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Ophiolites of the Kamchatsky Mys Peninsula, Eastern Kamchatka: Structure, Composition, and Geodynamic Setting

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Abstract—Ophiolites of the Afrika Mys Block of the Kamchatsky Mys Peninsula, eastern Kamchatka, are a fragment of an accretionary prism that formed in the Late Cretaceous–Eocene on the southern side of the Kronotsky island arc as a result of its collision with the Smagino volcanic uplift that arose at the post-Neocomian time on the subducting plate. On the basis of the geologic, geochemical, and paleomagnetic data available to date, it is established that ophiolites are heterogeneous in their origin and were formed in different geodynamic settings that changed progressively with time. The heterogeneous structure of ophiolites displays the evolution of a fragment of the oceanic lithosphere, which was not submerged into subduction zone, from its origination in the spreading center via transformation under conditions of the plume-related volcanic uplift to the involvement in the structure of the Kronotsky island arc, which is currently a constituent of the accretionary system of Kamchatka. The reconstruction of ophiolites tectonically fragmented in the accretionary prism allows recognition of (1) derivatives of an ocean ridge (ultramafic–gabbro–basaltic complex of the Mount Olen'ya Massif) conjugated with a transform fault and volcanosedimentary rocks of the Smagino volcanic uplift (cover of the oceanic crust) and (2) a fragment of the lithospheric mantle (ultramafic rocks of the Lake Stolbovoe Massif) exhumed in the process of collision and genetically related to the evolution of the volcanic uplift. In the course of evolution of the Kronotsky island arc, all these elements were overlapped by tephrogenic turbidites (Pikezh Formation) and quartz–feldspar graywackes (Pikezh Sandstone) that were involved in the accretionary prism as well. The paleotectonic reconstructions broadly support the petrologic conclusions about the complementary nature of different igneous complexes and ascertain the temporal sequence of events.

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INTRODUCTION

The eastern peninsulas of Kamchatka—Shipunsky, Kronotsky, and Kamchatsky Mys—are characterized by widespread occurrence of Paleocene and Eocene island-arc lavas, tuffs, and tephroids and may be regarded as fragments of the Kronotsky paleoarc [1, 13]. The Komandorsky Islands are often included in this arc too. The volcanic rocks of the Kamenisty Mys Formation on the Kronotsky Peninsula are the oldest in the Kronotsky arc and are dated at the Campanian–Maastrichtian [5] or even at the Coniacian–Santonian [24]. The Lower Paleogene sequences, which are prevalent in this zone, are deformed relatively weakly, making up open brachyform folds complicated by numerous steeply dipping faults.

The southern Kamchatsky Mys Peninsula, or the Afrika Mys Block, occupies a special place in the structure of the Kronotsky arc. The intensely deformed Cretaceous (post-Neocomian) deepwater volcanosedimentary complexes [36]; Alpine-type ultramafic rocks; and fragments of the layered pluton composed of ultramafic and gabbroic rocks, dolerites, and basalts are sharply predominant among the pre-Pliocene rocks [4, 8, 9, 37, 38].

These constituents of the Afrika Mys Block are correlated readily with units of the oceanic lithosphere and therefore considered to be elements of ophiolitic association [15, 16, 49, 74].

However, the main members of this association were formed in different geodynamic settings [19, 25–31, 36, 39, 40]. Therefore, it is important to understand whether their combination is a result of some deep tectonomagmatic processes, e.g., the multistage formation of the old oceanic crust before the origin of the island arc and tectonic juxtaposition of genetically distinct rock associations of different ages, or a reflection of the progressive stages of the evolution of the Kronotsky arc itself.

In this paper, we focus our attention on the first step to answering this question and try to specify the formation conditions of the main groups of igneous and sedimentary rocks in the south of the Kamchatsky Mys Peninsula. This area occupies a unique position at the junction of Kamchatka and the Aleutian arc and is relatively accessible. For this reason it is among the most visited and studied place in Kamchatka. The evolution of the Kamchatsky Mys ophiolites has been discussed repeatedly in the literature (see references). However, researchers have not yet come to a universally adopted sequence of geodynamic events that led to the formation of ophiolites. Therefore, a review of the data on the Kamchatsky Mys ophiolites available to date (mainly published in the Russian literature) would be useful.

GEOLOGIC OUTLINES

In its present-day structure, the Kamchatsky Mys Peninsula has the appearance of a recent uplift surrounded on three sides by narrow shelves and the steep continental slope of the Pacific Ocean and Bering Sea and on the fourth, western side by a depression filled with the Pliocene–Quaternary loose sediments and the large lakes Nerpich'e and Stolbovoe (Fig. 1, upper inset). The thin, discontinuous, slightly deformed cover of the Pliocene–Quaternary clay, sand, and pebbles of the marine–glacial origin overlaps most of the peninsula territory, whereas the underlying basement is composed of Cretaceous and Paleocene–Eocene complexes. The peninsula is divided into two blocks different in structure: the northern Lake Stolbovoe Block, consisting of the Paleocene–Eocene rocks, and the southern Afrika Mys Block, which will be characterized further in more detail. The boundary between these blocks is traced along the valley of the Second Pereval'naya River in the east and farther to the northern coast of Lake Nerpich'e. This boundary is probably controlled by a system of recent right-lateral strike-slip faults as an extension of the faults at the western ending of the Aleutian arc [1, 15].

The structure of the Afrika Mys Block is very complex and determined by the master faults. The oldest of them are the NW-trending, relatively low angle (as steep as 45°) thrust faults that dip to the southwest or the northeast. With a certain degree of conditionality, the Afrika Mys Block is subdivided in several domains bounded by large faults and therefore called blocks as well (Fig. 1, upper inset). The Mount Soldatsky and Mount Olen'ya massifs, the Smagino Monocline, the Pikezh Tectonic Zone, and the Mayachny Block (not considered in this paper) are distinguished most distinctly.

The Mount Soldatsky Massif, is composed predominantly of three groups of ultramafic rocks that differ in composition, structure, and origin (Fig. 1). The majority of these rocks are interpreted as a series of tectonic sheets complicated by serpentinite protrusions [3, 4, 18–21, 28].

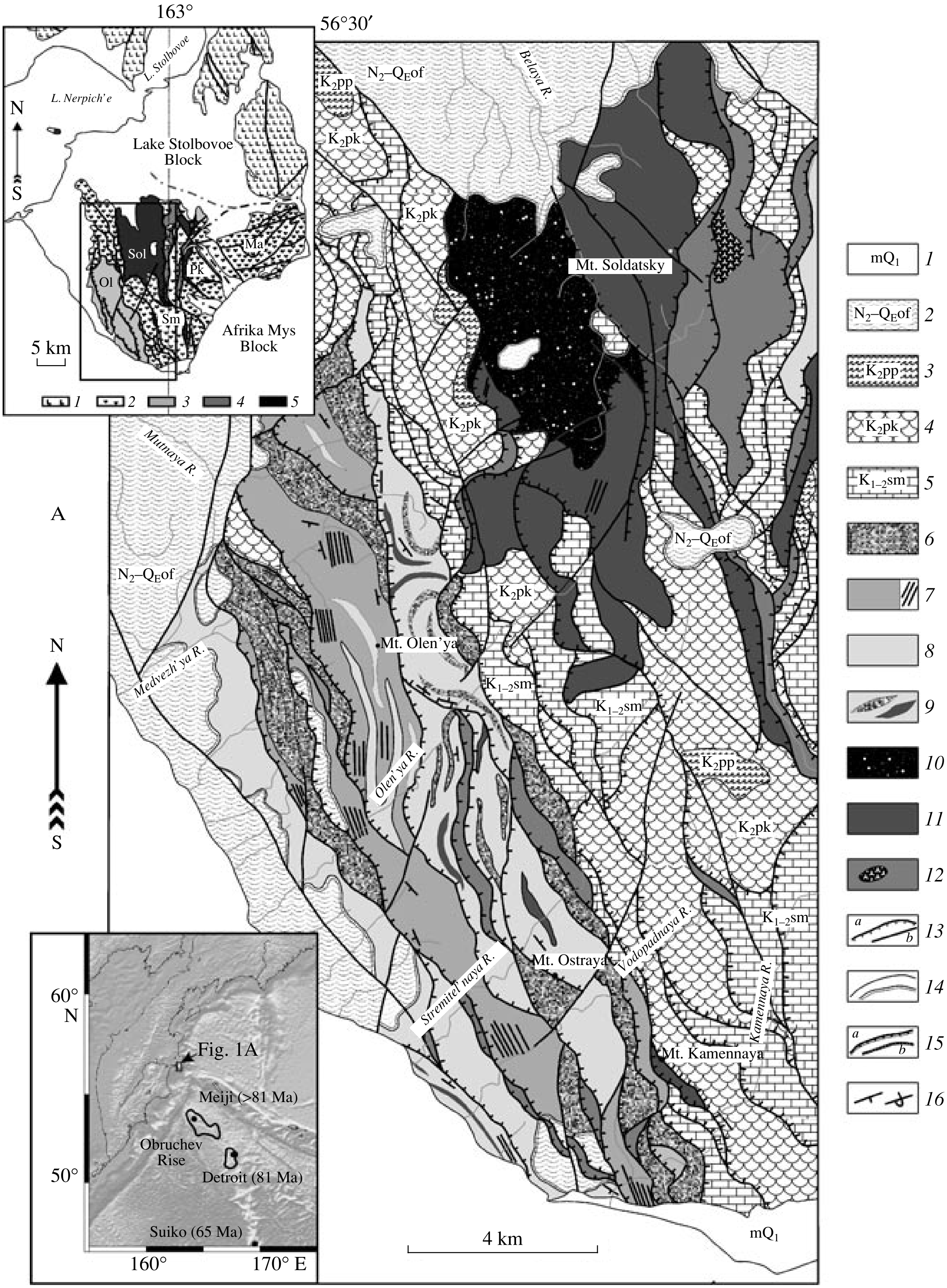
A westward-dipping tectonic sheet of serpentinite melange that reaches a few hundred meters in thickness is mapped at the base of the allochthon in the eastern portion of the Mount Soldatsky Massif (Fig. 1). The melange contains particular masses, blocks, and boulders of only slightly serpentinized peridotites up to a few hundred meters across; basaltic and gabbroic bodies (up to a few kilometers in size); and occasionally occurring chlorite–epidote schists and garnet amphibolites (tens of meters) [4, 18, 28, 39].

The westerly parts of the Mount Soldatsky Massif are composed of cumulative and restitic peridotites that occur as several sheets (layers?) a few hundred meters thick that overlie one another. The cumulative character of peridotites in the upper sheet (layer) is emphasized by poikilitic and coronary structure with participation of late generations of olivine, clinopyroxene, and Cr-spinel [4, 8, 9, 37, 38]. The enstatite- and clinopyroxene-bearing dunite, clinopyroxene-bearing harzburgite, websterite, wehrlite, and olivine clinopyroxenite are regarded as cumulates. These rocks make up lenses, stocklike dunite and veinlike clinopyroxenite bodies, and sheets hosted in harzburgite and clinopyroxene-bearing spinel harzburgite or even lherzolite and bounded by distinct smooth contacts [3, 4, 8, 9, 21, 37, 38]. The dunite sheets, varying from tens of centimeters to a few

Fig. 1. (A) Schematic geological map of the southwestern Kamchatsky Mys Peninsula; (B) tectonostratigraphic column of rock complexes making up the ophiolitic association, modified after [4, 14, 37, 38].

Panel A. (*1*) Quaternary marine sediments; (*2*) Upper Pliocene–Lower Pleistocene rocks of the Ol'khovsky Formation; (*3–5*) Afrika Mys Group: (*3*) Maastrichtian (?) Pikezh Sandstone; (*4*) Santonian–Campanian Pikezh green cherty tephroids; (*5*) Albian–Cenomanian Smagino red calcareous–cherty sediments, hyaloclastites, and pillow lavas; (*6–9*) Mount Olen'ya Massif: (*6*) basalts and dolerites; (*7a*) fine- and medium-grained isotropic gabbro, layered gabbro with gabbroanorthosite lenses, gabbro with fluidal structure, basaltic lenses, and schlieren; (*7b*) large swarms of basalt and dolerite dikes; (*8*) cumulative inequigranular (up to pegmatoid) diallage gabbro; (*9a*) lenses and sills of basalt in cumulative gabbro surrounded by gabbronorite and gabbro with various structures; (*9b*) xenoliths, schlieren, and lenticular units of ultramafic rocks in gabbro associated with melanocratic gabbro, troctolite, and clinopyroxenite; (*10–12*) Mount Soldatsky Massif: (*10*) cumulative dunite, clinopyroxene-bearing spinel harzburgite, websterite, wehrlite, and clinopyroxenite (late stage of massif formation); (*11*) restitic harzburgite and dunite (early stage of massif formation); (*12*) serpentinite melange with fragments of gabbro and garnet amphibolite; (*13a*) thrust faults and (*13b*) other faults; (*14a*) conformable stratigraphic boundaries and (*14b*) boundaries of unconformable onlap; (*15a*) stratigraphic boundaries complicated by faults; (*15b*) hot tectonic contacts sealed with rodingite; (*16*) dip azimuth of beds and other planar elements. *Upper inset.* Tectonic units of the southern Kamchatsky Mys Peninsula: (*1*) Paleogene complexes of the Lake Stolbovoe Block, (*2*) Upper Cretaceous Afrika Mys Group, (*3*) ultramafic–gabbro–basaltic complexes; (*4*) serpentinite melange; (*5*) ultramafic rocks. Tectonic units (letters in figure): (Ol) Mount Olen'ya Massif, (Sol) Mount Soldatsky Massif, (Sm) Smagino Monocline, (Pk) Pikezh Tectonic Zone, (Ma) Mayachny Block. *Lower inset.* Location of the studied area at the junction of Kamchatka, the Aleutian arc, and the Emperor Seamount Chain.

Panel B. *Photos to the tectonostratigraphic column*: (1, 2) pillow lavas of the Mount Olen'ya Massif, (3) initially vertical basaltic dike cutting through the initially horizontally layered gabbro and gabbroanorthosite, (4) intrusive body of cumulative diallage gabbropegmatite in the layered gabbro (photos by G.E. Nekrasov).


163°
56°30′
L. Stolbovoe
L. Nerpich'e
N
S
Lake Stolbovoe Block
Sol
Pk
Ma
Ol
Sm
Afrika Mys Block
5 km
1 2 3 4 5
Belaya R.
K2pp
N2–QEof
K2pk
Mt. Soldatsky
Mutnaya R.
A
K1–2sm
Mt. Olen'ya
Medvezh'ya R.
Olen'ya R.
Mt. Ostraya
Vodopadnaya R.
Stremitel'naya R.
Kamennaya R.
Mt. Kamennaya
60° N
50°
Fig. 1A
Meiji (>81 Ma)
Obruchev Rise
Detroit (81 Ma)
Suiko (65 Ma)
160°
170° E
4 km
mQ1
1
2
3
4
5
6
7
8
9
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14
15
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a
b

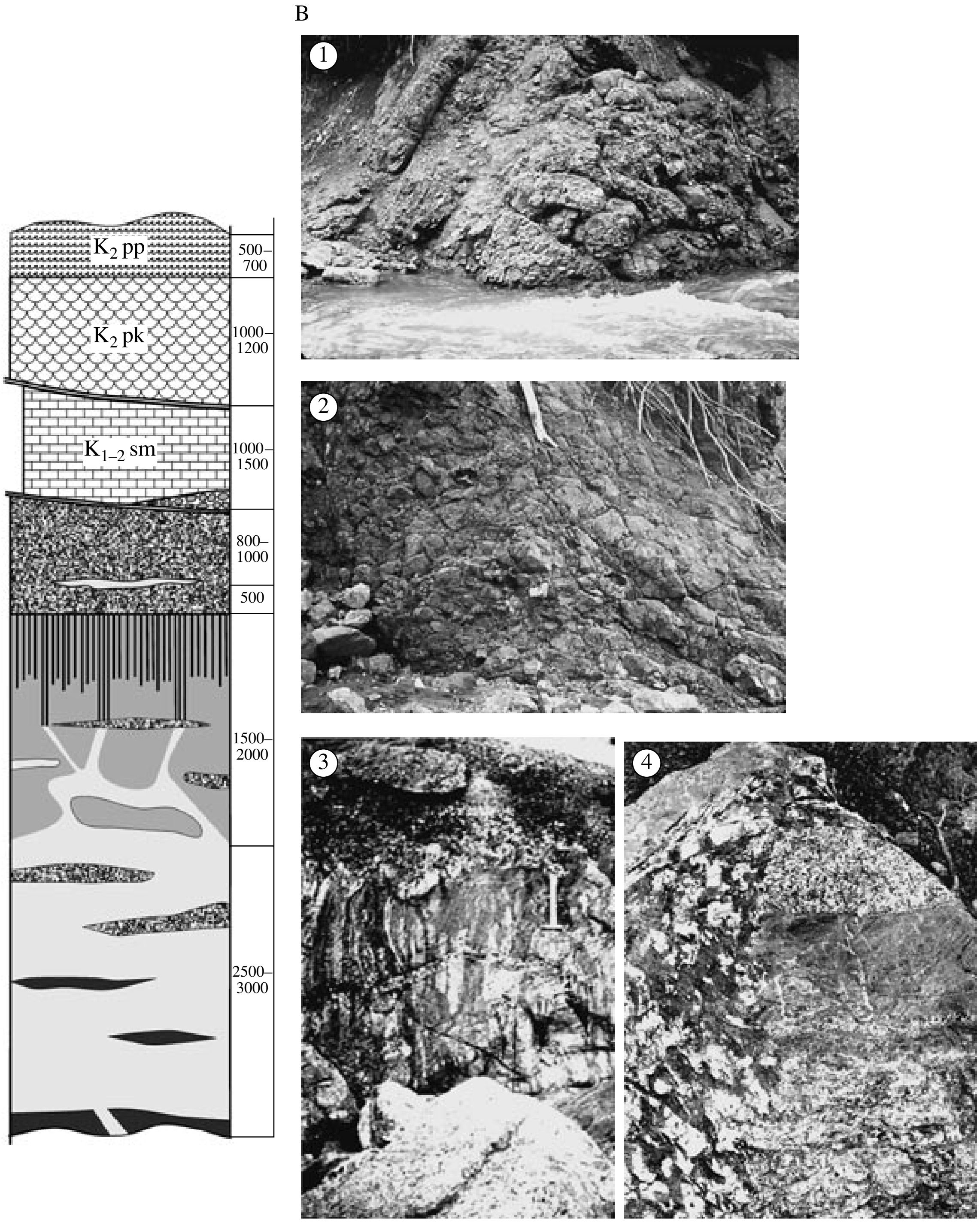


Fig. 1. (Contd.)

meters in thickness, alternate with spinel harzburgite. Chromitite schlieren are confined to dunite.

A gradual transition of ultramafic rocks into gabbro was described at Mount Osyp in the Pikezh Tectonic Zone [4]. In the virtually continuous section (<100 m thick) of the so-called banded complex, spinel harzburgite bands (1–2 m thick) alternate with dunite bands enriched in chromite schlieren and phenocrysts and with websterite and clinopyroxenite bands. Upsection, these rocks give way to banded fine- and medium-grained gabbro (up to 50 m in thickness).

The underlying restitic rocks are largely spinel harzburgite serpentinized to some degree (often rather strongly). Olivinite (epidunitic rocks) occur in harzburgite as separate spots vaguely related to the host rocks. Virtually all tectonic lenses and slices beyond the limits of the Mount Soldatsky Massif are composed of restitic peridotites as well. These complexes may confidently be correlated with abyssal peridotites of the present-day oceanic lithosphere and ophiolitic peridotites [42, 53, 71, 73, 76, 77, 79].

Direct evidence for the age of ultramafic rocks of the Mount Soldatsky Massif is limited by the results of the cumulative complex timing with Rb–Sr and Sm–Nd methods [12]. Unfortunately, the published data (Rb–Sr age of 78 Ma and Sm–Nd age of 93 Ma) are not accompanied by information on analytic and instrumental errors and cannot be regarded as fully reliable. The recalculation of the published data with the ISOPLOT program and the program used at the Laboratory of Geochronology of the Geological Institute, RAS, indicates that the measurement results are unstable and their errors are too great. These errors, especially as concerns the Rb–Sr dating, allow us to consider these data invalid (V.I. Vinogradov, personal communication). Nevertheless, the recalculated Sm–Nd isochrons preliminarily indicate that the cumulative rocks were formed 89–93 Ma ago in the Late Cretaceous.

The Mount Olen'ya Massif mainly consists of the ultramafic–gabbro–basaltic complex repeatedly described in the literature [4, 8, 9, 11, 14–16, 20, 23, 37–40]. Here, we add only some new data.

The section of the Mount Olen'ya Massif restored from separate fragments in the conjugated tectonic slices appears as follows (from top to bottom), see Figs. 1A and 1B.

(1) The unit of pillow lavas and dolerite sheets with lenses, schlieren, and spots of amphibole and amphibole-free gabbro, largely fine and medium grained (Fig. 1B, photos 1, 2). Basalts include porphyritic varieties, and dolerites commonly are aphyric and, less frequently, porphyritic rocks with small phenocrysts. The outer zones of pillows are composed of porphyritic basalt with cryptocrystalline groundmass. The phenocrysts include perfectly faced or resorbed crystals of olivine, augite, and labradorite. The late labradorite and andesine–labradorite make up glomeroporphyritic intergrowths. The groundmass is radiate, sheaf-shaped, and radiate–dendritic owing to the acicular and fibrous aggregates of clinopyroxene.

The inferred thickness of the unit is no less than 1000 m. Its lower portion devoid of pillow lavas and composed only of dolerite and gabbrodolerite sheets is transitional toward the underlying gabbroic rocks. The thickness of the transitional zone probably does not exceed 300 m.

(2) The unit of dolerites grading downward into equigranular gabbro with numerous dolerite and basalt sills and dikes (the so-called sheeted dike complex). Only the largest dike swarms may be mapped, although the dike and sills occur throughout the massif as isolated bodies, clusters, and dike fields. Northwest-trending dikes are predominant, while near-latitudinal and northeastern dikes are less frequent. The initial vertical attitude of these dikes is fixed only in the cases when they crosscut the layered or banded gabbro (Fig. 1B, photo 3). When the screens between dikes consist of isotropic gabbro, the thick (several meters) dikes are indistinguishable from sills of the same composition. The mapping of basaltic and doleritic sills and dikes meets difficulties because, at present, most rocks lie vertically. Some dikes contain diffuse spots and xenolith-like segregations of fine- and medium-grained gabbro. Contacts of dikes and, probably, sills with country gabbroic rocks are commonly "hot" and occasionally complicated by offsets. The approximate thickness of the unit is 1000 m.

(3) The unit of thinly and crudely layered, inequigranular gabbronorite; olivine gabbro; clinopyroxene; amphibole and amphibolized gabbro; leucogabbro; and gabbroanorthosite of various structures contains lenses and schlieren of anorthosite (Fig. 1B, photos 3, 4). Amphibolization of rocks is mainly secondary, although the late magmatic amphibole is also observable in gabbro. The amphibole-rich lenses are commonly concordant to the layering or banding of rocks, and only sporadic lenses crosscut the layering.

The relationships between gabbro and basalts that indicate the so-called "burial" of basalts in the gabbroic complex have been described precisely in this unit. The same (except for some details) relations are known from Oman, where the coexisting gabbro and basalts without chilled contacts were defined as fossil melt lenses [46, 51, 69, 70]. The absence of "hot" contacts and chilled margins is typical of such relationships (Fig. 2, sketch, photo 1). This phenomenon may be explained only in terms of emplacement of residual melt into the crystalline mush (cumulate of the parental melt) within the crust. Gabbroic rocks with variable structure (Fig. 2, photos 2–4), together with basaltic and doleritic lenses, most likely make up a transitional unit between the upper gabbro and the layered gabbro at the base of the unit of parallel dikes. The fine-grained gabbro of this transitional unit and of units occurring below are similar in appearance and composition to basalts and dolerites in the complex of parallel dikes. The thickness of unit (3) is estimated approximately at 100–150 m. The total thickness of layered gabbro below the complex of parallel dikes is assessed very tentatively at 700–1000 m.

(4) The unit of massive, spotty–banded, often pegmatoid diallage and olivine gabbro with schlieren, lenses, and inclusions of ultramafic rocks, troctolite, and melanocratic olivine gabbro; breccia of ultramafic fragments cemented with gabbro; shadow breccia with ultramafic fragments; and sills and branching dikes of coarse-grained gabbro (Fig. 1B, photo 4). The diallage gabbro consists of elongated clinopyroxene crystals and tabular, short-columnar crystals of calcic plagioclase (labradorite–bytownite). This unit is the most

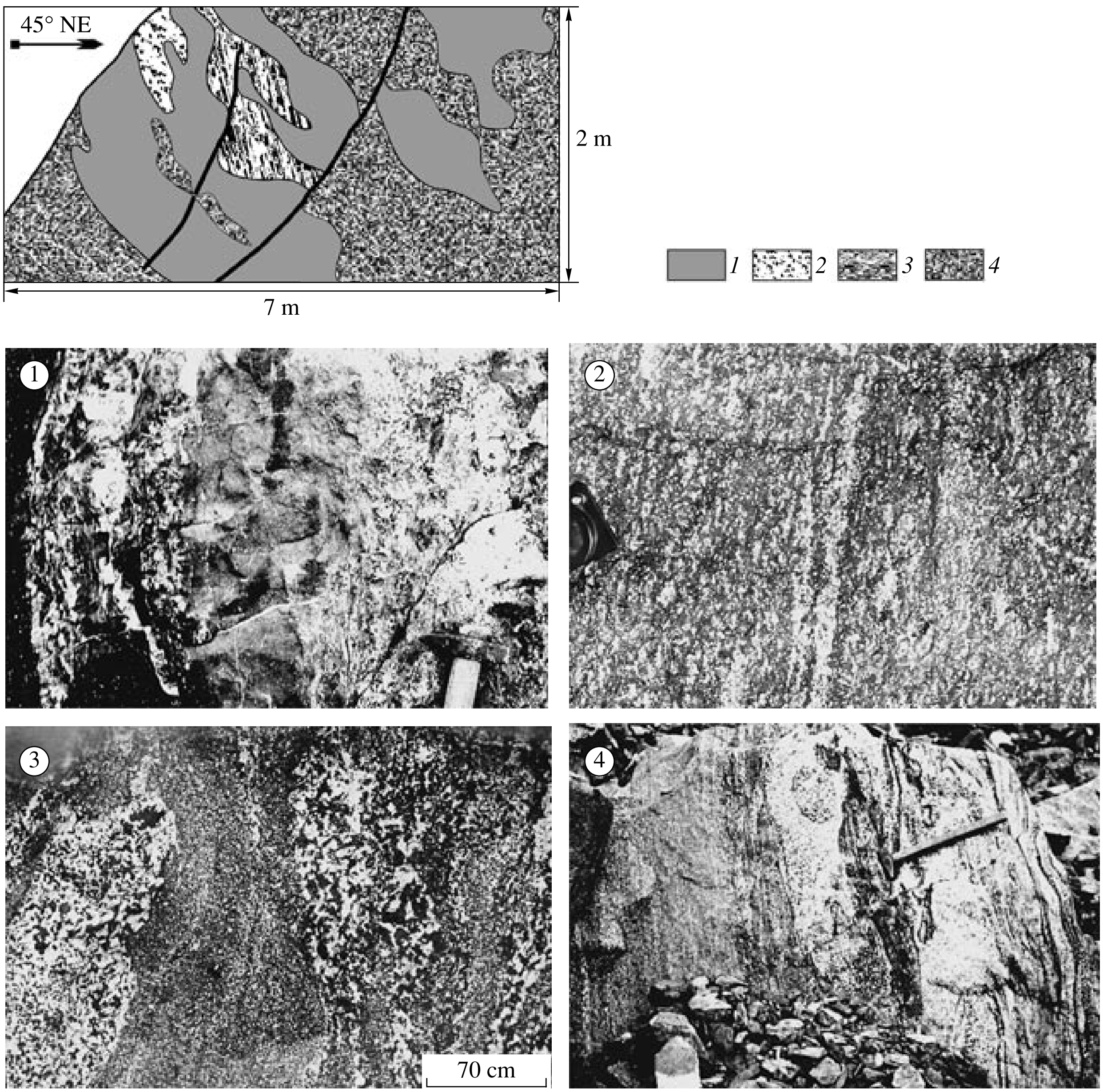


Fig. 2. Sketch of an outcrop at the Stremitel'naya River and photos (taken by G.E. Nekrasov) of gabbro and basalt in the fossil melt lens at the base of sheeted dike unit. *Sketch*: (*1*) fine-crystalline basalt with subtle fluidal structure; (*2–4*) gabbro varying from melanocratic fine-grained rocks to medium- and coarse-grained plagioclase-rich rocks. *Photos*: (1) small basaltic lens in gabbro; (2) banded fine-grained gabbro with lenses and veinlets enriched in plagioclase; (3, 4) spotted and spotted–banded, mainly fine grained and medium grained gabbro.

widespread in the body of the Mount Olen'ya gabbro; its total thickness probably reaches 3.5–4.0 km.

Both diallage gabbro and other gabbroic varieties are cumulates separated by a sharp intrusive contact from the overlying rocks of the Mount Olen'ya Complex. This contact is visible in a network of branching veins and their offsets and other crosscutting bodies of vague morphology (Fig. 1B, photo 4). The pegmatoid and coarse-grained gabbro are either concordant to the general pseudolayered and banded structure of this unit or occur as crosscutting, branching, and veined bodies. Numerous lenses and sill-like bodies composed of basalt and dolerite occur in this unit at higher levels. Some sills reach tens of meters in thickness. Schlieren, lenticular segregations, and spots of gabbro of various structures and diffuse outlines are observed within the sills, as in the units described above. Diallage gabbro and gabbropegmatite in the lower part of Unit 4, as well as cumulative olivine gabbro, contain numerous xenogenic inclusions, lenses, schlieren, and distinctly delineated xenoliths of ultramafic rocks, pyroxenites included (Fig. 3). The largest xenoliths reach 5×10 m^2

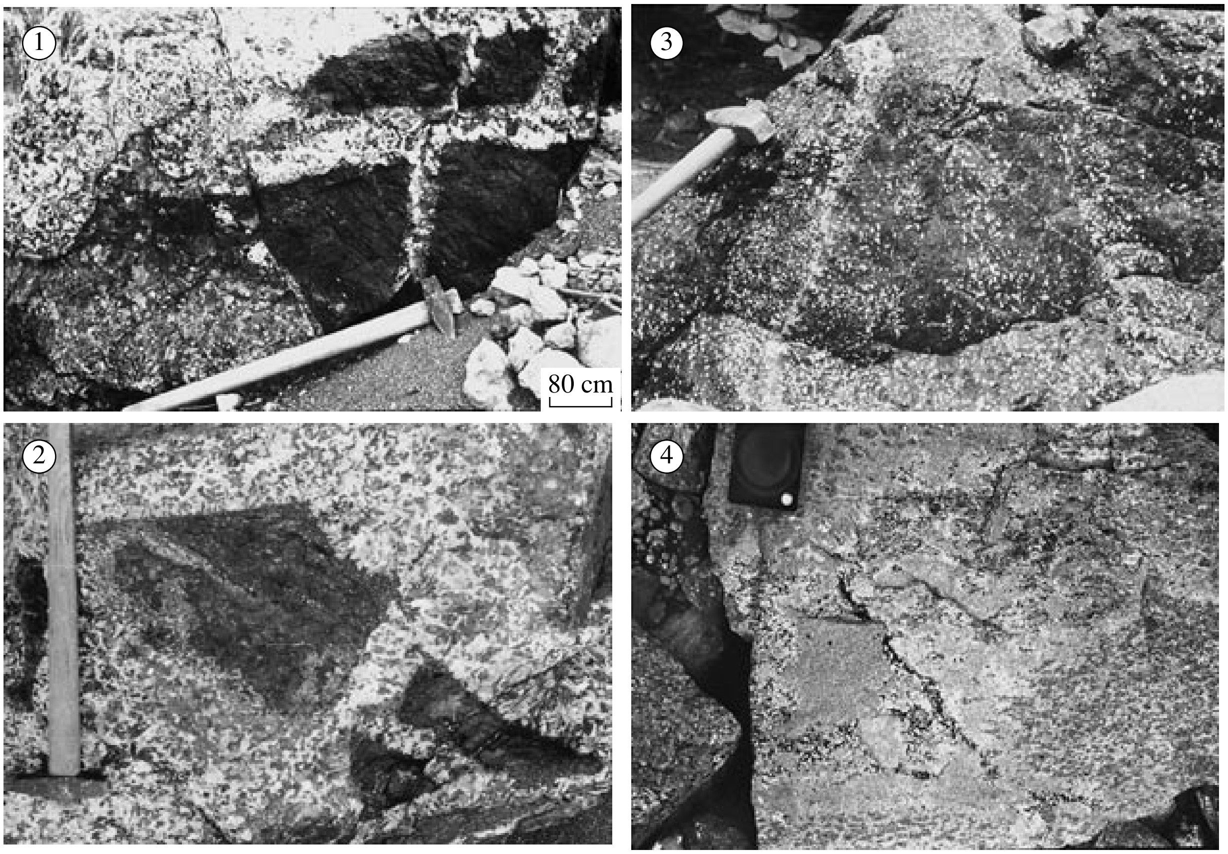


Fig. 3. Relationships of diallage gabbro with ultramafic xenoliths (photos by G.E. Nekrasov). (1–4) Progressive stages of reworking of harzburgite and dunite xenoliths via plagioclase peridotite and troctolite into shadow gabbroic breccia with sporadic relicts of peridotite protolith.

in size. As can clearly be seen from Fig. 3, photos 1–4, the ultramafic rocks are reworked by gabbroic melt up to the state of shadow xenoliths or the complete absorption by gabbro varying in structure.

Thus, the spots and irregular segregations of troctolite and olivine gabbro developed after harzburgite, lherzolite, and serpentinized dunite. Plagioclase-bearing peridotites are probably also a product of impregnation of ultramafic rocks with gabbroic melt. The partial serpentinization of peridotite apparently developed prior to its impregnation with gabbroic melt. As a rule, the diallage veinlets crosscut the fibrous structure of serpentinite with formation of brecciated, gneissic, or augen structure of rocks. Plagioclase appears in veinlets in increasing amounts along with clinopyroxene. The banded–fibrous fabric of serpentinite is retained only in xenomorphic or irregularly shaped relicts replaced completely with the secondary minerals. Without any doubt, the gabbroic section formed during several separate stages. In this regard, it is necessary to consider amphibole gabbro as the youngest rocks of the Mount Olen'ya Massif in more detail. Amphibole and amphibole–pyroxene gabbro and gabbronorite are medium-grained banded rocks with ophitic and poikilitic textures consisting of labradorite and andesine–labradorite (50–60%), hypersthene and/or clinopyroxene (up to 15%), hornblende (30–40%), and ore mineral. Clinopyroxene and brown hornblende are often replaced with bluish green or colorless amphibole and associated leucoxene. Olivine–amphibole–pyroxene gabbro is a banded rock with allotriomorphic granular and gabbroic (magmatic!) textures. The rock consists of labradorite and andesine–labradorite (55–60%), olivine (5–7%), hornblende (5–8%), and diallage (25%). The primary pale green hornblende (likely pargasite) and diallage are comparable in the degree of idiomorphism. Thus, they crystallized synchronously.

(5) The unit of ultramafic rocks that are represented mainly by harzburgite and lherzolite and to a lesser extent by dunite, which is strongly serpentinized and cut by pyroxenite, wehrlite (85–88% of olivine and 10% of clinopyroxene), and websterite bodies. Upsection, the ultramafic rocks give way to troctolite (50–65% olivine, 30–45% plagioclase, and 5–10% clinopyroxene) and olivine gabbro. Numerous inclusions, schlieren, and lenses of almost completely serpentinized ultramafic rocks are contained in augen and banded olivine gabbro with xenomorphic serpentinite inclusions. Dunite (mainly in schlieren and lenses) consists of olivine (up to 95%), magnetite, titanomagnetite,

less abundant ilmenite (5–7%), and sporadic clinopyroxenite grains. The slightly serpentinized lherzolite consists of 75–80% olivine (Fo_{89-91}), 8–12% diallage, and single orthopyroxene grains. Clinopyroxene is always xenomorphic and often contains olivine inclusions [8, 9]. The intense serpentinization obliterates the cumulative structure of rocks, although this structure is evident from detailed petrographic examination. The unit is cut through by dikes and sills of gabbro and gabbronorite. The apparent thickness is about 200–300 m. It is most likely that this unit is the uppermost portion of the crust–mantle transitional zone [51, 85, 87, 89]. In general, the Mount Olen'ya gabbroids may be compared with the third layer of the present-day oceanic crust [49, 50, 74].

The total thickness of the section of the Mount Olen'ya Massif as described in this paper probably reaches no less than 6 km. However, one can speak with certainty of fragmentary and highly incomplete character of this section.

There are no reliable data on the age of the Mount Olen'ya Massif. Several published K–Ar datings of whole-rock dolerite samples yielded 122–144 Ma [34]. At the same time, the K–Ar age of clinopyroxene and plagioclase fractions corresponds to 251 Ma. These estimates most likely do not fit the true age of rocks but demonstrate the complex, multistage formation of the Mount Olen'ya Massif.

Tectonic blocks of gabbro smaller than the Mount Olen'ya Massif are exposed within a melange sheet east of the Mount Soldatsky Massif. Plagiogranite veins and veinlets were found in one of such blocks at the headwater of the First Ol'khovaya River [28, 39, 40]. Plagiogranite and plagiogranite porphyry as a network of thin (a few centimeters to 2 m) veins and veinlets of insignificant extent cut through the fine-grained pyroxene and amphibole-bearing gabbro and low-Ti gabbronorite. Plagiogranite contains angular xenoliths of gabbro [39]. As was reported by M.V. Luchitskaya (personal communication and preprint of the Geological Institute, RAS, 2005), the magmatic zircons from plagiogranite were dated with the U–Pb method (SHRIMP) at 74.7 ± 1.8 Ma; this estimate corresponds to the Campanian Age. Luchitskaya and her colleagues combine gabbro and plagiogranite from the First Ol'khovaya River into one complex, which is not correlated with the Mount Olen'ya Massif. This conclusion is based on relatively scanty geochemical data supposedly indicative of the suprasubduction tectonic setting [39].

In general, the ultramafic–gabbro–basaltic complex of the ophiolitic association of the Kamchatsky Mys bears many attributes of the oceanic crust formed in the linear spreading zone. The 1.5-km fragment of the gabbroic section of the third oceanic crust layer penetrated by Hole 735B (ODP, Leg 176) in the southwestern Indian Mid-Ocean Ridge [49, 74] may be regarded as a close analogue of gabbroids from the Kamchatsky Mys, in particular by occurrence of felsic dikes that cut gabbro.

The volcanosedimentary rocks of the Afrika Mys Group [36] crop out in the southwest of the peninsula in the Smagino Monocline that separates the Mount Olen'ya and Mount Soldatsky massifs and form the Pikezh Tectonic Zone and the Mayachny Block that is located beyond the limits of the map shown in Fig. 1. The group consists of three rock associations. The main Pikezh association consists of gray–green clayey, silty, and less frequent sandy tephroids and tuffites, cherty to some or other degree, with lenses and interlayers of gray–green silicites and tuffaceous silicites. Clearly expressed but mostly not graded bedding is observed in some outcrops. Various basalts, basaltic andesites, and volcanic glass dominate as lithic fragments; fragments of clinopyroxene and moderately calcic plagioclase crystals occur also. This association occupies up to 75% of the volcanosedimentary group and was undoubtedly related to a powerful source of pyroclastic material, i.e., an island arc. Locally, it is completely dominant in the lower part of the Smagino Monocline, but more often, it is prevalent only in the upper part, where it was originally named the lower unit of the Pikezh Formation [37, 38], the section of which commonly begins with gravelstone and conglomerate bearing fragments of basalts typical of the Mount Olen'ya section. The lenses of plagiophyric basalts, basaltic andesites, and amygdaloid andesites, occasionally with a pillow-lava appearance, occur in the Pikezh sections [36]. The thickness of particular lenses does not exceed a few meters and commonly is less. Radiolarians from silicites of the Pikezh association mostly pertain to the Santonian–Campanian stratigraphic interval [6, 7, 33].

The peculiar Smagino association of the Afrika Mys Group [36] consists of reddish brown ferruginous mudstone often of hyaloclastic origin; red jasper; pink pelitomorphic limestone, as a rule, intercalating with jasper; and lenses of pillow and massive basaltic lavas. Limestone contains planktonic foraminifers and nannoplankton of the Albian–Cenomanian age, while radiolarians of the same age have been found in jasper [4–8, 33]. Particular blocks (layers) of the Smagino association occur not only as self-dependent, commonly thin tectonic slices but also as olistoliths and olistoplaques in a tuffitic matrix similar in composition to the tuffites of the Pikezh association. The volcanic rocks of the Smagino association that occupy more than one-third of its apparent thickness are diverse in composition, but represented largely by tholeiites. Potassic alkali basalts were first found in this association by Fedorchuk [30–32, 35]. In the course of geological mapping in 1999, it was ascertained that high-K basalt and dolerite mainly occur as subvolcanic sills conformable to the bedding of volcanosedimentary rocks [4].

Note that the rocks of the Smagino association contain neither terrigenous nor pyroclastic material. These rocks consist of purely pelagic sediments or peculiar hyaloclastites (reddish brown mudstones) that were formed by spraying of the basaltic melt in the bottom water [36]. The rate of deposition of such mudstones is unknown, but the rate of deposition of pelagic organogenic cherty and calcareous oozes is commonly much lower than the rate of deposition of island-arc tephroid sediments. It is evident that deposition of purely pelagic sediments without a pyroclastic admixture is impossible on arc slopes and in close proximity to the arc (in the forearc segment). We suggest that the green-colored tephroid rocks and tuffaceous silicites of the Pikezh association were deposited on submarine slopes and in the shelf zone of the Kronotsky island arc, while sometimes overfilling the deepwater trench. At the same time, the red beds of the Smagino association (intercalating cherts and limestones) were deposited not only at a distance from the Kronotsky arc but also long before its origin in the environment of the deepwater (no pyroclastics) basaltic volcanic activity (volcanics flows, subvolcanic intrusions, and hyaloclastic rocks). Such an origin of the rock associations that belongs to the Afrika Mys Group does not rule out that some particular units of the Pikezh association could have contained olistoliths and olistoplaques of the previously formed rocks belonging to the Smagino association.

Near the thrust fault that separated the Mount Olen'ya Massif and the rocks of the Smagino association, conglobreccia lenses often occur. The fragments of gabbroic and doleritic rocks are incorporated into the red clayey and carbonate cement. Conglobreccia at the base of the Smagino association most likely is of the edaphogenic origin related to the destruction and exposure of a portion of the lower crust on the oceanic floor, e.g., in the transform fracture zone.

Tephroids of the Pikezh association at the contact with the Mount Olen'ya Massif also often contain large (meters across) and small (centimeters) lenses of breccia, conglomerate, and gravelstone with fragments of the Mount Olen'ya basalts and less abundant diallage gabbro. The deposition of the gravelstone and conglomerate testifies to the dissected submarine topography in the process of deposition of the Pikezh tephroids.

The third rock association of the Afrika Mys Group is represented by quartz–feldspathic Pikezh Sandstone up to 700 m thick that crowns the section of this group. This is quite a special component of the section, which at best was only mentioned in most descriptions of the Afrika Mys ophiolitic complex. The composition of the Pikezh Sandstone [17, 41] clearly indicates that these rocks are products of erosion of the continental crust with predominance of granitic and metamorphic rocks, variously altered volcanics, and clayey sequences. The sialic assemblage of accessory minerals is typical [17]. The sandstone outcrops are identified readily with field radiometry owing to the high background radioactivity. The high contents of light and dark micas are characteristic. It is noteworthy that the Pikezh Sandstone markedly surpasses all other psammitic sequences of Kamchatka, both Cretaceous and Cenozoic, in the content of clastic material composed of metamorphic rocks, potassium feldspar, micas, and sialic accessory minerals. The provenance of this sandstone remains unknown. Almost all geologists that mapped and studied the Pikezh Sandstone pointed out that this unit conformably overlies the Pikezh tephroids with a gradual, but narrow, transitional zone [4, 17, 36, 41]. This relationship gives grounds for the approximate estimation of the total thickness of the Pikezh association at 1.5 km from the contact with the Pikezh Sandstone above to the red beds of the Smagino association below.

The total thickness of the volcanosedimentary complexes of the Afrika Mys Group is tentatively assessed at 3.0–3.5 km.

In addition to the aforesaid, note that radiolarians of the upper Paleocene–lower Eocene were recovered from red and green mudstones in blocks composed of the Smagino rock association. On this basis, the belt of conglobreccia, volcanic rocks, and mudstones at the boundary with the Mount Olen'ya Massif was classified as the special Mount Kamennaya Complex [8, 34, 35]. At the same time, the findings of the Paleogene radiolarians are also known beyond the limits of this zone, and tectonic wedges of the Mount Kamennaya Complex are depicted in the field of the Pikezh Formation. The development of the accretionary structure of the Afrika Mys Block probably continued throughout the entire Cenozoic, during which the periods of intense movements alternated with relatively quiet periods when the turbidity and bottom sediments made up a thin submarine sedimentary cover. Narrow tectonic wedges of such a cover might have formed in the process of progressive development of the accretionary structure. One such obvious example is a narrow meridional slice of relatively shallow-water sediments of the Miocene Tyushevka Group to the southeast of the Mount Soldatsky Massif. The same position may be suggested for more deepwater Paleocene and Eocene sediments conditionally belonging to the Mount Kamennaya Complex.

GEOCHEMISTRY AND PETROLOGY OF IGNEOUS ROCK COMPLEXES OF THE OPHIOLITIC ASSOCIATION

The processing of the published geochemical data on ultramafic rocks, gabbro, and basalts from the Afrika Mys Block allowed us to draw some petrologic and genetic conclusions.

The origin of the ultramafic rocks of the Mount Soldatsky Massif is the most debatable. According to Osipenko and Krylov [19] and Tsukanov et al. [11, 28], peridotites, which we consider restitic, have U-shaped REE patterns similar to the patterns of peridotites from the forearc zones of the Izu–Bonin–Mariana [59, 80] and South Sandwich [81] island-arc systems (Fig. 4). However, as is seen from the diagram, the restitic peri-

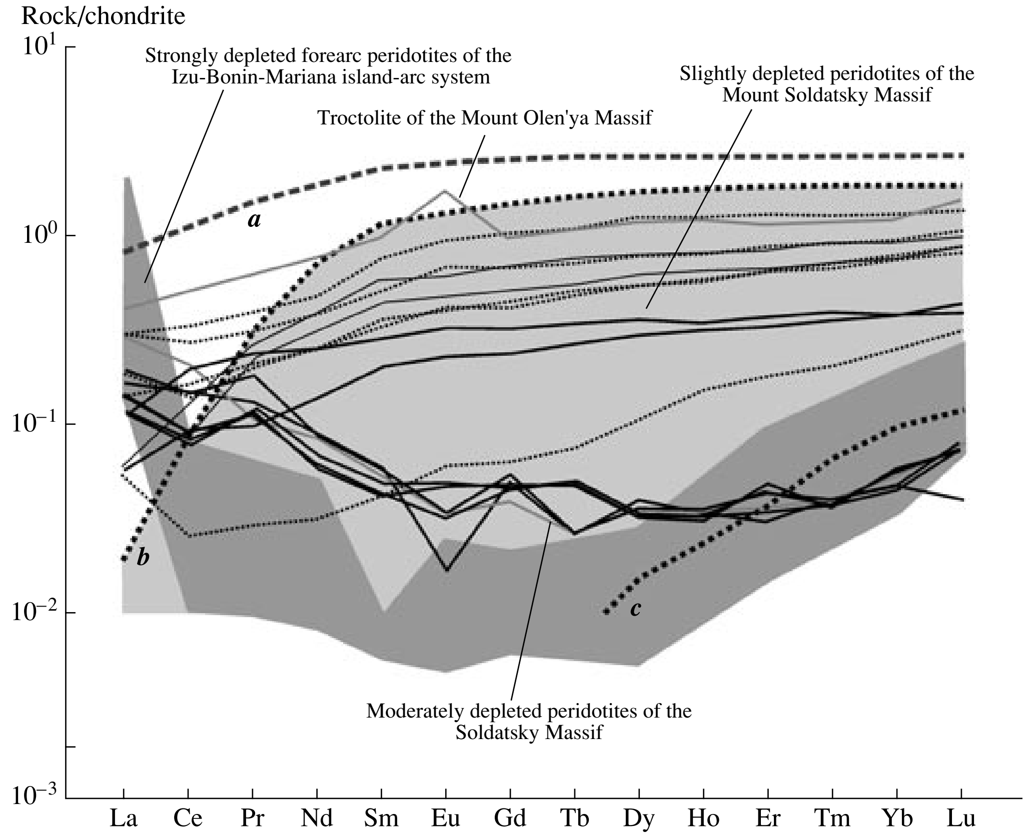


Fig. 4. Chondrite-normalized REE patterns of ultramafic rocks from the Mount Soldatsky and Mount Olen'ya massifs. Chondrite REE contents were taken from [88]. Solid black and dark gray lines are drawn after [19] and [11, 28], respectively. The following data were plotted for comparative purposes: ultramafic rocks from the Garrett Transform without samples that reveal a Eu anomaly (dotted lines), after [75]; ultramafic rocks from the transform fracture zone that transects the South Sandwich island-arc system (solid thin lines), after [81]; dark gray field of forearc ultramafic rocks from the Izu–Bonin–Mariana island-arc system, after [59, 80]; calculated compositions in a model of fractional melting [75]: (***a***) hypothetical primary melt parental for all basalts related to the Garrett Transform (heavy dashed line); dotted lines ***b*** and ***c*** bound the field of residual harzburgite at different degrees of partial melting (5% at ***b*** and 30% at ***c***).

dotites of the Mount Soldatsky Massif do not fit the forearc rocks dredged from the western walls of deep-water trenches in the aforementioned provinces in terms of both the total REE content and the shape of chondrite-normalized REE patterns. Therefore, the suprasubduction origin of the Mount Soldatsky Peridotite is, at least, not obvious. However, it is evident that the U-shaped REE pattern characterizes signifi-

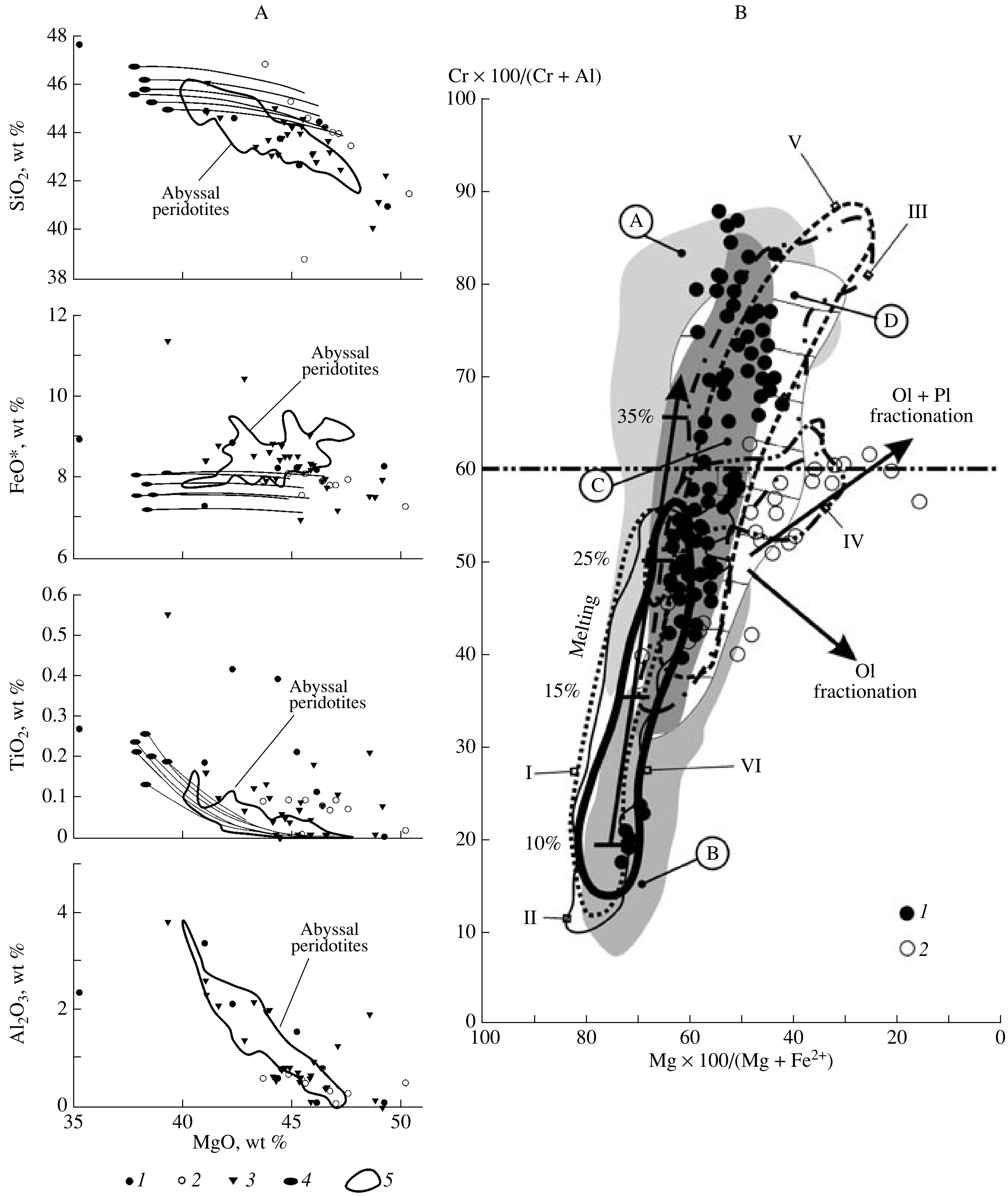
Fig. 5. Diagrams (A) SiO_2, FeO*, TiO_2, and Al_2O_3 versus MgO and (B) Cr# versus Mg# for peridotites of the Mount Olen'ya and Mount Soldatsky massifs on the Kamchatsky Mys Peninsula. The plotted data were taken from [3–5, 8, 9, 11, 19–21, 28, 37, 38]. The compositions plotted on diagrams (A) include ultramafic rocks impregnated with basaltic melt (olivine gabbro, troctolite, etc.); however, the compositions with <35 wt % MgO were omitted. All plotted compositions were recalculated to 100% volatile-free.

Panels A. (*1*) Ultramafic rocks from xenoliths in gabbroids of the Mount Olen'ya Massif and tectonic sheets of this massif; (*2*) restitic ultramafic rocks from blocks and sheets of the Pikezh Tectonic Zone (see text); (*3*) ultramafic rocks from the Mount Soldatsky Massif (both phases of its formation); (*4*) calculated compositions of the primitive mantle and trends of residual mantle material left behind after extraction of basaltic melts generated by polybaric near-fractional melting (1% of captured melt) at 25 kbar, after [73, 75]; (*5*) compositions of abyssal peridotites calculated from compositions of minerals and their modal contents, after [73, 75].

Panel B. (*1*) Spinels from harzburgite and lherzolite of the Mount Soldatsky Massif; (*2*) spinels from ultramafic rocks, troctolite, olivine gabbro, and dolerite of the Mount Olen'ya Massif and spinels of the second generation (films) from harzburgite of the Mount Soldatsky Massif. The fields of spinel compositions from different Alpine-type ophiolitic associations are shown for comparative purposes; the plotted compositions were taken from the paper by E. Pober and P. Faupl, Geol. Rdsch., Vol. 77 (1988), cited after [67]: (A) podiform chromitites (light gray), (B) lherzolite (gray), (C) harzburgite (dark gray), (D) ultramafic cumulates (hatched). The fields of spinel compositions from oceanic and island-arc mafic and ultramafic rocks: (I) abyssal peridotites [48]; (II) peridotite from the Atlantis II Fracture Zone [78]; (III) peridotite from the Conical Seamount in the Izu–Bonin–Mariana Forearc Zone [80]; (IV) harzburgite, plagioclase-bearing dunite, mylonitized amphibole–plagioclase peridotite, olivine gabbro, and ferrogabbro dikes from the Garrett Transform at the East Pacific Rise, after [45, 52, 75, 92]; (V) peridotite from serpentinite diapiric seamounts in the Izu–Bonin–Mariana Forearc Zone [59]; (VI) upgraded field of spinels from abyssal peridotites [78]. The horizontal dashed line at a Cr# of 60% is a boundary between compositional fields of spinels from abyssal peridotites and peridotites related to the island-arc systems [48]. Numerals in figure denote the degree of partial melting (% in the modeling trend).

cantly depleted ultramafic rocks, which are unknown among abyssal oceanic peridotites.

The cumulative peridotites from the Mount Soldatsky Massif classified by Osipenko and Krylov [19] as type-I peridotites and troctolite from the Mount Olen'ya Massif [28] reveal flat chondrite-normalized REE patterns with a slight enrichment in LREE and a marked Eu maximum that indicates the presence of cumulative plagioclase (Fig. 4). A similar REE pattern is characteristic of abyssal peridotites from the Garrett



Transform Fault in the East Pacific Rise [45, 52, 75, 92] and from the fault zone that crosses the South Sandwich suprasubduction system [81]. Cumulative peridotites from the Kamchatsky Mys Peninsula strongly depleted in LREE may be compared in this respect with abyssal peridotites and some ophiolites [42, 56, 71, 76–78, 83, 91].

The similarity of peridotites from the Mount Olen'ya and Mount Soldatsky massifs to the peridotites dredged from transform fracture zones and rift valleys of mid-ocean ridges in the Atlantic and Pacific oceans was pointed out for the first time by Peive [21] and is supported by comparison of compositions of ultramafic rocks from the Kamchatsky Mys to calculated compositions of abyssal peridotites (Fig. 5A), model compositions of the mantle, and residues of its partial melting [71, 76]. The diagrams clearly demonstrate the subdivision of the Mount Soldatsky ultramafic rocks into restitic and cumulative groups distinguished by geologic and petrographic criteria. Our consideration of the published data on major element compositions of ultramafic rocks broadly confirms the conclusions stated by Y. Niu et al. [71, 76], according to which abyssal peridotites are not merely a residue left behind after the removal of melt from juvenile mantle material but contain an excess of olivine and probably clinopyroxene. A part of restitic ultramafic rocks in the ophiolite association on the Kamchatsky Mys Peninsula are enriched in MgO relative to abyssal peridotites (Fig. 5A), thereby indicating a higher degree of partial melting as supported by REE patterns (Fig. 4) and the appearance of dunites. The relationships between TiO_2 and MgO testify that cumulative ultramafic rocks are enriched in olivine and clinopyroxene as a result of interaction of peridotites with diffuse or canalized flows of extracted melts [53, 54].

In the diagram Cr# versus Mg# for spinels (Fig. 5B), the ultramafic rocks from the Mount Soldatsky and Mount Olen'ya massifs follow two distinct trends, which, to a first approximation, may be named mantle and crustal. The Mount Olen'ya (crustal) trend deviates markedly toward a lower Mg# at a Cr# of 50–60% and may be compared with a trend typical of spinels from transform fracture zones [45, 52, 75, 92]. The secondary spinels (films) from the Mount Soldatsky ultramafic rocks also follow this trend [8]. The least chromic spinels from ultramafic rocks of the Mount Soldatsky Massif (mantle trend) correspond to lherzolites from the Alpine-type ophiolites and abyssal peridotites. The field of spinel compositions from the rocks of the Mount Soldatsky Massif [19, 20] largely fits the compositions of spinel from peridotites localized in transform zones, forearc systems, and cumulative peridotites [67]. However, at a Cr# > 75%, the compared trends diverge, once again casting doubt on the validity of classifying restitic peridotites from the Kamchatsky Mys as derivatives of suprasubduction zones.

The field of spinel compositions from peridotites of the Garrett Transform [75, 92] coincides almost completely with that from peridotites of the Mount Olen'ya Massif (Fig. 5B). Compositions of spinel from lherzolites reflect low degrees of partial melting in mantle sources (<10%), whereas compositions of spinels that are contained in harzburgite and cumulates, including dunites, indicate a higher degree of melting (no less than 15–20%). The field of dunites in Fig. 5B corresponds to the field of refractory peridotites. It is suggested that dunites from both massifs of the Kamchatsky Mys Peninsula are similar in composition and are cumulates rather than restites.

Gabbroic rocks from the Kamchatsky Mys correspond in structure (Fig. 6), as well as mineral and chemical compositions, to the gabbroic rocks of the third layer of the oceanic crust drilled during ODP Leg 176 in the southwestern Indian Mid-Ocean Ridge [49, 74]. Like the Mount Olen'ya Massif, this section is characterized by widespread occurrence of cumulates represented by two-pyroxene, clinopyroxene, and olivine gabbro and troctolite. More than two-thirds of the Mount Olen'ya section is occupied by cumulates of the mantle-derived melts that ascended into the lower crust and experienced fractionation in the course of cooling. The proportions of CaO and MgO contents in all varieties of cumulates (Fig. 6C) correspond, to a first approximation, to the An content in plagioclase and the Mg# of the bulk rock compositions and reflect equilibrium between plagioclase, olivine, clinopyroxene, and orthopyroxene. At the same time, the cumulative origin of most rocks in the considered section does not come into conflict with the inferred capturing of some amount of basaltic melt (Fig. 6C) during its removal from a crystal mush [46, 49–51, 64, 69, 70, 74] that actually represents a cumulate. The enrichment of some cumulates in magnetite and titanomagnetite may be related to the crystallization of residual melts in the lower crust [46, 49, 74].

In addition, the plagiogranite veins and dikes that cut gabbroic rocks on the Kamchatsky Mys Peninsula [39] make the gabbroic section similar to the section penetrated by the above-mentioned ODP Hole 735B [49, 74]. The felsic veins represent the last portion of the solidified residual melt separated as a result of magnetite and titanomagnetite fractionation that leads to the enrichment of the liquid phase in SiO_2. The amphibole gabbro was formed at the final stage of the magmatic process in the gabbroic layer of the oceanic crust [65, 74]. The oceanic amphibole gabbro contains a rather calcic plagioclase, and precisely $An_{77\text{-}82}$ was identified in amphibole gabbro from the Mount Olen'ya Massif and a small gabbro body near the First Ol'khovaya River [3, 39].

The cumulative gabbro on the Kamchatsky Mys Peninsula and the clinopyroxene therein are distinguished by low TiO_2 contents, a high Mg#, and a wide variation of the CaO/Al_2O_3 ratio (Fig. 6B). Only 5 of 67 samples in our selection contain more than 1 wt % TiO_2. These samples represent the highly evolved (the

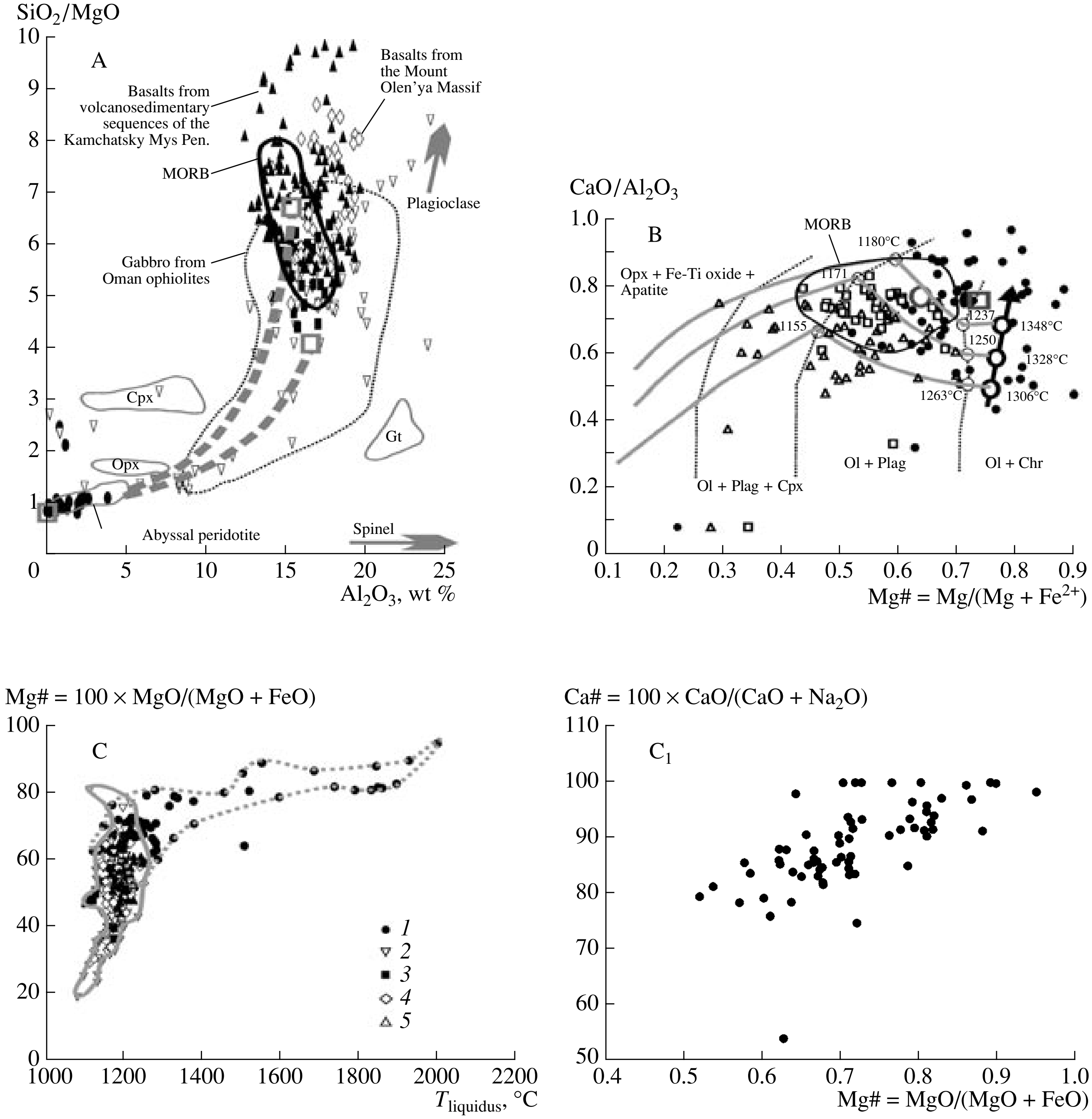


Fig. 6. Petrogenetic links of ophiolitic igneous complexes in coordinates: (A) SiO_2/MgO vs. Al_2O_3, wt %, after [42]; (B) CaO/Al_2O_3 vs. Mg#, after [74]; (C) Mg# vs. $T_{liquidus}$, °C = $1026e^{[0.01894 \cdot MgO,\ wt\ \%]}$, and ($C_1$) Ca# vs. Mg#, after [74]. (A) Rocks from the Kamchatsky Mys Peninsula: peridotite (filled ellipse), Mount Olen'ya gabbro (open triangles), sheeted dikes (filled rectangles), Mount Olen'ya dolerite and pillow basalt (open diamonds), volcanic rocks of the Smagino and Pikezh formations (filled triangles). The following fields are plotted on the diagram: orogenic, ophiolitic, and abyssal peridotites; MORB and Oman ophiolitic gabbro; clinopyroxene (Cpx); orthopyroxene (Opx); and garnet (Gt) from orogenic peridotites. Gray squares mark mixing lines between olivine Fo_{89} and the average MORB composition and gabbro from Oman ophiolites, after [42]. (B) Rocks of the Mount Olen'ya Massif: gabbro (filled circles), sheeted dikes (open squares), basalt and dolerite (open triangles). The following data are plotted on the diagram: the thin black contour indicates the field of MORB; the black arrow indicates the modeling composition generated by decompression melting; the circles with crosses correspond to the melt compositions extracted from the depths that provide 10, 15, and 20% melting (from bottom to top); the heavy gray lines indicate a decrease in the liquidus temperature of these three modeling melts at 1 kbar pressure, after Waver and Langmuir (1990), cited after [74]; the gray square indicates the approximate average composition of gabbroic rocks; the gray circle with a cross represent a parental melt in equilibrium with the most magnesian olivine Fo_{84} in the cumulate gabbro of the Mount Olen'ya Massif. (C, C_1) Trends of evolution of (*1*) cumulative gabbro and (*2–5*) basalts: (*2*) Smagino, (*3*) Pikezh, (*4*) Mount Olen'ya, and (*5*) complex of parallel dikes.

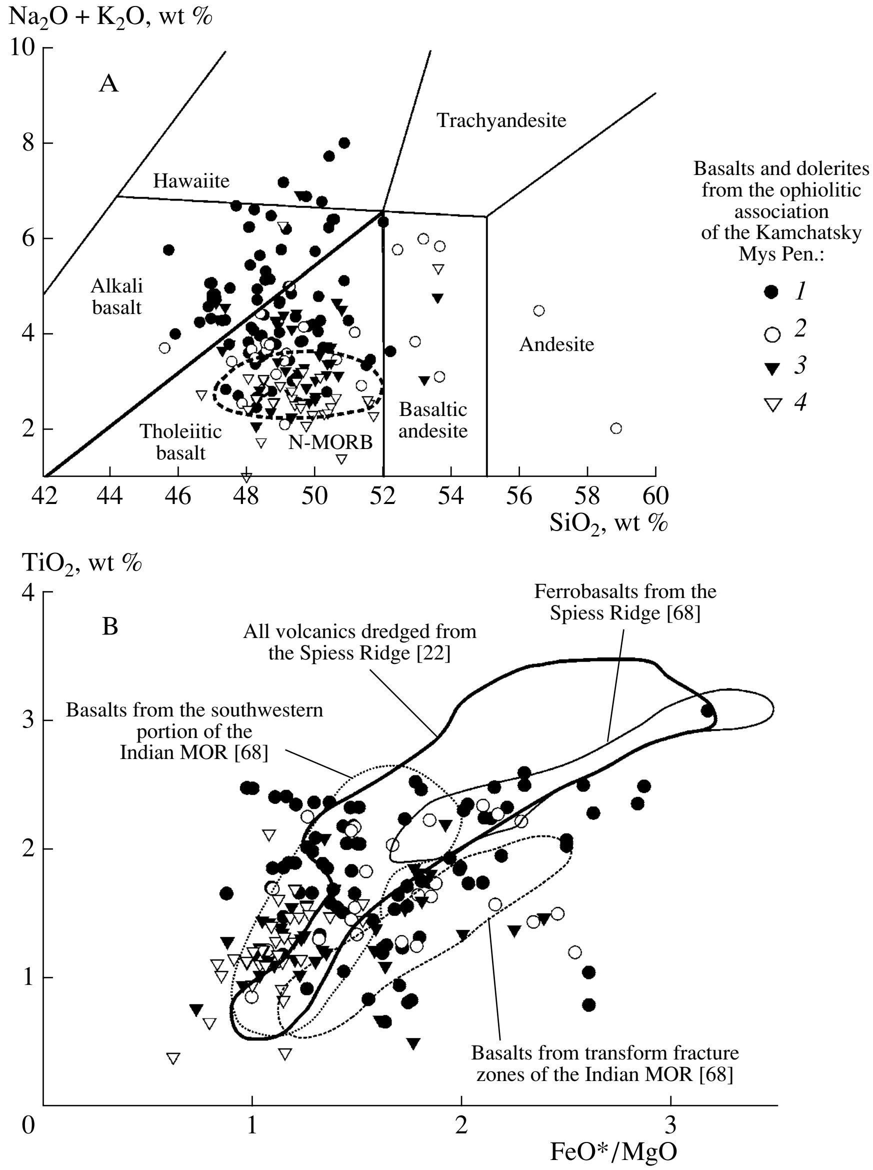


Fig. 7. Compositions of basalts and dolerites from the Smagino and Pikezh formations, the upper Mount Olen'ya volcanic rocks, and parallel dikes, after [3, 4, 8, 23, 25–27, 31, 32, 35–38], plotted on (A) the TAS classification diagram, after K. Koch, and (B) a TiO_2–FeO*/MgO diagram: (*1*) Smagino, (*2*) Pikezh, (*3*) Mount Olen'ya, (*4*) dike complex.

least magnesian) gabbro from the upper levels of the Mount Olen'ya section. The low TiO_2 content (>0.6%) in gabbroic cumulates cannot serve as a guide for the island-arc origin of these rocks, as is supposed in [28, 39].

The REE spectra of amphibole gabbro from the First Ol'khovaya River and the late plagiogranite veins therein [39] reveal a similarity to E- and N-MORB by the level of bulk contents and the shape of patterns. It may be suggested that these rocks are the products of crystallization of residual melt enriched in silica and aqueous fluid in the gabbroic layer of the oceanic crust [65].

The geochemistry of basalts in the Mount Olen'ya Massif, including a complex of parallel dikes, and of volcanic rocks from the volcanosedimentary sequence of the Afrika Mys Group was discussed in [4, 8, 11, 16, 21, 25–27, 29–32, 35, 36, 40]. In the TAS diagram (Fig. 7A), the data points of basalts cover a wide field from oceanic low-alkali tholeiites to high-alkali hawaiites and mugearites. The compositions of dikes and basalts of the Mount Olen'ya Massif almost completely overlap the field of N-MORB from the East Pacific Rise [50]. The volcanic rocks vary in composition from tholeiites to the evolved basaltic andesites and andesites. The subalkali and alkali potassium basalts from subvolcanic bodies of the Smagino association should be placed into a special group [4, 25–28, 35].

Some authors recognize a special group of Fe–Ti basalts [31, 32, 35]. The comparison of basalts from the

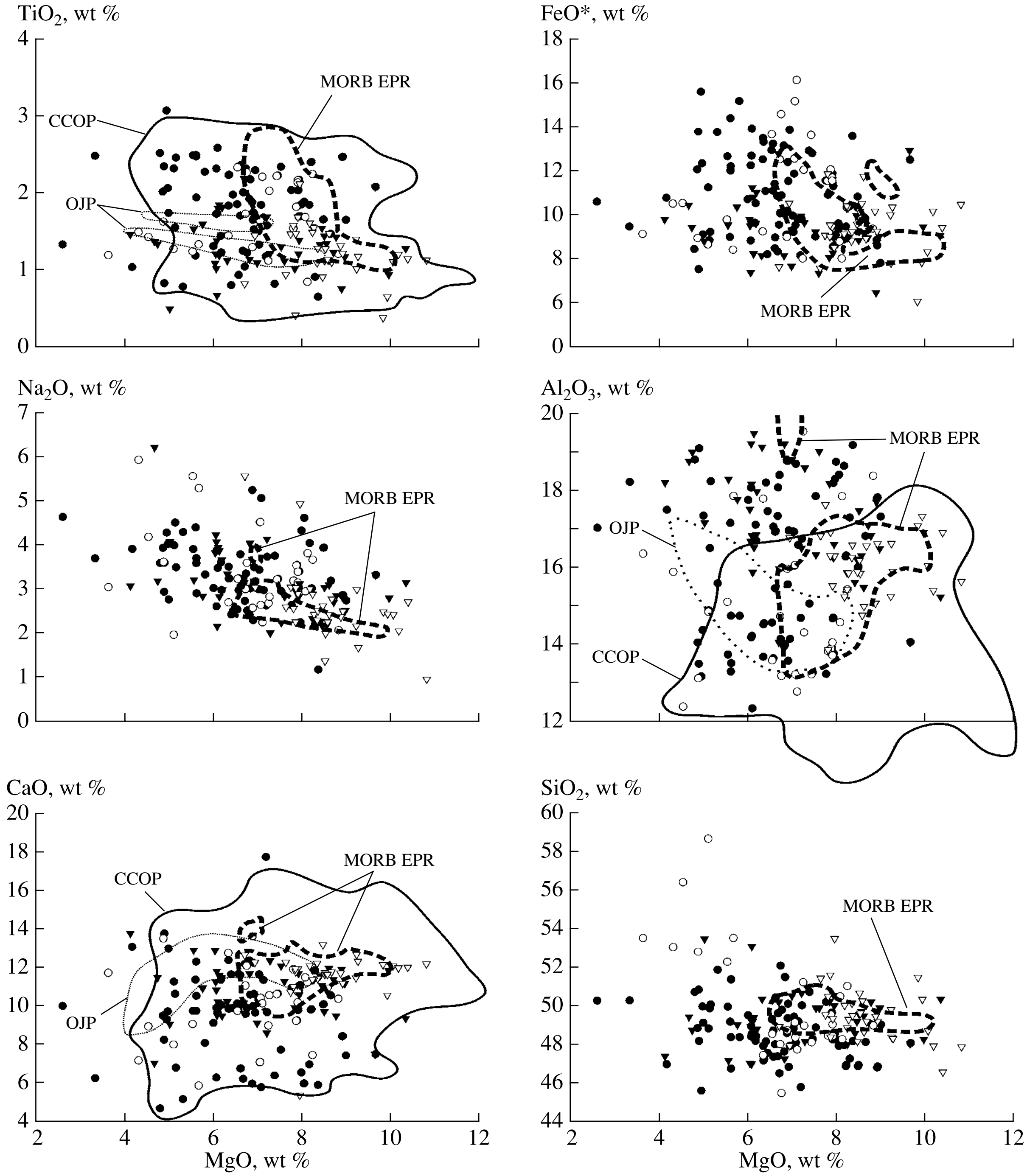


Fig. 8. Major oxides vs. MgO (wt %) in the basalts and dolerites of the Kamchatsky Mys Peninsula. See Fig. 7 for legend. The following compositions are plotted on the diagrams for comparative purposes: basalts of the East Pacific Rise (EPR), after [50]; Late Cretaceous basalts with <12 wt % MgO dredged and drilled at the Caribbean–Colombian (CCOP) and Ontong Java (OJP) oceanic plateaus, after [62, 63]. Boninites and boninite-like rocks (≥54 wt % SiO_2 and ≤0.5 wt % TiO_2 [61]) are absent among the rocks from the Kamchatsky Mys Peninsula.

Afrika Mys Block to the well-known Fe–Ti basalts from the Spiess Ridge in the Indian Ocean [22, 68] (Fig. 7B) shows than only a part of the Smagino and Pikezh volcanic rocks fits the ferrobasalts of this region in composition. In general, the tendency toward enrichment of volcanic rocks in Fe and Ti in the course of magma fractionation is typical of the Afrika Mys Group [16].

Proportions of TiO_2, SiO_2 and MgO contents (Fig. 8) show with confidence that no boninites or boninite-like rocks [60, 61] are present in the basaltic complexes of the Kamchatsky Mys Peninsula, a result that contrasts with the view stated in [19, 20, 28, 39, 40] as evidence in favor of the suprasubduction origin of these complexes. On the basis of Zr/Y, Zr/Nb, and La/Nb

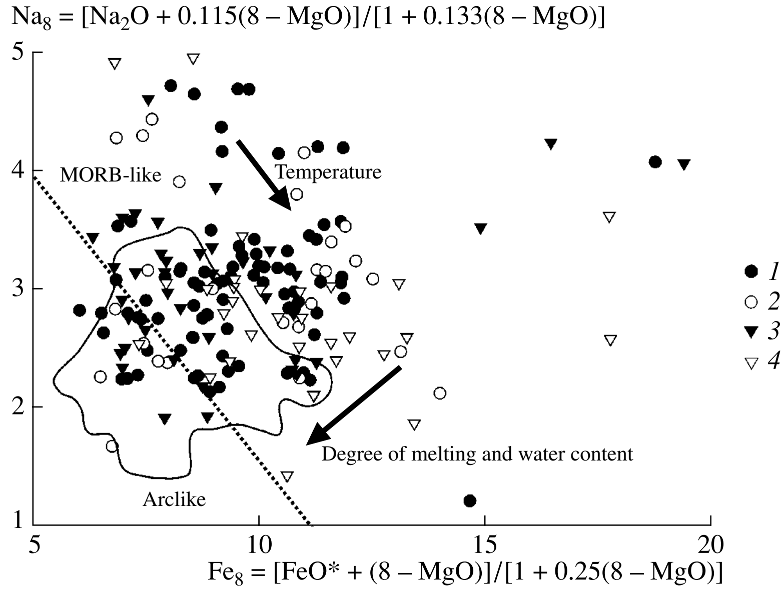


Fig. 9. Compositions of basalts and dolerites from the Kamchatsky Mys Peninsula plotted on the $Na_{8.0}$–$Fe_{8.0}$ diagram applied to the systematics of backarc basalts of the island-arc systems in the World Ocean, after [90]: (*1*) Smagino, (*2*) Pikezh, (*3*) Mount Olen'ya, (*4*) complex of parallel dikes. The contour shown in diagram is a field of backarc basalts from the main island-arc systems [90, Fig. 10]: the Lau Basin in the Tonga–Lau island-arc system, the Manus Basin in the New Britain–New Ireland system, the Mariana Basin in the island-arc system bearing the same name, and the Scotia Basin in the South Sandwich system. The dashed line divides the field into the MORB-like and arclike segments.

ratios and some other geochemical parameters, Fedorchuk and Tsukanov [40] selected a group of backarc basalts related to the so-called Mount Kamennaya Complex, presumably Paleocene–Eocene in age. To settle the question more specifically, we considered the basalts of the Afrika Mys Block in terms of the general systematics of backarc basalts [90] (Fig. 9), which is used by many geochemists [64, 82]. This systematics is based on parametric coefficients $Na_{8.0}$ and $Fe_{8.0}$ proposed by E.M. Klein and C.H. Langmuir (1987). Note that coefficient $Na_{8.0}$ is directly correlated with the depth of magma chambers in axial zones of mid-ocean ridges and with crust thickness, respectively, whereas coefficient $Fe_{8.0}$ is inversely correlated with the depth mentioned above [64].

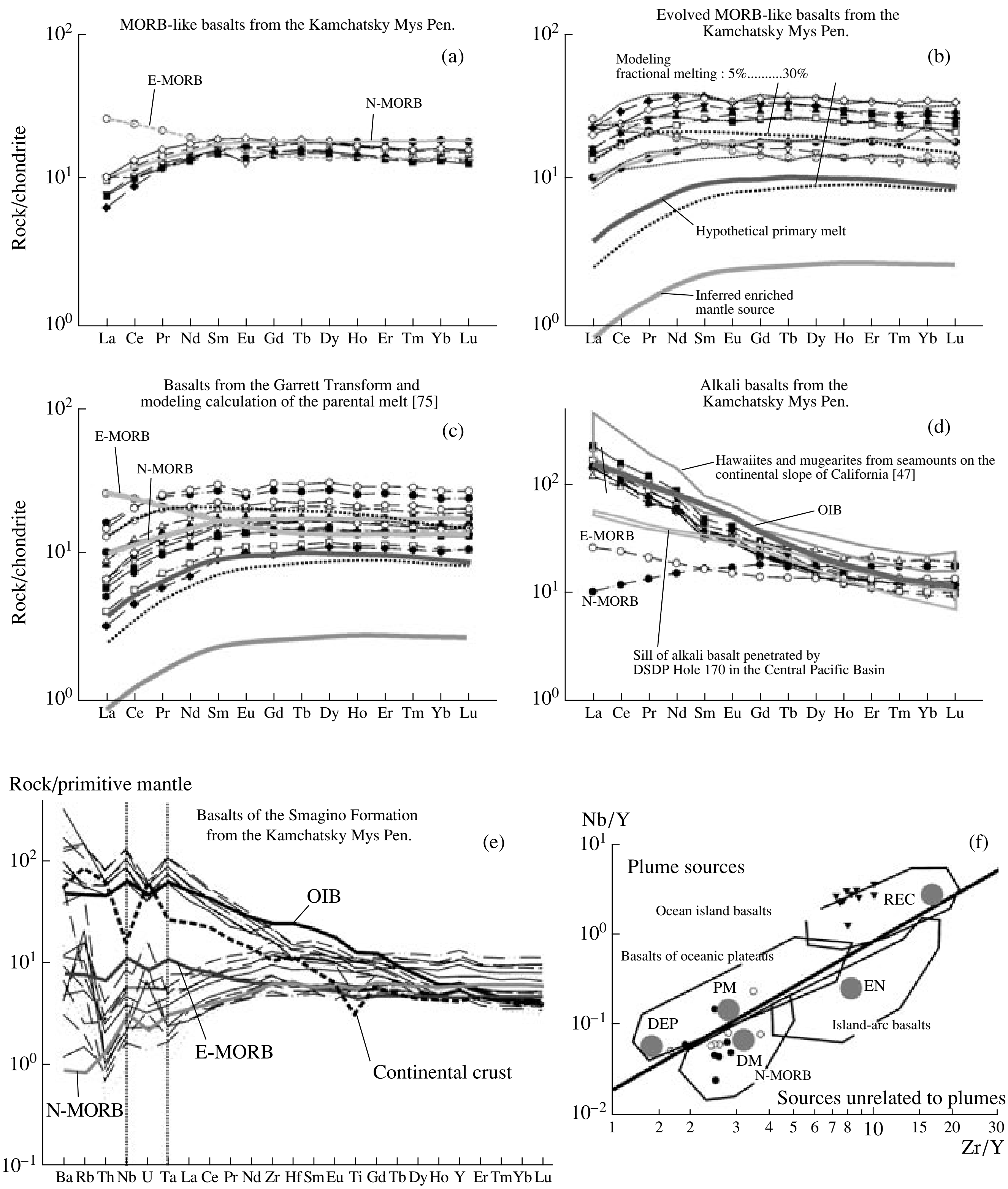
The bulk chemical compositions of basalts from the Kamchatsky Mys Peninsula do not strictly fit the field of backarc basalts in the main modern island-arc systems (Fig. 9). Only a partial overlapping of this field is noted; thus, the data points of all four basaltic complexes from the Kamchatsky Mys, including the complex of parallel dikes, fall into each segment of the diagram. In our opinion, this discrepancy implies that none of these basaltic complexes is backarc in origin. This interesting problem requires special consideration.

In general, the major oxide compositions in all groups of basalts (Fig. 8) except for primitive picrobasalts, which are absent in our selection, are correlated the best with compositions of basalts from the Caribbean–Colombian Oceanic Plateau that formed as a result of activity of the vast Cretaceous mantle plume [62, 63, 66]. The geochemical signatures of the studied basaltic complexes have allowed us to develop a concept of their plume-related origin [77, 78] and to sug-

Fig. 10. Chondrite-normalized REE patterns (chondrite REE contents were taken from [88]): (a, b, d) basalts of the Smagino Formation [25–27], (c) basalts from the Garrett Transform [75], (d) spidergram for the same basalts (normalized to primitive mantle [88]), (e) compositions of basalts from the Kamchatsky Mys Peninsula plotted on the Condie classification diagram of Nb/Y vs. Zr/Y [44]. The N-MORB (filled circles) and E-MORB (open circles) compositions are plotted on diagrams (a–d). Note that only one sample fits E-MORB in diagram (b). The REE patterns of basalts from the Kamchatsky Mys Peninsula, after [35], are also plotted on diagram (b) as thin lines. The fields of hawaiite and mugearite compositions (dark gray line) from seamounts on the continental slope of California [47], and compositions of alkali basalt (light gray line) from a sill 97 ± 2.5 Ma in age and penetrated by Hole 170 of DSDP Leg 17 [57] are plotted on diagram (d) for comparative purposes. Compositions of basalts from the Garrett Transform that transects the East Pacific Rise [75] are plotted on diagram (c). The calculated REE compositions of the parental melt (Mg# = 0.72 in equilibrium with Fo_{90}) in the model of fractional melting [75] are plotted on diagrams (b, c); the composition of the model mantle source is shown in Fig. 5. The compositions of N-MORB, E-MORB, OIB, and continental crust, after [72], are plotted on spidergram (e) normalized to the primitive mantle [88]. Vertical dotted lines mark the Nb and Ta contents. Diagram (f) [44]: (PM) primitive mantle, (DM) shallow depleted mantle, (DEP) deep depleted mantle, (EN) enriched mantle component, (REC) recycled mantle components.

gest that the Smagino association was formed at a within-plate volcanic uplift. In this regard, it is of interest to look for the source of huge masses of free silica and carbonates that is associated with the Smagino basalts. This is a topic of special investigation.

According to Savel'ev [25–27], the basaltic rocks of the Kamchatsky Mys Peninsula belong to the Smagino Formation. In terms of our stratigraphic scheme, four group of basalts are recognized from their REE contents (Fig. 10): (i) identical to N-MORB; (ii) identical



to E-MORB; (iii) identical to the evolved depleted D-MORB, which are similar to the basalts from transform fracture zones in oceans [45, 52, 75, 92] and to depleted basalts from oceanic islands [55, 61, 84]; and (iv) alkali basalts comparable by REE patterns with the Late Cretaceous alkali basalts from the central Pacific Ocean [57, 58]. With consideration for petrographic attributes reported by Savel'ev, it is clear that the basalts similar to N-MORB (Fig. 10a) belong to the upper basaltic unit of the Mount Olen'ya Massif, more specifically, to the fragments of the upper unit (see above) that crop out in the lower reaches of the Kamennaya River (Fig. 1). Three other groups of basalts (Figs. 10b, 10d), including E-MORB (one sample), evolved D-MORB, and alkali basalts that form subvolcanic facies, are related to the Smagino association proper. The spidergram for all four groups of basalts (Fig. 10e) shows distinct positive Nb and, to a lesser extent, Ta anomalies that testify to the complete absence of the suprasubduction (island-arc) components in all basaltic compositions [72, 73, 82, 88]. The REE patterns allowed us to correlate the evolved basalts with their counterparts in the Garrett Transform Fault Zone [45, 52, 75, 92]. Furthermore, it should be noted that the basalts depleted to some extent, in combination with N-MORB and alkali basalts, occupy an appreciable part of oceanic islands [55, 61, 77, 84].

DISCUSSION

The data considered above indicate that several igneous associations occur as fragments in ophiolites of the Kamchatsky Mys Peninsula.

First, this statement pertains to the Mount Olen'ya Massif, where the section of the oceanic crust is reconstructed from the ultramafic and gabbroic cumulates via their isotropic gabbro, overlying dolerite, and a reduced layer of parallel dikes toward the pillow basalts. The total thickness of this section most likely exceeds 6 km. The N-MORB geochemical signature of the upper rock complexes of the Mount Olen'ya section (parallel dikes, dolerites, and pillow basalts) completes this picture and allows us to suggest that we are dealing with a fragment of the oceanic crust that was formed in the linear spreading center somewhat before the Cenomanian Age. The peridotite xenoliths in the lower part of the diallage gabbro most likely are fragments of the upper lithospheric mantle in the mantle–crust transitional zone.

The other igneous complexes described above—restitic and cumulative peridotites of the Mount Soldatsky Massif and volcanic rocks of the Smagino association—are derivatives of the subsequent processes.

The Smagino tholeiitic basalts and subvolcanic bodies with N-MORB and largely D-MORB geochemical signatures, in combination with alkali basalt with OIB signatures, were formed at the within-plate volcanic uplift that began to evolve in the Albian.

According to the available data, which so far are limited and unreliable, the cumulative peridotites of the Mount Soldatsky Massif are close in age to the Smagino volcanic rocks or slightly younger. In addition, a part of the restitic ultramafic rocks of the Mount Soldatsky Massif might have been related to the deep processes beneath the Smagino Uplift, whereas the remainder belonged to the Mount Olen'ya spreading center. None of these complexes was formed in the suprasubduction setting. These conclusions are supported by (i) the deepwater oceanic formation conditions of the Smagino association [36]; (ii) the absence of boninites and boninite-like rocks as indicators of the suprasubduction setting; and (iii) the absence of metasomatic alteration of ultramafic rocks in the Mount Soldatsky Massif, a circumstance that might be expected if these rocks were constituents of the suprasubduction mantle wedge for a long time.

These results imply that the main body of igneous rocks pertaining to the ophiolite association of the Kamchatsky Mys Peninsula was formed before the origination of the subduction zone and related island arc. We suggest that the Mount Olen'ya pillow basalts, dolerite sills, and sheeted dikes genetically related to the Mount Olen'ya gabbroic cumulative complex are complementary to cumulative lherzolite, harzburgite, and olivinite of the Mount Olen'ya Massif and to the restitic ultramafic rocks that occur therein. The Smagino volcanic rocks are genetically related to the cumulative and restitic ultramafic rocks of the Mount Soldatsky Massif.

The $SiO_2/MgO–Al_2O_3$ diagram with plotted igneous rocks from ophiolites of the Kamchatsky Mys Peninsula (Fig. 6A) corroborates the above suggestions. As was shown by Bodinier and Godard [42], the basaltic melts and complementary Alpine-type, ophiolitic, and abyssal peridotites were derived from mantle sources that contain olivine, the average composition of which was Fo_{89} [42, 91]. As follows from Fig. 6A, the main igneous complexes of the Afrika Mys Block were formed along two trends: (i) the trend that extends from primitive mantle with Fo_{89} and embraces the entire ultramafic–gabbro–basaltic complex of the Mount Olen'ya Massif (trend of spreading) and (ii) the trend that starts at more depleted peridotites with Fo_{90} and extends to the igneous rocks of the Smagino volcanic uplift (plume-related trend). The complementary rocks naturally follow each of these trends. The generation of melts pertaining to the Smagino volcanic uplift was accompanied by separation of the repeatedly depleted ultramafic restites of the Mount Soldatsky Massif, on the one hand, and the cumulates that are saturated with olivine and clinopyroxene and associated with gabbro, on the other hand [77]. Dunites and spinel harzburgite occur in both complexes, thus revealing some of the differences discussed above. The appearance of excess olivine is treated as being a result of the ascent and cooling of the mantle melts in the mantle–crust transitional zone under equilibrium conditions in the thermal boundary layer [71, 76, 77, 87]. The compositions of MORB and abyssal peridotites fit various degrees of partial melting (10–22%) of the mantle material beneath mid-ocean ridges. The alkaline rocks of subvolcanic bodies testify to the minor degree of melting in the source [83].

The geophysical and petrologic studies of the axial magma chambers in mid-ocean ridges both in oceans and in ophiolitic complexes, e.g., in Oman [46, 50, 51, 69, 70, 74], have shown that the melting of the lithospheric or primitive mantle gives rise to the segregation of melt lenses and cumulative crystalline mush of gabbroic composition with a certain amount of interstitial liquid in the lower units of the oceanic crust [53, 54].

As has been show above, cumulative rocks make up more than half of the Mount Olen'ya Massif and most of them reveal a positive correlation between the Mg# and the Ca# (Fig. 6C_1). The relationship between the Mg# and the liquidus temperature (Fig. 6C) for Mount Olen'ya cumulates and basaltic complexes indicates a substantial difference in the trends of their evolution. Nevertheless, the melts solidified as dikes, pillow basalts, and buried lenses, together with cumulates (troctolite, clinopyroxene gabbro, olivine gabbro, gabbronorite, clinopyroxene-bearing dunite, wehrlite, and websterite), are derivatives of the same melt.

According to our calculations, the most magnesian olivine in cumulative troctolite with a Mg# of 0.841 [8, sample B-21/A] is in equilibrium with a melt having a Mg# of 0.636. However, this value is much lower than the calculated average Mg# of 0.716 for the entire cumulative gabbroic complex. Thus, the composition of the parental melt may be obtained through proportional summation of certain amounts of cumulative gabbro, parallel dikes (Mg# = 0.533), and the upper basalts and dolerites (Mg# = 0.551) (see Fig. 6B). Simple, although for some reasons speculative, calculations yield a parental melt with a Mg# of 0.639 for all three rock complexes. It is noteworthy that the global average Mg# of MORB is 0.55, while the Mg# of the Mount Olen'ya dikes and basalts is consistent with this estimate. While studying the autochthonous gabbroic section in ODP Hole 735B, Leg 176 Niu et al. [74] showed that mixing of 55–75% gabbroic cumulates with 25–45% basalts from the Atlantis II Fracture Zone extending nearby yields an initial melt composition with a Mg# of 0.637. A similar calculation for the rock complexes of the Mount Olen'ya Massif gave a Mg# of 0.639.

A melt with such a Mg# should have a complementary restite left in the source that fits the primitive mantle composition with Fo_{89} (Fig. 6A). In our case, peridotites within the cumulative complex of the Mount Soldatsky Massif and peridotitic xenoliths in the Mount Olen'ya gabbro may be such restites. Harzburgite sporadically occurring in both massifs contains $Fo_{90.2}$ on average [19]. According to the calculations performed by Walter [91], up to 30% polybaric near-fractional melting of the primitive mantle is required to obtain a restitic peridotite of such a composition [85, Table 1, column 8; Mg# = 0.893].

The REE patterns of the harzburgite cumulative complex complementary to the volcanic rocks of the Smagino Formation are close to those of oceanic abyssal peridotites (Fig. 4). Thereby, following Niu et al. [71, 72], we assume that the abyssal peridotites in the ocean are enriched in a less magnesian olivine (Fo_{85}) and in clinopyroxene. After crystallization of olivine in the thermal boundary layer, the melt is saturated with clinopyroxene, orthopyroxene, spinel, and amphibole during its ascent and cooling. As a result, these phases crystallize at transitional stages of ascent, as indicated by poikilitic structures in cumulative ultramafic rocks. Depending on the physical state of interstitial melt (penetrative or canalized flows), clinopyroxenite or websterite layers are formed. Localization of the melt and its high content provide formation of clinopyroxenite in the zone of mantle–crust transition. The transition from peridotite to gabbro in both the Mount Olen'ya and Mount Soldatsky massifs (Mount Osyp) is accompanied by clinopyroxenite sills and dikes. According to [74], clinopyroxene appears at the solidus at a temperature below 1180°C and a pressure below 2 kbar (Fig. 6C).

Based on samples taken from the Garrett Transform [75] (Fig. 4), modeling of fractional melting has shown that the ultramafic rocks in this fracture zone are residues left after a high degree of partial melting (20–25%) and extraction of the melt equilibrated with Fo_{90}. While percolating in the lithospheric mantle, the progressively evolving melt lefts behind Fo_{85} in the zone of percolation and cooling. In the samples of cumulates from the Kamchatsky Mys, such olivine corresponds to $Fo_{83\text{-}85}$, while the average Mg# of the cumulate is 0.880–0.887.

The REE patterns of the Smagino evolved basalts are combined in Fig. 10b with models elaborated by Niu and Hekinian [75]. According to this model, basalts from the Garrett Transform represent a melt that is characterized by a variable composition, dependent on the degree of melting, and more depleted in REE and other elements than N-MORB. Niu and Hekinian suggest that such a high degree of depletion could arise only owing to the remelting of once already depleted mantle source (see modeling data in Fig. 4). Such a source could generate a melt that is equilibrated with Fo_{90} and that has a Mg# of 0.720. Being emplaced at the crustal level, this melt could have formed the Mount Soldatsky cumulative ultramafic rocks (Mg# = 0.880–0.887) and the volcanic rocks of the Smagino Uplift with an average Mg# of 0.526. The ultramafic restite complementary to basalts and mafic cumulates is represented in the Mount Soldatsky Massif by the extremely depleted harzburgite with a Mg# of 0.915–0.919 [19]. A part of the cumulative gabbro of the Mount Olen'ya

Massif could have been formed when the mantle plume affected the oceanic crust in the Cenomanian and Turonian.

The formation of a layer of clinopyroxene-bearing dunite in the zone of mantle–crust transition is reproduced by an infiltration-integrated petrologic model proposed by Suhr et al. [87] and developed on the basis of data from the Bay of Islands ophiolites. The melt could have been produced in the primitive mantle owing to the decompression melting either in spreading zones, in large transform zones, or under the effect of a plume head. Having been removed from a depleted source, having ascended to the ocean bottom, and having crossed the mantle/crust boundary, the melt generated beneath the Smagino Uplift cooled and precipitated clinopyroxene and olivine on the paths of its propagation, while repeatedly enriching the lithosphere mantle and forming cumulative peridotites. The compositions of the Smagino volcanic rocks plotted on a Condie diagram [44] in Nb/Y–Zr/Y coordinates (Fig. 10f) furnish evidence for the suggestion that the Smagino volcanic uplift was related to a plume source that involved both the primitive mantle and the depleted lithospheric mantle. The restite that was left behind after this melting had an average Mg# of 0.915, whereas the average Mg# of the cumulative ultramafic rocks was 0.883. According to the model developed by Suhr et al. [87], cumulative ultramafic rocks are made up of both the lithospheric and the asthenospheric components. As judged from the Condie diagram, the Smagino basalts are also composed of heterogeneous components.

Savel'ev [25–27] explains the origin of alkali basalts in the Kamchatsky Mys Peninsula by effect of the Hawaiian hot spot that began to act in the Albian–Cenomanian, while reasonably assuming that the REE patterns of the Smagino alkali basalts (Figs. 10d, 10e) are similar to the REE patterns of within-plate basalts from Pacific oceanic islands at least in the pattern configuration, if not in the level of contents. Because N-MORB and evolved MORB (D-MORB) compositions from the Smagino Uplift that are plotted on the Condie diagram (Fig. 10f) are clustered near average compositions of the primitive and depleted mantle, whereas alkali basalts fall into the OIB field, the involvement of all these components of the lithospheric and asthenospheric mantle in the magma source is possible only with participation of a plume. However, as is shown in [86], the inferred plume was not the Hawaiian hot spot, which arose and evolved beneath the Pacific Plate, while the Smagino volcanic high was forming, most likely, on the Kula Plate and the Kronotsky arc was forming on the North American Plate.

A model of progressively integrated nonequilibrium melting proposed by Prinzhofer and Allègre [83] is applicable to basalts generated as a result of partial melting, the degree of which exceeds a percolation threshold estimated at 2–5%. A lower degree of melting does not allow the melt to integrate and propagate upward. It seems possible that the subvolcanic mode of occurrence of the Smagino alkali basalts is explained by this model.

Note that combination of the asthenospheric and lithospheric components in magma sources might have been provided by the head of a plume that contained both components [55, 77].

CONCLUSIONS: GEODYNAMIC INTERPRETATION OF THE TECTONOSTRATIGRAPHIC SEQUENCE OF ROCKS IN THE AFRIKA MYS BLOCK

The tectonostratigraphic sequence of the Afrika Mys Block comprises the Lower Cretaceous rocks typical of normal mid-ocean ridges (Mount Olen'ya Massif), the Smagino association of sediments and basalts that formed at the active volcanic high (plateau) in the Mid-Cretaceous time, the Pikezh tephroid association related to the island-arc volcanic centers (Senonian–Lower Eocene (?)), and the Maastrichtian (?) subarkosic sandstones derived from a continental source. In addition, the Late Cretaceous (?) cumulative and restitic ultramafic rocks make up large allochthonous sheets and numerous protrusions, which are important structural units.

Such a combination of rock complexes may be treated in two ways: (1) the Afrika Mys Block as an element of the Kronotsky island arc is a tectonized inlier of its basement related to the formation of subduction zone or (2) the block is a result of progressive accretion of rock complexes formed in different oceanic domains. In other words, the Afrika Mys Block is a part of the plate that could not have been submerged into the subduction zone. In this case, we may speak about collision of an island arc and a volcanic high. If no significance is attached to the faults that separate the Mount Olen'ya Massif and the Afrika Mys Group and it is assumed that this group is a normal stratigraphic succession, the observed combination of large elements of the tectonostratigraphic sequence may be regarded as a direct reflection of chronological events: origination of an oceanic plate in the spreading center–transformation of its certain part in the process of growth of volcanic uplift–collision with island arc. In this case, we have a complexly built and heterogeneous, but structurally common, ophiolitic association related to the long-term evolution of mantle magma sources that had created the oceanic crust in the course of variable conditions of melting.

We likely should discard the concept of the Afrika Mys Block as a basement of the Kronotsky arc that was formed on the place of the volcanic plateau, which, in turn, replaced the crust created by the mid-ocean ridge. Having referred the Pikezh rock association to the basement of the Kronotsky arc, we have to look for a vigorous source of tephra that preceded the Kronotsky volcanic activity. Finally, "driving" the Pikezh Sandstone into the basement of the Cretaceous Kronotsky arc, we only postpone the solution of the problem that concerns the provenance of this sandstone, while offering nothing new in this respect.

Except the Pikezh Sandstone, the other main constituents of the Afrika Mys Block—including ultramafic rocks of the Mount Soldatsky Massif; gabbroids of the Mount Olen'ya Massif; the Smagino association of basalt, limestone, and jasper; and the tuffaceous–cherty rocks of the Pikezh Formation—are products of the oceanic crust evolution that included its origination in the spreading center; the plume-related formation of the volcanosedimentary high and the related reworking of the lower crust; and finally, submergence into the subduction zone. From this standpoint, the different elements of the Afrika Mys Block may be regarded as fragments of a heterogeneous ophiolitic association. It may be added that the formation of the ultramafic cumulative complex at the volcanic uplift with an increase in the total Mg# of its crust probably caused the elevated buoyancy of the Afrika Mys Block, thus preventing the block's subduction [78].

At present, the Afrika Mys Block belongs to the zone of the eastern peninsulas of Kamchatka. Still in the late Miocene, these peninsulas were fragments of an intraoceanic rise that arose on the location of the Kronotsky arc, which was active in the Late Cretaceous, Paleocene, and Eocene. At the end of the Cretaceous time, this arc supplied a huge mass of tuffaceous material to the accretionary prism and, in the Eocene and onward, provided ophioliticlastic material to the trough that separated the outer arc from the volcanic front. The paleomagnetic data on declination of the eastern peninsulas and the Komandorsky Islands in the Eocene show that the arc most likely extended in the near-latitudinal direction [2]. As is judged from the mutual arrangement of the Lake Stolbovoe and Afrika Mys blocks, the front of this arc and the related accretionary prism faced southward, while the subduction zone dipped northward. Such an orientation is consistent with the suggestion that the Kronotsky arc did not move to the north in the Late Cretaceous and Paleocene.

In any interpretation, the structure and formation history of the Afrika Mys Block reflects the processes that proceeded at the boundaries of oceanic plates and within these plates. It is of interest to connect the kinematics of these plates with the events that left their imprints on the structure of the Afrika Mys Block and to understand whether it would be possible to correlate the Mount Olen'ya Massif with any real mid-ocean ridge, e.g., with the Kula–Pacific Ridge, and to regard the Hawaiian mantle plume as responsible for giving birth to the Smagino rock association and the cumulative ultramafic rocks. The consideration of the kinematics of the Kronotsky arc [86] may help settle these questions, but this complex problem is outside the scope of the presented paper.

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