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REE Distribution in Corundum-Bearing and Other Metasomatic Rocks during the Exhumation of Metamorphic Rocks of the Belomorian Belt of the Baltic Shield

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Abstract—The paper reports data on the distribution of REE in metasomatic rocks, including those with corundum, that were formed during the exhumation of the rocks of the Belomorian Belt at 1.9–1.75 Ga. This process is thought to have occurred concurrently with the horizontal extension and tectonic denudation of the upper crust, which, in turn, induced the massive release of fluids. The latter formed two major groups of silicic metasomatic rocks. The deepest-sitting corundum-bearing and other mafic metasomatic rocks are enriched in REE, alkalis, and alumina compared to the host rocks. The coeval acid metasomatic rocks such as orthotectites are, conversely, depleted in REE (with positive Eu anomalies), mafic elements, and HFSE but are also enriched in alumina. These complimentary rocks are thought to have been produced early during the exhumation of deep rocks under the effect of reduced fluids whose genesis was related to decompression. The silicic metasomatic rocks of the second group (with muscovite) have elevated REE concentrations (with negative Eu anomalies) and were formed by already oxidized fluids at shallower depths. The fact that the corundum-bearing metasomatic rocks are enriched in REE (in spite of the ultrabasic composition of these rocks) suggests that they were generated in an extensional environment with the participation of deep fluids, which enriched the rocks in Al, Na, K, Ba, Sr, Zr, and LREE.

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INTRODUCTION

The past years were marked by the acute interest of many researchers in problems related to the exhumation of metamorphic rocks [1], which is thought to be related to either compression or, more commonly, extension processes [2]. The structural aspects of extension processes, namely, gently dipping normal faults and the complexes of metamorphic cores, whose evolution results in the exposure of deep rocks at the surface, are now understood fairly well, although national researchers still pay inadequately little attention to them [3–5].

Extensional environments, namely, shock decompression, predetermines the explosion-like release of fluids, which form metasomatic rocks in both the metamorphic rocks and the overlying complexes. Hence, along with the structural aspects of exhumation, an important issue is the compositional transformations of deep rocks during their exhumation [6–8]. Moreover, recent studies have demonstrated that many minerals that were previously considered to be indicators of high pressures (corundum, sapphirine, garnet, kyanite, sillimanite, and even diamond) can be formed under the effect of fluids during the retrograde stage [9–11] but not during metamorphic culmination, which makes the compositional modification of decompressed rocks even more interesting. An important applied aspect of this problem is related to the fact that important rock transformations are often associated with the accumulation of valuable minerals. For example, the vast reserves of various gems in the Pamirs and Himalayas, which were believed to be of Paleozoic and even Precambrian in age, were proved to be formed no earlier than at lest 25 Ma, when the crystalline rocks were exhumed [9, 12].

The problem of the exhumation of high-grade Precambrian metamorphic rocks has long been ignored, and the occurrence of these rocks at the surface was most often explained by erosion. Because of this and in spite of the significance of this problem, the information of REE concentrations in metasomatic rocks coeval with the exhumation of deep rocks is very scarce. It is known that the behavior of REE is controlled by the mineralizing medium [13], a fact very important for understanding the constantly varying conditions when deep rocks are exhumed. Because of this, the distribution of REE can be regarded as a feature that can be used to reveal the conditions under which the metasomatic rocks were formed.

Based on his original data, the author set himself the task of elucidating the character of the REE distribution in the major types of metasomatic rocks produced when the metamorphic rocks of the Belomorian Belt, one of the most important structures of the eastern Baltic Shield (Fig. 1), were exhumed. He also attempted to quantify the effect of various physicochemical factors on the REE distribution during the formation of these rocks and to reproduce the possible migration ways of these elements.

The metasomatic and host rocks were analyzed for major components and Cr, Ni, Co, and V at the Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, in Irkutsk. Other trace elements and REE were analyzed at the Institute of the Lithosphere, Russian Academy of Sciences, in Moscow on a TEF XRF analyzer and a Monospec 1000 spectrometer by atomic emission spectrometry with inductively coupled plasma. The metrological characteristics of this method and their comparison with those of other analytical techniques used to analyze rocks for REE can be found in [14].

Modern studies at the Belomorian belt are mostly focused on its early evolutionary stages, whereas the late ones are commonly regarded as insignificant, which could not significantly disturb the composition and structure of the belt [15]. I believe that the actual situation is much more complicated, and no early evolutionary stages of the belt can be adequately comprehensively understood unless the main structural and compositional transformations of the rocks during their exhumation are studied thoroughly enough.

GEOLOGICAL OVERVIEW

Most protoliths of the Belomorian Belt were formed at 2.9–2.8 Ga and were then metamorphosed to the amphibolite and, sometimes, granulite facies and underwent tectonic flow and were affected by related migmatization [15]. The role of the latter process in the shaping of the modern structure of the belt remains largely uncertain: some researchers believe that most of the acid rocks were derived from amphibolite protoliths [16], whereas others maintain that the bulk composition of these rocks has not been principally modified and their protoliths were silicic [17]. The rocks of the Belomorian Belt were intruded by numerous (more than 5000) bodies of basic–ultrabasic rocks (known under the name of drusites [18]) at 2.5–2.45 Ga. These rocks crystallized at depths of 30–20 km and now compose rootless drop- or boudin-shaped bodies and only very rare dikes. A younger episode of drusite formation corresponded to 2.2–2.1 Ga and was synchronous with Jatulian volcanism [19], but these drusites are an order of magnitude less abundant. The most famous rocks of the Belomorian Block are muscovite and muscovite–rare metal pegmatites, which compose thousands of veins. The pegmatites were emplaced at 1.9–1.75 Ga under a pressure of 7 kbar [20], i.e., at depths of approximately 20 km. Geological and geochronological lines of evidence suggest that the rocks of the Belomorian Complex were at (or near) the surface at 1.75–1.7 Ga [21].

In spite of the huge number of studies devoted to the Belomorian Belt, the problem of the exhumation of its metamorphic rocks has never been seriously considered, although some researchers mention that this process could be related to the Svecofennian collision [15, 17]. Similar collision-related interpretations of the exhumation of metamorphic sequences were also proposed for most foldbelts around the world. However, the latest years witness amassing evidence that these processes occurred in extensional environments [1–8]. This publication is focused on this final evolutionary stage of the Belomorian Belt, which most probably also occurred in an extensional environment [21]. Structurally, the exhumation process of metamorphic rocks is a complicated phenomenon. This is not just the uplift of deep-sitting rocks in the form of a block but rather the extension of the crust with the rupture of its uppermost brittle portion and the ascent of the semiplastic middle and lower crustal material in the form of a brittle–plastic diapir (Fig. 2). The analysis of Paleoproterozoic structures in the eastern Baltic Shield reveals a significant role of strike-slip faulting [22], which suggests that the Belomorides were exposed at the surface owing to the action of at least two regional mechanisms: horizontal extension (across the belt) and strike-slip faulting (parallel to its strike). The former mechanism exposed the deep rocks at the surface and generated gently dipping normal faults, while the latter gave rise to a diversity of rotation structures (Fig. 1). This unusual dynamic environment predetermined the complicated character of the metasomatic processes, whose driving force was deep fluids of decompressional nature, which were released at a drastic pressure decrease at unchanging or increasing temperature, as is typical of extensional environments [22].

The metasomatic rocks of the final evolutionary stage of the Belomorian Belt can be provisionally subdivided into two groups: (i) basic rocks consisting of hornblende, micas, corundum, garnet, gedrite, kyanite, and epidote and (ii) silicic rocks composed of quartz; feldspars; mica; and, often, garnet.

The basic metasomatic rocks of the Belomorian Belt were described in just a few papers [23], and their corundum-bearing varieties were studied a little bit more thoroughly [24, 25]. The basic metasomatic rocks were formed within the age range of 2.45–1.8 Ga, as is determined by the fact that these rocks often replace drusites and are cut across by muscovite pegmatites. The corundum-bearing and related metasomatic rocks consist of garnet, amphibole, corundum, sapphirine, kornerupine, hugbomite, spinel, rutile, and staurolite and, accordingly, can be regarded as deep rocks, although there are still no accurate thermobarometric data on them (and they can hardly be obtained at all, inasmuch as most minerals in these rocks show unequilibrated relations). According to indirect evidence, the rocks are thought to have been initially formed under pressures of 8–6 kbar [25]. Varieties with corundum also contain such minerals as cordierite, chlorite, scapolite, clinozoisite, epidote, calcite, and sericite, which testify that the rocks could be formed at relatively shallow depths during the final evolutionary stage. Most mineral grains in the rocks are very large and often occur as sheaf-shaped and massive aggregates, which make these rocks principally different from the fine- to medium-grained host rocks. Garnet, gedrite, and cordierite-bearing metasomatic rocks are fairly widely spread in the Belt, while varieties with corundum occur only locally, with rocks with macroscopically discernible corundum found only at eight localities (Fig. 1). Regionally, the corundum-bearing metasomatic rocks are spatially restricted to the peripheral parts of ring structures, which are the metamorphic cores of the Belomorian Belt and were formed late in the course of its structural evolution. On a local scale, these rocks are related to recumbent folds typical local structures (Figs. 2, 3) band, more specifically, to their frontal parts or strike-slip fault boundaries [24]. It was previously believed that recumbent folds are generated in horizontal compression environments [26], but now, as the nature of gently dipping tectonic zones was revised (strike-slip faulting instead of overthrusting), many researchers think that these folds can be formed in extensional environments [27]. The upper parts of rock domains with corundum mineralization are usually armored by layers of giant-grained garnet amphibolites, which are also of metasomatic genesis and could serve as structural traps because of their very little permeability to deep fluids [28].

Another type of metasomatic rocks related to the exhumation stage of the Belomorian Belt are silicic rocks, which were classified into two groups according to geological setting, geochemistry, and mineralogy. The first group includes rocks of granitic composition, which compose vertical veins or, more rarely, orthotectic bodies or viscous tectonic zones made up of augen blastomylonites. The other group of the silicic metasomatic rocks comprises pegmatites of the muscovite and muscovite–rare metal associations and their schistose varieties with coarse-flaky muscovite (diaphthorite rock, according to [20]). The axial part of the Belomorian Belt shows ubiquitous gradual transitions from biotite-bearing migmatites to muscovite–biotite and, farther, muscovite schists. The composition of the rocks is thereby modified, as also are their textures and structures, so that banded migmatites, which are often referred to as aluminous or "rusty" gneisses, give way to muscovite schists. The latter are deformed into small isoclinal ptigmatitic folds with a clearly pronounced schistosity in the axial surface; predominantly gently dipping lineation; rotational, reverse, and boudinage structures; and, occasionally, with linear breccias and thin mylonite zones. The muscovite schists compose single zones in the crystalline rocks of the Belomorian Group, the thicknesses of these zones range from a few centimeters to 100 m and more, and these zones trend from hundreds of meters to 10 km (Fig. 3). Some geologists believe that their development is a single process with the emplacement of the muscovite pegmatites. Because of this, these rocks were studied more thoroughly, but many aspects of their origin and relations to the basic metasomatic rocks remain obscure. It should also be mentioned that the development of the muscovite pegmatites has long been considered within the framework of the magmatic and ultrametamorphic models, i.e., the pegmatites were thought to be the final products of granitic magmas or to correspond to the culmination of ultrametamorphic processes [29]. The ideas that the pegmatites could be related to the diaphthoresis of rocks of the Belomorian Group were pioneering [20]. Silicic metasomatic rocks with muscovite developed within units of kyanite-bearing rocks of the Chupa Formation in Karelia and Ena Formation in Murmansk oblast. Diaphthorites outside these units contain no muscovite but bear lenticular quartz or epidote. The structural setting of the acid metasomatics is not as evident as the setting of their basic analogues. Along with widespread linear vertical zones of muscovite schists, the "diaphthorites" occur as isolated patches that are conformable with the host rocks or have branches and tongues and consist of muscovite-bearing rocks among unaltered rocks of the Belomorian Group. The contours of these metasomatic fields are diffuse, they are often amoeba-shaped, and were often not mapped even in the course of the 1 : 10000 geological survey, which covered the whole central part of the Belomorian Belt [29].

The muscovite pegmatites occur as bodies of two morphological types: (i) snaky veins that cut across or are conformable with the host rocks and (ii) podiform tabular bodies that filled shear and tension cracks. These morphological differences of the pegmatite bodies can be explained by differences in the media (plastic and brittle-plastic) into which the pegmatites were emplaced, which corresponds to the uplifting of the

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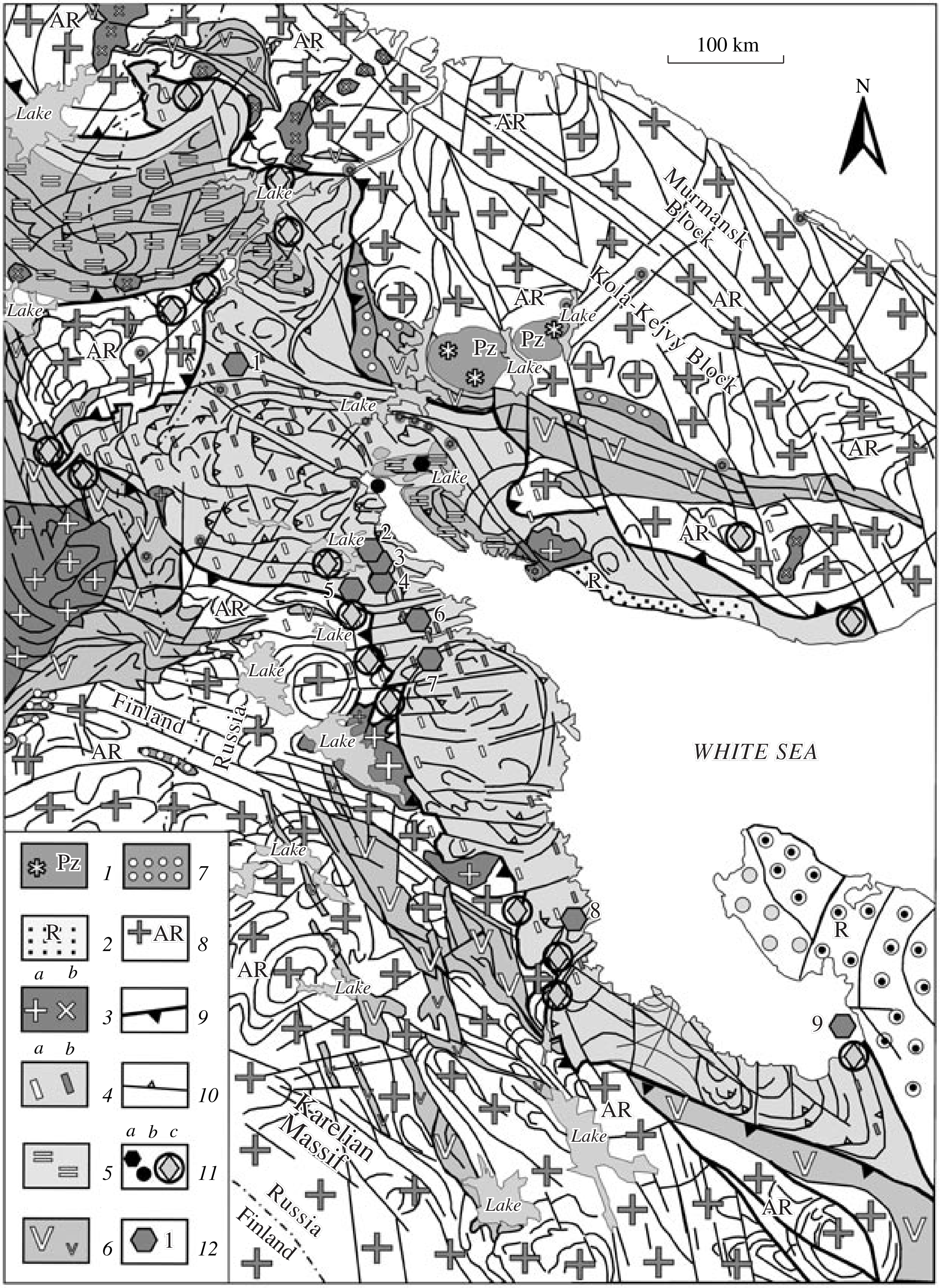
Fig. 1. Location of the Belomorian Belt and localities with corundum mineralization in the structure of the eastern Baltic Shield. (*1*) Devonian alkaline intrusions; (*2*) Riphean deposits, circles below the Vendian cover; (*3*) granitoids: (*a*) pre- and synkinematic (2.45–1.8 Ga), (*b*) postkinematic (1.8–1.7 Ga); (*4*, *5*) Lapland–Belomorian Complex of metamorphic cores: (*4*) Belomorian Belt (ancient middle crust): (*a*) muscovite–rare metal, (*b*) muscovite, circles beneath the Vendian cover; (*5*) Lapland granulite belt (ancient lower crust); (*6*) volcanic–sedimentary deposits (Karelian) (2.5–1.8 Ga); (*7*) layered intrusions (2.5 – 2.45 Ga); (*8*) pre-Karelian granite–greenstone basement (3.1–2.6 Ga) (upper crust); (*9*) detachment—boundary of the Lapland–Belomorian Belt (ancient bottom part of the upper crust); (*10*) vertical and oblique faults and their dips; (*11*) sampling sites of garnet-bearing rocks from: (*a*) garnet amphibolite and metaanorthosite from the Lapland Belt, (*b*) diatreme at Elovyi Island, (*c*) garnet–staurolite–muscovite–kyanite metasomatic rocks (1.8 Ga); (*12*) localities with corundum mineralization and their numbers: (1) Perusel'ka, (2) Lyagkomina, (3) Mount 128.4 m, (4) Dyadina Gora, (5) Notozero, (6) Khitostrov, (7) Varatskoe, 8) Shueretskoe (corundum was identified only in thin sections), (*9*) Kiiostrov.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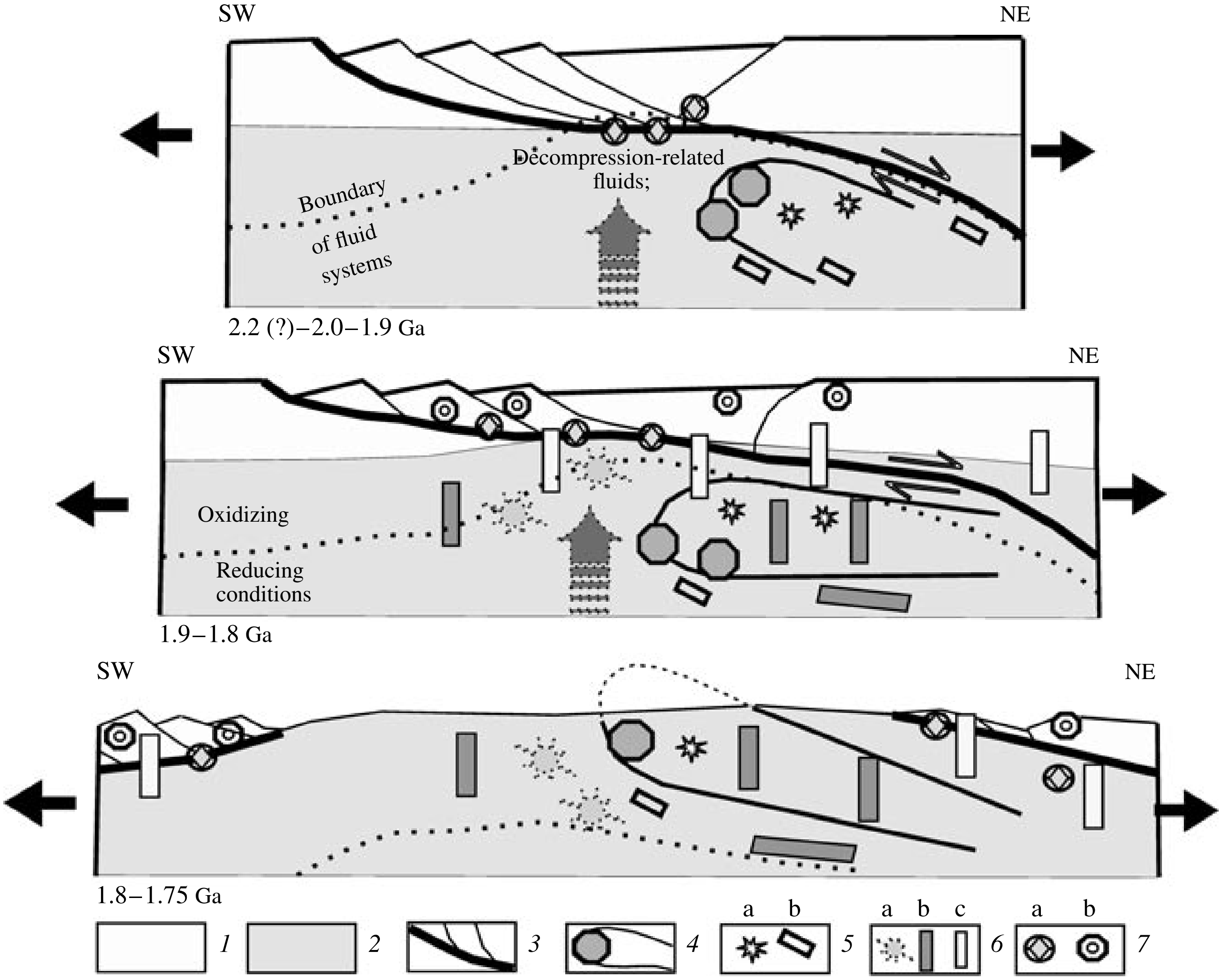

Fig. 2. Model for the exhumation of the middle crustal rocks of the Belomorian Belt and the structural setting of metasomatic rocks during the evolution of a gently dipping normal fault. (*1*) Brittle upper crust; (*2*) brittle–plastic middle crust; (*3*) gently dipping normal fault (heavy line) cutting through the crust and splay faults; (*4*) recumbent fold and basic metasomatic rocks (including their corundum-bearing varieties); (*5*) acid metasomatic rocks of the first group: (*a*) orthotectites and (*b*) blastomylonites; (*6*) acid metasomatic rocks of the second group: (*a*) diaphthorites, (*b*) muscovite pegmatites, (*3*) muscovite–rare metal pegmatites; (*7*) upper crustal metasomatic rocks: (*a*) garnet–staurolite–kyanite–muscovite rocks, (*b*) albitites with gold and base metal ore mineralization. (*4–7*) The scale is strongly exaggerated.

Belomorian Belt at 1.9–1.8 Ga. The muscovite pegmatites are cut by dike-shaped veins of muscovite–rare metal pegmatites, which were found not only in the Belomorian Belt itself, along its western (Northern Karelian Pegmatite Belt [30]) and eastern boundaries, but also in structures north of it, which composed a single continuous structure before the belt was exhumed (Fig. 2). Simultaneously with the development of the muscovite–rare metal pegmatites, all rocks of the Belomorian Belt and its older pegmatites in particular were affected by retrograde metamorphism, which resulted in the albitization of the rocks and in the crystallization of spessartine garnet and apple-green muscovite, epidote, and chlorite. These alterations are spread regionally throughout the whole belt, although they were more intense in discrete local zones [31]. Hence, the high-grade metamorphic rocks of the Belomorian Complex were exhumed concurrently with the development of basic metasomatic rocks and two groups of silicic metasomatic rocks and various veins, including pegmatites.

GEOCHEMISTRY OF THE CORUNDUM-BEARING AND OTHER BASIC METASOMATIC ROCKS

The most conspicuous feature of these rocks is their low silica contents, so that the rocks virtually always have an ultrabasic composition in terms of silica concentration, although their mineralogy and chemistry can broadly vary (Tables 1–3). The concentrations of all the elements show a broad scatter. The rocks are

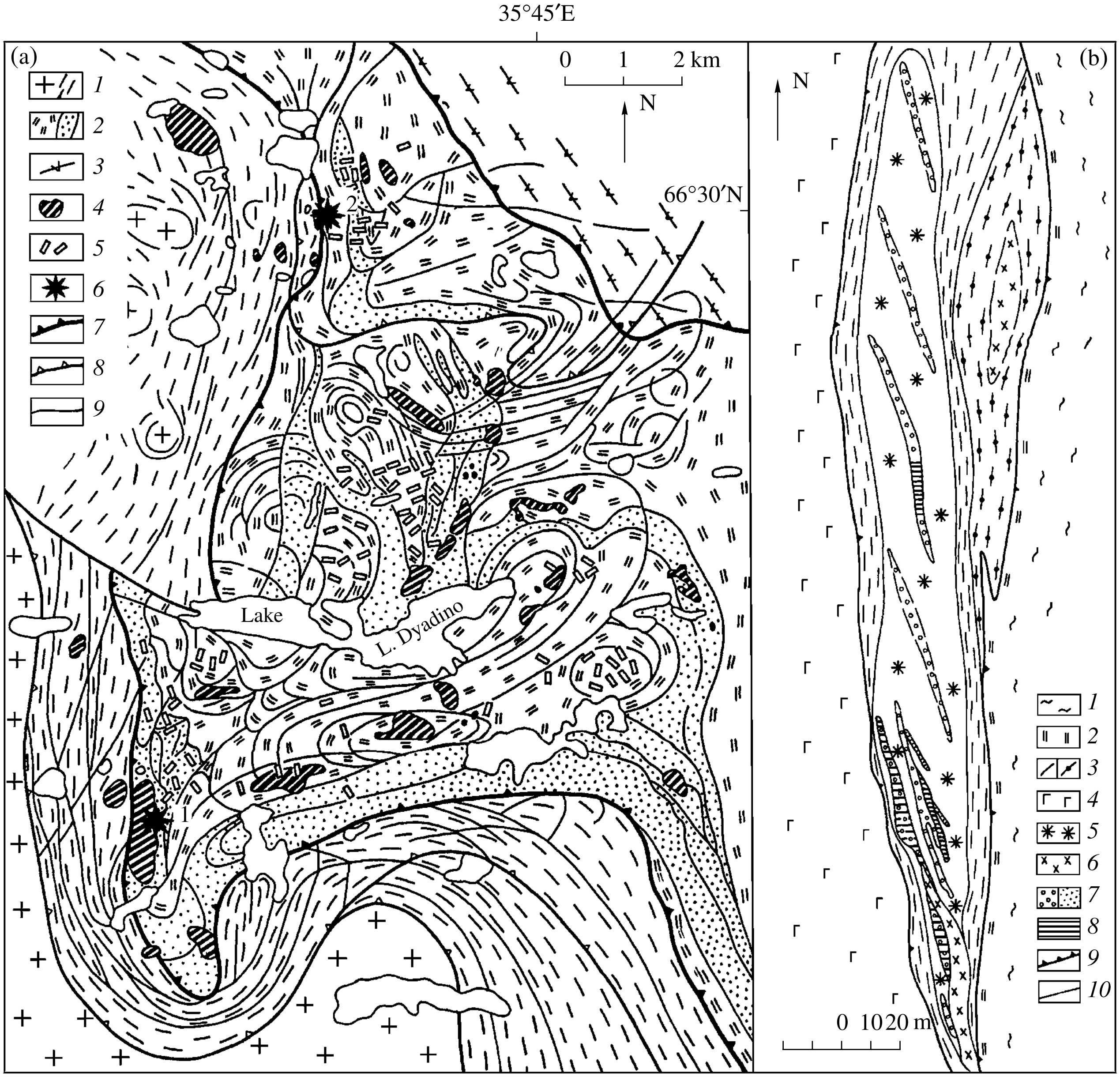

Fig. 3. Structural geological map of the field of the Tedino muscovite deposit: (a) an example of widespread recumbent folds and (b) detailed map of the Dyadina Gora occurrence of corundum mineralization (prepared using materials of the Northwestern Geological Survey). (a) (*1*) Granite-gneisses of the Western Complex, Belomorian Belt, and banded tectonites developing after these rocks; (*2*) aluminous gneisses of the Chupa Complex and "diaphthorites" developing after them; (*3*) amphibolites and migmatites of the Khetolambina Complex; (*4*) drusites; (*5*) muscovite pegmatites; (*6*) occurrences of corundum mineralization: (1) Dyadina Gora, (2) Mount 128 m (*7*) major faults; (*9*) gently dipping faults; (*9*) faults and structural lines identified in aerial photographs. (b) (*1*, *2*) Chupa Complex: (*1*) aluminous kyanite-bearing gneisses, (*2*) their silicified varieties (sample k133/1); (*3*) amphibolites and garnet amphibolites; (*4*) drusites (sample 733/1); (*5*) massive amphibole rocks with garnet, kyanite, and zoisite (sample 138/6); (*6*) quartz–clinozoisite rocks; (*7*) giant-grained garnet–gedrite rocks and scapolitites (sample 134/12); (8) localities with corundum mineralization; (9) major tectonic boundaries controlling the development of metasomatic rocks and their dips; (*10*) boundaries between petrographic varieties.

enriched in alkalis, with sodic and potassic rocks occurring close to one another (the former are predominant). Most of the rocks are rich in alumina and enriched in TiO_2, Zr, Cr, Ga, and Y. While the corundum-bearing rocks from Belomorie were described (however cursorily) in the literature [24, 25], no information on their REE distribution has ever been published. We analyzed the most principal rock types from occurrences of corundum mineralization for REE (Tables 1–3), whose concentrations in these rocks broadly vary and are

Table 1. Major varieties of basic metasomatic rocks composing occurrences of corundum-bearing rocks in the Belomorian Belt and the most typical host rocks

Component	1	2	3	4	5	6	7	8	9	10	11	12	13
	90/1	159/13	90/6	153/1	767/10	767/9	767/18	767/7	767/5	138/6	733/1	33/3	122/2
SiO_2	39.11	35.16	47.16	50.36	42.71	42.28	43.07	35.53	46.54	49.88	52.26	47.56	64.85
TiO_2	2.25	1.76	1.28	0.95	1.22	1.23	1.18	0.93	0.72	0.81	0.63	1.15	0.68
Al_2O_3	20.84	23.23	23.84	24.25	26.4	25.66	27.06	21.00	27.94	16.09	12.12	14.07	15.85
Fe_2O_3	18.41	18.91	10.73	8.57	9.94	10.0	11.97	15.45	7.38	10.15	11.23	14.58	6.87
MnO	0.15	0.17	0.07	0.05	0.07	0.09	0.15	0.17	0.09	0.08	0.16	0.22	0.07
MgO	9.67	7.83	5.79	4.19	7.05	6.42	6.41	18.02	3.61	19.37	12.87	7.34	3.02
CaO	6.47	9.88	4.74	4.98	7.56	9.33	7.19	1.06	9.23	2.41	7.59	12.91	1.51
Na_2O	2.53	0.47	4.89	5.64	3.36	3.3	2.36	1.7	3.73	0.72	2.22	0.87	2.17
K_2O	0.42	0.4	0.41	0.32	0.92	0.64	0.33	4.0	0.28	0.46	0.97	0.27	3.43
P_2O_5	0.04	0.03	0.06	0.06	0.02	0.18	0.02	0.13	0.11	0.05	0.11	0.03	0.05
LOI	0.63	2.27	1.12	0.66	0.66	0.53	0.62	2.07	0.42	0.71	0.04	0.92	1.33
Total	100.06	100.13	100.04	100.06	100.2	100.01	99.99	100.46	100.1	100.36	100.18	99.98	99.96
Rb	5	12	11	2	14	81	2	138	4	1	25	5	111
Ba	51	31	300	150	3287	150	230	1543	19	10	318	548	956
Sr	23	490	360	260	564	384	357	111	21	13	234	230	157
Zr	606	–	254	174	176	153	148	18	84	95	73	52	82
Y	36	24	17	14	32	27	33	180	12	7	10	27	17
Zn	52	37	38	26	181	78	141	180	156	73	124	81	93
Pb	4	1	9	89	9	9	8	15	2	1	4	6	13
Cu	7	13	7	1	3	4	6	4	280	6	109	17	24
Ga	–	–	–	–	49	63	43	40	28	–	23	17	26
Cr	729	300	416	372	140	116	150	1400	400	2530	–	207	150
V	340	200	278	158	–	–	–	–	–	172	–	320	–
Ni	–	531	428	176	252	258	223	587	463	975	342	130	82
Co	95	200	56	45	–	–	–	–	–	93	–	47	–
La	80	9	37	41	47	36	29	14	11	64	20	3.5	24
Ce	190	22	90	83	70	76	65	20	21	175	41	6.4	39
Nd	86	10	35	39	41	36	29	11	13	87	17	8.4	17
Sm	14	3.3	7.4	8.1	8.6	8	6.9	2.5	3.2	14	4.1	3.0	3.3
Eu	2.5	1.5	4.4	2.1	2.1	1.4	1.3	0.32	0.65	1.2	0.9	1.2	0.79
Gd	11	4.6	2.0	4.8	6.4	6.0	4.8	2.5	2.8	9.7	3.1	3.2	2.0
Er	4.6	3.4	1.4	1.4	2.4	4.0	3.2	1.1	1.1	3.9	2.2	2.2	0.74
Yb	3.2	3.6	0.83	1.7	2.5	3.1	3.7	1.4	1.4	3.6	1.3	1.9	0.95
$(La/Yb)_n$	16.8	1.7	17.7	16.1	13.3	7.7	5.2	7.4	5.8	11.8	10.3	1.6	17
Eu/Eu*	0.59	1.2	1.4	1.2	1.2	0.62	0.67	0.37	0.67	0.325	0.75	1.2	1

Note: Rocks: (1) giant-granular garnet amphibolite; (2) corundum–garnet rock; (3) plagioclase–garnet–amphibole–staurolite–biotite–corundum rock; (4) corundum–amphibole–garnet rock; (5) staurolite–amphibole rock; (6) amphibole–corundum rocks with plagioclase, biotite, and staurolite; (7) amphibole–garnet rock with plagioclase and corundum; (8) phlogopite–staurolite–garnet rock with amphibole and chlorite; (9) biotite–garnet–amphibole rock; (10) kyanite–gedrite rock; (11–13) host rocks: (11) drusite, (12) amphibolite replacing mafic granulite, (13) kyanite-bearing "gneiss." Sampling sites: (1, 3, 4, and 13) Khitostrov; (2, 12) Notozero; (5–9) Varatskoe; (10, 11) Dyadina Gora. Dashes mean not analyzed.

Table 2. Garnet-bearing metasomatic rocks from the Belomorian Belt

Component	1	2	3	4	5	6	7	8	9	10	11	12
	159/9	19	159/4	90/10	k87/1	136/10	k104/8	767/16	i11	i27	i26	107/11
SiO_2	34.95	39.52	39.54	39.72	39.36	38.98	42.46	50.88	37.96	51.60	63.66	75.32
TiO_2	2.24	2.81	1.63	1.46	3.83	0.91	2.09	0.95	3.21	1.22	1.29	0.07
Al_2O_3	26.21	16.16	21.57	26.22	11.61	21.11	12.16	22.86	16.76	15.16	11.1	10.02
Fe_2O_3	19.03	18.19	18.79	16.86	27.68	18.67	22.79	9.47	20.43	17.76	13.57	7.81
MnO	0.28	0.35	0.19	0.17	0.33	0.63	0.21	0.09	0.34.	0.28	0.17	0.16
MgO	8.11	7.83	9.77	7.9	3.91	10.41	6.4	3.86	6.71	2.73	1.51	1.8
CaO	5.53	12.54	6.76	3.4	9.89	7.09	11.2	5.89	12.43	9.74	6.86	1.90
Na_2O	0.27	1.31	0.43	2.18	1.61	0.44	1.2	5.25	0.83	0.93	0.72	1.44
K_2O	0.79	0.46	0.35	0.87	0.35	0.23	0.97	0.47	0.29	0.17	0.22	0.1
P_2O_5	0.28	0.49	0.11	0.01	1.84	0.16	0.31	0.14	0.77	0.44	0.31	0.01
LOI	2.66	0.44	1.05	0.41	0.36	1.59	0.5	0.15	0.42	0.2	0.68	0.58
Total	100.38	100.17	100.21	100.68	100.06	99.98	100.1	100.08	100.26	100.26	100.17	99.86
Rb	28	–	10	40	4	6	8	15	1	1	1	1
Ba	80	63	36	860	–	40	200	583	38	56	28	51
Sr	110	300	110	240	180	13	330	580	28	55	101	170
Zr	100	334	89	155	47	127	–	144	264	131	264	–
Y	64	42	34	40	42	32	–	20	50	43	58	–
Zn	150	119	64	60	–	56	16	71	89	54	34	–
Pb	1	8	1	6	–	1	–	16	6	5	77	–
Cu	11	41	14	27	42	9	98	5	429	108	607	19
Ga	–	25	–	–	–	–	–	34	14	15	24	–
Cr	350	47	280	556	2	2790	3	–	37	60	29	31
V	210	340	220	380	20	162	467	–	370	140	60	12
Ni	120	30	200	130	4	188	29	172	10	55	47	9
Co	85	54	90	73	33	41	73	–	40	5	5	9
La	2.9	52	3.8	45	23	13	22	30	52	32	29	6.5
Ce	6.1	100	6.8	110	64.2	28	73	50	99	55	42	25.6
Nd	3.3	62	3.4	49	42.8	12	42	30	77	30	25	15.2
Sm	1.5	14	2.3	9	9.4	2.8	7.4	5.9	19	7.2	10	3.0
Eu	0.83	3.4	0.6	1.2	2.8	0.6	1.8	1.3	4.5	1.8	2.2	0.5
Gd	3.1	10.0	3.5	6.6	8	2.9	4.4	4.5	13	6.9	10	4.4
Er	6.6	5.2	6.9	4.0	3.8	2.6	1.8	1.7	6.5	5.6	7.7	21.8
Yb	7.1	4.4	7.1	3.8	2.0	3.3	1.3	1.8	5.3	4.7	6.8	24.8
$(La/Yb)_n$	0.275	7.9	0.36	8	7.7	2.6	11.3	16.6	6.6	4.6	2.8	0.17
Eu/Eu*		0.84	0.65	0.46	0.96	0.64	0.89	0.73	0.8	0.76	0.69	0.43

Note: Rocks: (1) garnetite; (2) garnet amphibolite; (3) amphibole–garnet rock; (4) garnetite; (5) giant-granular garnet amphibolite; (6) corundum–amphibole–garnet rock; (7) garnet amphibolite with pyroxene; (8) garnet–biotite–plagioclase rock; (9) garnetite with sphene and amphibolite; (10) garnet–plagioclase–amphibole rock; (11) garnet–plagioclase–quartz rock; (12) garnet–quartz rock. Sampling sites: (1, 3) Notozero; (4, 6) Khitostrov; (5) Kotozero; (7) Pon'goma; (8) Varatskoe; (2, 9–11) Kiiostrov; (12) Shueretskoe.

Table 3. Major varieties of mono- and bimineralic rocks at occurrences of corundum-bearing rocks in the Belomorian Belt

Component	1	2	3	4	5	6	7	8	9	10	11	12
	159/21	33/11	767/2	90/9	i9	134/12	767/4	767/3	i21	107/26	107/23	767/20
SiO_2	38.57	42.79	62.05	59.78	53.27	42.15	40.89	40.92	41.93	42.48	47.19	46.83
TiO_2	0.46	0.15	0.02	0.29	0.08	0.28	1.38	1.48	0.13	1.36	0.15	0.28
Al_2O_3	25.61	25.43	22.84	22.98	25.47	35.35	18.91	23.61	24.26	18.8	45.29	38.79
Fe_2O_3	9.62	7.84	1.23	2.65	2.72	0.37	14.99	16.42	6.37	11.55	2.63	3.33
MnO	0.01	0.03	0.02	0.02	0.06	0.01	0.21	0.21	0.1	0.05	0.03	0.02
MgO	2.96	0.99	0.28	1.04	2.88	0.18	10.8	8.02	12.52	13.5	1.6	1.46
CaO	20.26	20.29	4.13	4.36	9.91	18.61	9.74	5.74	9.52	–	0.5	4.72
Na_2O	0.27	0.21	8.99	8.29	4.70	0.63	2.38	2.58	1.53	1.22	0.05	3.25
K_2O	0.12.	0.43	0.16	0.15	0.23	0.27	0.41	0.76	0.96	6.08	0.59	0.84
P_2O_5	0.05	0.06	0.15	0.11	0.01	0.09	0.03	0.03	0.01	0.04	0.25	0.02
LOI	2.03	1.77	0.11	0.34	0.62	2.12	0.68	0.36	2.59	0.6	0.42	0.42
Total	99.98	99.99	100.1	100.13	100.03	100.01	100.39	100.13	99.98	100.04	99.98	100.02
Rb	5	14	14	1	9	6	1	16	25	116	12	31
Ba	26	154	–	200	102	47	121	–	211	1500	420	300
Sr	2800	2020	606	570	683	5500	77	309	288	11	10	436
Zr	35	61	54	53	27	1	256	206	10	–	–	21
Y	35	16	14	4	14	2	25	38	5	–	20	15
Zn	18	69	3	5	10	5	221	276	59	–	41	29
Pb	3.5	4	12	13	–	1	9	15	–	–	3	9
Cu	7.8	94	19	9	20	1	107	12	–	3	8	7
Ga	–	12	44	–	19	–	49	40	28	–	–	52
Cr	230	–	10	40	–	32	400	100	2000	165	30	10
V	400	–	–	38	–	30	–	–	40	350	74	–
Ni	88	28	17	48	31	6	330	353	353	110	12	58
Co	87	–	–	13	–	1	–	–	37	39	4	–
La	23	24	7	21	2.1	3.8	92	41	6.2	8.6	38	3.4
Ce	57	55	15	42	3.9	5.8	120	82	7.8	20	110	7.0
Nd	32	20	6.7	19	2.5	2.8	63	40	4.4	11	65	4.3
Sm	8.6	3.0	1	3	0.9	1	12	9.4	0.9	3.1	14.4	1.4
Eu	2.7	1.3	1.1	1	0.37	0.6	2.6	1.7	0.37	<0.5	2.2	0.48
Gd	8.4	2.7	1.6	2	0.75	1.1	8.4	7.2	0.75	2.9	12.8	1.0
Er	4.4	1.0	1.2	0.6	0.46	0.4	2.5	3.4	0.66	<0.5	0.9	0.89
Yb	2.5	0.6	0.4	0.4	0.18	0.1	2.4	3.6	0.32	0.2	0.7	0.65
$(La/Yb)_n$	6.2	27	11.6	35.4	8	24.4	26	7.8	13.4	30	38	3.6
Eu/Eu*	0.97	1.4	2.62	1.2	1.3	1.7	0.77	0.61	1.4		0.49	1.24

Note: Rocks: (1, 2) clinozoisite rocks; (3–5) plagioclasite; (6) scapolitite; (7, 8) amphibole rock; (9) amphibole–corundum rock; (10) biotite rock replacing garnetite; (11) kyanite–biotite rock; (12) kyanite–plagioclase rock. Sampling sites: (1, 2) Notozero locality; (3, 7, 8, 12) Varatskoe; (4) Khitostrov; (5, 9) Kiiostrov; (6) Dyadina Gora; (10, 11) SHueretskoe.

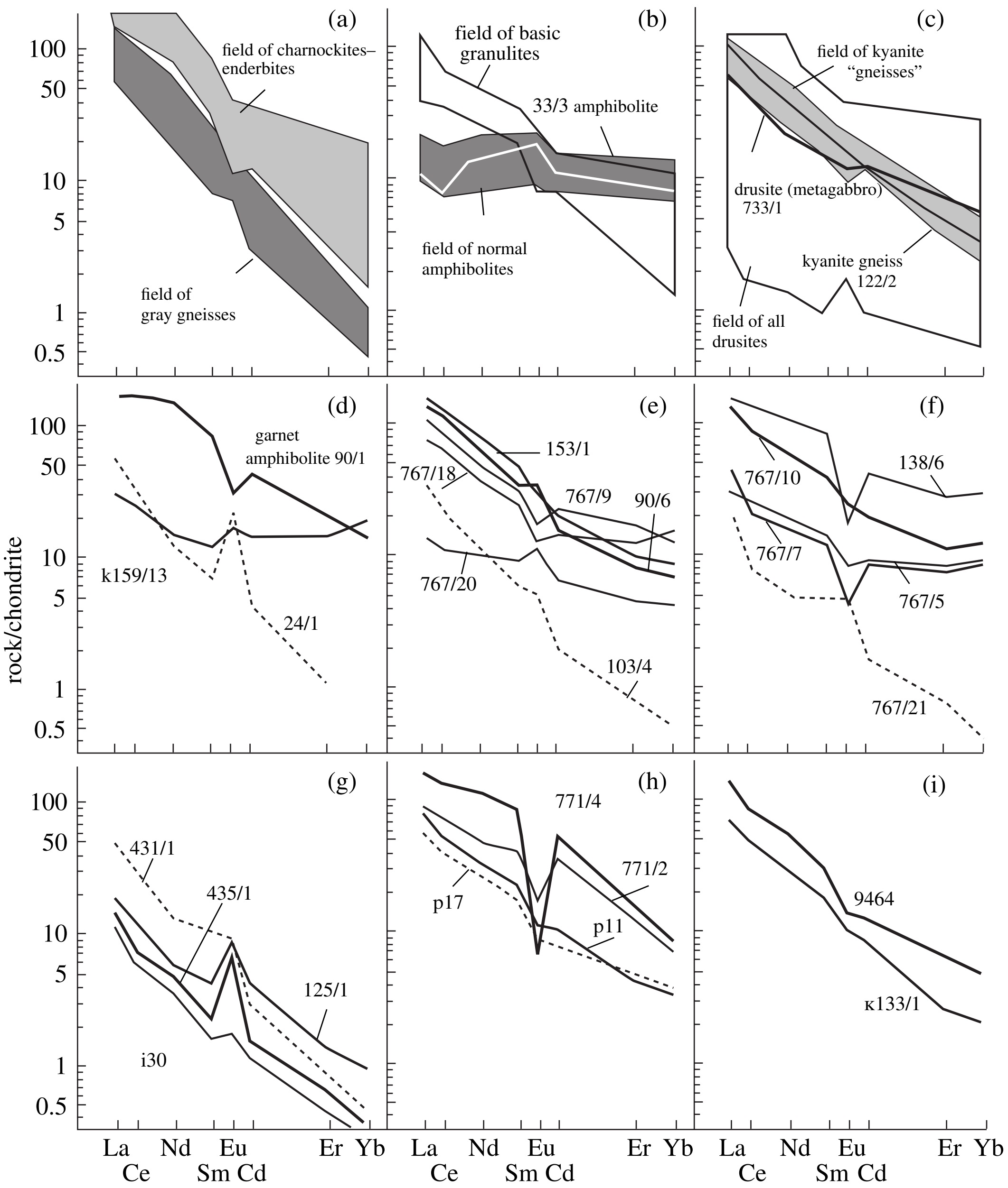

Fig. 4. Chondrite-normalized REE patterns of major types of (a–c) unaltered rocks from the Belomorian Belt and (d–i) metasomatic rocks: (d–f) corundum-bearing and (g–i) acid. Sample numbers correspond to those in Tables 1 and 4. Some acid metasomatic rocks are shown in Figs. 4d–4f with dashed lines.

mostly elevated, which is atypical of magmatic rocks of basic–ultrabasic composition. The host rocks (granite-gneisses of tonalite composition, aluminous "gneisses," amphibolites, drusites, and orthopyroxene–clinopyroxene granulites) bear REE concentrations typical of these rocks (Figs. 4a–4c). The major tendencies and relations in the behavior of REE in the corundum metasomatics are quite similar at various occurrences of these rocks, where giant-granular garnet–amphibole rocks are widespread. They are most strongly enriched in REE, particularly LREE, so that their REE patterns are fairly steep, $(La/Yb)_n > 15$, and show negative Eu anomalies. These anomalies are characteristics of the corundum-bearing rocks, with varieties richer in REE commonly displaying negative Eu anomalies and those poorer in REE having positive anomalies (Fig. 4d). The negative Eu anomalies are complimentary to the positive Eu anomalies typical of the rocks enriched in Sr: plagioclasites, clinozoisite (Figs. 5g, 5h) and kyanite (sample 767/20, Fig. 4e) rocks. Some of them (first of all, their plagioclase- and scapolite-bearing varieties) are dep-leted in REE.

It is worth mentioning the garnet-bearing rocks (Table 2, Fig. 5), which exhibit broadly varying REE

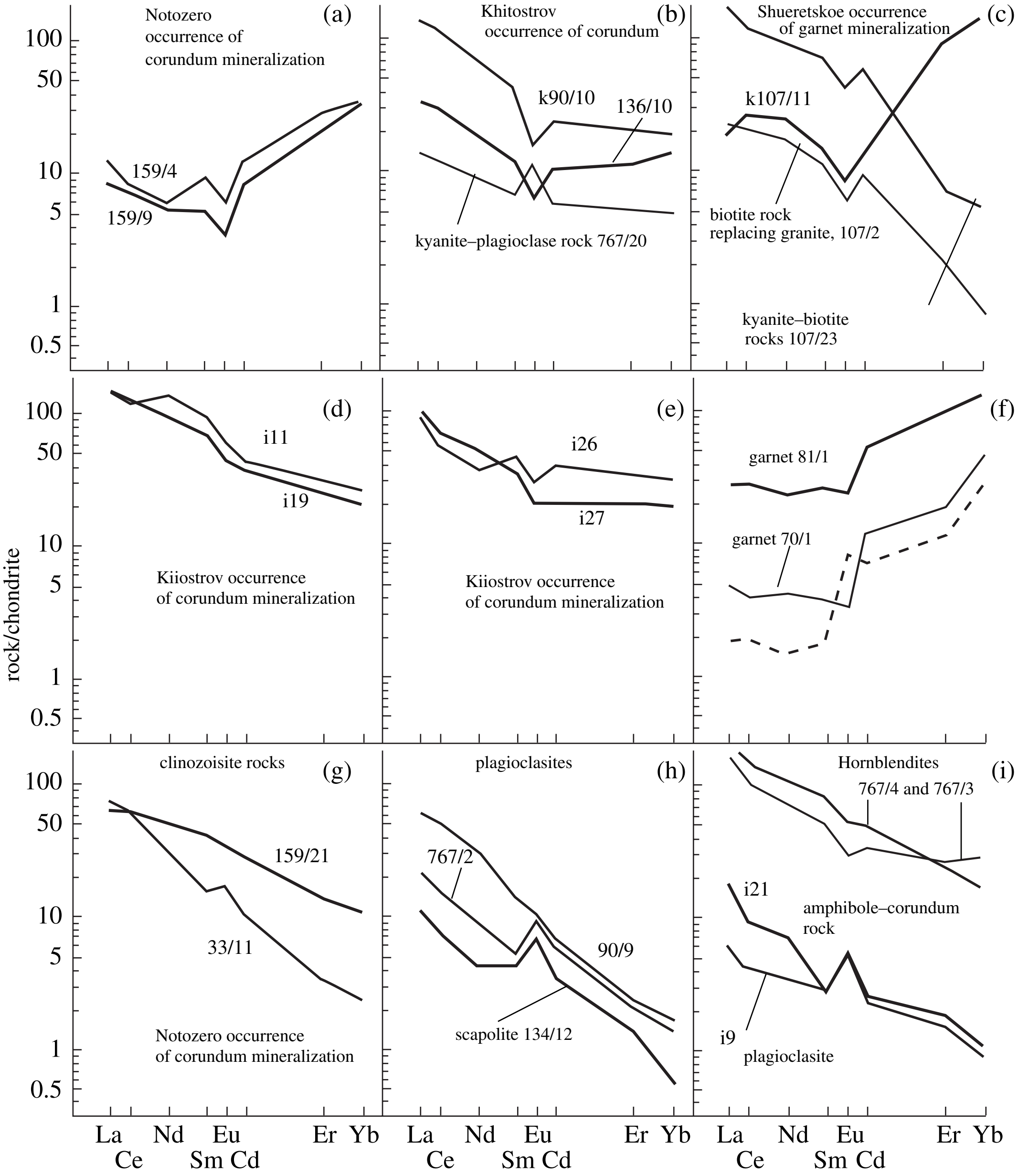

Fig. 5. Chondrite-normalized REE patterns of (a–e) garnet-bearing, (g–i) mono- and bimineralic metasomatic rocks of the Belomorian Belt, (f) garnets in rocks from the Lapland Belt (sample 81/1—garnet amphibolite, 70/1—metaanorthozite); the dashed line is the REE pattern of garnet from granulite composing a xenolith in a diatreme [33]. The sample numbers correspond to those in Tables 2 and 3.

concentrations. Garnet is widespread in the rocks of the Belomorian Belt and is particularly abundant in the aluminous gneisses of the Chupa Formation and in the amphibolites of the Khetolambina Formation. These rocks contain garnet crystals as large as 1 cm across, which are constrained to melanocratic layers of the metamorphic rocks. The metasomatic rocks have garnet grains up to 20 cm across, which compose lenticular aggregates, which are often monomineralic. Large garnet grains contain up to 50 vol % crystals of other minerals (hornblende, biotite, quartz, kyanite, and sulfides), and only their outermost 3- to 5-mm zones are almost free of these inclusions. The REE distribution in the garnet-bearing rocks is largely controlled by garnet, which can significantly concentrate these elements. The unusual REE concentrations in the garnet-bearing rocks (samples 159/4, 159/9, and k107/4; Fig. 5), whose $(La/Yb)_n < 1$, are explained by the fact that these rocks are monomineralic garnet aggregates or those with quartz, and, considering that quartz contains no REE, the tendencies of REE distribution in these rocks is controlled by the distribution of these elements in garnet, which also typically has $(La/Yb)_n < 1$. The determining factor of the enrichment of garnet in HREE is their smaller ionic radii than those of LREE, with the garnet structure (first of all, its small unit cell) more suitable for smaller REE ions [32]. This distribution of REE with negative Eu anomalies and enrichment in HREE is typical of garnet separated from the garnet amphibolites and metaanorthosites (Fig. 5f) of the Lapland Belt (Fig. 1). At the same time, garnet from granulite occured as a lower crustal xenolith in the diatreme on Elovyi Island has a positive Eu anomaly [33]. Most garnets from mantle xenoliths have no Eu anomalies [32], whereas this mineral from crustal rocks typically has these anomalies. Negative Eu anomalies is characteristic of garnet from corundum-bearing rocks and can be explained by complimentary Eu enrichment in other minerals that were formed concurrently with the garnet rocks: various plagioclasites, epidosites, and acid rocks with positive Eu anomalies. It is thus reasonable to suggest that garnets in these rocks, which were tectonized in the course of exhumation, have negative Eu anomalies, in contrast to rocks that were entrained as xenoliths and whose garnet either has no Eu anomalies at all or shows only positive anomalies.

The basic metasomatics exhibit a tendency toward the development of mono- and bimineralic rocks consisting of garnet, plagioclase, hornblende, gedrite, kyanite, scapolite, clinozoisite, etc. (Table 3). These rocks commonly have thicknesses of a few meters, although they are occasionally as thick as 15–20 m. The rocks are strongly differentiated in composition and almost always bear anomalous concentrations of major elements, for example, up to 20% CaO and up to 9% Na_2O. Most of these rocks are enriched in Al_2O_3 (occasionally, up to 45%). Except the plagioclase and scapolite rocks, they usually have high REE concentrations and show their differentiated distributions, with $(La/Yb)_n > 30$, and positive or negative Eu anomalies. The monomineralic rocks show positive correlations between the sums of REE contents and the distribution of REE in the predominant mineral: plagioclase, amphibole, scapolite, garnet, or biotite. The character of REE distribution in these minerals is usually explained with reference to the magmatic process, with minerals receiving strictly specified REE fractions from the melt depending on their properties. This is the so-called correlation coefficient, which usually does not change and can vary only depending on the basicity of the melt [34, 35]. The development of monomineralic rocks with the same REE distribution as in magmatic minerals suggests that minerals received REE concentrations during metasomatic transformations analogous to the REE concentrations in the analogous magmatic minerals. At the same time, the occurrence of fairly large bodies consisting of monomineralic rocks should also be explained. One of the possible explanations is based on the assumption of a significant fluid flow that could continuously precipitate certain minerals under favorable conditions.

GEOCHEMISTRY OF THE SILICIC METASOMATIC ROCKS

The vein pegmatoid granites (orthotectites) (Table 4) are classed with the metasomatics of the first group and were formed, judging form their geological relations, late in the course of the structural evolution of the Belomorian Belt, i.e., when its rocks were exhumed. These rocks contain almost no mafic minerals and are depleted in Fe, Mg, Mn, Ni, Cr, Zr, and Y and are rich in Al_2O_3, regardless of the Na_2O predominance over K_2O or vice versa [36]. The rocks are depleted in REE but always have positive Eu anomalies (Figs. 4d–4f, dashed lines). Compositionally analogous rocks often compose tectonic zones and occur in them in the form of blastomylonites with characteristic potassic feldspar and plagioclase augen or in the form of quartzite-like rocks (Fig. 4g). The acid rocks with positive Eu anomalies were most probably formed under the effect of reduced fluids and mark the pathways of their penetration into the upper crust [36]. The coarse-grained textures of the orthotectites and their richness in potassic feldspar make them similar to pegmatites, which led some researchers to regard them as “proto-pegmatites” [37].

The acid metasomatics of the second group (muscovite-bearing schists and pegmatites) bear principally different REE concentrations (Table 4). They typically have fairly high REE contents and show negative Eu anomalies. The muscovite–biotite varieties replacing kyanite gneisses have analogous REE concentrations but negative Eu anomalies [38] (Fig. 4h). The rocks dominated by muscovite, whose contents can be as high as 10% (sample 771/4), are strongly enriched in REE. The muscovite-bearing rocks include quartzite-like varieties, quartz veins and pockets, and also quartz cores of pegmatites. Compared to the schists or migmatites (after which these rocks develop), the quartzite-like rocks are less gneissose and sometimes almost massive, although their precursor gneissosity is still discernible. These rocks are depleted in mafic components and alkalis (Table 4), but their REE concentrations are very high (Fig. 4i). As muscovite-bearing rocks were formed in the central part of the Belomorian Belt at 1.8 Ga [39], abundant staurolite–kyanite–garnet–muscovite metasomatics (including varieties with fuchsite) developed in the peripheral parts of the belt at kyanite deposits: Udinskoe, Pebozerskoe, Khizovara, Ryabo-vaara, Irin-gora, Mount Lis’ya, Mount Kolikorva, Mount Korva-Tundra, Mount Tri Brata, and Mount Vyrmis. Much of these metasomatics replaced Late Archean or Paleoproterozoic supracrustal complexes, which then overlay the Belomorian Belt [21, 40]. Most of these rocks are enriched in Cr, whereas the deeper sitting garnet metasomatics are, conversely, depleted in this element (Table 2).

Table 4. Major varieties of acid metasomatic rocks of the Belomorian Belt

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	24/1	103/4	435/1	431/1	i30	767/21	94125	107/21	p11	p17	771/2	771/4	k133/1	9464
SiO_2	70.67	76.30	75.44	74.28	84.82	75.9	76.44	80.26	68.01	65.16	73.87	71.44	75.11	76.16
TiO_2	0.2	0.13	0.05	0.17	0.14	0.02	0.04	0.15	0.44	0.58	0.15	0.16	0.51	0.52
Al_2O_3	15.43	13.55	13.8	14.27	7.57	15.35	13.93	14.89	14.42	17.06	16.87	17.82	11.64	5.79
Fe_2O_3	1.37	1.54	1.02	1.64	2.46	0.92	0.93	2.07	6.44	5.08	1.54	0.96	2.17	6.89
MnO	0.02	0.01	0.01	0.01	0.04	0.01	0.01	0.01	0.09	0.06	0.01	0.01	0.02	0.08
MgO	0.37	0.43	0.09	0.34	0.37	0.21	0.1	1.12	2.5	3.2	0.38	0.37	0.79	4.16
CaO	1.02	3.08	1.44	1.58	1.55	2.1	1.15	0.1	2.65	2.1	1.83	1.5	8.86	4.38
Na_2O	2.91	4.14	2.66	4.42	1.95	3.03	4.75	0.14	2.8	3.12	3.06	3.08	0.18	0.56
K_2O	6.97	0.58	5.25	2.73	0.62	1.51	2.0.	0.67	1.5	2.33	1.94	3.07	0.13	0.44
P_2O_5	0.05	0.05	0.01	0.04	0.01	0.1	0.04	0.01	–	–	0.06	0.07	0.08	0.05
LOI	0.46	0.23	0.1	0.37	0.41	0.79	0.52	0.6	0.78	1.23	0.29	1.46	0.54	0.01
Total	99.9	99.8	100.1	100.1	100.1	100.1	99.98	100.2	99.7	99.95	100.01	100.13	100.03	100.03
Rb	113	14	101	53	24	27	60	14	52	96	45	79	4	14
Ba	6650	358	1109	1391	333	595	89	300	270	320	340	450	45	66
Sr	716	209	321	480	248	238	90	10	220	230	171	188	570	23
Zr	53	190	41	97	108	9	Ì/Ó	–	97	–	124	51	112	236
Y	11	6	7	9	13	10	5	–	12	–	16	19	7	19
Zn	18	21	63	32	12	1	15	–	72	–	22	24	12	68
Pb	14	9	20	20	8	12	20	–	9	–	76	151	–	5
Cu	46	17	21	6	19	18	6	8	49	52	18	7	2	40
Ga	17	11	14	16	12	46	19	–	–	–	61	58	–	13
Cr	–	–	–	–	67	40	–	18	200	220	60	50	28	90
V	–	–	–	–	45	–	–	38	130	150	–	–	61	–
Ni	9	22	12	12	10	13	–	12	110	100	18	13	34	53
Co	–	–	–	–	1	–	–	–	24	23	–	–	3	–
La	19	12	4.1	16	4.4	6.8	5.8	2.3	23	19	27	51	20	42
Ce	28	19	5.0	26	6.8	7.9	9.3	<10	46	41	60	125	47	73
Nd	7.4	79	2.6	8.7	3.0	3.8	3.5	<5	22	21	33	70	19	32
Sm	1.2	1.4	0.4	2.2	0.5	1.1	0.59	<3	4.8	4.1	11	18	4.3	6.8
Eu	1.6	0.5	0.48	0.6	0.19	0.39	0.2	<0.5	1.1	0.95	1.2	0.87	1.0	1.2
Gd	1.2	0.25	0.45	0.4	0.79	0.57	1.0	<1.0	3.4	3.2	11	13	2.8	4.2
Er	0.7	0.1	0.15	0.8	0.22	0.46	0.2	0.9	1.0	1.1	2.5	–	0.5	1.7
Yb	0.1	0.14	0.02	0.05	0.2	0.01	0.1	<0.5	0.87	0.82	1.5	1.9	0.5	1.2
$(La/Yb)_n$	120	60	120	230	12	100	100		19	16	12	18	27.6	23
Eu/Eu*	4.6	1.48	2.8	1.27	1.5	1.42	2.5		0.79	0.8	0.33	0.16	0.8	0.65

Note: Rocks: (1) vein giant-granular orthotectite (Lake Notozero); (2) vein plagiogranite (Lake Vazhenka); (3) silicified muscovite-bearing blastomylonite (Lake Gabozero); (4) silicified blastomylonite (Lake Gabozero); (5) secondary quartzite (Kii Island); (6) muscovite-bearing granite (Varatskoe corundum occurrence); (7) muscovite-bearing blastomylonite (Lake Kopatozero); (8) kyanite–biotite quartzite (Shoeretskoe deposit); (9, 10) biotite–muscovite schists (western part of Lake Loukhi) (major-element compositions are borrowed from [38]); (11) muscovitized neosome of kyanite-bearing plagiomigmatite (Lake Varatskoe area); (12) muscovite schist (same locality); (13) silicified and epidotized kyanite-bearing plagiomigmatite (Dyadina Gora deposit); (14) quartz–hornblende rock (Lake Seryak).

DISCUSSION

The fact that the corundum-bearing rocks are enriched in REE and LILE (in spite of the basic–ultrabasic composition of these rocks) suggests that they were formed in an extensional environment with the participation of deep fluids that enriched the rocks in Al, Na, K, Zr, and LREE. The higher REE concentrations in the corundum-bearing and related rocks (compared to the pristine varieties, Figs. 4, 5) suggest that the former are not residues after the derivation of an acid magma, because, otherwise, they should have been depleted in all REE and LREE in particular.

Geological observations indicate that the acid metasomatics with positive Eu anomalies are coeval or nearly coeval with the basic metasomatics, including their corundum-bearing varieties, and all of them corresponded to the initial exhumation stage of the Belomorian Belt. The occurrence of positive Eu anomalies in the acid varieties testifies that the rocks were formed under reduced conditions [36], which were caused by the inflow of deep decompression-related fluids early in the course of the extension. The proportions of most chemical elements in the basic and acid metasomatics with positive Eu anomalies are complimentary. The only exception is alumina, whose concentrations are high in both the acid and, particularly, the basic varieties. Note that the volumes of these two rock groups are commensurable, which suggests that these rocks could be genetically interrelated. There is also direct evidence that the corundum-bearing metasomatics were formed in a reduced environment: these are data on the fluids in these rocks [41] and finds of iozite, a rare mineral with the formula FeO [24], which is an indicator of reduced conditions.

A remarkable feature of the young rocks in the Belomorian Block (which reflects the exhumation of the block) is their high alumina contents. However, most researchers of the Belomorian Belt traditionally believe that the elevated alumina contents in the metamorphic rocks were predetermined by the chemistry of their protoliths [15, 17], with the corundum-bearing rocks exemplifying the uttermost accumulation of alumina in the sedimentary process, namely, that in the weathering crust [42]. It was not until quite recently that these rocks were considered to be metasomatic [24, 25], and doubts were cast about the “postulate” of the metasedimentary nature of the kyanite gneisses of the Belomorian Belt [40]. The modes and species in which alumina is transported always attracted our keen interest, because this component is commonly regarded as one of the most inert components in metasomatic and metamorphic processes. At the same time, many researchers do not doubt the high mobility of alumina, particularly in alkaline environments [43]. It is interesting that most tectonically exhumed middle and lower crustal rocks described in the literature commonly contain younger high-Al minerals, such as sillimanite, garnet, cordierite, and corundum [7]. This suggests that alumina mobility can even increase during decompression. Because of this, the anomalously high alumina contents in the peripheral parts of exhumed rock masses in general and the Belomorian Belt in particular call for an explanation. The high-Al (corundum-, garnet-, and kyanite-bearing) rocks are enriched in LILE and HFSE, including LREE, as well as P, F, and Cl [9], which suggests that alumina could be introduced into these rocks with solutions and gas emanations. The theoretical possibilities of alumina transport in alkaline hydrothermal and fluid environments were demonstrated in [44, 45]. For high-Al rocks in the central and peripheral parts of uplifted rock masses, the source of alumina (from which the solutions or fluids received their alumina) remains largely obscure. The fact that basic and coeval acid metasomatics are highly aluminous implies that these rocks could have been formed under the effect of deep fluids enriched in alumina. At the same time, this component could have been borrowed from “internal” sources in uplifted blocks of deep rocks affected by decompression. In this context, it is particularly interesting to analyze the Al_{YI}/Al_{IY} ratio in mafic minerals. The most general tendencies in mineral transformation related to the coordination of Al ions were first explored in detail by Sobolev in 1947, 1949, and 1970 [46]. Addressing illustrative examples of many reactions, he has demonstrated that a pressure increase results in the $Al_{IY} \longrightarrow Al_{YI}$ in silicates, a process coupled with a volume decrease; hence, it is justified thermodynamically. Correspondingly, a pressure decrease brings about the opposite exothermal reactions with the $Al_{VI} \longrightarrow Al_{IV}$ transition. Aluminum atoms thereby become more convenient to form complex compounds with volatile components. The example of corundum-bearing metasomatic rocks from eastern Pamir was previously invoked [9] to demonstrate that the enrichment of the rocks in alumina is correlated with their enrichment in REE, alkalis, and fluorine [9]. The most realistic fluid agent able to form acid metasomatic rocks (i.e., to derive them from the pristine rocks by leaching Al, Ti, Fe, Mg, Mn, REE, P, Zr and Y from these rocks and redepositing these elements as high-Al metasomatics) is a hydrogen-bearing mixture with appreciable concentrations of gases such as AlH_3, which are characterized not only by high energy capacities but also by the ability to transport many chemical elements [47].

The younger metasomatics of the second group, which a have a principally different character of REE distribution and negative Eu anomalies, were most probably already produced in an acidic environment simultaneously with brittle deformations. These metasomatic rocks have no complimentary analogous within the Belomorian Belt, and the mafic components that leached from these rocks were redeposited outside the belt within the Karelian Massif, which was then situated above the belt (Fig. 2). The fluids of this stage produced a huge amount of near-surface metasomatics in the eastern part of the Karelian Massif [48], which was pushed westward from the extension axis during the ascent of the Belomorian Belt. The changes in the REE patterns of various types of the metasomatic rocks definitely suggest that, when the rocks of the Belomorian Belt were exhumed, they were originally affected by flows of reduced fluids. In the course of their further ascent, these rocks occurred in the oxidation zone [28], and the conditions of the removal and concentration of elements became different. The occurrence of corundum in the Belomorian Belt supports this idea, because, as was demonstrated in experiments, corundum can be most easily produced at high temperatures when the alkaline and reduced gas column is transformed into an acid gas–fluid one [49]. Hence, the corundum-bearing metasomatic rocks were produced under the effect of deep hydrogen-bearing fluids with AlH_3, which could actively transport (along with Al) also alkalis and other elements. Obviously, some of the fluids were produced during decompression, in response to the denudation of overlying rocks.

CONCLUSIONS

1. REE are typomorphic elements of the basic and acid metasomatic rocks that were generated when the high-grade metamorphic rocks of the Belomorian Belt were exhumed. These rocks show three types of REE patterns: (a) asymmetric patterns with positive Eu anomalies and depleted in other REE, Ti, Zr, and Y, as is typical of the acid rocks of thin orthotectite veins and zones of augen blastomylonites; (b) weakly asymmetric patterns, sometimes reversely inclined and with predominantly negative Eu anomalies, which are typical of the basic metasomatics; and (c) weakly asymmetric patterns with pronounced negative Eu anomalies, as is characteristic of the acid metasomatics.

2. Under reduced conditions, REE were leached from acid rocks, together with mafic components, and could be redeposited under favorable conditions at the boundaries of various rocks and form corundum-bearing metasomatic rocks.

3. The systematic changes from the acid metasomatics with positive Eu anomalies (which suggest reduced conditions) to varieties with negative Eu anomalies (oxidized conditions) correspond to the exhumation of deep metamorphic rocks of the Belomorian Belt.

4. One of the most important driving forces of the redistribution of material in uplifted crustal blocks are fluids released during decompression. Flows of fluids with gaseous Al and Si hydrates are the most favorable for the transportation of REE, Al, Fe, Mg, Ca, Ti, Na, K, P, Cr, and Zr, i.e., components ubiquitously enriching zones with corundum mineralization.

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