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Geodynamic Conditions of Volcanism and Magma Formation in the Kurile–Kamchatka Island-Arc System

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Abstract—The conditions of magma formation were reconstructed on the basis of characteristic features of the evolution of the Kurile–Kamchatka island-arc system, structural and chemical zoning patterns of volcanic complexes, and available published data on peridotite and basalt melting and stability of hydrous minerals. It was shown that the volcanic arc of the Sredinnyi Range of Kamchatka occurs now at the final stage of subduction, whereas subduction beneath the volcanic arc of eastern Kamchatka began at the end of the Miocene, after its jump into the present-day position. The volcanism of Southern Kamchatka and the Kuriles has occurred under steady-state subduction conditions since the Miocene and is represented by typical island-arc magmas. The latter are generated in a mantle wedge, where the melting of water-saturated peridotite occurs in a high-temperature zone under the influence of fluid. The formation of the frontal and rear volcanic zones was related to the existence of two levels of water release from various hydrous minerals. During the initial and final stages of subduction, as well as in the zone of Kamchatka–Aleutian junction, partial melting is possible in the upper part of the subducted slab in contact with a hotter mantle material compared with the mantle in a steady-state regime. This is responsible for the coexistence of predominant typical island-arc rocks, rocks with intraplate geochemical signatures, and highly magnesian rocks, including adakites.

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INTRODUCTION

The formation of magmas in island arcs is among the most important problems of modern petrology. In contrast to divergent plate boundaries (rift zones), where the material of the upper mantle melts in response to a pressure decrease (decompression melting), melting in subduction zones may involve to a varying degree both the metamorphosed material of the mantle wedge under the influence of fluid flows and decompression due to convective upwelling and the upper part of the subducted lithospheric plate at the expense of additional heating.

Since the advent of the subduction model, two main opinions have been developed on the process of melting and magma generation (Green, 1980; Gill, 1981; Tatsumi, 1989; Avdeiko, 1994). According to one of them, melting is mainly due to additional heating by friction; some authors believe that melting is restricted to the subducted oceanic crust (Marsh and Carmichael, 1974; Brophy and Marsh, 1986), and others suppose the involvement of both the oceanic crust and the base of the mantle wedge (Nichols and Ringwood, 1978; Kay, 1980). According to the other opinion, the material of the mantle wedge is melted under the influence of water and other volatile components released from the underthrust oceanic crust (Kushiro, 1975; Gill, 1981; Tatsumi, 1989). The latter model has gained support in almost all island arcs, including the Kuriles (Popolitov and Volynets, 1981; Avdeiko, 1994).

On the other hand, it has recently been shown that the most abundant island-arc lavas formed by fluid-induced melting of the mantle wedge, i.e., in accordance with the second model, may coexist under certain geodynamic conditions with peculiar magnesian calc-alkaline rocks, adakites, which are thought to be generated by partial melting in the oceanic crust (Defant and Drummond, 1990; Peacock et al., 1994; Yogodzinski et al., 1995, 2001).

The Kurile–Kamchatka island-arc system is a suitable place for the reconstruction of geodynamic conditions of magma generation. This region hosts a variety of island-arc series of volcanic rocks (Fig. 1), including adakite-type rocks, which are presumably related to the melting of subducted crust. Typical island-arc series are often accompanied by small amounts of rocks with intraplate geochemical signatures (Volynets, 1994). The Kurile–Kamchatka island-arc system is also characterized by variable structural and tectonic conditions of volcanic occurrences and geodynamic parameters of subduction. First, there are segments with steady-state subduction (Kuriles and Southern Kamchatka), as well as those assigned to the initial (Eastern Kamchatka) and final (Sredinnyi Range) stages of subduction (Avdeiko et al., 2002). Second, the typical island arc of the Kurile segment is changed along the strike by the active conti-

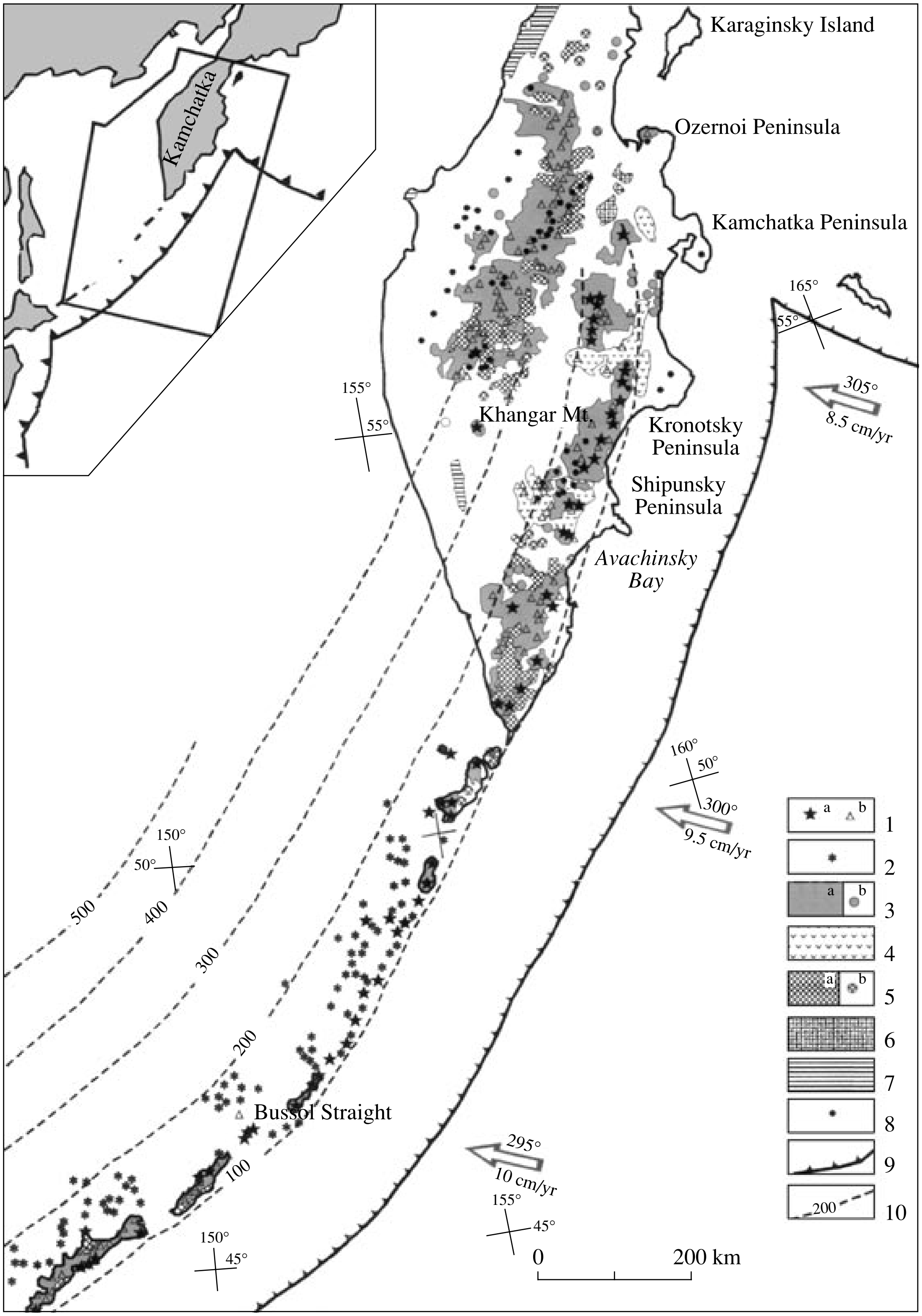

Fig. 1. Spatial distribution of Cenozoic autochthonous volcanic associations in the Kurile–Kamchatka island-arc system, modified after Avdeiko et al. (2002). (1) Subaerial (a) active and (b) extinct volcanoes; (2) submarine volcano; (3) area of (a) occurrence and (b) local exposures of Quaternary volcanic associations; (4) Pliocene–Eopleistocene volcanic associations; (5) area of (a) occurrence and (b) local exposures of Miocene–Pliocene volcanic associations; (6) Eocene–Oligocene volcanic associations of the Kamchatka–Aleutian junction; (7) Paleogene volcanic associations; (8) local exposures of volcanic rocks with intraplate geochemical characteristics (Volynets, 1994); (9) trench axis; and (10) isoline of the depth of the seismic zone (upper boundary of the subducted Pacific plate).

nental margin of the Kamchatka segment. Third, there are segments with normal and oblique subduction, segments with normal and thickened oceanic crust in the underthrust Pacific plate, and the junction zone between the Kurile–Kamchatka and Aleutian arcs and the transform boundary between the Pacific and North American plates.

This paper is an attempt at systematizing spatial structural, petrological, and geochemical data as well as evidence on the evolution of volcanism in order to reconstruct the geodynamic conditions of formation of various rock types in the Kurile–Kamchatka island-arc system. The material presented in this paper was obtained mainly by the authors during the investigation of submarine and subaerial volcanoes of the Kurile island arc in nine cruises of the R/V *Vulkanolog* and the investigation of volcanism at the Aleutian–Kamchatka junction in the framework of the Russian–German project KOMEX-2.

STRUCTURAL AND TECTONIC CONDITIONS OF THE OCCURRENCE OF CENOZOIC VOLCANISM

Volcanic Arcs

The present structure of the Kurile–Kamchatka region is composed of volcanic belts of various ages. These belts are autochthonous volcanic arcs or their fragments formed above subduction zones (Avdeiko et al., 2002). Let us consider briefly their main features important for the reconstruction of the geodynamic conditions of magma formation.

Three main volcanic complexes of different ages were formed in the Cenozoic above subduction zones in Kamchatka (Fig. 1). The oldest Eocene–Oligocene complex makes up a volcanoplutonic belt in the Western Kamchatka–Koryak continental margin, which was described in detail by Filatova (1988). The southwestern branch of this belt is known as the Western Kamchatka volcanic arc. The Kinkil volcanic complex of this arc is a 1500–1800 m thick differentiated suite ranging from basalt to rhyolite and dominated by intermediate and silicic volcanics. Volcanoplutonic facies are often more abundant than volcanic facies in this arc, especially in its southwestern segment, where volcanic facies are only sporadically exposed.

A Neogene–Quaternary subduction complex of volcanic and, occasionally, intrusive rocks is widespread in the Sredinnyi Range of Kamchatka, Southern Kamchatka, and some islands of the Kuriles. This complex is composed of both normal series rocks ranging from basalt to dacite and rhyolite, with the most common composition being andesite, and alkaline rocks: trachybasalt, trachyandesite, etc. These rocks mark a system of two volcanic arcs: Central Kamchatka and Southern Kamchatka–Kurile (Avdeiko et al., 2002), which were initiated in the late Oligocene and early Miocene and have developed up to the Recent.

Sheimovich and Patoka (2000) distinguished six volcanic associations in the igneous complexes of the Sredinnyi Range and Southern Kamchatka (named after the predominant rock type): Miocene andesites, Miocene–Pliocene rhyolites and dacites, Pliocene basaltic andesites, early Pleistocene basalts, Pleistocene–Holocene basaltic andesites (including all active volcanoes), and Holocene basalts (areal volcanism). Except for the rhyolite–dacite and areal basaltic volcanic associations, each particular association is represented by a differentiated series of volcanic rocks from basalt to rhyolite, and intrusive facies from gabbro to granite are widespread in the Miocene–Pliocene associations. Active subduction-type volcanism is at present widespread in Southern Kamchatka, whereas the volcanic activity of the Sredinnyi Range practically terminated in the Holocene. Only Ichinskii and Khangar volcanoes are still potentially active (Melekestsev et al., 2001).

The Greater Kurile Range contains volcanic complexes of similar compositions and ages (*Geological and…*, 1987): green tuff, volcanic–siliceous–diatom, basaltic andesite, and andesite complexes. The former three complexes are of Cenozoic age and occur only in the flanks of the Greater Kurile Range: in Shumshu and Paramushir islands of the northern Kuriles and in Urup, Iturup, and Kunashir islands of the southern Kuriles. The oldest among them is the green tuff complex of Oligocene(?)–middle Miocene age, the volcanic rocks of which are represented by lavas and lava breccias of basalt, andesite, and dacite compositions. Intrusive rocks are represented by quartz diorites only. In contrast to the association of Southern Kamchatka and, especially, the Sredinnyi Range, the volcanics of the Kuriles show definite indications of submarine eruptions. The andesite complex of the Kuriles is represented by Quaternary volcanoes, many of which are still active.

In contrast to the Sredinnyi Range, Southern Kamchatka, and the Kuriles, there are no subduction-related volcanic rocks of Oligocene–Miocene age in Eastern Kamchatka, including the Central Kamchatka Depression. There is a group of Pliocene–Pleistocene volcanic rocks, including basalts, andesites, and dacites in varying proportions and their subvolcanic facies. Similar to the Kuriles, the andesite association is represented by Quaternary volcanoes, including active ones (Fig. 1).

In general, the volcanic arcs of Kamchatka and the Kuriles are characterized by the occurrence of diverse volcanic rocks, among which differentiated igneous series are distinguished: from island-arc tholeiites typical of ensimatic (intraoceanic) island arcs to calc-alkaline series most common in the ensialic island arcs (Bogatikov and Tsvetkov, 1988). The comprehensive petrochemical and geochemical characteristics of island-arc associations of Kamchatka and the Kuriles were reported in a number of publications (Volynets et al., 1990b; Volynets, 1994; Avdeiko et al., 1991; etc.).

Basaltic andesites and andesites are predominant in the Kuriles (60–70%), and the volcanic complexes of Kamchatka contain more basalts (~50%) and felsic rocks compared with the Kuriles.

Thus, three subduction complexes of volcanic associations occur within the Kurile–Kamchatka island-arc system; their age decreases gradually toward the Pacific Ocean. In addition, the predominant island-arc rocks are often accompanied in the Sredinnyi Range and Eastern Kamchatka by sporadic occurrences of volcanics with intraplate geochemical characteristics (Volynets, 1994).

A more complicated situation was observed at the Aleutian–Kamchatka junction, where volcanic rocks with typical island-arc and intraplate geochemical characteristics associate with adakite-type rocks. The spatial arrangement of volcanic complexes with a decrease in age toward the Pacific Ocean is disturbed in the northern margin of the Central Kamchatka Depression by island-arc rocks of Eocene–Oligocene age (Fig. 1). These rocks were in part described by Portnyagin et al. (2005).

Basement of Volcanic Arcs

The basement of the Cenozoic subduction-related volcanic arcs has a complex heterogeneous structure, which comprises accretionary complexes (terranes) formed in different geodynamic settings. The reconstruction of the history of tectonic development must account for the fact that each arc has its own basement different from the basements of older and younger conjugate arcs, although the compositions of rocks and even their ages are often similar. This is explained by the fact that only a negatively buoyant lithospheric plate with oceanic crust can be subducted. If a plate with continental crust of any origin or with thickened oceanic crust approaches a subduction zone, collision and blocking of the subduction zone occur, and a new subduction zone or its segment can be generated. Several collisional stages produced a thrust-and-fold structure including ophiolite oceanic complexes of island arcs, marginal seas, and forearc basins, as well as metamorphic complexes of controversial age (*Explanatory Notes…*, 2000; *Map of…*, 1999).

The basement of the Western Kamchatka arc includes thick terrigenous sequences (Lesnovskaya, Omgonskaya, and Kikhchikskaya groups), which were formed in the Cretaceous under continental-shelf and marginal-sea conditions. Layers of cherty and siliceous volcanic rocks appear in the upper parts of the section. The basement of the Central Kamchatka arc is composed mainly of volcanic deposits (Irunei and Kirganik formations) and metamorphic rocks of the Sredinnyi Range in the south. The basement of Eastern Kamchatka is composed of Cretaceous–Paleogene volcanic, volcanosedimentary, and terrigenous complexes accumulated under conditions of an island arc, back-arc, and forearc basins. The complexes formed in various facies of the island-arc system are tectonically juxtaposed and make up nappe and imbricate structures of individual highs (*Accretionary Tectonics…*, 1993). Of particular importance is also serpentinite mélange, which occurs in the structure of particular slices or separates the slices.

The allochthonous complexes of the eastern peninsulas (Kamchatka, Kronotsky, and Shipunsky) compose a frontal (tectonic) arc in the present structure. This area includes island-arc series, which had been formed without any structural changes from the Late Cretaceous to the end of the Eocene. Their basement was composed of Early Cretaceous oceanic complexes. The peninsulas are separated from the eastern ranges by the extended Tyushevskii Depression filled mainly with terrigenous deposits varying in age from the Eocene to the Miocene. There are two opinions on the timing of accretion of the Kronotsky island arc to the previously formed continental margin. Some authors (Zinkevich and Tsukanov, 1992) argued that this event coincided with the major structural rearrangement of the whole margin during the middle Eocene compressional stage. According to the other opinion (Konstantinovskaya, 1999), the closing of the Tyushevskii Depression and accretion of the eastern peninsulas occurred in the late Miocene, which resulted in tectonic overthrusting of the Oligocene–Miocene deposits of the depression by the Paleocene–Eocene Vetlovskii complex along the Grechishkin thrust. The latter scenario seems to be more plausible.

Evolution of Volcanic Arcs

The presented data on the spatial distribution of island-arc associations, as well as seismic, gravimetric, and seismic tomography observations allow us to interpret the tectonic history of the region as a development of discrete island-arc systems decreasing in age toward the Pacific Ocean. Figure 2 presents a model of their evolution starting from the end of the Oligocene on a map and sections corresponding to various time periods. Western Kamchatka probably comprised a system of volcanic arcs in the Paleogene. They are now represented by discrete fragments of volcanic sheets. Filatova (1988) interpreted them as a subduction-related continental margin volcanic belt.

Since the end of the Oligocene, a system of two arcs has existed in Kamchatka and the Kuriles (Central Kamchatka and southern Kamchatka–Kuriles) separated by transform faults (Fig. 2). South of the junction with the Aleutian arc, the formation of this system was controlled by the subduction of the Pacific plate, and in the north, by the subduction of the young Komandor plate. These arcs are marked in the present structure by corresponding associations of volcanic rocks (Fig. 1) and a positive gravity anomaly in the frontal tectonic arc (Avdeiko et al., 2002; Fig. 2).

In the end of the Miocene, a jump of the subduction zone occurred, and the present structure of the Kurile–

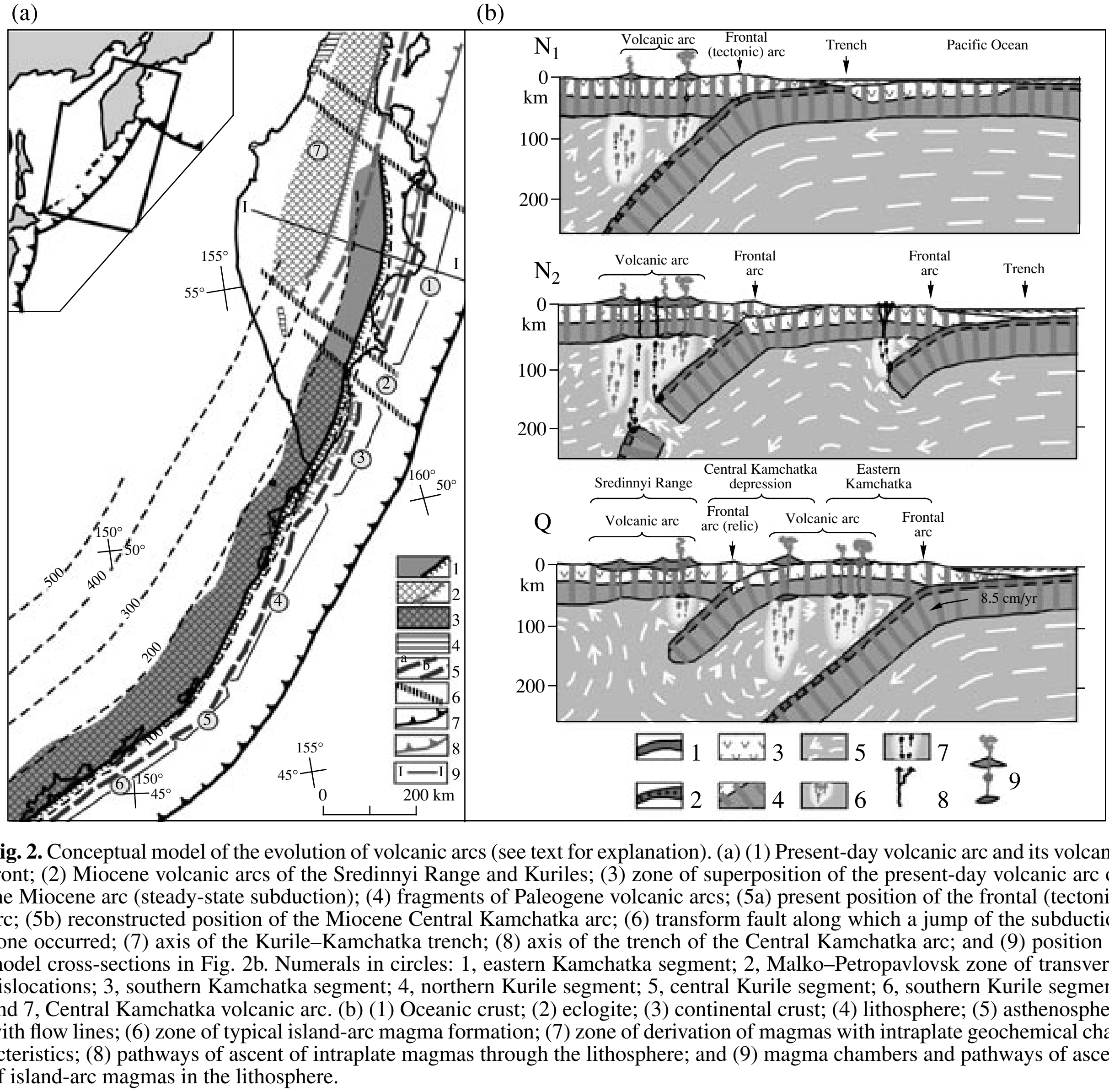

Fig. 2. Conceptual model of the evolution of volcanic arcs (see text for explanation). (a) (1) Present-day volcanic arc and its volcanic front; (2) Miocene volcanic arcs of the Sredinnyi Range and Kuriles; (3) zone of superposition of the present-day volcanic arc on the Miocene arc (steady-state subduction); (4) fragments of Paleogene volcanic arcs; (5a) present position of the frontal (tectonic) arc; (5b) reconstructed position of the Miocene Central Kamchatka arc; (6) transform fault along which a jump of the subduction zone occurred; (7) axis of the Kurile–Kamchatka trench; (8) axis of the trench of the Central Kamchatka arc; and (9) position of model cross-sections in Fig. 2b. Numerals in circles: 1, eastern Kamchatka segment; 2, Malko–Petropavlovsk zone of transverse dislocations; 3, southern Kamchatka segment; 4, northern Kurile segment; 5, central Kurile segment; 6, southern Kurile segment; and 7, Central Kamchatka volcanic arc. (b) (1) Oceanic crust; (2) eclogite; (3) continental crust; (4) lithosphere; (5) asthenosphere with flow lines; (6) zone of typical island-arc magma formation; (7) zone of derivation of magmas with intraplate geochemical characteristics; (8) pathways of ascent of intraplate magmas through the lithosphere; and (9) magma chambers and pathways of ascent of island-arc magmas in the lithosphere.

Kamchatka island-arc system was formed. The main reason for the jump is the accretion of the Kronotsky paleoarc, which composes a terrane of the eastern peninsulas in the present structure of Kamchatka (Konstantinovskaya, 1999; *Explanatory Notes…*, 2000). Thick volcanic and terrigenous complexes of this paleoarc and its root systems made up the upper part of the Pacific plate and probably provided its positive buoyancy (Fig. 2). The blocking of the subduction zone was probably aided by the previously accreted complexes of the Achaivayam–Valaginskii paleoarc (*Accretionary Tectonics…*, 1993; Konstantinovskaya, 1999), which are now included in the allochthonous basement of the Eastern Kamchatka volcanic arc (Avdeiko et al., 2002). Subduction beneath the Sredinnyi Range gradually ceased after the jump.

There are two possible scenarios for the termination of subduction: (1) gradual cessation of the movement of the subducted oceanic slab without its further descent and (2) detachment and descent into the mantle of the heavier part of the oceanic slab below the basalt–eclogite transition zone (~150 km) with the influx of hotter mantle material from beneath the slab into the mantle wedge through the resulting slab window. The results of seismic tomography suggest that the latter scenario operated in the Sredinnyi Range. In this zone, an isolated body with high P-wave velocity was detected at depths of 600–1000 km (Gorbatov et al., 2000; Fig. 7, section *E–E'*). This body can be interpreted as a detached fragment of the Pacific plate. Given a convergence rate of 7.6 cm/yr (Gorbatov and Kostoglodov, 1997), the upper margin of the high-velocity body had to descent to a depth of about 600 km

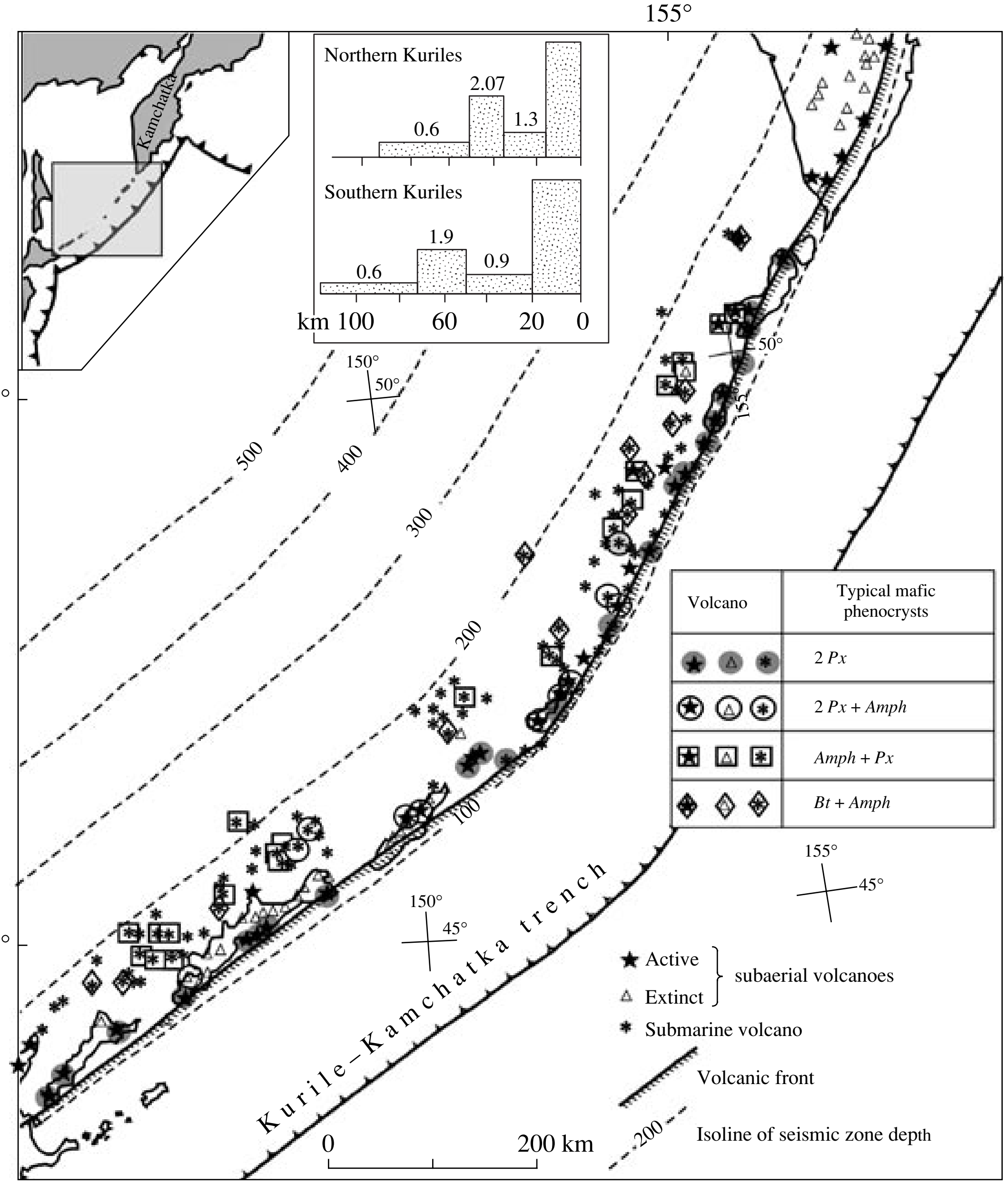

Fig. 3. Mineralogical characteristics of the subaerial and submarine volcanoes of the Kurile island arc. The inset shows histograms for the number of volcanic centers per 1000 km^2 across the Kurile arc relative to the distance of the volcanic front (Avdeiko et al., 1991).

within 9–10 Myr, which is in agreement with the age of the onset of subduction beneath Eastern Kamchatka. In the *D–D'* section through Southern Kamchatka, there was neither subduction zone jump nor slab rupture, and the frontal margin of the Pacific plate descended to the same depth of 1000 km. The rupture and formation of a slab window in the Pacific plate are shown in the section for Pliocene time (Fig. 2b).

Figure 2a shows the segments that were distinguished in the Kurile–Kamchatka island-arc system.

Eastern Kamchatka (segment *1*, Fig. 2a) represents the initial stage of subduction. The age of the oldest volcanic rocks formed above the subduction zone corresponds to the end of the Miocene (Volynets et al., 1990b). However, subduction probably began earlier, about 10 Ma ago, because the leading edge of a subducted slab descends to a depth of 110 ± 5 km, where magma is formed, within 2.8–2.9 Myr. This estimate is based on the analysis of geodynamic parameters, which will be considered below.

In Southern Kamchatka (segment *3*) and the Kuriles (segments *4–6*), an almost steady-state subduction regime has been established since the end of the Oligocene (approximately 25 Ma). There is an anomalous

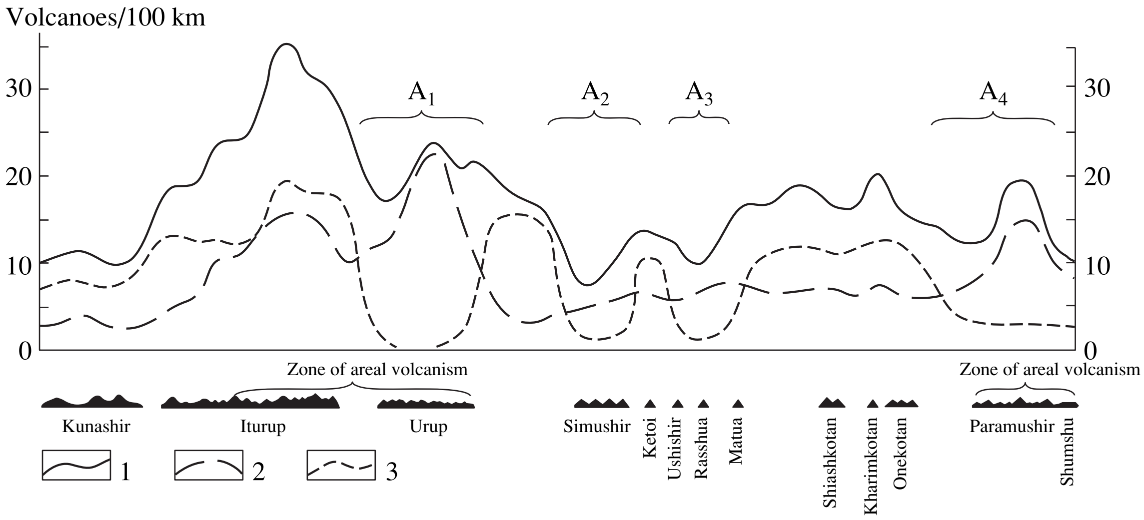

Fig. 4. Number of volcanic centers per 100 km along the Kurile island arc, modified after *Submarine Volcanism…* (1992). (1) For the whole arc; (2) for the frontal zone, and (3) for the rear zone. A_1, A_2, A_3, and A_4 are the nonvolcanic areas in the rear zone.

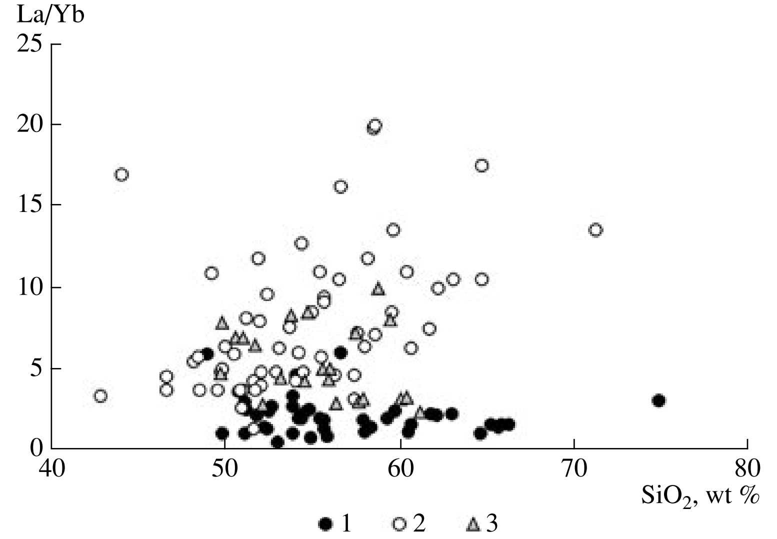

Fig. 5. Diagram of La/Yb versus SiO_2 for the Quaternary lavas of the Kurile island arc, modified after Avdeiko et al. (1991). (1) Volcanoes of the frontal zone, (2) volcanoes of the rear zone, and (3) volcanoes of the transitional zone.

area known as the Malko–Petropavlovsk zone of transverse dislocations (segment *2*), which is located at the place where a system of transform faults occurred at the southern boundary of the jump of the subduction zone in the end of the Miocene.

After the jump of the Central Kamchatka volcanic arc to its present-day position, it represents the stage of subduction termination and, correspondingly, the attenuation of subduction-related volcanism (Fig. 2b).

GEODYNAMIC PARAMETERS OF VOLCANISM

The geodynamic parameters of magma formation and volcanism are largely controlled by the characteristics of the subducted plate. The most important among them are the depths of the upper boundary of the subducted slab, i.e., of the roof of the seismic zone, beneath the volcanic front and beneath the volcanoes of the rear zone most distant from the volcanic front, because they constrain the conditions of magma formation in the mantle wedge (Tatsumi, 1989; Avdeiko, 1994). The same parameters and the slope of the subduction slab control the width of the volcanic arc (belt) and the presence or absence of frontal and rear volcanic zones (Avdeiko, 1994). Another important parameter for retrieving magma formation conditions is the distance between the trench axis and the zone of a sharp increase in the slope of the subducted slab. These parameters define the path length of the slab from the beginning of its subduction, i.e., from the trench axis, to the zone of

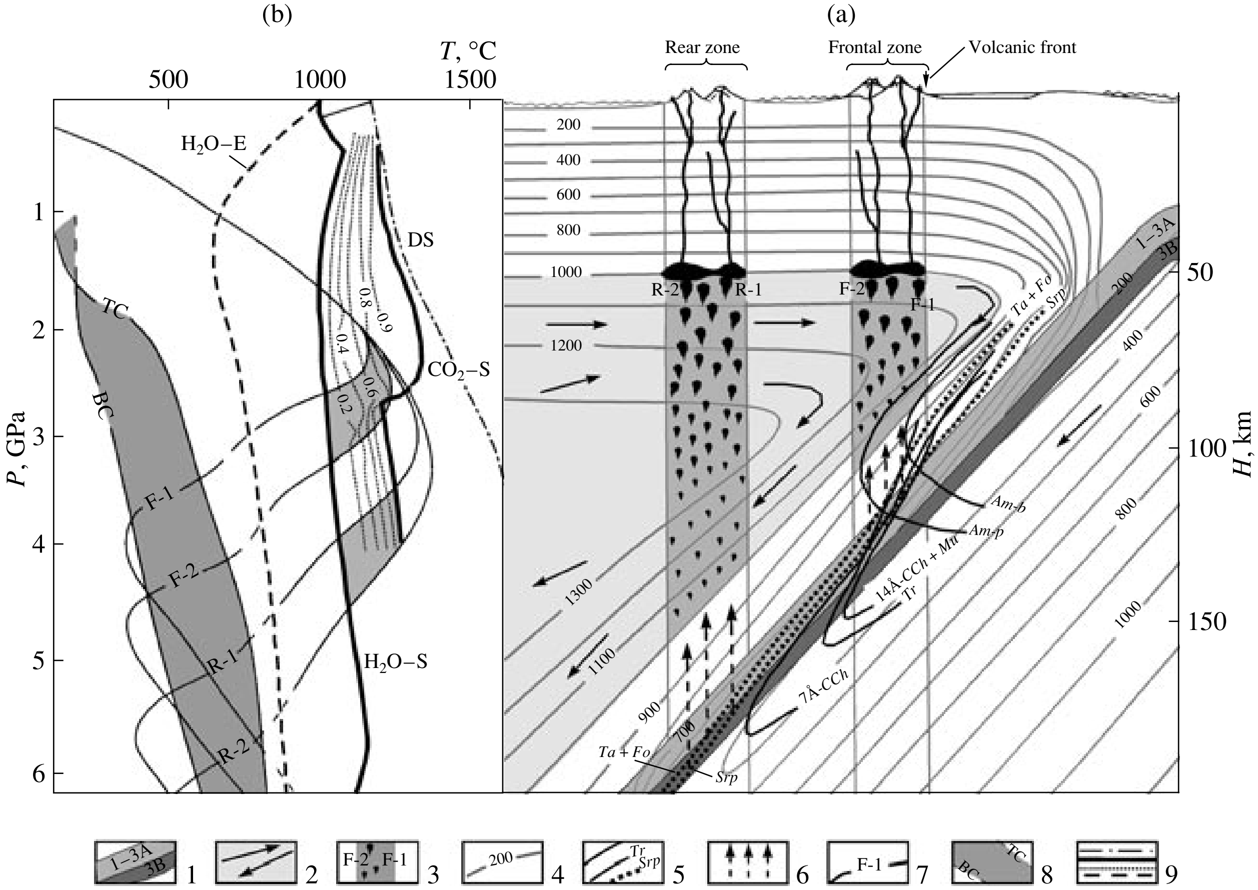

Fig. 6. Conditions of magma formation beneath the Kurile island arc, modified after Avdeiko (1994). (a) (1) Oceanic crust layers; (2) direction of material movement in the mantle wedge and suprasubduction mantle; (3) zones of magma formation beneath the frontal (F-1 and F-2) and rear (R-1 and R-2) volcanic zones; (4) isotherms (Honda and Uyeda, 1983); (5) dehydration curves of hydrous minerals: *Am*-b, amphibole in basalt; *Am*-p, amphibole in peridotite; 7Å-CCh, 7Å clinochlore; 14Å-*CCh* + *Mu*, 14Å clinochlore and muscovite; *Srp*, serpentine; *Ta* + *Fo*, talc + forsterite; and *Tr*, tremolite; and (6) pathways of fluid ascent. (b) (7) Geotherms beneath the frontal (F-1 and F-2) and rear (R-1 and R-2) volcanic zones; (8) geotherms for the top (TC) and bottom (BC) of the oceanic crust; (9) solidus lines for the dry mantle (DS), water-saturated mantle (H_2O–S), CO_2-saturated mantle (CO_2–S), mantle with various H_2O/CO_2 proportions (0.2–0.8), and water-saturated basalt or eclogite (H_2O–E).

magma formation beneath the volcanic front. The subduction velocity defines the travel time of the plate for this distance and the structure of the temperature field. This provides insight into the timing of the initial stage of subduction: the time of descent of the frontal edge of the subducted slab into the presumable magma formation zone must be added to the age of the oldest volcanic rocks.

The table presents the geodynamic parameters of the Quaternary volcanism of the Kurile–Kamchatka island-arc system according to Avdeiko et al. (2002) with some modifications and refinement on the rate of convergence (Gorbatov and Kostoglodov, 1997) and the geometry of the seismic zone (Fedotov et al., 1985). The table does not show data on the Central Kamchatka arc, because, in our opinion, it was formed above an independent, currently inactive subduction zone (Avdeiko et al., 2002). The available data are insufficient for the reconstruction of the geodynamic parameters of this arc, but they were probably similar to those of Eastern Kamchatka.

As can be seen from the table, the depth of the seismic zone beneath the volcanic front is almost constant at 110 ± 5 km, and the maximum depth beneath the most distant volcanoes from the volcanic front is no more than 220 km. It was previously shown that such depths of the seismic zone are favorable for melting in the mantle wedge owing to the release of volatiles, primarily water, from the subducted lithospheric plate (Avdeiko, 1994). The total width of the volcanic arc is usually no more than 100 km.

The rate of convergence of the Pacific and Eurasian plates ranges from 7.5 cm/yr at the latitude of the Kronotsky Peninsula to 8.2 cm/yr at the latitude of Kunashir Island (Gorbatov and Kostoglodov, 1997). These values and the distance from the trench axis to the volcanic front allow us to estimate the time of interaction between the surface of the Pacific plate with the

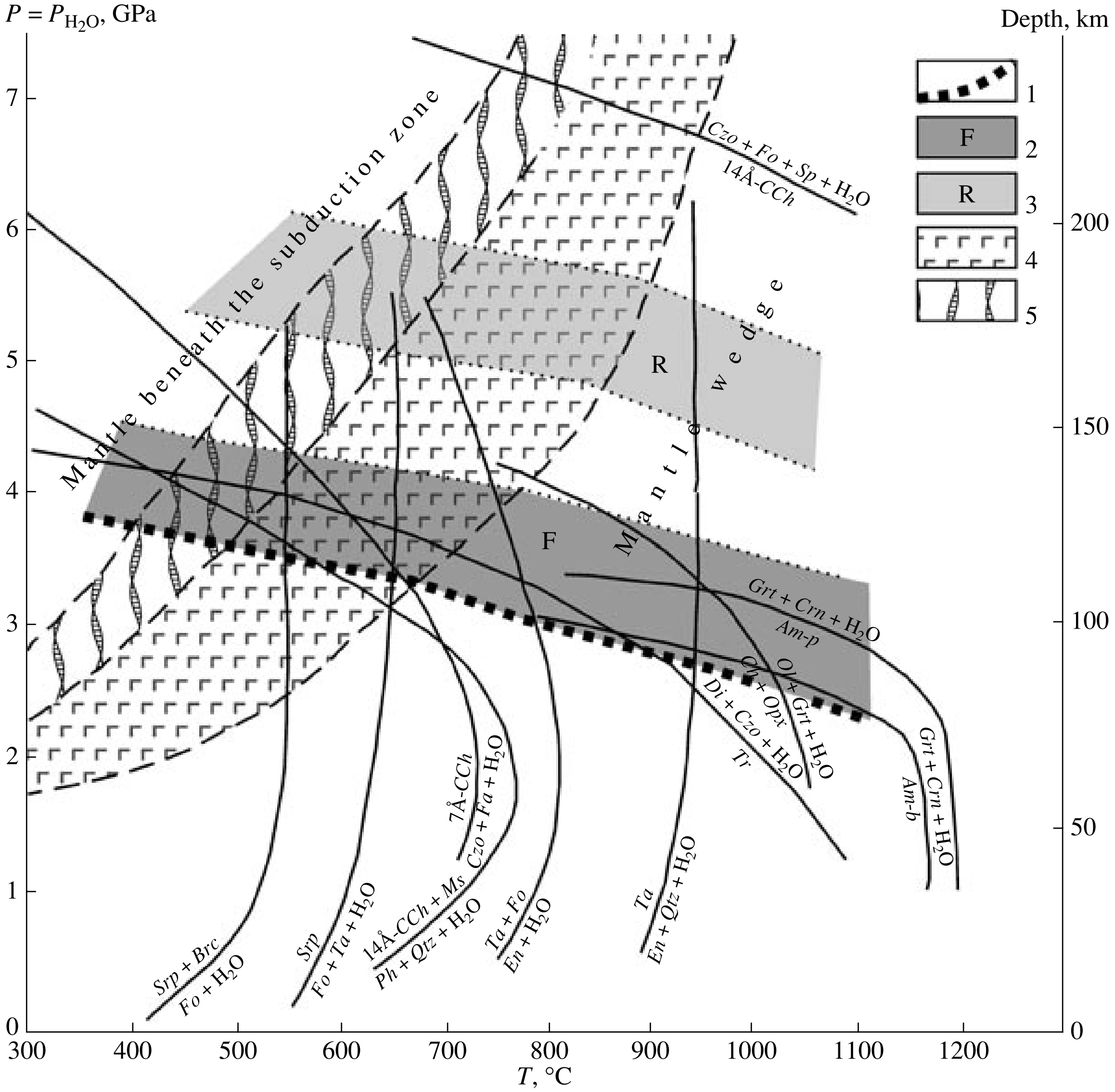

Fig. 7. *P–T* diagram of the stability (dehydration) of hydrous minerals. *P–T* characteristics of the (1) volcanic front, (2) frontal zone, (3) rear zone, (4) layers 1–3A (sediments, basalts, and gabbro) of the oceanic crust and (5) layer 3B (serpentinite) of the oceanic crust. Mineral abbreviations are after Kretz (1983) and Fig. 6.

Eurasian plate and the base of the mantle wedge before the onset of melting. This time ranges from 2.8–2.9 Myr for eastern Kamchatka to 3.0–3.2 Myr for the southern Kuriles.

QUATERNARY VOLCANISM OF THE KURILE–KAMCHATKA ARC

As was mentioned above, the Kurile and Southern Kamchatka segments of the arc are characterized by steady-state subduction and are made up of typical island-arc complexes. The main features of volcanism are discussed below by the example of the Kurile arc, which was extensively studied by us (*Submarine Volcanism…*, 1992; Avdeiko, 1994; Avdeiko et al., 1991).

Spatial and Structural Position of Volcanoes

Figure 3 shows the location of 105 active and extinct subaerial volcanoes and 93 submarine volcanoes. A characteristic feature of the spatial distribution of volcanoes is that almost all of them are clustered into chains oriented at varying angles to the general strike of the arc up to the formation of transverse volcanic zones. The linear chains are probably confined to faults acting as magma conduits.

An important structural characteristic is the position of the volcanic front relative to the trench and seismic zone. The spatial distribution of Quaternary volcanoes shows a transverse zoning expressed in variations in the density of volcanic centers across the strike of the arc (inset in Fig. 3). Both in the northern and southern Kuriles, there are frontal and rear volcanic zones sepa-

Geodynamic parameters of the occurrence of Quaternary volcanism in the Kurile–Kamchatka island-arc system

Geodynamic parameter	Eastern Kamchatka	Avachinsky Bay region	Southern Kamchatka	Northern Kuriles	Bussol Strait	Southern Kuriles
L_{min}, km	190–200	205	200–205	180–200	160	185–200
L_{dir}, km	190–200	205	200–205	185–205	175	215–255
L_b, km	130–140	145	140–145	135–145	140	140–155
V, cm/yr	7.6	7.6	7.7–7.8	7.9–8.0	8.1	8.2
$\alpha°$	80–90	90	85–90	76–85	74–51	45–50
$\beta°$	35–51	51	50–51	45–50	50	40–50
H_f, km	105–115	115	110	105–115	105	105–110
H_{max}, km	195	180	205	210	210	220
T, Ma	2.8–2.9	3.0	2.9–3.0	2.9–3.0	2.9	3.0–3.2
d, km	50–70	70	40–60	55–80	110	70–115
H, km	~40	42–47	40–45	25–35	27–30	25–45

Note: L_{min} and L_{dir} are the distances from the trench axis to the volcanic front (L_{min}, minimum, and L_{dir}, along the direction of Pacific plate motion); L_b is the distance from the trench axis to the sharp bend of the Pacific plate (increase in the slope of the seismic zone); V is the velocity of plate convergence (Gorbatov and Kostoglodov, 1997); $\alpha°$ is the angle between the direction of Pacific plate motion and the arc strike; $\beta°$ is the slope of the seismic zone at depths of 40–200 km; H_f and H_{max} are the depths of the subduction zone, beneath the volcanic front and the maximum value, respectively; T is the travel time of the plate from the onset of subduction to the descent to a depth of 105 km, i.e., beneath the volcanic front; d is the width of the volcanic arc; and H is the crust thickness.

rated by a zone of low volcanic activity and a zone of declining activity in the rear part of the arc. It is characteristic that the majority of volcanoes in the frontal zone (87%) are subaerial, whereas those in the rear zone are mostly submarine (83%). Thus, only a combined analysis of subaerial and submarine volcanoes may provide some realistic insight into their spatial distribution in the arc–trench system.

There are several characteristic features in the distribution of volcanoes along the arc. The number of volcanic centers per 100 km of arc length varies from 7 to 20 for the whole arc, increasing up to 36 in the regions of multi-vent volcanism (Fig. 4). The distribution of volcanoes is relatively uniform in the frontal zone (3–8 volcanoes per 100 km) except for the regions of multi-vent volcanism, whereas it is strongly nonuniform in the rear zone: nonvolcanic areas alternate with areas where the density of volcanic centers is much higher than in the frontal zone.

The existence of frontal and rear volcanic zones and the heterogeneous distribution of volcanoes along the arc suggest that the conditions of magma generation in the mantle wedge are the main controlling factor. The confinement of volcanoes to linear zones reflects the conditions of magma ascent in the lithosphere through fault-controlled magma conduits (*Submarine Volcanism…*, 1992).

Zoning in the Chemistry and Mineralogy of Lavas

Zoning in the composition of lavas and its relation to the depth of the seismic zone were discussed in a number of publications, including the book *Submarine Volcanism…* (1992), which focused on this problem. Some characteristics of the mineral composition of lavas are shown in Fig. 3. The lavas of the frontal zone are characterized by the two-pyroxene phenocryst assemblage, whereas similar lavas from the rear zone, including basalts, contain amphibole and biotite. Moreover, spinel occurs only in the lavas of the rear zone, where zircon is rather common. There are also significant differences in the composition of phenocrysts and microlites of plagioclase, olivine, and pyroxene (Volynets et al., 1990a).

Geochemical differences between the lavas of the frontal and rear zones are even more pronounced. The concentrations of K, Rb, Ba, Sr, F, Be, Nb, Zr, U, Th, Ni, Cr, and light REE increase, and those of Fe and V decrease from the frontal to the rear zone. The quantitative differences can be clearly seen in the primitive mantle-normalized diagrams for lithophile trace elements, and even the maximum concentrations of the large ion lithophile elements (LILE) and light rare earth elements (LREE) in the lavas of the frontal zone are lower than the minimum concentrations of these elements in the lavas of the rear zone (Avdeiko et al., 1991; Fig. 4).

The contrasting difference between the lavas of the frontal and rear zones can be illustrated by REE distribution (Fig. 5). The La/Yb ratio in the frontal zone is almost constant in lavas with various silica contents and in general lower than in the rear zone. The lavas of the rear zone show an increase in this ratio with increasing SiO_2 content. It is interesting that the lavas of the transitional zone fall within the fields of either the frontal or rear zone but not between the fields.

The zoning along and across the arc is manifested in strontium and neodymium isotopic ratios (Avdeiko et al., 1991). The lavas of the rear zone show lower average and minimum $^{87}Sr/^{86}Sr$ ratios; the lowest values were observed in the middle Kuriles, whereas $^{87}Sr/^{86}Sr$ tends to increase toward both Kamchatka and Japan (Avdeiko et al., 1991; Fig. 6). The lavas have mantle-like Sr and Nd isotopic signatures, whereas the lavas of the frontal zone show in general higher Sr and Nd isotopic ratios (Avdeiko et al., 1991; Fig. 7).

The observed contrasting character of the petrochemical and isotopic zoning and the confinement of volcanoes to the frontal and rear zones separated by the zone of low volcanic activity suggest that there are two zones of magma formation corresponding to two levels of water release from the subducted lithospheric slab (Avdeiko, 1994). The conditions of magma formation beneath the Kurile island arc, which occurs in the steady-state subduction regime, are discussed below.

MODEL OF MAGMA FORMATION BENEATH THE KURILE ISLAND ARC

Using the presented data on the volcanism of the Kurile island arc, experimental evidence on the melting of peridotite and basalt under various *P–T* conditions (Mysen and Boettcher, 1975; Wyllie, 1979; Lambert and Wyllie, 1972) and hydrous mineral stability (Kitahara et al., 1966; Delany and Helgeson, 1978; etc.), and numerical simulation of the structure of the temperature field in a subduction zone (Honda and Uyeda, 1983), Avdeiko (1994) proposed a model of magma formation beneath the Kurile island arc. The model is valid for the steady-state regimes of the majority of island arcs. The main parameters of volcanism that provided a basis for this model are briefly described here.

Transverse petrochemical and geochemical zoning is typical of the overwhelming majority of island arcs, including the volcanic arcs of the Kurile–Kamchatka system. A fundamentally new feature established by us for the Kurile island arc is that the transition from the frontal to the rear zone is not gradual but rather abrupt in some parameters. This is a key point allowing us to suppose the existence of two magma-generating zones (Avdeiko et al., 1991).

The distribution of temperature in a subduction zone and an overlying mantle wedge is the main control on the location of partial melting regions beneath an island arc. The thermal structure depends on a number of factors, including the velocity and slope of the subduction zone, its maturity, the age of the underthrust plate, the intensity of forced convection, degree of hydration and dehydration of minerals, etc. Various numerical models have been proposed for its calculation. It is remarkable that the thermal structures proposed by various authors are generally similar to one another, although the temperature estimates may be very different as a result of the complexity of accounting for various factors. One of such factors is frictional heating, but its influence is not as considerable as was proposed in some early investigations of subduction-related volcanism (Marsh and Carmichael, 1974), and accounting for this factor rises the temperature of the subduction zone by no more than 50°C (Peacock et al., 1994).

The processes of hydration, dehydration, and magma formation beneath the Kurile island arc were evaluated using as a working model the model of Honda and Uyeda (1983), who calculated the distribution of temperature beneath particular arcs including the Kurile arc. The section presented in Fig. 6 shows the structure of the temperature field according to this model across the Kurile island arc and corresponding *P–T* conditions of possible magma formation regions beneath the frontal and rear zones. The *P–T* diagram (Fig. 6b) shows geotherms at the base and at the top of the oceanic crust in the subducted slab (two geotherms for the frontal zone and two, for the rear zone), the solidus lines of dry and water-saturated peridotite, the solidus of peridotite at various proportions of H_2O and CO_2, and the solidus of water-saturated basalt (eclogite). It is clearly seen in the *P–T* diagram that the geotherms at the base and at the top of the oceanic crust do not cross the wet basalt solidus, i.e., there is no melting of the oceanic crust and, even more so, the underlying parts of the subducted slab in this temperature model. Melting in the upper part of the oceanic crust may begin only if its temperature will increase by 80–100°C (Fig. 6b). The melting of mantle-wedge peridotite, both beneath the frontal and rear zones, is possible within a rather wide temperature range under excess H_2O and at various H_2O and CO_2 fractions (Figs. 6a, 6b).

The main water source at the depths of magma formation is dehydration of hydrous minerals in a subducted oceanic slab, because pore water escapes at a depth of less than 40 km. The resulting CH_4–H_2O fluid does not reach the mantle wedge but enters the accretionary prism (Peacock, 1990). There are two possible mechanisms of aqueous fluid influx into the zone of magma formation in the mantle wedge: (1) dehydration of hydrous minerals in the subducted slab and subsequent upward migration of fluid directly into the magma-producing region of the mantle wedge and (2) a multistage process including dehydration of the uderthrust plate at higher levels accompanied by hydration and subsequent dehydration of the base of the mantle wedge entrained downward by the subducted slab (Tatsumi, 1989).

Let us assess the possibility of these processes for the Kurile island arc using the accepted temperature model. Similar to Fig. 6b, the *P–T* phase diagram for hydrous minerals (Fig. 7) shows geotherms in the frontal and rear volcanic zones for the given temperature distribution. It is clearly seen that most hydrous minerals (amphibole in basalt, amphibole in peridotite, 7Å clinochlore, 14Å clinochlore in association with muscovite, and tremolite) dehydrate directly below the frontal volcanic zone. The stability curves of serpentine and talc in association with forsterite intersect layer 3B of the oceanic crust (serpentinized peridotite), where these minerals can occur directly below the rear zone. There are no apparent water sources in the segment of the subducted oceanic crust between the frontal and rear volcanic zones, i.e., beneath the zone of weak volcanic activity: 7Å clinochlore stability curve crosses this region along layer 3B (Fig. 6b), where this mineral is practically absent. The same can also be concluded from the analysis of the stability curves of these minerals in the section with isotherms (Fig. 6a).

Thus, under the given distribution of temperature, the dehydration of hydrous minerals occurs at two levels directly beneath the frontal and rear volcanic zones. There are no apparent water sources beneath the middle zone, and, correspondingly, there are no conditions for magma generation. In our opinion, this is responsible for the discrete character of some parameters of the transverse chemical and mineral zoning and the similarity of the volcanic rocks of the middle zone to the rocks of either the frontal or the rear zone. The model of magma formation derived from the data presented here is shown in Fig. 8. Water and other volatile components released from the subducted oceanic crust migrate upward and cause melting in the high-temperature part of the mantle wedge. In addition, it cannot be excluded that water released from the subducted slab in the forearc region promotes hydration of minerals at the base of the mantle wedge entrained downward by the subducted slab (forced convection). The subsequent dehydration of amphibole, serpentine, talc in association with forsterite, and other hydrous minerals at the base of the mantle wedge may serve as an additional water source beneath the frontal zone (Fig. 6a).

The general mechanism of H_2O release from the subduction slab and, correspondingly, the scenario of magma formation hold for other island arcs with a hotter or colder subduction zone. However, a shift of the system of isotherms in the oceanic crust and the base of the mantle wedge to the left (colder subduction zone) or to the right (hotter subduction zone) compared with the Kurile arc will change the position of the volcanic front as well as the frontal and rear zones. This can be exemplified by the Mariana arc with a steeper subduction zone, where no distinctive frontal and rear zones exist.

Of special importance for magma formation is the estimation of the amount of volatiles that could participate in this process compared with their amount in island-arc magmas. Our calculations (Avdeiko, 1994) by the Peacock (1990) method accounting for geodynamic parameters showed that the subduction zone of the Kurile island arc releases ~10 times more H_2O and ~50 times more CO_2 than the amount of these components in the island-arc magmas. The major portion of H_2O is supplied into the magma source region from the sediments and basalts of layers 1 and 2 of the oceanic crust for the frontal zone and layer 3B (serpentinized peridotite) for the rear zone. The amount of water produced by the dehydration of layer 3B is two times higher than that due to the dehydration of other layers of the oceanic crust. As was mentioned above, an additional water source beneath the frontal zone could be related to the dehydration of hydrous minerals at the base of the mantle wedge. Therefore, the relative amounts of water beneath the frontal and rear volcanic zones can be somewhat different. More hydrous conditions beneath the rear zone are suggested by the presence of water-bearing minerals (amphibole and biotite) in the rocks of this zone. On the other hand, Ishikawa and Tera (1997) used a few determinations of B isotopes and B/Nb ratios in samples from the Kurile arc collected by us during cruises of the R/V *Vulkanolog* to suppose a decrease in the role of water away from the frontal zone. A more comprehensive B/Nb data set (Avdeiko et al., 1991) is more consistent with an increase in the abundance of H_2O toward the rear zone. Thus, the problem of quantifying relative water amounts in the frontal and rear zones requires further investigations.

The numerical simulation of the temperature field of subduction zones at various subduction rates and ages of the subducted oceanic crust (Peacock et al., 1994) demonstrated that there is no melting of the oceanic crust at steady-state subduction. Its partial melting requires very stringent conditions: an increase in the temperature of the upper part of the subducted slab above 750°C owing to, for example, unusually high shear stresses (more than 100 MPa) or subduction of a very young (younger than 2–5 Ma) oceanic lithosphere.

Thus, the melting of the high-temperature zone of a mantle wedge under the influence of water and other volatile components is the most plausible model for the Kurile island arc, as well as for other island arcs and active continental margins with a steady-state subduction regime, including Southern Kamchatka (Figs. 6, 8). On the other hand, a change in the structure of the thermal field, especially an increase in the temperature of the subducted slab and adjoining mantle zones by more than 80–100°C may cause partial melting in the subducted slab and the appearance of volcanic rocks with somewhat different characteristics. The conditions of formation of such rocks are discussed below.

VARIATIONS IN THE CONDITIONS OF MAGMA FORMATION

As was mentioned above, rocks with intraplate geochemical characteristics and adakites occur together with predominant typical island-arc lavas within the Eastern Kamchatka and Central Kamchatka arcs between the Malko–Petropavlovsk zone of transverse dislocations and the zone of continuation of the Aleutian arc in Kamchatka. The volcanism in this region, compositions of volcanic rocks, and their spatial distribution were characterized in detail by Volynets et al.

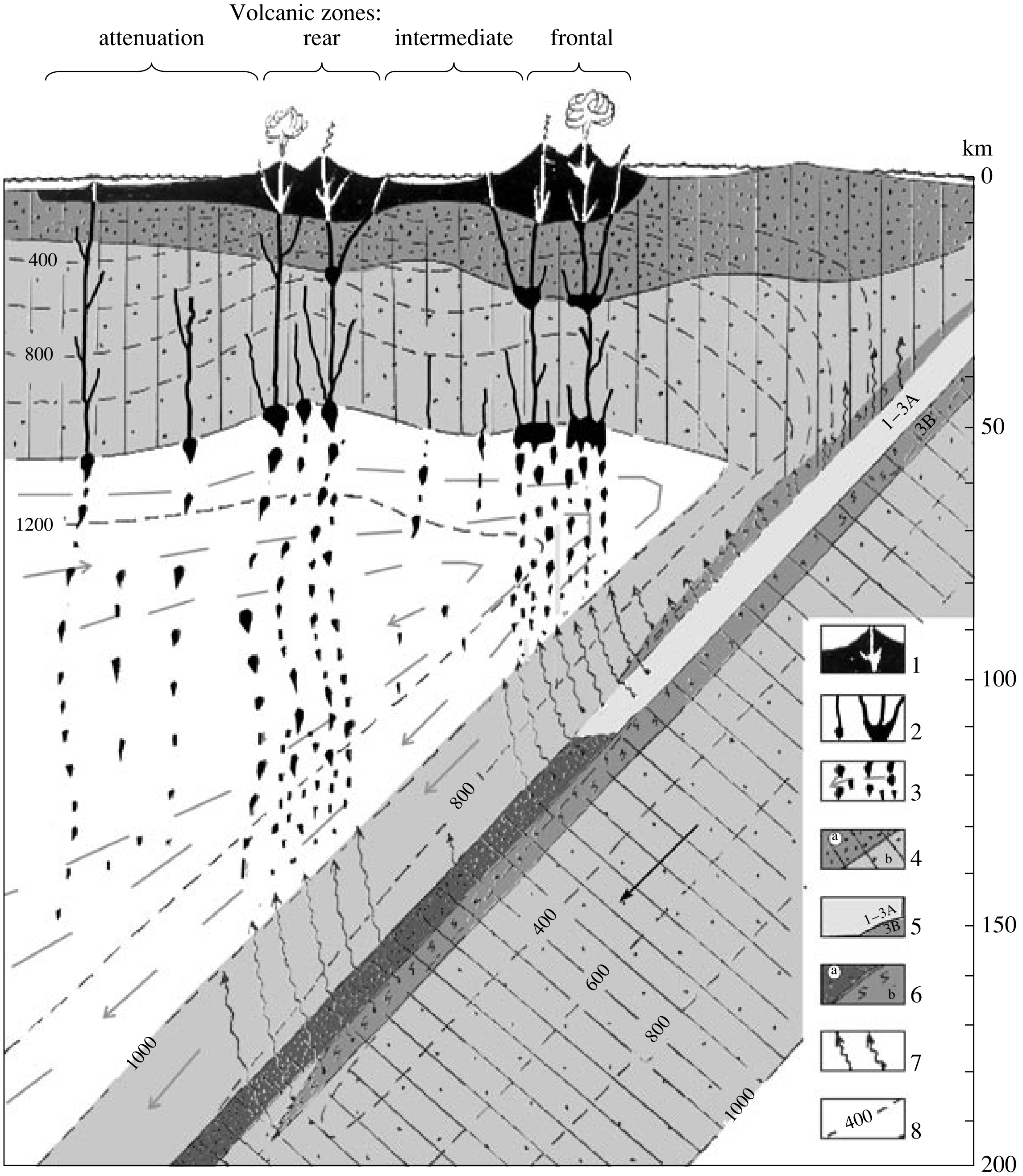

Fig. 8. Model of magma formation beneath the Kurile island arc. (1) Volcanoes and volcanic rocks; (2) magma chambers and magma ascent pathways in the lithosphere; (3) zones of magma formation and unfocused ascent; (4a) continental crust; (4b) continental lithosphere; (5) layers of the oceanic crust; (6a) eclogites and (6b) serpentinites of the oceanic crust; (7) fluid ascent pathways; and (8) isotherms.

(1990a, 1997, 1999). The volcanic rocks that were distinguished by Volynets into the intraplate geochemical type are rather widespread and form small volcanic bodies in Western Kamchatka, the Sredinnyi Range, and Eastern Kamchatka (Fig. 1). Compared with island-arc rocks, they are enriched in Ti, Nb, and Ta and show no negative Ta–Nb anomalies in primitive mantle-normalized spider diagrams. Volynets (1994) considered two hypotheses for their formation. According to one of them proposed first by Ringwood (1990), the source of the enrichment of these elements in "intraplate" magmas, as well as typical island-arc magmas, is a subducted oceanic crust, but the paths of influx of Ti, Nb, and Ta are different from those of other elements. The formation of typical island-arc magmas occurs in a regular way by melting of mantle wedge material under the influence of fluids separated from the subducted slab. The low concentrations of Ta, Nb, and Ti in island-arc magmas are explained by the fact that these elements reside mainly in rutile, and their solubility in fluid is low (Tatsumi et al., 1986). At temperatures higher than 750°C, partial melting of oceanic basalt is possible under water-saturated conditions (Peacock et al., 1994) (Fig. 6b), and these melts are rich in Ti, Nb, and Ta, which was shown by the experimental data of Tatsumi et al. (1986). Volynets argued that this scenario is applicable only for the formation of the late Miocene–Pliocene alkaline potassic basaltoids of Western Kamchatka occurring mainly as subvolcanic bodies. This model seems to be plausible, especially taking into account that these rocks show negative Ta–Nb anomalies on the spider diagrams of D. Wood, although this anomaly is less pronounced (Volynets, 1994; Fig. 10). However, this hypothesis does not explain the reason for the temperature increase.

In order to explain the appearance of intraplate magmas in Eastern Kamchatka and the Sredinnyi Range, Volynets (1994) invoked a hypothetical source formed by the hot material of enriched mantle plumes interacting with the MORB-type depleted mantle. According to his model, the inactive (extinct) subduction zone beneath the Sredinnyi Range does not prevent the ascent of mantle plumes coming from great depths into the region of the mantle wedge above the subduction zone, where intraplate-type volcanics were formed together with much more abundant island-arc rocks in late Miocene–Pliocene time. In Eastern Kamchatka, late Miocene alkali basalt and Pliocene alkali olivine basalt series with intraplate characteristics were formed before the island-arc stage of volcanism; a new subduction zone separated the mantle plumes from the mantle wedge in the Pliocene, which resulted in the absence of intraplate volcanism in the Pleistocene and Holocene.

We do not reject the possibility of such a scenario for the formation of intraplate volcanism, but point out the following circumstances. First of all, intraplate-type magmas are characteristic only of that segment of the island arc system where a jump of the subduction zone happened in the late Miocene–Pliocene (Figs. 1, 2). In addition, intraplate-type volcanism coexisted with island-arc volcanism both in space and time in the Sredinnyi Range and predated island-arc volcanism in Eastern Kamchatka. The termination of island-arc volcanism in the Sredinnyi Range caused a cessation of intraplate volcanism, i.e., the mantle plume was exhausted simultaneously with the attenuation of island-arc volcanism.

Taking into account these facts, we propose another scenario for the occurrence of intraplate-type volcanism. If the hypothesis of the detachment of the subducted part of the plate beneath the Sredinnyi Range after the termination of subduction in the late Miocene is correct, a hotter mantle material from beneath the subduction zone (Fig. 2) rather than a mantle plume will intrude into the resulting window. As a result, partial melting of oceanic basalts and sediments in the upper part of the subducted slab will be possible owing to an increase in temperature by 80–100°C. The major portion of magmas will be formed by fluid-assisted melting of mantle material following the island-arc scenario. In such a case, both typical island-arc magmas and magmas enriched in Ti, Nb, and Ta, i.e., magmas with intraplate geochemical signatures will be derived. The cessation of island-arc volcanism in response to the exhaustion of fluids from the subducted slab will result in the termination of the intraplate volcanism, because the two types of magmas owe their origin to a water source, which is related in the case considered to the dehydration of serpentine and talc.

The same mechanism can be invoked to explain the appearance of intraplate-type magmas in Eastern Kamchatka in the Pliocene, before the occurrence of island-arc volcanism. During the initial stage of subduction, the leading edge of the subducted plate contacts a hotter mantle material, which results in partial melting of sediments and basalts in the oceanic crust and formation of melts with high Nb, Ta, and Ti concentrations.

The region of the Aleutian–Kamchatka junction is also characterized by the occurrence of peculiar volcanism. One of the important petrological features of the zone of junction of Kamchatka with the Aleutian arc is the wide occurrence of magnesian basalts, basaltic andesites, and andesites (adakites) (Volynets et al., 1997, 1999). Magnesian basalt is the predominant rock type in Kharchinskii and Zarechnyi volcanoes and in the Kharchinskii zone of cinder cones. Similar basalts were documented among the volcanic rocks of lateral eruptions of Klyuchevskoy Volcano and the Tolbachik regional zone of cinder cones. The volume of magnesian rocks in the junction zone is about ten times that in all other volcanoes of Kamchatka together. The volcanoes of the junction zone, especially of the Klyuchevskoy group, are distinguished by the high intensity of volcanism. This zone comprises about one-third of the volcanic material erupted by all Kamchatka volcanoes during the past 800–850 ka, and more than half of this material has been erupted during the past 50 ka (Melekestsev, 1980).

According to modern geodynamic concepts, in the junction zone between the Kurile–Kamchatka and Aleutian island arc systems, there is no subduction of the Pacific plate beneath Kamchatka north of Shiveluch Volcano. The northern margin of the Pacific plate either terminates or plunges north of this volcano. Nonetheless, there are two Quaternary stratovolcanoes (Nachikinskii and Khailyulya) and a number of small edifices in this area. The Quaternary rocks of this region display transitional characteristics between island-arc and oceanic volcanics (Portnyagin et al., 2005).

What were the specific features of magma formation conditions in the junction zone between Eastern Kamchatka and the Aleutian arc which resulted in the formation of magnesian rocks in contrast to the steady-state regime of the Kuriles and Southern Kamchatka? Oblique subduction changing into a transform fault provided conditions in the Kamchatka–Aleutian junction for the rupture and spreading of the descending Pacific plate and intrusion of the material of the hot deep mantle into the suprasubduction zone. The high temperature of melt is suggested by liquidus temperatures of ~1280°C obtained for magnesian olivine from Zarechnyi Volcano by Volynets et al. (1999). The calculation of the structure of the thermal field showed that temperature at the contact of the northern margin of the subducted Pacific plate with the hotter mantle can increase in such a case by 200–300°C (Tastumi et al., 1994). In addition to the melting of mantle peridotite under the influence of water and other volatiles and the eruption of magnesian basalts, partial melting of the oceanic crust becomes possible at the contact with hotter mantle material with the formation of adakite-type magnesian andesites (Yogodzinski et al., 2001). The possible melting of the oceanic crust in the region of Shiveluch, Kharchinskii, and Zarechnyi volcanoes is supported by some geochemical parameters typical of adakites, in particular, the high concentrations of Sr and Ba and low concentrations of heavy REE at high FeO/MgO and La/Yb and low K/La ratios (Volynets et al., 1999).

Thus, the appearance of rocks with intraplate geochemical characteristics among island-arc volcanics and the occurrence of adakite-type magnesian rocks in the junction zone between the Kurile–Kamchatka island-arc system and the Aleutian arc can be explained by the same mechanism of partial melting of the upper part of the subducted slab owing to the relatively high temperatures of the adjoining mantle regions.

CONCLUSIONS

The present structure of the Kurile–Kamchatka island-arc system is controlled by volcanic belts of various ages, which developed above subduction zones. The Central Kamchatka–Kurile system of arcs existed in the end of the Oligocene and in the Miocene. The Central Kamchatka arc of this system was located at the place of the present-day Sredinnyi Range (Fig. 2). It included a clearly manifested volcanic arc, and a tectonic (nonvolcanic) arc and a trench were reconstructed; the northern part of the trench is buried under sediments in the western Komandor basin and was detected by modern gravimetric and seismic methods. Seismic data suggest that there are probably still small movements in the subduction zone of this system.

In the end of the Miocene and the beginning of the Pliocene, the segment between the Avachinsky Bay and the Kamchatka Peninsula jumped into its present-day position as a result of the blocking of the subduction zone, probably owing to the accretion of Eastern Kamchatka peninsulas. The subduction zone beneath the Sredinnyi Range was extinguished, although volcanism occurred there as late as the Holocene, and two potentially active volcanoes are still retained.

In the segment south of the Malko–Petropavlovsk zone of dislocations, i.e., in Southern Kamchatka and the Kuriles, subduction has occurred almost without changes from the end of the Oligocene. In the northern part of Southern Kamchatka, the northeastern structures of the present-day arc were superimposed on the northwestern units of the late Oligocene–Miocene arc (Fig. 2).

Based on the tectonic history of the island-arc stage of region development and the geodynamic parameters of the subduction zone, the following regions (segments) were distinguished in the modern Kurile–Kamchatka island-arc system: Central Kamchatka, Eastern Kamchatka, Northern Kuriles, Central Kuriles, and Southern Kuriles. The Eastern Kamchatka segment represents the initial stage of subduction, the Central Kamchatka arc corresponds to the stage of attenuation of subduction, and the other regions are characterized by steady-state subduction with various geodynamic parameters.

The volcanism of Kamchatka and the Kuriles is accompanied by steady-state subduction and produces typical island-arc magmas. They were generated in the mantle wedge, where water-saturated peridotite melting is induced in the high-temperature zone by fluids released from the subducted slab. The existence of two volcanic zones, frontal and rear, is related to two levels of water release from different hydrous minerals. Most hydrous minerals dehydrate beneath the frontal zone. The source of water beneath the rear zone is the dehydration of serpentine and talc.

The development of geochemical peculiarities of lavas from the frontal and rear zones is beyond the scope of this paper. This problem will be addressed in our future studies on the basis of new geochemical and isotopic data obtained in the laboratories of the IFM GEOMAR, Germany. We note here some differences in the geochemical characteristics of the lavas, particularly those related to fluid composition. As can be seen in Figs. 7 and 8, the fluids of the frontal and rear zones were formed by dehydration of minerals at different initial temperatures and probably in different amounts. The fluids of the frontal zone ascend to the magma generation zone through the basalts and sediments of the oceanic crust, whereas those of the rear zone percolate through the whole oceanic crust. However, the basalts and sediments of layers 1 and 2 of the oceanic crust must be previously depleted in soluble components in the frontal zone. Compared with the fluids of the rear zone, the fluids of the frontal zone occur under lower pressure and travel a shorter distance to the magma generation zone.

The composition of melt could also be changed under varying *P*–*T* conditions en route to the surface within the mantle wedge. In our opinion, within the lithosphere and continental crust, there are no factors capable of influencing the compositions of magmas of the frontal and rear zones in the case of steady-state subduction.

The junction zone between the Kurile–Kamchatka island-arc system and the Aleutian arc and the Sredinnyi Range show anomalous features. After the cessation of subduction in Eastern Kamchatka at the beginning of formation of a new subduction zone, partial melting in the upper part of the subducted plate was possible in these segments. This resulted in the eruption of lavas with intraplate geochemical signatures and lavas with adakitic compositions. The partial melting of the oceanic crust is related to an increase in temperature owing to the contact with hotter mantle zones compared with normal island-arc conditions. Such conditions were probably developed in the Miocene and Pliocene in the Central Kamchatka arc in response to the detachment of the descending Pacific plate and intrusion into the resulting window of hot mantle material from beneath the subduction zone. These processes were caused by the blocking of the subduction zone beneath the Sredinnyi Range and its jump into the present-day position. The same conditions existed in the late Miocene–Pliocene at the front of the Pacific plate during the formation of a new subduction zone beneath Eastern Kamchatka. Similar relationships were observed within the Aleutian–Kamchatka junction at the northern margin of the descending Pacific plate.

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