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Cretaceous Ultramafic Volcanism in the Sredinnyi ~~Mountain~~ Range, Kamchatka

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1 **Abstract**—Late Mesozoic metapicrites and metapicrobasalts occur in all apoterrigenous rock sequences in Kamchatka's Sredinnyi crystalline massif, forming sheets, flows, and sills ranging between a few and 100 m or greater in thickness. Metapicrites possess geochemical parameters that are intermediate between mid-oceanic ridge tholeiites and island-arc tholeiites, which is typical of volcanic rock complexes in marginal basins.
4 The host rocks are terrigenous rock sequences of the Kikhchik series and its metamorphosed analogues, viz., the Kolpakov, Kamchatka, and Malkino series, which were formed in a common continental-margin sedimentary basin during the late Mesozoic sedimentation cycle with the same source, which was a province in the eastern margin of the Asian continent. The extension of continental crust in the Cretaceous sedimentary basin and intersections by faults of the same age as that of the Okhotsk–Chukchi volcanogenic belt, com-
3 bined to produce basite and ultrabasite volcanism. Emplacement of mantle material (the ascent of mantle
4 plumages) accompanied by deep hydrogen-rich fluids into the basement of the crust from volcanogenic terrigenous deposits of the marginal basin produced considerable temperature increases in the crust, as well as magmatic replacement of volcanogenic sedimentary rock sequences with the subsequent generation of magma chambers and ascent of acid volcanic and granitoid rocks into the upper crust.

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INTRODUCTION

Ultramafic volcanic rocks of various ages and in different geotectonic settings are characteristic of both continental and oceanic structures. They occur widely in shields and on platforms, in geosynclinal fold systems, and in highly permeable zones, which are systems of deep-seated crustal faults.

The first researcher to describe ultramafic rocks in Kamchatka was Shcherbakov (1938), who discovered them in geological traverses of the peninsula. However, later work classified these rocks as diabase, porphyrite, or intrusive hyperbasite, ascribing them to various suites and complexes whose ages were variously determined to range from the Precambrian to the Late Cretaceous.

Later work revealed that the ultramafic volcanic and subvolcanic rocks (picrites and picrobasalts) date back to the Late Mesozoic and showed that they are encountered
1 throughout all apoterrigenous rock sequences in Kamchatka's Sredinnyi crystalline massif (Bondarenko, 1997a, 1997b; Konnikov et al., 2010; Tararin, 1981, 1989; Khanchuk, 1985). The thickest stratified bodies of metapicrites (in the form of sheets, flows, and sills) a few to 100 m or greater in thickness, are characteristic for the Alistor suite (Khanchuk, 1985) and are confined to poorly metamorphosed deposits of the Kikhchik series on the western slopes of the Sredinnyi Range.

The terrigenous deposits in Kamchatka (the Kikh- 4
chik, Lesnovskii, Ukelayat, and Omgon series) formed within a major continental-margin sedimentary basin that extended for a length of about 500 km. Clastic material came to this basin from the northeastern margin of the Asian continent (Grechin, 1979; Konstantinovskaya, 1997; Sokolov, 1992; Shapiro et al., 1993, 2008; Shevchenko et al., 2009). One feature that is specific to the flyschoidal deposits of these series consists in the quartz-feldspar composition of the sandstones, alternation with aleurolites and argillites, and the presence of conformable stratified bodies of tholeiitic basalts and their tuffs, indicating the formation of terrigenous rocks in the 4
crust of an opening sea basin (Chekhovich, 2010; Shapiro et al., 2001).

The Kikhchik series (whose lower part is classified as the Khozgon suite) is composed of deep-sea flyschoidal deposits, as follows from determinations of benthic foraminifera (Chekhovich, 2010). These deposits later served as the protolith for metamorphic formations of the Kolpakov, Kamchatka, and Malkino series (Solov'ev, 2008; Shapiro et al., 2008; Hourigan et al., 2009).

U–Pb SHRIMP age determinations for zircons from the most metamorphosed rocks in the Kolpakov and Kamchatka complexes show that the terrigenous rock 4
sequences accumulated from the end of the Early Creta-

ceous and continued to be accumulated until the end of the Late Cretaceous to Early Paleogene (Solov'ev, 2008; Hourigan et al., 2009).

The lower part of the Kikhchik series on the western slopes of the Sredinnyi Range is dominated by argillites and aleurolites that contain boudinated inclusions of sandstones and calc-silicate rocks that are a few centimeters to a few meters across. The overlying rocks are sandy varieties that alternate with aleurolites and argillites. The upper section consists of flyschoidal alternations of apopelitic and apopsammitic rocks, with the latter prevailing.

The sedimentary deposits in the basin were intruded at the end of the early Cretaceous by numerous stratified bodies and sills that consisted of picrites, picrobasalts, and basalts whose time of emplacement was synchronous with the incipient Okhotsk–Chukchi volcanogenic belt in the Asian continental margin (Akinin and Miller, 2011). The generation process was due to the ascent of upper-mantle material toward the bottom of the continental crust. During the subsequent evolution of the magmatism the magmatic process involved the crustal substratum of the marginal basin, with intermediate and acidic volcanism being observed within the Kamchatka region (the Pensantai rock sequence of western Kamchatka is 90 Ma old (Badredinov et al., 2012), the Khavyvenskaya series in eastern Kamchatka is 100 Ma old (Tararin et al., 2012), the Kvakhon suite of the Sredinnyi Range (Tararin et al., 2013), and a shallow granitoid magmatism (Krutogorovo and Kol' intrusive complexes in the Sredinnyi Range about 80 Ma old (*Gosudarstvennaya* ..., 2006; Luchitskaya, 2012; Luchitskaya and Solov'ev, 2010; Solov'ev, 2008; Hourigan et al., 2009)).

A similar geological structure characterizes the Sea-of-Okhotsk massif, which occupies practically all of the Sea of Okhotsk area (Bogdanov and Chekhovich, 2002; Nekrasov, 2006). The massif clearly shows a Miocene to Quaternary sedimentary blanket overlying compacted sediments that lie on a sialic continental crust (Emel'yanova et al., 2012; Mishkin, 2012) that contain sills and stratified bodies of basic igneous rocks (Bogdanov and Chekhovich, 2002).

FACTUAL MATERIAL

A brief Geological Review

Unconnected exposures of basic and ultramafic Cretaceous rocks in western and central Kamchatka form a nearly north–south trending, long (about 500 km) belt and are considered to be fragments of the Omgon–Palana volcanic belt (Bogdanov and Chekhovich, 2002), tectonic blocks of the Kvakhon island arc (Konstantinovskaya, 2003; Sidorchuk and Khanchuk, 1981), or those of the West Kamchatkan volcanic arc (Chekhovich and Sukhov, 2005; Chekhovich et al., 2006).

The volcanic products of this island arc and rocks of fault structures are widely abundant in the Sredinnyi Range of Kamchatka. They consist of basic rocks (basalt, picrobasalt, and their tuffs) and, to lesser degree, of ultramafic rocks (picrite and its tuffs) that have experienced regional metamorphism that is an isofacies with the host terrigenous formations in the Kolpakov, Kamchatka, and 4
Malkino metamorphic complexes. These rocks form stratified bodies, deposits, and dikes that are commonly (especially when found in zones of high-temperature metamorphism) separated into discrete fragments or boudins. The bodies have variable thicknesses, but most of these are a few meters thick, more rarely reaching a few tens of meters. It is only in the Andrianovka and Alistor suites of the Malkino complex that basic and ultramafic rocks compose a larger part of their sections.

Well-preserved magma bodies of ultramafic volcanic rocks are found among the Alistor deposits (Khanchuk, 1985). The Alistor type section was described at the divide between the right tributaries of the Kolpakov River (Alistor and Stopol'nik, see (Khanchuk, 1985)) and includes flows of pillow and massive pyroxene picrites, picrobasalts, members of hyaloclastites and hyaloclastite breccias, quartzites, crystalline clastite tuffs of basaltic composition, and interbeds of siliceous aleurite clayey rocks (Bondarenko, 1997a, 1997b; Khanchuk, 1985). The Alistor suite is estimated to be 1000 m thick (Bondarenko, 1997a, 1997b).

According to Konnikov et al. (2010), the Alistor suite is dominated by psephitic and psammitic tuff lavas and picrobasalt tuffs that have experienced green schist metamorphism, causing olivine and pyroxene to be replaced with chlorite and amphibole. Geochemical evidence shows that the original formations for the Alistor ultrabasites were ophiolite rocks (see the above reference).

Alistor metavolcanic rocks are widely abundant on the right banks of the riverheads of the Levaya Kol' River, at the divide between the Levaya Kol' and the Pravaya Kol', and on the left bank of the Nemtik River in the middle of the Sredinnyi Range. Metamorphosed picrites, picrobasalts and, to a lesser degree, basalts and their tuffs make up stratified bodies and sills on the right banks of the riverheads of the Levaya Kol' River (Figs. 1 and 2) among the Kikhchik apoterrigenous rocks (argillite, aleurolite, and 1
sandstone) that have been metamorphosed in the green schist facies. The largest sill of olivine clinopyroxene picrite, which is approximately 200 m thick, can be followed nearly north–south for a distance of about 4 km (see Figs. 1 and 2). Its top contains a chilling zone composed of picrobasalt (see Fig. 1, observation site 728). A similar picrite sill has been mapped at the divide between the Pravaya and Levaya Kol', where it is 50–60 m thick. Thinner stratified bodies among the Kikhchik apo- 1
terrigenous deposits mostly consist of picrobasalts, basalts, and their tuffs (the divide of the Pravaya Kol' and the Suntunk rivers). Several thick sills that consist of Alistor volcanic rocks are banded. Ultramafic varieties are

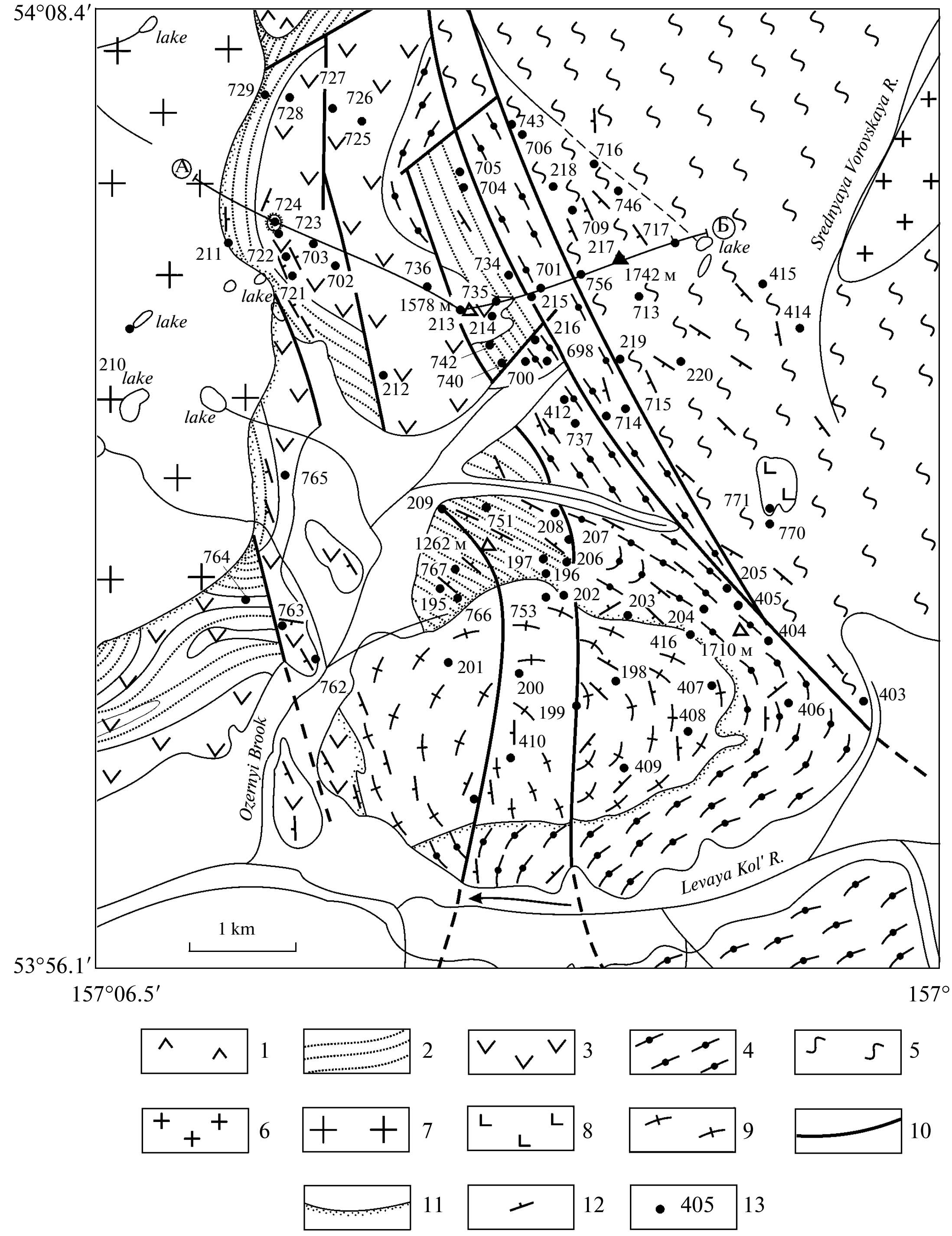

Fig. 1. A schematic geological map of the upper reaches of the Levaya Kol' River.

(1) Cherepanovo suite: andesites, basaltic andesites, tuffs (Paleocene), (2) Kikhchik series: aleurolites, argillites, polymictic sandstones, siliceous calcareous boudins, (3) Alistor suite: metapicrites, metapicrobasalts, tuffs, (4) Kheivan suite: phyllites, crystalline schists, micaceous metasandstones, (5) Kolpakov series: plagiogneisses, migmatites, boudinated interbeds of amphibolite, garnet amphibolites, and basic crystalline schists, (6), syn-metamorphic leucocratic garnet–micaceous granites and pegmatites, (7) Tertiary granites and granodiorites of the Lavkino intrusive complex, (8) metamorphosed gabbroids, (9) gneiss-like granodiorites and quartz diorites in the Kol' intrusive body, (10) tectonic discontinuities, (11) contact aureoles, (12) elements of attitude for stratification, banding, and gneiss-shaping, (13) observation sites. The A–B line marks the geological section (Fig. 2).

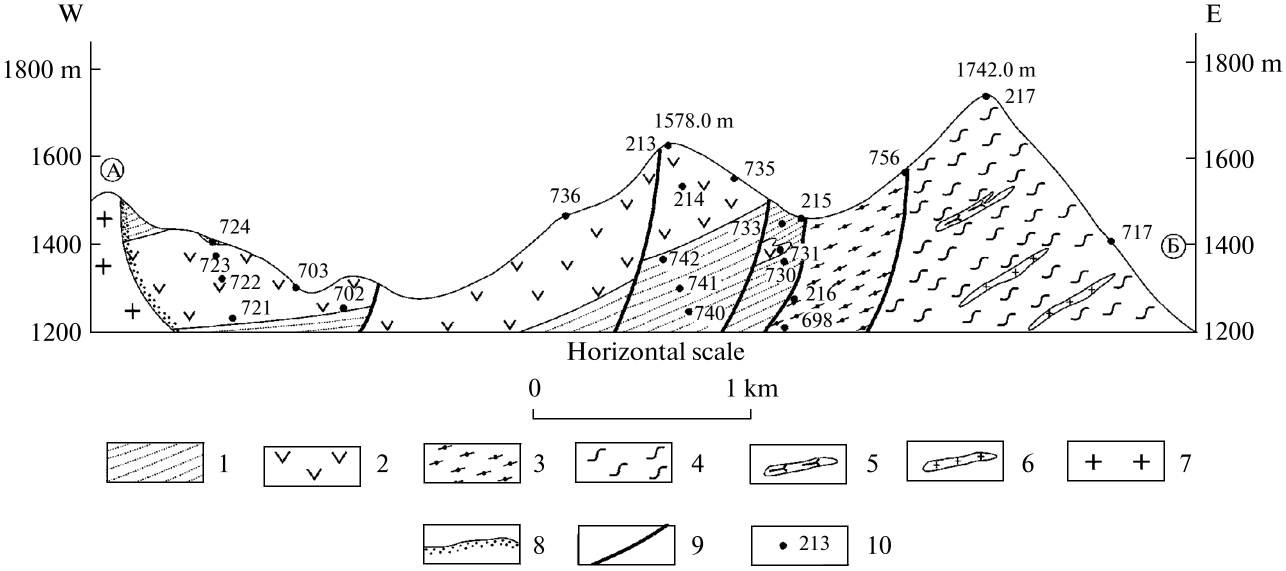

Fig. 2. A geological section along the A–B line (Fig. 1) in the upper reaches of the Levaya Kol' River

(1) Kikhchik series: aleurolites, argillites, polymictic sandstones, siliceous calcareous boudins, (2) Alistor suite: metapicrites, metapicrobasalts, tuffs, (3) Kheivan suite: phyllites, crystalline schists, micaceous metasandstones, (4) Kolpakov series: plagiogneisses, migmatites, boudinated bodies of amphibolites, garnet amphibolites, and basic crystalline schists, (5) bodies of amphibolites, garnet amphibolites, and basic crystalline schists among the Kolpakov rocks, (6) syn-metamorphic leucocratic garnet micaceous granites and pegmatites, (7) granites and granodiorites of the Lavkino intrusive complex, (8) unconformable layering, (9) tectonic discontinuities, (10) observation sites.

confined to their lower parts, while the upper parts are composed of basaltoid rocks.

Mineral Associations and Mineral Composition

The metapicrites that compose the magma bodies at the riverhead of the Levaya Kol' River and at the divide of the Pravaya and Levaya Kol' are greenish grey, frequently broken-down rocks. They consist of porphyric impregnations of olivine, monoclinic pyroxene, chromous spinel and, less frequently, of brown amphibole (Table 1) in a magnetite–serpentine–chlorite–tremolite–actinolite felted groundmass aggregate.

Porphyric olivine excretions (X_{Mg} = 0.75–0.85[1], see Table 1) that dominate the impregnations have been largely replaced with serpentine and secondary magnetite. The concentration of CaO in the picrite olivine is very low; it is comparable with that in the olivines that are found in the serpentinized harzburgites and boninites of deep-sea trenches and forearc basins (*Petrologicheskie* ..., 1996; Danyushevsky et al., 1995; Sobolev and Danyushevsky, 1994; Walker and Cameron, 1983] and with that of olivine in the ultrabasites of zonal dunite–clinopyroxenite–gabbro intrusive rocks in the Koryak–Kamchatka region (Sidorov et al., 2012), but is different compared with picrite olivine that is found in intraoceanic plateaus and anomalous segments of mid-oceanic ridges (Ramsay et al., 1984). Olivine impregnations in picrite–basalt rocks from western Kamchatka (Ledneva et al., 2005) are characterized by higher levels of calcium oxide concentrations (CaO > 0.28 wt %) compared with the Sredinnyi Range picrites, which makes them more similar to picrite olivines and picrobasalt olivines in oceanic plateaus (Ledneva et al., 2005).

Impregnations of monoclinic pyroxene in the metapicrites of the Levaya Kol' riverheads consist of salite, augite, or magnesium augite (X_{Mg} = 0.70–0.80, see Table 1) and are commonly replaced with actinolite. Low-titanium brown chromous spinel contains higher concentrations of zinc oxide and is replaced with chromous magnetite and magnetite at the periphery of crystals (see Table 1). In addition to spinel, the picrites also contain vanadium-bearing ilmenite.

The picrites in the type section of the Alistor suite (Alistor R.) consist of diopside impregnations (X_{Mg}) that are as large as 0.5 mm across and, more rarely, of olivine pseudomorphs that are immersed in the groundmass that consists of chlorite and low amounts of tremolite and albite (Khanchuk, 1985).

Psephitic tuffs and tuff breccias of picrobasalts that are found on the left bank of the Kolpakov River along its

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[1] Here and below we use the following symbols: Ab for albite, Chl for chlorite, Cpx for monoclinic pyroxene (c stands for the center and r for the edge of a crystal), *CrMt* for chromous magnetite, Hbl for hornblende, Ilm for ilmenite, Ol for olivine, Spl for spinel, and X_{Mg} = Mg/(Fe + Mn + Mg). The minerals were analyzed by V.M. Chubarin and I.A. Tararin using JXA-5A and Camebax analyzers at the Far East Geological Institute and in the Institute of Volcanology and Seismology.

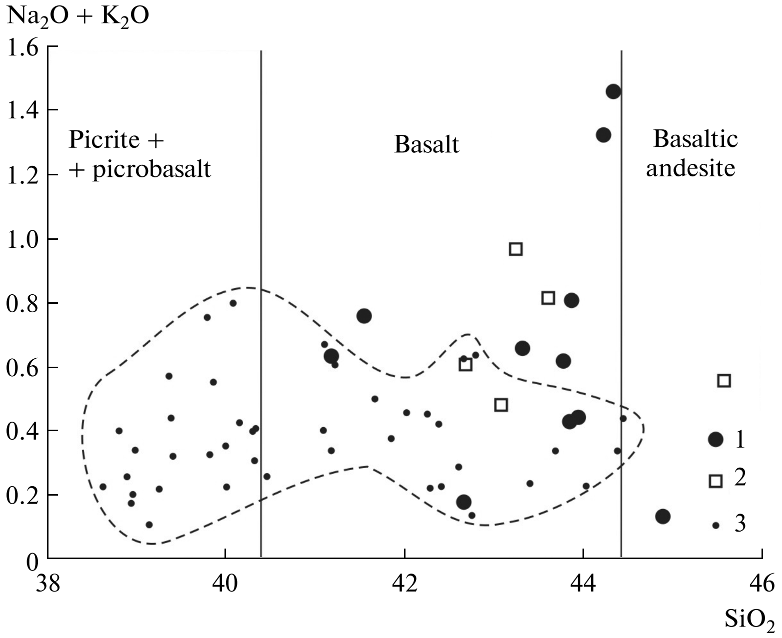

Fig. 3. A SiO_2–($Na_2O + K_2O$) diagram for metapicrites and metapicrobasalts of the Alistor suite:
(1) data (Table 2), (2) after (Bondarenko, 1997a, 1997b), (3) picrites and picrobasalts from dikes, sills, volcanic breccias, and diatremes of eastern Kamchatka (Markovskii and Rotman, 1981).
The highlighted fields in Figs. 3 through 5 mark the compositions of ultramafic rocks in eastern Kamchatka (Markovskii and Rotman, 1981).

middle reaches among predominant metabasite volcanic rocks (metadolerites and their tuffs) are composed of clasts of strongly altered picrites, crystals of clinopyroxene and ore minerals among a pelitomorphous groundmass that has been replaced with an epidote–chlorite–actinolite–prenite–pumpellyite aggregate with small amounts of albite. Metapicrite inclusions in psephitic tuffs have angular, flattened shapes, are 2–3 cm across, and make about 10–30% of the rock volume. The longer axes of the clasts (the ratio of clast length to clast thickness usually ranges between 3 to 1 and 10 to 1) are commonly oriented in a single direction.

The Geochemistry of Metavolcanic Rocks

The chemical composition and geochemical characteristics of metapicrites and metapicrobasalts found in the Sredinnyi Range are listed in Table 2 and in a series of classification diagrams (Figs. 3 through 6). Table 2 shows that these rocks are dramatically depleted in typically crustal elements (Rb, K, and P), providing evidence of a mantle source of these metavolcanic rocks.

When plotted on an SiO_2–($Na_2O + K_2O$) diagram (see Fig. 3), these rocks have basaltic compositions and are characterized by very low concentrations of alkali oxides, especially potassium oxides (the concentration of potassium oxide is commonly below 0.1–0.3%), as well as by extremely low concentrations of Rb (< 0.1 g/t) and lower concentrations of Sr. It is supposed that the higher concentrations of silicon oxides in the Alistor metavolcanic rocks compared with the eastern Kamchatka picrites (Markovskii and Rotman, 1981) are due to a sialic origin of the basement in central Kamchatka (Kostitsyn et al., 2012) where all metamorphic and magmatic complexes of the region were formed.

The FeO*/MgO–TiO_2 diagram in Fig. 4 provides evidence of a higher iron content and lower concentrations of titanium oxides in the metavolcanic rocks under consideration here compared with the picrites that are found in the Troodos Mountains and on Gorgona Island (*Magmaticheskie* ..., 1988) and the picrites of eastern Kamchatka (Markovskii and Rotman, 1981).

The metavolcanic rocks typically contain aluminum oxide prevailing over calcium oxide (see Table 2, Fig. 5). Compared with the eastern Kamchatka picrites, the metavolcanic rocks studied here show higher iron content (FeO*/MgO) and lowerCaO/Al_2O_3 ratios varying within 0.6–1.2.

The REE spectra of the Alistor ultramafic metavolcanic rocks (see Fig. 6) are characterized by enrichment in heavy REEs relative to light ones ($La_n/Sm_n = 0.02–0.04$; $La_n/Yb_n = 0.02–0.16$), possibly indicating a differentiation of the original melt accompanied by olivine being accumulated in the picrites. The Eu minimum is typical of the REE spectra of these rocks. Judging by the REE distribution, the metavolcanic rocks studied here have

Table 1. Representative microprobe analyses of minerals in metapicrites and metapicrobasalts of the Alistor suite on the western slope of Kamchatka's Sredinnyi Range

Component	725										722
	Ol$_c$	Ol$_r$	Cpx$_c$	Cpx$_r$	Hbl	Spl$_c$	Spl$_r$	Spl$_{mantle}$	CrMt	Ilm	Ol
SiO_2	39.27	38.66	52.42	50.57	44.23	–	–	–	0	0	39.12
TiO_2	–	–	0.18	0.39	0.53	0.52	0.34	2.61	2.38	48.20	–
Al_2O_3	–	–	1.85	3.71	13.67	22.55	22.70	1.92	1.31	0	
Cr_2O_3	–	–	–	0.01	0.07	35.58	34.83	4.77	2.75	0	–
Fe_2O_3		–	–	–	–	7.62	7.78	60.96	63.08	2.09	–
FeO	20.89	21.70	6.08	6.57	7.50	27.09	27.03	31.75	31.26	38.69	13.78
MnO	0.23	0.23	0.00	0.00	0.00	0.62	0.60	0.21	0.26	3.55	0.83
MgO	40.60	39.68	16.35	15.53	16.03	4.82	4.75	0.05	0	0.90	45.15
NiO	0.22	0.19	0.00	0.00	0.00	0.09	0.03	0.16	0.16	0	Í.î.
CaO	0.01	0.04	21.32	21.43	12.42	–	–	–	0	0	–
Na_2O	–	–	0.02	0.01	2.50	–	–	–	0	0	–
K_2O	–	–	0.00	0.00	0.10	–	–	–	0	0	–
Total	101.22	100.50	98.22	98.22	97.05	98.89	98.06	102.43	101.20	99.06$^{1)}$	98.88
X_{Mg}	0.744	0.763	0.827	0.808	0.792	0.199	0.196	–	–	–	0.846
Wo	–	–	43.7	44.5	–	–	–	–	–		–
En	–	–	46.6	44.9	–	–	–	–	–		–
Fs	–	–	9.7	10.6	–	–	–		–		–

Component	722				212				174		
	Cpx	Hbl	Spl	Ilm	Ol$_c$	Ol$_r$	Cpx	Hbl	Cpx$_c$	Cpx$_r$	Hbl^1
SiO_2	53.59	43.41	–	0	38.80	38.17	51.64	45.02	52.41	51.66	46.83
TiO_2	0.00	0.61	0.41	49.08	0.00	0.00	0.02	0.41	0.17	0.37	1.56
Al_2O_3	0.84	14.45	9.70	0.00	0.00	0.00	0.37	14.17	4.50	3.45	10.59
Cr_2O_3	0.00	0.53	42.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	–	–	15.81	19.26	–	–	–	–	–	–	–
FeO	6.52	6.83	28.27	24.24	22.26	23.74	11.73	9.12	7.30	10.08	12.82
MnO	0.00	0.00	1.04	4.33	0.08	0.20	0.58	0	0.01	0.02	0.00
MgO	14.47	16.72	2.71	1.18	39.03	36.08	10.46	14.94	16.16	15.27	15.57
NiO	0.59	0.00	Í.î.	0.00	0.17	0.17	0.00	0.03	0.00	0.07	0.02
CaO	23.76	11.62	–	0.43	0.02	0.01	23.49	12.14	20.22	17.96	10.31
Na_2O	0.00	2.37	–	0.00	0.00	0.00	0.00	2.66	0.06	0.26	2.98
K_2O	0.00	0.00	–	0.00	0.00	0.00	0.00	0.11	0.00	0.01	0.14
Total	100.66$^{2)}$	97.14	100.14	98.53	100.36	98.37	98.29	98.60	100.83	99.15	100.82
X_{Mg}	0.798	0.815	0.100	0.048	0.757	0.735	0.589	0.745	0.798	0.729	0.684
Wo	48.5	–	–	–	–	–	49.8	–	41.8	38.2	–
En	41.1	–	–	–	–	–	30.8	–	46.4	45.1	–
Fs	10.4	–	–	–	–	–	19.4	–	11.8	16.7	–

Table 1. (Contd.)

Component	174				765				702		
	Hbl^2	Spl^1_c	Spl^1_r	Spl^2	Ol	Hbl^2	Spl	Chl	Cpx^1_c	Cpx^1_r	Cpx^2
SiO_2	54.76	0	1.05	0	38.96	53.36	0.05	37.18	51.91	51.54	50.37
TiO_2	0	0.15	0.08	0.13	0.01	0.20	0.11	0.06	0.20	0.24	0.40
Al_2O_3	3.33	27.47	20.68	26.24	0.04	4.86	59.44	14.10	3.33	1.83	5.15
Cr_2O_3	0.00	39.62	34.07	42.04	0.02	0.00	3.09	0.10	0.00	0.00	0.00
Fe_2O_3	–	5.46	10.21	5.20	–	–	4.47	–	–	–	–
FeO	6.29	12.44	26.23	9.12	20.50	6.37	17.84	6.71	7.17	9.06	7.11
MnO	0.00	0.39	2.16	0.33	0.28	0.09	0.11	0.11	0.00	0.32	0.00
MgO	21.39	15.43	3.01	17.42	40.99	17.69	15.43	29.99	15.24	13.20	17.45
NiO	0.09	0.20	0.09	0.19	@H.o.	–	–	@H.o.	0.01	0.03	0.01
ZnO	@H.o.	@H.o.	1.60	@H.o.	@H.o.	–	–	@H.o.	@H.o.	@H.o.	@H.o.
CaO	10.69	0.00	0.04	0.00	0.03	12.69	0.09	0.05	21.49	21.87	22.10
Na_2O	0.19	0.00	0.00	0.00	0.03	0.60	0.03	0.03	–	0.93	0.06
K_2O	0.06	0.00	0.00	0.00	0.01	0.07	0.01	0.04	–	0.01	0.00
Total	98.80	101.16	99.74	100.67	100.87	95.93	100.67	88.37	99.35	99.03	99.95
X_{Mg}	0.858	0.608	0.132	0.687	0.779	0.830	0.556	0.887	0.791	0.721	0.787
Wo	–	–	–	–	–	–	–	–	44.5	47.3	45.9
En	–	–	–	–	–	–	–	–	43.9	38.0	42.6
Fs	–	–	–	–	–	–	–	–	11.6	14.7	11.5

Component	702				736		762				1329/1
	Spl_c	Spl_r	Spl_{mantle}	CrMt	Cpx_1	Cpx_2	Cpx^1_c	Cpx^1_r	Cpx^2	Ab	Cpx
SiO_2	–	–	–	0	50.28	47.43	50.63	50.91	47.08	68.61	50.90
TiO_2	0.14	0.15	0.05	0.05	0.24	1.45	0.46	0.73	1.68	–	0.72
Al_2O_3	20.56	17.98	0.47	0.47	5.18	3.43	4.32	2.27	5.92	19.47	3.14
Cr_2O_3	36.76	37.41	21.30	21.30	0.00	0.06	0.00	0.00	0.00	–	–
Fe_2O_3	8.58	10.55	46.62	20.09	–	–	–	–	–	–	–
FeO	31.16	30.09	30.08	55.66	9.02	16.48	8.88	14.61	13.10	0.77	11.19
MnO	1.98	2.09	1.27	1.27	0.00	0.04	0.00	0.27	0.00	–	0.20
MgO	1.05	0.99	0.00	0	14.74	14.00	14.93	14.26	12.11	–	14.09
NiO	0.04	0.12	0.02	0.02	0.00	0.00	0.00	0.10	0.03	–	–
ZnO	0.84	1.24	0.01	0.01	0.00	0.00	0.00	0.00	0.00	–	–
CaO	–	–	–	0	19.65	16.97	21.30	17.50	17.51	0.07	19.01
Na_2O	–	–	–	0	0.07	0.05	0.04	0.55	0.18	11.71	0.36
K_2O	–	–	–	0	0.02	0.00	0.01	0.00	0.06	0.02	0.01
Total	101.11	100.62	99.82	98.87	99.20	99.91	100.57	101.20	97.67	100.65	99.62
X_{Mg}	0.043	0.041	–	–	0.794	0.602	0.750	0.631	0.622	–	0.688
Wo	–	–	–	–	41.6	34.4	43.5	35.9	39.3	–	40.2
En	–	–	–	–	43.5	39.5	42.4	40.7	37.8	–	41.4
Fs	–	–	–	–	14.9	26.1	14.1	23.4	22.9	–	18.4

Samples 174, 212, 702, 722, 725, 736, and 765 are metapicrites; samples 762 and 1329/1 are metapicrobasalts. The samples were taken at the head of Ozernyi Brook, which is a right tributary of the Levaya Kol' River (see Fig.1). Fe^{2+} and Fe^{3+} in spinel, magnetite, and ilmenite were calculated from stoichiometric relations. N.d. means Not determined.

* The total also includes (1) 0.63 % V_2O_3: (2) 0.89 % Yb_2O_3. Hbl_2 in sample 174 is secondary amphibole.

Table 2. Chemical composition (wt %) and geochemical parameters (g/t) in metapicrites and metapicrobasalts from the Alistor and Andrianovka suites, Kamchatka's Sredinnyi Range

Component	174	721-A	722	723	763-V	765	736	5555-3	212	762	5555	728	775	824-V	853
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	43.91	43.79	43.84	44.88	42.63	41.18	44.31	43.83	43.31	41.53	44.19	48.48	43.69	54.01	50.67
TiO_2	0.22	0.39	0.34	0.37	0.27	0.43	0.19	0.23	0.40	0.98	0.18	2.41	0.36	0.99	0.88
Al_2O_3	9.07	9.24	8.15	7.22	8.60	11.35	10.01	7.34	9.96	10.49	9.83	13.48	8.02	14.79	13.76
Fe_2O_3*	9.98	12.25	12.02	11.49	12.08	14.61	10.43	12.70	15.46	14.79	10.52	15.14	11.71	11.51	12.13
MnO	0.15	0.16	0.20	0.14	0.16	0.18	0.14	0.17	0.20	0.19	0.20	0.23	0.15	0.10	0.17
MgO	21.98	20.09	22.34	23.66	21.35	22.46	20.03	20.91	19.66	17.57	18.16	6.54	23.45	7.25	8.83
CaO	8.35	9.63	8.37	6.76	8.48	7.61	8.68	9.22	8.16	8.33	10.04	9.21	6.44	8.61	8.69
Na_2O	0.42	0.61	0.80	0.13	0.17	0.63	1.36	0.42	0.65	0.76	1.32	3.61	0.29	1.94	3.43
K_2O	0.03	0.01	0.01	0.01	0.01	0.01	0.10	0.01	0.01	0.01	0.01	0.08	0.01	0.15	0.19
P_2O_5	0.01	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.04	–0.06	0.02	0.20	0.03	0.20	0.07
P.p.m.	5.62	3.40	3.51	5.61	5.72	1.23	4.28	4.31	1.90	5.43	4.95	0.22	5.89	0.77	1.34
Total	99.74	99.60	99.61	100.30	99.50	99.72	99.55	99.16	99.75	100.14	99.42	99.60	100.04	100.32	100.16
Rb	<0.1	<0.1	0.69	1.07	<0.1	0.11	0.12	0.54	<0.1	0.19	0.16	0.30	<0.1	0.94	2.52
Sr	4.69	92.38	59.53	15.08	6.90	32.44	11.80	21.81	20.50	98.43	18.29	419.78	40.48	310.03	114.28
Ba	3.37	8.85	8.70	5.28	2.33	6.31	18.25	5.16	7.05	4.84	3.59	68.88	20.36	36.13	47.18
Zr	6.31	14.97	11.83	13.38	8.14	14.39	6.72	8.69	13.51	44.16	4.48	142.44	11.01	38.88	40.50
Y	9.71	11.10	9.59	7.80	7.80	9.97	7.99	10.85	11.33	12.66	12.34	23.70	9.64	25.52	17.07
Nb	0.18	0.26	0.14	0.15	0.17	0.15	0.45	0.10	0.53	0.88	0.09	5.93	0.25	1.53	1.56
Co	73.01	75.61	77.66	85.76	91.11	96.86	77.71	78.01	87.16	86.61	68.11	47.90	96.16	35.53	47.29
Cr	1870	1097	1390	936.9	1881	2177	1616	1482	1620	1062	3991	195.8	2146	116.9	267.5
Ni	1107	998.2	1139	1365	1273	1057	1043	1089	1115	898.5	608.4	138	1526	57.4	156.7
V	134.4	193.2	160	149.8	127.1	187.6	154.6	203.57	203.3	261.4	180.47	433.7	158.9	310.6	299.32
Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
La	0.26	0.21	0.15	0.21	0.08	0.03	<0.03	0.06	0.58	1.80	0.03	6.90	0.49	6.53	1.89
Ce	0.68	0.67	0.51	0.64	0.33	0.52	0.31	0.45	1.37	3.52	0.11	20.30	0.57	14.28	5.24
Pr	0.15	0.18	0.15	0.14	0.10	0.16	0.08	0.11	0.25	0.69	0.08	3.28	0.19	2.14	0.90
Nd	0.90	1.51	1.45	1.34	0.93	1.32	0.70	0.87	1.65	4.63	0.51	17.36	1.27	11.49	5.19
Sm	0.42	0.98	0.85	0.69	0.58	0.93	0.39	0.52	0.89	2.19	0.43	5.88	0.68	3.37	2.05
Eu	0.21	0.53	0.41	0.17	0.18	0.43	0.11	0.29	0.28	0.80	0.23	1.85	0.23	0.99	0.60
Gd	0.99	1.65	1.48	1.31	0.98	1.66	0.88	1.24	1.76	2.87	0.98	6.20	1.05	4.05	2.53
Tb	0.19	0.28	0.22	0.20	0.19	0.29	0.17	0.29	0.32	0.43	0.24	0.83	0.21	0.69	0.48
Dy	1.68	2.06	1.90	1.67	1.61	2.13	1.44	1.74	2.12	2.99	2.01	5.47	1.57	4.58	3.20
Ho	0.37	0.46	0.36	0.31	0.34	0.42	0.32	0.40	0.50	0.54	0.46	1.04	0.34	0.94	0.67
Er	1.16	1.18	1.05	0.91	0.95	1.14	1.02	1.14	1.42	1.37	1.47	2.78	1.06	2.75	2.03
Tm	0.18	0.18	0.17	0.13	0.16	0.15	0.17	0.14	0.19	0.19	0.22	0.34	0.17	0.36	0.31
Yb	1.25	1.21	0.99	0.88	1.05	1.07	1.22	1.08	1.40	1.22	1.45	1.92	0.89	2.30	2.06
Lu	0.20	0.19	0.18	0.15	0.16	0.19	0.18	0.17	0.18	0.19	0.22	0.30	0.16	0.35	0.30
Hf	0.22	0.42	0.34	0.37	0.24	0.40	0.21	0.28	0.33	1.01	0.16	2.74	0.26	0.92	0.96
Ta	0.01	0.02	0.01	<0.01	<0.01	<0.01	0.02	<0.01	0.12	0.05	<0.01	0.37	0.02	0.08	0.10

Table 2. (Contd.)

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pb	<0.5	2.50	2.20	2.25	1.26	1.01	<0.5	<0.05	0.81	1.67	1.70	1.71	<0.5	2.24	0.79
Th	0.03	0.02	0.03	0.04	<0.01	<0.01	0.03	0.01	0.04	0.16	0.01	0.63	0.01	0.89	0.14
U	0.10	0.01	0.02	0.04	0.03	<0.01	0.02	0.00	0.03	0.02	0.03	0.20	0.02	0.31	0.12

Samples 1–12 are from the Alistor suite, 13–15 from the Andrianovka suite. Samples 1–8 and 13 are metapicrites, 9–11 are metapicrobasalts, 12, 14, and 15 are metabasalts. Sampling sites: 1 the divide of the Pravaya and Levaya Kol' rivers; 2–7, 9, 10, and 12 Ozernyi Brook (a right tributary of the head of the Levaya Kol' R.); 8 and 11 were in the left bank area of Kolpakov R.; 13–15 head of Krutogorovo R.

Concentrations of SiO_2, p.p.m. were determined by gravimetry, concentrations of the other elements were determined by atomic emission spectrometry with inductively coupled plasma using an ICAP-6500 Duo spectrometer at the Analytical Center, Far East Geological Institute. The REEs and trace components were determined by mass spectroscopy with inductively coupled plasma using an Agilent 7500 instrument at the Analytical Center. Sample preparation involved refusion with lithium metaborate.

* All iron is in the form Fe_2O_3.

compositions that are similar to those of picrites in ophiolite complexes (*Magmaticheskie* ..., 1988), while being different in having slightly higher concentrations of silicon and aluminum oxides.

In chemical terms, the Alistor metapicrites are similar to the komatiites on Newfoundland Island in North America (Upadhyáy, 1978] or to the komatiites from the Abitibi greenstone belt, Canada (Pyke et al., 1973). The Alistor picrobasalts have higher LREE concentrations: (La/Sm)N = 0.5–1.2, (La/Yb)N = 0.6–2.4 and a barely visible Eu minimum compared with the metapicrites.

The Alistor metavolcanic rocks are similar with model mantle compositions in the concentrations of trace elements; they are different in having lower NiO concentrations. Compared with chondrites the metavolcanic rocks studied here have higher Ti/Zr and Zr/Nb ratios and a lower Ti/Y ratio. The TiO_2/Al_2O_3 ratios are similar to those for chondrites, varying within 0.01–0.09.

The compositional variation in ultramafic volcanic rocks is probably controlled by a combination of several different processes that reflect both the conditions of melt generation and melt differentiation at different levels in the crust.

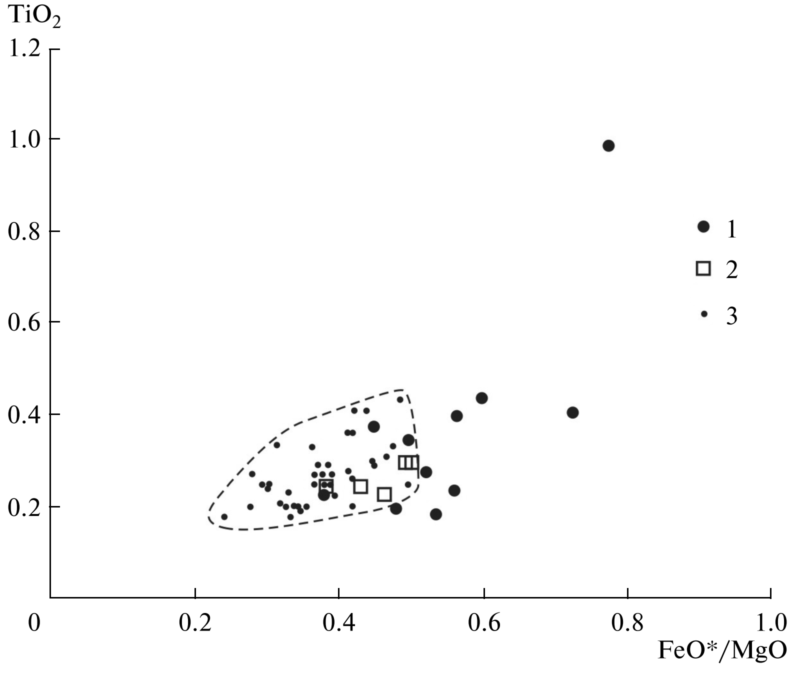

Fig. 4. A FeO*/MgO–TiO_2 diagram for metapicrites and metapicrobasalts of the Alistor suite. For legend see Fig. 3.

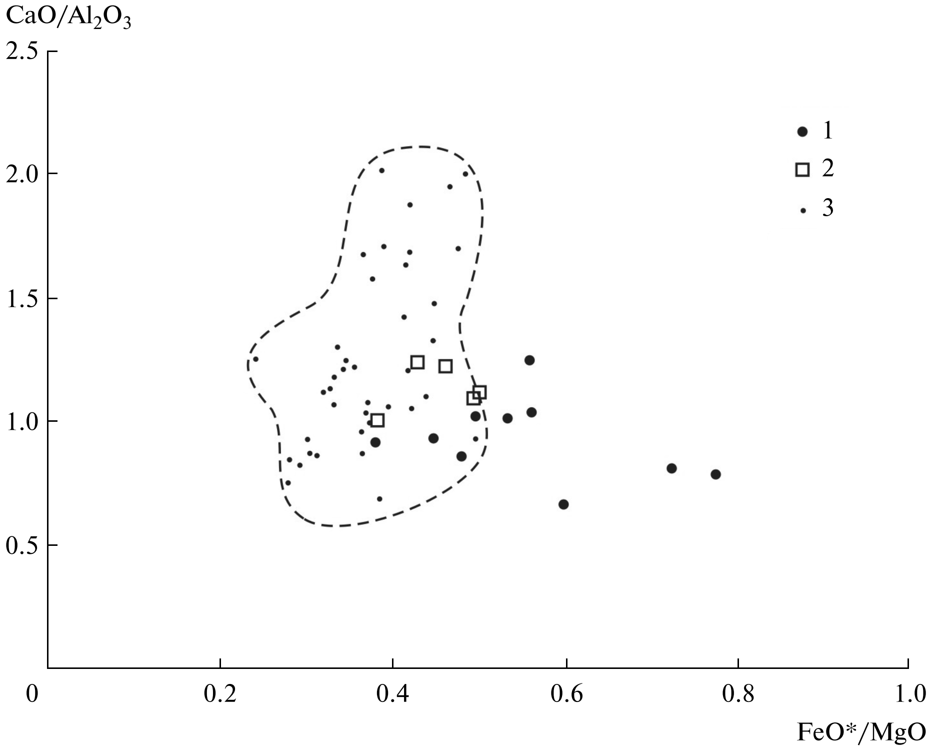

Fig. 5. A FeO*/MgO–Al_2O_3/CaO diagram for metapicrites and metapicrobasalts of the Alistor suite. For legend see Fig. 3.

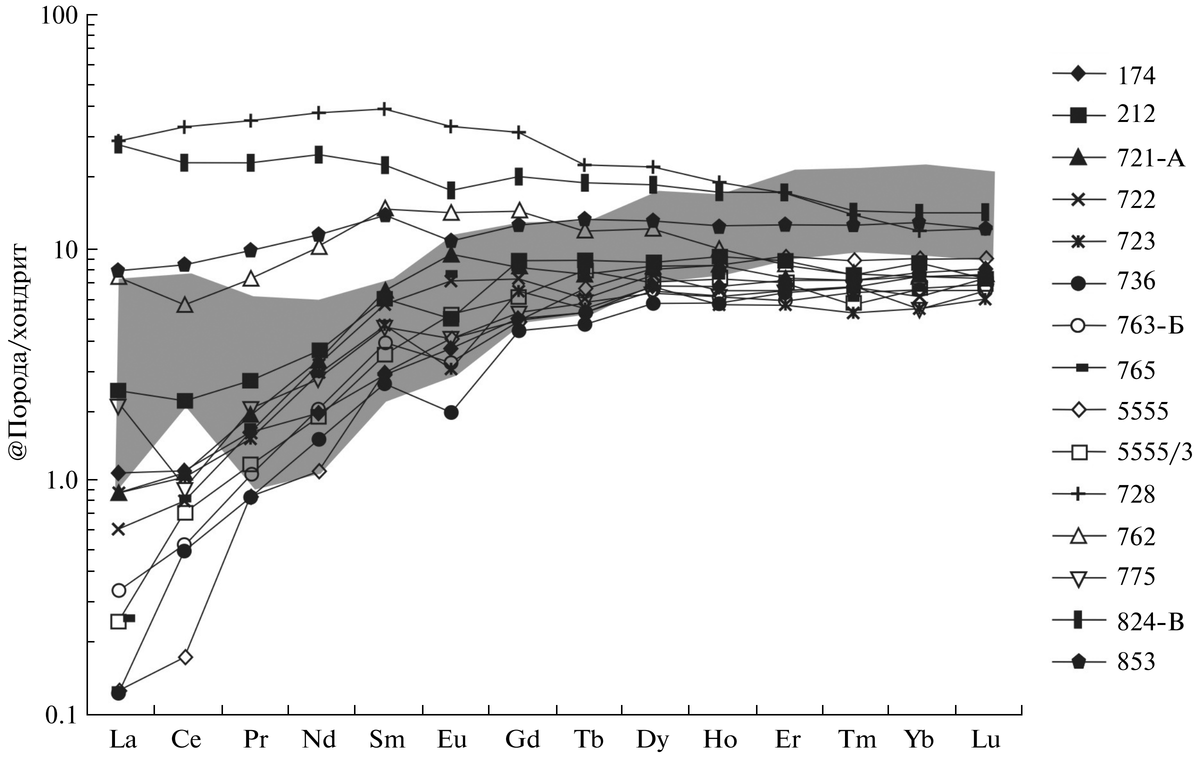

Fig. 6. The chondrite-normalized (McDonough and Sun, 1995) distribution of REE concentrations in metapicrites and metapicrobasalts of the Alistor suite. The REE field for picrobasalts of the Alistor suite at the divide between the Levaya Kheivan and Kolpakov rivers is stippled (Konnikov et al., 2010). Samples 762, 853, 824-V, and 728 are basic and ultramafic metavolcanic rocks of the Andrianovka suite at the Sredinnyi Range.

RESULTS AND DISCUSSION

The host rocks of the Alistor ultramafic volcanic rocks 4 are the Kikhchik terrigenous rock sequences and similar metamorphosed series, the Kolpakov, Kamchatka, and Malkino series, with the age of the original rocks in these being in the range from the end of the Early Cretaceous to the Late Cretaceous based on U–Pb SHRIMP isotopy of zircons (Kostitsyn et al., 2012; Solov'ev, 2008; Hourigan et al., 2009). The Sm–Nd isotope geochemical studies of the metamorphic rocks in these series show similarities in the isotope composition of neodymium and in the mean isotope ratios ^{147}Sm/^{144}Nd = 0.1148–0.1223, ^{143}Nd/^{144}Nd = 0.512394–0.512470, and εNd = –2.8 to 1 –4.2 in the apoterrigenous rocks, indicating the geochemical identity of the source areas that produced the formations (Kuz'min and Bogomolov, 2013].

The series of these rocks, which are traditionally classified as belonging to different-aged formations from the Archean to the Late Mesozoic (*Geologiya SSSR*..., 1964) 4 make a complex of terrigenous deposits that formed in a common continental-margin sedimentary basin during the Late Mesozoic sedimentation cycle, with the sediments being brought from the same source province in the eastern margin of the Asian continent. The Sm–Nd 2 model datings for the Kolpakov, Kamchatka, Malkino, and Kikhchik series are close to each other and reflect a Late Proterozoic (1.17 billion years) age for the source areas of sedimentary material (Kuz'min and Bogomolov, 2013). Similar conclusions were also drawn by Kostitsyn et al. (2012) from dating of zircons and an analysis of the U–Pb and Sm–Nd isotope ratios for metamorphic rocks in the basement of the Sredinnyi Range of Kamchatka. In the opinion of Kostitsyn et al. (2012), the higher isotope ratios of strontium in the basement metamorphic rocks reveal the old age of their sources.

Extension of the continental crust in the Cretaceous sedimentary basin and the intersections of this basin with faults that came into being simultaneously with the generation of the Okhotsk–Chukchi volcanogenic belt (Akinin and Miller, 2011) caused the ascent of mantle material 3 and the beginning of basite and ultrabasite volcanic occurrences. Some discrete volcanic centers originated at the Early/Late Cretaceous boundary in the deeper part of 4 the basin, where terrigenous deposits were accumulating. Volcanoclastic basite material accumulated on the slopes of volcanoes in these centers, while tuffogenic turbidites with horizons of siliceous tuffites and chert were deposited far from the centers.

Mantle material was emplaced into the crustal bottom 4 from terrigenous deposits of the marginal basin along with deep hydrogen-rich fluids to cause a considerable temperature rise in the crust, magmatic replacement of volcanogenic sedimentary sequences, the generation of crustal magma chambers, and subsequent ascent of acidic volcanic rocks and granitoid rocks into the upper crustal horizons.

To sum up, the metapicrites and metabasites from sections of terrigenous deposits in the Sredinnyi crystalline 4 massif present a record of a Late to Early Cretaceous opening of the continental-margin sedimentary basin that originated on continental crust in the eastern margin of the Asian continent and was accompanied by emplacement of mantle basite melts with special geochemical parameters into the terrigenous deposits. The special 4 parameters were due to extension of a sialic crust and interaction between the melts and continental crustal rocks. Intensive Late Cretaceous basite and ultrabasite 3 volcanism in Kamchatka was probably due to the ascent of mantle plumages, which carried hydrogen-rich fluids.

CONCLUSIONS

Late Cretaceous metapicrites and metapicrobasalts are encountered in all apoterrigenous rock sequences of 1 the Sredinnyi crystalline massif, forming sheets, flows, and sills between a few meters and 100 m or greater in thickness. Metapicrites possess geochemical parameters that are intermediate between mid-oceanic ridge tholeiites and island-arc tholeiites, which is typical of complexes of volcanic rocks in backarc (marginal) basins.

The host rocks for metapicrites and metapicrobasalts are terrigenous rock sequences of the Kikhchik series and 4 its metamorphosed analogues (the Kolpakov, Kamchatkan, and Malkino series), which were formed in a common continental-marginal sedimentary basin during the late Mesozoic sedimentation cycle; they received material from the same source province in the eastern margin of the Asian continent. The extension of continental crust in the Cretaceous sedimentary basin and intersections of it by faults that originated simultaneously with the generation of the Okhotsk–Chukchi volcanogenic belt were the beginning of basite and ultrabasite volcanic occurrences. 3 The emplacement of mantle material accompanied by deep hydrogen-rich fluids into the crustal bottom from the volcanogenic terrigenous deposits in the marginal 4 basin produced a considerable rise of crustal temperatures, magmatic replacement of volcanogenic sedimentary rock sequences with subsequent generation of magma chambers, and the ascent of acidic volcanic rocks and granitoid rocks into upper crustal horizons.

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SPELL: 1. apoterrigenous, 2. datings, 3. ultrabasite, 4. terrigenous