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Early Cenozoic Magmatism in the Continental Margin of Kamchatka

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Abstract—The paper presents isotopic–geochemical features of magmatic rocks that were produced at the continental margin of Kamchatka during its various evolutionary stages. Continental-margin magmatism in Kamchatka is demonstrated to have evolved from the Paleocene until the present time. The Paleocene and Middle–Late Eocene magmatic complexes show features of suprasubduction magmatism. The magmatic melts were derived from isotopically heterogeneous (depleted and variably enriched, perhaps, as a consequence of mixing with within-plate melts) mantle sources and were likely contaminated with quartz-feldspathic sialic sediments. The Miocene preaccretion stage differs from the Paleogene–Eocene one in having a different geochemical and isotopic composition of the mantle magma sources: the magmatic sources of the Miocene suprasubduction magmas contained no compositions depleted in radiogenic Nd isotopes, whereas the sources of the within-plate magmas were enriched in HFSE. The Late Pliocene–Quaternary postaccretion magmas of the Eastern Kamchatka Belt are noted for the absence of a within-plate OIB-like component.

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INTRODUCTION

An interesting problem related to active continental margins is the dependence of characteristics of the continental-margin magmatism on collisional tectonic events at these margins. As was demonstrated in numerous publications (Sokolov, 1992; *Accretion Tectonics…*, 1993; Kovalenko, 2003; and others) the most widely spread type of collision is that between an island arc and continent, which will be discussed below.

This problem is attacked along several lines: (1) the determining and comparison of isotopic and tectonic characteristics of the mantle and crustal sources of pre- and postcollision magmatism in the active continental margin; (2) the study of the geochemical and isotopic characteristics of the mantle and crustal sources of magmatism in the island-arc terrane that underwent collision with the continental margin; and (3) the generalization and synthesis of all aforementioned data and tectonic materials in order to elucidate the processes of interaction between the upper mantle and crust during the arc–continent collision. Modern literature includes only sparse publications devoted to this problem. Most of them are devoted to postcollision or, rarely, syncollision magmatism (for example, Sajona et al., 2000; Elburg et al., 2002; and others). We are not aware of publications presenting comprehensive analysis of this problem with the application of modern geochemical and isotopic techniques.

Kamchatka and Southern Koryakia are thought to be a good example of an active continental margin (Sokolov, 1992; *Accretion Tectonics…*, 1993; Kovalenko, 2003; and others). Late Cretaceous–Cenozoic volcanism in the continental margin of Kamchatka and Koryakia developed simultaneously with significant arc–continent collision events: the tectonic docking of two large arc terranes to the continent in the Early Eocene and Pliocene (*Accretion Tectonics…*, 1993; Kovalenko, 2003; Shapiro and Lander, 2003). The Paleocene magmatic complexes in the continental margin were formed before the accretion events. The Middle Eocene volcanic sequences of western Kamchatka that are part of the Western Kamchatka–Koryakia Volcanic Belt mark the termination of the Early Eocene accretion stage and overlay, with a significant angular unconformity, complicatedly deformed older rocks. The Miocene–Early Pliocene magmatic rocks of the Central Kamchatka Volcanic Belt and some areas in eastern Kamchatka were produced before the Pliocene accretion stage, while the Late Pliocene–Quaternary sequences of the Eastern Kamchatka Volcanic Belt were formed after it. Our research was centered on the elucidation and comparison of the geochemical characteristics of the mantle and crustal magma sources in the

Asian continental margin at Kamchatka before and after this collision. We did not intend to develop tectonic models of collision, because this would have require knowledge of the magmatic sources of island-arc terranes involved in this collision.

The most detailed data are now available on the Miocene–Quaternary magmatism of Kamchatka (Koloskov, 2001; Perepelov, 2005; Fedorov and Shapiro, 1998; Churikova et al., 2001; Hochstaedter et al., 1994; Kepezhinskas et al., 1997; Kersting and Arculus, 1995; Turner et al., 1998; Volynets et al., 1999; and others). The first geochemical data on the Paleocene–Eocene magmatic complexes were published in (Puzankov, 1994; Gladenkov et al., 1997; Shantser and Fedorov, 1999). Here we present newly obtained results of the petrologic–geochemical study of Paleocene and Middle Eocene magmatic rocks from the continental margin of Kamchatka and compare characteristics of magmatism in the Kamchatkan continental margin before and after each accretion episode.

GEOLOGIC SETTING OF PALEOCENE AND EOCENE VOLCANIC COMPLEXES IN KAMCHATKA

The autochthonous volcanic complexes whose origin is related to Early Cenozoic magmatic processes in the continental margin of Kamchatka include, in our opinion, the Paleocene volcanic complexes of the Utkholok Peninsula and Omgon Range and the Middle-date Eocene volcanogenic sequences of western and central Kamchatka (Fig. 1). The Paleocene complexes were produced before the Early Eocene pulse of tectonic activity at Kamchatka, while the Middle and Late Eocene compositions were generated after it.

The *Paleocene volcanic complex* of the Utkholok Peninsula is made up of subaerial two-pyroxene basalts, amphibole andesites, rhyolites, and agglomerated and psephitic tuffs of andesite composition, fine-grained tephroids with scorched detritus and fragments of imprints of leaves. The thickness of this sequence varies from a few dozen to a few hundred meters. The whole-rock K–Ar age of the volcanics corresponds to the Late Maastrichtian–Early Danian (60 ± 4, 61 ± 5, 56 ± 4, 63 ± 4 and 64 ± 4 Ma) (Gladenkov et al., 1977). The volcanic complex is conformably overlain by the flyschoid terrigenous sequence of Cape Zubchatyi, which consists of quartz-feldspathic subarkose sandstones, mudstones, and siltstones, which were likely deposited on the continental slope and foot of the Asian continental margin. These rocks are overlain (through an erosion surface and angular unconformity) by the Middle Eocene Snatol'skaya and Kovachinskaya formations (Gladenkov et al., 1997).

In the Omgon Range, the Paleocene volcanic rocks compose sills of basic and acid rocks in the flyschoid quartz–feldspar sequence of the Omgon Group, which is compositionally similar to the Cape Zubchatyi Formation and also seem to mark the Asian continental margin (Kovalenko, 2003). The zircon fission-track ages of the sills are 63 ± 7 and 61 ± 7 Ma (Ledneva et al., 2006). The quartz–feldspathic rocks were dated at the Albian–Early Senonian based on the flora and microfauna (*Geology of the USSR*, 1964) and at 80 ± 4, 85 ± 4, 100 ± 6, and 102 ± 19 Ma by fission tracks in zircon (Solov'ev, 2005). The whole structure is overlain (with an erosion surface and angular unconformity) by the Middle Eocene Snatol'skaya Formation (Gladenkov et al., 1997).

The **Middle–Late Eocene Complex** of western and central Kamchatka (Fig. 1) was produced after the Early Eocene stage of tectonic accretion in Kamchatka, and the neoautochthonous complex of the Asian continental margin overlies (with an erosion surface and sharp angular unconformity) the accretion–folded structures. The complex consists of subaerial lavas of a differentiated basalt–andesite–dacite–rhyolite association, lava breccias, and blocky agglomerate tuffs. The whole-rock K–Ar dates of these rocks are as follows: 46 ± 2, 37 ± 1, 43 ± 5, 46 ± 1, and 41 ± 1 for Cape Kinkil (Gladenkov et al., 1990); 48 ± 1, 49 ± 2, 47 ± 3, 49 ± 3, 49 ± 2, 50 ± 1, 45 ± 1, 47 ± 2, 49 ± 2, 49 ± 1, 50 ± 2, 48 ± 2, 51 ± 2, 47 ± 3, and 53 ± 2 Ma for the shore of the Penzhina Bay between the Pustaya River and the mouth of the Shamanka River (Bagdasaryan et al., 1994); 46 ± 0.2 (basaltic andesite), 44 ± 2 (Shamanka granitoid intrusion) (Fedorchuk and Izvekov, 1992) for the central part of the Kamchatka Isthmus; 46 ± 1.3 Ma for the watershed area between the Pravaya Lesnaya and Shamanka rivers (Gladenkov et al., 1997). The Rb–Sr plagioclase, hornblende, and biotite dating of the Shamanka intrusion yielded, respectively, 47 ± 1, 44 ± 1, and 44 ± 1 Ma (Solov'ev et al., 2002); volcanics from Cape Khairyuzova were dated by the fission track method at 30 Ma (A.V. Solov'ev, personal communication).

Volcanic rocks of roughly the same age are known elsewhere in Kamchatka, but they are mostly contained there in terranes. For example, Late Cretaceous–Early Paleocene volcanic, siliceous–volcanic, and volcanic–sedimentary deposits occur in eastern and central Kamchatka as nappes and slices. The Late Cretaceous–Eocene volcanic and volcanic–sedimentary sequence in the eastern peninsulas and capes of Kamchatka are thought to be remnants of these ensimatic island arcs (Achaivayam–Valagin and Kronotskaya) and marginal marine basins, which closed in the Early Eocene and Miocene (*Accretion Tectonics…*, 1993; Kovalenko, 2003; Levashova, 1999; and others). According to paleomagnetic data, the island arcs were distant from the continental margin (Kovalenko, 2003; Levashova, 1999). The Late Cretaceous–Early Paleocene association of basalt, dacite, and rhyolite sills and dikes that was recognized by A.N. Sukhov and A.B. Kuz'michev in the basin of the Tikhaya River and the Panshetayam Range, western Kamchatka, and were emplaced into Late Cretaceous siliceous–tuff sequences of the Palana

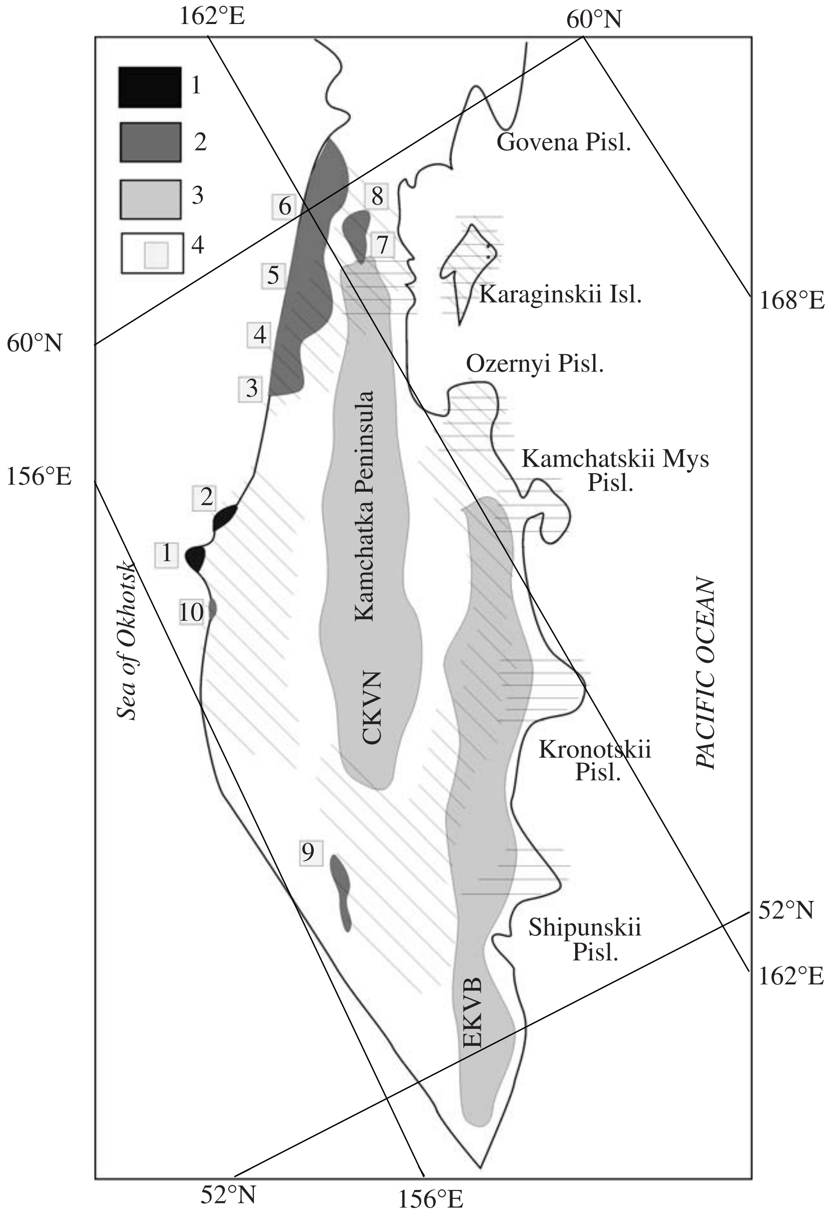

Fig. 1. Early Cenozoic magmatic complexes in western Kamchatka.

(1–3) Magmatic complexes of the continental margin of Kamchatka: (1) Paleocene, (2) Middle Eocene, (3) Miocene–Quaternary; (4) our study areas: 1—Utkholok Peninsula, 2—Omgon Range, 3—mouth of the Anadyrka River–Cape Kinkil, 4–Cape Tevi, 5—Cape Rebro, 6—Podkagernaya Bay, 7—upper reaches of the Shamanka River, 8—Shamanka intrusion, 9—Mount Chernaya, 10—Cape Khairyuzov. CKVB and EKVB are the Central and the Eastern Kamchatka Volcanic Belt, respectively; hatching shows areas with pronounced rock deformations: Middle Eocene (diagonal hatching) and Miocene (horizontal hatching).

island arc, which also occurred at the continental margin according to paleomagnetic data (Kovalenko, 2003), seems to also have an exotic nature. The K–Ar age of these subvolcanic bodies corresponds to 67 ± 4, 72 ± 5, 61 ± 2, 65 ± 4, 59 ± 4 and 74 ± 2 Ma (Sukhov and Kuz'michev (2005). These researchers point to striking similarities between the compositions of these magmatic rocks and their host pyroclastic deposits in the Palana island arc.

METHODS

Here we consider only the Paleocene and Eocene autochthonous magmatic complexes of the continental margin of Kamchatka (Fig. 1). Samples of the Paleocene magmatic rocks were collected in the Utkholok Peninsula and Omgon Range. The Eocene sequences were studied at six areas: at the mouth of the Anadyrka River–Cape Kinkil, Cape Tevi, central part of the Kamchatka Isthmus, Cape Rebro–Podkagernaya Bay, Mount Chernaya, and Cape Khairyuzova.

The factual basis for the analysis of the geochemistry of the volcanic rocks was provided by data obtained on more than 150 samples, which were provided for us by courtesy of A.E. Shantser, V.I. Grechin, and A.V. Koloskov and collected by the authors of this paper. Major oxides were determined by conventional techniques of "wet" chemistry; the concentrations of trace elements and REE in samples form Utkholok Peninsula were analyzed by INAA, quantitative spectral methods, and XRF at the Geological Institute, Russian Academy of Sciences, (Shantser and Fedorov, 1999) accurate to 10%. The other samples (34 samples of magmatic rocks and 11 samples of sedimentary rocks) were analyzed at the Institute of Analytical Instrument Making, Russian Academy of Sciences, in St. Petersburg accurate to 5–10%.

Microprobe analyses of minerals were made on a Camebax microprobe at the Institute of Volcanology and Seismology, Far East Division, Russian Academy of Sciences.

The Nd isotopic composition was measured at the Geological Institute, Kola Research Center, Russian Academy of Sciences, in Apatity on a Finnigan MAT-262 (RPQ) seven-collector mass spectrometer by the method described in (Bayanova, 2004). The isotopic composition of the LaJolla Nd standard $^{143}Nd/^{144}Nd = 0.511833 \pm 6$, 2σ, $N = 11$) was measured precise to 0.0024% (2σ). An analogous precision was achieved in the replicate analyses of the new Japanese standard JNd_i1 ($^{143}Nd/^{144}Nd = 0.512072 \pm 2$, 2σ, $N = 44$). The error in the $^{147}Sm/^{144}Nd$ ratios, which was calculated from seven analyses of the Sm and Nd concentrations in the BCR-1 standard, was 0.2% (2σ). The blank was 0.3 ng for Nd and 0.06 ng for Sm. The measured Nd isotopic ratios were normalized to $^{148}Nd/^{144}Nd = 0.241570$ and then normalized to $^{143}Nd/^{144}Nd = 0.511860$ in the LaJolla standard. The decay constant were compiled from (Steiger and Jäger, 1977).

PETROGRAPHY

The **Late Maastrichtian(?)–Early Danian volcanics of the Utkholok Complex** are rocks of a differentiated basalt–andesite–dacite–rhyolite association that compose relatively thin flows with blocky jointing and a massive structure. The texture of these rocks is porphyritic, and they abound in phenocrysts (up to 20–25%). Basalts of the Utkholok Complex contain phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and ore minerals. The texture of the rocks is apohyalopilitic and microdoleritic. The plagioclase occurs as large zonal crystals, whose cores correspond to labradorite ($An_{74–67}$) and intermediate and outer zones are composed of andesine. The clinopyroxene composes large (up to 1 mm) euhedral crystals corresponding to calcic augite in composition ($Wo_{41.5–45.4}En_{47.2–43.6}Fs_{7.7–14.5}$). According to its Al^{IV}–TiO_2 proportions (Le Bas, 1962), the clinopyroxene was classed with subalkaline (including calc–alkaline) varieties. The Cr concentration in the phenocrysts strongly varies and is correlated with FeO*/MgO (FeO* = FeO + $0.9Fe_2O_3$). Olivine is rare and is usually strongly altered.

The **Early Paleocene complex of the Omgon Range** comprises sills and dikes of ilmenite and titanomagnetite gabbro-dolerites, quartz microdolerites, biotite granites, and granite aplites, whose detailed petrographic description was given in (Ledneva et al., 2006).

The **Middle Eocene lavas of the Kinkil Complex** are strongly dominated by a significantly differentiated basalt–andesite–dacite–rhyolite association. The texture of the rocks is porphyritic, with abundant phenocrysts. Phenocrysts in the basalts and basaltic andesites are plagioclase, clinopyroxene, orthopyroxene, and, more rarely, olivine and magnetite. The groundmass is dominated by plagioclase laths and grains of clinopyroxene and ore minerals. The texture of the groundmass is intersertal, apohyalopilitic, microdoleritic, or more rarely, glomerophyric. The andesites contain no olivine phenocrysts but bear amphibole, and the dacites and rhyolites contain biotite and quartz. The groundmass texture varies from pilotaxitic to microlitic in the andesites to cryptocrystalline in the dacites and rhyolites. Plagioclase occurs in the basalts as large (up to 1.5 mm) zonal crystals, often with fused and corroded cores. Their composition varies from labradorite to andesine ($An_{74–48}$). Many plagioclase crystals show both normal and oscillatory zoning. The andesites and andesite-dacites contain, along with plagioclase, also potassic feldspar ($Or_{35}Ab_{55.9}$). The clinopyroxene phenocrysts are augite of the composition $Wo_{37.6–48.0}En_{35.4–47.3}Fs_{10.4–15.4}$. They differ from phenocrysts in lavas of the Utkholok Complex in having lower Cr concentrations and lower alkalinity. The orthopyroxene is less ferrous compared to bronzite from the lower volcanic unit and corresponds to hypersthene ($Wo_{2.5–3.3}En_{58.8–69.1}Fs_{27.7–36.1}$). Amphibole in the andesites and dacites is common hornblende. Biotite was found in the dacites and rhyolites. Quartz occurs as anhedral interstitial grains.

Basalts and basaltic andesites of the Kinkil Complex typically bear glomerophyric aggregates of orthopyroxene and clinopyroxene, plagioclase, and ore minerals, which are characteristic of orogenic volcanics (Gill, 1981). The genesis of these aggregates may be related to either the concurrent fractionation of several minerals or the decomposition of pargasitic hornblendes. The secondary alterations of the rocks are pronounced unevenly and generally insignificant.

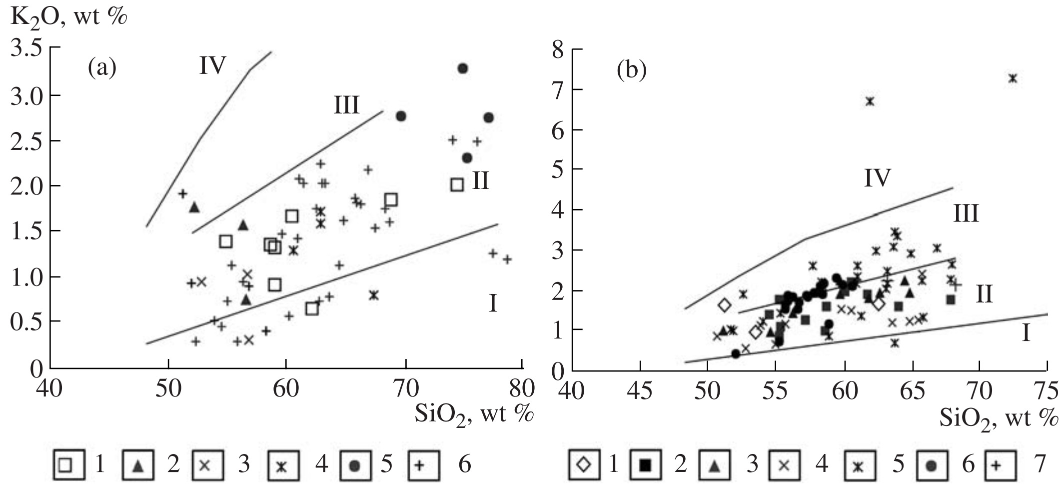

Fig. 2. K_2O–SiO_2 classification diagram for (a) Paleocene and (b) Eocene volcanic rocks in western Kamchatka.

(a) Paleocene rocks: (1) Utkholok Peninsula; (2–5) Omgon Range (Ledneva et al., 2006); (2) ilmenite gabbro-dolerites, (3) titanomagnetite gabbro-dolerites, (4) quartz microdiorites, (5) granite-aplites and biotite granite: (6) Omgon Range (D.V. Kovalenko's collection).

(b) Eocene rocks: (1) mouth of the Anadyrka River– Cape Kinkil; (2) Cape Tevi; (3) central Kamchatka Isthmus; (4) Cape Rebro – Podkagernaya Bay; (5) Mount Chernaya; (6) Cape Khairyuzova; (7) Shamanka intrusion.

Volcanic series (Peccerillo, Taylor, 1976): (I) low-potassium, (II) moderate-potassium calc-alkaline, (III) high-potassium calc-alkaline, (IV) shoshonite.

GEOCHEMISTRY

Major Elements[1]

Paleocene magmatic complexes. In terms of silicity, the Paleocene rocks compose a continuous series from basalt ($SiO_2 \geq 50$ wt %) to rhyolite. According to their ($Na_2O + K_2O$)–SiO_2 ratio (Kuno, 1966), these rocks are subalkaline (Shantser and Fedorov, 1999). In the SiO_2–FeO*/MgO and FeO*–FeO*/(FeO* + MgO) classification diagrams (Miyashiro, 1974), the composition data points of the rocks plot within the field of the calc–alkaline series. In the K_2O–SiO_2 diagram (Pecerillo and Taylor, 1976), most of the rocks fall within the field of moderately potassic calc–alkaline series, and some of the samples occur in the field of low-potassic rocks (Fig. 2).

The Paleocene volcanics are characterized by variable contents of major elements. The volcanic rocks from the Omgon Range have TiO_2 concentrations depending on the Mg# of the rocks and their SiO_2 contents. The high-Mg basaltic andesites bear TiO_2 concentrations close to 1 wt %. As the Mg# of the rocks decreases from 60 to 45, their TiO_2 concentrations increase to 2.5 wt % at practically unchanging SiO_2 concentrations, and then TiO_2 concentration in these rocks decreases to 0.4 wt % at Mg# = 10–25 and SiO_2 = 70–75 wt % (Figs. 3a, 3g, 3i). Analogous dependences of the Fe and P concentrations on the Mg# and SiO_2 concentrations were detected in rocks from the Omgon Range (Figs. 3c, 3f, 3j). The TiO_2 concentrations in rocks at the Utkholok Peninsula decreases from 1.2 wt % in the basaltic andesites to 0.5 wt % in the dacites and rhyolites (Figs. 3a, 3i). The P concentrations also decrease as the Mg# of the rocks decreases from 0.2 to 0.08 wt %. The Fe concentrations increase as Mg# of the rocks decreases from 70 to 45 and then decreases (Fig. 3h). Many of the lavas, including the andesites, are highly magnesian (~6 wt % MgO), and a few samples from the Utkholok Peninsula and Omgon Range can be classed with high-Mg andesites ($SiO_2 > 54$ wt %, Mg# > 0.50; Kelemen, 1995) (Fig. 3g).

The **Eocene magmatic complexes** also compose a continuous series in terms of SiO_2 concentration, range from basalt ($SiO_2 \geq 50$ wt %) to rhyolite, and belong to the calc–alkaline series. In the K_2O–SiO_2 diagram (Pecerillo and Taylor, 1976), the compositions of the rocks from all areas, except Mount Chernaya and Cape Khairyuzova, plot within the field of moderately potassic calc–alkaline series. The volcanics from Cape Khairyuzova are generally more potassic and group along the boundary between the high- and moderate-K calc–alkaline series, and the volcanics from Mount Chernaya cluster in the region of moderate- and high-K series (Fig. 2). The volcanic rocks of various areas also differ in TiO_2 concentrations (Figs. 4a, 4j), and the TiO_2–SiO_2 dependence of the rocks defines a broad negative trend. The compositions of volcanics from the mouth of the Anadyrka River–Cape Kinkil and from Cape Khairyuzova have the lowest TiO_2 concentrations (≤ 1 wt %), and the rocks from Cape Tevi have the high-

[1] All tables of geochemical and isotopic analyses are available from the authors via e-mail: pi_fedorov@mail.ru (Fedorov Petr Ivanovich) and dmitry@igem.ru (Kovalenko Dmitry Vyacheslavovich)

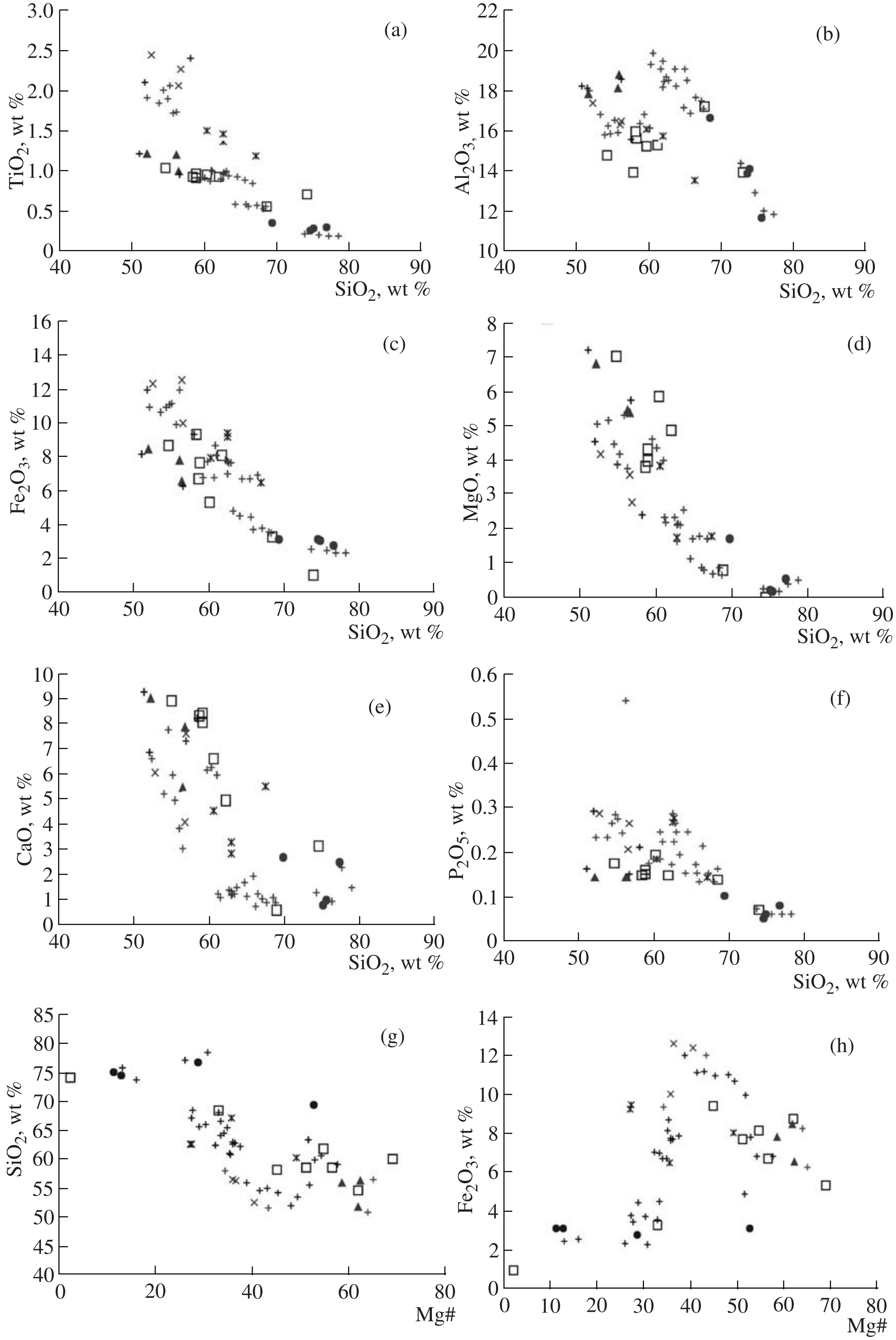

Fig. 3. Variations in the concentrations of major and trace elements in Paleocene magmatic rocks from western Kamchatka. See Fig. 2a for symbol explanations.

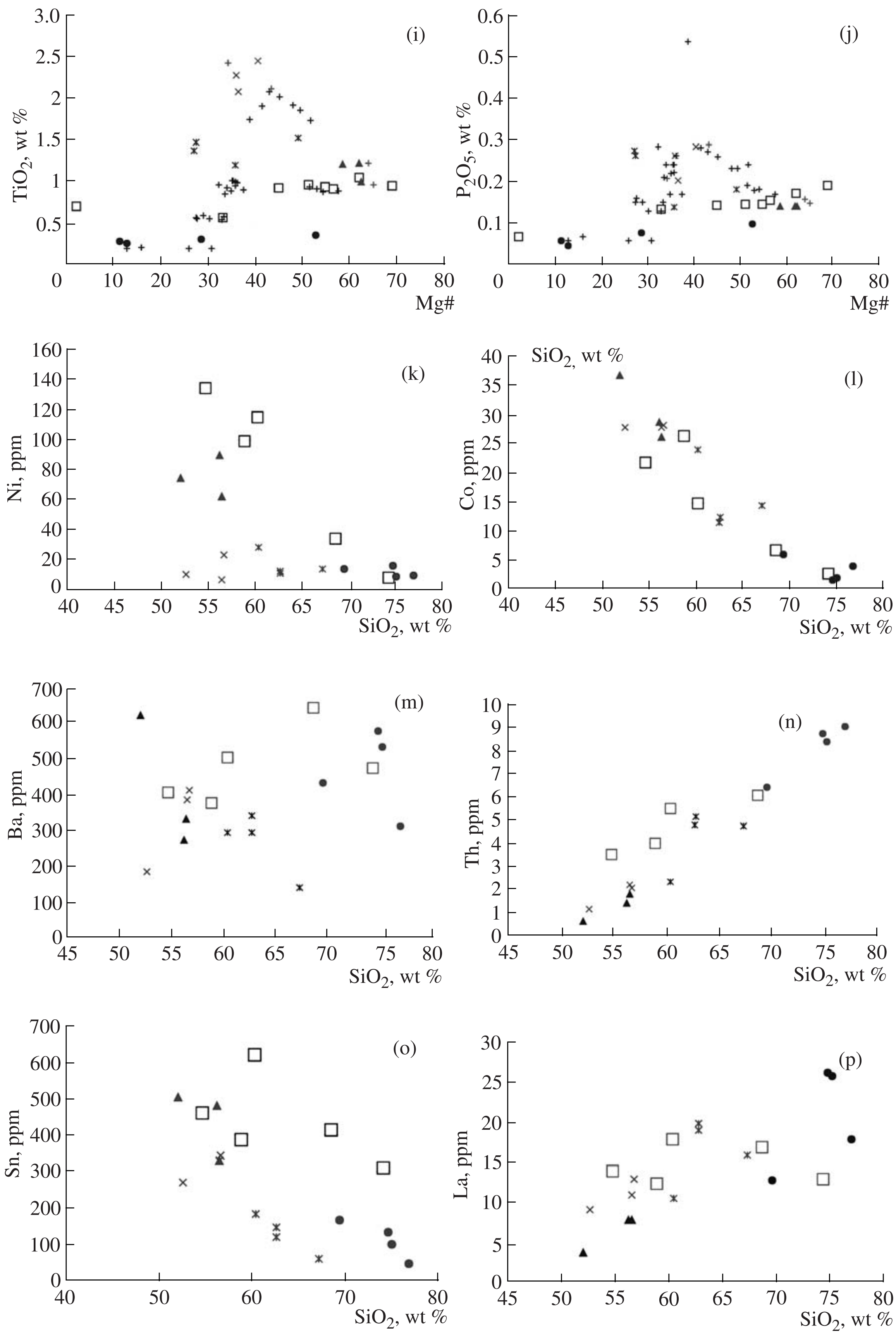
(i)
TiO2, wt %
Mg#
(j)
P2O5, wt %
Mg#
(k)
Ni, ppm
SiO2, wt %
(l)
Co, ppm
SiO2, wt %
SiO2, wt %
(m)
Ba, ppm
SiO2, wt %
(n)
Th, ppm
SiO2, wt %
(o)
Sn, ppm
SiO2, wt %
(p)
La, ppm
SiO2, wt %

Fig. 3. (Contd.).

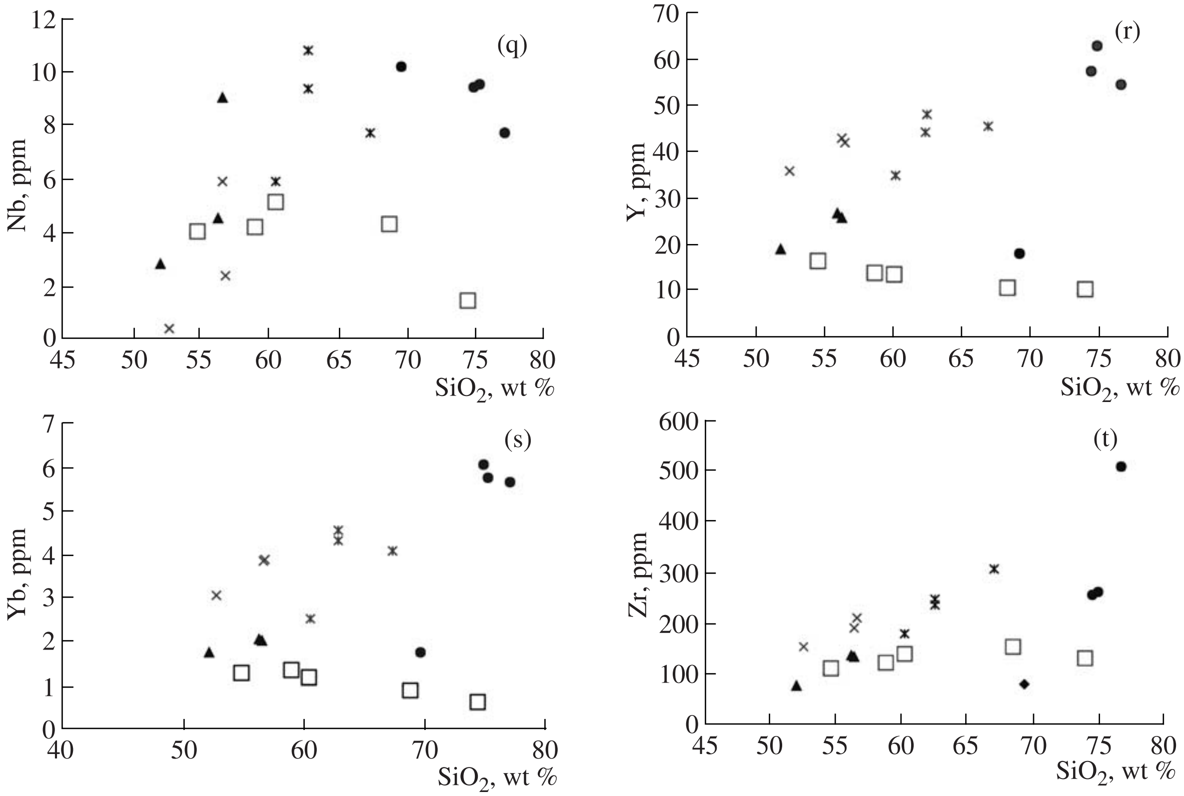

Fig. 3. (Contd.).

est TiO_2 concentrations (up to 1.4 wt %), whereas the TiO_2 concentrations in rocks from all other areas fall into the relatively Ti-rich and Ti-poor groups. The dependences of Fe_2O_3 and CaO on SiO_2 in the rocks define negatively sloped trends (Figs. 4c, 4e). The Al_2O_3 concentrations in the basalts are slightly lower than in the lavas of continental-margin belts (*Magmatic…*, 1987). The Al_2O_3 concentrations of the andesites increase and then decrease again with the transition to the dacites (Fig. 4b). Most of our study areas contain high-Mg rocks, and most of these rocks (or even all of them in Cape Khairuzova) can be regarded as high-Mg andesites (Table 2, Fig. 4i).

Trace elements

The concentrations of trace elements in the *Paleocene rocks* from Utkholok Peninsula and Omgon Range (Ledneva et al., 2006) show broad variations. The Ni and Co concentrations range form 140 to 7 and from 37 to 2 ppm, respectively. The Cr concentrations occasionally reach 230 ppm. The V contents are negatively correlated with the SiO_2 contents. The highest concentrations of these elements were detected in the high-Mg basalts and andesites.

The Th concentrations in the rocks from the Omgon Range show a strong positive correlation with the silicity of these rocks at SiO_2 concentrations from 52 to 77 wt % (Fig. 3n). Also positive but weaker correlations with the silicity of the rocks are displayed by the concentrations of Y, REE (Figs. 3p, 3r, 3s), and HFSE (Figs. 3q, 3t), whereas the Sr concentrations are negatively correlated with silicity (Fig. 3o).

The volcanics of the Utkholok Peninsula compose an individualized group and are significantly different from the rocks of the Omgon Range in having lower concentrations of HFSE, HREE, and Y (Fig. 3).

The REE and trace-element patterns of Paleocene volcanics in western Kamchatka are generally typical of suprasubduction volcanic rocks. For example, most of the primitive mantle-normalized (Sun and McDonough, 1989) patterns of the Paleocene rocks display progressive enrichment in LILE and LREE relative to HFSE, MREE, and HREE and are characterized by Ta and Nb minima (Fig. 5). A noteworthy feature of these rocks is negative Th (and also often Ba) anomalies. The relatively high-Mg gabbro-dolerites of the Omgon Range are slightly enriched in HFSE relative to MORB and depleted arc volcanics. For example, the Nb concentrations reach 9 ppm, and the rocks have no Ti minima but show Zr maxima (Ledneva et al., 2006). Analogous enrichment in Nb was also recorded in the acid low-Mg rocks from the Omgon Range, but it can largely be related to melt fractionation. The low-Mg gabbro-dolerites show insignificant enrichment in Ti and Zr at strong depletion in Nb.

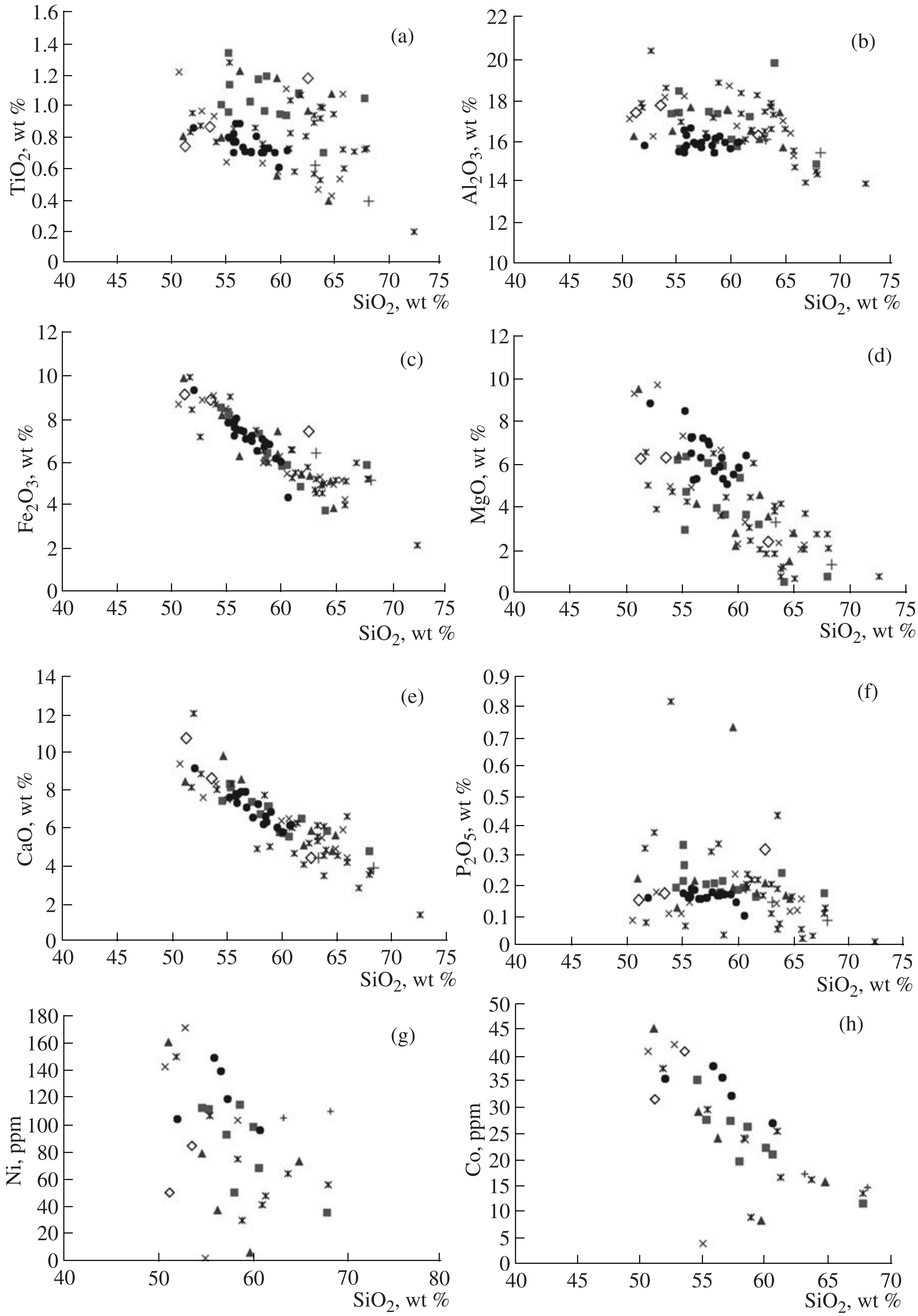

Fig. 4. Variations in the concentrations of major and trace elements in Eocene magmatic rocks from western Kamchatka. See Fig. 2a for symbol explanations.

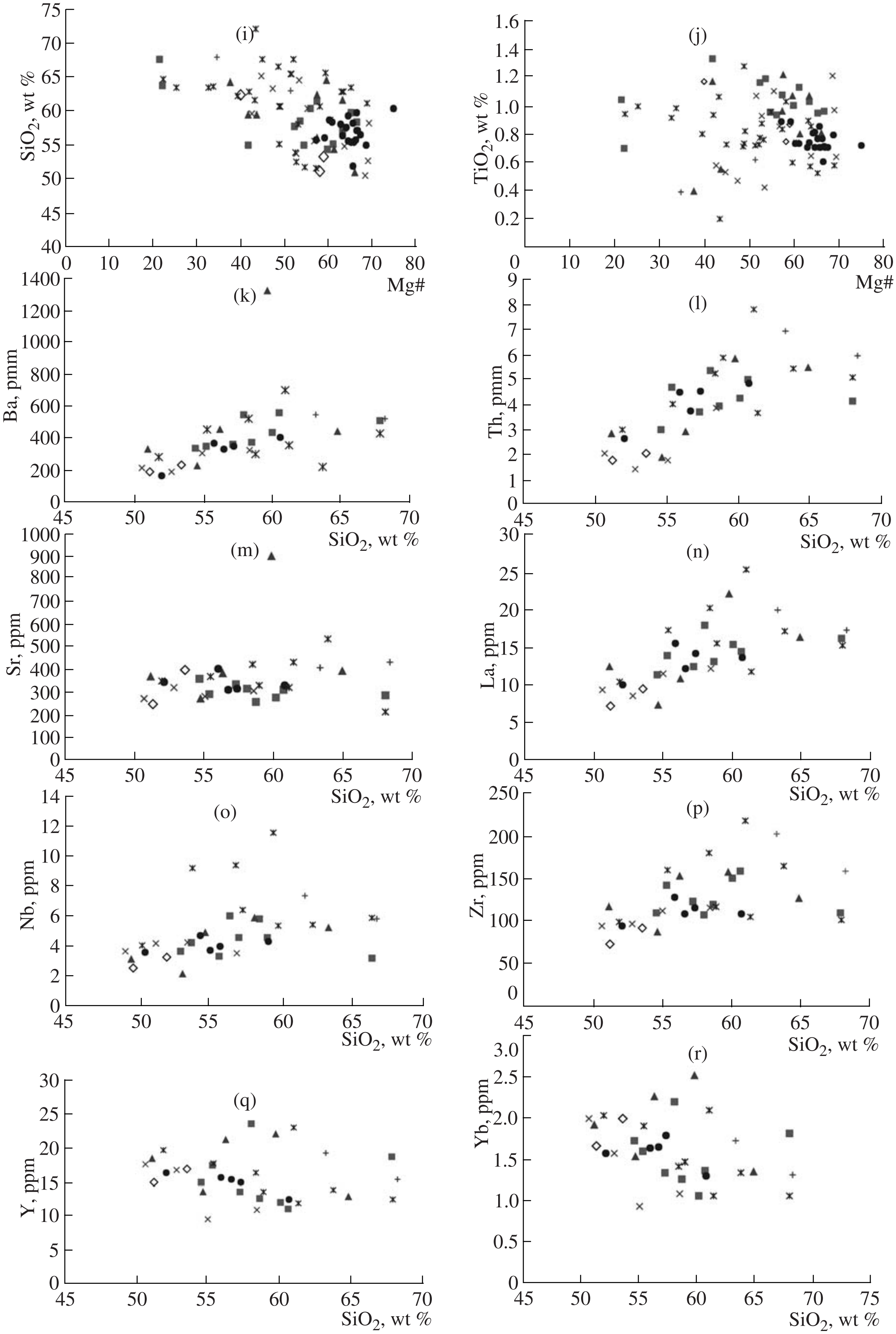
(i)
SiO2, wt %
Mg#
(j)
TiO2, wt %
Mg#
(k)
Ba, pmm
SiO2, wt %
(l)
Th, pmm
SiO2, wt %
(m)
Sr, ppm
SiO2, wt %
(n)
La, ppm
SiO2, wt %
(o)
Nb, ppm
SiO2, wt %
(p)
Zr, ppm
SiO2, wt %
(q)
Y, ppm
SiO2, wt %
(r)
Yb, ppm
SiO2, wt %

Fig. 4. (Contd.).

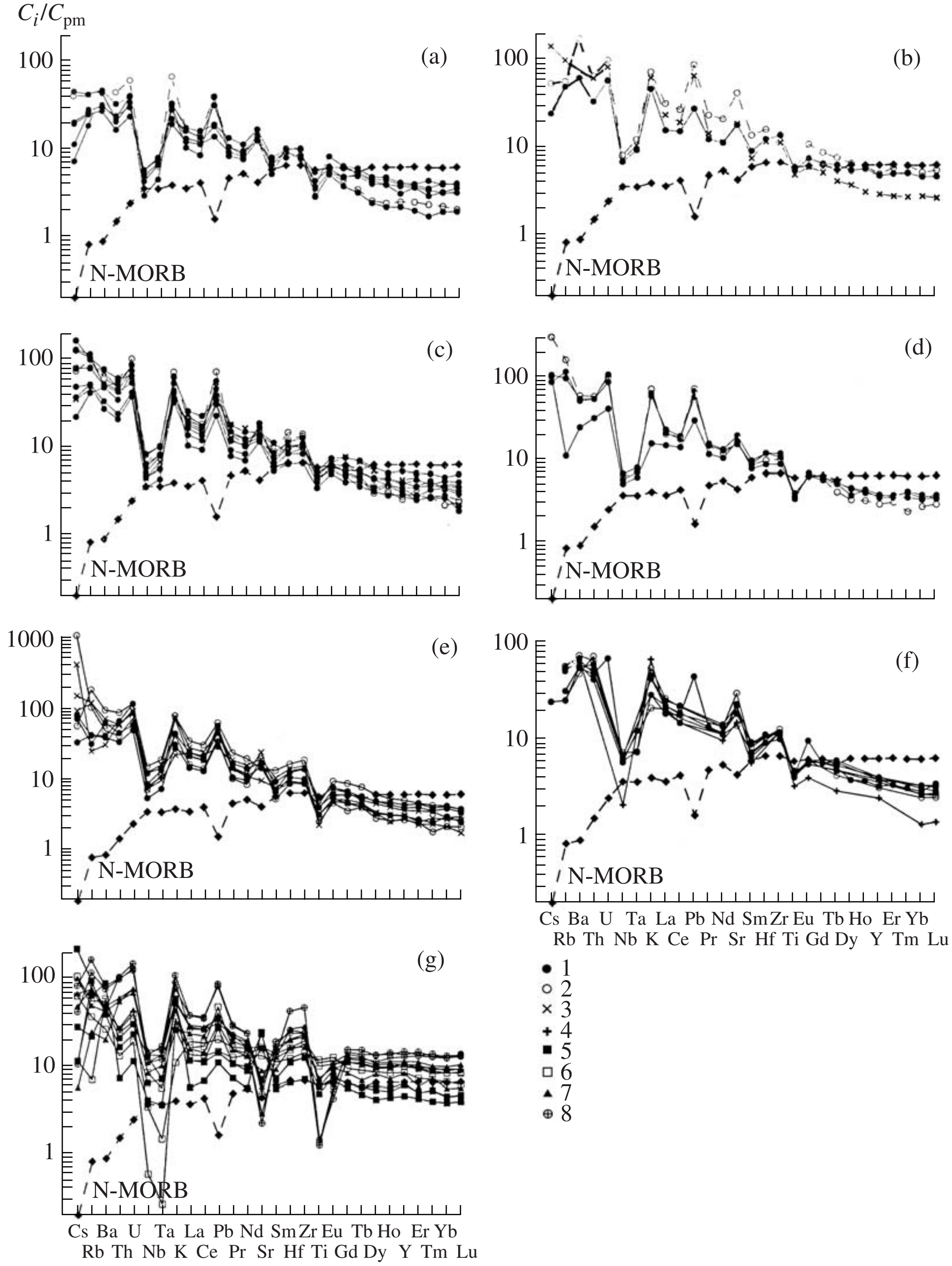

Fig. 5. Distribution of incompatible elements in Early Cenozoic magmatic rocks from western Kamchatka.
(a–g) Volcanic areas: (a) mouth of the Anadyrka River–Cape Kinkil; (b) central Kamchatka Isthmus; (c) Cape Tevi; (d) Cape Khairyuzova; (e) Mount Chernaya; (f) Utkholok Peninsula; (g) Omgon Range.
(1) Basalts and basaltic andesites; (2) andesites; (3) dacites; (4) rhyolites; (5–8) Omgon Range (Ledneva et al., 2006): (5) titanomagnetite gabbro-dolerites; (6) ilmenite gabbro-dolerites; (7) quartz microdiorites; (8) granite aplites.
Concentrations of incompatible elements in rocks are normalized to the primitive mantle (Sun and McDonough, 1989).

Some andesites and dacites from the Utkholok Peninsula show features of derivatives of adakite melts. Their La_n/Yb_n ratios range from 9 to 21, and the concentrations of Y and Yb vary form 11 to 17 and from 0.6 to 1.4 ppm, respectively. The Sr/Y ratio of the volcanics is lower than in typical adakites (27–44), but all compositions of these rocks plot within the adakite field in the Sr/Y–Y diagram

(Defand and Drummond, 1990). Two andesite samples from this group are characterized by a high-Mg composition.

The dependences of the concentrations of trace elements on SiO_2 for the *Eocene magmatic rocks* are shown in Fig. 4. Most elements first show an increase in their concentrations with the SiO_2 content increasing to 60–62 wt % and then their decrease with a further increase in the silicity. The exceptions are Y and HREE: the volcanics of Cape Tevi, central part of the Kamchatka Isthmus, Mount Chernaya, and Cape Khairyuzova display an increase in the concentrations of these elements with increasing silicity of the melts, perhaps, due to the fractionation of clinopyroxene and hornblende from the melts. The lavas from Cape Rebro–Podkagernaya Bay also exhibit an increase in the Y and HREE concentrations as the silicity of the rocks increases to 60–62 wt % SiO_2 and a subsequent decrease in the former concentrations (Fig. 4). Some samples from the Mount Chernaya area have elevated Nb concentrations (up to 10 ppm).

The spidergrams of trace elements and REE for the Eocene rocks from all of our study areas (Fig. 5) are also typical of suprasubduction rocks. Similarly to the Paleocene rocks, they are enriched in LILE and LREE relative to HFSE, MREE, and HREE. They display Ba, Th, Ta, and Nb minima. Some of the high-Mg volcanics are slightly enriched in Zr and Nb relative to MORB (central part of the Kamchatka Isthmus and the area of Mount Chernaya). The MREE and HREE patterns of these rocks are depleted relative to MORB (Fig. 5). The REE patterns show no Eu minima, which could have been indicative of plagioclase fractionation from the melt.

Some of the Mount Chernaya andesite-dacites have low concentrations of Y (12–14 ppm) and Yb (1.0–1.3 ppm) at high La_n/Yb_n ratios (11–13), which makes them similar to derivatives of adakite melts. However, similarly to the Paleocene "adakites," they are noted for lower Sr/Y ratios (35–38).

Nd ISOTOPIC COMPOSITION

The Nd isotopic composition of the *Paleocene rocks* was studied in two samples of lavas from the Utkholok Peninsula and four samples from basaltic and basaltic andesite sills with various Ti concentrations in the Omgon Range (Fig. 6a). The least fractionated gabbro-dolerite sills in the Omgon Range are characterized by positive $\varepsilon_{Nd}(T)$ values (+8.2 and +8.1), which implies that the sources of these rocks were depleted in radiogenic Nd. More fractionated varieties of these rocks have lower positive $\varepsilon_{Nd}(T)$ values (+4.9 and +6.3). The $\varepsilon_{Nd}(T)$ values of the lavas from the Utkholok Peninsula are +6.9 and +6.3.

The *Middle–Late Eocene rocks* are generally characterized by a less radiogenic Nd isotopic composition. The $\varepsilon_{Nd}(T)$–SiO_2 diagram (Fig. 6b) shows two types of the trends: (1) a clearly pronounced negative trend for all analyzed samples from Cape Khairyuzova in the central part of the Kamchatka Isthmus and, perhaps, also one sample from Cape Rebro–Podkagernaya Bay and (2) a trend nearly parallel to the abscissa for all samples from Cape Tevi and Mount Chernaya and a few samples from Cape Rebro–Podkagernaya Bay. Analogous dependences of the isotopic composition of the Eocene rocks are also shown by their Mg#.

The rocks defining the former trend (Fig. 6, isotopic succession *1*) show the most contrasting $\varepsilon_{Nd}(T)$ values equal to +7.2 and –1.5. This trend is extrapolated to the MORB composition in the region of depleted sources and to the composition of the Late Cretaceous–Early Cenozoic sialic subarkose quartz-feldspathic sediments of Kamchatka in the region of enriched sources (Figs. 6b, 6c). For the rocks defining the other trend (Fig. 6, isotopic succession *2*), the $\varepsilon_{Nd}(T)$ values range from +3.3 to +5.4. Note that this trend also approximates the moderate-Ti rocks, while the former trend includes Ti-poorer rocks, except a single sample, which is most strongly depleted in radiogenic Nd. The high-Mg andesites of the complex are involved in both trends (Fig. 6b).

DISCUSSION

The mineralogy of the Paleocene and Eocene magmatic rocks from the continental margin of Kamchatka and the distribution of major components in them (low Ti and high Al concentrations) and trace elements (their enrichment in LILE and LREE relative to HFSE, MREE, and HREE, clearly pronounced Ta–Nb minima and Pb maxima) testify that the rocks were formed in a suprasubduction environment. Below we analyze the types of the mantle sources of the Paleocene and Eocene magmas, the degrees of their contamination with sialic material, and the possibility of their derivation from rocks of subducted lithospheric slabs, as well as the fluid regime of the derivation of these magmas.

Mantle Source and Indications of the Contamination of the Mantle Magmas with Sialic Material

Paleocene complexes. The high positive values of $\varepsilon_{Nd}(T)$ (+8) for the least fractionated rocks from the Omgon Range suggest their relation to a depleted mantle source. A somewhat lower $\varepsilon_{Nd}(T)$ from +6 to +7, was shown by two samples (andesite and rhyodacite) of lavas in the Utkholok Peninsula volcanic complex. Since the $\varepsilon_{Nd}(T)$ values of the Utkholok rocks with various degree of fractionation are similar, it is reasonable to suggest that the magmatic melts were not strongly contaminated with crustal material and characterize the isotopic composition of the mantle source. Fractionated rock varieties in sills at the Omgon Range have lower ε_{Nd} relative to less fractionated varieties. Because the rocks of the sills exhibit a correlation between their

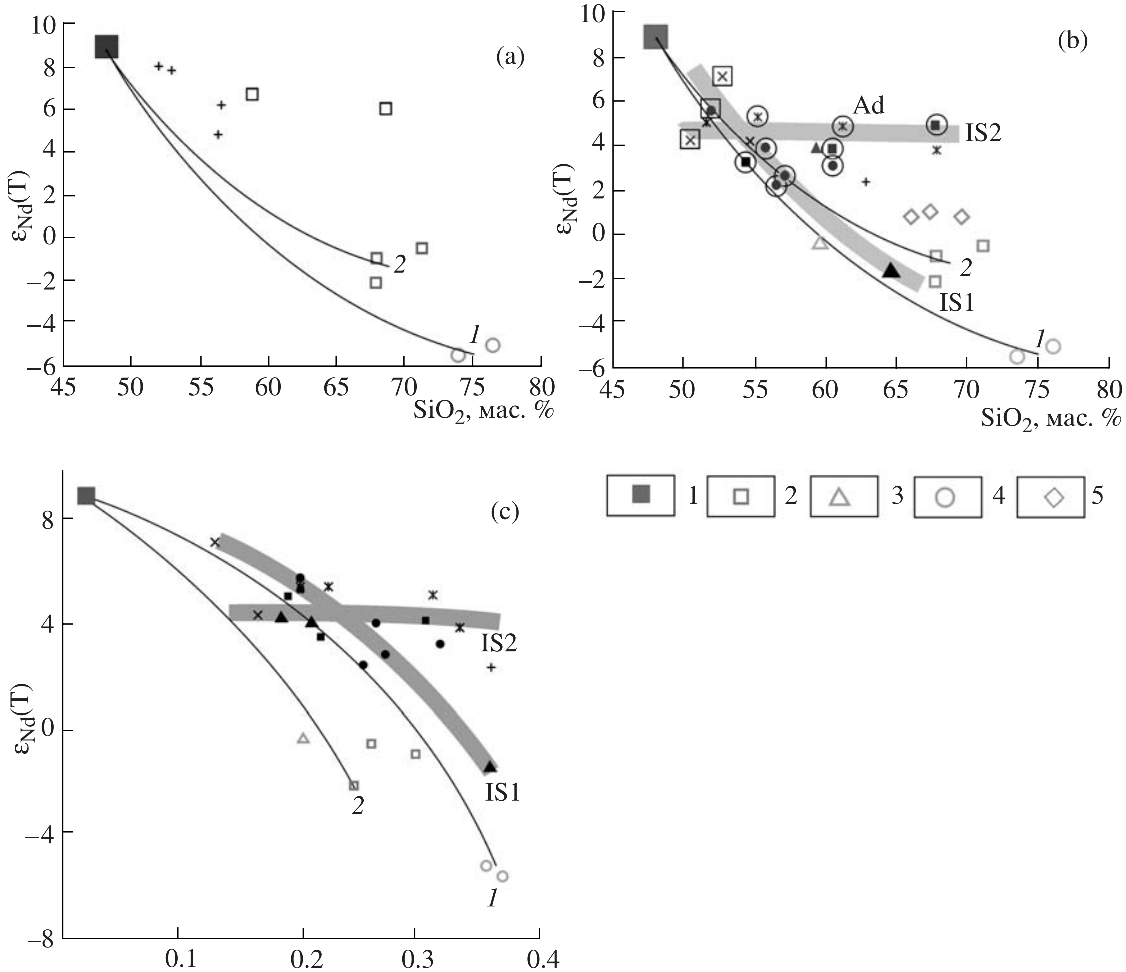

Fig. 6. Dependences (a, b) $\varepsilon_{Nd}(T)$–SiO_2 and (c) $\varepsilon_{Nd}(T)$–Th/Nd for (a) Paleocene and (b, c) Eocene magmatic rocks in Kamchatka. (1) MORB; (2–5) quartz–feldspar terrigenous rocks: (2) Omgon Range, basin of the Rassoshina River, (3) Utkholok Peninsula, (4) central Kamchatka Isthmus, (5) Karaginskii Island. IS1 and IS2 are isotopic successions 1 and 2; Ad—adakite; 1 and 2 mixing lines calculated for MORB compositions and various groups of quartz-feldspathic sediments. Symbols in squares are rocks containing >9 wt % MgO, symbols in circles are rocks with >6 wt % MgO. Other symbols are as in Fig. 2.

$\varepsilon_{Nd}(T)$ values and SiO_2 concentrations, the magmatic melts that produced these sills may have been contaminated with sialic material, for example, the host quartz-feldspathic sediments. Figure 6a shows that the composition of rocks from the sills plot above the mixing line calculated for a depleted MORB-like source and the quartz-feldspathic sediments of western Kamchatka. This is likely explained by the fractionation of the magmatic melts that formed the Omgon sills.

Eocene complex. As was demonstrated above, the rocks of the Eocene complex display two types of correlations of their Nd isotopic composition and SiO_2 concentrations (Fig. 6b, isotopic successions *1* and *2*). The least fractionated (MgO = 9.7 wt %) rocks (first trend) have the highest $\varepsilon_{Nd}(T)$ values (+7.2), which characterize the depleted mantle source.

The strong negative correlations between $\varepsilon_{Nd}(T)$ and SiO_2 demonstrate that the mantle island-arc magmas were likely contaminated with sialic rocks with low ε_{Nd}. Inasmuch as trend *1* is extrapolated to the compositional region of the Late Cretaceous–Early Cenozoic quartz-feldspathic subarkose sedimentary rocks, which compose the basement for the Early Cenozoic volcanic complexes, it is reasonable to suggest that these rocks were the contaminant of the Eocene suprasubduction magmas. The calculated mixing lines in $\varepsilon_{Nd}(T)$–SiO_2 and $\varepsilon_{Nd}(T)$–Th/Nd diagrams (Fig. 6) show that the origin of the rocks with the lowest $\varepsilon_{Nd}(T) = -1.5$ requires 40 to 50% contamination with quartz-feldspathic sediments. Conceivably, these sediments hosted magmatic chambers with the suprasubduction melts and were gradually partly melted by them.

The second trend approximates all of the analyzed compositions of rocks from Cape Tevi and Mount Chernaya and a few samples from Cape Rebro–Podkagernaya Bay. The volcanics from Cape Tevi show weak positive correlations between $\varepsilon_{Nd}(T)$ and SiO_2, and the volcanic rocks from the Mount Chernaya area display a weak negative correlation. The second trend is generally almost parallel to the abscissa at SiO_2 contents from 50 to 67 wt %. The $\varepsilon_{Nd}(T)$ values of this trend vary from +3.3 to +5.4 and display mild enrichment of source in radiogenic Nd. The least fractionated sample (SiO_2 = 50.5 wt %, MgO = 9.3 wt %) from this section is characterized by $\varepsilon_{Nd}(T)$ = +4.3. There may be two possible explanations of these $\varepsilon_{Nd}(T)$ – SiO_2 correlations. First, this could be a consequence of insignificant contamination with sialic material. In this situation, the acid sialic material contaminating the lavas should have been characterized by $\varepsilon_{Nd}(T)$ close to +3. As follows from available data on the isotopic composition of Kamchatkan complexes (Kovalenko et al., 2005; Kovalenko, unpublished data), the pre-Eocene volcanic rocks include practically no such varieties. Second, the magmatic rocks defining trend *2* could have not been contaminated by crustal sialic material, and their Nd isotopic composition was related to the enrichment of the mantle source of the magmas. It should be emphasized once again that all rocks defining this trend are richer in Ti than the rocks of trend *1*, and some lavas from the Mount Chernaya area are slightly enriched in Nb. The Eocene lavas of Kamchatka defining these two correlations generally show no significant differences in their HFSE contents. The second scenario seems to be more probable. If it realistically describes the actual situation, the Eocene magmatic rocks of Kamchatka were derived from various mantle sources, ranging from depleted, which generated high-Mg lavas of the first isotopic trend, to slightly enriched, with $\varepsilon_{Nd}(T)$ close to +3 and +5 (trend *2*).

We cannot rule out that the rocks of trend *2* could be produced by the mixing of magmas from mantle sources depleted and enriched in radiogenic Nd. For example, the high-Mg lavas with $\varepsilon_{Nd}(T)$ = +3 and Nd = 12 ppm belonging to trend *2* could be formed by the mixing of 83% magma from a depleted source [Nd = 7.3 ppm, $\varepsilon_{Nd}(T)$ = +9)] and 17% magma from an enriched source like OIB [Nd = 38.5 ppm, $\varepsilon_{Nd}(T)$ = –3)]. Since the Eocene magmatic rocks depleted in radiogenic Nd occur in the northern and southern parts of the Kamchatka Peninsula, it is highly probable that the mantle beneath much of the Early Cenozoic continental margin of Kamchatka was heterogeneous and included depleted and weakly enriched domains.

Most of the *Paleocene* and *Eocene* high-Mg volcanics in the continental margin of Kamchatka are depleted in REE and Y (Fig. 5), a feature usually explained by the presence of garnet in the magmatic source (Defant and Drummond, 1990; Kelemen, 1995; and others). Figure 7 shows calculated lines of the equilibrium partial melting of garnet and spinel lherzolites (Sajona et al., 2000). As can be seen, the data points of the variably fractionated Paleocene volcanics from the Omgon Range lie on the melting line of spinel lherzolite, whereas most lavas from the Utkholok Peninsula are compositionally close to adakites and cluster near the melting line for garnet lherzolite or lie above this line. Some of the Eocene rocks plot on the melting line of model garnet lherzolite, and some of them lie above this line, similarly to the Utkholok lavas. All of the basalt compositions, including the lavas with MgO > 9 wt % and a few compositions of the least fractionated or contaminated high-Mg andesites cluster around the melting line of garnet lherzolite. The data points above the melting line of garnet lherzolite belong mostly to fractionated rocks, adakite, and high-Mg andesites. In this association, the high-Mg andesites of Cape Khairyuzova are significantly contaminated with quartz-feldspathic sediments. Obviously, the rocks plotting on the melting line of garnet lherzolite and above it are variably depleted in Yb relative to LREE. This was most probably caused by amphibole and clinopyroxene fractionation from the melt.

It is thus established that the Paleocene and Eocene magmatic rocks were derived from either garnet-bearing or garnet-free sources. The *Paleocene* rocks of the Omgon Range were melted from a garnet-free source, whereas the adakites of the Utkholok Peninsula were derived from a garnet-bearing source. All of the *Eocene* rocks (basalts, high-Mg andesites, and adakites) were derived from garnet-bearing sources. The basic Eocene and Paleocene melts were likely produced by the melting of peridotites in the mantle wedge (Gill, 1988): spinel lherzolites (Paleocene sills of the Omgon Range), at depths of less than 60 km, and garnet lherzolites (Eocene basalts), at depths of no less than 60 km (stability facies of garnet) (Fig. 7). The genesis of the adakites and high-Mg andesites was likely related to the melting of subducted oceanic crustal material (Defant and Drummond, 1990; Kelemen, 1995; and others).

Fluid Regime

The activity of fluids in suprasubduction zones is estimated from the concentrations of elements that can be mobilized by fluids, such as K, Rb, Ba, Sr, Pb, U, and Cs. The concentrations of all of these elements in the Paleocene and Eocene suprasubduction magmatic rocks of Kamchatka are much higher than in MORB, a fact suggesting the involvement of fluids in the generation of the magmas. In the Ba/La–Th/La (Fig. 8) diagram, the compositions of the least fractionated Paleocene and Eocene lavas from Kamchatka fall within the fields of island arc rocks. The Ba/La ratios of the Paleocene rocks vary from 30 to 40, and reach as high as 160 in only one sample; these ratios of the Eocene lavas range from 20 to 30. Similar values of this ratio of the Paleocene and Eocene lavas in Kamchatka testify that the suprasubductional reworking of the mantle wedge of the Early Cenozoic continental margin in Kamchatka took place at a similar fluid regime.

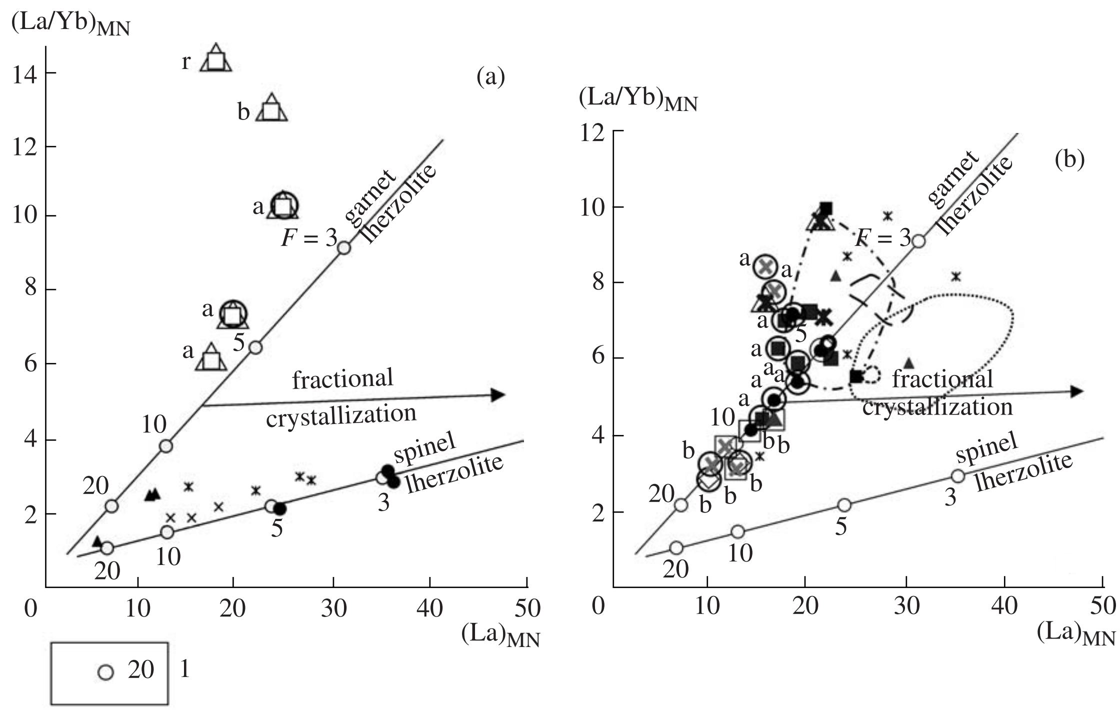

Fig. 7. $(La/Yb)_{MN}$–La_{MN} diagram (Sajona et al., 2000) for (a) Paleocene and (b) Eocene lavas of Kamchatka.

(*1*) Melt compositions corresponding to various degrees of lherzolite partial melting *F* (%). The diagram shows lines of equilibrium partial melting of garnet lherzolite (59% olivine, 15% orthopyroxene, 20% clinopyroxene, and 6% garnet) and spinel lherzolite (60% olivine, 20% orthopyroxene, 14.5% clinopyroxene, 5.5% spinel). The fractional crystallization of the magmatic melts increases the La_{MN} value at an insignificant change in $(La/Yb)_{MN}$ (Sajona et al., 2000). Symbols in squares correspond to components with MgO > 9 wt %, symbols in circles are compositions with MgO > 6 wt %, and those in triangles are adakites. Rocks: a—andesites, b—basalts, d—dacites, r—rhyolites. Other symbols are as in Fig. 2.

COMPARISON OF CHARACTERISTICS OF THE PRE- AND POSTACCRETION MAGMATISM IN THE CONTINENTAL MARGIN OF KAMCHATKA

Early Eocene stage of tectonic accretion. The Early Eocene stage of tectonic accretion in Kamchatka was related to the collision of the Late Cretaceous–Early Cenozoic Achavayam–Valagin island arc with the continental margin. Our date presented above indicate that the Paleocene (preaccretionary) and Mid–Late Eocene (postaccretionary) magmatism in the Kamchatkan continental margin show similarities in some of their characteristics:

(1) the Paleocene and Eocene magmatic complexes show suprasubduction geochemical features;

(2) the Paleocene and Eocene magmatic rocks include varieties produced by melts that were generated by the melting of metasomatically recycled rocks of the mantle wedge and, perhaps, also by adakite melts produced by the melting of adakites in the subducted slab;

(3) the Paleocene and Eocene magmas of the Kamchatkan continental margin are characterized by relatively broad (compared to the isotopic compositions of the Kamchatkan Cretaceous and Cenozoic rocks [Kovalenko et al., 2005; Kepezhinskas et al., 1997; Volynets et al., 1999, 2006; and others)] variations in the Nd isotopic composition. Conceivably, the magmas were derived from heterogeneous mantle sources and were contaminated with sialic material [with low $\varepsilon_{Nd}(T)$ values].

At the same time, the Paleocene and Eocene magmatism in the continental margin of Kamchatka show certain differences. For example, the mantle sources of the Paleocene magmatic rocks of the Omgon Range were in the stability field of spinel-bearing lherzolites (Ledneva et al., 2006), while the sources of the Eocene rocks were in the field of garnet-bearing peridotites. The degree of depletion of the mantle sources in radiogenic Nd and the contamination of the mantle melts with sialic material are also different for the Paleocene and Eocene complexes. All of these differences can be explained by the limited amount of available materials on the Paleocene continental-margin complexes, which were mapped only in two areas in Kamchatka.

It can be concluded that the Early Eocene stage of tectonic accretion did not result in any principal changes in the magmatic processes at the continental margin of Kamchatka.

Pliocene stage of tectonic accretion. The Pliocene (6–1 Ma) stage of accretion in Kamchatka was related to the docking of the Kronotskii island arc to the conti-

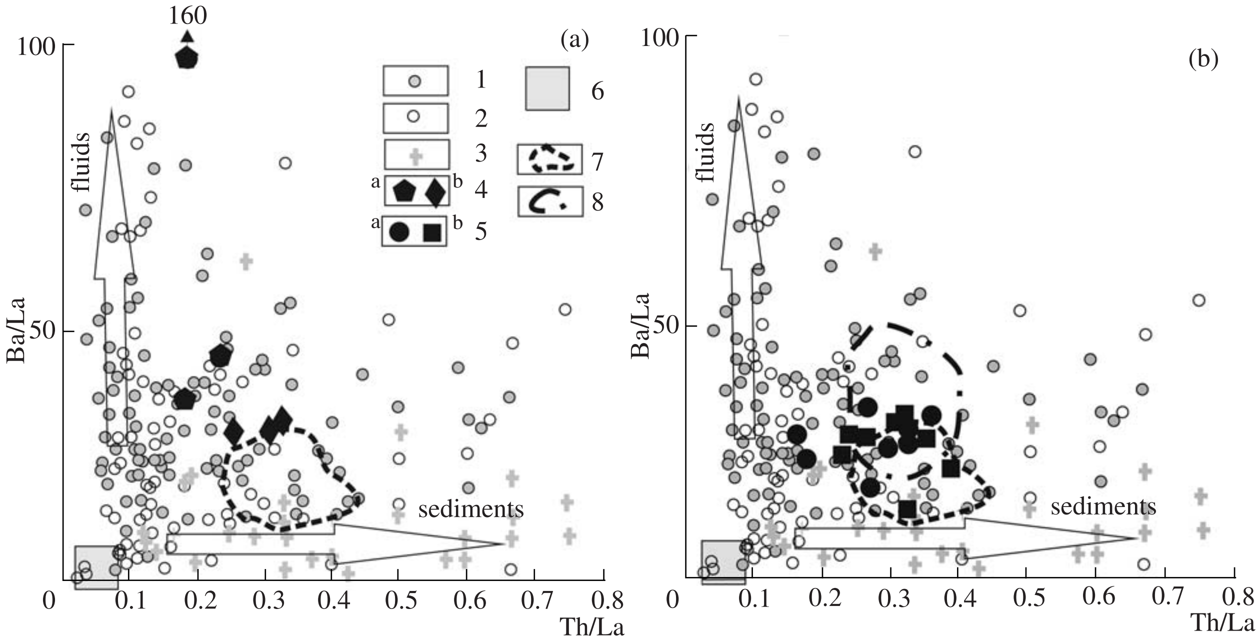

Fig. 8. Ba/La–Th/La diagram (Kelemen, 1995) for (a) Paleocene and (b) Eocene magmatic rocks of Kamchatka.
(1–3) Rocks from modern island arcs: (1) ensimatic arcs, (2) ensialic arcs, (3) boninites; (4) compositions of Paleocene magmatic rocks of Kamchatka: (a) Omgon Range, (b) Utkholok Peninsula; (5) Eocene magmatic rocks of Kamchatka: (a) rocks belonging to isotopic succession 1, (b) rocks belonging to isotopic succession 2; (b) MORB compositions; (7, 8) compositions of quartz-feldspathic terrigenous rocks of Kamchatka: (7) Late Cretaceous, (8) Eocene. Arrows along the abscissa and ordinate show, respectively, the contribution of sedimentary material and fluids to magmatic processes in the subduction zones.

nental margin. Fragments of this arc are now contained in structures of the Kamchatskii and Kronotskii peninsulas (Levashov, 1999; Shapiro and Lander, 2003). Magmatism of that accretion stage was restricted to the Miocene–Quaternary Central Kamchatka Volcanic Belt and, judging from the radiological dates (14–5 Ma), to some areas in the Eastern Kamchatka Belt (Volynets et al., 1999; and others). Postaccretion magmatism formed Late Pliocene–Quaternary lavas in the Eastern Kamchatka Volcanic Belt, although magmatism continued after the accretion of the Kronotskii arc until the Holocene in most areas of the Central Kamchatka Belt (Volynets, 2006) and remains active until nowadays in the southern part of the belt.

The isotopic and geochemical characteristics of Miocene–Quaternary rocks in the Central Kamchatka Volcanic Belt (Kepezhinskas et al., 1997; Fedorov and Shapiro, 1998; Volynets et al., 1999; Ivanov et al., 2004; Perepelov, 2005; Volynets, 2006; and others) notably differed from those of the Paleocene–Eocene rocks. The most reliable data were obtained on its Quaternary evolutionary stage (Volynets, 2006). The older Miocene–Pliocene stages were examined only fragmentarily in various areas within the Payalpan volcanic structure in the southern part of the belt (Ivanov et al., 2004), near Tekletunup volcano, in the Ozernovskii district in the central part of the belt (Perepelov, 2005; Volynets, 2006), and in the Kamchatka Isthmus in the northern part of the belt (Fedorov and Shapiro, 1998; Kepezhinskas et al., 1997). All of the areas show similar tendencies: the Miocene–Early Pliocene sequences are dominated by suprasubduction rocks depleted in HFSE and enriched in radiogenic Nd, whereas the younger (up to Holocene) sequences consist mostly of rocks enriched in HFSE and radiogenic Nd, which were produced by the mixing of suprasubduction and OIB-like magmas, or only the latter. The rocks generated by the adakite melts were found only in the north of the belt (Kepezhinskas et al., 1997). No indications of magma contamination with sialic material were detected.

The Miocene–Early Pliocene (preaccretion) magmatism in the Eastern Kamchatka Belt formed HFSE-enriched OIB-like melts, which were derived from sources of composition varying from depleted to enriched ($\varepsilon_{Nd}(T)$ = +2.8, $^{87}Sr/^{86}Sr$ = 0.70442; Volynets et al., 1999). The younger (postaccretion) Late Pliocene–Quaternary and modern magmatism in the belt is characterized by typically suprasubduction composition: the magmatic rocks are depleted in HFSE and enriched in radiogenic Nd. No adakite melts were found in the belt, and no evidence of melt contamination with crustal material were found (Koloskov, 2001; Churikova et al., 2001; Kerstig and Arculus, 1995; Turner et al., 1998; Volynets et al., 1999; and others).

This leads us to the conclusion that continental-margin magmatism in Kamchatka evolved from the Paleocene to the present time. It retained many of its features in the Paleocene–Eocene, in spite of the extensive tectonic accretion in the Early Eocene. The Miocene preaccretion stages differed from the Paleocene–Eocene stage in having other compositions of the mantle magma sources: the magmatic sources of the Miocene suprasubduction magmas were depleted in radiogenic Nd and enriched in radiogenic Sr [ε_{Nd} from +7 to +8 and $^{87}Sr/^{86}Sr$ = 0.703–0.704), while the sources of the within-plate magmas were enriched in HFSE. The Late Pliocene–Quaternary postaccretion magmas of the eastern Kamchatka Belt are noted for the absence of within-plate OIB-like components.

Various explanations can be proposed for the revealed features of continental-margin magmatism in Kamchatka. For example, it was hypothesized (Shantser and Fedorov, 1999) that the Paleocene and Eocene magmas were derived in relation to rifting and the associated partial decompressional melting of the mantle source, which had been metasomatically recycled during older subduction processes. Because of this, collision processes could merely insignificantly affect the character of the magmatism. The Miocene–Quaternary volcanism was likely controlled by the activity of simultaneous subduction beneath the continent. Hence, the differences in magmatism before and after the accretion of the Kronotskii island arc could be related to the restyling of subduction zone beneath the Asian margin. Other possible models may assume that the Paleocene–Eocene and Miocene–Quaternary continental-margin magmatism in Kamchatka was related to coeval subduction zones (Kovalenko, 2003). In this case, the Early Eocene accretion event should have not resulted in the transformation of subduction beneath the continent. In any event, all of these models can be validated only on the basis of additional studies.

CONCLUSIONS

(1) It was determined that continental-margin magmatism in Kamchatka evolved from the Paleocene to the present time.

(2) It retained many of its characteristics in the Paleocene–Eocene, in spite of active accretion in the Early Eocene. The Paleocene and Middle–Late Eocene magmatic complexes are characterized by features of suprasubduction volcanism. The magmatic melts were derived from isotopically heterogeneous (depleted and variably enriched, perhaps, as a consequence of mixing with within-plate melts) mantle sources, which could be variably reworked by adakite melts and were likely contaminated with quartz-feldspathic sialic sediments.

(3) The Miocene preacretion magmatic stage differed from the Paleocene–Eocene one in having other geochemical and isotopic compositions of the mantle sources of the melts: the magmatic sources of the Miocene suprasubduction magmas contained no compositions with a low $\varepsilon_{Nd}(T)$ and high $^{87}Sr/^{86}Sr$, and the sources of the within-plate magmas were enriched in HFSE.

(4) The Late Pliocene–Quaternary postaccretion magmas of the Eastern Kamchatka Belt are distinguished for the absence of within-plate OIB-like components.

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