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Late Cretaceous–Paleocene Magmatic Complexes of Central Kamchatka: Geological Settings and Compositional Features

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Abstract—A comparative analysis of the Late Cretaceous–Paleocene volcanism was conducted for four areas of Kamchatka: the Pravyi Tolbachik–Levaya Shchapina–Adrianovka interlfuve (the northern part of the Tumrok Range), the area south of the Ipuin River and Mt. Khrebtovaya (the northern Valaginsky Range), the area of Mt. Savul'ch (the upper reaches of the Kitil'gina River, northern Valaginsky Range), and the Kirganik–Levaya Kolpakova interfluve (the Sredinny Range). New petrochemical, geochemical, and isotopic data on the volcanic rocks from these areas are reported. The examination of this material, together with already published data on volcanic and plutonic rocks of similar composition and age, made it possible to establish the following: (1) the considered basaltoids are ascribed to the subalkali basalt–trachyandesite series with transition toward a meymechite–picrite rock association; (2) the alkali content in the rocks of the Valaginsky–Tumrok–Sredinny ranges increases simultaneously with the increase of the Rb content, while the contents of HFSE and radioactive elements decrease and then again increase. Two trends are identified in the Yb_n–Ce_n diagram: a positive trend spanning most of the volcanic and plutonic rocks and a negative trend defined by the data points of the meymechite–picrite association. The first trend reflects the rock evolution during crystallization differentiation, while the second trend was produced by different degrees of melting of initial protolith. The possible geodynamic reconstructions of this volcanism are discussed as well.

Key words: volcanics, meymechite, picrite, basalt, petrochemistry, geochemistry, isotopy, Kamchatka Peninsula.

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INTRODUCTION

This paper continues a series of publications devoted to the petrological–geochemical study of the Upper Cretaceous–Paleocene volcanogenic rocks of Kamchatka. The great body of new material and the comparative analysis of the volcanic activity in different areas of this large region made it possible to revise its geodynamic interpretation in the framework of the relevant problem of studying the ocean–continent transition zone. The first paper (Kovalenko et al., Geokhimiya, in press) was dedicated to the northern cross-section of the region, including the areas of Karaginsky Island, the Kumroch Range, the basins of the Belaya, Levaya Lesnaya, and Tikhaya rivers, and a site in the Palana district.

In this paper, we consider four areas: the Pravyi Tolbachik–Levaya Shchapina–Adrianovka interfluve (the northern part of the Tumrok Range), the south of the Ipuin River–Mt. Khrebtovaya area (the northern Valaginsky Range), the Mt. Savul'ch area (the upper reaches of the Kitil'gina River, northern Valaginsky Range), and the Kirganik–Levaya Kolpakova interfluve (the Sredinny Range).

The considered areas have been studied to different extents during state geological survey and numerous thematic works: the Eastern Kamchatka Zone [4, 5, 9, 13, 14, 20, 23] and the Central Kamchatka zone [15–19]. At the same time, numerous problems concerning the chemical composition of magmatism of these areas and its geodynamic interpretation remain controversial or have been modified during accumulation of new factual material. Most researchers emphasize that the compositional specifics of this volcanism is difficult to explain in the frameworks of the known geodynamic settings. Its characteristic feature is the presence of high-Mg rocks (picrites, meymechites) in East Kamchatka and alkali basaltoids among the volcanic products of all the considered areas.

The nomenclature of the ultrabasic rocks and their relations with basic rocks are strongly debated. In the first works devoted to the Kamchatka ultrabasic rocks, they were described as meymechites [8, 21]. Two directions were outlined in their subsequent study: (1) these rocks were distinguished as independent picritic series [9] or unusual member of high-K island arc magmatic spectra [23]; (2) the ultrabasic high-K rocks were continued to be called meymechites. Together with the

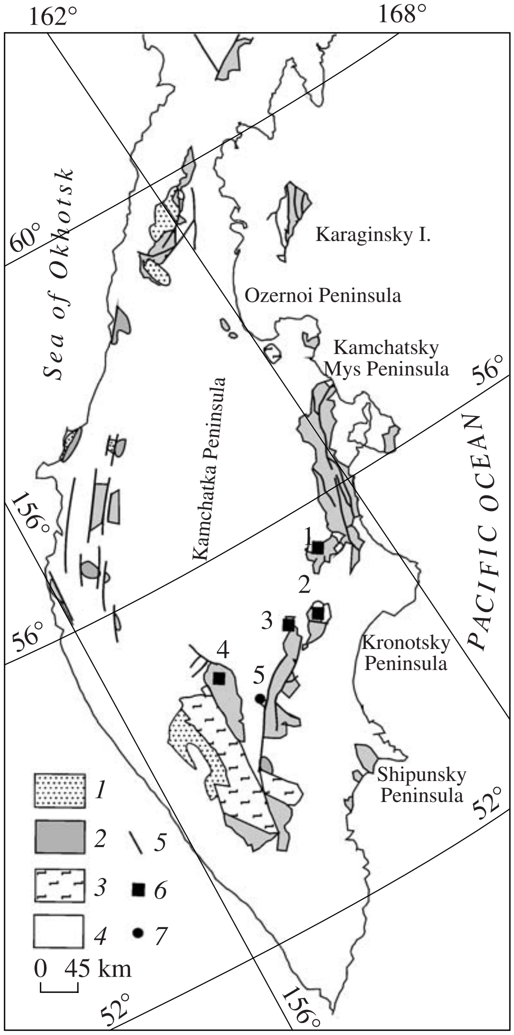

Fig. 1. Areas of detailed geological and isotopic-geochemical studies.

(*1*) Upper Cretaceous–Lower Paleogene mainly sandy-clayey and silty rocks with intercalations of tuffaceous material; (*2*) Late Cretaceous–Early Paleocene mainly volcanogenic and more rarely siliceous–volcanogenic and volcanogenic–sedimentary rock complexes; (*3*) metamorphic complex of the pre-Cretaceous basement; (*4*) Late Cenozoic rocks; (*5*) tectonic disruptions; (*6–7*) areas of detailed studies: (1) Pravyi Tolbachik–Levaya Shchapina rivers (northern part of the Tumrok Range), (2) Ipuin River–Mt. Khrebtovaya (northern part of the Valaginsky Range), (3) Mt. Savul'ch (upper reaches of the Kitil'gina River, northern part of the Valaginsky Range), (4) Central Kamchatka zone (Kirganik–Levaya Kolpakova rivers (Sredinny Range), (5) Sharomsky Cape, the study area of V.S. Kamenetsky (comparative material).

associated picrites and K–Na basic rocks, they were united in the Valaginsky alkali-ultrabasic complex [13].

The subalkali and alkali volcanic rocks that developed in the central part of the Sredinny Range of Kamchatka (the Kirganik Formation), together with plutonic rocks of the same age, were distinguished as the Late Cretaceous–Paleogene trachybasalt–gabbro–syenite formation [16]. The wide abundance of coeval alkali rocks in Northern and Central Kamchatka, the Lesser Kuriles, and on Hokkaido Island gave grounds to unite them into a common alkali province [6]. However, the genetic affinity of the Late Cretaceous–Paleocene basaltoids of the Eastern Ranges of Kamchatka and, hence, the character of the transverse zoning remain unclear. Based on the major- and trace-element composition, they were subdivided into the following rock associations: the Valaginsky alkali ultrabasic–basic complex [13]; the shoshonite–latite [10], tholeiitic picrite–basalt–andesite [20], and calc-alkaline series [11] of the Valaginsky Range; and the high-K island-arc series of the Tumrok salient [5].

The endogenic regimes of the tectonic setting of this magmatism are also ambiguously interpreted. The most popular concept is accretionary tectonics, which suggests a thrust–nappe structure of the ocean–continent transition zones [4, 5]. In the light of these ideas, the considered rock associations are island-arc rocks of different ages that were formed in the Paleopacifics and then juxtaposed in a single structure owing to accretion. However, the idea that the considered Cretaceous–Paleocene rocks are of riftogenic nature and were formed in the ocean–continent boundary zone without significant displacements is becoming increasingly popular [3, 6].

This work addresses the manifestations of the Late Cretaceous–Paleocene volcanism of three Kamchatka ranges: the Tumrok, Valaginsky, and Sredinny (Fig. 1). Based on new petrochemical, geochemical, and Nd-isotopic composition data, their classification, source composition, formation settings, and melt evolution are discussed. Possible variants of the reconstruction of the geodynamic setting of this volcanism are proposed.

THE GEOLOGICAL SETTING OF THE LATE CRETACEOUS–PALEOCENE MAGMATIC COMPLEXES OF CENTRAL KAMCHATKA

The Eastern Kamchatka Zone

The area of the Pravyi Tolbachik–Levaya Shchapina rivers (the northern part of the Tumrok Range). It is seen from the presented scheme (Fig. 2) that the area is made up of volcanogenic and tuffaceous–sedimentary rocks of Late Cretaceous (the Khapitskaya K$_2$hp and Bushukinskaya K$_2$bsh formations) and Paleocene (the Stanislavskaya Ꝑ$_1$st Formation) age. A small alkali gabbroid massif of Late Cretaceous age is located in the northern part of the area. The lithogeochemical sampling encompassed the rocks of the Khapitskaya Formation. They are represented by massive and pillow lavas, and lithoclastic psammitic and psephitic tuffs of basic composition. The flows are from 3–5 to 20–30 m thick. The basalts are amygdaloidal, rarely dense massive rocks containing from 3–5 to 40–50% phenocrysts of pyroxene, plagioclase, and less common serpentinized olivine. The strongly chloritized groundmass contains individual euhedral grains of cli-

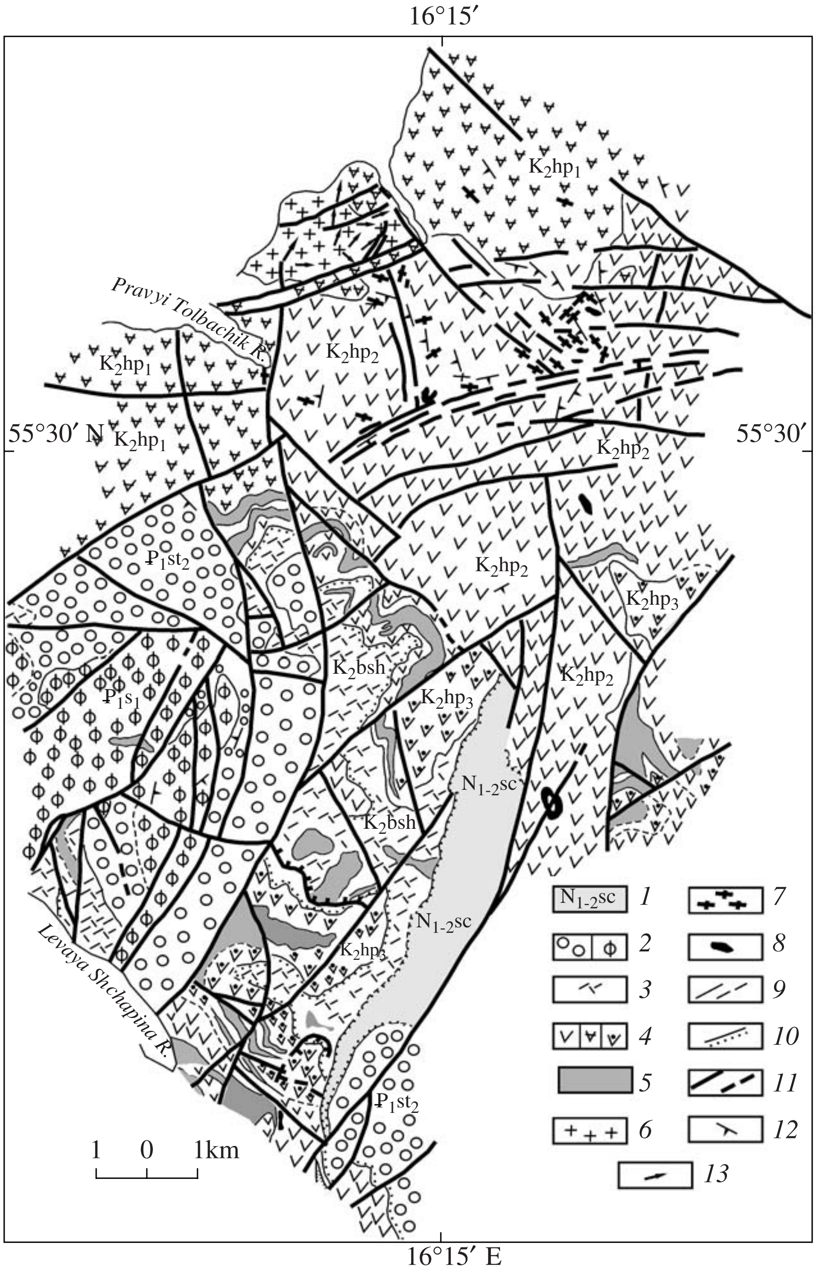

Fig. 2. Geological scheme of the Pravyi Tolbachik–Levaya Shchapina river areas (northern part of the Tumrok Range). (*1–5*) rock complexes: (*1*) Miocene tuffaceous sandstones, (*2*) sedimentary–volcanogenic rocks of Paleogene age (different sequences of the Stanislavskaya Formation Ꝑ$_1$, st$_{1-2}$), (*3*) Late Cretaceous sedimentary–volcanogenic rocks (Bushuikina Formation K$_2$bsh), (*4*) Late Cretaceous essentially volcanogenic complex (different sequences of the rocks of the Khapitskaya Formation K$_2$hp), (*5*) sills and sheeted bodies of the Late Cretaceous gabbrodiabases, (*6*) wehrlites, pyroxenites, gabbros, and diorites of Late Cretaceous–Paleogene age (small intrusive body), (*7*) dikes of basaltic porphyrites, (*8*) dikes, sills, and extrusions of the Late Cretaceous meymechite–picrite complex, (*9*) geological boundaries (established and inferred), (*10*) boundaries of discordant bedding of Neogene rocks, (*11*) tectonic disruptions (traced and inferred); (*12*) strike and dip of the bedded rocks; (*13*) elements of prototectonics. The map was compiled using the materials of field works of A.V. Koloskov and V.A. Seliverstov in 1970.

nopyroxene, plagioclase plates, grains and aggregates of magnetite, rare biotite, and actinolite amphibole. There are also dikes, sheeted bodies, and extrusions of meymechite–picrite composition. The dikes are from 1–1.2 m to 10–15 m thick and traced over the strike for up to 150 m. One of the extrusions has a funnel shape with a diameter up to 45 m near the surface. Ultrabasic rocks demonstrate coarse banding and pillow or cake-like jointing. There is also coarse breccia with fragments from 10–20 cm to 1–1.2 m in size. The ultrabasic

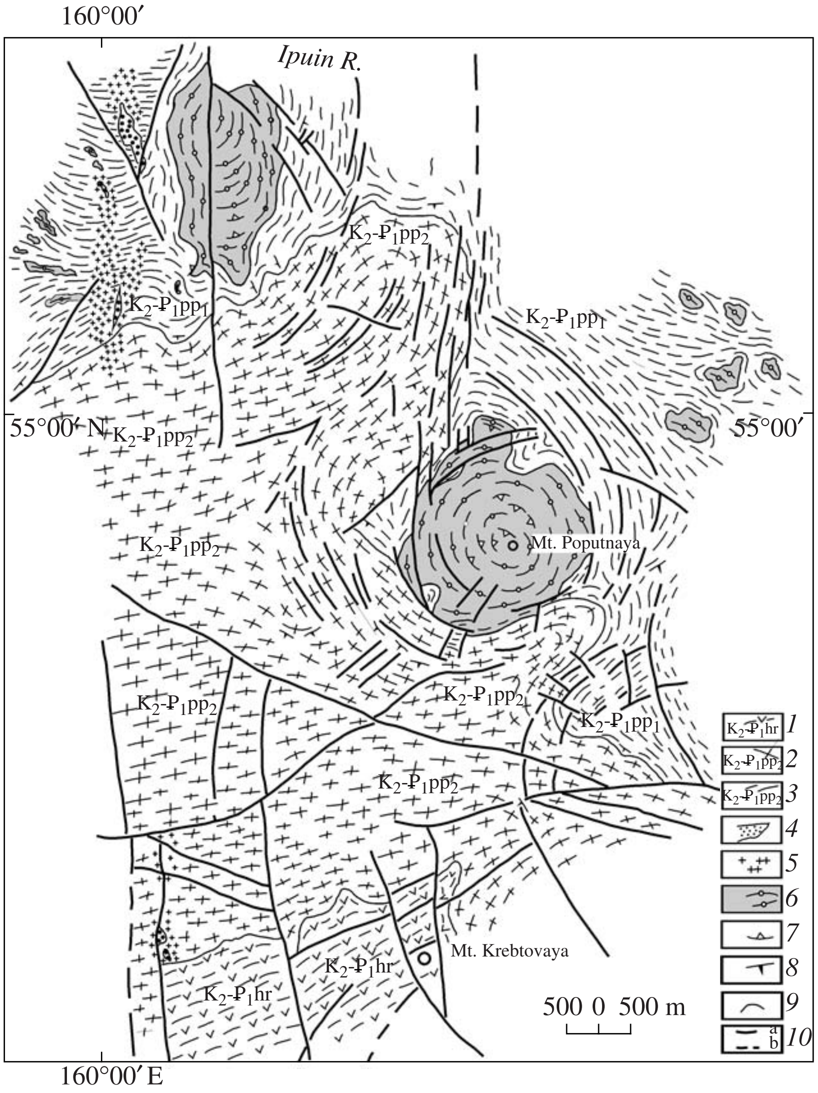

Fig. 3. Geological scheme of the Ipuin River–Mt. Khrebtovaya area (northern part of the Valaginsky Range).

(*1–3*) Late Cretaceous–Paleocene complexes: (1) meymechite–picrite (Khrebtovaya Formation K_2–Ꝑ$_1$hr), (*2*) tuffaceous–lava, (*3*) siliceous–silty (Poputnaya Formation K_2–Ꝑ$_1$pp), (*4*) small bodies of gabbrosyenites, diorites, and microdiorites of Late Cretaceous (?) age, (*5*) zone of alkali metasomatism, (*6*) bodies of serpentinized alpine-type ultrabasic rocks of Late Cretaceous age, (*7*) plane elements of prototectonics, (*8*) strike and dip of the bedding, (*9*) geological boundaries, (*10*) faults ((a) proved and (b) inferred). Compiled using the materials of A.V. Koloskov and V.A. Seliverstov (1970).

rocks have a porphyritic texture and contain up to 60–70% phenocrysts. The latter are dominated by olivine, which forms zoned crystals up to 0.5–1 mm in size, as well as euhedral more rarely elongated clinopyroxene occasionally forming glomeroporphyritic intergrowths with olivine. The microlitic and intersertal groundmass is built up of clinopyroxene, amphibole, phlogopite, K-feldspar, apatite, plagioclase, Cr-spinel, and chloritized and serpentinized glass. The upper part of the section of the Khapitskaya Formation is cut by numerous sills and sheeted gabbrodiabase bodies, which contain up to 20–30% plagioclase and clinopyroxene. Based on finds of Late Cretaceous radiolarians and remains of inocerams in other localities of the Khapitskaya Formation, its age was taken to be the Late Cretaceous, while finds of spores, pollens, and foraminiferas points to the Paleocene age of the Stanislavskaya Formation. The rocks of the area are strongly deformed with a predominance of steeply dipping sublatitudinal and submeridional faults.

The Ipuin River–Mt. Khrebtovaya Area (The Northern Part of the Valaginsky Range). The most part of the considered area (Fig. 3) is made up of two contrasting sequences: a siliceous–siltstone sequence occupying the eastern and northern part of the area and an overlying tuffaceous–lava sequence, which spans the entire central part of the considered area. The first sequence consists of intercalated sandstones, siltstones, and mudstones, with abundant siliceous material. It comprises two comparatively large bodies of serpentinized alpine-type hyperbasites and numerous small bodies of serpentinites, serpentinized peridotites, and pyroxenites. Another sequence consists of coarse agglomerate tuffs, and tuff breccia with scarce layers of pillow lavas of basaltic and trachybasaltic composition. The rocks contain up to 15–20% phenocrysts of clinopyroxene and plagioclase and, more rarely, serpentinized olivine, which are variably altered with the formation of amygdules filled with epidote–chlorite and, occasionally, actinolite aggregate. There are also thin (40–50 cm) ultrabasic dikes with phenocrysts and subphenocrysts (up to 40–60%) of olivine and clinopyroxene. On the geological map, both of the sequences are assigned to the Poputnaya Formation (K_2–₽$_1$pp) of the Late Cretaceous or Cretaceous–Paleocene age. However, the sharp difference in the lithology and spatial association of the alpine-type ultrabasic massifs (their analogues occur in the Kumroch Range and on the peninsulas) and siliceous–siltstone sequence possibly attest to a greater age gap between these sequences. Small diorite bodies and fields of feldspathic metasomatism possibly of a younger age were found locally in the submeridional zones in the northern and southwestern part of the area. The southern part of the area hosts a unit of ultrabasic lavas and variolitic tuffs (K_2 = ₽$_1$hr, the Khrebtovaya Formation) containing from 30–40 to 50–60% phenocrysts and subphenocrysts. Among them, the most abundant are zoned high-Mg olivines varying in size from 1–3 to 5–7 mm. The scarce clinopyroxene phenocrysts are diopside–salites in composition and have a size of no more than 1–2 mm. Their amount sharply increases (up to 40–45% of phenocrysts) in the alkali–ultrabasic and basic rocks of the Valaginsky Complex [13]. The groundmass of ultrabasic volcanics contains microlites and individual grains of clinopyroxene, Cr-spinels, magnetite, biotite, and apatite, as well as devitrified and serpentinized glass. As is seen in the scheme (Fig. 3), the rocks of the area are strongly faulted. A well expressed central-type structure overthrust by a volcanogenic sequence is recognized in the area of the dunite–harzburgite massif of Mt. Poputnaya.

The Mt. Savul'ch Area (The Upper Reaches of the Kitil'gina River, Northern Valaginsky Range). The geological structure of the area with allowance for the data of the detailed geological survey and the author's materials is shown in Fig. 4. The area is made up of tuffs and lavas of basalts, trachybasalts, andesites, trachyandesites, and ultrabasic rocks of the Late Cretaceous–Paleocene age, which were ascribed to the different sequences of the Poputnaya (K_2–₽$_1$pp) Formation. The units of ultrabasic lavas and variolitic tuffs are assigned to the Khrebtovaya Formation (K_2–₽$_1$hr). The younger terrigenous deposits of the Oligocene–Miocene Tyushevka Group (₽$_3$–N_1ts) are developed in the eastern and southeastern part of the area. The central part of the area exposes a small dunite–wehrlite–clinopyoxenite–gabbro massif. Small bodies of the same composition (as well as diabases and diorites) and dikes of diorites and ultrabasic rocks (with thicknesses from a few meters to 30–50 m) typically occur among the Cretaceous–Paleocene sedimentary–volcanogenic rocks. Greenstone-altered amygdaloidal basalts contain phenocrysts of plagioclase and clinopyroxene. The ultrabasic tuffs are highly sericitized and contain relict olivine. In several exposures, these tuffs contain rounded enclaves (from 3–5 cm to 15–20 cm) of carbonatites. The latter consist of single phenocrysts, more rarely intergrowths of crystals, mainly relict clinopyroxene (diopside–fassaite in composition); aggregates of small, mainly andradite garnet; and magnetite embedded in the chlorite–serpentine–carbonate groundmass. The rocks of the area experienced fold and block tectonics.

Central Kamchatka Zone

The volcanic activity of the Late Cretaceous–Paleocene time in the considered area (Fig. 5) is represented by the rocks of the Irunei (K_2ir) and Kirganik (K_2–₽$_1$kr) formations.

The Irunei Formation. The rocks of the Irunei Formation are developed on the eastern slopes of the Sredinny Range as a discontinuous band from 1–3 to 10–15 km extending from the upper reaches of the Ichi River in the north to the Ozernaya Kamchatka River in the south. They are represented by terrigenous–siliceous flyschoid deposits (sandstones, siltstones, siliceous shales, and tuffites) in the lower part of the formation and by volcanogenic–sedimentary rocks in its upper parts. The volcanic rocks comprise tuffs and lavas of basalts, basaltic andesites, trachybasalts, and rare andesites. The rocks are massive, amygdaloidal, and porphyitic. Phenocrysts (15–40 vol %) are represented by variable amounts of clinopyroxene, plagioclase, and subordinate amphibole. The groundmass is characterized by a variable grade of crystallinity and metamorphism.

The thickness of the Irunei Formation is 3000 m. Finds of flora and fauna testify to the Santonian–Campanian age.

The Kirganik Formation. The rocks of this formation are locally exposed among the rocks of the Irunei Formation in the basins of the Chengnuta, Pravyi and Levyi Kirganik, and Sharomskaya rivers; in the heads of the Zhupanka and Bogdanovskaya rivers; and on the left side of the Andrianovka River. It is stratigraphically higher than the Irunei Formation. The Kirganik Formation contains tuffaceous–sedimentary and sedimentary rocks, lavas, lava breccias, tuffs, subvolcanic bodies, and dikes. In terms of petrography, the magmatic rocks are subdivided into two associations: (1) plagioclase-bearing rocks represented by basalts, trachybasalts, tra-

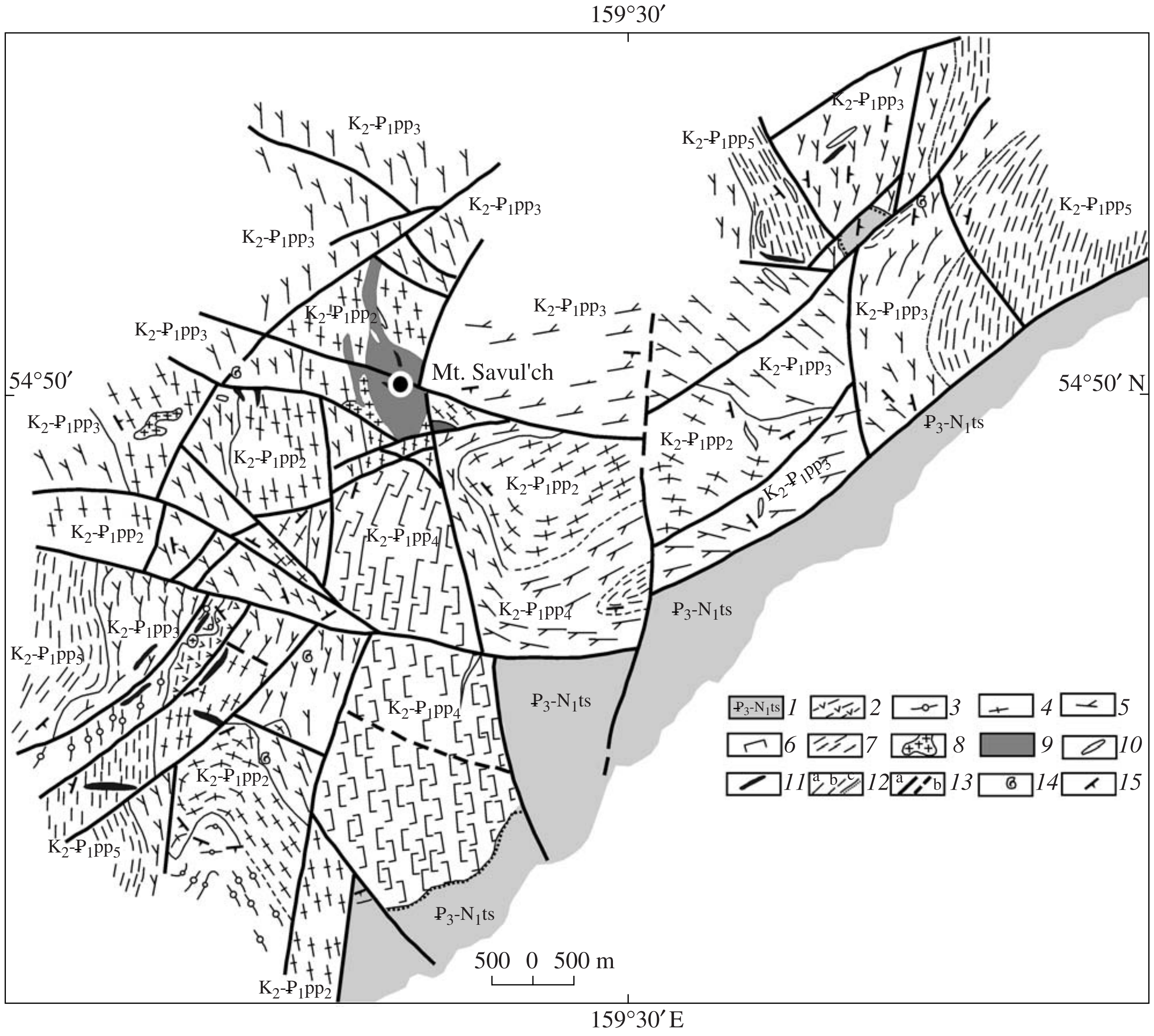

Fig. 4. Geological scheme of the Mt. Savul'ch area (upper reaches of the Kitil'gina River, northern part of the Valaginsky Range). (*1–7*) rock complexes: (*1*) tuffaceous sandstones of Oligocene–Miocene age (Tyushevka Group Ᵽ$_3$–N$_1$ts); (*2*) Late Cretaceous–Paleocene meymechite–picrite complex (Khrebtovaya Formation K$_2$–Ᵽ$_1$hr); (*3–7*) different units of the volcanogenic–sedimentary rocks of the Late Cretaceous–Paleocene Poputnaya Formation (K$_2$–Ᵽ$_1$pp); (*8*) small intrusive bodies of gabbrosyenites and diorites; (*9*) bodies of serpentinized harzburgites, wehrlites, and pyroxenites of Late Cretaceous age; (*10*) gabbrodiabase dikes; (*11*) picrite–meymechite dikes; (*12*) geological boundaries ((a) established, (b) inferred, and (c) discordant bedding of the rocks); (*13*) tectonic faults ((a) proved and (b) inferred), (*14*) Inoceram beds; (*15*) dip and strike of the rocks. Compiled using the materials of A.V. Koloskov and V.A. Seliverstov (1980), and A.V. Koloskov and G.B. Flerov (2003).

chybasaltic andesites, tephrites, and essexites (subvolcanic bodies) and (2) plagioclase-free rocks represented by absarokites, analcime and epileucite shonkinites (lavas, subvolcanic bodies, and dikes), and orthoclase pyroxenites (sills). The rocks of the first association usually contain from10–20 to 40% phenocrysts of salite, plagioclase, and magnetite and occasionally hydrobiotite and orthoclase (in latites). The sills and subvolcanic bodies are made up of porphyritic rocks abundant in subphenocrysts and microphenocrysts of pyroxene and plagioclase. The second association shows the same percentage of phenocrysts but lacks plagioclase (at a wide abundance of salite), is higher in orthoclase, contains phenocrysts of analcime and epileucite, and leucite inclusions in pyroxenes. The volcanic rocks of the Kirganik Formation experienced intense metasomatic alteration and bear traces of regional greenstone metamorphism. The thickness of

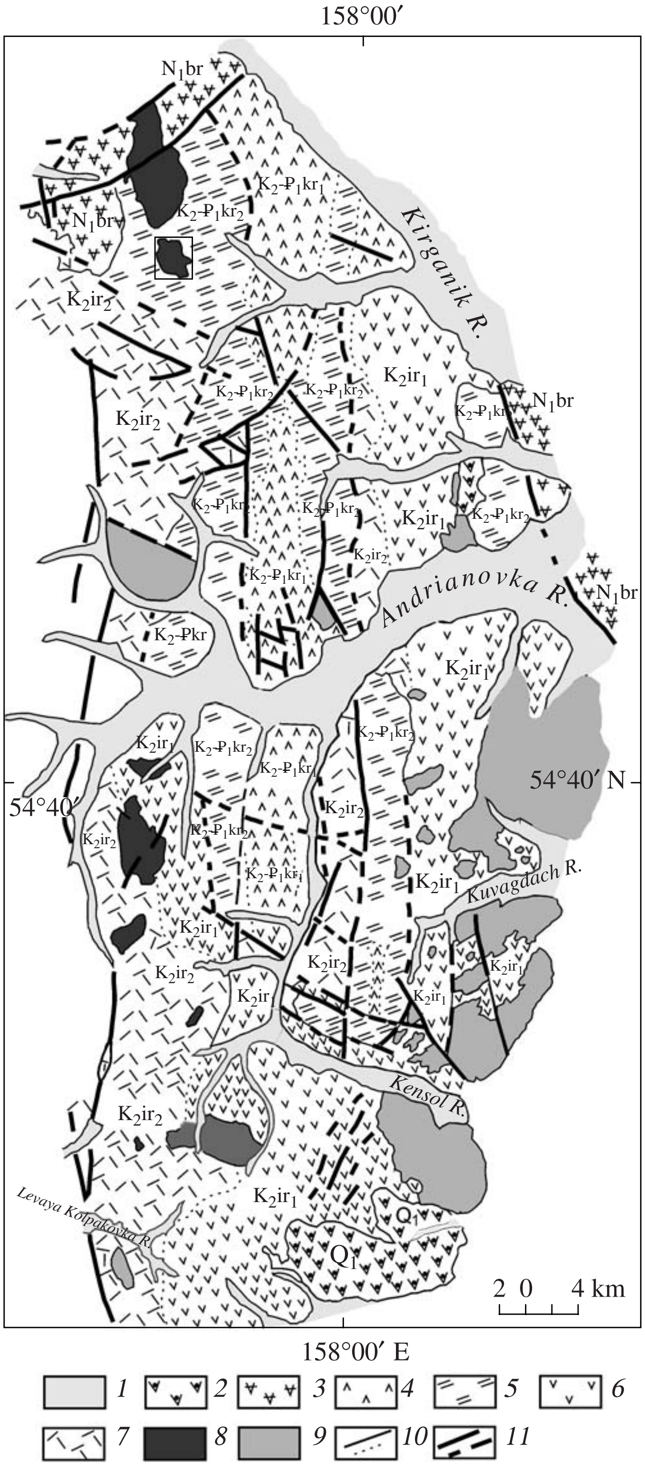

Fig. 5. Geological scheme of the area of the Sredinny Range in Kamchatka (Kirganik–Levaya Kolpakova rivers).

(*1–7*) rock complexes: (*1*) Quaternary rocks, (*2*) Early Quaternary mainly lava complex, (*3*) Miocene sedimentary–volcanogenic complex (Berezovskaya Formation N$_1$br), (*4*) Late Cretaceous–Paleocene essentially volcanogenic and (*5*) tuffaceous–volcanogenic (Kirganik Formation K$_2$–Ꝑ$_1$kr), (*6*) essentially volcanogenic and (*7*) siliceous–tuffaceous complexes of the Late Cretaceous age (Irunei Formation K$_2$ir), (*8*) Miocene gabbro–granodiorite–granite massifs, (*9*) Late Cretaceous–Paleogene complex differentiated (from dunites to monzonites and syenites) intrusive bodies; (*10*) geological boundaries (stratigraphic and facies), (*11*) faults (proved and inferred). The map was compiled using the materials of field works (G.B. Flerov, A.V. Koloskov, and O.N. Volynets (1960–1970s)) and the materials of a geological survey.

the formation is estimated to be within 3000 m. The paleontological finds and K–Ar determinations constrain the age of the Kirganik Formation to the Late Cretaceous–Middle Eocene.

The spatial juxtaposition of the volcanic rocks of the Irunei and Kirganik formations suggests the inheritance of the locality and character of the volcanic centers. The rocks of both the formations are strongly dislocated, deformed into steep folds, and cut by numerous faults into blocks.

ANALYTICAL TECHNIQUE

The least altered samples were taken for our studies. The rock-forming oxides were analyzed using conventional "wet" chemistry at the Analytical Center of the Institute of Volcanology and Seismology of the Far East Branch of the Russian Academy of Sciences (analysts T.V. Dolgova and G.V. Lets) and using the XRF method (RFA) at the Vinogradov Institute of Geochemistry and Analytical Chemistry of the Siberian Branch of the Russian Academy of Sciences in Irkutsk (analysts A.K. Klimova and L.P. Koval) using a CRM-25 quantometer. The trace elements were determined by ICP-MS using an ICP-MS PlasmaQuad3 VG Elemental mass spectrometer at the Institute of Analytical Instrument Making of the Russian Academy of Sciences in St. Petersburg. In order to control the drift of the relative sensitivity of the instrument, standard solutions of heavy metals (Ti, Cr, Ni, Cu, and Pb) and the BCR-1 standard sample were analyzed in each series (5–10 samples). The REE were calibrated using a multielement standard REE solution of Matthew Johnson. The relative error in the element determination was no worse than 5–10%. The measurements of the Nd isotopic composition were conducted at the Geological Institute of the Kola Scientific Center of the Russian Academy of Sciences (Apatity) using a seven-channel Finnigan MAT-262 mass spectrometer (RPQ). The error in the reproducibility of the LaJolla Nd standard of 0.511833 ± 6 (2σ, $N = 11$) was no more than 0.0024% (2σ). The same error was obtained during parallel measurements of the new Japanese standard JNd$_i$1 = 0.512072 ± 2 (2σ, $N = 44$). The error in the ^{147}Sm/^{144}Nd ratio taken during the statistical treatment of the Sm and Nd concentrations in the BCR-1 standard was 0.2% (2σ), which is the average of seven measurements. The laboratory blanks were 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 recal-

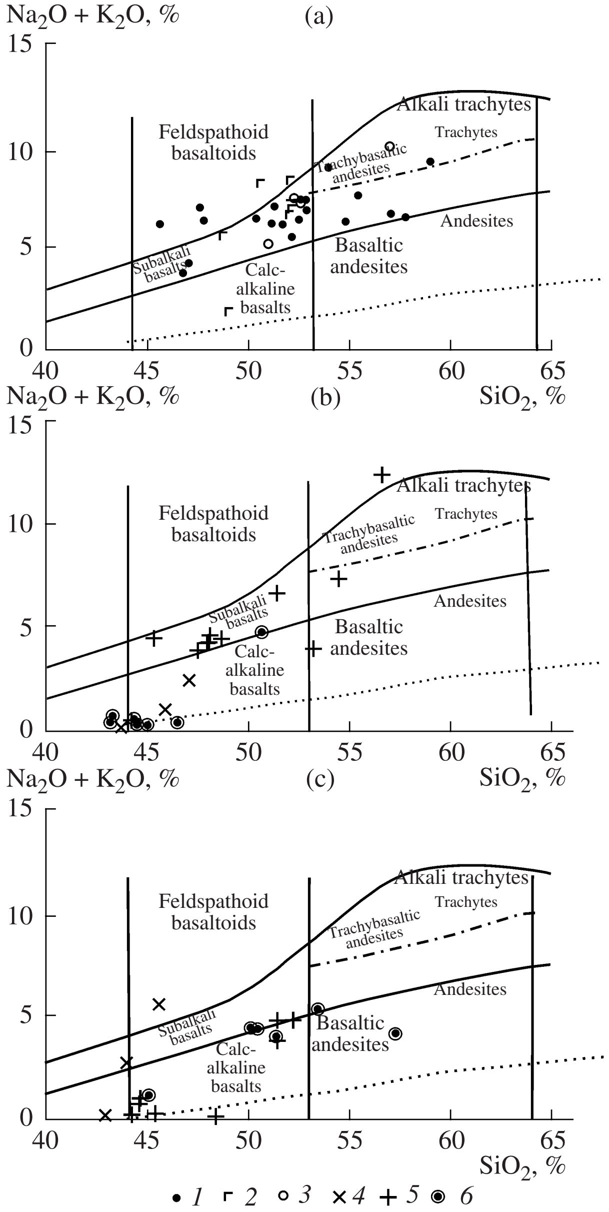

Fig. 6. (Na$_2$O + K$_2$O)–SiO$_2$ diagram for the Late Cretaceous–Paleocene volcanics of Kamchatka.

(a–c) ranges: Sredinny (a), Tumrok (b), and Valaginsky (c); volcanics: (*1–2*) Kirganik Formation, (*1*) shoshonite series [6, 15, 17, 18], (*2*) potassic alkali series [6, 17, 18], (*3*) Irunei Formation (Table 1), (*4*) data from [23], (*5*) Table 1, (*6*) data from [20].

culated to the ^{143}Nd/^{144}Nd ratio of 0.511860 in the LaJolla standard.

COMPOSITIONAL FEATURES

Major Elements

New data on the composition of the volcanic rocks of the studied regions are presented in Tables 1–3 and were plotted in the diagrams in Figs. 6–7 together with the available literature data. As is seen from the presented materials, the considered volcanics define a continuous compositional series varying in a relatively narrow SiO$_2$ range (from 43 to 59%) at significant variations of the Mg# (Mg# = 46–94). The basic rocks are characterized by a total alkali content from 3 to 12% versus the SiO$_2$ content and can be ascribed to subalkali basalt–trachybasaltic andesite series (Fig. 6). However, some data points deviate toward a lower alkali content (mainly the rocks of the Valaginsky Range) or are plotted in the field of alkali basalts (the Kirganik Formation of the Sredinny Range). The total Na$_2$O and K$_2$O content in the ultrabasic rocks according to the presented materials ranges from 0.1 to 3%, but it can reach 10% [11]. They can be regarded as a single meymechite–picrite series. As compared to the similar rocks of continental areas (the Maymecha–Kotui region), the Kamchatka ultrabasic rocks have a lower TiO$_2$ content (TiO$_2$ < 0.7%). In the diagrams of the major components versus the Mg number (Fig. 7), the rocks define a continuous series from ultrabasic rocks to basaltoids. The range of the compositional variations significantly widens showing some regional and serial differences. In particular, the shoshonite series contains a group with an elevated TiO$_2$ content (Fig. 7a). The potassic alkali series of the region is characterized by somewhat elevated P$_2$O$_5$ (Fig. 7b) and MnO (Fig. 7f) contents but lowered Al$_2$O$_3$ (Fig. 7c). The latter is possibly consistent with the main mineralogical signature of these series (plagioclase-bearing shoshonite and plagioclase-free potassic alkali series). The compositions of the rocks of the eastern ranges in terms of the major-element composition are plotted in the field of shoshonite series of the Sredinny Range. Only some basalts of the Tumrok Range correspond to the less aluminous potassic alkali series of the Kirganik Formation (Fig. 7c).

Trace Element Composition

As is seen in Fig. 8, most of the data points of the volcanic rocks are plotted in the field of plutonic rocks, which once more emphasizes their affiliation to a single volcanoplutonic formation. The combined consideration of these diagrams makes it possible to divide the subalkali basalt–trachybasaltic andesite series of the volcanic complex into two subtypes: (a) Rocks enriched in high-field strength elements (Zr, Hf, Nb), uranium, and thorium but depleted in rubidium, and less alkaline rocks; this subtype is most abundant in the Valaginsky Range and shows some correlation with the shoshonite series of the Sredinny Range; (b) Rocks depleted in high field strength elements, uranium, and thorium but enriched in rubidium and more alkaline; this subtype is confined to the Tumrok Range and correlated with the potassic alkaline series of the Kirganik Formation. Thus, the observed geochemical zoning has a complex character: in the series of the Valaginsky–Tumrok–Sredinny ranges, the rocks show an increase

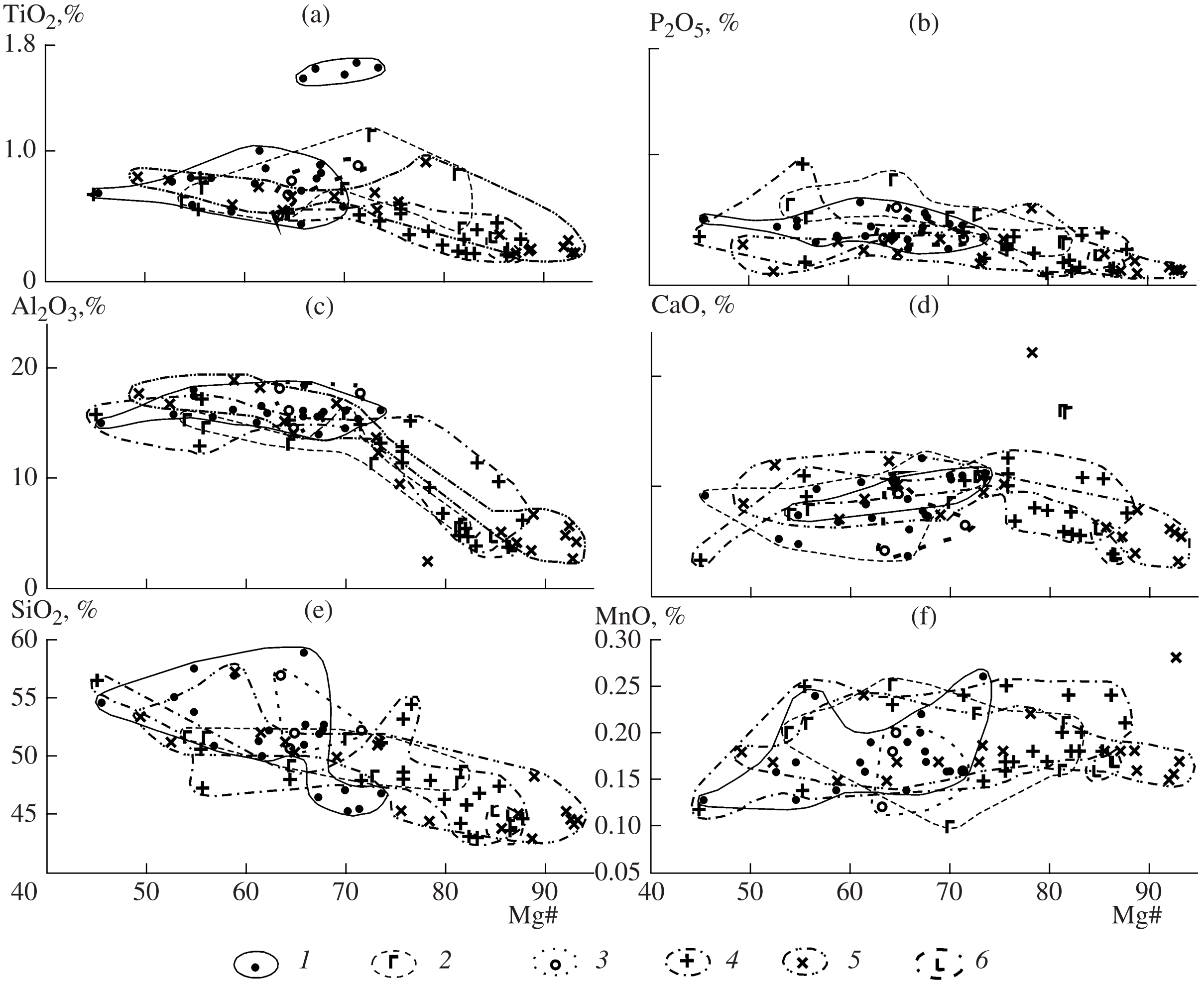

Fig. 7. Major-element variations versus the Mg number for the Upper Cretaceous–Paleocene rocks of Kamchatka. (*1–3*) volcanic rocks of the Sredinny Range in Kamchatka: (*1*) shoshonite and (*2*) potassic alkali series of the Kirganik Formation, (*3*) rocks of the Irunei Formation (Table 1); (*4–6*) volcanics: (*4*) Tumrok Range, (*5*) Valaginsky Range, (*6*) Sharomsky Cape area, according to the data from [23]. In addition to the data from Table 2, we used the same materials as for Fig. 6. Mg# = Mg/(Mg + Fe^2 + Fe^3) ×100.

in alkalinity accompanied by an increase in rubidium, while the contents of high field strength and radioactive elements decrease and then increase. The trace-element compositions of the basalts of the Sharomsky Cape are plotted between the fields of the Valaginsky and Tumrok ranges (Figs. 8a, 8b, 8c, 8g, 8h). Such a dependence is observed in any range of K alkalinity and expressed, on the one hand, in the behavior of the elements that are mobile in the fluid phase and, on the other hand, in the melts, which presumably points to the primary specifics of the magmas. The shoshonite series of the Sredinny Range is characterized by "excess" enrichment in high field strength elements (and possibly thorium) as compared to the potassic alkali series and plutonic complex. This is possibly related to the additional "pulses" of the deeper seated portions of the melt. The rocks of the Irunei Formation in all the diagrams in Fig. 8 are plotted in the field of shoshonites of the Kirganik Formation.

Neodymium Isotopy

The Nd isotopic composition of the volcanic rocks of the studied areas (Table 3) varies in a narrow range and shows no dependence on the SiO_2 content and Mg number (Fig. 9). The values of $\varepsilon_{Nd}(t)$ range from +6.67 to +9.71 in the SiO_2 range from 44 to 57% and MgO from 6.66 to 33.93%. The lowered values (+6.67) found in the high-Ti basalts of the shoshonite series of the Sredinny Range may indicate the independence of the corresponding magmatic source; however, solving this problem requires additional materials. These data are consistent with the available materials on isotopic composition (ε_{Nd} from +10.7 to +9.1) of pyroxenes from picrites and basalts of the eastern ranges of Kamchatka [23] and pyroxenes and syenites ($\varepsilon_{Nd}(t)$ from +5.6 to +9.0) from the volcanic and plutonic complexes of central Kamchatka [7].

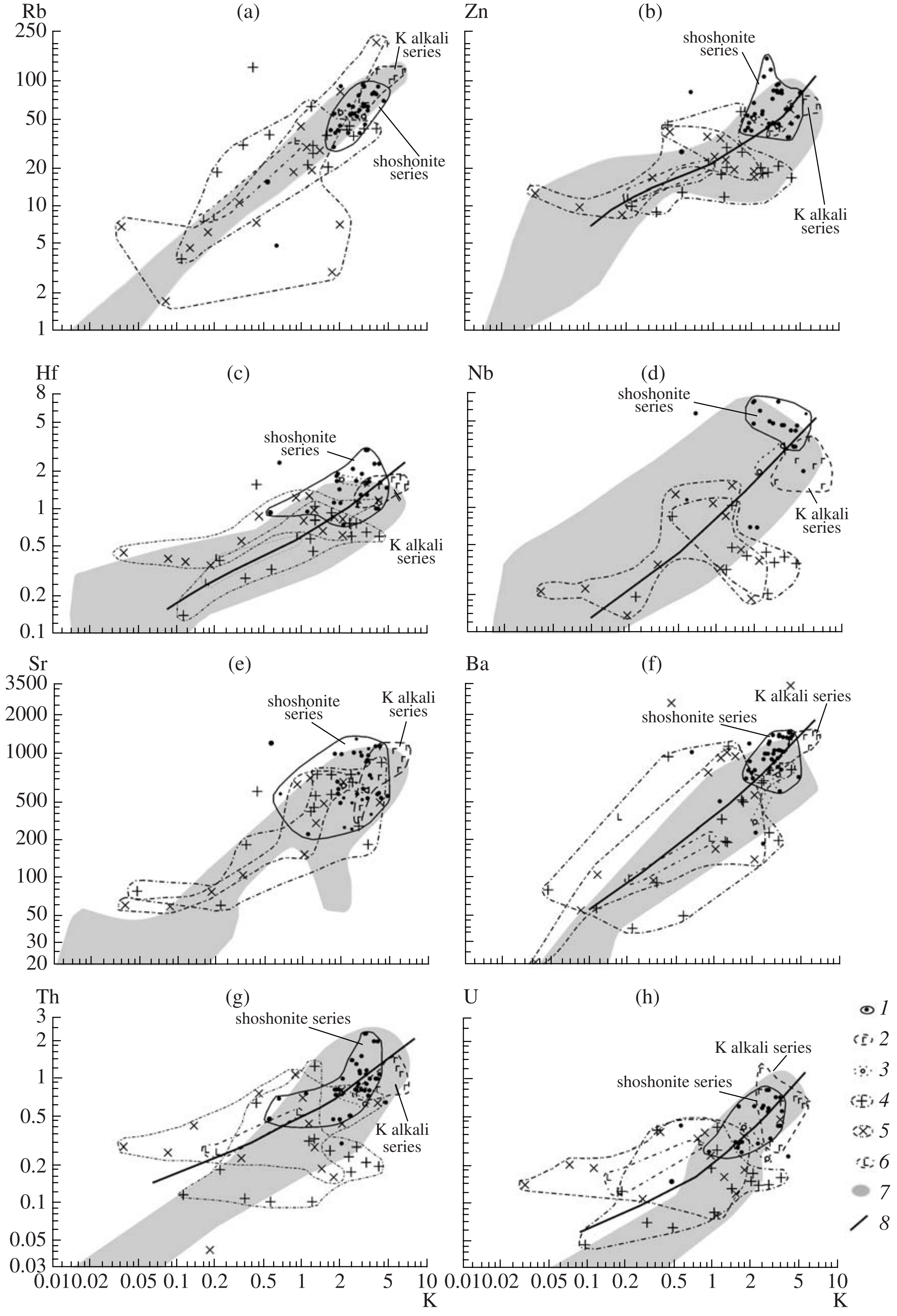

Fig. 8. The trace element variations versus the potassic alkalinity for the Upper Cretaceous–Paleocene rocks of Kamchatka. (*1–6*) the same as in Fig. 7; (*7*) field of the Late Cretaceous–Paleogene plutonic rocks of the Sredinny Range and the eastern ranges of Kamchatka (after [19] and unpublished analyses of A.V. Koloskov), (*8*) the discriminant line between the shoshonite and potassic subalkali–alkali series.

DISCUSSION

Analysis of the Existing Concepts

The considered volcanogenic complexes are spatially separated and belong to different formations that are characterized by different proportions of sedimentary–volcanogenic and volcanogenic material; the volcanic associations contain both basic and ultrabasic rocks. The most controversial problem is the relations between these rocks. Some geologists believe that the ultrabasic and basic rocks are genetically different and were formed from different magmatic sources [9, 19]. The formation of the first group is considered to be related to the high melting degree of the mantle protolith under moderate-pressure conditions, possibly, with participation of trans-magmatic fluids [9]. The series of less magnesian rocks is considered as the product of the evolution of independent melts that were supplied from different-depth mantle sources [19]. In contrast, other researchers argue that these rock groups are genetically linked and were formed through evolution of a single mantle source [5, 23]. Stratigraphically, the ultrabasic rocks in each area are bracketed between subalkali basaltoid sequences. In addition, the ultrabasic dikes and sills at the Valaginsky and Tumrok ranges are located among the alkali basic rocks of different formations, which suggests a genetic relation between these rocks having different Mg numbers. In the diagrams presented in Figs. 7–8, the ultrabasic and basic rocks of the volcanic complex define a single evolution trend coinciding with the variation trend of plutonic rocks (Fig. 8).

The problem of the high (mainly potassic) alkalinity of the volcanic rocks remains open. According to concept [19], the primary subalkali melts of the shoshonite series were formed by crystallization differentiation of basaltic magma under the influence of transmagmatic K-bearing fluid, while the high-K alkali melts were derived by interaction of the latter with pyroxenite magma. The highest-alkali lamproite-like rocks of the Uzkii Creek (northern part of the Valaginsky Range) were formed [13] owing to low-degree fractional melting of primitive deep-seated material that was depleted in TiO_2, Ta, and Nb and enriched in K, Ba, Sr, Rb, Zr, and Y. The evolution of the fluid-magmatic system occurred in equilibrium with phlogopite or biotite [6]. There is also the opinion that the extremely high K contents in some samples were produced by postmagmatic redistribution of alkalis in the rocks of the Tumrok Sequence [5] or by postmagmatic potassic metasomatism of basic volcanic rocks of the Valaginsky Range [1] and cannot reflect the magmatic specifics of these areas. Strong postvolcanic potassic metasomatism manifested itself in the formation of large zones of essentially orthoclase metasomatites around conduits of the Kirganik paleovolcanoes [16, 17] or in the local submeridional zones in some areas of the Valaginsky Range. However, these facts are consistent with the revealed alkali specifics of the melts.

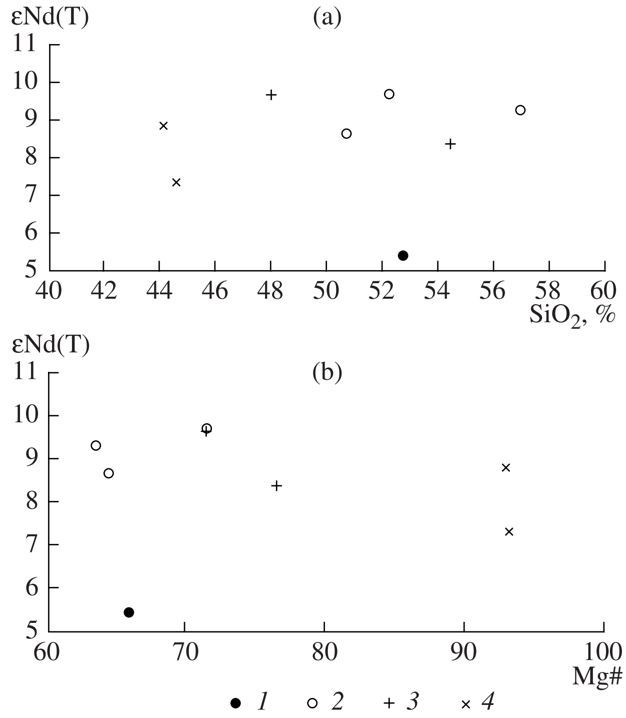

Fig. 9. Variations of ε_{Nd}(T)–SiO_2 (a) and ε_{Nd}(T)–Mg# (b). (*1–2*) Sredinny Range: (*1*) shoshonite series (basalts with elevated TiO_2 content), (*2*) Irunei Series, (*3*) Tumrok Range, (*4*) Valaginsky Range.

All this indicates a common composition and close geodynamic setting of the Upper Cretaceous–Paleocene magmatism of the considered area.

Let us consider the reasons for the compositional diversity of these rocks as a result of this magmatism.

Role of Shallow Differentiation

Crystallization differentiation. According to the data of [17], crystallization differentiation is a decisive factor in the evolution of the shoshonite and potassic alkali series of the Sredinny Range. The analysis of the diagrams shown in Figs. 7–8 allows us to extend this conclusion to the magmatic rocks of all the considered areas. Actually, a decrease in the Mg number is accompanied by an increase in the aluminoslicate component and TiO_2, which can be caused by the subsequent transition from an essentially olivine subliquidus mineral assemblage to the olivine–pyroxene, pyroxene–plagioclase, and essentially plagioclase assemblage (Fig. 7). As will be shown below, such a trend in the compositional evolution of the volcanic rocks is confirmed by some characteristics of the melt inclusions on transition from subliquidus host olivine to clinopyroxene. In the same direction, both the volcanic and plutonic complexes show an increase in the contents of K and other elements correlating with it (Fig. 8).

Table 1. Chemical composition (wt %) of the rocks of the Tumrok, Valaginsky, and Sredinny ranges

Component	1	2	3	4	5	6	7	8	9	10	11	12	13
	7032/10	7034/2	7042/2	7054	7065/1	7072	7032/4	7043	7088/4	7032	7041	K-7134	7012/1
SiO_2	48.7	44.18	46.76	40.12	45.32	52.7	46.53	49.48	56.03	40.69	45.84	45.3	45.62
TiO_2	0.54	0.38	0.5	0.3	0.43	0.35	0.5	0.45	0.66	0.27	0.51	0.77	0.53
Al_2O_3	11.85	10.71	14.51	5.54	9.26	14.71	10.88	12.76	15.76	5.2	14.65	16.48	11.77
Fe_2O_3	3.01	3.75	6.56	5.67	4.51	4.19	4.42	9.86	3	4.07	5.57	7.73	5.87
FeO	6.18	6.89	5.51	5.8	7.04	3.5	6.01		5.17	8.05	6.03	5.57	6.47
MnO	0.13	0.2	0.23	0.19	0.17	0.16	0.24	0.14	0.12	0.2	0.22	0.24	0.16
MgO	7.2	14.37	8.02	24.3	13.65	6.66	9.32	6.91	1.76	26.22	8.65	6.34	10.18
CaO	10.34	10.24	10.36	6.86	10.25	6.76	12.09	10.47	3.49	6.08	9.43	8.74	9.61
Na_2O	2.16	1.24	2.03	0.16	0.76	3.28	0.57	1.52	0.29	0.17	2.31	2.85	0.81
K_2O	1.39	1.29	1.94	0.05	2.87	3.78	3.47	4.92	12.1	0.31	1.89	1.47	3.03
P_2O_5	0.29	0.36	0.39	0.24	0.33	0.36	0.28	0.20	0.38	0.13	0.36	0.17	0.26
H_2O–	0.67	1.82	1	2.11	3.31	0.38	1.72	n.d.	0.35	1.46	1	n.d.	2
H_2O+	n.d.	4.26	2.4	8.7	n.d.	2.74	n.d.	n.d.	n.d.	n.d.	3.24	n.d.	n.d.
H_2Otot	0.68	n.d.	n.d.	n.d.	3.85	n.d.	3.14	3.14	1.36	6.6	n.d.	4.01	5.6
CO_2	7.28	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	100.49	99.69	100.21	100.04	99.7	99.57	99.17	99.86	100.47	99.45	99.7	99.67	101.91

Component	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	7271	7186	7162	7392	7388	7358	7479-3	P-1/24	G3-63	G97/35	G97/38	G97/39	G97 40	m-4053
SiO_2	39.72	49.06	50.42	40.80	50.51	49.74	44.34	39.85	41.56	49.70	51.08	55.86	50.31	51.04
TiO_2	0.2	0.66	0.54	0.24	0.54	0.7	0.24	0.82	0.3	0.85	0.76	0.50	0.66	1.50
Al_2O_3	2.36	13.18	12.16	4.34	15.01	17.43	6.13	2.19	5.28	16.89	14.28	17.81	16.00	17.94
Fe_2O_3	5.75	5.66	12.3	9.85	2.18	2.66	4.46	5.78	9.6	8.65	10.43	6.40	10.96	8.77
FeO	4.16	3.41	n.d.	n.d.	8.05	7.18	5.89	4.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	0.25	0.16	0.18	0.14	0.15	0.23	0.15	0.2	0.15	0.15	0.20	0.12	0.18	0.19
MgO	33.93	9.07	8.55	28.92	4.97	4.03	22.45	14.54	30	5.47	4.84	2.80	5.00	4.27
CaO	2.88	10.47	9.4	5.56	12.29	8.59	7.22	19.91	5.47	6.29	9.24	4.18	10.54	6.02
Na_2O	0.1	2.96	2.93	0.14	2.46	2.19	0.12	0.76	0.5	4.44	3.03	4.32	4.54	5.99
K_2O	0.09	1.44	1.68	0.04	1.18	2.33	0.04	0.48	0.36	2.39	3.75	5.86	0.65	0.75
P_2O_5	0.11	0.15	0.21	n.d.	0.35	0.26	0.08	0.52	0.1	0.33	0.58	0.35	0.36	0.27
H_2O–	0.62	n.d.	n.d.	n.d.	0.13	0.37	1.73	0.52	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O+	9.58	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2Otot	n.d.	3.69	1.54	9.60	2.04	5.51	7.24	3.97	6.42	4.78	1.74	1.50	n.d.	3.28
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	5.94	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Total	99.75	99.91	99.911	99.63	99.86	101.22	100.09	100.08	99.74	99.95	99.93	99.7	99.19	100.02

Note: (1–13) Tumrok range (upper reaches of the Pravyi Tolbachik River), Khapitskaya Formation: (1) Ol–Px basalt, (2) alkali picrobasalt, (3) Px porphyrite, neck, (4) picrite, sill, (5) alkali picrite, (6) Px–Pl basalt, (7) Px–Pl basalt, sheeted body, (8) Px porphyrite, flow, (9) Px–Pl basalt, (10) picrite, (11) Px basalt, dike, (12) Pl poprhyrite, (13) basalt, dike; (14—22) Valaginsky Range, (14) picrite, Mt. Khrebtovaya area, Khrebtovaya Formation, (15–22) Poputnaya Formation: (15) diabase, sill in the vicinity of Mt. Poputnaya, (16) Ol–Px basalt, near Mt. Poputnaya, (17) picrite, near Mt. Poputnaya, (18–19) basalts, north of Mt. Poputnaya, (20) picrobasalt, Shiroky Range, (21) carbonatite, enclaves in picritic tuff, upper reaches of the Kitil’gina River, (22) picrite, dike, Mt. Ostraya; (23–27) Sredinny Range, Khim River area, basalts of individual flows, (23–26) Irunei Formation, (27) Kirganik Formation.

Table 2. Trace-element composition of the rocks of the Tumrok (1–12), Valaginsky (13–21), and Sredinny (22–26) ranges

Component	1	2	3	4	5	6	7	8	9	10	11	12	13
	7032/10	7034/2	7042/2	7065/1	7072	7032/4	7043	7088/4	7032	7041	K-7134	7012/1	7271
Li	4.75	13.23	10.09	10.74	1.92	13.09	2.43	2.51	8.66			16.44	4.03
Be	0.37	0.53	0.41	0.59	0.54	0.59	0.35	1.38	0.27			0.42	0.30
Sc	18.47	33.52	37.52	36.98	28.74	30.86	24.02	9.24	20.96		39.77	33.28	11.60
Ti	2596.86	2292.07	3817.10	2026.25	2550.17	2464.39	2176.14	3354.21	1281.32			2558.12	728.64
V	224.49	246.20	366.72	202.75	268.87	265.90	191.34	131.68	120.83		524.06	277.80	93.73
Cr	377.45	626.29	424.31	563.60	198.03	301.86	332.02	122.43	1264.02		31.83	494.25	1862.99
Co	28.88	51.87	45.14	53.40	28.82	41.49	34.05	12.85	90.00		49.62	46.07	105.41
Ni	127.90	214.29	76.18	272.20	73.67	99.50	85.78	10.22	563.69	156.00	23.08	159.99	1539.17
Cu	6.80	20.25	124.88	96.11	105.53	72.97	46.20	38.10	60.14	225.00	185.94	145.46	33.63
Zn	38.65	35.89	64.97	72.15	47.41	59.77	40.00	52.64	77.58	94.00	83.00	81.06	81.76
Ga	11.18	9.51	13.71	10.65	11.79	14.16	11.14	15.32	5.73	19.00	15.29	12.41	3.02
Rb	26.92	21.90	20.85	44.86	42.54	36.60	42.32	131.76	18.83	37.00	30.58	41.02	1.76
Sr	462.29	342.89	473.98	581.27	186.90	263.85	837.20	488.85	61.36	676.00	676.12	676.00	58.94
Y	15.54	10.49	14.31	11.07	11.01	10.75	9.27	19.17	5.90	21.00	13.33	11.59	3.17
Zr	20.76	18.35	27.65	18.40	21.31	19.06	17.18	46.24	10.16	58.00	29.87	20.53	9.93
Nb	0.49	0.33	0.42	0.21	0.41	0.37	0.36	0.87	0.20		1.08	0.45	0.23
Cs	0.14	0.52	0.08	1.45	0.05	0.02	0.01	0.06	0.67		1.08	0.60	0.07
Ba	194.52	291.56	400.02	599.21	203.14	229.05	736.03	947.05	39.67	426.00	1113.87	569.36	55.11
La	2.82	2.60	3.05	2.25	2.43	3.04	2.43	4.99	2.07	3.40	6.99	2.80	1.83
Ce	7.76	6.88	7.83	6.26	6.71	7.45	6.85	13.33	5.55	8.70	15.73	6.89	4.47
Pr	1.15	0.98	1.18	0.87	0.93	1.06	1.04	1.93	0.76		2.22	1.08	0.67
Nd	6.33	5.03	6.38	4.20	4.61	5.64	4.95	8.62	4.04	6.40	9.64	5.07	2.77
Sm	1.87	1.79	2.21	1.47	1.60	1.55	1.63	2.84	0.99	2.60	2.63	1.69	0.94
Eu	0.68	0.56	0.82	0.57	0.58	0.59	0.51	0.99	0.31	0.70		0.65	0.31
Gd	2.58	1.87	2.56	1.78	1.58	1.67	1.49	2.67	1.03	2.40	3.25	1.75	0.76
Tb	0.42	0.33	0.38	0.36	0.34	0.32	0.29	0.52	0.16			0.32	0.13
Dy	2.99	1.92	2.49	1.81	2.01	1.73	1.78	3.03	0.99		2.51	1.94	0.63
Ho	0.61	0.46	0.51	0.40	0.49	0.43	0.37	0.73	0.24		0.55	0.41	0.12
Er	1.74	1.10	1.34	1.28	1.21	1.06	1.17	2.04	0.62	1.60	1.50	1.33	0.22
Tm	0.31	0.20	0.24	0.16	0.21	0.16	0.18	0.29	0.10		0.24	0.17	0.04
Yb	1.58	1.16	1.62	1.24	1.27	0.92	0.88	1.90	0.51	1.50	1.49	1.32	0.31
Lu	0.24	0.14	0.23	0.16	0.19	0.18	0.14	0.32	0.10		0.20	0.17	0.05
Hf	0.82	0.58	0.93	0.61	0.66	0.77	0.61	1.58	0.39		1.04	0.77	0.40
Ta	0.05	0.03	0.04	0.03	0.03	0.03	0.02	0.07	0.02		0.16	0.04	0.02
Pb	0.74	5.65	2.88	5.69	3.11	3.21	2.92	6.08	2.27	10.00	5.27	2.90	1.53
Th	0.33	0.32	0.26	0.18	0.22	0.29	0.20	0.64	0.18		1.26	0.24	0.26
U	0.27	0.19	0.13	0.18	0.14	0.14	0.17	0.39	0.13		0.41	0.15	0.21

Table 2. (Contd.)

Component	14	15	16	17	18	19	20	21	22	23	24	25	26
	7186	7392	7388	P-1/24	7358	7479-3	7162	G3-63	G97/35	G 97/38	G 97/39	G 97/40	m-4053
Li		8.54	7.38		1.66	16.68	6.03	4.44	7.85	8.88	3.97	9.53	24.81
Be		0.56	0.63		1.03	0.17	0.33	0.31	0.82	0.93	0.95	0.68	1.07
Sc	44.75	17.99	31.59	33.64	37.40	31.71	44.18	18.36	36.80	27.39	9.61	29.86	13.28
Ti		1166.37	3782.02		2785.39	1085.17	2477.12	1256.62	4735.75	3567.04	2898.68	3616.84	8488.75
V	326.84	110.17	330.32	194.84	404.55	117.85	237.33	95.03	329.72	267.78	204.89	287.95	228.84
Cr	353.21	1930.63	68.86	451.08	263.07	1464.63	223.98	1420.50	54.56	75.68	22.10	45.72	18.50
Co	36.12	81.50	26.17	31.12	24.93	86.86	38.85	79.20	24.51	27.00	15.14	27.41	24.26
Ni	65.30	941.45	15.58	184.68	41.11	456.85	44.44	905.05	19.95	11.76	9.79	20.74	24.22
Cu	111.84	48.43	142.27	100.51	144.49	22.41	106.59	7.16	126.05	86.20	63.73	96.69	14.80
Zn	51.62	82.22	75.09		37.09	61.87	55.61	69.76	64.75	63.72	59.22	60.40	67.34
Ga	12.25	5.00	18.96	1.80	19.02	5.13	9.59	4.80	16.66	14.20	16.34	14.23	20.13
Rb	19.37	6.90	29.62	7.60	7.19	6.37	27.85	10.70	56.16	52.80	88.25	15.58	4.98
Sr	276.25	60.30	636.07	57798.85	585.69	76.50	394.28	105.62	555.53	508.04	964.18	1206.76	475.38
Y	14.37	5.50	17.33	12.22	11.94	7.11	13.34	6.89	18.41	19.31	15.91	14.45	15.77
Zr	23.90	12.93	35.77	40.44	19.52	8.79	19.88	16.72	51.34	44.39	80.25	27.31	80.73
Nb	1.53	0.22	0.86	1.30	0.38	0.14	0.46	0.36	1.95	3.16	5.69	1.18	16.86
Cs	0.06	0.77	0.43	0.06	0.01	1.27	0.28	0.71	0.72	0.35	0.34	0.14	0.63
Ba	1008.72	21.33	896.45	2496.61	139.15	8.89	926.84	93.76	279.26	661.23	1201.27	162.01	1006.69
La	4.85	2.61	5.51	6.55	3.55	0.37	1.26	1.73	11.17	4.87	11.52	5.17	9.15
Ce	11.90	7.29	13.82	14.32	8.05	1.41	4.32	4.56	27.69	12.66	24.94	13.97	19.41
Pr	1.80	0.96	1.97	2.22	1.20	0.24	0.70	0.70	3.69	1.79	3.23	2.03	2.51
Nd	7.51	4.30	9.77	10.93	6.41	1.38	3.82	4.07	16.50	8.56	13.90	10.71	11.33
Sm	2.009	1.18	2.68	2.73	2.21	0.57	1.48	1.28	4.01	2.88	3.31	2.80	2.75
Eu		0.26	0.98	1.08	0.76	0.23	0.65	0.38	1.10	1.05	1.36	1.03	0.99
Gd	2.88	1.12	2.60	3.09	2.33	0.69	1.91	1.31	3.82	3.05	3.36	3.18	2.87
Tb		0.15	0.52	0.46	0.38	0.14	0.40	0.21	0.54	0.60	0.55	0.46	0.46
Dy	2.78	0.97	2.75	2.28	2.32	0.88	2.51	1.22	2.96	3.46	3.00	2.54	2.90
Ho	0.62	0.23	0.66	0.45	0.44	0.22	0.53	0.26	0.68	0.74	0.63	0.60	0.61
Er	1.78	0.54	1.96	1.27	1.37	0.58	1.60	0.91	1.87	2.22	1.81	1.63	1.65
Tm	0.28	0.08	0.31	0.18	0.19	0.08	0.21	0.13	0.26	0.30	0.23	0.23	0.24
Yb	1.73	0.42	1.91	1.13	1.20	0.70	1.35	0.68	1.65	2.15	1.62	1.35	1.52
Lu	0.24	0.08	0.27	0.17	0.23	0.10	0.22	0.12	0.30	0.31	0.27	0.19	0.23
Hf	0.98	0.45	1.27	0.87	0.83	0.36	0.67	0.57	1.69	1.51	2.43	0.92	2.32
Ta	0.20	0.01	0.08	0.07	0.03	0.01	0.03	0.02	0.12	0.21	0.41	0.09	1.14
Pb	0.97	3.38	2.19	43.43	2.33	0.86	1.63	0.35	3.96	6.28	9.46	2.47	3.60
Th	0.28	0.29	0.44	0.76	0.43	0.04	0.19	0.23	0.75	0.62	2.02	0.47	0.69
U	0.08	0.14	0.24	0.37	0.19	0.02	0.16	0.11	0.41	0.23	0.93	0.93	0.42

Note: The sample numbers correspond to those in Table 1. Contents of elements are given in ppm.

Table 3. Isotopic composition of the Late Cretaceous–Early Paleocene magmatic rocks of Central Kamchatka

Sample no.	Rock	Age (Ma)	Content, ppm		Isotopic ratios		Model age CHUR (Ma)	ε_{Nd}(T)
			Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (T)		
Tumrok Range								
7042/2	picrobasalt	80	1.958	6.351	0.186404	0.513126 ± 20	–7456	9.63
7072	Px-Pl basalt	80	1.400	4.807	0.176069	0.513057 ± 25	–3125	8.38
Valaginsky Range								
304/82	picrite	80	1.576	6.232	0.152923	0.512992 ± 7	–1249	7.35
7271	picrite	80	0.877	3.173	0.167179	0.513075 ± 13	–2291	8.83
Sredinny Range								
4053	high-Ti basalt	80	3.162	13.589	0.140664	0.512888 ± 18	–689	6.67
G-97-35	basalt	80	3.727	17.031	0.132297	0.513102 ± 18	–1110	9.71
G-97-39	basalt	80	2.672	11.416	0.141515	0.513085 ± 19	–1249	9.28
G-97-40	basalt	80	2.636	9.820	0.162232	0.513064 ± 20	–1911	8.66

Note: The sample numbers (except for 304/82) correspond to those shown in Table 1.

Crustal Contamination of Magmas

The presence of disequilibrium minerals (orthopyroxene, Cr-spinels, grossulars) in the rocks of the shoshonite series of the Kirganik Formation is considered [17] as an indication of the contamination of the initial melts by foreign material at different depth levels. A different interpretation of these data was considered above. As to grossular, garnets of similar composition were found in the monomineral garnet veins in the rodingites of ophiolite complexes of eastern Kamchatka [14]. In addition, accumulations of small garnet grains of mainly andradite composition were discovered in the hydrothermally altered tuffs and related carbonatites in the upper reaches of the Kitil'gina River. This indicates a metasomatic origin of this mineral. The fairly low Sr isotopic compositions of the clinopyroxenes in combination with the absence of correlation links between the Nd isotopic composition and the SiO_2 content suggest only insignificant contamination.

Mantle Sources

Clinoenstatite inclusions were noted in low-Ca olivine from the Tumrok picrites [23]. These observations are consistent with data on the presence of orthopyroxene in the subalkali basalts of the shoshonite series, olivine inclusions in clinopyroxene from latite, and Cr-spinels (Cr_2O_3 = 49.5%) in trachybasalt and porphyritic pyroxenite [17]. These minerals are extremely rare in the alkali volcanic rocks; therefore, their appearance in the shoshonite series of Kamchatka was considered as an xenogenic phase [17]. However, we cannot exclude that this "boninitic" assemblage represents a relict phase of primary low-Ca boninite-like initial melts, as was supposed for the indicator clinoenstatite [23].

In [5], the MgO content in the initial melts of the picrite–meymechite series is estimated from the calculated groundmass composition as being 9–11 wt %. Later estimates based on the compositions of melt inclusions in clinopyroxenes and olivines yielded 16.6–20.3 wt % MgO for the Valaginsky Range and 19.0–23.8% for the Tumrok Range [23]. We attempted to solve this problem using geochemical data. The Yb_n–Ce_n diagram initially was used [13] in order to demonstrate the difference of the alkali ultrabasic complex from the rocks of the absarokite and shoshonite–latite series of the Valaginsky Range. The use of a great volume of additional information significantly increased its diagnostic possibility. As is seen from Fig. 10a, the basalts of the studied areas form a common trend of positive Yb–Ce correlation with the most evolved data points of the Sredinny Range rocks containing no liquidus olivine and the least evolved data points being those of the volcanic rocks of the Tumrok and Sharomsky

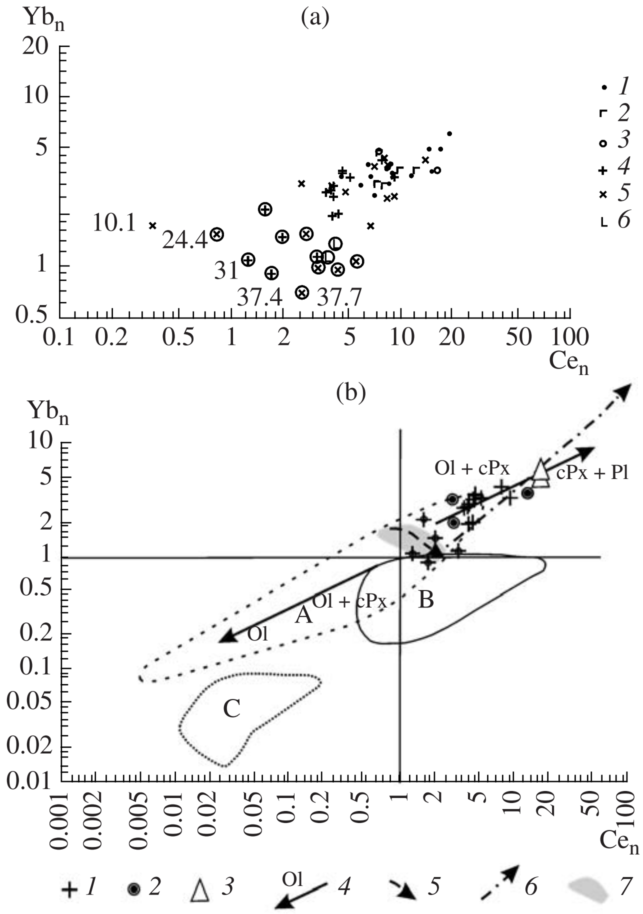

Fig. 10. Diagram of Yb$_n$–Ce$_n$ for the Upper Cretaceous–Paleocene rocks of Kamchatka.

(a) data on entire volcanogenic complexes, (*1–6*) the same as in Fig. 7. The circled symbols denote meymechite–picrite association of the corresponding areas, and the numbers near the symbols are the MgO content (wt %, water-free base).

(b) data on the volcanics of the Tumrok Range with additional fields. (*1*) bulk composition (the crosses with spots are meymechite–picrite association); (*2–3*) melt inclusions in olivine (*2*) and clinopyroxene (*3*) phenocrysts. In addition to the data from Table 2, we used materials from [20, 22]. (*4–6*) compositional trends (with accumulation of the corresponding minerals) for the rocks of plutonic or volcanic complexes of subalkali series (*4*), increasing Mg# in the rocks of the meymechite–picrite association (*5*), compositional evolution of the rocks of the Skaergaard massif (*6*), (*7*) field of the inferred compositions of the parental melts for both complexes of subalkali series. Compositional fields: (A) plutonic rocks of subalkali series, (B) Sp-peridotite xenoliths of the Veneto volcanic province (Italy), (C) alpine-type ultrabasic massifs (Poputnaya and Krysha mountains, Fig. 3). Data from [19, 22–24] and unpublished materials of A.V. Koloskov were used. Elements were normalized in accordance with [25]. The Yb–Ce correlations in the pyrolite are shown after [25].

cape (with phenocrysts of olivine and clinopyroxene). The data points of the meymechite–picrite association extend as a field across the data points of this sequence, demonstrating the independent trend of increasing Mg# with negative Yb–Ce correlation. Let us consider separately the basalts of the Tumrok Range, including the data on the composition of melt inclusions in the phenocryst minerals from picrites (Fig. 10b). The data points of the melt inclusions are plotted at the same basaltic trend, completely overlapping its values. The most evolved compositions correspond to the melts that are in equilibrium with clinopyroxene phenocrysts (the subliquidus assemblage). The compositional field of the subalkali plutonic complex, on the one hand, is extended along the same trend and directed toward the accumulation of olivine (the transition to dunites) and, on the other hand, toward the predominance of pyroxene and plagioclase (the formation of wehrlites, pyroxenites, and gabbroids), as is shown by the arrows. This field is significantly shifted relative to the field of alpine-type ultrabasic rocks, once more emphasizing the differences in their formational affiliation. The "strict" mineralogical control suggests that the entire basaltic trend results from the crystallization differentiation of the melts with the subsequent settlement of olivine and clinopyroxene plus plagioclase. This assumption is also confirmed by the similar trend in the variations of the corresponding components during the fractional crystallization of the melts of the Skaergaard Massif. A trend of negative correlation for the meymechite–picrite association is directed toward the field of metasomatically altered spinel peridotites from deep-seated xenoliths in the basanites of the Veneto province (Italy). These rocks demonstrate an increase in Mg# at a practically constant mineralogical composition, which can be related to the different degree of melting of mantle source, while the unusual accumulation of LREE is the result of the deep-seated metasomatism, as was supposed for xenoliths in the basanites of Italy or for the manifestations of the Cretaceous–Paleogene magmatism of the Sredinny Range with the participation of transmagmatic fluids [9, 19]. The area with the highest Fe compositions of the rocks of the meymechite–picrite association (MgO = 24–37) within the "A" field in Fig. 10b was taken as the possible compositions of parental magmas for the volcanic and plutonic complexes. Judging from the composition of the deep-seated inclusions in the meymechite tuffs of Kamchatka [12], the parental melts were formed in the garnet stability field.

Role of Additional Factors

We cannot exclude the contribution of boninite-like parental melts in the genesis of the considered volcanic rocks, but rocks of such composition are not known in this area. This implies the influence of an additional alkali factor at the earliest stages of the evolution of the corresponding melts. However, it should be noted that its role varies in the different regions and during the formation of the different rock series. Against the background of the elevated alkalinity of initial melts (leucite inclusions in the pyroxene phenocrysts from the shonkinite porphyry), this component increases during the crystallization differentiation of the rocks. In some cases, however, this pattern is disturbed either owing to the significant accumulation of alkalis (mainly potassium) or a sharp change in the trends for individual elements. For instance, a sharp increase in the K alkalinity simultaneously with elevated Rb, Zr, and Y contents in the lamproite-like rocks of one of the areas of the Valaginsky Range [13] indicates the local contribution of an additional source—possibly, fluid enrichment of initial melts. The potassic alkali series of the Sredinny range is more differentiated than the shoshonite series. The contents of some elements (Ba, Sr, Hf) in the rocks of this series are beyond the ranges typical of the rocks of the plutonic complex, presumably indicating a significant contribution of alkali fluid enrichment. The rocks of the shoshonite series of the Sredinny Range show a disturbance in the trend of subsequent increase of concentrations of some elements (Nb, Hf, Zr, Sr, and Ti) during the crystallization differentiation. Judging from a set of the elements, an additional source of fluid–melt type can be inferred for these rocks.

Fluid Regime of Magma Generation

The parental melts were presumably enriched in fluid components. This follows from the fact that practically all the rock varieties contain numerous pores and amygdales often filled with hydrothermal minerals. The melt inclusions in picrite minerals [23] have elevated Cl contents, which are significantly higher than those in any known "primitive melts." Note that the water content in the Kamchatka ultrabasic melts is lower than that in the boninites and island arc tholeiites [23].

THE GEODYNAMIC SETTING AND THE INFERRED ENDOGENIC REGIME OF THE FORMATION OF THE LATE CRETACEOUS–EARLY PALEOCENE MAGMATIC SUBALALKALI FORMATION OF KAMCHATKA

Practically all available geodynamic interpretations suggest that the subalkali magmatism under consideration was formed in an island arc setting [5, 15, 18, 20, 23, and others]. At the same time, many scientists noted the "unusual character" of this magmatism. Some researchers argue that the subalkali basaltic and alkali ultrabasic volcanism of Kamchatka was formed within a wide submarine plateau on the oceanizied continental crust [13]. The "island arc geodynamics" is supported by the trace element composition of the volcanic rocks: low HFSE contents, high LILE contents, and an elevated role of the fluid component in the melts. However, similar characteristics are typical of volcanic manifestations in distinct geodynamic settings, for instance, on the continental margin.

The weak transverse zoning observed in Kamchatka is typical of "subprasubduction volcanism." It is also known that the alkali rocks in the island arc systems commonly occur in the rear zones. In the studied area, however, the uniform subalkali magmatism slightly varying in terms of the alkali content, Mg#, and other components spans large areas. In addition, its basic and, in some areas, alkali ultrabaisc composition is not typical of the continental margin.

We can agree with the concepts in [3] that the considered magmatic rock complexes are related to some transitional setting. However, the question arises of transition between which geodynamic regimes is observed. In the indicated work, the change of the endogenous regimes is considered in the frameworks of the evolution of the continental crust at the expense of the oceanic margin. This conclusion, however, is inconsistent with the presence of continental blocks in the form of crystalline massifs of the Sredinny, Ganal'sky, and Khavyven uplifts surrounded by the later mafic volcanic belts.

The ideas of the basification of the continental crust proposed by Belousov [2] and developed in [13] seem to be more probable. The formation of the considered magmatic complexes presumably should be ascribed to this transition period. Also note the different structural control in the volcanic manifestations in different regions of Kamchatka. Within the eastern ranges, the magmatism (mainly volcanism) occurred in the relatively stationary setting of rigid structures and riftogenesis. The Sredinny Range at that time was characterized by a nonstationary setting of folding and faulting (thrusting?), which facilitated the formation of intermediate chambers (a large amount of fairly large intrusive massifs) and the appearance of magmatism both in the volcanic and plutonic form. This explains the significant differences in the composition of the volcanic products: the formation of more differentiated products at different lithospheric levels in the Sredinny Range and less differentiated rocks (close to the composition of the primary melt) in Eastern Kamchatka.

CONCLUSIONS

(1) The analysis of new analytical data, together with already published materials on the volcanic rocks, as well as plutonic rocks of close composition and age, made it possible to establish that the considered basaltoids are ascribed to the subalkali basalt–trachybasaltic andesite series with deviations toward the meymechite–picrite rock association.

(2) The magmatic complexes show intricate geochemical zoning. In the Valaginsky–Tumrok–Sredinny Range, the alkalinity of the rocks increases simultaneously with the increase of the Rb content, while the contents of HFSE and radioactive elements decrease and again increase.

(3) Two trends are identified in the Yb_n–Ce_n diagram: a positive trend spanning most of the compositions of the volcanic and plutonic rocks and a negative

trend defined by the meymechite–picrite association. The former trend reflects the direction of the rock evolution during the crystallization differentiation, while the latter trend illustrates the different degree of melting of the initial protolith and the contribution of deep-seated alkali metasomatism.

(4) The composition of the initial melts was determined by the influence of two factors: (a) the generation from the mantle protolith that was depleted in the Nd and Sr isotopic composition and Ti, Ta, and Nb and enriched in Ba, Sr, Rb, Zr, and Y and (b) the influx of LREE, Ti, Nb, Ta, K, Hf, Zr, Sp, and P with the deep seated melts and fluids.

(5) The observed differences in the composition of the rocks of both the volcanic and plutonic complexes are related mainly to the crystallization differentiation; the mantle melts were not contaminated by crustal material.

(6) Certain differences in the composition of the volcanic rocks from the eastern ranges and the Sredinny Range of Kamchatka, on the one hand, were caused by the different degree of magmatic differentiation (the role of intermediate chambers for magmatism in Central Kamchatka) and, on the other hand, by the influence of an "additional component," which defined the geochemical specifics of the shoshonite series of the Kirganik Formation.

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