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# Geochemistry of Granitization and Magmatic Replacement of Basic Volcanic Rocks in the Contact Aureole of the Yurchik Gabbronorite Intrusion, Ganal Range, Kamchatka

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**Abstract**—Geological and geochemical data indicate that the formation of the granulite-like rocks in the contact aureole of the Yurchik gabbronorite intrusion of the Ganal Range, Kamchatka, was caused by the contact metamorphism, metasomatism, and local melting of the initial volcanosedimentary rocks of the Vakhtalka Sequence of the Ganal Group. The temperature in the inner part of the aureole reached 700–800°C and caused the transformation of the basic volcanic rocks of the sequence into two pyroxene–plagioclase, clinopyroxene–amphibole–plagioclase, and amphibole–plagioclase hornfelses, while sedimentary rocks were converted into garnet–biotite ± cordierite hornfelses. The hornfelsed basic volcanic rocks were locally subjected to metasomatic alteration and magmatic replacement with formation of biotite–orthopyroxene–plagioclase metasomatic bodies containing biotite–orthopyroxene–plagioclase ± garnet veinlets and aggregates. During these processes, sedimentary interlayers were converted into garnet enderbites at 700–800°C and 3.2–4.8 kbar. The comparison of the chemical composition of basic volcanic rocks of the Vakhtalka Sequence and their transformation products indicates that the metasomatic alteration and magmatic replacement correspond to siliceous–alkaline metasomatism (granitization) and cause subsequent and uneven influx of $SiO_2$, $Al_2O_3$, $Na_2O$, $K_2O$, Rb, Ba, Zr, Nb, and Cl and removal of Fe, Mg, Mn, Ca, Cr, Co, Ti, Y, and S. REE data on basic metavolcanic rocks, hornfelses, and metasomatites suggest that the processes of hornfelsation, metasomatism, and magmatic replacement of the initial volcanic rocks were accompanied by significant increase in LREE and slight decrease in HREE. The Sr and Nd isotope study of the rocks in the aureole showed that the initial basic volcanic rocks of the Vakhtalka Sequence are isotopically close to both mature island arc tholeiites and mid-ocean ridge basalts. The metasomatic alteration and magmatic replacement of volcanic rocks in the aureole lead to the decrease of $^{143}Nd/^{144}Nd$ and increase of $^{87}Sr/^{86}Sr$ approximately parallel to mantle array. Pb isotopic ratios in the studied rocks become more radiogenic from initial metavolcanic rocks to metasomatites.
It is suggested that the processes of metamorphism, metasomatism, and magmatic replacement were caused by highly mineralized mantle fluids, which percolated along magmatic channels serving as pathways for gabbroid magma.

***Keywords:*** basic volcanics, hornfelses, gabbronorites, metasomatites, granitizaition, magmatic replacement, Ganal Range, Kamchatka

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## INTRODUCTION

The role of fluids in the transfer of chemical components during magmatic and metasomatic processes is one of hotly debatable problems in the modern geological literature. New achievements in the framework of this problem are publications dedicated to the formation of oceanic granitoids by fluid-assisted metasomatic transformation of basic basement. Geochemically similar high-temperature metasomatic transformations of basic rocks are observed in the outer contact zone of the Yurchik gabbronorite massif at Kamchatka, the characteristics of which is considered in this work.

The find of high-temperature granulite-like metamorphic rocks (garnet enderbites) in the contact aureole of the Yurchik gabbronorite intrusion of the Ganal Range of Kamchatka gave rise to a long-term discussion regarding their origin and facies affiliation [1–7]. Some researchers considered these rocks as independent ancient (mainly Precambrian) complex of sialic basement of East Kamchatka [1–3], which served as the base for the formation of all subsequent rocks. Other geologists suggest that these metamorphic rocks were formed during contact reactions in response to the emplacement of the large Yurchik gabbronorite intrusion into Cretaceous volcanosedimentary deposits of the Ganal Group [4–8].

Our previous works in this region were devoted to the study of the enderbitization, gabbroization, and magmatic replacement in the contact aureole of the Yurchik gabbronorite intrusion [6, 9–13]. In this work, we report new REE and Sr, Nd, and Pb isotope data on the metamorphic rocks of the Vakhtalka Sequence of the Ganal Group, which were subjected to metasomatism, granitization, and magmatic replacement in the contact aureole of the Yurchik intrusion, and discuss the problems of genesis of granulite-like rocks.

## METHODS

REEs were analyzed by ICP-MS on Agilent 7500c at the Analytical Center of the Far East Geological Institute of the Far East Branch of the Russian Academy of Sciences. The $SiO_2$ and L.O.I. were determined by gravimetry, while other petrogenic elements were analyzed by inductively coupled plasma atomic emission spectrometry on an ICP-6500 at the Analytical Center of the Far East Geological Institute of the Far East Branch of the Russian Academy of Science. Some trace elements were determined by XRF on an automated S4 Pioneer spectrometer at the Analytical Center of the Far East Branch of the Russian Academy of Sciences. Samples for elemental ICP-MS and ICP-AES analyses were decomposed by fusion with lithium metaborate ($LiBO_2$) in a mixture sample : flux 1 : 3. Trace element abundances were determined with standard deviation less than 10%.

Sr, Nd, and Pb isotope compositions were analyzed at the Institute of Geochemistry of the Siberian Branch of the Russian Academy of Sciences on a Finnigan MAT 262 mass spectrometer (Baikalian Analytical Center of Collective Use of the Siberian Branch of the Russian Academy of Sciences, Irkutsk). Measured Sr isotope composition was corrected to $^{87}Sr/^{86}Sr$ = 0.71024 ± 1 in NBS-987 standard at recommended $^{87}Sr/^{86}Sr$ = 0.71025. The Nd isotope analysis was controlled by JND-1 standard with $^{143}Nd/^{144}Nd$ = 0.512100 ± 5 at recommended value of 0.512116. The values of $^{143}Nd/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratios in samples were calculated using ICP-MS data obtained at the Analytical Center of the Far East Geological Institute of the Far East Branch of the Russian Academy of Sciences. Measured $^{87}Sr/^{86}Sr$ ratios in samples were not normalized to the recommended value in the VNIIM standard.

Instrumental mass-fractionation during the Pb isotope analysis was corrected using "zero-time correction" [14, 15]. The value of measured Pb isotope composition of NBS-981 standard was $^{206}Pb/^{204}Pb$ = 16.939 ± 2; $^{207}Pb/^{204}Pb$ = 15.492 ± 2; $^{208}Pb/^{204}Pb$ = 36.706 ± 8 at the recommended $^{206}Pb/^{204}Pb$ = 16.937, $^{207}Pb/^{204}Pb$ = 15.491, and $^{208}Pb/^{204}Pb$ = 36.721.

## BRIEF GEOLOGICAL REVIEW

The Yurchik intrusion represents a phacolith-like body around 22 km long, which intruded the voclanosedimentary rocks of the Ganal Group and caused their metamorphism (Fig. 1). The most significant thickness of gabbroid rocks (up to 1500 m) identified by the intensity of magnetic field was established in the northern part of the massif (Fig. 2). In this area, the host rocks of the Vakhtalka Sequence of the Ganal Group experienced maximal heating and intense hornfelsation, which was overprinted by processes of metasomatic and magmatic replacement.

The Yurchik Massif is made up of early gabbronorites with small cortlandite bodies and later magmatic rocks varying in composition from lherzolites, wehrlites, and troctolites to melanocratic clinopyroxene–amphibole gabbros [5, 9]. Late postmetamorphic gabbroids are exposed mainly in the southern and southeastern portions of the intrusion, where they cut across the early gabbronorites, host rocks of the Ganal Group, and gneissose amphibole–biotite granitoids, which we interpret to represent the acid derivatives of the Yurchik intrusion. The late gabbroids are geochemically similar to the derivatives of the island-arc aluminous low-potassium tholeiites [16].

In the marginal zones, the early gabbronorites are gneissose, cataclased, and diaphthorized up to formation of gabbro amphibolites due to superimposed amphibolite-facies regional metamorphism [5, 7, 9], which spanned also hornfels aureole, volcanosedimentary rocks of the Ganal Group, and amphibole–biotite granitoids. This regional metamorphism was likely caused by intense thrusting and piling of different lithotectonic complexes into nappe package during formation of thrust-imbricated tectonic structure of the Ganal Range [17]. It is suggested that this metamorphism occurred simultaneously with regional metamorphism of the sediments of the Kamchatka Median Crystalline Massif (52–55 Ma). The timing of regional metamorphism of the rocks of the Ganal Range is constrained between the emplacement of the early gabbronorites and peridotites of the Yurchik intrusion (U–Pb SHRIMP age of 85 Ma [18]) and the formation of postmetamorphic gabbroids with $^{40}Ar/^{39}Ar$ and U–Pb SHRIMP dates within 20–25 Ma [16, 19].

The Vakhtalka Sequence (800–900 m thick) lying at the base of the Ganal Group consists mainly of basic metavolcanics (amphibolites, amphibole and clinopyroxene–amphibole schists) with boudined interlayers of garnet–biotite ± cordierite plagiogneisses from 10–20 cm to 10–15 m and more thick, dacitic metavolcanics, quartiztes, and occasional marbles [13]. The basic volcanic rocks of the Vakhtalka Sequence are dated by

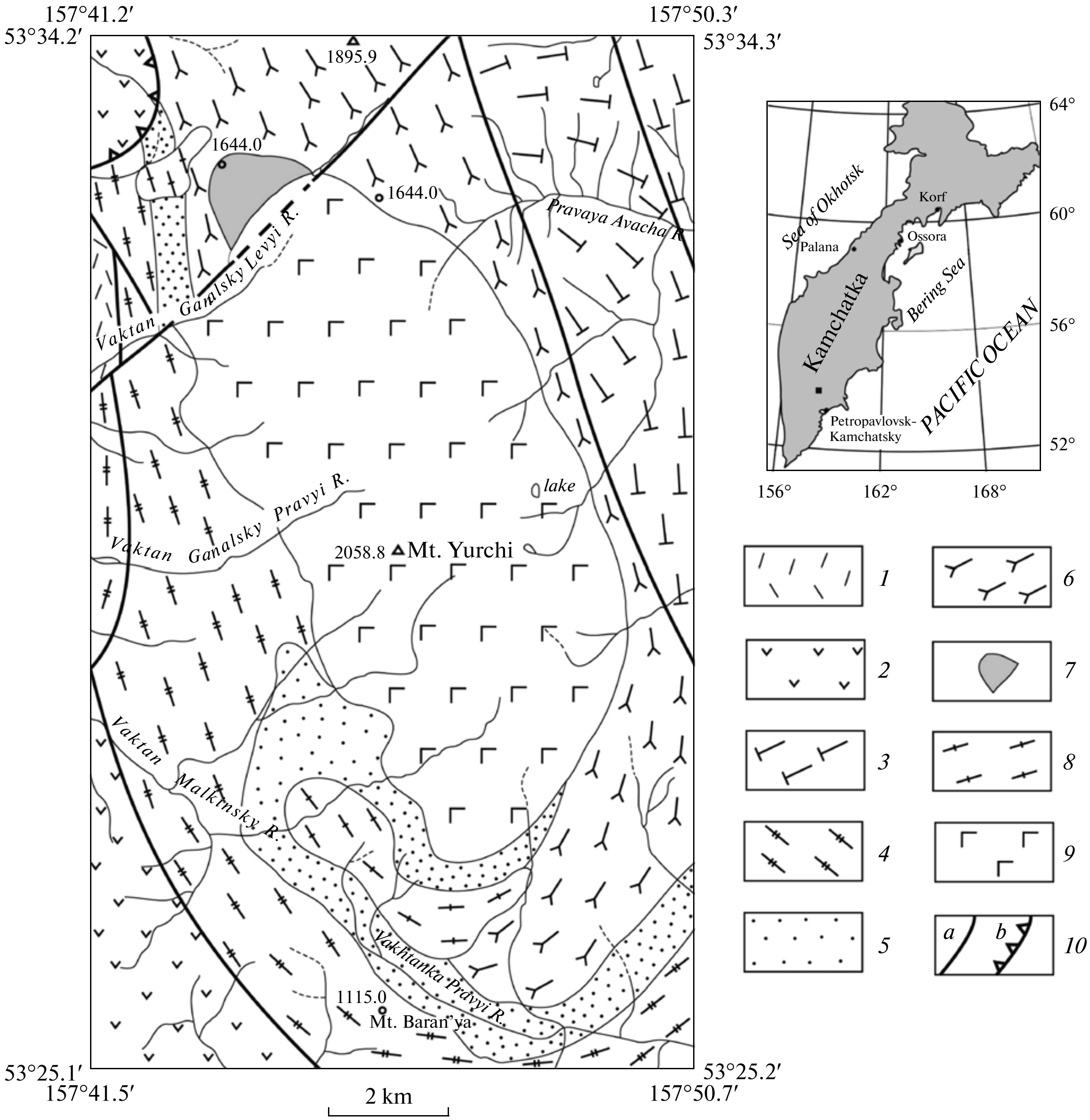


**Fig. 1.** Schematic geological map of the Yurchik gabbronorite intrusion, Ganal Range.

(*1*) Neogene tuffs and volcanic rocks, (*2*) siliceous shales, siltstones, tuffites, tuffs, altered basalts, shales, and sandstones of the Late Campanian–Maastrichtian Irunei Formation; (*3*) greenstone altered felsic, intermediate and less common basic volcanic rocks and their tuffs, and terrigenous rocks of the Late Cretaceous Stenovaya Group; (*4–6*) Cretaceous Ganal Group: (*4*) terrigenous–volcanogenic (D'yavol'skaya) sequence, (*5*) terrigenous (Voevodskaya) sequence, (*6*) essentially volcanogenic (Vakhtalka) sequence; (*7*) zone of intense hornfelsation, metasomatism, and magmatic replacement of the rocks of the Vakhtalka sequence; (*8*) gneissose amphibole–biotite plagiogranites; (*9*) gneissose gabbronorites and postmetamorphic clinopyroxene–amphibole gabbro and peridotites of the Yurchik Massif (undivided), (*10*) faults (a), thrusts (b). Inset shows the position of the Yurchik intrusion.

U–Pb SHRIMP zircon method at 116.2 ± 1.3 and 120 ± 1.5 Ma [20]. In addition, these volcanic rocks contain numerous xenogenic zircons of the Triassic–Carboniferous, Early Paleozoic, and Proterozoic age [20].

## PETROGRAPHY AND MINERALOGY OF THE METAMORPHIC ROCKS

The basic volcanic rocks of the Vakhtalka Sequence in the inner portions of the contact aureole were con-

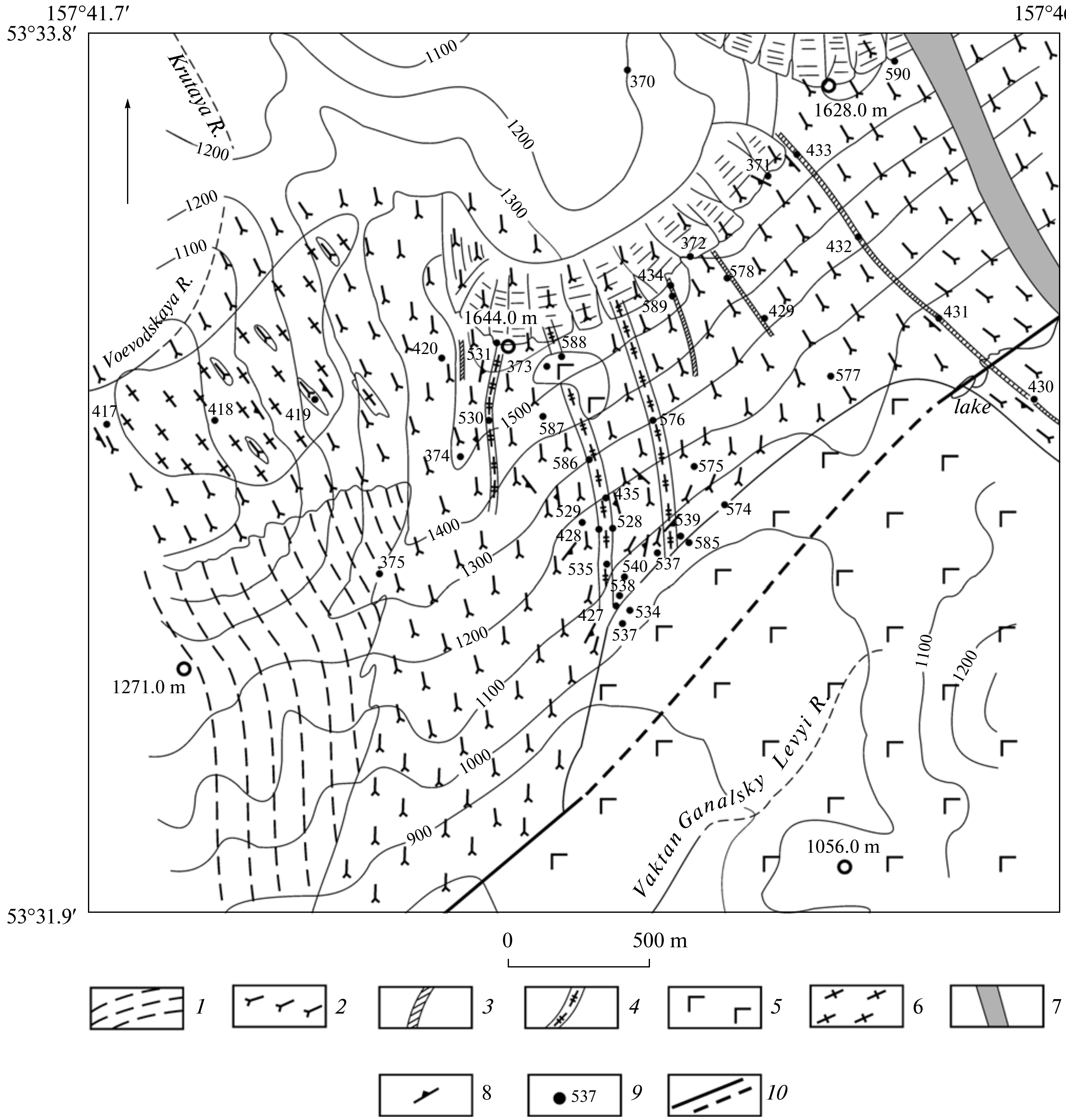


**Fig. 2.** Geological scheme of the contact aureole in the northern part of the Yurchik gabbroid intrusive (heads of the Vaktan Ganal'sky Levyi).

(*1–3*) metamorphic rocks of the Ganal Group: biotite and garnet–biotite plagiogneisses of the Voevodskaya sequence (*1*), amphibole, clinopyroxene–amphibole, and two pyroxene–amphibole hornfelses after basic volcanic rocks of the Vakhtalka Sequence, biotite–orthopyroxene–plagioclase metasomatites (*2*), interlayers of biotite and garnet–biotite plagiogneisses (*3*), (*4*) garnet–orthopyroxene–cordierite–biotite enderbite bodies; (*5*) gneissose gabbronorites, (*6*) gneissose amphibole–biotite plagiogranites, (*7*) zone of intense pyritization of the intercalation unit of basic, intermediate, and felsic volcanic rocks, (*8*) strikes and slips of schistosity, gneissosity, and banding, (*9*) observation points, (*10*) faults. Horizontal lines are with a step of 100 m.

verted into fine-grained amphibole, clinopyroxene–amphibole, and two pyroxene–amphibole hornfelses [12, 13] consisting of Mg-hornblende or Fe-rich pargasite ($X_{Mg} = 0.60–0.67$)[1], plagioclase ($X_{An} = 0.8–0.5$),

[1] $X_{Mg} = Mg/(Mg + Fe + Mn)$; $X_{An} = Ca/(Ca + Na + K)$.

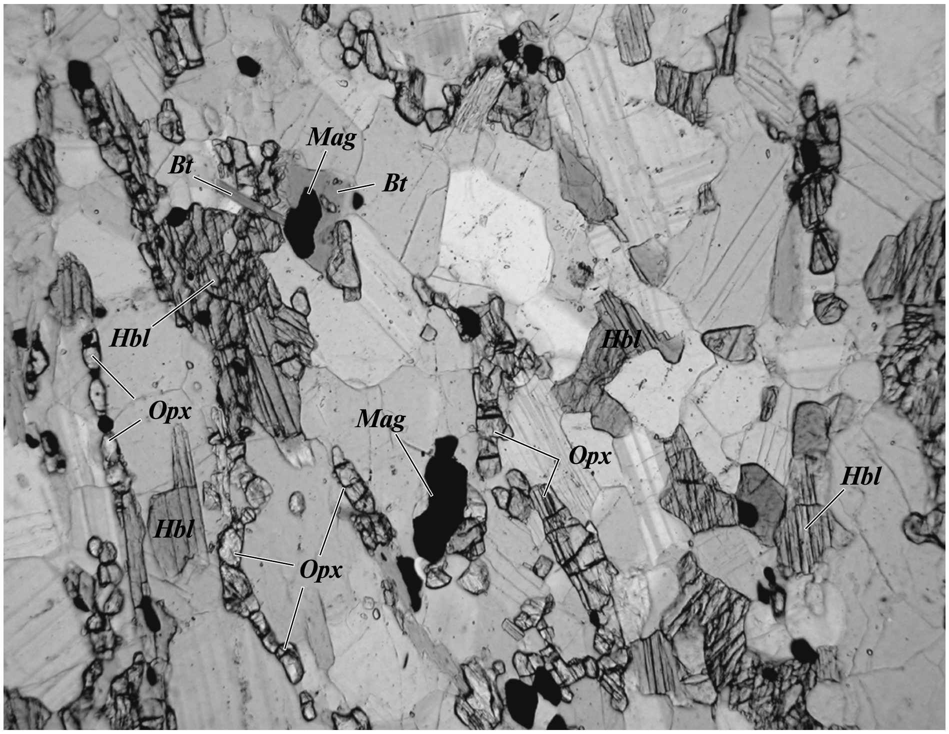


**Fig. 3.** Metasomatic replacement of brownish–green hornblende (*Hbl)* by orthopyroxene (*Opx*) in the basic hornfelses of contact aureole of the Yurchik gabbronorite intrusion. Sample 537-S, without analyzer. (*Bt*) biotite, (*Mag*) magnetite.

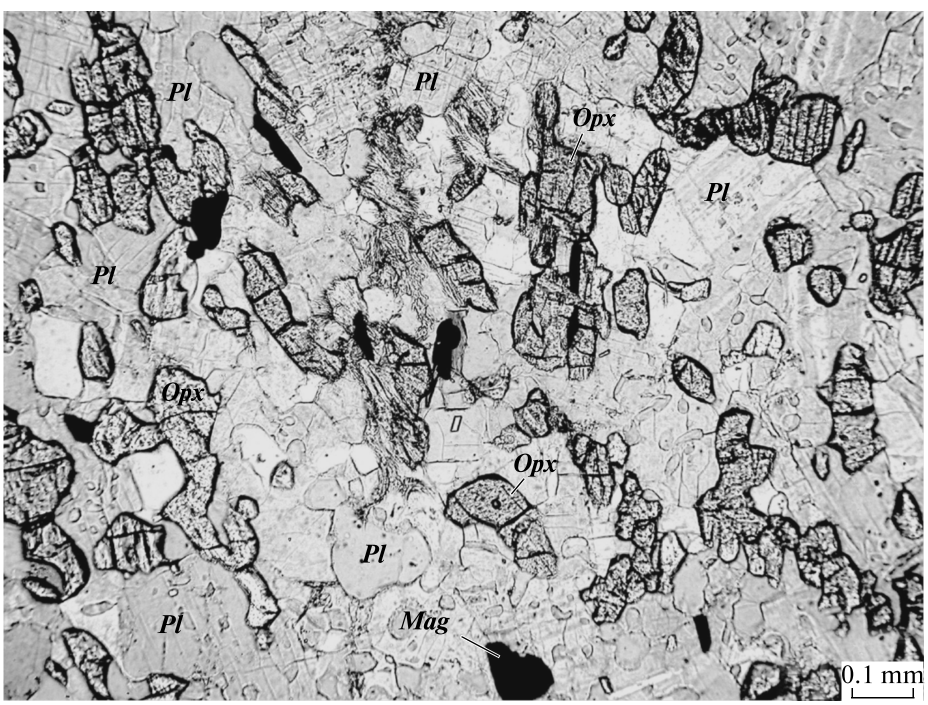


**Fig. 4.** Fine-grained biotite–orthopyroxene–plagioclase metasomatite. Sample 427-I, without analyzer. (*Opx*) orthopyroxene, (*Pl*) plagioclase, (*Mag*) magnetite.

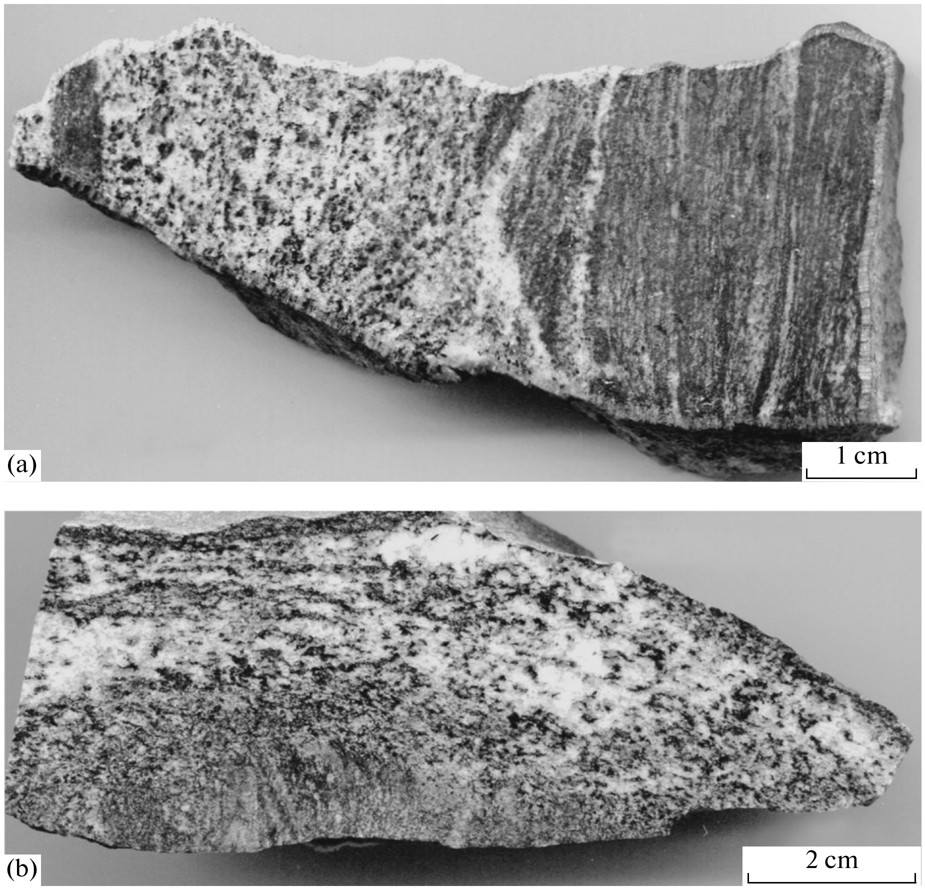


**Fig. 5.** Leucocratic migmatite biotite–orthopyroxene–plagioclase veinlets in the fine-grained biotite–orthopyroxene–plagioclase metasomatites. (a) sample 535-K, (b) sample 574.

clinopyroxene ($X_{Mg}$ = 0.68–0.77), and less common orthopyroxene ($X_{Mg}$ = 0.70–0.72). The maximum temperature of contact metamorphism reached 700–800°C [13].

Basic hornfelses were locally subjected to metasomatic transformations. At the initial stages of metasomatism, amphibole in hornfelses was replaced by individual small crystals and chains of orthopyroxene (Fig. 3). As a result, practically all hornfelses from the northern part of the contact aureole were variably metasomatized and replaced by association of fine- and ultra-fine-grained metasomatites (Fig. 4) consisting of orthopyroxene ($X_{Mg}$ = 0.58–0.63), plagioclase $An_{45}$, variable amount of biotite ($X_{Mg}$ = 0.60–0.75), apatite, and Fe–Ti oxides.

Intensification of the metasomatic processes gave rise to the intense debasification of hornfelses and their local magmatic replacement expressed in the development of thin leucocratic biotite–orthopyroxene—plagioclase ± garnet migmatite veinlets and aggregates (Fig. 5) with magmatic hypidiomorphic texture and coarser (up to 1–2 and more millimeters) mineral crystals. Detailed mineralogy of metasomatic transformations and magmatic replacement of basic hornfelses from this aureole is considered in [13].

The formation of biotite–orthopyroxene–plagioclase ± garnet leucocratic veinlets and aggregates, which are similar to the leucosome of typical migmatites, in metasomatites indicates a local melting (magmatic replacement) of the initial hornfelses preliminarily altered by metasomatic processes. Metasomatic rocks as well as migmatic veinlets and aggregates differ in sharply elevated content of apatite, which indicates the high concentration of volatiles (water, phosphorus, chlorine, and fluorine) in metamorphosing fluids. Neomorphous orthopyroxene and biotite from metasomatites and migmatite veinlets are characterized by the higher Fe more fraction, while plagioclase has lower Ca content as compared to the similar minerals from hornfelses [13]. The content of garnet in the migmatite veinlets usually is no more than few %. It has the following composition: *Alm* 60–63%, *Prp* 15–17, *Sps* 13–14, *Grs* 8–10, $X_{Mg}$ = 0.17–0.18.

Further intensification of metasomatic processes and magmatic replacement of hornfelses enforced debasification of initial basic volcanic rocks and led to the appearance of single thin garnet enderbite veinlets,

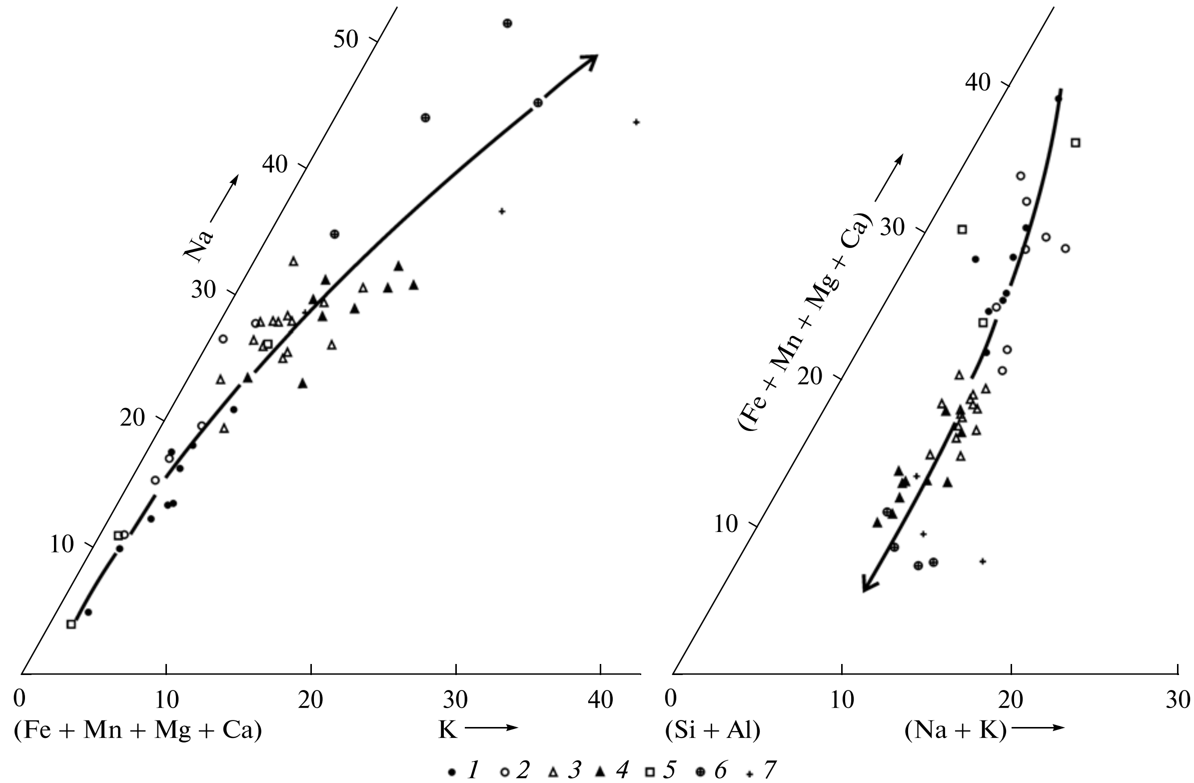


**Fig. 6.** Petrochemical diagrams showing metasomatic transformation and magmatic replacement of hornfelsed basic volcanic and sedimentary rocks of the Vakhtalka Sequence in the contact aureole of the Yurchik intrusion after [12, 13].
(*1–2*) hornfelsed volcanic rocks: clinopyroxene–amphibole–plagioclase (*1*) and amphibole–plagioclase (*2*) composition, (*3*) biotite–orthopyroxene–plagioclase metasomatites, (*4*) garnet enderbites, (*5*) xenoliths of basic metavolcanic rocks (hornfelses) in garnet enderbites, (*6*) charnockites, (*7*) metamorphosed felsic volcanic rocks (metadacites). Arrows show the variation trend of hornfelsed basic metavolcanics of the Vakhtalka Sequence during granitization and magmatic replacement.

which in addition to orthopyroxene, biotite, and plagioclase, contain quartz, cordierite, garnet, and rare K-feldspar. The large bodies of the garnet enderbites are formed only during magmatic replacement of boudined terrigenous beds located among basic metavolcanic rocks of the Vakhtalka Sequence (Fig. 2). Thermodynamic conditions of the formation of the garnet enderbites determined using garnet–orthopyroxene geothermobarometer [21] correspond to 700–800°C and 3.2–4.8 kbar [13].

## GEOCHEMISTRY OF THE METAMORPHIC ROCKS

The comparison of the chemical composition of basic volcanic rocks from the Vakhtalka Sequence in the contact aureole and their transformation products [12, 13] shows that the processes of metasomatism and magmatic replacement correspond to the siliceous–alkaline metasomatism (granitization), which leads to the subsequent but uneven input of $SiO_2$, $Na_2O$, $K_2O$, Rb, Ba, Zr, Nb, and Cl and removal of Fe, Mg, Mn, Ca, and some trace elements (Cr, Co, Ti, Y, S), thus causing intense debasification of initial rocks (Fig. 6). Similar behavior of elements during granitization was noted in [22]. In spite of the fact that scales of granitization during regional and contact metamorphism are different, the behavior of chemical elements (input–removal) is controlled by the same trends.

The comparison of REE contents in the basic volcanic rocks of the Vakhtalka Sequence, their hornfelsed varieties, and metasomatites suggests that the metasomatic transformation and magmatic replacement of initial rocks is accompanied by increase in LREE and slight decrease in HREE (Table 1, Fig. 7). Primitive mantle-normalized multicomponent discrimination diagrams of the volcanic rocks of the Vakhtalka Sequence and products of their metasomatic transformation and magmatic replacement show no any suprasubduction geochemical features.

The results of Sr, Nd, and Pb isotope study of the rocks of the Vakhtalka Sequence that enclose the Yurchik gabbroid massif are presented in Tables 2, 3 and in Figs. 8–10. Isotope Nd–Sr systematics[2] of initial volcanic rocks, hornfelses, and metasomatites (Fig. 8)

[2] It was shown [4] that the Sr and Nd isotope compositions of the studied rocks reveal no signs of the existence of ancient sialic crust in the Ganal Range.

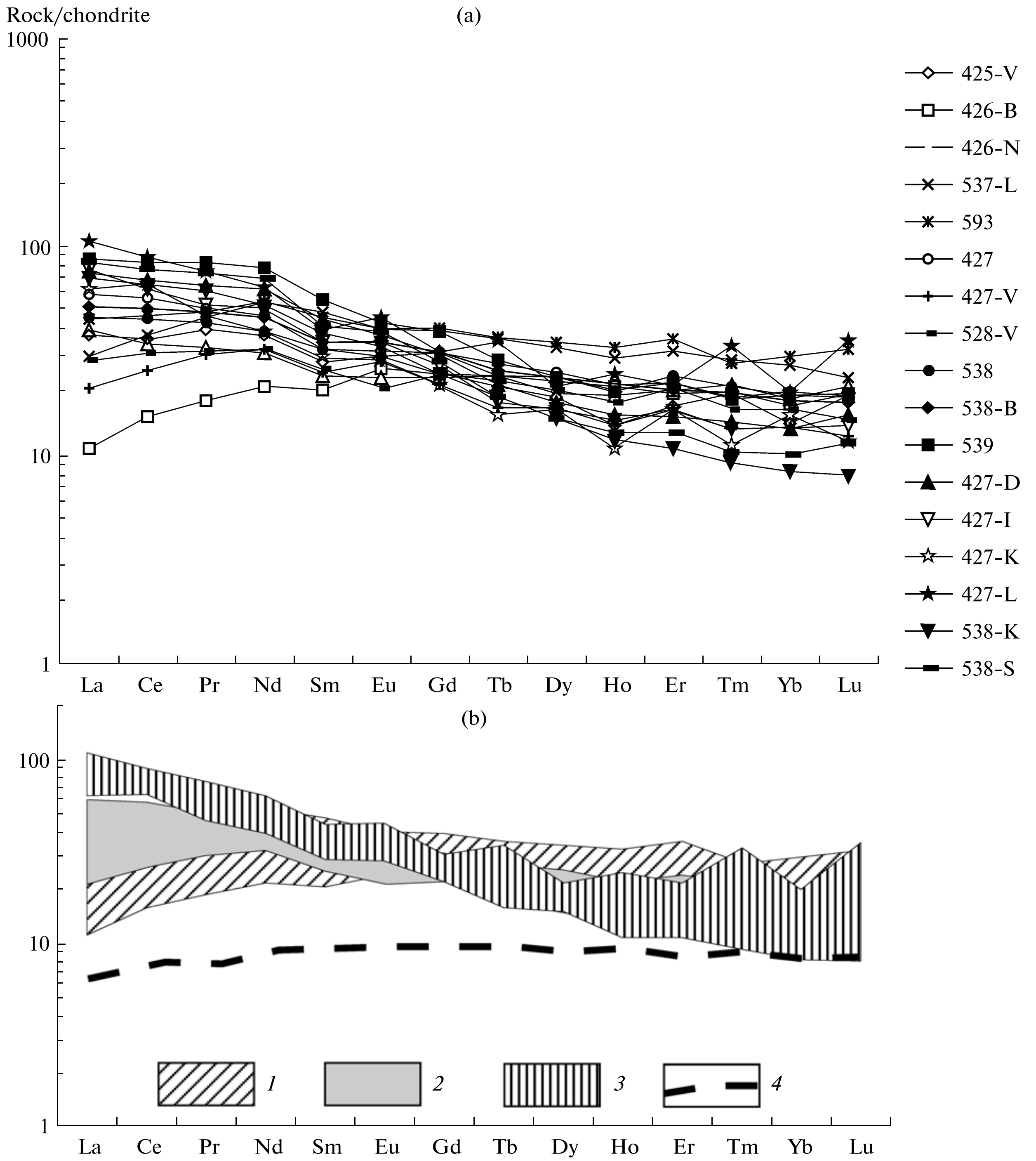


**Fig. 7.** Chondrite-normalized [23] REE contents (Table 1) in the initial basic volcanic rocks of the Vakhtalka Sequence, amphibole and amphibole–clinopyroxene hornfelses and biotite–orthopyroxene–plagioclase metasomatites (a). Fields of normalized REE contents for basic volcanic rocks (*1*), hornfelses (*2*), and metasomatites (*3*) from the contact aureole of the Yurchik intrusion (b). (*4*) average composition of the tholeiitic basalt from the mid-oceanic ridge [24].

indicates that all the three rock groups are close to the mantle correlation array. In the diagram (Fig. 8), the compositions of the studied volcanic rocks are confined to the fields of the mid-ocean ridge tholeiitic basalts (εNd (0) = + 10.1 [25], as well as to the fields of mature island arcs such as Kamchatka (εNd (0) = +9.4 [26] or Honshu (εNd (0) = + 4.5 [27, 28]. Variations in Nd isotope composition of hornfelses fall in the region of the highest positive values of these isotope ratios (εNd (0) = from +9.5 to +10.7), whereas metasomatites have lower values of εNd from +4.0 to +9.1.

Based on εNd distribution, the metamorphic rocks of the Vakhtalka Sequence are divided into two groups (Table 2): (1) εNd(0) from +4.0 to +4.5, which com-

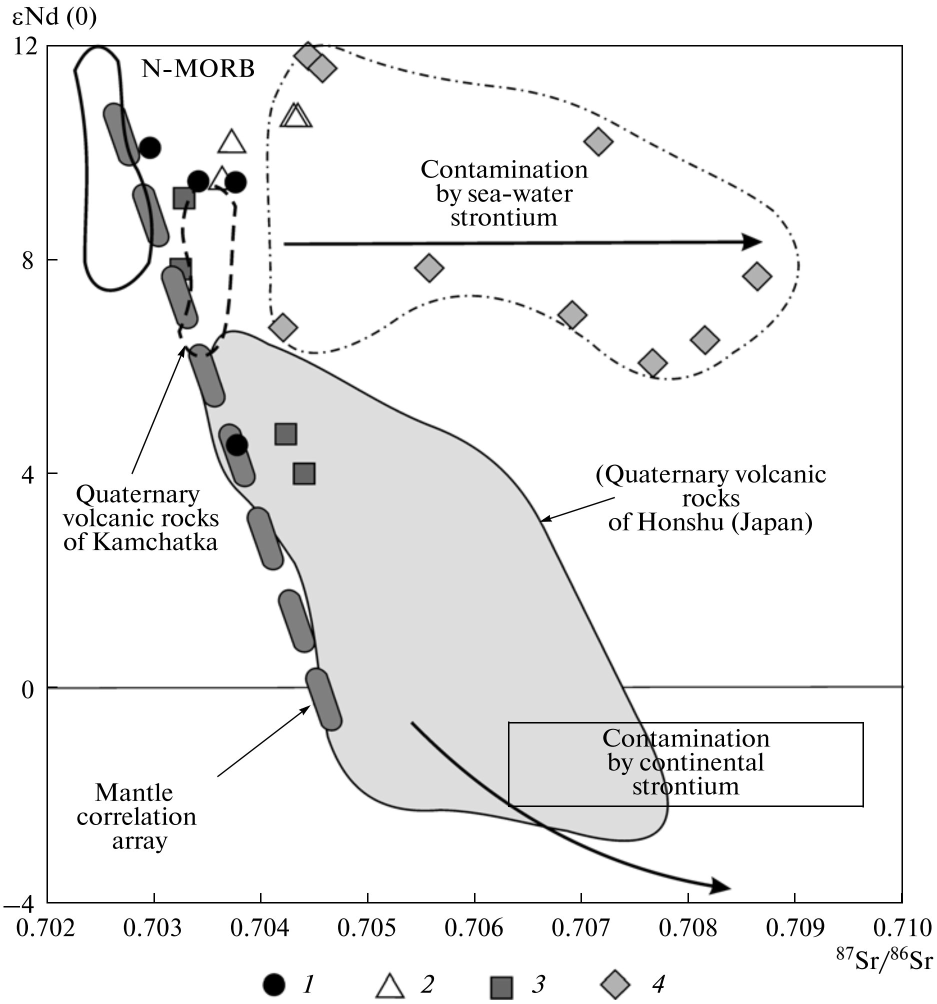


**Fig. 8.** Sr–Nd isotope systematics of the metamorphic and metasomatic rocks from the contact aureole of the Yurchik gabbronorite intrusion (Table 2) as compared to the Pacific N-MORB [25]; Quaternary basalts of Kamchatka [26] and Honshu [27, 28]. Symbols: (*1*) basic metavolcanic rocks; (*2*) amphibole and clinopyroxene–amphibole hornfelses, (*3*) biotite–orthopyroxene–plagioclase metasomatites; (*4*) metamorphic rocks of the Khavyven Upland, East Kamchatka [29].

prises both initial volcanic rocks and metasomatites and (2) εNd(0) from +7.8 to +10.7, which includes volcanic rocks, hornfelses, and metasomatites. Observed variations in Nd isotope compositions show no correlation with metasomatic and metamorphic transformations and could be explained by either different composition of protolith, which produced the volcanic rocks of the Vakhtalka Sequence, or by selective contamination with crustal material having low εNd.

Variations of Pb isotope composition in the initial volcanic rocks, hornfelses, and metasomatites (Table 3, Fig. 9) are within the field of Quaternary volcanic rocks of Kamchatka [26] and tholeiitic basalts of the Pacific Ocean [25], lying closely to the depleted mantle Pb evolution curve [31].

Examination of REE distribution (Table 1) shows that the metasomatites as compared to the initial volcanic rocks and hornfelses demonstrate significant increase in La/Yb ratio, i.e., metasomatic transformations were accompanied by LREE influx. It is important, in this regard, to consider the behavior of isotope systems depending on variations of this parameter as indicator of the transformation degree of host rocks. Diagram εNd (0) versus $(La/Yb)_N$ (Fig. 10a) shows two subhorizontal trends corresponding to the above distinguished rock groups 1 and 2, which indicates the absence of relation between LREE influx during granitization and variations in the initial Sm–Nd isotope characteristics of the protolith.

The values of $^{87}Sr/^{86}Sr$ in the studied rocks show more complex behavior. It is seen in the diagram of Sr–Nd correlation (Fig. 8) that some compositions of hornfelses and metasomatites are clearly shifted to the right from mantle correlation array, which may be explained by the presence of seawater Sr in the fluid that caused metasomatism and granitization. However, the influence of this factor on the composition of rocks of the Vakhtalka Sequence appeared less significant than

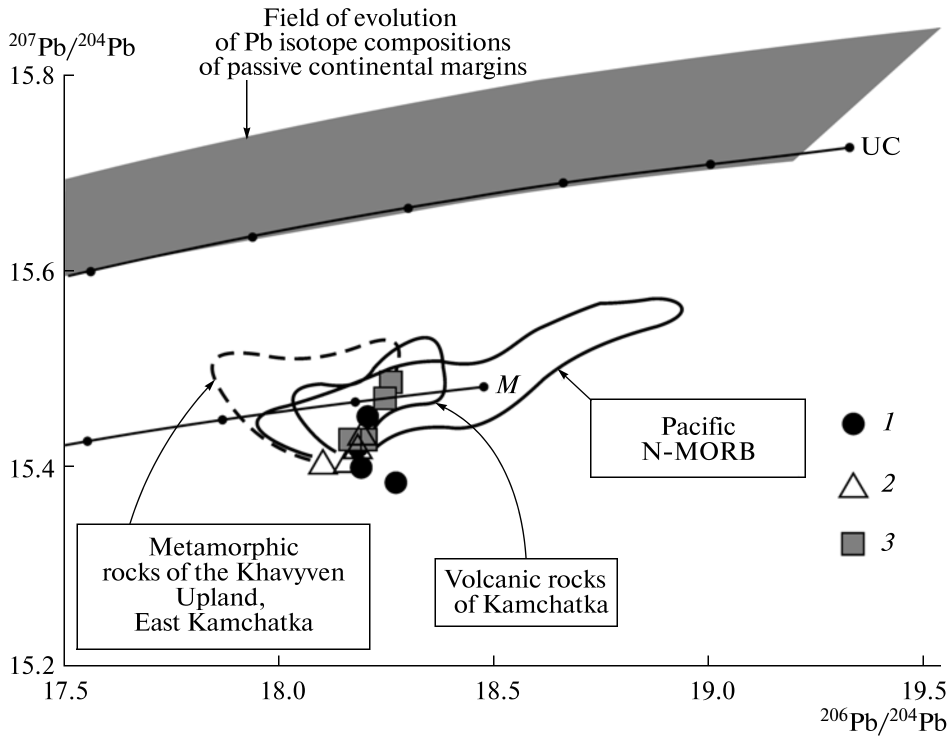


**Fig. 9.** $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagram for the metamorphic and metasomatic rocks from the contact aureole of the Yurchik gabbronorite intrusion:

Symbols (1–3) are shown in Fig. 8. Fields of evolution of Pb isotope composition in the rocks of passive continental margins are calculated using data from [30]. Fields of Pb isotopic composition shown according to literature data: (*1*) Quaternary basalts of Kamchatka [26]; (*2*) N-MOR basalts of the Pacific Ocean [25]; (*3*) metamorphic rocks of the Khavyven Upland of East Kamchatka [29]; UC is the evolution curve of Pb isotopic composition of the upper continental crust, *M*, the same, in depleted mantle [31].

in the metamorphic rocks of the Khavyven Upland of East Kamchatka [29].

In the diagram $^{87}Sr/^{86}Sr$ – $(La/Yb)_N$ (Fig. 10 b), the series of metavolcanic rocks–metasomatites of Group 1 defines a clear positive correlation, i.e., Sr isotope composition becomes more radiogenic with metasomatic transformations, which suggests the contribution of seawater Sr in these processes. For Group 2, the radiogenic increase in Sr isotope composition is observed in the series of volcanic rocks–hornfelses with low $(La/Yb)_N = 1.8–3.7$ and Sr < 400 ppm, whereas hornfelses and metasomatites with higher $(La/Yb)_N$ ratios and high Sr contents are characterized by the same Sr isotope composition as initial volcanic rocks. This is likely related to the buffer effect of high Sr content in protolith, which significantly decreases the degree of its dilution by Sr introduced with metasomatic processes.

The Pb isotope composition of both these groups becomes more radiogenic from initial volcanic rocks to metasomatites (Fig. 10c), which may indicate insignificant input of radiogenic–"crustal" lead with metamorphosing fluid as compared to the Pb isotope composition of protolith.

Thus, the metasomatic transformations and granitization of the basic volcanic rocks of the Vakhtalka Sequence, which encloses the Yurchik gabbroid massif, were expressed in the Sr, Nd, and Pb variations in the series of volcanic rocks (protolith)–hornfelses–metasomatic rocks. The Sm–Nd isotope system of the studied metasomatic process remains inert and reflects primary properties of the rocks. Sr isotope composition becomes more radiogenic due to involvement of seawater Sr into fluid phase. However, high Sr content in protolith may buffer this effect. The more radiogenic Pb isotope composition of metasomatites as compared to the initial rocks is related to some input of "crustal" Pb in metasomatic system.

## DISCUSSION

The possibility of granitization of basic and ultrabasic rocks under the influence of highly mineralized fluids with formation of granitoids was theoretically demonstrated by D.S. Korzhinskii [32] and confirmed by experimental and theoretical studies [33–35]. According to these concepts, granitization is referred to as magmatic replacement of initial basic rocks under the effect of highly mineralized alkaline-silicic mantle flu-

**Table 1.** Contents of petrogenic, trace, and rare-earth elements in the basic metavolcanic rocks, hornfelses, and metasomatites from the contact aureole of the Yurchik gabbronorite intrusion, Ganal Range, Kamchatka

| Component | Basic metavolcanic rocks—amphibole schists and amphibolites | | | | | Amphibole, clinopyroxene–amphibole, and two-pyroxene–amphibole hornfelses | | | | | | Biotite–orthopyroxene–plagioclase metasomatites | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 425-V | 426-B | 426-N | 537-L | 593 | 427 | 427-V | 528-V | 538 | 538-B | 539 | 427-D | 427-I | 427-K | 427-L | 538-K | 538-S |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| $SiO_2$ | 51.37 | 47.82 | 59.30 | 45.10 | 48.86 | 44.78 | 43.90 | 48.50 | 46.55 | 47.20 | 48.51 | 50.72 | 55.60 | 54.05 | 50.30 | 48.26 | 49.70 |
| $TiO_2$ | 0.93 | 1.44 | 0.76 | 1.16 | 1.40 | 1.86 | 0.88 | 1.08 | 1.66 | 1.69 | 1.16 | 0.81 | 1.05 | 0.94 | 0.77 | 0.70 | 0.83 |
| $Al_2O_3$ | 18.14 | 16.38 | 14.96 | 18.39 | 18.60 | 15.09 | 17.33 | 14.16 | 16.59 | 16.75 | 18.40 | 19.82 | 17.49 | 18.27 | 21.78 | 22.58 | 21.89 |
| $Fe_2O_3$ | 9.18* | 10.30* | 4.14 | 3.09 | 5.74 | 4.66 | 6.16 | 2.76 | 4.75 | 3.22 | 6.25 | 5.77 | 2.52 | 2.26 | 8.87* | 4.52 | 5.11 |
| FeO | | | 5.25 | 7.15 | 6.30 | 5.41 | 6.09 | 7.83 | 4.40 | 5.95 | 6.05 | 3.65 | 8.26 | 7.49 | | 3.50 | 3.57 |
| MnO | 0.13 | 0.21 | 0.22 | 0.19 | 0.26 | 0.14 | 0.21 | 0.20 | 0.12 | 0.14 | 0.15 | 0.17 | 0.20 | 0.22 | 0.13 | 0.16 | 0.14 |
| MgO | 6.31 | 8.58 | 4.27 | 10.27 | 5.94 | 10.80 | 11.04 | 11.64 | 7.63 | 8.98 | 6.66 | 4.30 | 3.75 | 3.81 | 3.44 | 3.48 | 3.71 |
| CaO | 5.31 | 10.98 | 6.27 | 10.91 | 7.57 | 12.05 | 10.65 | 8.39 | 13.40 | 10.40 | 7.29 | 8.93 | 7.43 | 8.12 | 7.24 | 9.70 | 8.67 |
| $Na_2O$ | 4.65 | 2.94 | 3.22 | 2.19 | 3.97 | 2.27 | 1.90 | 2.28 | 2.29 | 3.26 | 3.11 | 3.89 | 2.79 | 3.10 | 3.89 | 4.14 | 3.84 |
| $K_2O$ | 1.98 | 0.43 | 0.66 | 0.53 | 0.86 | 1.47 | 0.42 | 1.26 | 1.59 | 1.16 | 1.74 | 0.83 | 0.43 | 0.57 | 1.40 | 1.15 | 0.91 |
| $P_2O_5$ | 0.22 | 0.11 | 0.18 | 0.25 | 0.21 | 0.33 | 0.16 | 0.16 | 0.34 | 0.27 | 0.46 | 0.49 | 0.29 | 0.30 | 0.22 | 0.83 | 1.16 |
| L.O.I. | 1.16 | 0.35 | 1.26 | 1.05 | 0.80 | 0.98 | 1.33 | 1.46 | 0.95 | 1.06 | 0.36 | 0.35 | 0.10 | 0.60 | 0.84 | 0.43 | 0.43 |
| Total | 99.37 | 99.56 | 100.49 | 100.28 | 100.51 | 99.84 | 100.07 | 99.72 | 100.27 | 100.08 | 100.14 | 99.73 | 99.91 | 99.73 | 98.86 | 99.45 | 99.96 |
| Rb | 18.85 | 2.46 | 8.576 | 4.26 | 6.103 | 12.84 | 2.995 | 18.35 | 20.37 | 2.615 | 19.41 | 2.258 | 2.63 | 5.05 | 32.69 | 6.487 | 5.174 |
| Sr | 519.3 | 177.8 | 410.7 | 723.4 | 353.4 | 334.4 | 632.7 | 250.9 | 289.8 | 375.6 | 771.2 | 1561 | 639.8 | 673.9 | 691.1 | 1501 | 1569 |
| Y | 17.56 | 21.95 | 19.89 | 31.61 | 36.48 | 23.37 | 15.72 | 19.9 | 22.61 | 22.57 | 23.76 | 16.89 | 16 | 13.817 | 19.84 | 13.01 | 16.78 |
| Ba | 547 | 63.16 | 726.7 | 213.3 | 208.1 | 255 | 150.9 | 211.2 | 142.8 | 92.59 | 1061 | 925.6 | 728.2 | 843.7 | 1904 | 574.5 | 556.3 |
| Zr | 79.59 | 77.22 | 66.87 | 41.44 | 139.8 | 175.9 | 32.52 | 67.71 | 157.8 | 124.7 | 240.1 | 107.7 | 138.3 | 138.36 | 159.7 | 63.53 | 128 |
| Nb | 4.72 | 7.08 | 2.33 | 2.38 | 2.49 | 13.82 | 1.12 | 4.45 | 9.58 | 8.13 | 3.54 | 1.89 | 15.99 | 6.06 | 7.08 | 1.62 | 2.34 |
| Cs | 0.531 | 0.055 | 0.446 | 0.091 | 0.070 | 0.174 | 0.089 | 0.536 | 0.382 | 0.033 | 0.205 | 0.093 | 0.181 | 0.22 | 1.16 | 0.081 | 0.090 |
| La | 8.929 | 2.583 | 9.483 | 7.077 | 10.72 | 14.10 | 4.998 | 6.762 | 10.79 | 12.15 | 20.58 | 18.18 | 18.41 | 14.803 | 25.23 | 16.57 | 20.01 |
| Ce | 22.26 | 9.347 | 21.12 | 23.14 | 28.67 | 34.91 | 15.53 | 18.89 | 27.69 | 30.98 | 51.20 | 41.91 | 38.55 | 40.8 | 54.1 | 39.64 | 47.88 |
| Pr | 3.686 | 1.714 | 3.057 | 4.288 | 4.497 | 4.699 | 2.805 | 2.924 | 3.982 | 4.553 | 7.819 | 6.07 | 4.849 | 4.351 | 7.114 | 5.689 | 6.863 |
| Nd | 17.15 | 9.816 | 14.26 | 24.94 | 24.8 | 21.37 | 14.77 | 14.74 | 17.90 | 20.96 | 36.02 | 28.70 | 23.13 | 18.074 | 28.97 | 23.84 | 32 |
| Sm | 4.20 | 3.04 | 3.56 | 7.24 | 6.80 | 4.74 | 3.67 | 3.84 | 4.86 | 5.14 | 8.18 | 6.63 | 5.13 | 4.29 | 5.90 | 5.65 | 6.18 |

**Table 1.** (Contd.)

| Com-ponent | Basic metavolcanic rocks—amphibole schists and amphibolites | | | | | Amphibole, clinopyroxene–amphibole, and two-pyroxene–amphibole hornfelses | | | | | | Biotite–orthopyroxene–plagioclase metasomatites | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 425-V | 426-B | 426-N | 537-L | 593 | 427 | 427-V | 528-V | 538 | 538-B | 539 | 427-D | 427-I | 427-K | 427-L | 538-K | 538-S |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| Eu | 1.67 | 1.47 | 1.34 | 2.27 | 2.31 | 1.79 | 1.59 | 1.19 | 1.69 | 1.97 | 2.44 | 2.14 | 1.95 | 1.60 | 2.57 | 1.87 | 2.19 |
| Gd | 4.93 | 4.87 | 4.66 | 8.00 | 8.11 | 6.21 | 4.38 | 4.90 | 6.12 | 6.35 | 7.84 | 6.05 | 5.38 | 4.35 | 6.13 | 4.89 | 5.57 |
| Tb | 0.775 | 0.861 | 0.859 | 1.307 | 1.324 | 0.993 | 0.614 | 0.823 | 0.872 | 0.921 | 1.028 | 0.792 | 0.654 | 0.571 | 1.25 | 0.690 | 0.686 |
| Dy | 4.68 | 5.54 | 4.87 | 8.07 | 8.54 | 6.20 | 4.18 | 5.06 | 5.93 | 5.69 | 5.81 | 4.38 | 4.10 | 4.12 | 5.31 | 3.71 | 3.69 |
| Ho | 0.982 | 1.173 | 1.06 | 1.587 | 1.799 | 1.194 | 0.757 | 0.979 | 1.107 | 1.086 | 1.112 | 0.855 | 0.813 | 0.593 | 1.352 | 0.654 | 0.704 |
| Er | 2.77 | 3.15 | 3.31 | 5.019 | 5.773 | 3.579 | 2.671 | 3.382 | 3.824 | 3.27 | 3.60 | 2.448 | 2.667 | 2.648 | 3.45 | 1.735 | 2.062 |
| Tm | 0.491 | 0.502 | 0.535 | 0.707 | 0.688 | 0.466 | 0.329 | 0.412 | 0.528 | 0.489 | 0.465 | 0.361 | 0.331 | 0.276 | 0.833 | 0.230 | 0.257 |
| Yb | 2.298 | 2.768 | 3.011 | 4.362 | 4.788 | 3.275 | 2.20 | 2.669 | 3.112 | 2.963 | 3.146 | 2.16 | 2.224 | 2.5274 | 3.244 | 1.347 | 1.632 |
| Lu | 0.478 | 0.491 | 0.523 | 0.575 | 0.798 | 0.470 | 0.305 | 0.360 | 0.464 | 0.446 | 0.488 | 0.385 | 0.341 | 0.289 | 0.881 | 0.198 | 0.282 |
| Hf | 2.973 | 2.825 | 2.767 | 2.008 | 5.568 | 5.333 | 1.685 | 2.76 | 4.377 | 4.034 | 7.826 | 3.939 | 4.685 | 3.516 | 5.809 | 2.265 | 4.263 |
| Ta | 0.631 | 1.935 | 0.566 | 0.296 | 0.287 | 1.248 | 0.222 | 0.473 | 2.472 | 0.682 | 0.345 | 1.65 | 1.646 | 0.628 | 2.205 | 0.228 | 0.465 |
| W | 0.177 | 0.259 | 0.807 | 0.470 | 0.185 | 0.198 | 0.315 | 0.361 | 0.368 | 0.185 | 0.368 | 0.261 | 0.489 | <0.1 | 0.907 | 0.355 | 0.550 |
| Pb | 3.183 | 1.52 | 9.164 | 6.617 | 2.601 | 1.970 | 1.535 | 3.489 | 2.041 | 2.117 | 9.543 | 10.64 | 6.582 | 7.48 | 16.8 | 9.886 | 8.590 |
| Th | 0.834 | 0.168 | 2.172 | 0.124 | 1.22 | 0.950 | 0.132 | 0.280 | 0.815 | 0.179 | 1.552 | 0.734 | 2.42 | 0.69 | 7.554 | 0.988 | 0.398 |
| U | 0.511 | 0.122 | 0.718 | 0.035 | 0.504 | 0.243 | 0.021 | 0.159 | 0.390 | 0.092 | 0.689 | 0.181 | 0.498 | 0.18 | 1.521 | 0.181 | 0.120 |
| V | 235.9 | 229.5 | 202.3 | 300.7 | 290.5 | 108.3 | 302.1 | 278.6 | 93.73 | 265.3 | 302.6 | 185.6 | 299 | 257.55 | 220.4 | 167.5 | 187.1 |
| Cr | 62 | 243 | 76 | 246 | 51 | 195 | 314 | 492 | 173 | 244 | 107 | 11 | 35 | 34 | 43 | 50 | 41 |
| Co | 29 | 40 | 20 | 31 | 27 | 37 | 38 | 41 | 29 | 35 | 29 | 21 | 24 | 23 | 24 | 18 | 26 |
| Ni | 24 | 127 | 32 | 34 | 18 | 156 | 48 | 149 | 84 | 102 | 32 | 16 | 22 | 23 | 25 | 46 | 52 |

All iron as $Fe_2O_3$. Contents of petrogenic elements are given in wt %, trace and rare-earth elements, in ppm.

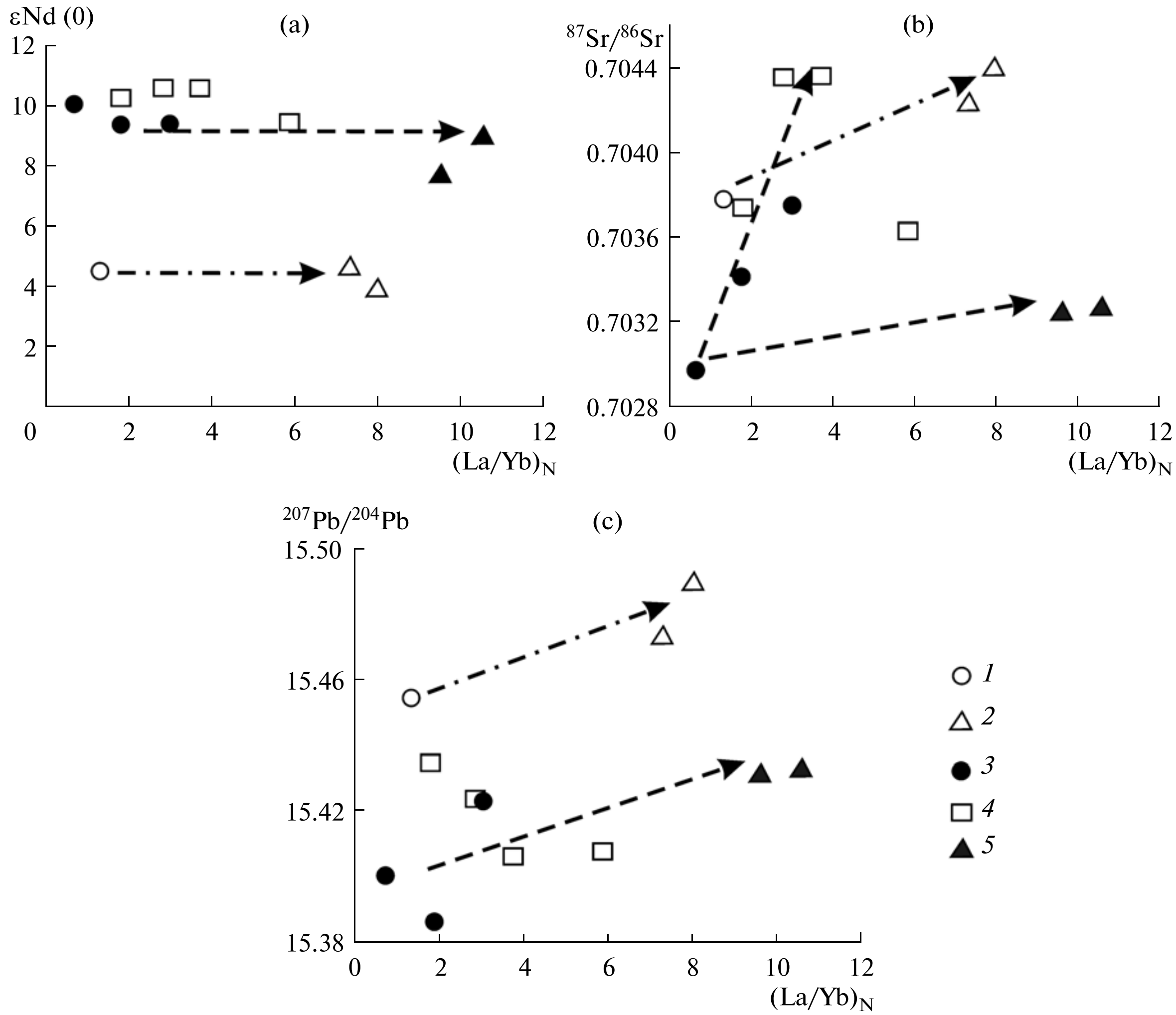


**Fig. 10.** Variations of εNd (0) (a), $^{87}Sr/^{86}Sr$ (b), and $^{207}Pb/^{204}Pb$ (c) versus $La/Yb_{(N)}$ for the host rocks of the Yurchik Massif: (*1*, *2*) metabasic rocks and metasomatites of group (1); (*3*–*5*) basic metavolcanic rocks, hornfelses, and metasomatites of group (2). Arrows show the trend of compositional variations of hornfelsed basic volcanic rocks of the Vakhtalka Sequence during granitization and magmatic replacement.

ids, which are formed in the course of mantle degassing and cause debasification and "bleaching" of the rocks with increasing melting (formation of shadow and banded migmatites).

Experimental data confirm that mineralized aqueous–hydrocarbonic fluid generating in mantle incongruently dissolve silica and alkalis as well as some lithophile elements (Rb, Li, REE, and others) in mantle rocks [33]. The decrease in temperature and pressure with ascent to the upper crustal levels leads to the decrease of alkalis and silica solubility, thus causing metasomatic change and nonisochemical partial melting of crustal protolith, and, finally, granitization. According to [33], these processes require strong heating in zone of fluid influence (temperature in the zone of fluid discharge should be higher than that of the granite solidus) and sufficient thickness of crustal protolith (around 15 km), which provides the high solubility of mantle matter by fluids.

Our studies showed that the strong heating of host rocks of the Vakhtalka Sequence was noted for the northern part of the contact aureole, where the Yurchik Massif is characterized by the highest thickness (heads of the Vaktan Ganalsky Levyi River) and its crystallization occurred at depths around 15 km, which determined the development of intense hornfelsation, metasomatic transformations, and magmatic replacement (granitization) of the initial basic volcanic rocks and sedimentary intercalations (Figs. 1, 2). Similar phenomena of high-temperature hornfelsation, metasomatic alteration, and magmatic replacement of basic metavolcanic and metasedimentary rocks of the Vakhtalka Sequence were also noted in the southern part of the Yurchik intrusion (in the heads of the Vaktan

**Table 2.** Sr and Nd isotope ratios in the basic metavolcanic rocks (amphibolites, amphibole schists), hornfelses, and metasomatites of the Vakhtalka Sequence from the contact aureole of the Yurchik gabbronorite intrusion of the Ganal Range, Kamchatka

| Ordinal no. | Sample | Rock | Rb, ppm | Sr, ppm | $^{87}Sr/^{86}Sr \pm 2\sigma$ | Sm, ppm | Nd, ppm | $^{143}Nd/^{144}Nd \pm 2\sigma$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 425-V | Basic metavolcanic rocks | 25.11 | 547.4 | 0.703817 ± 20 | 3.71 | 14.62 | 0.513111 ± 7 |
| 2 | 426-B | ″ | 2.51 | 193.5 | 0.703053 ± 29 | 2.99 | 9.06 | 0.513156 ± 6 |
| 3 | 537-L | ″ | 4.35 | 762.2 | 0.703786 ±14 | 6.29 | 21.73 | 0.512866 ± 6 |
| 4 | 593 | ″ | 6.69 | 376.7 | 0.703440 ± 21 | 5.72 | 21.02 | 0.513115 ± 6 |
| 5 | 539 | Hornfels | 21.22 | 807.3 | 0.703670 ± 18 | 7.06 | 31.76 | 0.513111 ± 7 |
| 6 | 538 | ″ | 29.22 | 309.7 | 0.704494 ± 25 | 4.12 | 16.53 | 0.513174 ± 6 |
| 7 | 427-V | ″ | 2.79 | 677.0 | 0,703742 ± 13 | 3.65 | 13.78 | 0.513152 ± 9 |
| 8 | 427 | ″ | 15.34 | 368.0 | 0,704415 ± 15 | 4.56 | 19.99 | 0.513171 ± 7 |
| 9 | 427-L | Metasomatite | 47.74 | 743.7 | 0.704504 ± 22 | 4.90 | 25.34 | 0.512825 ± 7 |
| 10 | 427-K | ″ | 5.12 | 729.8 | 0.704249 ± 20 | 4.10 | 20.58 | 0.512863 ± 11 |
| 11 | 538-S | ″ | 7.92 | 1649.0 | 0.703291 ± 27 | 5.80 | 29.14 | 0.513089 ± 6 |
| 12 | 538-K | ″ | 8.70 | 1523.0 | 0.703261 ± 22 | 4.43 | 21.70 | 0.513021 ± 5 |

Concentrations of Rb, Sr, Sm, and Nd (in ppm) were determined by ICP-MS at the Analytical Center of the Far East Geological Institute, Far East Branch, Russian Academy of Sciences.

**Table 3.** Pb isotope ratios in the basic metavolcanic rocks (amphibolites and amphibole schists), hornfelses, and metasomatites from the contact aureole of the Yurchik gabbronorite intrusion of the Ganal Range, Kamchatka

| Ordinal no. | Sample | Rock | U | Th | Pb | $^{206}Pb/^{204}Pb$ | $^{207}Pb/^{204}Pb$ | $^{208}Pb/^{204}Pb$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 425-V | Basic metavolcanic rocks | 0.18 | 0.38 | 3.18 | 18.182 | 15.423 | 37.672 |
| 2 | 426-B | ″ | 0.03 | 0.06 | 1.52 | 18.190 | 15.402 | 37.604 |
| 3 | 537-L | ″ | 0.01 | 0.08 | 6.62 | 18.207 | 15.454 | 37.908 |
| 4 | 593 | ″ | 0.25 | 0.77 | 2.60 | 18.272 | 15.387 | 37.634 |
| 5 | 539 | Hornfels | 0.23 | 0.98 | 9.54 | 18.162 | 15.408 | 37.605 |
| 6 | 538 | ″ | 0.25 | 0.60 | 2.04 | 18.185 | 15.424 | 37.679 |
| 7 | 427-V | ″ | 0.02 | 0.08 | 1.53 | 18.193 | 15.435 | 37.838 |
| 8 | 427 | ″ | 0.17 | 0.70 | 1.97 | 18.105 | 15.406 | 37.638 |
| 9 | 427-L | Metasomatite | 0.69 | 5.43 | 16.80 | 18.206 | 15.491 | 38.128 |
| 10 | 427-K | ″ | 0.29 | 1.82 | 7.48 | 18.245 | 15.474 | 38.064 |
| 11 | 538-S | ″ | 0.05 | 0.30 | 8.59 | 18.174 | 15.433 | 37.749 |
| 12 | 538-K | ″ | 0.09 | 0.61 | 9.89 | 18.199 | 15.432 | 37.777 |

Pb isotope ratios were measured with accuracy no worse than 0.05 rel. %. Concentrations of U, Th, and Pb (in ppm) were analyzed by ICP-MS at the Analytical Center of the Far East Geological Institute, Far East Branch, Russian Academy of Sciences.

Malkinskii River) at the contact with postmetamorphic gabbroids, but scales of this process are limited by few tens of centimeters [5, 9].

Thus, the study of altered rocks of the Vakhtalka Sequence of the Ganal Group in the contact aureole of the Yurchik gabbronorite intrusion indicates that their transformation was caused by high-temperature hornfelsation accompanied by superimposed metasomatic alteration of the hornfelses and their local magmatic replacement. All these processes are spatiotemporally related in complementary way with each other, and were caused by percolating highly mineralized fluids. It is suggested that metasomatism and magmatic replacement of basic volcanic and sedimentary rocks of the Vakhtalka Sequences were assisted by highly mineralized mantle fluids filtering through magmatic channels, which served as pathways for gabbroid melt.

## CONCLUSIONS

Presented geological and geochemical data testify that the formation of the granulite-like rocks in the contact aureole of the Yurchik gabbronorite intrusion in the Ganal Range of Kamchatka was caused by contact metamorphism, metasomatism, and local melting of the initial volcanosedimentary rocks of the Vakhtalka Sequence of the Ganal Group. In the inner part of the aureole, where temperature reached 700–800°C, the basic volcanic rocks of the sequence were transformed into two-pyroxene–plagioclase, clinopyroxene–amphibole–plagioclase, and amphibole–plagioclase hornfelses, while sedimentary rocks, into garnet–biotite±cordierite hornfelses. Locally, hornfelsed basic volcanic rocks were metasomatically altered into biotite–orthopyroxene–plagioclase metasomatites. Local magmatic replacement of the metasomatites in the zones of most intense fluid filtration led to the formation of biotite–orthopyroxene–plagioclase ± garnet migmatite veinlets and aggregates, while sedimentary interlayers were converted into bodies of garnet enderbites, which were formed at 700–800°C and 3.2–4.8 kbar.

The comparison of chemical composition of the Vakhtalka Sequence and products of their transformation indicates that metasomatic alteration and magmatic replacement chemically correspond to siliceous–alkaline metasomatism (granitization) and cause subsequent and uneven influx of $SiO_2$, $Na_2O$, $K_2O$, Rb, Ba, Zr, Nb, and Cl and removal of Fe, Mg, Mn, Ca, and some trace elements (Cr, Co, Ti, Y, and S) from replaced rocks. The comparison of REE contents in the initial volcanic rocks, their hornfelsed varieties, and metasomatites revealed significant increase in LREE contents and slight decrease in HREE during metasomatic alteration and magmatic replacement of the metavolcanic rocks. The study of Sr and Nd isotope compositions in the rocks of the aureole showed that the initial basic volcanic rocks of the Vakhtalka Sequence are isotopically close to the tholeiites of mature island arcs and basalts of mid-ocean ridges. The metasomatic alterations of initial volcanic rocks and their hornfelsed varieties lead to the decrease of $^{143}Nd/^{144}Nd$ ratio and increase of $^{87}Sr/^{86}Sr$ in compliance with a common mantle array. Lead isotope composition of metasomatic rocks is more radiogenic as compared to initial volcanic rocks, which may indicate that metamorphosing fluid contained insignificant amount of more radiogenic, "crustal lead" as compared to the Pb composition of protolith.

It is suggested that metasomatism and magmatic replacement of the rocks from the contact aureole of the Yurchik intrusion was caused by highly mineralized mantle fluids, which percolated along magmatic channels that served as pathways for gabbroid magma.

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