typomorphic features of feldspars, which can be used as sensitive indicators of mineral formation conditions and localization of ore mineralization in the Khibiny pluton.

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