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The Late Miocene–Pliocene Transform Margin of Kamchatka

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Abstract—Testing of the geochemical compositions of the Late Cenozoic volcanic rocks of Kamchatka on new discriminant diagrams confirmed the existence of different geodynamic settings at that time. Late Miocene (~6 Ma)–Pliocene volcanic rocks of Eastern Kamchatka and the Central Kamchatka Depression, as well as the Late Pliocene (~3.5 Ma)–Holocene alkaline, calc–alkaline, and adakite volcanic rocks in the central part of the Sredinnyi Range are shown to be similar to the volcanic rocks of the Pacific-type transform margins. At the same time, the Miocene–Holocene volcanic rocks of Southern Kamchatka, the Miocene–Early Pliocene volcanic rocks of the Sredinnyi Range, and the Pleistocene–Holocene volcanic rocks of Eastern Kamchatka resemble the volcanic rocks of convergent margins. In central Kamchatka (from the coast to the Sredinnyi Range), igneous complexes typical of the transform margin were formed at the end of the Miocene–Pliocene, during the collision of the Kronotsky island-arc terrane and the movement of the Pacific plate. The geochemistry of the transform-margin volcanic rocks is caused by the upwelling of the subslab asthenosphere, both into the collision zone and the zone of the Sredinnyi Range volcanic arc, following the Commander–Kronotsky microplate slab segmentation and breakoff.

Keywords: convergent and transform margins, slab segmentation, sublab asthenosphere, geochemistry, discriminant diagrams, Kamchatka

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INTRODUCTION

According to most researchers, two convergent margins, the Early Oligocene–Miocene and present ones, existed in Kamchatka during the Late Cenozoic geodynamic evolution. They formed immediately after the 6–4-Ma collision of the Late Cretaceous–Eocene Kronotsky epioceanic island arc with the Kamchatka continental block [1, 3, 53, 69, and others]. However, these geodynamic models of continuous subduction are inconsistent with the genesis of Late Miocene–Pliocene (in Eastern Kamchatka and Central Kamchatka Depression) and Pliocene–Holocene (in Sredinnyi Range) alkaline volcanic rocks with typical within-plate geochemical signatures [2, 5, 6, 21, 31, 39, 55]. Geodynamic models proposed to explain the genesis of these rocks in general suggest either the emplacement of subslab asthenosphere in a subduction zone with subsequent slab segmentation [2, 3, 16, 31] or the impact of mantle plume, which was formed in the asthenosphere beneath the Pacific plate to the east of the Kurile–Kamchatka deep-water trench (~400–500 km), and its displacement with a convective flow to the again formed subduction zone [2].

The authors of [65] analyzed the seismic structure of the mantle beneath Kamchatka and proposed a model of subduction zone migration with episodic slab breakoff. The idea of catastrophic slab breakoff beneath Kamchatka is also considered in [71] to explain the absence of a subsiding slab beneath the western part of the Aleutian arc, at the contact with the Kamchatka arc [72]. The alternative explanations of the nature of similar and near coeval alkaline rocks of Kamchatka and debates concerning asthenosphere diapirism highlighted the need in a model involving these opposite concepts.

It was previously proposed that transform plate sliding (transform margin) with areal asthenospheric diapirism existed between Miocene and modern convergent margins of Kamchatka [43, 45]. Such a model provides a reasonable explanation for the simultaneous occurrence of the Kronotsky terrane collision and alkaline within-plate magmatism in the collision zone. However, this model disagrees with the tight spatiotemporal association of within-plate alkaline basalts and typical island-arc volcanic series [2, 3, 16, 20, 21, 31, 59, and others].

At the same time, numerous geological data on the Late Cenozoic Pacific margin showed that calc-alka-

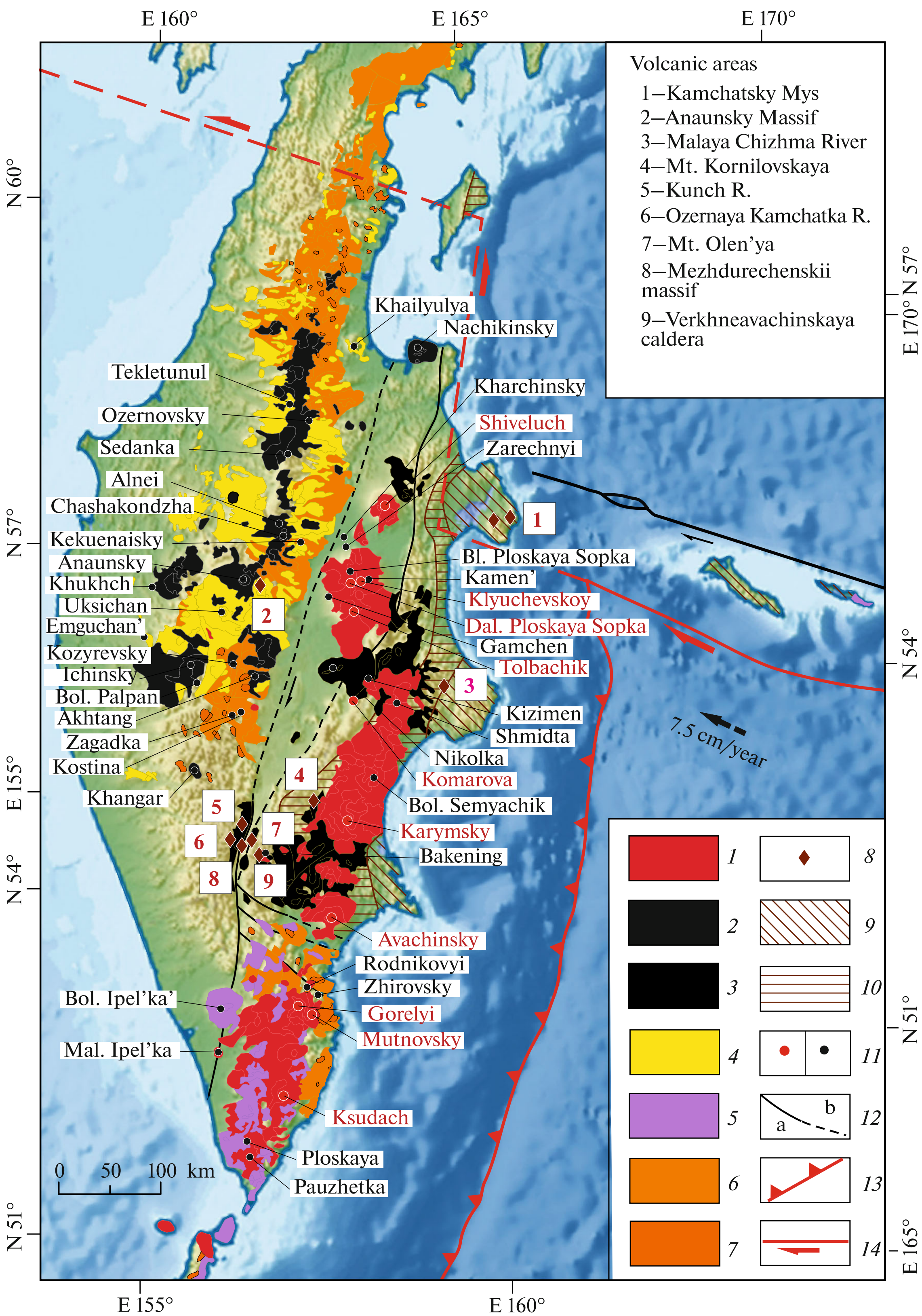

Fig. 1. Late Cenozoic geological-geodynamic complexes of Kamchatka. (*1*) Late Pleistocene–Holocene suprasubduction volcanic rocks; (*2*) Late Pleistocene–Holocene transform-type volcanic rocks; (*3*) Late Miocene–Early Pleistocene transform-type volcanic rocks; (*4*) Pliocene–Early Pleistocene undivided suprasubduction and transform-margin volcanic rocks; (*5*) Pliocene–Early Pleistocene suprasubduction volcanic rocks; (*6–7*) Oligocene–Miocene suprasubduction volcanic rocks (*6*) and granitoids (*7*); (*8*) Pliocene dike fields of alkaline basalts; (*9*) Kronotsky terrane of the Late Cretaceous–Paleogene island arc; (*10*) Vetlov–Govena terrane of the Oligocene–Miocene accretionary wedge; (*11*) active (a) and extinct (b) volcanoes and volcanic massifs; (*12*) faults; (*13–14*) convergent (*13*) and transform (*14*) plate margins. The scheme was compiled using data [32] modified after [28, 31, 33, 53].

line, peraluminous, and adakitic rocks typical of convergent margins could occur on transform margins in association with rocks with within-plate geochemical signatures [13]. However, owing to their complex compositions and the absence of transform-margin composition fields in the existing discriminant diagrams, the criteria of their geochemical differences have not been established. The discriminant diagrams proposed in this work to separate the magmatic rocks of convergent and transform margins [66] provide a new insight into the geodynamic reorganization of Kamchatka in the Late Miocene–Pliocene.

THE BRIEF GEOLOGICAL CHARACTERISTICS AND LATE CENOZOIC VOLCANIC COMPLEXES OF KAMCHATKA

The Kamchatka Peninsula together with a chain of the Kurile islands are usually regarded as a single ensialic island-arc system with continuous deep-water trenches, active volcanic belt, and subduction zone [1, 17, 23]. However, unlike the Kurile arc, which has existed since the Oligocene, the modern Kamchatka structure was formed during the last few Myr. As early as the Pleistocene and even at the beginning of Holocene (<0.1 Ma), the northern and southern segments of the Kurile–Kamchatka zone evolved differently. The boundary between the two segments with different geological histories does not coincide with the sea–land transition, but runs along the Petropavlovsk–Malka transverse dislocation zone (PMZ), to the south of Avacha Volcano [69]. The peninsula has an intricate structure and comprises three Quaternary volcanic belts: the Eastern volcanic belt extending to the south of the peninsula and the Northern Kurles; Klyuchevskoy belt including the Shiveluch and Klyuchevskoy volcanic groups; and the rear belt of the Sredinnyi Range (Fig. 1). From the east, Kamchatka is in contact with the Aleutian island arc with a transform margin in the Commander sector. An arbitrary continuation of this boundary in Kamchatka constrains the distribution of active volcanoes from the north [23] (Fig. 1).

The basement of the Kamchatka island arc is composed of Cretaceous and Cenozoic terranes and post-accretionary complexes, which reflect the NW to SE growth of continental crust [18, 19, 22, 36, 44, 53, and others]. The western part of the Kamchatka Peninsula is dominated by Upper Cretaceous–Early Paleogene turbidites [36, 51] with subordinate Cretaceous rift-related ultrabasic volcanics [37] and Paleocene basalts [24], which mark the formation of a transform continental margin at the end of the Campanian after cessation of subduction beneath the Okhotsk–Kamchatka volcanic arc [42–44 and references therein].

The granite–metamorphic complex of the southern Sredinnyi Range likely represents a part of this margin that was transformed during the Eocene collision of the Late Cretaceous–Paleocene island arc [25, 53, 67]. The collision and slab breakoff with subsequent upwelling of subslab asthenosphere at ~ 52 Ma resulted in the formation of the granite–metamorphic complex of the Sredinnyi Range and the simultaneous emplacement of norite–cortlandite intrusions [25 and references therein]. To the east, a combination of Cretaceous–Paleogene terranes of intra-oceanic island arcs, accretionary wedges, and ophiolites was accreted to and thrust onto the continental margin in the Eocene (~52–46 Ma) under east-dipping subduction (Achaivayam–Valagin paleoarc) or was thrust beneath the margin in the Late Miocene–Pliocene (6–4 Ma) during west-dipping subduction (Kronotsky–Commander paleoarc) [18, 19, 22, 36, 53]. Post-accretionary volcanic complexes have been formed in western Kamchatka since Eocene. The Middle–Early Oligocene complexes are represented by alkaline (K–Na and K), as well as subalkaline basalts of dispersed rifting [31, 41], which were likely formed in a transform-margin setting after oblique island-arc collision [19]. Suprasubduction volcanic arc was formed within the Stredinnyi Range and Southern Kamchatka in the Late Oligocene [31, 53]. The Kronotsky terrane of the Late Cretaceous–Eocene island arc with a fragment of Late Cretaceous accretionary wedge on the Kamchatksy Mys Peninsula [46, 47, 70] is distinguished in easternmost Kamchatka (Fig. 1). The accretion of this epioceanic terrane to the Kamchatka continental block began ~7–6 Ma and jammed the Oligocene–Miocene oceanic subduction that existed between the Kronotsky arc and Kamchatka (Kronotsky microplate) [53, 69, 79 and references therein]. Indicator complexes of this subduction are the Vetlov–Govena accretionary wedge terrane and continental volcanic belt of the Sredinnyi Range [50, 53, 79]. The youngest sediments of the accretionary wedge in the Kronotsky area are Oligocene–Miocene flysch, which contains inclusions of the Early–Middle Miocene pelagic cherts [4]. All this indicates that the accretion of the Kronotsky arc began in the Late Miocene [53, 70]. The upper age limit of this event is estimated from the angular unconformity between deformed Lower and Middle Miocene marine sediments and horizontally lying Upper Miocene–Pliocene volcanic rocks [70]. A single volcanic arc has been formed in the Eastern and Southern Kamchatka since Late Pleistocene.

Four Late Cenozoic volcanic areas are traditionally distinguished in Kamchatka: Eastern Kamchatka, Southern Kamchatka, the Central Kamchatka Depression (CKD), and the Sredinnyi Range. Volcanic rocks with within-plate signatures were not found in Southern Kamchatka, are present among Late Miocene–Pliocene volcanic complexes in Eastern Kamchatka, the Miocene–Early Pleistocene complexes in the CKD, and the Late Pliocene–Holocene volcanic complexes in the Sredinnyi Range.

Eastern Kamchatka

The Eastern Kamchatka volcanic zone is a large post-accretionary structure, which was initiated to the north of the PMZ in the terminal Miocene. At present, this zone is a plateau with numerous stratovolcanoes between the eastern coast peninsulas (Shipunskii and Kronotsky volcanoes) and the Eastern Range.

In Eastern Kamchatka, the Late Cenozoic volcanic sediments with angular unconformity lies on the Oligocene–Miocene rocks of an accretionary wedge (Fig. 1). Two stages of Late Cenzoic volcanism, Early to Late Miocene–Pliocene and Late Pleistocene–Holocene (modern stage), are distinguished in this zone. They differ in the composition of magmatic rocks. The late stage is represented by alternation of basaltic, basaltic andesite, and andesite–dacite–rhyolite rocks of the calc-alkaline series [14, 15, 31, 59, 80]. The early stage differ from the late stage in the presence of flows, sills, and dikes of alkaline and subalkaline basalts and their intrusive analogues, in association with intermediate–mafic calc-alkaline and adakite-like rocks [3, 5, 6, 31, 38–40]. The alkaline basalts alternate with calc-alkaline basalts [31]. The lower age limit of the early stage according to paleontological data is determined as Late Miocene [5] and is consistent with new Ar–Ar dates of 5.8–5.6 Ma on basaltic andesite ignimbrites [56]. The upper boundary is poorly constrained; available data indicate that this stage includes the entire Pliocene [2] and likely the Early Pleistocene [33].

Southern Kamchatka

The Southern Kamchatka volcanic zone occupies the southern termination of the peninsula, being separated from other zones by the PMZ (Fig. 1). Three large volcanic stages are distinguished in the Late Cenozoic evolution of the region. The first stage is related to the formation of Oligocene–Miocene volcanogenic sediments of the andesite formation. The second stage is dated by the Late Miocene–Pliocene, with strong pulses of subaerial basalt–andesite–rhyolite volcanism. The latest stage is related to the formation of numerous Quaternary volcanoes, scoria, and lava cones [e.g., 26].

The Late Cenozoic volcanic complexes of Southern Kamchatka are represented by geochemically homogenous sequences of mildly alkaline basalts, andesites, dacites, and rhyolites [49, 57, 62, 77, 78].

The Central Kamchatka Depression

The Central Kamchatka graben-like depression (rift) is located between the Sredinnyi and Vostochnyi ranges and is pinched out in the southwest in the juncture with the PMZ. The CKD was initiated in the Late Pliocene [27] or Miocene [52].

The triangle shape of the CKD is likely caused by dextral strike slip (Fig. 1).

Two magmatic stages are distinguished in the CKD: Late to Middle Pleistocene–Holocene and Early to Late Miocene–Early Pleistocene. The late stage is represented by differentiated series of mildly alkaline basalt–rhyolites of the Klyuchevskoy, Tolbachik, Shiveluch, Ploskie Sopki, Kamen, Zarechnyi, and Nikolka volcanoes [3, 11, 59, 76]. The early stage comprises Late Pliocene–Early Pleistocene lavas of the Nachikinsky and Khailyula volcanoes [75], the Pliocene (~3.2–2.7 Ma) high-Mg andesite and Nb-enriched adakite association of the Mezhhdurechnyi massif and Mt. Olen'ya [31], as well as the Late Miocene volcanic plateaus of the Ozernaya Kamchatka and Kunch rivers with an age of 6.35–6.22 Ma [21].

Sredinnyi Range

The volcanic belt of the Sredinnyi Range was formed at the end of Oligocene–beginning of the Miocene and rests on the deformed Cretaceous–Paleogene structures of the peninsula with an angular unconformity [1, 31, 53]. The volcanic rocks of the belt are traced in the NE direction along the Sredinnyi Range (Fig. 1). In the southern part of the range, up to Khangar Volcano, the subduction zone is traced at a depth of ~400 km and is not found further northward [60, 64, 65].

Two stages of Late Cenzoic magmatism with different compositions of volcanic rocks are distinguished in the Sredinnyi Range: late Pliocene–Holocene and early Oligocene–Miocene–Early Pliocene stages [31]. The late stage differs from the early stage in the presence of alkaline basalts together with calc-alkaline basalts, andesites, and dacites. The onset of the late stage is reliably determined by Ar–Ar dates on basanites of Mt. Khukhch at 3.78 ± 0.05 Ma [81], on basaltic andesites of Mt. Kostina at 3.47 ± 0.12 and 3.40 ± 0.08 [9], on hawaiites of the Emguchan massif 2.97 ± 0.42 Ma [31] and, thus can be conditionally established at 3.5 Ma. It is pertinent to emphasize that Pevzner [28] established a much lower amount of Holocene volcanics among Quaternary volcanic rocks of the Sredinnyi Range [8] compared to those indicated at the State Geological Maps. It was proved, in particular, that Holocene volcanism is absent within the Pliocene Uksichan volcanic center [28].

MATERIALS AND METHODS

Geodynamic events were reconstructed using geochemical data on all Late Cenozoic volcanic complexes of Kamchatka. Data on revealing additional criteria of geodynamic settings were chosen, first of all, with allowance for the geochronological age of magmatic complexes described in detail in the previ-

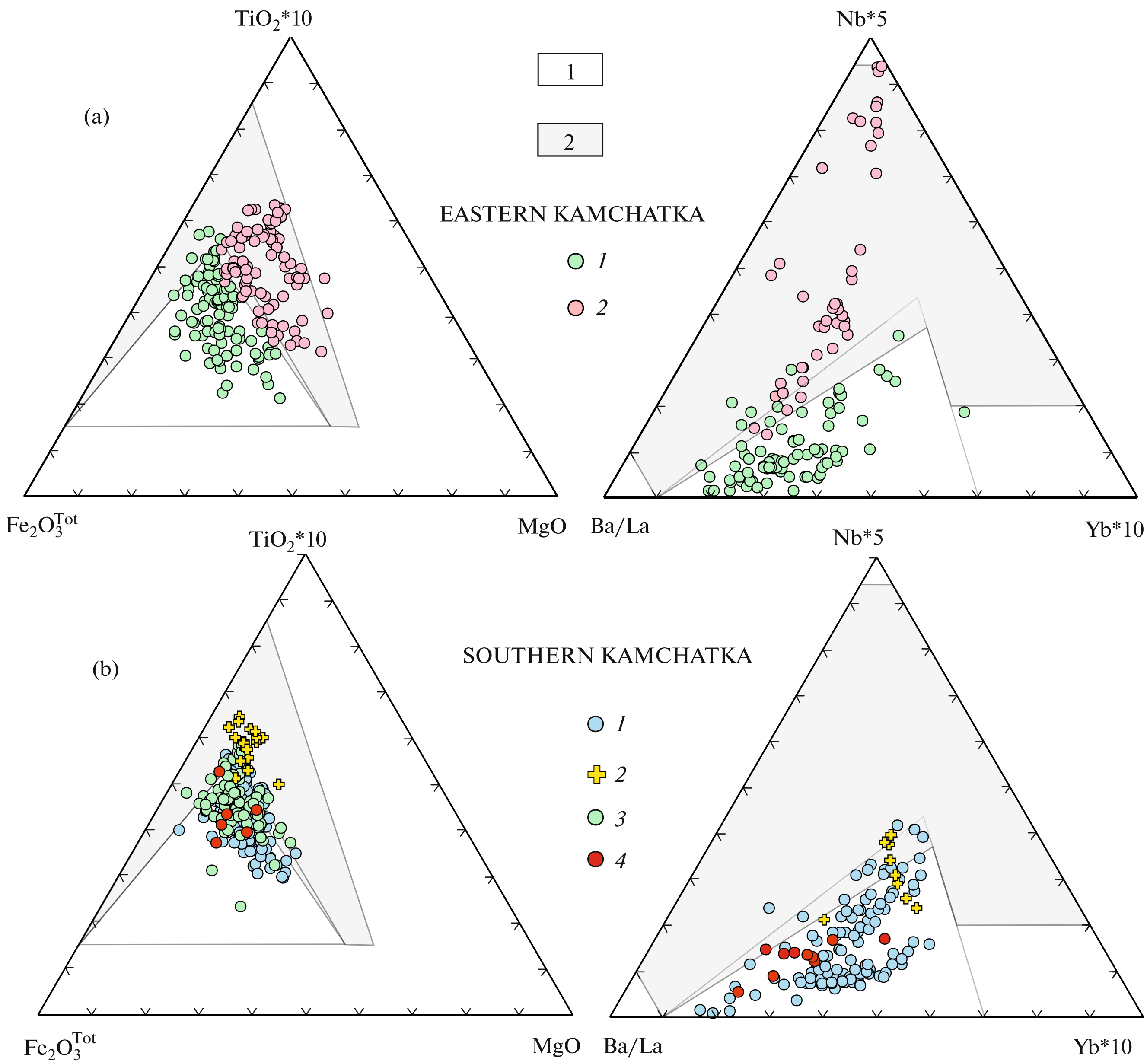

Fig. 2. Discriminant geodynamic diagrams [66] for Late Cenozoic volcanic rocks of Kamchatka with fields of magmatic rocks (1) zones of suprasubduction island-arc and continental-margin types (convergent margins) and (2) magmatic rocks of transform sliding of lithospheric plates (transform margins of continents and island arc).

(a) Eastern Kamchatka (199 analyses): (*1*) Late Pleistocene–Holocene basalts, basaltic andesites, dacites, rhyodacites, and rhyolites of the Karymsky and Bol'shoi Semyachik volcanic massifs [14, 15]; Late Pleistocene–Holocene volcanic rocks of the Gamchen, Shmidt, Komarov, and Kizimen volcanoes [59]; modern basaltic andesites of Avacha volcano [80]. (*2*) Late Miocene–Pliocene volcanic rocks: Late Miocene basalts of the Shchapinskaya Formation [5]; Middle Miocene gabbroids and Late Miocene basalts of the Mt. Kornilovskaya area, eastern spurs of the Valaginsky Range [6]; Late Miocene alkaline gabbroids and trachydolerites of the Kronotsky isthmus, Mal. Chazhma River, and Kamchatsky Mys Peninsula [38–40]; Late Miocene–Pliocene adakites and Nb-enriched basalts of Eastern Kamchatka [3]; basaltic andesite and andesite ignimbrites (5.78–5.58 Ma) of the Verkhneavachinskaya caldera [56]. (b) **Southern Kamchatka (309 analyses):** (*1*) Late Pleistocene–Holocene (Q) tholeiitic basalts and trachyandesites of the Mutnovsky, Gorelyi, Pauzhetka, Ploskaya, and Ksudach volcanoes [49, 57, 62, 77]. (*2*) Middle Pleistocene (0.36–0.23 Ma after [77]) dacites and rhyolites of Gorelyi Volcano [49, 57, 62, 77, 78]. (*3*) Pliocene–Late Pleistocene (4–0.5 Ma) rhyolite ignimbrites and extrusions of the Karymshin volcanic center, Bol'shaya and Malaya Ipel'ka volcanoes [26, 57, 58]. (*4*) Miocene–Pliocene lava-pyroclastic sequences of the Zhirovsky and Rodnikovyi paleovolcanoes [44, 48]. **(c) Central Kamchatka Depression (391 analyses):** (*1*) field of the Late Pleistocene–Holocene volcanic rocks of the Klyuchevskoy, Tolbachik, Shiveluch, Ploskie Sopki, Kamen', Kharchinsky, and Zarechnyi volcanoes [3, 10, 11, 59, 63] and Holocene volcanic rocks of Tolbachik volcano [76]. (*2*) Late Pleistocene–Holocene basalts and basaltic andesites of monogenetic centers of Bakening volcano [61]. (*3*) Late Pleistocene Nikolka Volcano [21, 59]. (*4*) Early Pleistocene lavas of the Nachikinsky and Khailyula volcanoes [75]. (*5*) Pliocene (~3.2–2.7 Ma) rocks of high-Mg# andesite and NEB-adakite associations of the Mezhdyrechnyi Massif and

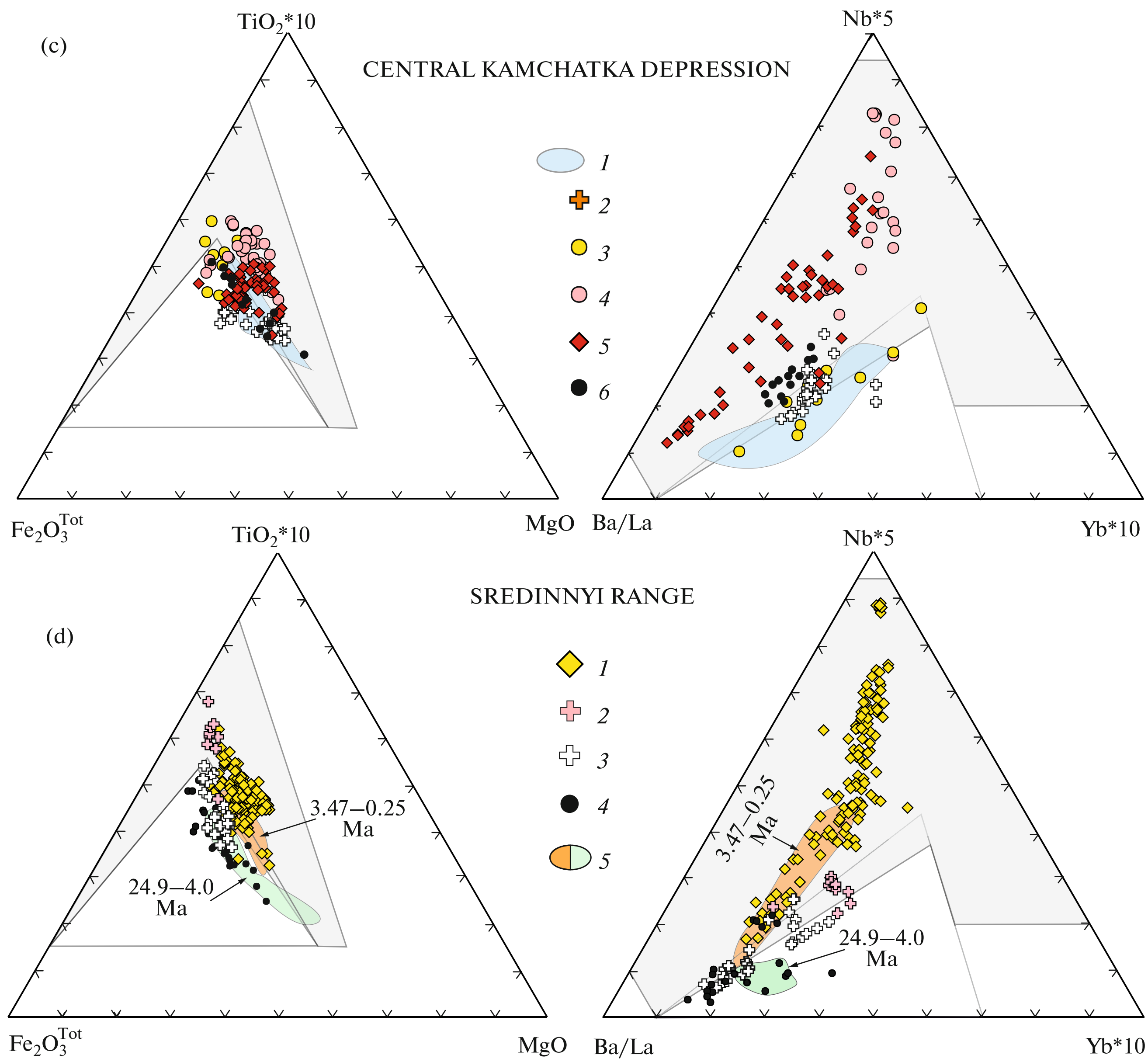

Fig. 2. (Contd.)

Mt. Olen'ya [31]. (*6*) plateau volcanics (6.35–6.22 Ma) of the Ozernaya Kamchatka and Kunch rivers [21]. (d) **Sredinnyi Range (318 analyses):** (*1*) Late Pliocene–Early Holocene volcanic rocks of the Tekletunup, Ozernovsky, Sedanka, Alnei–Chashakondzha, and Kekuknaisky monogenetic cones [81]; trachybasalts (1.7–1.86 Ma) of the areal zone of the Kekuknaisky volcanic massif [31]; basalts and trachybasalts of the Bol'shoi Payalpan [31]; basaltic andesites–rhyodacites of the Akhtanga and Ichinsky volcanoes [8, 59]; Middle–Late Pliocene subvolcanic basanites of Mt. Khukhch (3.78 Ma) and Emguchan' Massif (2.77 Ma) [31]. K-Ar dates on the volcanic rocks of the Ichinsky (0.35 Ma), Khangar (0.35 Ma), Akhtang (1.2–0.8 Ma) volcanoes, Mts. Yurtinaya, Kostina, Zagadka, Kozyrevka, and Anaunsky volcanic area (3.2–1.9 Ma) [29, 30]. (*2*) Pliocene trachytes and trachydacites (3.56–3.34 Ma [57]) of Uksichan Volcano [16]. (*3*) Pliocene trachybasalts and trachyandesites of the earlier stages of Uksichan shield volcano [8, 16]. (*4*) Miocene–Middle Pliocene (up to 3.64 Ma) volcanic rocks from the Ozernovskoe, Dvukhruchnoe and Kryuki, Noksichan plateau area [8, 57, 59, 81]; shoshonites and latites (5.70 Ma [57]) of Tekletunup Volcano [31]. (*5*) Composition fields of the Late Oligocene–Early Pliocene volcanic rocks of the Akhtang and Kostina mounts [9].

ous sections. Geochemical database includes in general over 1200 analyses of different rocks and is given in the Supplement to the paper (see Table S1).

In compliance with the aim of this paper, we applied discriminant diagrams for major oxides $TiO_2 \times 10 - Fe_2O_3^{Tot} - MgO$ and trace elements $Nb \times 5 - Ba/La - Yb \times 10$, which are able to separate the magmatic rocks of suprasubduction island-arc and continental margin settings (related to convergent margins) from rocks formed on a transform margin with confidence [66].

DISCUSSION

The modern structure of Kamchatka was formed in two stages of westward accretion of the Cretaceous–Paleogene island arcs. The first Early Eocene stage involved the accretion of the Late Cretaceous–Paleocene Achaivayam–Valagin arc [53]. We may suggest that collision resulted in the formation of transform continental margin with characteristic Middle Eocene–Early Oligocene alkaline and subalkaline basaltic magmatism in Western Kamchatka [31, 41]. This stage was completed by the formation of the Late Oligocene–Miocene convergent margin, whose volcanic arc is located in the Sredinnyi Range, on Southern Kamchatka, and continues to the Kurile Islands [1], while the accretionary wedge (Vetlov–Goven terrane) is developed in Eastern Kamchatka and Karaginsky Island (Fig. 1) [53].

The second, Late Miocene–Pliocene stage was marked by the accretion of the Kronotsky–Commander arc. In Eastern Kamchatka, volcanic complexes began to form at the end of Miocene and overlaid the Oligocene–Miocene accretionary wedge and Kronotsky arc terrane after its collision. Since Late Miocene volcanic rocks are known only in the south of the volcanic zone (Upper Avacha caldera and Mt. Kornilovskaya), the age of post-collisional volcanism is likely rejuvenated from the south northward, which is consistent with a model of incipient collision of the Kronotsky arc in the Shipunskii block area and its propagation northeast up to Kamchatskii Mys. This stage was completed by the formation of the modern convergent margin of Kamchatka in the Late Pleistocene [53, 69].

The compositional trends of Late Pleistocene–Holocene volcanic rocks of Eastern Kamchatka are noteworthy; in the discriminant diagrams they fall in the field of convergent margins, whereas Late Miocene–Pliocene alkaline and calc-alkaline rocks plot in the transform margin field (Fig. 2a*)*. The compositions of the Miocene–Holocene volcanic rocks of Southern Kamchatka are located mainly in the field of convergent-margin rocks (Fig. 2b), except for the Middle Pleistocene dacites and rhyolites of Gorelyi volcano in the major oxide diagram, which is likely related to their more siliceous (SiO_2 > 63 wt %) composition.

In the CKD, the post-accretionary Late Miocene–Pliocene volcanic rocks rest on fore-arc complexes of the Oligocene–Miocene volcanic arc [53] and their age is also rejuvenated in the northern direction [21]. The compositions of these complexes form separate fields in the presented discriminant diagrams. In particular, the compositions of the Late Pleistocene–Holocene volcanic rocks fall in the field of convergent margins, while those of the Late Miocene–Early Pleistocene volcanic rocks are plotted in the transform-margin field. The volcanic rocks of the Late Pleistocene Nikolka volcano are characterized by "transitional" compositions in Fig. 2c. This could be explained by analogy with the Shiveluch and Klyuchevskoy active volcanoes, which in general are clustered in the field of convergent margins, but in the major-component diagram partially plot in the transform-margin field (transitional zone), which is consistent with data on upwelling of hot asthenosphere along subducted Pacific Plate margin [12].

In the Sredinnyi Range, magmatic rocks similar to transform-margin volcanic rocks occur from 3.5 Ma, whereas pre-Early Pliocene rocks fall exclusively in the convergent-margin field (Fig. 2e). This is consistent with the estimated time of the change of suprasubduction volcanic rocks to within-plate types [31, 55] or a hybrid type [9]. It should be taken into amount that the oldest volcanic rocks of the transform margin in the Sredinnyi Range are known only in its central part, i.e., at the latitude of simultaneous volcanic rocks of the CKD and Eastern Kamchatka.

The generalization of the geological and geophysical data of previous studies and testing of geochemical compositions of Late Cenozoic volcanic rocks in the author's diagrams allowed us to specify the geodynamic evolution of Kamchatka for the last 10 Myr (Fig. 3). A tectonic reconstruction of ~10 Ma is acceptable. In the Miocene, the Pacific subduction continued beneath Southern Kamchatka. It has been suggested that the Kronotsky microplate distinguished in [53] subsided beneath central the Sredinnyi Range, while the Commander plate subsided beneath the northern part [50, 79] (Fig. 3a), or a single Commander–Kronotsky microplate existed [35]. At ~6 Ma, the southern part of the Kronotsky arc collided with the Kamchatka arc; the amalgamation was completed by 4–3.5 Ma [34, 53] (Fig. 3b). The collision of the Kronotsky terrane was accompanied by the transform sliding of the Pacific Plate along its eastern boundary and the subsidence of the plate in the northern direction. Pliocene basalts, andesites, and dacites of the Vodopadskaya Formation of the Commander islands [54] serve as a possible indicator of this subduction.

As shown in [13 and references therein], transform-margin magmatic complexes are formed not in the transform fault, but beside it, which make them fundamentally different from the magmatically active segment of the transform fault intersecting the spreading ridge. The transform-margin magmatism is not restricted to the transform fault, but is caused by the upwelling of the subslab asthenosphere after the cessation of subduction. Since the Earth is a globe (geoid), the cessation of subduction during island arc collision is inevitably followed by sliding of the oceanic plate along the transform amagmatic fault. The subslab

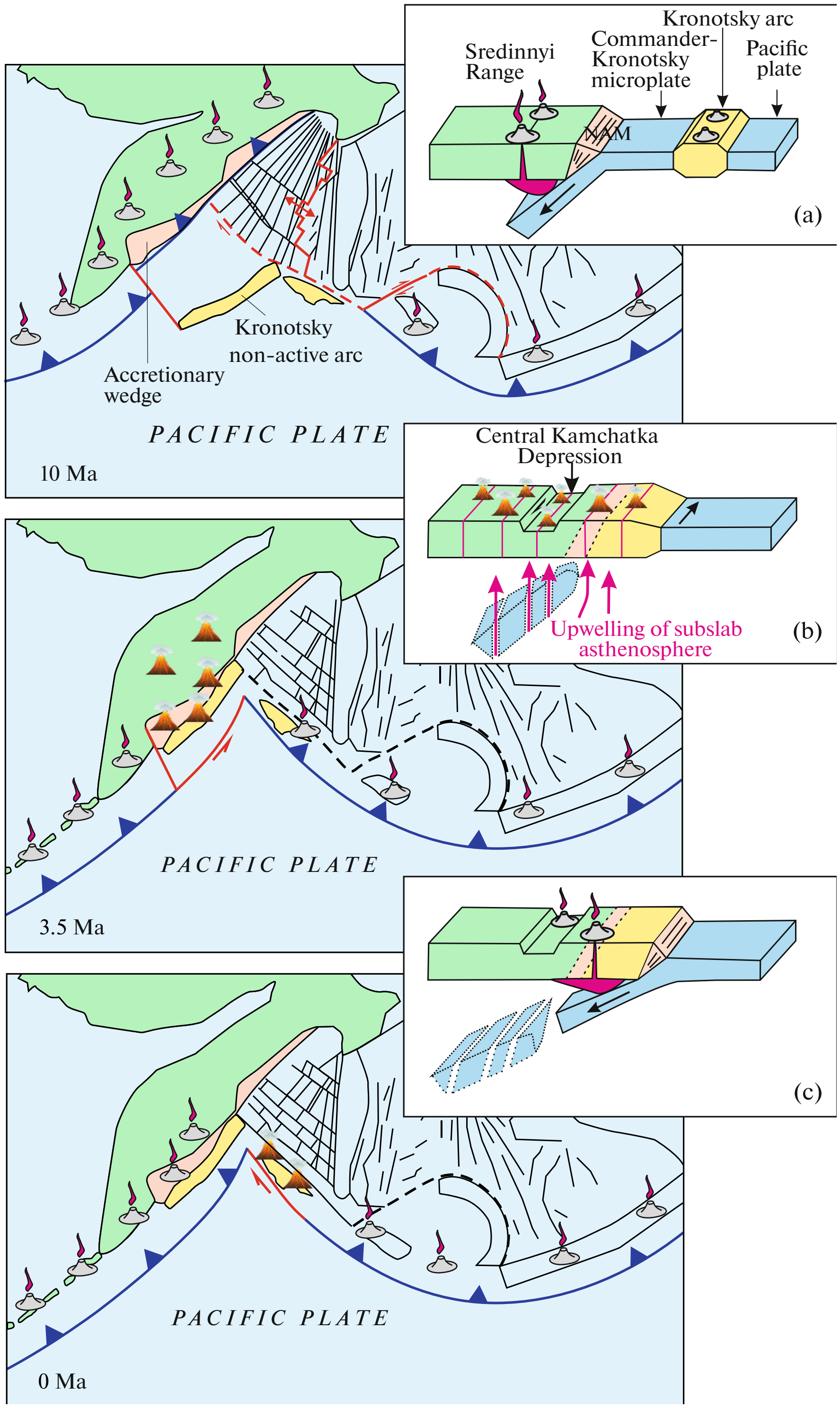

Fig. 3. Paleogeodynamic reconstructions for Kamchatka

asthenosphere is less dense than the slab. When subduction stops it rises through weakened and destructured slab zones. The asthenosphere is a source of alkaline rocks with within-plate (OIB) signatures. However, unlike plume settings, in transform margins, they are supplemented by adakites formed through slab melting around the slab window and in a subslab mantle and by calc-alkaline rocks derived through mantle wedge melting prior to continental subduction [74 and references therein]. Calc-alkaline magmatic rocks are apriori regarded as suprasubduction rocks. At the same time, these "island-arc" rocks in the proposed author's diagram are separated into rocks related to convergent and transformed margins [66].

We may suggest that the formation of a transform margin in Kamchatka was accompanied by slab fragmentation and breakoff, with identification of a slab fragment on the continuation of the modern slab based on seismic tomography data [65]. Slab breakoff led to the upwelling of the less dense subslab asthenosphere, which caused slab melting and determined the hybrid geochemical signatures of these volcanic rocks. Asthenosphere upwelling spanned the Oligocene–Miocene accretionary wedge and Kronotsky terrane (Fig. 3b). In this case, it is not necessary to relate the formation of Eastern Kamchatka adakites to subduction, as proposed in [3]. It is known that adakites are also present in the transform margin of Baja California, where oceanic subduction is absent, while formation of these rocks is explained by melting of a fossil slab under the influence of the subslab asthenosphere after the end of subduction [74]. The proposed model of the formation of slab fragmentation and breakoff explains the simultaneous accretion of the Kronotsky terrane and the occurrence of alkaline magmatism directly in the collision zone after jamming of a subducion zone. More alkaline composition of Eastern Kamchatka basalts compared to the Sredinnyi Range basalts [55] and the appearance of such unusual rocks as basaltic andesite ignimbrites [56] are likely caused by the absence of asthenospheric wedge between a slab and a handing plate beneath the Vetlov accretionary wedge and Kronotsky terrane. In this case, post-subduction basalts of the Sredinnyi Range were formed above the mantle wedge.

The Pleistocene was marked by the formation of the modern convergent margin of Kamchatka and transform margin along the Commander islands, whose indicators were the Pleistocene–Holocene submarine volcanoes to the north of the Commander Islands [82] (Fig. 3c). In the Sredinnyi Range, the transform-margin alkaline magmatism continued in the rear part of a new convergent margin but has no relation with the modern subduction zone, as indicated by the absence of slab beneath the Holocene volcanic rocks of the Sredinnyi Range based on seismic data [60, 64, 65, 68]. Such a phenomenon is not unique and, for instance, was described in British Columbia. In this region, the transform plate boundary was replaced by the convergent margin with the Garibaldi volcanic arc in the Pliocene. In the rear part, at a distance of approximately 250 km from the coast, the Wells Gray-Cleawater volcanic field of alkaline basalts has formed since 3.5 Ma and was active in the Holocene simultaneously with magmatism of the Garibaldi arc [e.g., 73]. The slab of the Garibaldi arc does not reach the alkaline volcanic field, as the modern slab of the Kamchatka arc does not reach the alkaline volcanic belt of the Sredinnyi Range [60].

CONCLUSIONS

New discriminant diagrams show that the Late Miocene (~6 Ma)–Pliocene volcanic rocks of Eastern Kamchatka and the Central Kamchatka Depression, as well as the Late Pliocene (~3.5 Ma)–Holocene volcanic rocks of the central part of the Sredinnyi Range, are identical to the volcanic rocks of the Pacific-type transform margin, whereas the Miocene–Holocene volcanic rocks of South Kamchatka, Miocene–Early Pliocene volcanic rocks of the Sredinnyi Range, and Pleistocene–Holocene volcanic rocks of Eastern Kamchatka resemble volcanic rocks of convergent margins.

These data are consistent with the results of geological and geophysical studies and make it possible to reconstruct the Late Miocene–Pliocene transform margin in Kamchatka. This margin was formed during accretion of the Kronotsky–Commander island arc and sliding of the Pacific plate.

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