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Geochemistry of Granitic Migmatites in the Northeastern and Southwestern Belomorian Belt: An Example of Karelia

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Abstract—Comparative petrological and geochemical characteristics are presented for the rocks from two areas in northern Karelia in the northeastern and southwestern parts of the Belomorian Mobile Belt. Both of the areas were determined to consist of plagioclase and plagioclase–microcline migmatites, plagiogranites, and granites, but the northeastern part is volumetrically dominated by plagioclase migmatites and plagiogranites corresponding to tonalites and trondhjemites in composition. The rocks of the southwestern part of the belt are rich in plagioclase and microcline. Based on the geological relations between the rocks and their petrography and geochemistry, it is demonstrated that the plagioclase migmatites of tonalite and trondhjemite composition were produced by the migmatization of amphibolites and differ from intrusive tonalites and trondhjemites. The rocks examined in both parts of the belt reveal a similar petrochemical and geochemical evolution with similar behaviors of major and some trace elements (except Ba and Sr), which were controlled by migmatization processes. Compared with the rocks of the northeastern part of the belt, those in its southwestern portion are enriched in Ba and Sr, with the differences in the behavior of these elements possibly controlled by variations in the depths at which the rocks were formed in different geodynamic environments.

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INTRODUCTION

The Belomorian Belt of the Baltic Shield lately attracts keen interest of both national and foreign researchers [1–3]. The high-grade metamorphic rocks that underwent migmatization and multistage deformations almost everywhere in the belt are gneiss–migmatites of Precambrian age, analogous to those known at all ancient shields. Most recent publications devoted to the Belomorian Belt deal with its geology and geodynamics and with the geochronology of its rocks or present information on its reconstructed multistage geological evolution. Subduction and collision models are proposed that reportedly account for many structural features and evolutionary aspects of this belt. In the 1940s–1950s, the rocks composing the belt were stratified and were afterward regarded as formations for more than half a century. Now these formations are referred to as nappes (within the scope of these formations), and the belt itself is thought to be an accretionary–collision zone [1, 4]. At the same time, the composition of rocks, especially such as tonalites, trondhjemites, and granites, which are inherent components of the continental crust, call for close examination because the genesis of these rocks is still largely uncertain. Rocks of tonalite–trondhjemite composition account for a significant part of the Belomorian migmatites. These rocks are characterized by close spatial association with amphibolites, although the volumes of the latter in the migmatite fields are generally insignificant. In maps of the regional tectono-petrographic complexes, tonalites account for 49%, trondhjemites for 33%, and amphibolites for only 3% of the total area [5].

This publication is devoted to the genesis of tonalite–trondhjemite rocks, which is considered using the example of two areas in northern Karelia: one in the northeastern and the other in the southwestern parts of the Belomorian Mobile Belt (Figs. 1a, 1b) [6]. We have also conducted a comparative petrochemical and geochemical study of petrographically similar rocks of these two areas, which were reportedly [1] formed in distinct geodynamic environments. The material for this paper was collected during the documentation of geological profiles and detailed geological mapping (on scales of 1 : 1000 and 1 : 5000) conducted in northern Karelia. The most important profiles were run through the northeastern part of the belt (near Kiv-Guba Bay, Urakko Lake, Mount Girvas Bor), in the northern shore of Chupa Bay (near the village of Keret’), and also near the lakes of Uzkoe Khetolambino and Gremyakha and the village of Kovda. The cross sections in the southwestern part of the belt were documented north of Leet Lake, near Mount Turkov Varak, north and east of Mount Ryabo-Vaara, along the road to the town of Chupa, and along the St.-Petersburg–Murmansk high-

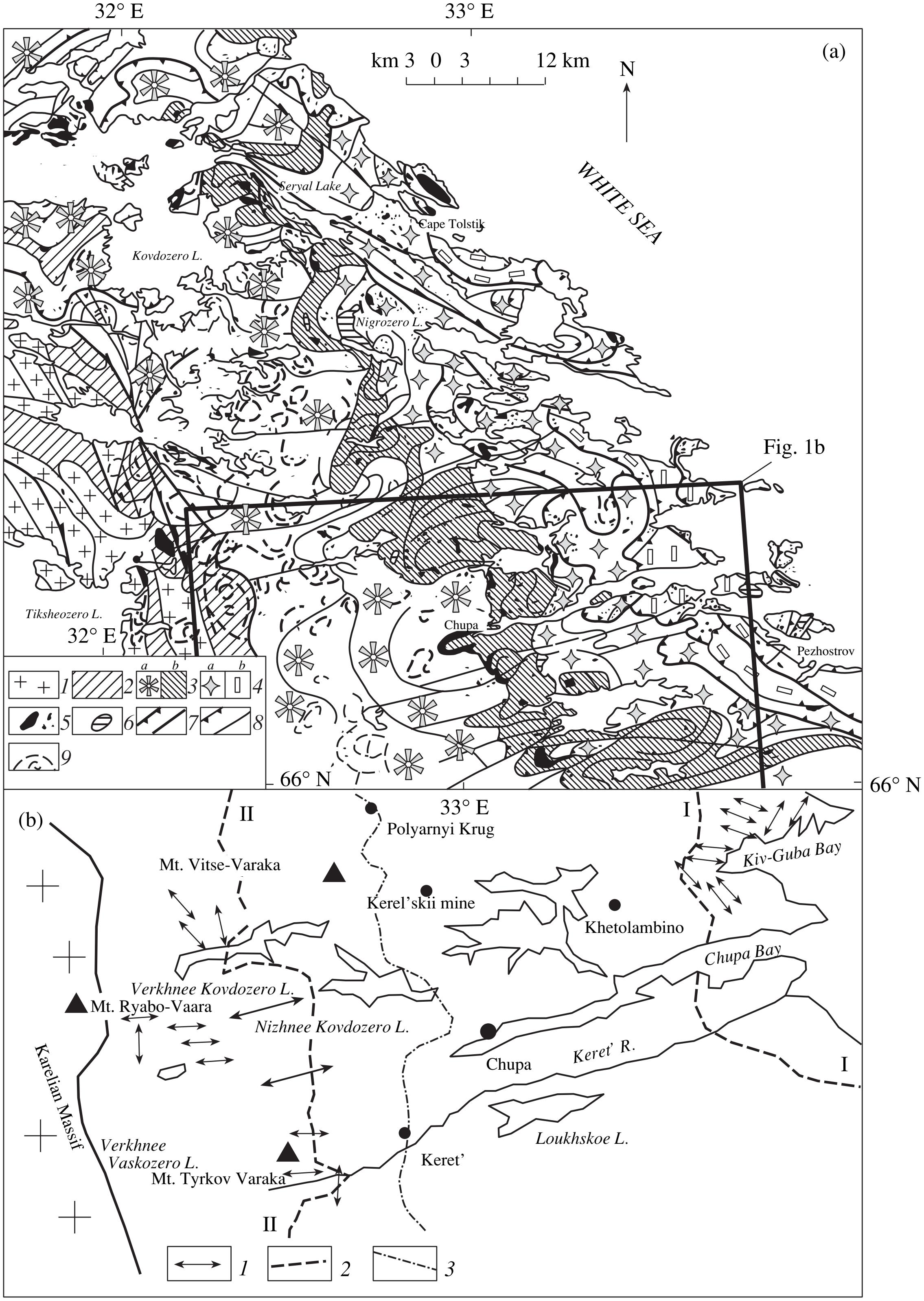

Fig. 1. (a) Schematic map of the central part of the Belomorian Belt with its tectono–stratigraphic complexes and major faults (modified after [6]) and (b) index map of the study area. (a) (*1*) Archean granite-gneisses of the Karelian Massif; (*2*) Late Archean northern Karelian greenstone belt; (*3, 4*) Late Archean Belomorian Group: (*3*) (*a*) Zapadnyi Complex, (*b*) Chupa Complex; (*4*) (*a*) Khetolambino Complex, (*b*) Keret' Complex; (*5*, *6*) drusites (coronites) (2.45 Ga): (*5*) gabbro-anorthosites and ultrabasites, (*6*) anorthosites; (*7*) major normal and other faults; (*8*) other faults; (*9*) ring structures in the Zapadnyi Complex. (b) (*1*) Geological profiles with detailed documentation; (*2*) study areas: northeast of profile I–I and southwest of profile II–II, (*3*) railroad.

way (between the distance posts of 1026/1027 and 1028/1029 km).

GEOLOGICAL AND PETROGRAPHIC OVERVIEW

Chuikina et al. [7] distinguished the following five formations composing the territory of northern Karelia (listed from bottom to top and from southwest to northeast): Zapadnaya, Kotozero, Chupa, Khetolambino, and Keret'. According to these geologists, the Chupa Formation is dominated by garnet–biotite and kyanite–garnet–biotite gneisses; and the other formations consist of various proportions of amphibole–biotite, epidote–biotite, and biotite gneisses and amphibolites, with the highest amounts of amphibolites typical of the Khetolambino Formation, with the lowest amounts of these rocks occurring in the Keret' and Zapadnaya formations. We examined rocks of the two latter formations. The Keret' Formation composes the northeastern part of the Belomorian Belt, and the Zapadnaya Formation makes up its southwestern part (from ~10–15 km west of the railroad to the eastern boundary of the Karelian Massif). Both formations are volumetrically dominated by rocks of tonalite–trondhjemite composition, which are often referred to as granite-gneisses. Some authors [8] considered the rocks of the Zapadnaya Formation to be the basement of the Belomorides, and Shurkin et al. [9] believed that the rocks of the northeastern and southwestern parts of the belt are the opposite limbs of a large syncline structure and attributed them to the Keret' Formation, whose thickness was estimated by these researchers at >3 km. The rocks ascribed to the Keret' Formation are recently combined by some geologists into an intrusive complex of tonalite–trondhjemite composition that was produced in an island-arc environment, and the rocks of the Zapadnaya Formation are thought to be close to magmatic rocks of the continental crust [1].

Now it is thought senseless to subdivide the Belomorian Belt into formations, and thus, below we will refer to the Keret' Formation simply as the rocks of the northeastern part of the Belomorian Belt, and the rocks of the southwestern part of this belt will be used instead of the Zapadnaya Formation.

Migmatites

We have established that the rocks of the northeastern and southwestern parts of the belt are strongly migmatized and transformed into migmatites, plagiogranites, and microcline granites, which were produced by the alterations of amphibolites and, to a lesser extent, of pale gray garnet–biotite plagioclase gneisses via their interstitial saturation with mobile solutions (granitization). These gneisses and amphibolites are preserved among the rocks merely as relics. Amphibolites, which account for 3–5% of the overall volumes of the formations, occur as relatively thin layers, which are often strongly bleached due to "dilution" with the migmatite material or gradually disappear along the strikes due to their aforementioned transformation [10] in the succession amphibolite ⟶ biotite–hornblende plagioclase migmatite ⟶ hornblende–biotite plagioclase migmatite ⟶ biotite plagioclase migmatite ⟶ nebulitic biotite plagioclase migmatite (plagiogranite) ⟶ biotite plagioclase–microcline migmatite ⟶ biotite granite. Amphibolite relics can also be preserved among the leucocratic rocks in the form of boudins, small fragments or their clusters or, more rarely, relatively small monomineralic amphibole lenses. The plagioclase migmatites of both parts of the belt, particularly its northeastern portion, typically contain epidote (~5%), which commonly occurs in the rocks as pockets, together with biotite, relict hornblende, and magnetite. Their microscopic examination indicates that epidote + biotite (often with vermicular quartz) + magnetite develops after hornblende during the migmatization of amphibolite, and hornblende relics are often preserved inside these pockets in the form of grain fragments, usually with ungeometric, corroded boundaries. Chains of these pockets can be observed in outcrops, where they mark the remnants of an almost completely migmatized amphibolite bed. Amphibolite alterations during migmatization start with its recrystallization, when the rock becomes heterogeneous and acquires an aggregative structure. The newly formed mineral is biotite, which replaces hornblende. The biotite produced early in the course of this process is unusual: it develops in the form of narrow and long laths of bright brown color. The mineral is magnesian, n_m = 1.635. With the further development of the migmatization process, the amphibolites become bleached because of hornblende and biotite replacement by plagioclase and, to a lesser extent, by quartz with the simultaneous changes in mineral chemistries. The plagioclase becomes more sodic: from oligoclase $An_{28–31}$ and andesine An_{36} in the pristine rocks to oligoclase $An_{15–20}$ in the final migmatization products. The N_m of the biotite increases from 1.635 at the beginning of the process to 1.658–1.661 in the biotite granite. Thus, the progress in the migmatization process results in changes in the composition of minerals and mineral assemblages until the final equilibria are reached: *Qtz* + *Pl* + *Hbl* + *Bt* and *Qtz* + *Pl* + *Bt* (rocks of tonalite and trondhjemite composition, respectively). According to [11], the stability of the granitization products of amphibolites is related to the establishing of discrete compositional levels during metasomatism that coincide with magmatic analogues. The temperatures at which the tonalites are formed is, according to the biotite–hornblende equilibrium [11], 540–550°C. Our data shows this temperature is 500–610°C. Amphibolites are replaced by fields of leucocratic rocks: hornblende–biotite and biotite plagioclase migmatites.

The plagiogranites and microcline granites occur as small patches of ungeometric shapes, which grade into nebular or normal migmatites. Their contacts with the host rocks are unclear and diffuse. However, the microcline granites sometime compose thin oblique veinlets with sharp contacts. In contrast to the plagioclase migmatites and plagiogranites, which have medium-grained textures, the microcline granites have variable grain sizes, ranging from intermediate to coarse and even pegmatoid. The later is particularly typical of granites in the southwestern part of the study area.

Plagioclase–microcline granites in the southwestern part of the belt are spread particularly widely in the area of Notozero Lake and north of it. In the study area south of Notozero Lake, they compose small bodies that grade into pale gray migmatized rocks, with the granite bodies having diffuse and indiscernible contacts. Such transition zones from microcline granite to plagioclase migmatite consist of hybrid rocks: the pinkish microcline granite preserves patches of plagioclase migmatites with relict schistosity, which demonstrates that the microcline granites developed after the plagioclase rocks. Bands of the microcline granites are elongated conformably with the schistosity of the migmatites in this part of the belt. The southwestern part of the belt contains more microcline granites. The rocks composing this area are small-grained, finely laminated, with a clearly pronounced orientation of biotite chains and leucosome stripes in the migmatites and with feldspar augen and thin lenses of quartz, which are elongated conformably with the general schistosity of the rocks. Lenticular quartz grains in these rocks are larger and occur more frequently within transition zones from microcline granites to plagioclase migmatites. These textural and structural features of rocks in the southwestern part of the belt indicate that the rocks were formed at active tectonic processes.

Microscopically, the rocks of both parts of the belt are similar. The textures of the plagioclase migmatites are heterogranoblastic, with homeoblastic patches corresponding to relics of unmigmatized gneisses or with patches of nematogranoblastic textures in relict amphibolites. The rocks affected by deformations and blastesis have blastoclastic or blastomylonitic fabrics and augen–schistose structures. The major minerals of these rocks are biotite ± hornblende + plagioclase + quartz ± microcline, and the minor minerals are epidote and very rare garnet. The typical accessories are apatite, zircon, sphene, orthite, and magnetite. The secondary minerals are carbonate, muscovite, and scapolite. The migmatites are characterized by variable proportions of major minerals, particularly quartz and biotite. Variations in the quantitative proportions of minerals are the most characteristic of migmatites of the initial stages of amphibolite migmatization, when hornblende is replaced by biotite, plagioclase, and quartz. For example, the content of quartz changes from 3–5% in the rocks of initial stages to 25–30% in the rocks of final migmatization stages, and the biotite contents simultaneously decrease from 30% to 5–7%. In nebular varieties of the migmatites, biotite plagiogranites, and microcline granites, the proportions of minerals gradually become approximately equal (Tables 1, 2). When numerous thin sections are examined, it can be seen that the rocks have broadly variable proportions of rock-forming minerals, which correspond to variable degrees of the replacement of some minerals by others during the metasomatic development of the migmatites.

PETROCHEMISTRY AND GEOCHEMISTRY

Below, we compare migmatites and granites in the study areas in the northeastern and southwestern parts of the Belomorian Belt and consider the petro- and geochemical characteristics of these rocks. Chemically, the plagioclase migmatites of both territories correspond to tonalites, and their nebular varieties and the plagiogranites to trondhjemites as they were determined in [12] (Tables 1, 2). In the O'Connor diagram modified by Barker, the data points of their compositions plot within the fields of the tonalites and the trondhjemites, respectively, and the compositions of the microcline granites fall into the field of granites. As can be seen from this diagram, the migmatites (tonalites) grade into their nebular varieties, trondhjemites. The compositions of some trondhjemites plot within the field of tonalites, thus highlighting the variations in the contents of major rock-forming minerals in the migmatites (Fig. 2).

According to the ratios of the sum of alkalis to silica, the compositions of the migmatites also occur within the field of tonalites, and the nebular migmatites and plagiogranites plot within the field of plagiogranites. The microcline granites are heterogeneous: most of them correspond to subalkaline granites, and occasional varieties are subalkaline leucogranites (Fig. 3). In an $Al_2O_3/(Na_2O + K_2O) - Al_2O_3/(CaO + Na_2O + K_2O)$ diagram [13], all of the rocks are highly aluminous (Fig. 4), which is corroborated by their Al_2O_3 contents. The latter is usually >15%, which is, according to [14], characteristic of aluminous tonalites and trondhjemites. The $Al_2O_3/(CaO + Na_2O + K_2O)$ ratio is almost always higher than one (Fig. 4), with the only exception of occasional tonalite samples. A value of 1.1 of this ratio was used by White and Chappell [15] to class rocks with types I and S. As can be seen from Fig. 5 and Tables 1 and 2, this ratio of our rocks can be either lower or higher than one. Accordingly, the granitoids of the northeastern part of the belt were derived from both magmatic and sedimentary rocks, and the source of those in the southwestern part consisted predominantly of magmatic rocks. Earlier [10] we demonstrated that the intrusive protoliths of the Belomorian amphibolites were basalts.

Table 1. Chemical and modal composition of rocks from the northeastern part of the Belomorian Belt

Component, wt %	Tonalites						Trondhjemites									
	240-8	G-20-73	G-14-73	3312	3113	2935-5a	3334-1	2031-g	2938-1	2929-2	243	2927-2	2925-2	G-22-73	240-5	3167a
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	58.46	60.54	64.86	67.24	68.08	68.28	68.78	68.96	68.98	69.14	69.24	69.24	69.58	69.60	69.68	69.74
TiO_2	0.77	0.92	0.40	0.32	0.31	0.32	0.64	0.05	0.32	0.27	0.22	0.32	0.32	0.37	0.27	0.21
Al_2O_3	19.60	18.12	18.27	18.17	14.53	17.17	14.81	16.96	16.26	17.37	16.98	16.92	17.17	16.56	16.92	16.30
Fe_2O_3	1.48	2.36	1.35	0.62	2.61	0.47	1.36	0.70	0.74	0.29	0.53	0.65	0.53	1.04	0.60	0.04
FeO	3.45	3.44	2.29	1.86	1.73	2.23	2.64	1.44	2.22	2.08	1.65	1.65	1.29	1.58	2.37	1.37
MnO	0.07	0.06	0.04	0.03	0.03	0.04	0.01	tr.	0.04	0.03	0.04	0.03	0.01	0.09	0.04	cÎ.
MgO	2.85	1.96	1.73	0.93	1.93	0.99	1.36	1.08	1.58	0.88	1.04	1.33	0.98	0.93	0.62	0.79
CaO	5.94	6.38	4.60	3.51	3.78	2.48	3.22	5.27	2.53	3.10	3.98	3.06	4.86	2.94	3.04	3.41
Na_2O	5.00	4.31	4.71	5.60	5.00	4.80	4.42	4.18	3.98	4.42	4.54	4.36	4.47	4.87	5.50	6.00
K_2O	1.60	1.20	1.37	1.38	1.70	2.62	1.65	tr.	1.85	1.73	0.93	1.98	0.60	1.50	1.20	1.24
P_2O_5	n.d.	–	–	–	0.19	n.d.	–	0.08	–	–	–	–	–	–	–	0.10
LOI	0.85	0.98	0.66	0.47	0.04	0.68	0.03	0.14	1.00	0.28	0.79	0.63	0.42	0.51	0.09	0.28
H_2O	0.13	n.d.	0.06	0.08	0.32	0.17	0.08	0.60	0.09	0.18	0.07	0.14	0.10	n.d.	0.05	0.12
Total	100.20	100.27	100.34	100.21	100.21	100.25	99.70	99.46	99.59	99.77	100.01	100.31	100.32	99.93	100.38	99.77
F, %	68.5	78.5	72.4	77.1	73.1	77.8	78.5	71.2	70.4	77.5	72.8	68.5	70.1	77.7	86.0	70.1
f, %	61.1	62.0	63.3	72.1	53.8	74.7	71.5	63.3	64.8	77.3	67.5	61.7	63.1	68.7	83.3	69.5
Qtz	7.6	8.9	23.2	14.4	30.6	31.0	21.5	26.9	30.8	27.0	28.4	20.0	23.6	20.9	36.0	17.8
Kfs	n.d.	n.d.	n.d.	n.d.	2.2	0.5	7.3	n.d.	3.7	4.7	n.d.	8.8	n.d.	2.0	0.6	2.1
Pl	75.2	69.5	62.9	73.9	60.1	57.0	65.7	62.5	56.7	60.6	62.4	58.4	66.7	65.5	59.2	74.5
Bt	7.8	7.6	10.0	10.7	5.5	9.0	3.1	0.5	6.7	5.1	6.5	10.8	3.1	9.7	4.0	4.3
Hbl	5.1	9.4	1.5	n.d.	n.d.	n.d.	n.d.	9.0	n.d.	n.d.	n.d.	n.d.	4.2	n.d.	n.d.	0.6
Grt	n.d.	n.d.	n.d.	n.d.	0.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Acc.	0.9	0.7	0.2	0.2	0.2	0.85	0.3	0.2	0.2	0.7	0.3	0.1	0.2	0.8	0.7	0.7
Second.	3.4	3.7	2.2	0.85	n.d.	1.55	2.1	n.d.	1.7	1.9	2.4	1.0	2.2	1.2	0.1	0.9

Table 1. (Contd.)

Component, wt %	Trondhjemites											Granites			
	3138a	2911	5092-5	2935-5	G-1-73	G-6-73	3335	2929-8	2906-1	2910-1	G-25-73	2933-1	338	2908-2	G-25-2-73
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
SiO_2	70.12	70.18	70.34	71.52	71.52	71.60	71.73	72.40	72.52	73.50	73.60	69.50	71.52	72.76	73.96
TiO_2	0.08	0.18	0.28	0.21	0.42	0.17	0.11	0.16	0.25	0.12	0.02	0.22	0.29	0.11	0.07
Al_2O_3	17.44	17.16	15.96	16.05	15.47	16.28	16.39	16.35	15.66	15.86	16.82	16.52	14.60	15.79	15.17
Fe_2O_3	1.44	0.50	0.40	0.54	1.52	0.61	0.29	0.41	0.57	0.39	0.03	0.61	0.93	0.27	0.88
FeO	0.22	1.22	2.16	1.42	1.42	1.25	1.22	1.01	1.44	0.93	0.21	1.36	1.32	1.07	0.28
MnO	tr.	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02	0.001	0.03	0.02	0.02	0.01
MgO	0.66	0.60	0.81	0.67	0.41	0.48	0.62	0.57	0.59	0.44	n.d.	0.95	0.32	0.42	0.14
CaO	3.84	3.03	3.08	2.78	2.94	2.70	2.37	3.20	2.86	2.70	3.28	2.88	1.36	2.35	1.30
Na_2O	5.52	5.54	4.72	4.80	4.50	5.14	4.80	4.64	4.44	5.10	5.43	4.50	3.52	4.61	4.00
K_2O	1.00	1.13	1.68	1.55	1.37	1.19	1.33	0.85	1.10	0.85	0.67	2.77	5.17	2.55	4.03
P_2O_5	0.11	–	–	–	–	–	–	–	–	–	–	–	0.21	–	–
LOI	–	0.45	0.42	0.45	0.49	0.57	0.76	0.38	0.34	0.13	0.26	0.72	1.02	0.18	0.23
H_2O	0.23	0.07	0.14	0.16	0.08	n.d.	0.04	0.13	0.05	0.19	0.02	0.12	0.16	0.08	n.d.
Total	100.54	100.08	100.02	100.18	100.17	100.01	99.69	100.12	99.85	10023	100.24	100.18	100.49	100.21	100.07
F, %	76.0	78.3	80.0	78.7	89.6	82.8	75.7	75.9	81.3	79.4	100.0	72.2	89.8	80.3	91.2
f, %	73.7	72.5	77.4	73.5	81.6	77.2	72.0	69.9	76.2	73.6	100.0	65.0	84.4	76.9	73.3
Qtz	19.2	37.5	29.3	29.0	22.1	30.4	13.5	33.8	29.5	23.3	23.2	25.2	30.0	25.0	36.3
Kfs	2.0	0.9	3.0	3.2	1.2	0.6	0.2	0.3	2.1	0.7	0.3	18.8	43.0	23.1	25.5
Pl	66.8	52.0	545	55.0	65.6	60.4	78.4	62.1	61.9	70.8	74.5	45.3	20.0	44.8	36.0
Bt	10.9	8.3	8.7	9.7	8.8	8.0	7.1	3.8	6.3	5.0	1.6	6.8	5.0	6.9	1.8
Hbl	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Grt	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Acc.	0.5	0.3	0.4	0.2	0.3	0.3	0.4	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.6
Second.	0.2	1.0	3.2	3.1	2.0	0.3	0.4	0.6	0.2	0.2	0.4	3.8	0.5	n.d.	n.d.

Note: (1, 11, 15) Northern shore of Kiv-Guba Bay, near Gremyakha Lake; (2, 3, 14, 21, 22, 27, 31) near Mount Kirvas-Bor; (4, 7, 23) eastern side of Uzkoe Khetolambino Lake; (6, 9, 10, 12, 13, 20, 24, 28, 30) north of the western tip of Kiv-Guba Bay; (5, 16, 17, 18, 25, 26) north of the eastern shore of Urakko Lake; (8, 19, 29) northern shore of Chupa Bay, near the village of Keret'. Here and in all tables below, major elements were determined at the Laboratory of Geology, Karelian Scientific Center, Russian Academy of Sciences, analysts G.K. Rodionova, V.I. Kemenshchikova, and A.K. Mokeeva, dashes mean not analyzed, n.d. means not detected. Minerals: *Qtz* – quartz, *Pl* – plagioclase, *Kfs* – potassic feldspar, *Bt* – biotite, *Hbl* – hornblende, *Grt* – garnet, Acc. – accessory minerals, Second. – secondary minerals; compositional parameters: $F = (Fe^{3+} + Fe^{2+})/(Fe^{3+} + Fe^{2+} + Mg)$, $f = Fe^{2+}/(Fe^{2+} + Mg)$, CC is the Chappel criterion = $Al_2O_3/(CaO + K_2O + Na_2O)$, mole. Mineral proportions were counted in thin sections. Here, in tables below, and in the text, tonalites are plagioclase migmatites of tonalite composition, and trondhjemites are nebular varieties of plagioclase migmatites and plagiogranites of trondhjemite composition.

Table 2. Chemical and modal composition of rocks from the southwestern part of the Belomorian Belt

Component, wt %	Tonalites				Trondhjemites						Granites		
	2737	2880-1	66-1	2706-1	2879-6	86-2	2879-1	72-5-10	2734-3	2886-1	2733/1A	2700-3	2700-5
	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	62.24	66.68	66.90	67.55	68.56	69.30	69.60	69.90	73.46	75.36	69.14	69.46	70.96
TiO_2	0.39	0.58	0.84	0.37	0.42	0.35	0.40	0.20	ÒÎ.	0.42	0.44	0.40	0.25
Al_2O_3	20.84	16.66	15.80	17.76	16.22	17.10	16.10	16.76	15.75	14.08	15.15	15.76	15.55
Fe_2O_3	0.58	1.69	1.21	0.43	0.84	0.27	1.07	0.55	0.24	0.29	0.60	0.55	0.73
FeO	1.72	2.51	2.97	1.99	2.30	2.03	2.01	1.29	0.86	1.65	1.86	1.65	1.07
MnO	0.05	0.06	0.05	0.05	0.05	0.02	0.04	0.02	0.01	0.01	0.05	0.02	0.03
MgO	0.94	1.44	1.21	0.96	1.09	0.97	1.05	0.90	0.17	0.49	1.07	0.81	0.44
CaO	4.37	3.94	2.61	3.26	3.68	2.77	3.30	3.20	2.14	2.74	4.20	2.16	2.12
Na_2O	4.86	4.22	3.89	5.12	4.57	5.49	4.71	4.62	5.58	2.75	4.81	4.12	4.43
K_2O	3.31	1.60	3.59	1.63	1.35	1.32	1.50	1.28	1.30	1.45	2.77	4.35	3.66
P_2O_5	–	–	0.21	–	–	–	–	–	–	–	–	–	–
LOI	0.64	0.09	1.04	0.48	0.11	0.65	0.42	0.89	0.25	0.73	0.25	0.58	0.43
H_2O	0.24	0.62	0.06	0.08	0.70	0.10	0.10	0.12	0.21	0.02	0.02	0.15	0.11
Total	100.2	100.09	100.28	99.68	99.89	100.37	100.30	99.75	99.97	99.99	100.38	100.01	99.78
F, %	75.6	78.5	81.2	76.1	78.5	75.3	78.6	72.0	89.4	83.7	74.5	77.5	83.6
f, %	70.5	69.5	76.1	72.8	73.4	73.1	71.4	65.2	87.0	81.6	69.4	72.5	76.1
CC	1.06	1.06	1.05	1.11	1.03	1.11	1.05	1.14	1.09	1.28	0.82	1.04	1.04
Qtz	14.3	25.1	15.2	19.0	27.2	17.9	25.3	8.2	23.1	21.5	19.6	23.2	14.9
Kfs	19.9	2.9	8.3	3.5	n.d.	n.d.	2.7	0.2	6.8	n.d.	17.8	35.9	20.0
Pl	52.9	58.4	60.0	67.0	59.7	64.0	62.0	78.2	64.4	60.3	51.1	32.6	59.5
Bt	7.4	10.2	13.9	8.7	7.7	18.1	9.5	12.3	3.6	11.3	10.3	6.0	4.5
Accessory	1.4	0.6	1.4	1.5	0.4	0.1	0.4	0.5	0.2	0.1	1.2	0.7	0.6
Secondary	4.0	2.8	1.0	0.2	0.5	0.2	0.1	0.6	1.9	0.1	n.d.	1.6	0.5

Table 2. (Contd.)

Component, wt %	Granites											
	2708-4	2955	2706-5	2706-3	2709-2	2708-3	2709-1	2699	2699-2	2706-2	2879-4	2733/5B
	14	15	16	17	18	19	20	21	22	23	24	25
SiO_2	71.50	71.66	71.68	71.70	72.16	72.30	72.44	72.68	72.68	72.86	72.90	73.49
TiO_2	0.27	0.27	0.24	0.26	0.22	0.30	0.23	0.15	0.14	0.24	0.09	tr.
Al_2O_3	15.49	11.64	15.46	15.62	14.82	15.09	14.99	14.56	14.79	15.11	15.48	15.53
Fe_2O_3	0.66	2.33	0.98	1.02	0.71	0.98	0.95	0.89	0.80	0.83	0.29	0.11
FeO	1.08	1.14	0.79	0.86	1.15	1.00	0.93	0.67	0.64	0.72	1.22	0.71
MnO	0.03	0.02	0.01	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
MgO	0.25	0.87	0.14	0.45	0.29	0.45	0.22	0.23	0.27	0.26	0.11	0.19
CaO	1.82	3.96	2.04	2.18	1.44	2.12	1.74	1.44	1.52	1.64	1.90	1.45
Na_2O	4.62	4.41	4.62	4.37	3.75	4.81	4.43	4.19	3.94	4.62	4.03	4.15
K_2O	3.33	2.87	3.22	3.08	4.65	2.47	3.77	4.40	4.45	3.63	3.61	3.52
P_2O_5	–	–	–	–	–	–	–	–	–	–	–	–
LOI	0.45	0.49	0.29	0.31	0.37	0.49	0.33	0.87	0.31	0.33	0.22	0.17
H_2O	0.11	0.07	0.11	0.09	0.10	0.08	0.11	0.15	0.14	0.10	0.08	0.20
Total	99.61	99.73	99.60	99.96	99.69	100.12	100.16	99.75	99.70	100.36	99.95	99.54
F, %	89.7	82.8	94.2	83.6	89.1	84.4	91.4	89.1	86.9	88.0	94.3	84.7
f, %	84.8	63.1	88.6	71.2	84.1	74.3	84.9	80.0	75.8	77.8	93.1	83.3
CC	1.08	0.66	1.05	1.07	1.07	1.06	1.04	1.01	1.05	1.05	1.11	1.17
Qtz	7.7	27.4	28.9	19.4	18.6	20.4	10.6	24.3	24.8	19.9	20.7	30.1
Kfs	14.4	12.8	17.1	16.8	17.0	15.0	12.9	33.4	35.4	19.7	27.6	20.1
Pl	50.3	53.4	46.8	57.9	57.8	55.8	70.1	38.9	35.0	55.1	47.9	45.9
Bt	21.1	4.9	6.5	6.1	6.3	6.3	5.7	2.5	3.1	4.9	1.7	3.6
Accessory	2.5	0.4	0.7	0.1	0.2	1.7	0.3	0.9	0.9	0.4	0.2	0.1
Secondary	3.9	2.3	n.d.	0.1	0.1	0.8	0.4	0.3	0.8	n.d.	1.9	0.1

Note: (3, 6) West of Mount Turkov Varak; (13, 14, 16–23) near Leet lake; (2, 5, 10, 24) along the St. Petersburg–Murmansk highway (distance posts 1026, 1028, and 1029); (7, 8, 15) east of Mount Ryabo-Vaara, along the road to the township of Chupa; (1, 4, 9, 11, 12, 25) north of Leet Lake.

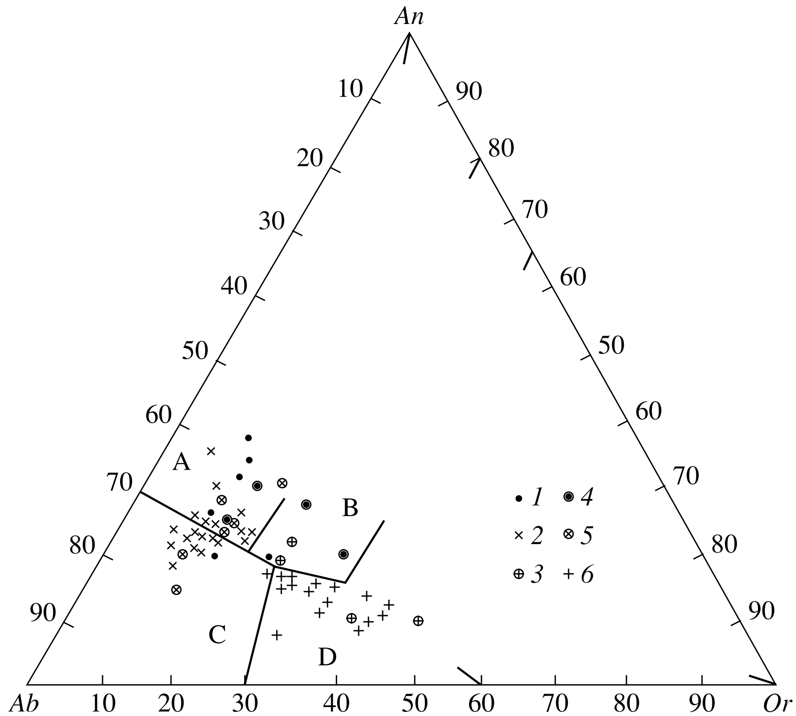

Fig. 2. O'Connor diagram modified by Barker [12] for the compositions of rocks from the northeastern and southwestern parts of the Belomorian Belt. Compositional fields: A—tonalites; B—granodiorites; C—trondhjemites; D—granites. (*1–3*) Rocks of the northeastern part of the Belomorian Belt; (*4–6*) rocks of the southwestern part of the Belomorian Belt: (*1, 4*) tonalites, (*2, 5*) trondhjemites, (*3, 6*) granites.

In discriminant diagrams for the compositions of rock series, the granites of both study areas within the Belomorian Belt show the following tendencies. All plagioclase rocks of the northeastern part have K_2O–SiO_2 proportions corresponding to tholeiitic and calc-alkaline fields (approximately an equal number of rock samples in each field), and the rocks from the southwestern part plot exclusively within the calk-alkaline field (Fig. 6) [16, 17]. At the same time, all compositions of these rocks from both parts of the belt plot within the field of calc–alkaline rocks in the diagrams of Miyashiro [18] (Fig. 7) and AFM (Fig. 8).

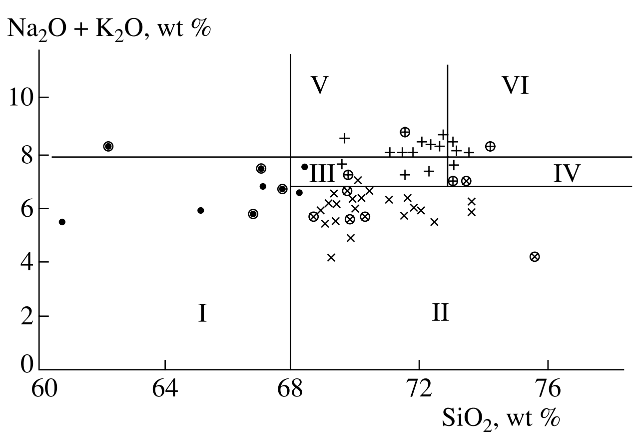

Fig. 3. ($Na_2O + K_2O$) vs. SiO_2 diagram for the compositions of the granitoids. Compositional fields: (I) tonalites, (II) plagiogranites, (III) granites, (IV) leucogranites, (V) subalkaline granites, (VI) subalkaline leucogranites. See Fig. 2 for symbol explanations.

Most samples of the microcline granites with elevated K concentrations correspond to high-K calc–alkaline rocks in the K_2O–SiO_2 diagram. Some of these rocks plot within the field of tholeiitic compositions, and the rest correspond to calc–alkaline rocks in diagrams that involve Mg and Fe (Figs. 6–8). The data points of the microcline granites from the Pazhma Massif in the Notozero areas behave analogously [19].

The comparison of the distribution of major elements in analogous rocks from the two parts of the Belomorian Belt (Table 1 and 2) indicates that the concentrations of these elements are similar, and the rocks differ only in that the tonalites are slightly richer in Fe, Mg, and Ca and somewhat poorer in K in the northeastern part of the belt. All of the migmatites of tonalite and trondhjemite composition and granites in the southwestern part are noted for elevated total Fe content and greater degrees of Fe oxidation, which suggests differences in the redox conditions at the compared areas.

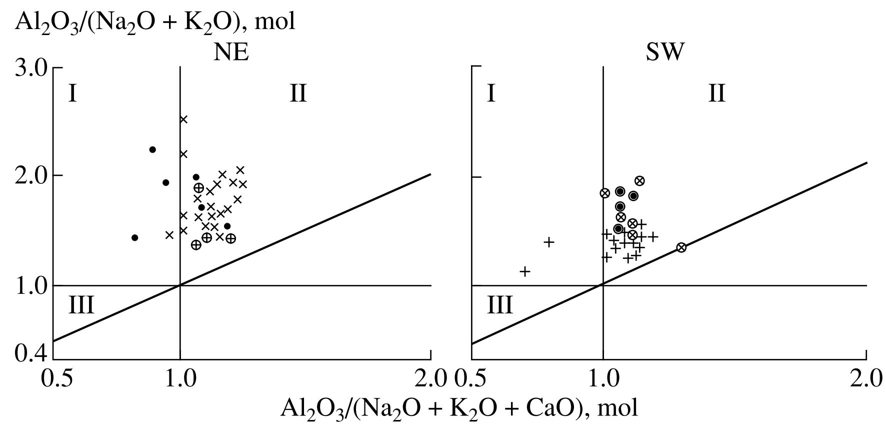

Fig. 4. $Al_2O_3/(Na_2O + K_2O + CaO)$ vs. $Al_2O_3/(Na_2O + K_2O)$ diagram for the rocks of the northeastern (NE) and southwestern (SW) parts of the Belomorian Belt. Compositional fields: (I) moderately aluminous, (II) highly aluminous, (III) highly alkaline. See Fig. 2 for symbol explanations.

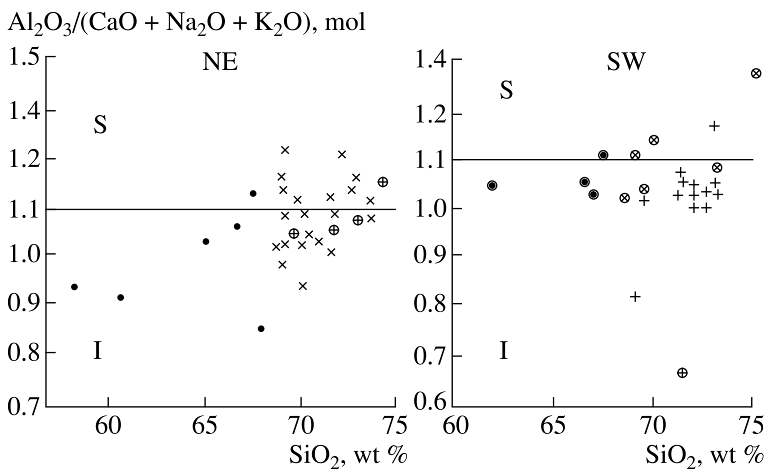

Fig. 5. White and Chappell [15] diagram for the rocks of the northeastern (NE) and southwestern (SW) parts of the Belomorian Belt. S—sedimentary, I—intrusive types of granitoids. See Fig. 2 for symbol explanations.

TRACE ELEMENTS

The distributions of trace elements in the two parts of the belt show both similarities and differences (Tables 3, 4). All of the rocks are typically depleted in such lithophile elements characteristic of granites as Rb, Zr, Nb, and Y, whose concentrations approach the average concentrations in granites of the lithosphere [20] (as is the case with Zr) or are three–seven times below the clarkes (Rb, Y, and Nb). The granitoids of the northeastern part are enriched in Ba and Sr, whose concentrations approach those of crustal granites (for example, Ba concentration is 583 ppm, compared with 840 ppm) and higher than them (as is the case with Sr: 193 against 110 ppm). The rocks of the southwestern part are enriched in these elements: Ba = 1126 ppm, and the Sr concentration is four times higher than the average concentration and twice as high as those in the granitoids from the northeastern part of the belt (Tables 3, 4). While the Ba concentrations of all of the rocks tend to slightly increase with increasing K contents, the

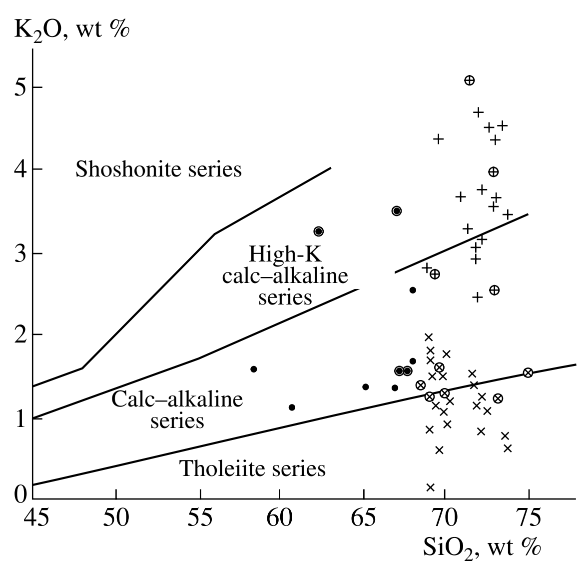

Fig. 6. Harker [16] diagram for the rocks of the northeastern and southwestern parts of the Belomorian Belt. The boundaries of the compositional fields of series are according to Ringwood [17]. See Fig. 2 for symbol explanations.

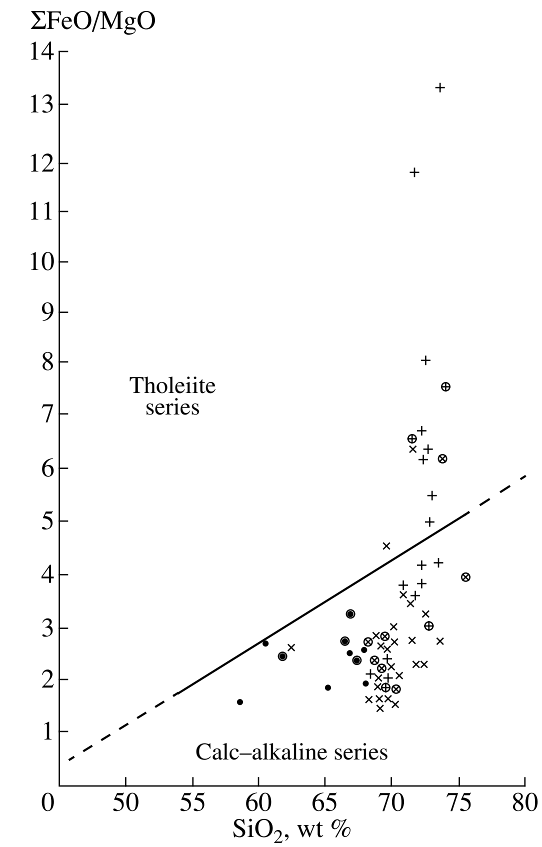

Fig. 7. Miyashiro [18] diagram for the rocks of the Belomorian Belt. See Fig. 2 for symbol explanations.

distributions of Sr show no systematic correlations with an increase in the silicity of the rocks or with their enrichment in plagioclase. Conversely, less silicic tonalites have Sr concentrations similar to those in the acid trondhjemites and microcline granites or even somewhat lower than them (Tables 1–4, Figs. 9a, 9b). As can be seen from these figures, there is no clear correlation of the concentrations of Ba and, particularly, Sr with the concentrations of major "host" elements: K and Ca. Ba and Sr enrichment in the feldspars of magmatic rocks is known to be directly correlated with their crystallization temperature [21]. Thus, the distribution of Ba and Sr suggests that the granites have crystallized under different conditions.

The behavior of siderophile and chalcophile elements and Ga corresponds to that typical of granitoids, i.e., the rocks gradually enriched in them. The exception is Ni, whose contents in the rocks of both parts of the belt are higher than its average concentration in the granites of the lithosphere (4.5 ppm), varying from 9 to 36 ppm. The granites in the southwestern part of the belt are twice poorer in Ni than the analogous rocks in its northeastern part. As was demonstrated in [10], Ni is concentrated in hornblende and biotite. Conceivably, the differences in the levels of Ni concentrations are related to variations in the contents of these minerals in the rocks (Tables 1, 2).

REE. In both parts of the belt, the REE distribution was examined in the trondhjemites, microcline

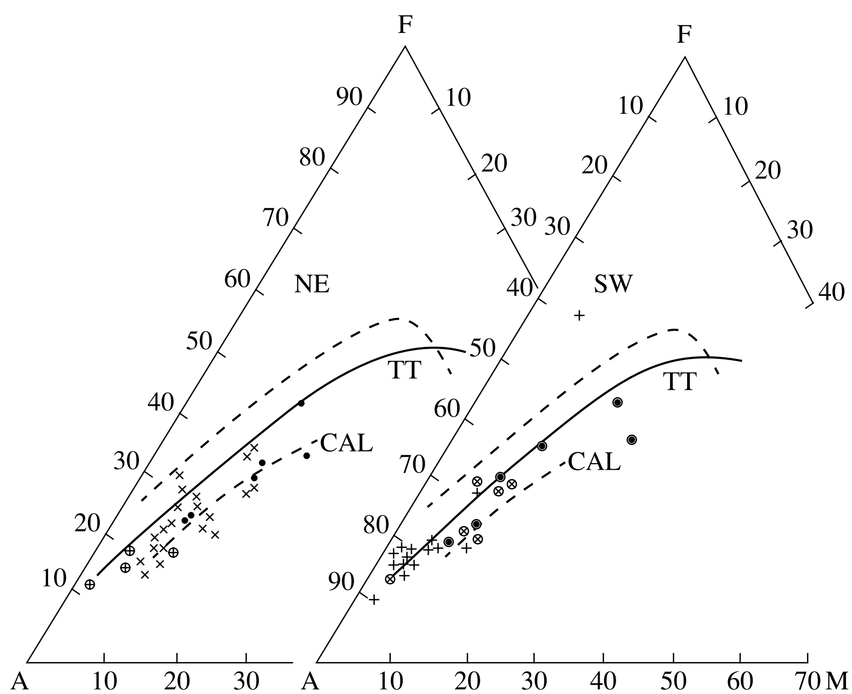

Fig. 8. AFM diagram for the granitoids of the northeastern (NE) and southwestern (SW) parts of the Belomorian Belt. The solid line separates the fields of the calc–alkaline (below) and tholeiite (above) series. TT—tholeiitic, CAL—calc–alkaline trends. See Fig. 2 for symbol explanations.

Table 3. Trace-element compositions of rocks from the northeastern part of the Belomorian Belt

Component, ppm	Tonalites		Trondhjemites									Granites		
	240-8	2935-5-a	3334-1	2938-1	2929-2	2927-2	G-22-73	240-5	5092-5	2935-5	G-1-73	2933-1	338	2908-2
Rb	79	59	45	43	44	49	64	32	43	47	66	47	98	56
Ba	526	685	171	427	345	242	388	459	304	895	504	596	183	801
Sr	100	161	177	203	230	181	231	339	226	220	376	135	167	178
Zr	137	100	150	217	185	181	164	108	105	128	78	101	206	114
Nb	–	3	7	–	3	–	5	2	3	4	5	–	7	3
Y	24	9	23	7	7	8	13	8	9	8	12	8	5	10
Ni	62	34	52	41	27	12	26	26	34	15	28	15	25	18
Pb	11	8	12	16	6	5	10	14	10	9	10	5	15	12
Ga	11	18	15	14	18	17	18	15	19	17	18	14	12	15
Zn	83	46	78	55	52	65	63	40	59	140	36	33	33	32
Cu	18	18	28	37	19	16	21	20	18	19	18	13	18	25
La	–	6.1	–	–	19	–	18	–	–	8.1	23	–	3.1	–
Ce	–	11	–	–	36	–	30	–	–	14	27	–	4.5	–
Nd	–	3.0	–	–	14	–	13	–	–	10	10	–	2.0	–
Sm	–	1.0	–	–	3.8	–	3.5	–	–	1.5	2.1	–	1.0	–
Eu	–	0.4	–	–	0.51	–	0.83	–	–	0.49	0.73	–	0.4	–
Gd	–	0.62	–	–	1.3	–	1.0	–	–	0.52	0.96	–	0.5	–
Yb	–	0.22	–	–	0.16	–	0.27	–	–	0.066	0.22	–	0.12	–
$(La/Yb)_N$	–	15.74	–	–	67.4	–	37.7	–	–	69.6	59.5	–	14.65	–

Note: See Table 1 for the location of the sampling sites. Here and in Table 4, trace elements were determined at the Laboratory of Physicochemical Method of the Institute of the Lithosphere of Inner and Marginal Seas, Russian Academy of Sciences, by emission spectral analysis with inductively coupled plasma, analyst L.B. Efremova; other elements were analyzed by XRF on a TEFA analyzer, analysts A.T. Savichev and T.V. Sokolova.

Table 4. Trace-element compositions of rocks from the southwestern part of the Belomorian Belt

Component, ppm	Tonalites		Trondhjemites				Granites			
	2880-1	2706-1	2879-6	86-2	2879-1	72-5-10	2733/1A	2700-3	2700-5	2708-4
Rb	26	46	28	32	41	22	87	98	78	41
Ba	617	811	227	402	936	308	889	2026	2277	1655
Sr	513	393	866	376	370	844	307	435	517	461
Zr	118	133	155	147	107	124	151	213	164	139
Nb	3	3	3	3	3	–	–	–	3	3
Y	6	7	9	10	7	6	13	9	6	8
Ni	17	19	19	32	23	9	24	21	25	19
Pb	11	17	17	4	11	8	14	15	17	15
Ga	15	20	26	18	14	23	19	16	16	16
Zn	57	36	45	55	47	45	55	45	37	26
Cu	9	22	19	10	46	16	17	16	16	19
La	–	–	–	14	12	–	–	–	12	–
Ce	–	–	–	31	24	–	–	–	24	–
Nd	–	–	–	15	9.7	–	–	–	7.8	–
Sm	–	–	–	2.7	1.9	–	–	–	1.4	–
Eu	–	–	–	0.64	0.4	–	–	–	0.43	–
Gd	–	–	–	0.73	1.1	–	–	–	0.5	–
Yb	–	–	–	0.14	0.18	–	–	–	0.10	–
$(La/Yb)_N$	–	–	–	56.9	38.1	–	–	–	68.0	

Component, ppm	Granites								
	2955	2706-5	2706-3	2709-2	2708-3	2709-1	2699	2699-2	2706-2
Rb	112	70	69	131	60	124	123	121	118
Ba	992	1458	1163	727	1375	1320	1272	1987	943
Sr	395	490	494	196	361	272	260	509	325
Zr	101	116	245	110	198	94	88	213	104
Nb	5	3	–	–	–	–	2	2	–
Y	17	9	8	12	11	9	9	9	11
Ni	35	15	20	20	25	10	12	19	17
Pb	15	17	19	22	10	24	18	22	24
Ga	17	17	16	24	15	21	22	21	19
Zn	123	45	37	28	47	24	24	43	41
Cu	10	14	22	14	13	17	17	20	10
La	–	–	–	–	–	3.7	–	23	17
Ce	–	–	–	–	–	7.9	–	36	37
Nd	–	–	–	–	–	2.0	–	17	10
Sm	–	–	–	–	–	1.0	–	1.0	2.9
Eu	–	–	–	–	–	0.65	–	0.53	0.92
Gd	–	–	–	–	–	0.5	–	1.1	0.78
Yb	–	–	–	–	–	0.095	–	0.13	0.16
$(La/Yb)_N$	–	–	–	–	–	27.1	–	100.3	60.2

Note: See Table 2 for the location of the sampling sites.

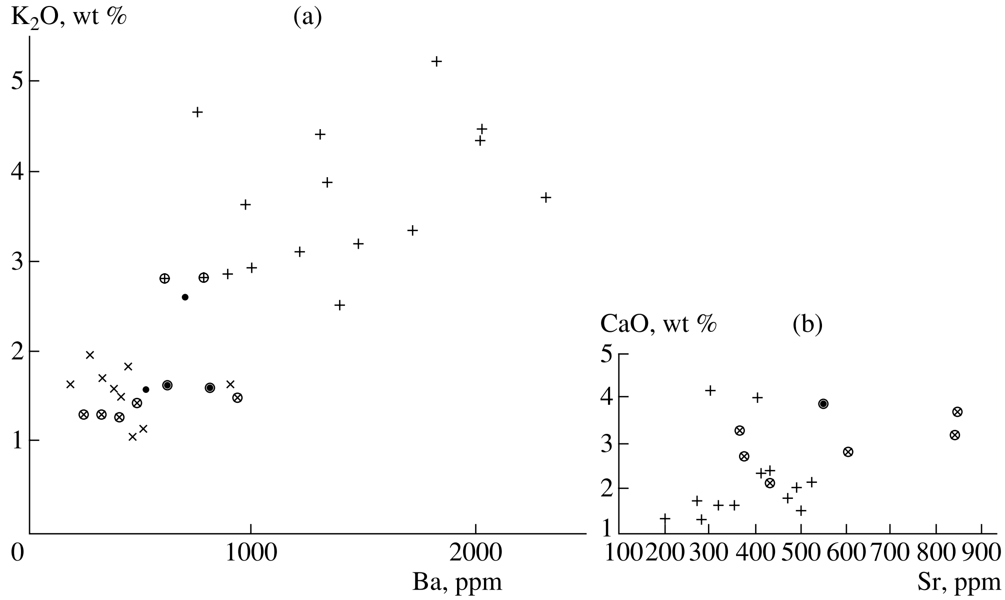

Fig. 9. (a) K_2O vs. Ba and (b) CaO vs. Sr diagrams for the rocks of the Belomorian Belt. See Fig. 2 for symbol explanations.

granites, and in one tonalite sample (Table 3, sample 2935-5a). As can be seen in the chondrite-normalized REE patterns (Figs. 10a–10c), the trondhjemites and microcline granites of the northeastern part of the belt have REE patterns similar to those of the analogous rocks in the southwestern part of the belt. The trondhjemites are noted for relatively high concentrations of LREE and strong depletions in HREE, with a strong fractionation of these elements [La_N/Yb_N = 40–70]. The rocks have very low Eu anomalies or even do not show them at all. A tonalite sample from the northeastern part of the belt has an REE pattern close to that of the trondhjemites (Fig. 10a), which suggests that the trondhjemites could have developed after the tonalites. When the REE patterns of the migmatites of tonalite and trondhjemite composition are compared with those of intrusive tonalites and low-K granodiorites from the Peninsula Range Batholith, North America [22], one can see that these rocks differ in the degrees of enrichment in LREE and, particularly, HREE (Figs. 10a, 10b, 10d). The configurations of the REE patterns of these rocks are also similar to the patterns assumed in the model for the origin of Archean trondhjemites, tonalites, and dacites via the melting of amphibolites or eclogites, but our rocks are much richer in LREE [14].

The microcline granites can be subdivided into two groups according to their REE concentrations, particularly those of La and Ce. One of the groups is noted for relatively high La and Ce contents (12–23 and 24–37 ppm, respectively) and is notably depleted in HREE. The $(La/Yb)_N$ ratios of this group vary from 60 to 100. The rocks of this group have positive Eu anomalies, whose heights slightly vary from sample to sample (Fig. 10c). In contrast to this group, the other group of the microcline granites typically has relatively low REE concentrations and low $(La/Yb)_N$ ratios of 15–27. However, as the rocks of the first group, these rocks have positive Eu anomalies. The different levels of Eu concentrations in these granites are consistent with their different plagioclase contents. For example, sample 2709-1, which is enriched in plagioclase (up to 70%, Table 2), has the highest Eu anomaly. We have previously described the two analogous groups of granites that were the final products of amphibolite migmatization and had different levels of REE concentrations [10]. The enrichment of the migmatization products of amphibolites in LREE and their depletion in HREE is related to the bleaching of these rocks with a decrease in the contents of mafic and some accessory minerals and suggests an elevated overall activity of strong bases during the metasomatic replacement of the amphibolites.

We have no original structural or isotopic data on the rocks that would make it possible, when considered together with geochemical data, to elucidate the geodynamic environments in which these rocks were produced. Hence, using geochemical data alone and plotting them in conventionally used geodynamic diagrams in terms of major elements, we attempted to determine the conditions under which these rocks could have been produced.

According to the petrogenetic interpretation of granitoid rocks based on multicationic parameters [23], the tonalites and trondhjemites of the northeastern and southwestern parts of the Belomorian Belt were derived under conditions corresponding to a precollisional environment, and the plagioclase–microcline granites were produced during collision (Fig. 11). The genetic relation of the plagioclase–microcline granites to colli-

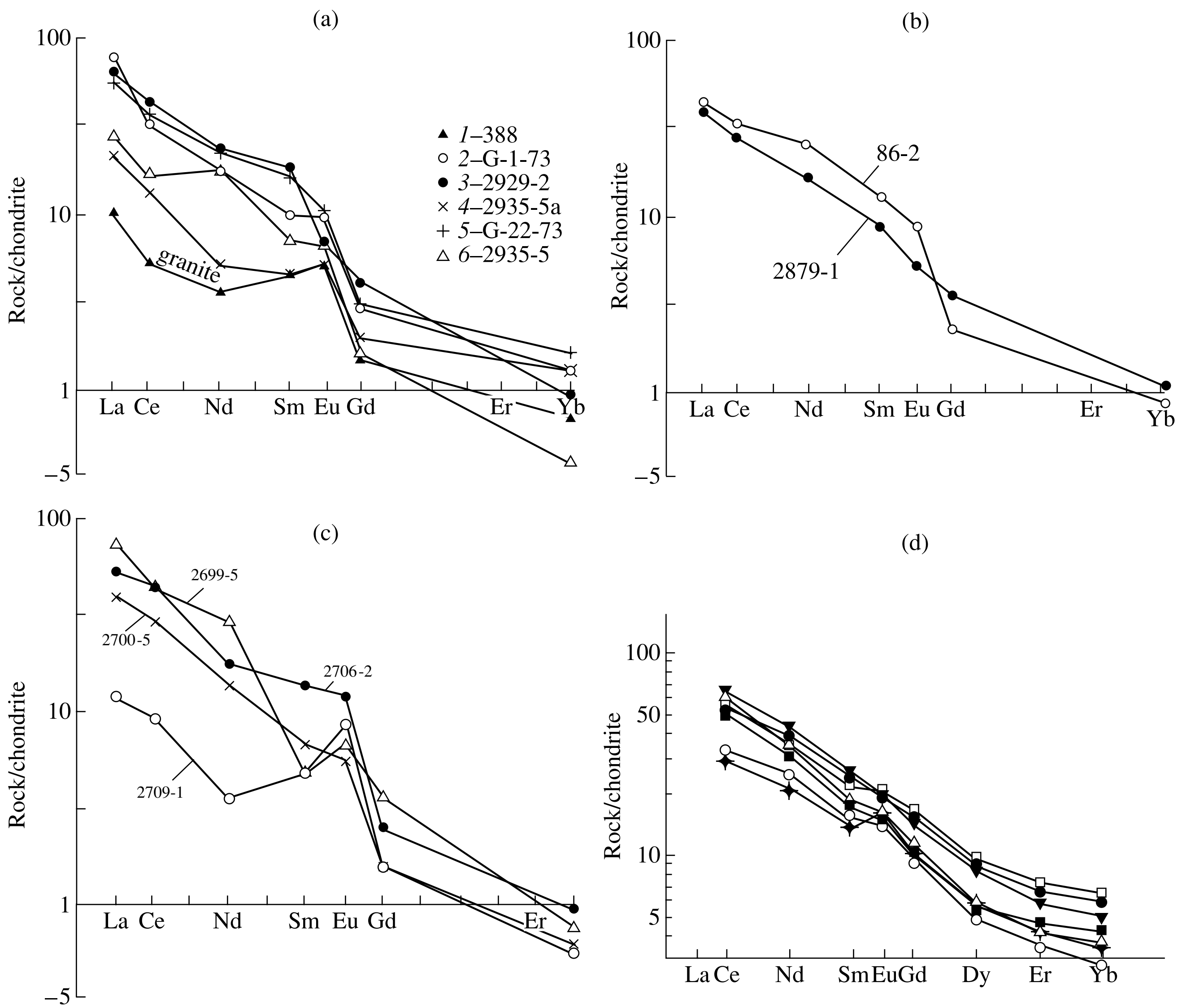

Fig. 10. Chondrite-normalized REE patterns for (a, b, c) granitoids of the Belomorian Belt and (d) for analogous rocks from the Peninsula Range Batholith [22]. (a) Rocks of the northeastern part of the belt: (*1*) granite, (*2, 3, 5, 6*) trondhjemites, (*4*) tonalite. (b, c) Rocks of the southwestern part of the belt: (b) trondhjemites, (c) granites. (d) Tonalites and low-K granodiorites (after [22]).

sion also follows from the position of the data points in the Pearce diagram [24], in which the composition points of these and other rocks from both parts of the belt plot within the field of arc rocks but, unlike the latter, are significantly shifted toward the syncollisional field (Fig. 12).

Thus, according to these diagrams, the plagioclase granitoids were most probably produced in an island-arc environment, and the plagioclase–microcline granites were derived in a collisional environment.

DISCUSSION

The analysis of the materials presented above indicates that the rocks of the northeastern and southwestern parts of the Belomorian Belt are migmatites with relics of layers and lenses of amphibolites (and a lesser amount of pale gray garnet–biotite plagioclase gneisses) with subordinate amount of anatectic material, which has no sharp boundaries and consists of plagiogranites and microcline granites. As can be seen from Tables 1 and 2, which demonstrate the quantitative proportions of minerals in the rocks (calculated in thin sections), the petrography of the migmatites is quite uniform. The mineral assemblages of the rocks exposed at the modern erosion surface within the territories in question are *Hbl + Bt + Pl + Qtz, Bt + Pl + Qtz*, and *Bt + Pl + Qtz + Mic*. The migmatites are characterized by a very uneven distribution of rock-forming minerals and variations in the compositions of these miner-

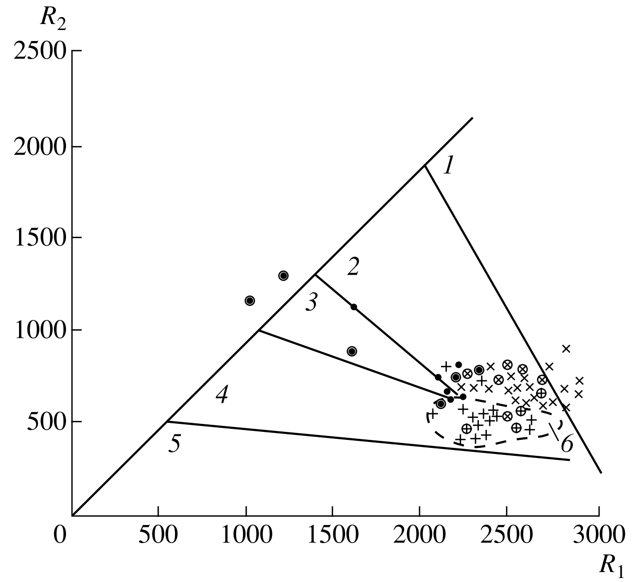

Fig. 11. Diagram of tectonic environments [23] for the granitoids of the northeastern and southwestern parts of the Belomorian Belt. Compositional fields of granitoids: (*1*) mantle fractionation, (*2*) precollisional, (*3*) postcollisional, (*4*) late orogenic, (*5*) anorogenic, (*6*) syncollisional. $R_1 = 4Si - 11(Na + K) - 2(Fe + Ti)$, $R_2 = 6Ca + 2Mg + Al$. See Fig. 2 for symbol explanations.

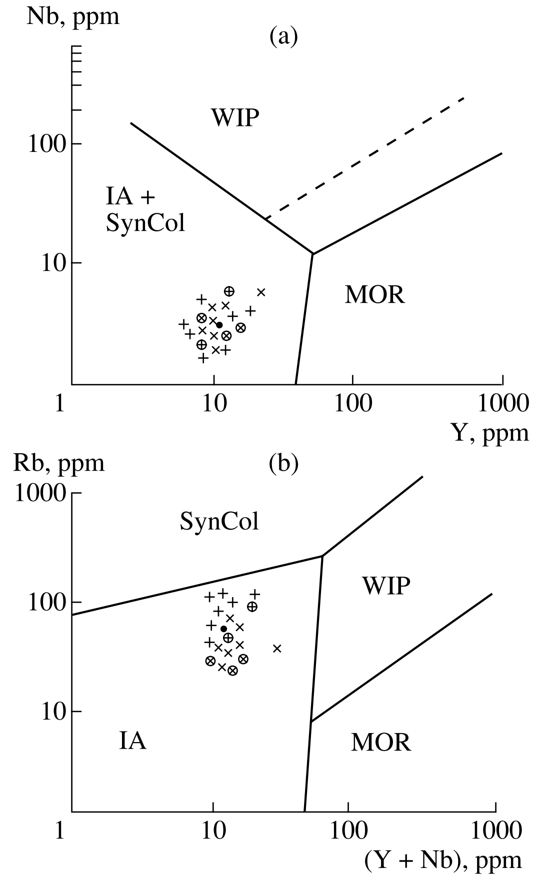

Fig. 12. Pearce et al. [24] diagram for the granitoids of the Belomorian Belt. Compositional fields of granitoids: IA—island arc, SynCol—syncollisional, MOR—of mid-oceanic ridges, WIP—within-plate. See Fig. 2 for symbol explanations.

als (the plagioclase becomes more sodic, the hornblende and biotite become more ferrous) with an increase in the degree of migmatization.

These petrographic features, gradual transitions between the rocks observable in exposures, and the distributions of major and trace elements (including REE) suggest that the rocks composing the northeastern part of the Belomorian Belt cannot belong to an intrusive tonalite–trondhjemite complex [1]. An intrusive complex is a complete set of derivatives (from ultramafic to acid) coming from a common chamber, which are coeval, have an analogous setting in the tectonic zone, and similar metallogenic features [25, p. 345]. The rocks of the northeastern part of the Baltic Belt do not display this complex of characteristics. In the well-known phase diagram of Tuttle and Bowen [26], the composition points of the metamorphic granites definitely plot away from the region of anchieutectic compositions. In other diagrams (Figs. 2, 3), migmatite varieties of certain composition plot within a number (but not a single) of fields. The reason for this was the uneven inflow of alkali–silicic fluids that facilitated metasomatism in the rocks. Analogous conclusions were also drawn by other researchers that examined Belomorian metasomatic granites [27]. In a Ca–Na–K diagram [28], the migmatites of both parts of the belt, corresponding to the compositions of tonalites and trondhjemites, do not cluster along the tonalite–trondhjemite trend but cut across it and define a swarm of data points that grades into a compositional field of the microcline granites (Fig. 13). This arrangement of the compositions of the rocks in the diagram argues that these rocks were not intrusive and that the microcline granites developed after the tonalites and trondhjemites.

Thus, the totality of geological, petrographic, and geochemical data on these rocks suggests that they had a metasomatic genesis. Note that the plagioclase–microcline granites that commonly develop in the rear zone of granitization could also sometimes be produced via the local derivation of a granitic magma (i.e., are anatectic).

Some researchers [29] point to multistage migmatization in the Belomorian province. They also believe that the migmatites of tonalite and trondhjemite composition were formed in the Belomorian Belt via the volumetric replacement of biotite–hornblende and biotite–epidote tonalitic orthogneisses and mafic crystalline schists. (It is pertinent to stress that, according to our data, these gneisses are the leucosome of the migmatites that replaced amphibolites and, to a lesser degree, pale gray garnet–biotite plagioclase gneisses).

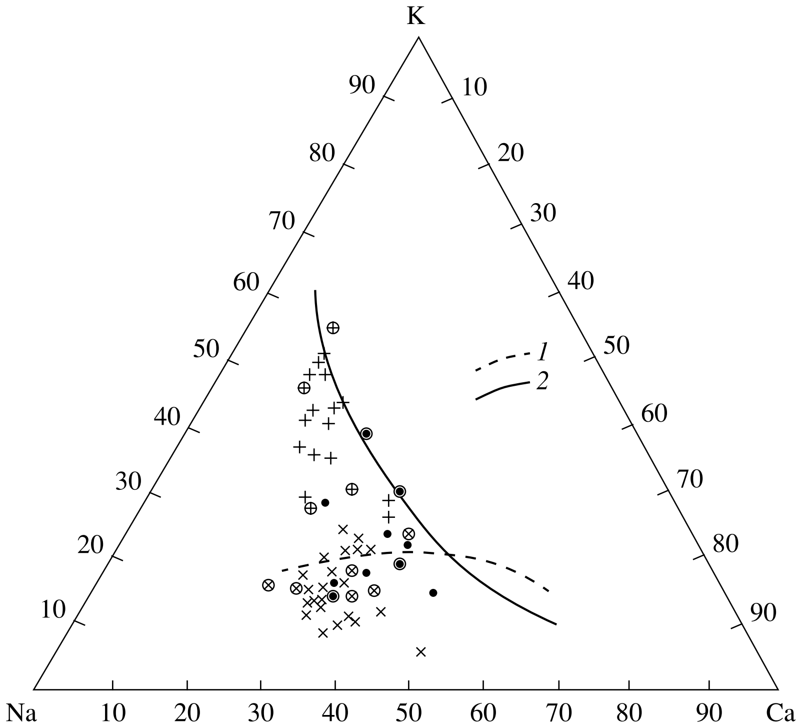

Fig. 13. K–Na–Ca diagram for the rocks of the Belomorian Belt. Trends: *1*—tholeiite–trondhjemite, *2*—calc–alkaline. See Fig. 2 for symbol explanations.

Confirming our observations, these authors point out the interstitial development of potassic feldspar that replaces plagioclase. They also believe that the origin of migmatites was followed by the development of diatexic melting chambers.

The comparison of analogous rocks in the two parts of the belt indicates that their petro- and geochemical characteristics are closely similar, and this enabled us to calculate the average compositions of granitoids for each of these parts. We compared the rocks of tonalite and trondhjemite composition, which were formed metasomatically via the granitization of amphibolites, with their analogues from various regions. For example, it is obvious from the comparison of the plagioclase migmatites from both parts of the belt with the tonalites of the Peninsula Range Batholith, whose rocks are typical products of island-arc magmatism [22], that the rocks in question have different concentrations of practically all major and most trace elements. We also compared our plagioclase granites with intrusive granites of the Coastal Taigonos Belt of the Koryak–Kamchatka Foldbelt [30]. As can be seen from Table 5, the rocks display more differences than similarities.

The plagioclase–microcline granites were compared with granites from three areas: (1) the Lachlan foldbelt in Southeast Australia, in which these rocks were derived from the lower crust [22]; (2) Eastern Taigonos Belt of the Koryak–Kamchatka Foldbelt, in which these rocks are reportedly [30] similar to I-type granitoids of active margins; and (3) the granitoids of Karakoram in northern Pakistan. It can be seen from the comparison of rows 3, 7, 9, and 10 of Table 5 that the plagioclase–microcline granites have concentrations of major oxides and characteristic trace elements practically identical to those of the Karakoram granites, whose evolution was related to lower crustal melts in collision belts [31].

This comparison indicates that the compositions of the tonalites and trondhjemites that are the products of the plagioclase migmatization of amphibolites do not resemble the compositions of analogous intrusive rocks. At the same time, the plagioclase–microcline granites that dominate in the southwestern part of the study area in the Baltic Shield, and are often the products of anatectic melts, are similar to intrusive granites, and their compositions are close to those of granite in collision zones (Table 5). The textures and structures of rocks in the southwestern part of the belt suggest that they were affected by tectonic processes and underwent cataclasis, mylonitization, and later blastesis. It is possible that the tectonic processes were related to collision, which caused the local development of melting chambers where the pressure decreased.

According to [1], the Archean granites in both parts of the Belomorian Belt were produced within a narrow age range of 2.75–2.65 Ga, and their model ages are 2.8 ± 0.5 Ga. The genesis of the plagioclase–microcline granites can likely be compared with the genesis of similar rocks in the Pazhma Massif, which is located near our study area at Notozero Lake and whose age is

Table 5. Average compositions of rocks from the northeastern and southwestern parts of the Belomorian Belt in comparison with analogous rocks from elsewhere

Component, wt %; element, ppm	Belomorian Belt										Other areas				
	northeastern part					southwestern part									
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10
SiO_2	64.58	70.57	71.94	69.24	69.59	65.84	71.03	71.84	66.12	69.30	63.41	69.65	60.9	67.8	71.43
TiO_2	0.51	0.24	0.17	0.30	0.28	0.55	0.30	0.23	0.52	0.35	0.64	0.40	1.0	0.6	0.26
Al_2O_3	17.64	16.46	15.52	16.72	16.57	17.77	16.00	15.00	16.6	15.72	15.70	14.17	16.0	14.7	14.61
Fe_2O_3	1.73	0.63	0.67	0.82	0.80	0.98	0.54	0.83	0.72	0.78	1.57	0.97	–	–	1.59
FeO	2.52	1.47	1.01	1.70	1.61	2.30	1.69	1.03	1.93	1.71	3.60	2.24	5.2	1.9	–
MnO	0.045	0.02	0.02	0.029	0.028	0.05	0.025	0.02	0.04	0.03	0.09	0.07	–	–	0.03
MgO	1.73	0.78	0.46	0.99	0.92	1.14	0.78	0.40	0.92	0.92	2.71	1.35	2.5	1.7	0.34
CaO	4.45	3.25	1.97	3.51	3.32	3.55	2.97	2.11	3.20	2.82	5.70	3.03	6.2	3.4	1.74
Na_2O	4.90	4.83	4.16	4.84	4.76	4.52	4.62	4.35	4.50	4.41	3.45	3.14	4.3	4.4	3.96
K_2O	1.65	1.21	3.63	1.31	1.61	2.53	1.37	3.59	1.83	2.89	1.69	3.47	1.0	2.8	4.25
LOI	0.61	0.40	0.54	0.45	0.46	0.56	0.51	0.39	0.53	0.62	–	–	–	–	0.38
H_2O	0.13	0.12	0.09	0.11	0.12	0.25	0.21	0.11	0.23	0.15	–	–	–	–	0.11
Rb	69	48	67	51.9	55	36	31	102	33	75	49	170	26	68	157
Ba	607	415	1076	450	584	714	468	1391	550	1126	451	504	255	621	1038
Sr	131	217	164	201	193	432	607	381	556	434	268	209	181	274	514
Zr	119	146	140	141	141	126	133	149	131.7	143	130	151	131	98	135
Nb	3	4	5	3.9	4	3	3	3	3	3	5.1	11.7	4.0	5.0	10.5
Y	17	11	8	11.6	11	7	8	10	7.5	10	24	33	26	12	9
Ni	48	29	19	32.5	30	18	21	20	20	4.5	18	7	–	–	3.4
Pb	95	10	11	10	10	14	10	18	11	16	8	20	–	–	44
Ga	14.5	16.8	13.7	16.4	15.8	17.5	20	18	19	18.7	16	16	–	–	–
Zn	64	65	33	65	51	46.5	49	44	48	43	66	48	–	–	40
Cu	18	22	19	20	20	15.5	23	16	20.3	17	16	10	–	–	–
F, %	75.5	77.2	81.7	76	76.8	78.4	78.2	85.2	78.6	81.4	63.6	–	73.0	59.2	–
f, %	65.7	71.0	73.8	69.3	69.6	72.5	73.7	76.9	73.3	74.5	–	–	–	–	–
CC	0.99	1.14	1.08	1.07	1.07	1.07	1.12	1.02	1.09	1.04	0.9	–	0.8	0.9	1.02
Number of samples	6	21	4	27	31	4	6	15	10	25	174	1024	11	10	20

Note: (1) Tonalites; (2) trondhjemites; (3) granites; (4) tonalites and trondhjemites; (5) tonalites, trondhjemites, and granites; (6) tonalites, Peninsula range Batholith; (7) granites, Lachlan foldbelt; (6, 7 according to [22]); (8) granitoids, Coastal Taigonos belt; (9), same, Eastern Taigonos belt (8, 9 according to [30]); (10) Karakoram granites [31].

slightly older than 2660 ± 10 Ma [19]. The Pazhma granites display petrochemical characteristics close to those of our rocks: both groups of rocks contain microcline and dark brown high-Fe biotite, have high total Fe content, and belong to the high-K calc–alkaline series. The microcline rocks in the southwestern part of the belt typically have pegmatoid patches, perhaps, due to Proterozoic tectono-thermal recycling.

Some researchers believe that the Belomorian Belt is a postcollisional zone, with collision occurring there in several stages: at 2.74–2.66 [32], 2.73–2.71 [33], and 2.68–2.60 [1] Ga. The tectonic motions that accompanied the collisional processes facilitated migmatization and granitization of the rocks. For example, Bibikova et al. [33] believe that collision at 2710 ± 15 Ma was associated with a number of migmatization stages.

Several researchers maintain that tonalites and trondhjemites are produced by the partial melting of mafic rocks. However, experimental data indicates that the melting of oceanic crustal rocks gives rise to tonalite–trondhjemite melts enriched in CaO and having Ca/(Mg + Fe) ratios higher than those in naturally occurring analogues [34]. Other geologists confirm the results of our research and believe that partial acid melts are derived as a direct consequence of metasomatic alterations. Relations between granite formation and intense metasomatic transformations are beyond doubt [35].

CONCLUSIONS

The results of our research led us to the following conclusions:

(1) The rocks composing the northeastern and southwestern parts of the Baltic Mobile Belt in our study area are hornblende–biotite, biotite, and biotite–epidote plagioclase migmatites, their nebular varieties, plagiogranites, and biotite plagioclase–microcline migmatites and granites. The wide occurrence of amphibolite relics that are gradually replaced by plagioclase granitoids of progressively more and more silicic composition led us to recognize a succession of migmatized rocks from amphibolite (original metamorphic rock) to biotite plagioclase–microcline granite (final migmatization product), with intermediate members of hornblende–biotite and biotite plagioclase migmatites. The field relations of rocks in this migmatization succession, relations between their minerals observed in thin sections, systematic variations in the chemistry of these minerals with increasing silicity of the rocks (the plagioclase becomes progressively more sodic, and the hornblende and biotite become more ferrous), and the behavior of major and trace elements (the removal of mafic components, such as Fe, Ca, and Mg, the enrichment of the rocks in silica and alkalis, and the absence of rock enrichment in trace lithophile elements when the silicity of these rocks increases) suggest that the rocks of this succession were produced by granitization with the participation of high-temperature alkali–silicic fluids.

(2) The plagioclase migmatites and their nebular varieties and plagioclase granites compositionally correspond to tonalites and trondhjemites, which belong to the calc–alkaline series. They were produced metasomatically and differ from their intrusive analogues.

(3) The proportions of major components in the plagioclase–microcline granites indicate that these rocks are different and correspond to subalkaline granites, subalkaline leucogranites, and granites proper, whose compositions correspond to the high-K calc–alkaline series. These rocks are commonly formed in the rear zone of migmatization and can also occasionally be of anatectic genesis.

(4) The major-component compositions of rocks from both of the study areas are similar. The rocks of the southwestern part of the belt are slightly poorer in Fe, Mg, and Ca and richer in K than the plagioclase migmatites of the northeastern part. These differences are insignificant, as can be seen, for example, from the nearby arrangement of the data points of all rocks in various petrochemical diagrams.

(5) The rocks of both areas have similar concentrations of most trace elements, including REE, and are characterized by strong depletion in Rb, Nb, Y, and Zr (whose contents are three to seven times lower than those of acid lithospheric rocks). All rocks of the southwestern part of the belt are strongly enriched in Sr and, particularly, Ba relative to their analogues in the northeastern part (434 and 193 ppm, respectively for Sr and 1126 and 584 ppm for Ba). These differences in the Sr and Ba contents of the rocks suggest that they were derived under different conditions.

(6) The petrochemical characteristics of the rocks composing the northeastern and southwestern parts of the Belomorian Belt suggest that these rocks had similar petrochemical and geochemical evolutions related to migmatization, although these rocks were derived in different environments.

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