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Early Devonian Suprasubduction Ophiolites of the Southern Urals

A. A. Belova[a, b], **A. V. Ryazantsev**[a], **A. A. Razumovsky**[a], **and K. E. Degtyarev**[a]
[a] *Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia*
[b] *Faculty of Geology, Moscow State University, Moscow, 119991 Russia*
e-mail: belova_a@bk.ru

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Abstract—The composition of ophiolites widespread in the southern Urals shows that they were formed in a suprasubduction setting. Low-Ti and high-Mg sheeted dikes and volcanic rocks vary from basalt to andesite, and many varieties belong to boninite series. The rocks of this type extend as a 600-km tract. The volcanic rocks contain chert interbeds with Emsian conodonts. Plagiogranites localized at the level of the sheeted dike complex and related to this complex genetically are dated at 400 Ma. The ophiolites make up a base of thick island-arc volcanic sequence. The composition of the igneous rocks and the parameters of their metamorphism indicate that subduction and ascent of a mantle plume participated in their formation. The nonstationary subduction at the intraoceanic convergent plate boundary developed, at least, from the Middle Ordovician.

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INTRODUCTION

Subduction-related ophiolites are widesperad in the Paleozoides of the southern Urals. Sheeted dikes and overlying volcanic rocks are distinguished by low and moderate Ti and elevated Mg contents. Some rocks fit boninite in composition. Depleted harzburgites are predominant in the lower part of the section. The Early Devonian age of the upper part of the ophiolite complex is established from biostratigraphic and isotopic geochronological data.

Maegov [30] was the first to compare the sheeted dikes of the Khabarny massif with island-arc tholeiites and basaltic andesite. At the same time, it was suggested that the dikes were formed in zones of secondary extension of the marginal sea [28]. Later on, suprasubduction ophiolites were described in the Buribai area of the West Magnitogorsk Zone [26] (Fig. 1). Boninites occurring in the Devonian Baimak–Buribai Formation overlie the sheeted dike complex. A complex of low-Ti and high-Mg sheeted dikes close to boninite in composition is described in the Khabarny massif situated to the south [46].

Ophiolites of this type are overlapped by typical island-arc volcanics. Their discontinuous outcrops are traced along the western margin of the Magnitogorsk Megazone for 600 km from the latitude of the town of Uchaly in the north. Ophiolites of this type are known in the West Magnitogorsk, Cis-Sakmara–Voznesenka, and Sakmara zones. The southernmost outcrops are located in the West Mugodzhary Zone [65] as a continuation of the Magnitogorsk Megazone. Fragments of crustal rocks of the Ordovician ophiolites are widespread in the northern Cis-Sakmara Voznesenka Zone, the Kempirsai Allochthon, and melange of the Sakmara Zone [13, 55, 61]. The Ordovician ophiolites differ from the Devonian counterpart in geochemistry. In some places, ophiolites differing in age and composition converge and intercalate. New data on the structure, composition, and age of the upper part of the ophiolitic association characterizing the early stage of development of the subduction zone above which the Devonian volcanic series of the Magnitogorsk Zone were formed are considered in this paper along with the results of previous investigations. The data obtained make it possible to distinguish ophiolites different in age and formed in various geodynamic settings.

STRUCTURAL ZONING OF THE SOUTHERN URALS

Many publications are devoted to structural demarcation of the southern Urals. The synthesis of these data can be found in the monograph by Puchkov [37] and in the book summarizing the results of works under the Urseis-95 program [8]. The central position in this region is occupied by the Magnitogorsk Megazone (Synform) that comprises the rocks of the paleooceanic sector, island-arc complexes, and Middle Paleozoic ophiolites (Fig. 1). The lower structural level of the synform at its western limb (Cis-Sakmara–Voznesenka Zone) is composed of Ordovician ophiolites and island-arc and backarc volcanics making up the marginal Sakmara, Kraka, and Sukhteli allochthons. The allochthonous complexes of the paleooceanic sector overlie paleocontinental complexes which form the margin of the East European paleocontinent in the west (Bashkir Anticlinorium and Uralatau Zone of the Central Ural Megazaone) and the Kochkar–Adamovka Zone of the East Ural Megazone in the

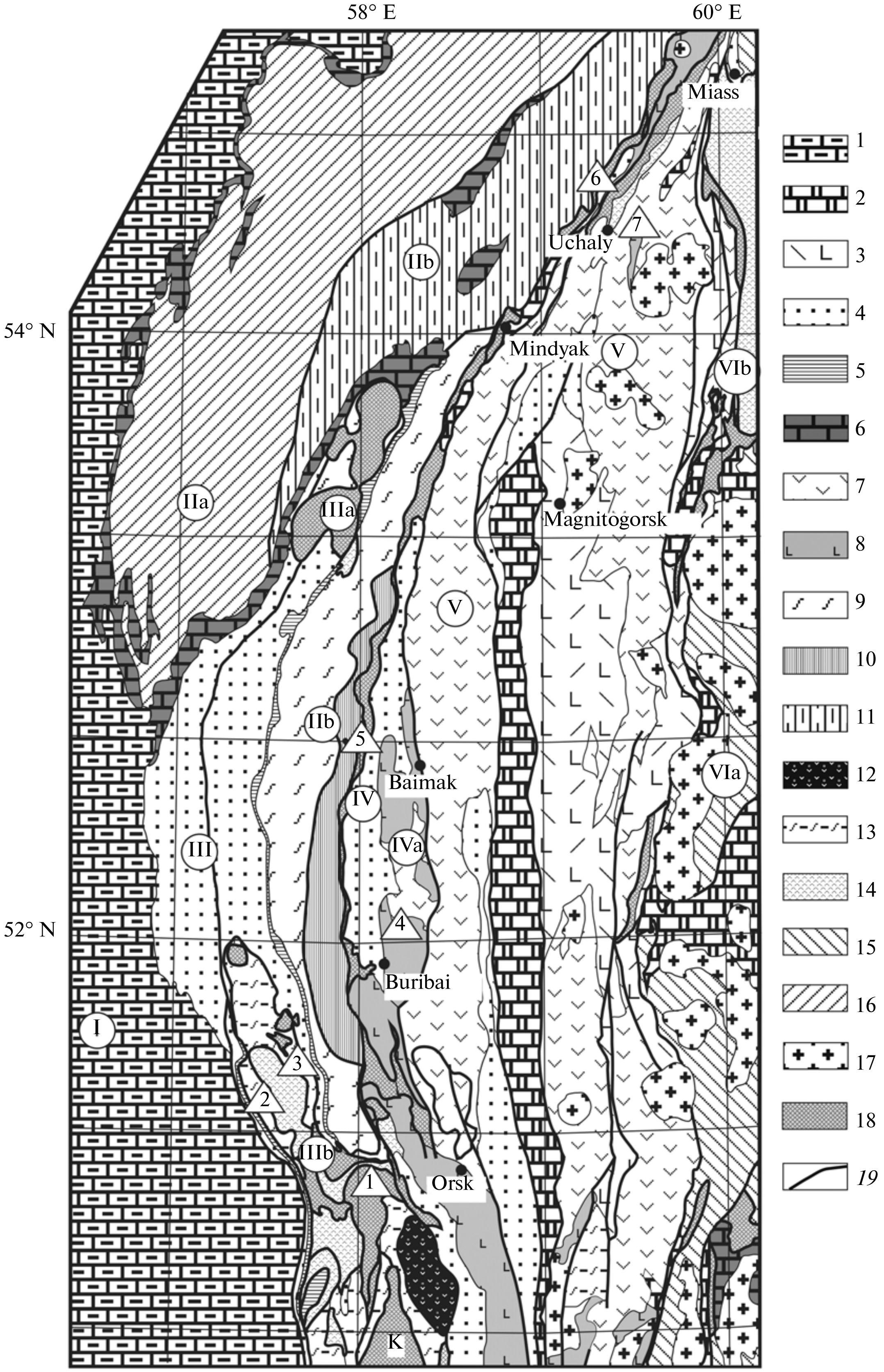
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Fig. 1. Main tectonic units and rock complexes in the western part of the southern Urals. (*1*) Carboniferous and Permian flysch and molasse in the Ural Foredeep; (*2*) Carboniferous terrigenous–carbonate and carbonate rocks; (*3*) Lower Carboniferous volcanic rocks; (*4*) Famennian graywacke; (*5*) Devonian (Lochkovian–Frasnian) condensed cherty sequence; (*6*) Middle Ordovician–Upper Devonian terrigenous and carbonate rocks; (*7*) Middle–Upper Devonian volcanic and volcanosedimentary rocks; (*8*) Emsian volcanic rocks and sheeted dike complex; (*9–11*) Uraltau Zone: (*9*) Paleozoic and partly pre-Paleozoic quartzitic schists (Suvanyak Complex), (*10*) Maksyutovo Complex of eclogites and glaucophane schists, (*11*) Neoproterozoic metamorphic rocks; (*12*) Vendian volcanic and volcanosedimentary rocks; (*13*) Ordovician, Silurian, and Devonian cherty, terrigenous, and tuffaceous sedimentary complexes; (*14*) Ordovician, Silurian, and Devonian volcanic complexes; (*15*) Precambrian metamorphic rocks of the basement and Ordovician terrigenous–carbonate rocks of the cover in the East Ural Megazone; (*16*) Precambrian Complexes of the Bashkir Anticlinorium; (*17*) Middle and Late Paleozoic granitoids; (*18*) mafic–ultramafic complexes and serpentinite melange; (*19*) fault. Tectonic unites (numerals in circles): I, Ural Foredeep; II, Central Ural Megazone: IIa, Bashkir Anticlinorium and IIb, Uraltau Zone; III, Zilair Synclinorium: IIIa, Kraka Allochthon and IIIb, Sakmara Allochthon; IV, Cis-Sakmara–Voznesenka Zone; V, Magnitogorsk Megazone (Va, Aktau–Tanalyk Zone); VI, East Ural Megazone: VIa, Kochkar–Adamovka Zone and VIb, Sukhteli Allochthon. Areas and sites of detailed studies (numerals in triangles): 1, Khabarny; 2, Ramazanovo; 3, New Rakityanka; 4, Buribai; 5, Chingizovo; 6, Kalkan; 7, Buidy; K, Kempirsai massif.

east. These structural elements consist of Precambrian basement and Lower–Middle Paleozoic sedimentary cover. The Main Ural Fault and the East Magnitogorsk faults bound the Magnitogorsk Synform in the west and the east, respectively. According to seismic profiling [8], these fault zones dip in opposite directions to meet each other. The boundary between the western paleocontinental and paleooceanic sectors is marked by the Suvanyak and Maksyutovo metamorphic complexes of the Uraltau Zone, as well as by graywackes of the Zilair Formation. The structural zoning of the South Ural Paleozoides reflects the evolution of Ordovician and Devonian intraoceanic volcanic arcs and the basins separating them from the western continental margin.

LOCALIZATION OF SUPRASUBDUCTION OPHIOLITES

The Aktau–Tanalyk Zone (Buribai Area)

The sheeted complex and related volcanic rocks corresponding to boninite in composition were first described along the Tanalyk River in the Buribai area [26] (Fig. 1). These rocks occur in the western part of the West Magnitogorsk Zone, which is often called the Aktau–Tanalyk Zone. According to [23, 32], the volcanic section is subdivided into the Baimak–Buribai Formation and the overlying Upper Tanalyk Formation, both considered to be Lower Emsian. They underlie the sequence containing Emsian conodonts. This area is a type locality of these volcanic sequences, which have been studied rather completely [23, 96] and are used as reference stratigraphic units for regional correlation.

The Baimak–Buribai Formation is subdivided into dolerite–basalt, pillow-basalt, and rhyodacite–basalt sequences that are related to the initial stage of ensimatic island-arc formation [7, 23, 66, 96]. High-Mg tholeiitic and picritic pillow lavas and boninitic variolites dominate in the lower sequences. Low-Mg tholeiites and subalkali basalts are noted as well. Calc-alkaline dacite, rhyodacite, basaltic andesite, and basalt occur in the upper sequence. The mafic rocks of the lowermost sequence are distinguished by negative Nb, Ta, Zr, Hf, and Ti anomalies and enrichment in LILE [23]. The geochemical attributes of the lower sequences of the Baimak–Buribai Formation indicate that the sequence was formed in the suprasubduction setting with participation of fluids and as a product of high-degree partial melting of depleted mantle peridotite.

The continuous basalt–andesite–dacite–rhyolite series is predominant in the Upper Tanalyk Formation [23].

The Sakmara Zone

The rocks of the Sakmara Zone form a nappe, and the Cis-Sakmara–Voznesenka Zone is its root (Fig. 1). The nappe consists of a number of particular allochthons composed of rocks derived from the transitional continent-to-ocean zone [14, 16, 17, 37, 52–55]. The lower allochthons are composed of bathyal sedimentary and volcanosedimentary complexes formed at the rise of the passive continental margin. The island-arc and backarc volcanic complexes are predominant in the upper allochthons. The lower and upper allochthons are separated by serpentinite melange and polymictic olistostromes. The allochthonous Khabarny mafic–ultramafic massif with ophiolites and the Kempirsai ophiolitic massif situated to the south are related to the Sakmara Zone as well.

The Khabarny Massif

The well-exposed Chabarny massif is distinguished by a complete section and has been studied in detail [2, 29, 39, 41, 46, 50, 70–72, 74, 91]. The massif is a tectonic nappe locallized in the structural saddle (synform) between the Uraltau and Ebeta antiforms (Fig. 1). The northern and western margins of the Khabarny massif overlie a system of tectonic nappes composed of Ordovician volcanic and sedimentary rocks (Guberlya Formation), Lower–Middle Devonian volcanic and sedimentary rocks, and Upper Devonian olistostromes [54, 55]. The northeastern part of the massif is disturbed by the left-lateral strike-slip Main Ural Fault that cuts off the Akkermanovka fragment of the

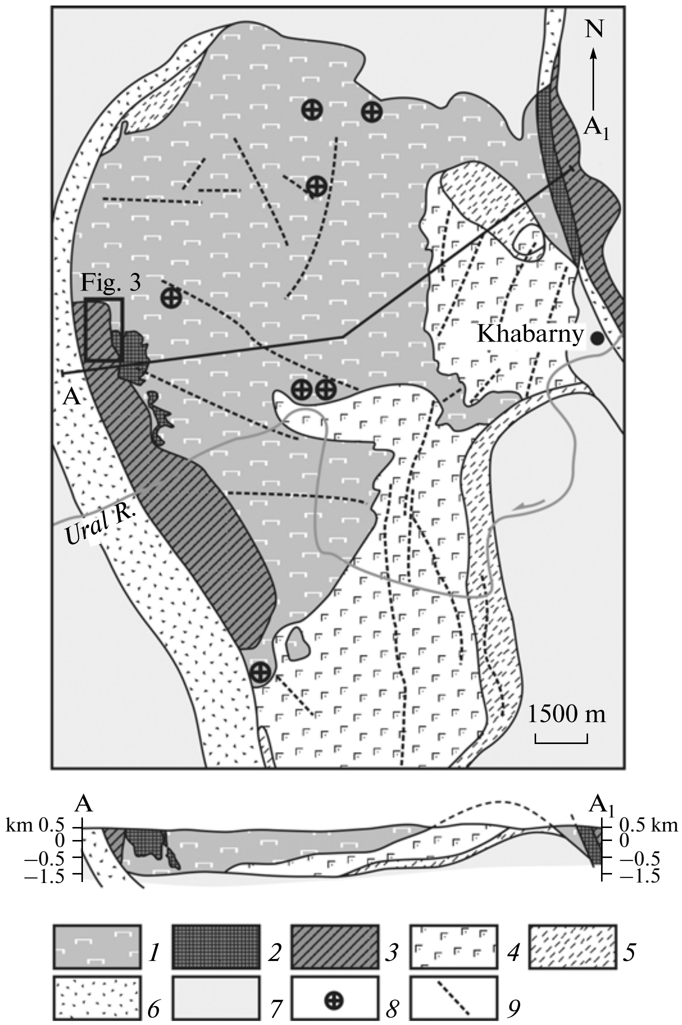


Fig. 2. Geological scheme of the Khabarny massif, simplified and modified after [72, 78]. (*1*–*3*) complexes of ophiolite association: (*1*) dunite–harzburgite, (*2*) layered, (*3*) dike and volcanic (including zone of the upper magma chamber); (*4*) East Khabarny dunite–clinopyroxenite–websterite–gabbronorite complex; (5) amphibolite and crystalline schists of allochthon sole; (*6*) melange with serpentinite matrix; (*7*) Paleozoic complexes underlying the Khabarny Allochthon; (*8*) intrusions of the Molostovsky Complex (out of scale); (*9*) neoautochthonous gabbrodolerite dikes.

crustal rocks pertaining to the ophiolitic section. To the north of this fragment, serpentinite and a block of sheeted dikes (Uzembaevo fragment) crops out [49]. Further to the north, a large fragment of ultramafic rocks (Khalilovo massif) is displaced along the strike-slip fault. The nappe system in the saddle (synform) between the Uraltau and Ebeta antiforms is symmetric. In the northern Ebeta Antiform, the Khabarny massif is underlain by volcanic, terrigenous, and cherty rocks containing Ordovician and Devonian fossils [64]. Zones of glaucophane-schist metamorphism are noted at the northern and southern limbs of the synform. The Vendian subvolcanic intrusions and granitoids occur at the northern periclines of the Ebeta and Uraltau antiforms [3, 63]. The Khabarny massif is a rootless tectonic nappe 1500 m thick [34, 78]. The nappe is composed of a complete set of elements pertaining to the ophiolitic association; in addition, dunite–gabbro–pyroxenite intrusions and metamorphic rocks occur therein.

The rock complexes that make up this massif were formed in different geodynamic settings and occupy certain structural levels progressively substituting one another (Fig. 2).

The lower structural level is composed of *metamorphic complexes*. In the northwest of the Khabarny massif, these are amphibolite developed after the subalkali oceanic basalt [69]. In the northeastern part of the allochthon, mica schist, amphibolite, garnet gneiss, and migmatite are exposed in a tectonic window [70]. According to the data published by Pushkarev [42, 43, and references therein], the lower structural level in the eastern part of the massif is composed of apobasaltic amphibolite, whereas amphibolite and melanocratic wacke intercalated by quartz and arkosic sandstones occur at the upper structural level. The metamorphic grade and degree of deformation increase upward toward the contact with the mafic and ultramafic intrusive rocks of the East Khabarny Complex. The garnet amphibolite of the upper level is a product of retrograde metamorphism of the granulites. The Sm–Nd age of this metamorphism is 415 ± 8 Ma [43]. A similar age of metamorphism was obtained with the K–Ar method [41]. These data are regarded as evidence for the relationship of metamorphism to the obduction of ophiolites [43]. The same geodynamic conditions of metamorphism are suggested in [9].

The next structural level corresponds to the *East Khabarny dunite–clinopyroxenite–gabbro intrusive complex*. It is assumed that these rocks have intrusive contact with the underlying metamorphic rocks and the overlying dunite–harzburgite complex [2, 39]. Some authors do not include this intrusive complex into the ophiolitic assemblage [2 and references therein]. The Sm–Nd age of the websterite pertaining to this complex is 411 ± 12 Ma [42, 43, 45, 47]; the ^{39}Ar–^{40}Ar age of the phlogopite from this complex is 415 ± 3 Ma [41]. These dates are comparable to the age of the underlying metamorphic rocks. The Molostovsky Complex comagmatic to the East Khabarny Complex comprises minor ring intrusions that cut through harzburgite. The Sm–Nd age of the Molostovsky Complex is 415 Ma [42, 43, 47].

Mantle ultramafic rocks are composed largely of harzburgite; a small amount of dunite bodies is noted; lherzolite is extremely rare [39]. As follows from the drilling results, harzburgite and dunite intercalate in the section. Pargasite occurs in the interstices between olivine and orthopyroxene [2]. Two phases of high-temperature deformation are documented in the harzburgite on the basis of structural observations [78]. Persistent ductile flow with the formation of penetrative linear and planar mineral aggregates is related to the first stage, whereas most dunite bodies, schlieren, and enstatitite veins were formed during the second stage. The degree of deformation and development of directive structures increases near the contact with the East Khabarny intrusive complex. The appearance of anisotropic andradite–grossular garnet is regarded as a result of the contact effect as well [2].

In the western part of the massif, the harzburgite section is built up by the *dunite–wehrlite–pyroxenite–gabbronorite banded complex* (association of Mount Kirpichnaya) and the similar Akkermanovka association in its northeastern part. The association of Mount Kirpichnaya combines dunite–wehrlite–clinopyroxenite and gabbronorite–plagiowebsterite layered intrusions hosted in the dunite–harzburgite mantle tectonites. The Akkermanovka association is composed of wehrlite, olivine clinopyroxenite, clinopyroxenite, olivine gabbro, and gabbronorite. The above-listed rocks make up banded and schlieren–banded fragments of the lower crustal plutonic complex, which occasionally underwent tectonic disintegration.

The variation in the structure of the layered complex of the same ophiolitic section probably characterizes lateral heterogeneity of the crustal layer consisting of spatially separated intrusions similar in composition but differing in age [48].

The section is built up by *gabbro–plagiogranite* and *sheeted dike complexes* (Fig. 3). The former complex is composed of gabbro, gabbrodiorite, diorite, and plagiogranite that occur as sills and dikes merging into a stockwork, which cuts through the serpentinized harzburgite and banded complex [50, 91]. The contacts between particular bodies within the complex often become diffuse. The next magmatic bodies probably invaded incompletely solidified rocks with the formation of taxitic structures, numerous schlieren-like segregations, skialiths, swarms, and trails of two mingling melts. The rocks have direct chemical counterparts in various segments of the sheeted dike complex. This zone is probably a fragment of a magma source that fed sheeted dikes. Plagiogranite at the bottom of the sheeted dike complex commonly serves as a matrix of magmatic breccia with gabbrodiorite, diorite, and dolerite fragments. Such magmatic breccia often occupies the inner zone of composite dikes with marginal dolerite zones. The breccia bodies are 5–7 m thick. They are cut through by dolerite dikes and plagiogranite veins up to 0.7 m thick. Parallel dikes are composed of ophitic gabbrodolerite, dolerite, and porphyritic basalt with aphanitic groundmass. Several generations of dikes differ in orientation. The early generation of sheeted dikes filled isolated and variously oriented extension axes in apoharzburgite serpentinite and small bodies of pegmatoid gabbroic rocks. Dolerite dikes of the late generation also made up minispreading fragments combined with numerous small swarms. The dispersed character of spreading is confirmed by the variable orientation of extension vectors in the coeval structural elements and by the transition from early to late minispreading centers. The progressive rotation of the opening axis expressed

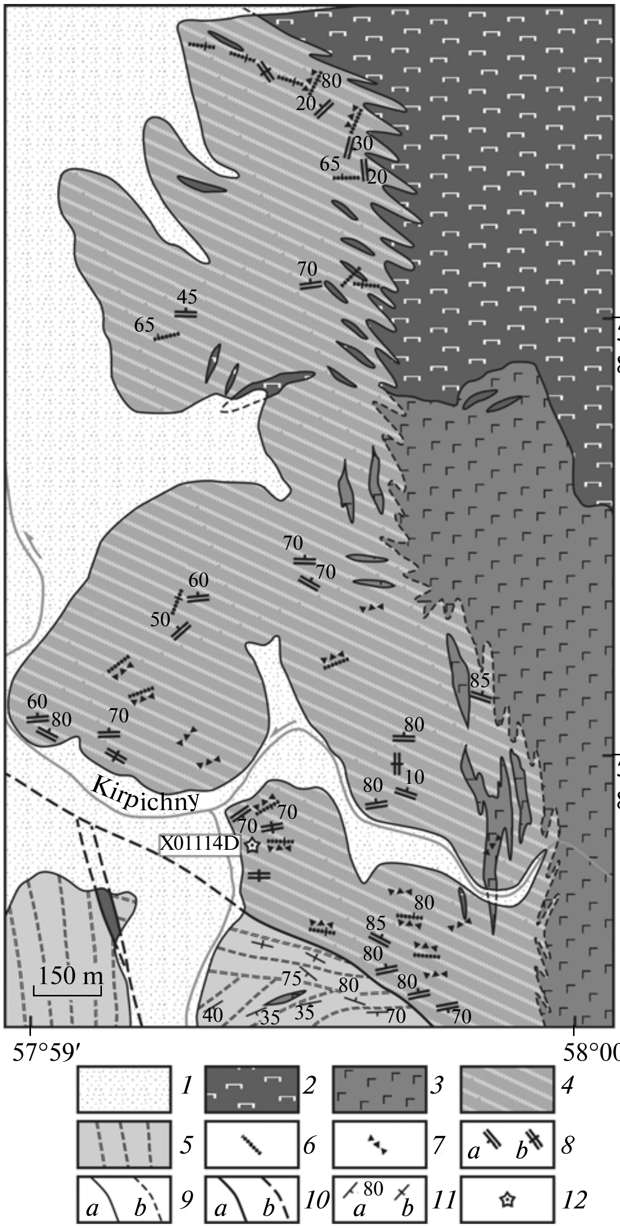


Fig. 3. Geological scheme of the Kirpichny Ravine area occupied by gabbro–plagiogranite association, simplified and modified after [50]. (*1*) Quaternary alluvium and fan sediments; (*2*) lizardite and antigorite serpentinite, including foliated variety, replacing dunite and harzburgite; (*3*) layered complex: gabbronorite, olivine gabbro, plagiowebsterite; (*4*) gabbro–plagiogranite association: amphibole gabbro, gabbrodiorite, and diorite; (*5*) sheeted dike complex: gabbrodolerite and dolerite; (*6*) plagiogranite veins; (*7*) zone of breccia; (*8*) isolated dolerite dike: (*a*) slanted and (*b*) vertical; (*9*) geological boundaries: (*a*) proved and (*b*) inferred; (*10*) faults: (*a*) proved and (*b*) inferred; (*11*) strike and dip symbols: (*a*) slanted and (*b*) vertical; (*12*) location of zircon sampling.

Results of the U–Pb (SHRIMP II) study of zircons from the plagiogranite in the ophiolite section of the Khabarny massif (sample X01114D)

Point of measuremen	$^{206}Pb_c$ %	U ppm	Th ppm	$^{232}Th/^{238}U$	$^{206}Pb^*$ppm	$^{206}Pb/^{238}U$ Age, Ma (1)		$^{206}Pb/^{238}U$ Age, Ma (2)		$^{206}Pb/^{238}U$ Age, Ma (3)	
X-1.1	0.41	191	183	0.99	10.8	408	±11	408	±11	404	±13
X-2.1	0.60	176	166	0.98	10.1	413	±11	413	±11	415	±13
X-3.1	2.28	170	136	0.82	8.44	353	±9.8	351	±9.5	355	±12
X-4.1	0.30	227	168	0.77	12.2	391	±10	391	±10	392	±11
X-5.1	0.77	287	378	1.36	16.5	415	±11	416	±11	421	±14
X-6.1	2.02	130	488	3.88	7.3	399	±12	397	±11	485	±43
X-7.1	0.30	121	51	0.44	6.58	395	±11	394	±11	394	±11
X-8.1	0.59	103	69	0.69	5.44	382	±10	382	±11	386	±12
X-9.1	0.61	476	413	0.89	29.5	445	±11	446	±11	444	±13
X-10.1	0.67	130	141	1.13	7.17	400	±11	399	±11	395	±13
X-11.1	0.65	231	199	0.89	12.7	397	±10	397	±10	397	±12
X-12.1	2.59	93	57	0.64	5.27	403	±12	402	±11	403	±13
X-13.1	0.68	141	151	1.10	7.7	395	±10	395	±10	395	±13
X-14.1	0.27	285	198	0.72	15.8	402	±10	402	±10	401	±12

Notes: The uncertainty of measurements is given at 1σ; Pb_c and Pb^* are common and radiogenic lead, respectively; the uncertainty of standard calibration is 0.86%; common lead corrected taking into account the following: (1) measured ^{204}Pb; (2) $^{206}Pb/^{238}U-^{207}Pb/^{235}U$ concordant age, and (3) $^{206}Pb/^{238}U-^{208}Pb/^{232}Th$ age.

in regular cutting-off of early dike packets by late packets at acute angles, as well as knee bends of the packets, are evidence for the shear component during formation of the dike complex. Thus, the dike complex of the Khabarny massif developed under heterogeneous conditions of dispersed spreading [50].

Upsection, the dike complex gives way to the *volcanic complex*. At the transitional level, the dikes and sills are associated with lava flows. Pillow lavas are predominant. The outer zones of the pillows are often porphyritic and enriched in amygdules, whereas the inner zones are aphyric.

The U–Pb (SHRIMP II) zircon age of the plagiogranite was determined in the Akkermanovka fragment in the northeast of the Khabarny massif [45]. The wide scatter of the obtained isotope ratios was explained by the metamict state of the zircon. One group of measurements yielded an intersection of concordia and discordia at 394 ± 2 Ma.

We analyzed zircons from the plagiogranite matrix of magmatic breccia (sample X01114D) in the west of the massif at 51°07′56.9″ N and 57°59′16.6″ E (Fig. 3); here and hereafter, all coordinates are given in the WGS'84 system. Crosscutting dolerite dikes are noted throughout this zone. The zircons for isotopic study were selected from a fraction of 0.2 mm. The crystals are transparent, elongated, euhedral, with oscillatory rhythmic zoning (Fig. 4; table). Of 14 measurements, 10 yielded concordant age of 399.8 ± 6.2 Ma. Here and hereafter, the measurements were performed on a SHRIMP II microprobe at the Center for Isotopic Studies, Russian Geological Research Institute, analyst S.L. Presnyakov. Xenogenic zircon grains are not ruled out, e.g., grain X-9.1, which yielded about 445 Ma. The concordant age corresponds to the late Emsian. In the Magnitogorsk Megazone, the Baimak–Buribai Formation has the same age [32]. As was mentioned above, the high-Mg boninite-like hypabyssal rocks of the Khabarny ophiolitic section are correlated in age with the rocks of this formation [46].

The dikes and associated volcanics are close in geochemical characteristics. These are basalt, basaltic andesite, and andesite of normal alkalinity (2.2–5.7 wt % Na_2O, 0.1–0.6 wt % K_2O) belonging to the tholeiitic and calc–alkaline series (Fig. 5). The MgO content is inversely correlated with SiO_2, varying from 15 wt % at 50 wt % SiO_2 to 4.2 wt % at 58.7 wt % SiO_2. The iron mole fraction varies from 29 to 52% and the Mg # is 48–71. The TiO_2 and Al_2O_3 contents are 0.2–1.6 wt % and 12.1–18.6 wt %, respectively. The data points of the dikes and volcanic rocks make up common trends in Harker diagrams, indicating that both are comagmatic. The trace element contents normalized to the primitive mantle composition correspond to E-MORB, revealing negative Th, Ta, Nb, and Zr anomalies and positive Ba, K, and Sr anomalies (Fig. 6). The chondrite-normalized REE patterns are flat and occasionally have a Eu minimum.

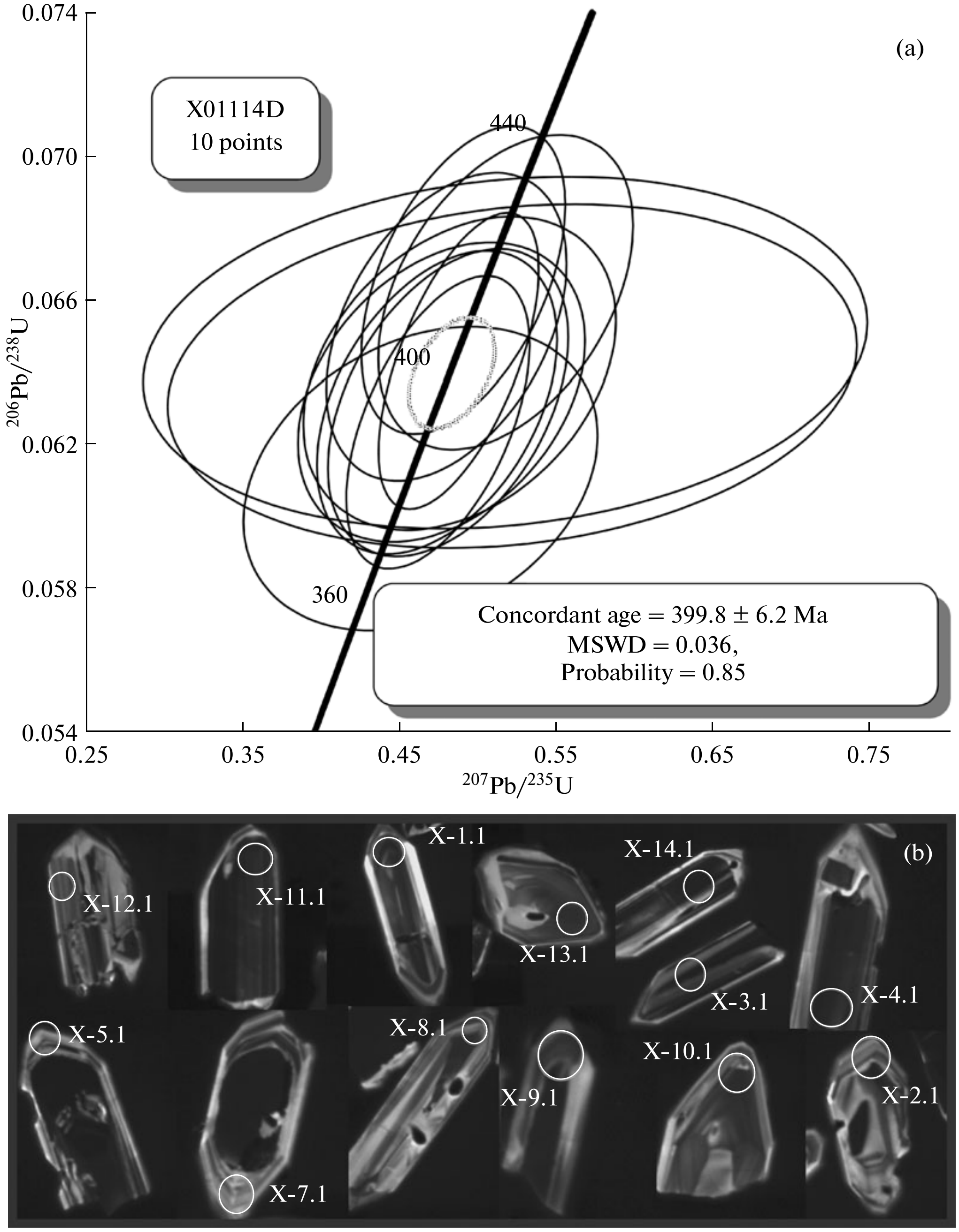
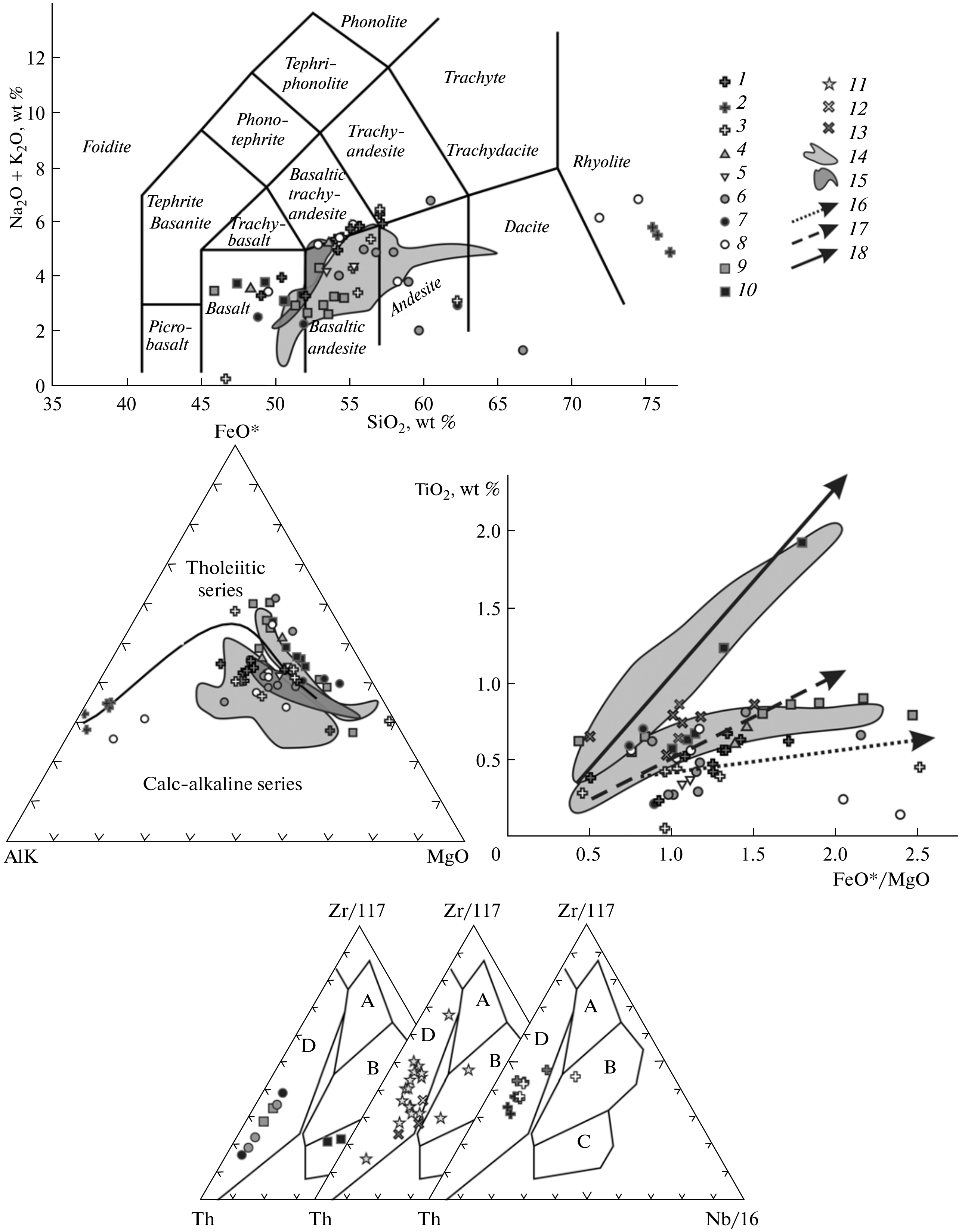


Fig. 4. Results of U–Pb (SHRIMP II) study of zircons from the western part of the Khabarny massif: (a) concordant age of zircons from plagiogranite (sample X01114D)—matrix of magmatic breccia from the upper level of gabbro–plagiogranite assemblage; (b) cathodoluminescent microphotographs of zircon grains; circles are craters of isotope ratio measurements.

Serpentinite melange

The serpentinite melange in the Sakmara Allochthon contains amphibolite blocks cut through by packets of dolerite dikes with suprasubduction geochemical signatures [57]. In addition, fragments of ophiolite sections and blocks of para- and orthometamorphic rocks occur in the melange. Devonian rocks formed on the oceanic floor—cherts, sedimentary, tectonic–sedimentary, and hydrothermal mixtites—are widespread [54, 57]. These are ophicalcite, ophicalcitic breccia, chert, and ophioclastic rocks. The Emsian and Givetian reef limestones are often incorporated into the melange. Foliated serpentinite and less abundant bedded clastic serpentinite rocks are the matrixes.

Blocks of amphibolites similar to the metamorphic rocks underlying the Khabarny ophiolitic massif are ubiquitous in the melange. In the western Sakmara


Na$_2$O + K$_2$O, wt %
SiO$_2$, wt %
0
2
4
6
8
10
12
35
40
45
50
55
60
65
70
75
Phonolite
Tephri-phonolite
Trachyte
Phono-tephrite
Trachy-andesite
Trachydacite
Foidite
Rhyolite
Basaltic trachy-andesite
Tephrite Basanite
Trachy-basalt
Dacite
Basalt
Andesite
Picro-basalt
Basaltic andesite
1
2
3
4
5
6
7
8
9
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17
18
FeO*
Tholeiitic series
Calc-alkaline series
AlK
MgO
TiO$_2$, wt %
0
0.5
1.0
1.5
2.0
2.5
FeO*/MgO
Zr/117
Zr/117
Zr/117
A
B
C
D
Th
Th
Th
Nb/16

Fig. 5. Chemical compositions of rocks from the upper part of Early Devonian ophiolite section plotted in discriminant geochemical diagram. (*1–8*) Cis-Sakmara–Voznesenka Zone: (*1–3*) Kalkan massif: (*1*) dolerite dikes, (*2*) plagiogranite, (*3*) basalt and basaltic andesite; (*4*) basalt and dolerite near Lake Urgun; (*5*) basalt of the Baimak–Buribai Formation near Mansurovo Village; (*6–8*) area near Chingizovo Village: (*6*) dolerite and granodiorite from sheeted dike complex, (*7*) basalt from the lower (?) sequence of the Baimak–Buribai Formation associated with ophiolites, (*8*) volcanic rocks of the upper sequence of the Baimak–Buribai Formation; (*9–10*) West Magnitogorsk Zone near Buidy Village: (*9*) dolerite dikes, (*10*) basalt from the Baimak–Buribai Formation; (*11–15*) Sakmara Zone: (*11*) dolerite from sheeted dike complex of the Khabarny massif, (*12*) dolerite dikes near Ramazanovo Village, (*13*) dolerite dikes southwest of Lower Rakityanka Village, (*14*) volcanic rocks and dolerite from the Medyanka River valley and dolerite from sheeted dike complex of the Khabarny massif, (*15*) dolerite dikes near Ramazanovo and Lower Rakityanka villages; (*16–18*) geochemical trends: (*16*) boninite series, (*17*) island-arc tholeiitic and calc-alkaline basalts, (*18*) MORB-type basalts. Compositional fields in diagrams: A, N-MORB; B, E-MORB; C, OIB; D, IAB.

Allochthon, north of the Ramazanovo Village, amphibolite occurs as a N–S-trending block extending for a kilometer and reaching 300 m in width. In the northwestern part of this block, amphibolite is combined with micaceous quartzite. In the west, metamorphic rocks contact with isotropic gabbro crossed by small plagiogranite veins and with broken sheeted dikes incorporated into the melange in the east. Amphibolite is a melanocratic rock with sporadic leucocratic interlayers. Banding is deformed into SW-verging isoclinal folds a few meters in amplitude and with ridge-shaped hinges. The dip azimuth is 240° SW to 340° NW, ∠60–85° and 20–30° NE, ∠60–90°. The amphibolite is cut by dolerite dikes; single bodies, swarms, and dike-in-dike packets are noted. The relative volume of the dikes decreases eastward from 50 to 1–5%. Two generations of dikes are observed. The first generation consists of fine- to medium-grained dolerite dikes 1–3 to 7–9 m in thickness. The dip azimuth varies from 90° E to 150° SE, largely 100–140° ESE; ∠10–65° (commonly ∠20–30°). Some dikes dip at an azimuth of 280–320° WNW, ∠70°. The dikes of the first generation are tortuous in plan view and have obtuse endings. Aphanitic and fine-grained dolerite veins 3–5 to 20–60 cm in thickness belong to this generation as well. The second generation includes dikes dipping at an azimuth of 40–60° NE, ∠40–65°. Less frequently, dikes are low-angle or nearly vertical and the dip azimuth is 120–140° SE, ∠70–90°. The contacts of these dikes are accompanied by brecciation of the country amphibolites.

In the eastern part of the Sakmara Allochthon, 4 km southwest of New Rakityanka Village, amphibolite is enclosed into taxitic gabbro. Both rocks are densely injected by dolerite veins varying in orientation and often clustering into packets. The amphibolite, gabbro, and dikes are cut through by a large (up to 1 km) stock of tonalite and plagiogranite. The granitoids are, in turn, cut through by swarms and packets of dolerite dikes pertaining to the late generation. Banding in the amphibolites dips at an azimuth of 200–240° SW, ∠20–40°. The dike packets reveal two preferential orientations: dip azimuths 320–340° NNW, ∠60–80° and 85–90° E, ∠40–60°.

The dikes in both areas are similar in geochemistry (Figs. 5, 6) and correspond to calc-alkaline basalt and basaltic andesite (1.6–4.6 wt % Na_2O and 0.2–2.3 wt % K_2O). The rocks contain 6.1–18 wt % MgO, 12–15 wt % Al_2O_3, and 0.5–0.8 wt % TiO_2. The iron mole fraction is 36–46%; Mg # is 54–78. The trace element contents normalized to the composition of the primitive mantle are similar to E-MORB and reveal negative Ta, Nb, and Zr anomalies and positive K, Pb, and Sr anomalies. No anomalies were detected in the chondrite-normalized REE patterns; the La/Yb ratio is 2–3.

The Northern Cis-Sakmara–Voznesenka Zone

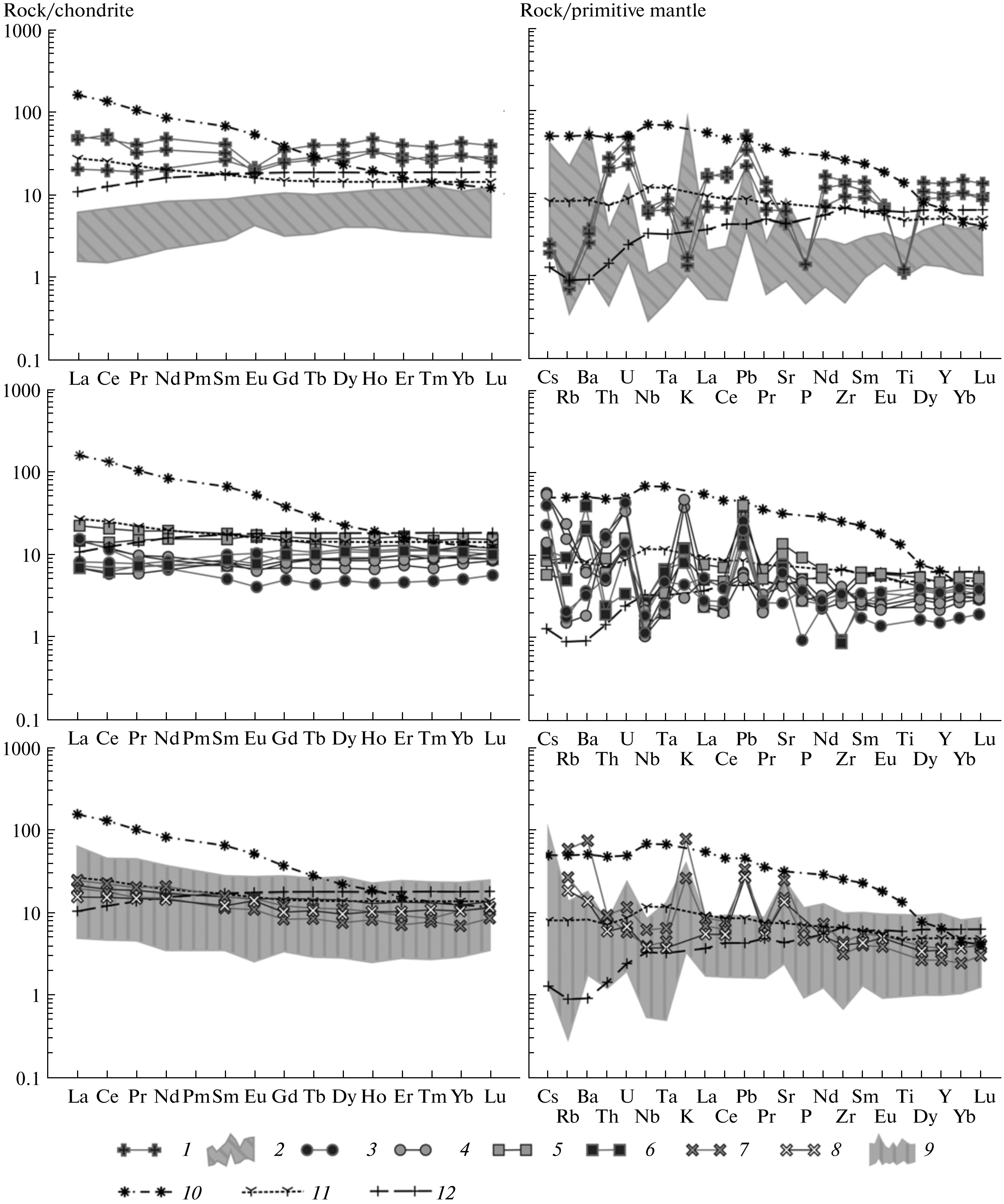
Position of ophiolites. In the north of the Cis-Sakmara–Voznesenka Zone, ophiolites occur as small lherlolite- and harzburgite-type massifs [61] among the serpentinite melange. The harzburgite-type massifs are considered in this paper; however, information important for reconstruction of the geodynamic settings is given to the lherzolite-type ophiolites, too.

The serpentinite melange occupies a narrow (6–8 km) tract between the metamorphic rocks of the Ulutau Zone in the west and the Lower–Middle Devonian rocks of the West Magnitogorsk Zone overlying the melange in the east (Fig. 7). The following structural elements and complexes are distinguished from west to east:

(1) The Uraltau Zone, where the Riphean quartzite and quartzitic schists is overlain, being separated by metamorphosed serpentinite, by a tectonic sheet composed of sandstone, siltstone, and chert; Lochkovian conodonts were found in the latter at the top of Mount Serekei [57]. The sedimentary complexes were formed at the passive margin of the East European Platform.

Subdivisions 2–4 described below belong to the Cis-Sakmara–Voznesenka Zone.

(2) The tectonic sheet as a narrow (200–300 m) lens about 2 km in extent is composed of green aphyric basalt containing lenses of gray chert and sedimentary breccia with chert and siltstone fragments. The chert from the northern part of the lens contains *Pandorinellina stainhornensis* (Ziegler) characteristic of the Emsian Stage at one point and *Polygnathus Trigonicus* Bisch. et Ziegler, *Panderodus* sp., and *Belodella* sp. pertaining to the upper Eifelian at another point. The medium-Ti basalt is comparable in geochemistry with the volcanic rocks in the basins underlain by oceanic crust.


Rock/chondrite
Rock/primitive mantle
1000
100
10
1
0.1
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Cs Rb Ba Th U Nb Ta K La Ce Pb Pr Sr P Nd Zr Sm Eu Ti Dy Y Yb Lu
1
2
3
4
5
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7
8
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12

Fig. 6. Spidergrams and REE patterns of rocks from the upper part of the Early Devonian ophiolite section. (*1–4*) Cis-Sakmara–Voznesenka Zone: (*1, 2*) Kalkan massif: (*1*) plagiogranite, (*2*) basalt, basaltic andesite, and dolerite; (*3, 4*) near Chingizovo Village: (*3*) basalt from the lower (?) sequence of the Baimak–Buribai Formation associated with ophiolites, (*4*) dolerite and plagiogranite from sheeted dike complex; (*5, 6*) West Magnitogorsk Zone near Buidy Village: (*5*) dolerite dikes, (*6*) basalt from the Baimak–Buribai Formation; (*7–9*) Sakmara Zone: (*7*) dolerite dikes southwest of Lower Rakityanka Village, (*8*) dolerite dikes near Ramazanovo Village, (*9*) dolerite from sheeted dike complex of the Khabarny massif; (*10–12*) typical trace element contents, after Sun and McDonough (1989): (*10*) OIB, (*11*) E-MORB, (*12*) N-MORB.

(3) The tectonic sheet composed of lherzolite-type ophiolitic massifs (Nurali, Tetlambetovo, Mindyak) [61, 92] and serpentinite melange with blocks of garnet ultramafic rocks and amphibolites.

In the largest Nurali massif, plagioclase lherzolite, harzburgite, and dunite alternate from west to east. The transitional zone from harzburgite to dunite contains numerous dunite veins in harzburgite veinlets. Further to the east, the banded complex gives way to amphibole gabbro and gabbrodiorite.

Blocks and small bodies of garnet ultramafic rocks previously known only in the Mindyak massif are now established within a 120-km tract from the latitude of Absalyamovo Village in the north to Kubagushevo Village 12 km south of the Mindyak Settlement in the south (Fig. 1). Similar rocks occur in the Kraka massifs situated to the west of the Uraltau Zone [24]. The garnet-bearing ultramafic rocks near Burangulovo Village were formed at $T = 920–870°C$ and $P \geq 10.5$ kbar from the garnet–clinopyroxene equilibrium [58]. The respective parameters for the ultramafic rocks in the Mindyak pluton are T = 1200–800°C and P = 15–20 kbar [38, 42]. The Sm–Nd age of the garnet ultramafic rocks in the Mindyak massif is 406–399 Ma [38, 42, 94]; the U–Pb age of the zircon from the garnet pyroxenite is 410 Ma [59]. The Pb/Pb age of the zircon cores is 467 Ma [94].

We estimated the U–Pb (SHRIMP II) age of the zircons in four samples of garnet pyroxenite near the villages of Burangulovo and Kubagushevo. The grains consist of cores and wide marginal rims (up to 50% of the grain volume). In all samples, the morphology and internal structure of the cores and rims furnish evidence for reworking under conditions of granulite or eclogite metamorphic facies. The concordant age of garnet pyroxenite sample A601/8 taken near Burangulovo Village is 416.1 ± 6.1 Ma. Similar estimates have been obtained for most cores and rims. One core with homogeneous metamorphic structure yielded, however, 457 ± 15 Ma and another core, 437.2 ± 9.6 Ma. The concordant age of the rims and reworked cores in sample 7322-1 of rodingitized garnet-free pyroxenite exposed near Kubagushevo Village to the south of the Mindyak massif was estimated at 416.5 ± 2.3 Ma. Five meters away from this outcrop, garnet pyroxenite (sample 7322-2) is dated at 413.8 ± 2.1 Ma (rims and reworked cores). Cores with relict metamorphic structure yielded 429.4 ± 5.4 and 441.7 ± 3.0 Ma. Sample A606 of garnet pyroxenite taken near Barangulovo Village 30 m south of observation point (OP) A-601/8 contained zircon grains with the same morphology and internal structure as in the other samples, but the age range is much wider, from 2438 ± 45 to 503 ± 11 Ma. These data defy reasonable interpretation but are consistent with the results obtained in the Uzyan Kraka massif, where similar rocks yielded an age range of 2037 ± 20 to 378 Ma [24]. The dating of garnet ultramafic rocks reflects the multistage history of mantle material transformation. The repeated estimates within the interval of 410 to 416 Ma mark the last metamorphic episode, probably predated by older events.

An extended pluton of amphibole gabbro and gabbrodiorite occurs in the serpentinite melange to the east of the banded complex. The U–Pb zircon age of the gabbroic rocks is 400 Ma [68, 73].

The ophiolitic rocks are cut through by dikes that locally make up stockworks. The dikes composed of low-Ti and high-Mg basalt and basaltic andesite [59] are close in composition to the Early Devonian dike complexes occurring at the other sites described in this paper.

The Ural lherzolite-type ophiolite massifs resemble the ophiolites of the Alpine–Apenninian Belt (Lanzo, etc.), which are assumed to be derived from the subcontinental lithosphere. In the Urals, they are linked to the initial stage of intracontinental rifting [89]. According to one of the conjectures, the formation of lherzolite-type ophiolites is related to the Early Ordovician rifting [59]. They bear signs of high-pressure and high-temperature reworking in the Early Devonian (410–416 Ma). It is evident that these complexes also underwent alteration under suprasubduction conditions later at the very end of the Early Devonian (400 Ma), when they were intruded by amphibole gabbro and dikes.

(4) Tectonized basalts, tuffites, and cherts with the conodonts characterizing the stratigraphic interval from the upper Llanvirnian to the lower Caradocian [55] extend to the east of the Nurali massif as a tectonic lens 400–500 m in thickness. These rocks are correlated to the Guberlya Formation of the Sakmara Zone that comprises the backarc complexes. Blocks of cherty rocks and basalts of the Lower Silurian Dergaish Formation and carbonaceous slates of the Lower Silurian–Lochkovian Sakmara Formation are noted in this tract as well. The upper tectonic nappe combines the Frasnian cherty rocks and the conformably overlying graywacke flysch of the Famennian Zilair Formation and Carboniferous carbonate rocks. The

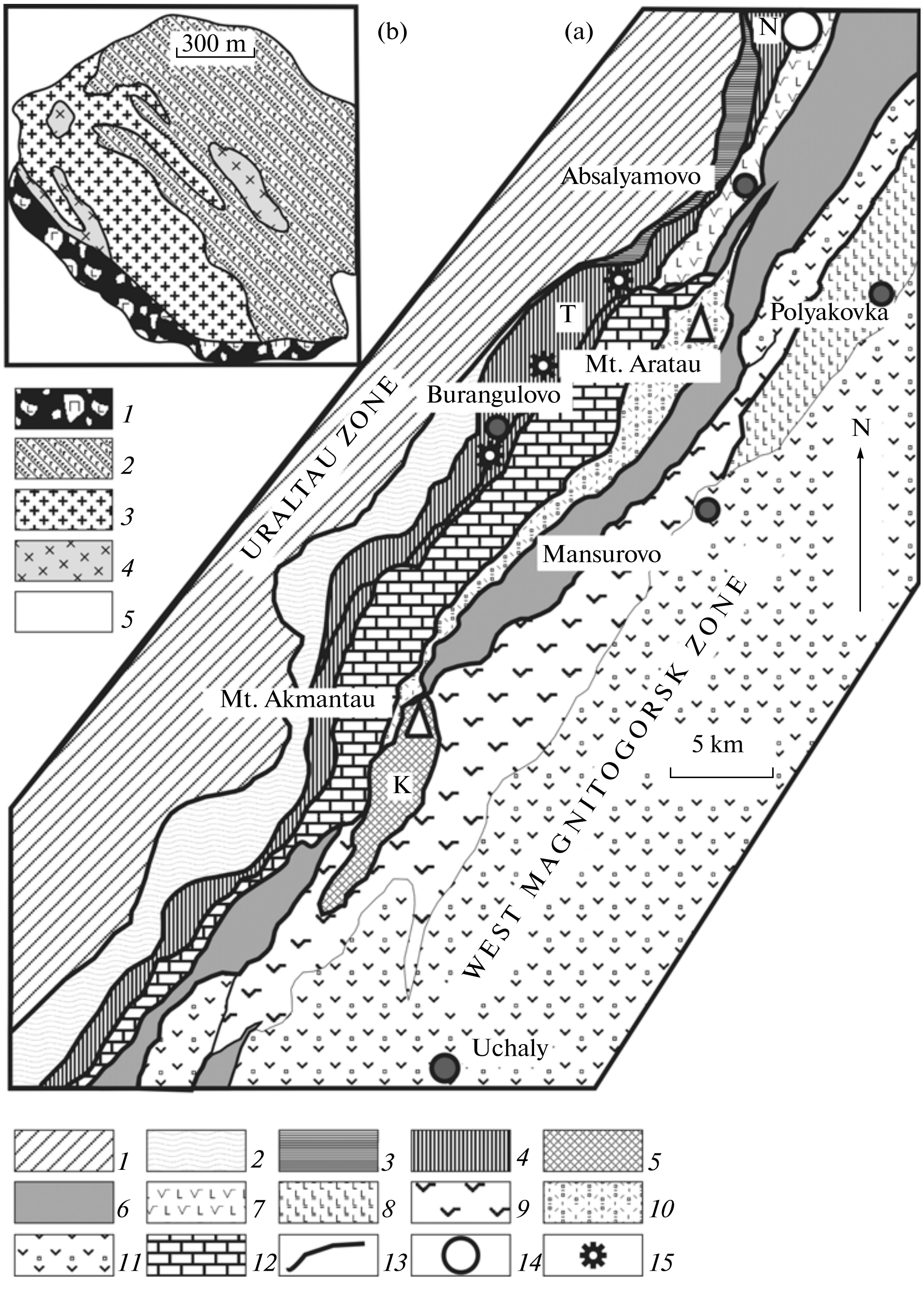

Fig. 7. (a) Tectonic units and rock complexes in the northern Cis-Sakmara–Voznesenka and West Magnitogorsk zones and (b) detailed structure of sheeted dike complex on Mount Akmantau, simplified after [75]. **Panel (a)** (*1, 2*) Uraltau Zone: (*1*) Riphean quartzite and schist, (*2*) Lower Devonian chert, sandstone, and siltstone; (*3*) Lower–Middle Devonian basalt, chert, and breccia; (*4*) lherzolite-type massif and related melange; (*5*) harzburgite-type massif; (*6*) serpentinite melange related to harzburgite-type massifs; (*7*) Middle–Upper Ordovician basalt, chert, and tuffite; (*8*) basalt and chert of the Ordovician Polyakovka Formation; (*9*) tectonic blocks of the Ordovician Polyakovka and the Emsian Baimak–Buribai formations in the melange; (*10*) lavas and tuffs of the Emsian basalt–basaltic andesite–dacite–rhyolite series; (*11*) basalt and basaltic andesite lavas and tuffs of the Eifelian Irendyk Formation and overlying Middle–Upper Devonian volcanosedimentary rocks; (*12*) Upper Devonian chert, sandstone, siltstone, and tuffite; (*13*) fault; (*14*) location of the dated gabbrodiorite samples [68, 73]; (*15*) outcrop of garnet ultramafic rocks. Mafic–ultramafic massifs (letters in figure): N, Nurali; T, Tetlambetovo; K, Kalkan. **Panel (b)**. (*1*) serpentinite melange; (*2*) sheeted dike complex; (*3*) plagiogranite; (*4*) granodiorite; (*5*) Cenozoic loose sediments.

basal serpentinite melange contains fragments of Lower and Middle Devonian cherts and Middle Devonian limestone [57].

(5) The tectonic sheet occurring further to the east is composed of harzburgite-type ophiolites [76, 92]. The largest segments of the ophiolite section occur

near Lake Kalkan and Mount Akmantau (Fig. 7). The melange of this tract is a tectonic mixture of the Devonian and Ordovician ophiolites, which sharply differ in geochemistry. The Ordovician cherts and basalts of the Polyakovka Formation underlie cherts and basalts of the Lower Silurian Dergaish Formation, in turn, underlying carbonaceous cherty slates of the Silurian–Lower Devonian Sakmara Formation. Various elements of the ophiolite section are overlapped by reef limestone with Praghian–Emsian conodonts [31, 32, 56]. To the south of the latitude of the town of Uchaly, the limestone is intercalated by sedimentary breccia with clay–carbonate cement and serpentinite fragments. The limestone is overlapped by the Emsian volcanic section (lavas and tuffs varying in composition from basalt to rhyolite). The volcanic rocks are intercalated by limestone and chert containing Emsian conodonts [31, 62]. To the east, the limestone is redeposited and occurs as fragments in the tuffaceous terrigenous rocks of the Lochkovian Mansurovo Sequence with mixtite units. Near Mansurovo Village, this sequence unconformably overlies tectonic slices of Ordovician and Silurian rocks. Upward, the cherty and tuffaceous sequence with Emsian conodonts [31] gives way to the Eifelian Irendyk Formation composed of basalt and basaltic andesite (lavas and tuffs) and overlying Middle–Upper Devonain volcanic and sedimentary sequences. The rocks of the Irendyk Formation correspond to the initial stage of volcanism in the Magnitogorsk island arc.

Structure of ophiolite section

The harzburgite-type ophiolite section in this area has been described in detail by Chaplygina and Degtyarev [75, 76].

The restite complex crops out as the Kalkan massif, a steeply dipping tectonic sheet 6.0 × 2.5 km in area which strikes from north to south. The sheet consists of serpentinized harzburgite; about 10% of its volume is occupied by dunite and, to a lesser extent, pyroxenite veins. The veins are conformable to banding in harzburgite or make up crosscutting stockworks.

The banded dunite–wehrlite–pyroxenite–gabbro complex occurs in the serpentinite melange to the north of the Kalkan massif as a system of steeply dipping tectonic sheets up to 20 km in extent. Taxitic varieties are observed locally. The complex is deformed into nearly meridional folds with steep hinges. All fragments of the banded complex are cut through by variously oriented gabbrodiorite dikes a few decimeters to a few meters in thickness. In some places, they are concentrated in the upper part of the peridotite section.

The sheeted dike complex and plagiogranite make up a wide (~1 km) tract, where they extend discontinuously for 5–6 km to the north of Mount Akmantau. Within this tract, near-vertical dolerite dikes make up NW-trending packets (Fig. 7). The thickness of these dikes varies from decimeters to 3–4 m. Dolerite and porphyritic gabbrodolerite are predominant; konga diabase with xenomorphic quartz grains is noted. The dike complex is cut through by plagiogranite and quartz diorite bodies up to 200 m thick. The granitoid rocks contain numerous dolerite xenoliths.

The U–Pb age of the zircon from the plagiogranite at Mount Akmantau (54°26′52.0″ N, 59°20′37.1″ E) determined at the Institute of Precambrian Geology and Geochronology in St. Petersburg should be regarded as a preliminary estimate. The lower intersection of the discordia with the concordia corresponds to 399 ± 15 Ma. This date is consistent with the age of the plagiogranite from the Khabarny massif. At the same time, another point marks the upper intersection of the discordia with the concordia at 464 ± 21 Ma, indicating the probable occurrence of xenogenic zircon.

The complex of volcanic and cherty rocks is traced from the Kalkan massif in the south to Mansurovo Village in the north. The complex is composed of pillow basalt, basaltic andesite, and andesite, which occur as tectonic sheets and blocks in the serpentinite melange. The blocks of Ordovician and Devonian rocks are tectonically mixed. The Ordovician volcanic and cherty rocks of the Polyakovka Formation make up a system of large tectonic sheets. North of Polyakovka Village, the collected conodonts correspond to the stratigraphic interval from the upper Arenigian to the Ashgillian, included [55, 56]. The volcanic rocks and dikes of the Polyakovka Complex vary in composition from picrite to trachyandesite enriched in alkali metals and related trace elements, resembling ocean-island volcanics in this respect. At the same time, they reveal Ta and Nb minimums.

Suprasubduction igneous rocks conventionally referred to the Silurian [11] or Ordovician [75, 76] have earlier been suggested here from geochemical data. We assume the occurrence of Devonian volcanic rocks and cherts on the basis of correlation with other areas, where the Devonian age of the similar rocks is supported by finds of conodonts close to Buidy and Chingizovo villages and by the zircon age of the plagiogranite. The aphyric and porphyritic lavas with large plagioclase phenocrysts were metamorphosed under conditions of greenschist facies and underwent propylitic alteration.

The dikes and associated volcanics are close in geochemistry (Figs. 5, 6). Both correspond to calc-alkaline basalt, basaltic andesite, and andesite of normal alkalinity (1.0–6.2 wt % Na_2O, 0.1–2.2 wt % K_2O). MgO and SiO_2 are inversely correlated in the range of 11 wt % MgO at 52 wt % SiO_2 to 4 wt % MgO at 55 wt % SiO_2. The TiO_2 and Al_2O_3 contents vary in the ranges of 0.2–0.6 wt % and 13–17 wt %, respectively. The spectra of the microelements normalized to the primitive mantle composition are similar to the E-MORB spectra but distinguished by negative Th, Ta, Nb, Zr, and Ti and positive Ba, K, Pb, and Sr anomalies. The chondrite-normalized REE patterns

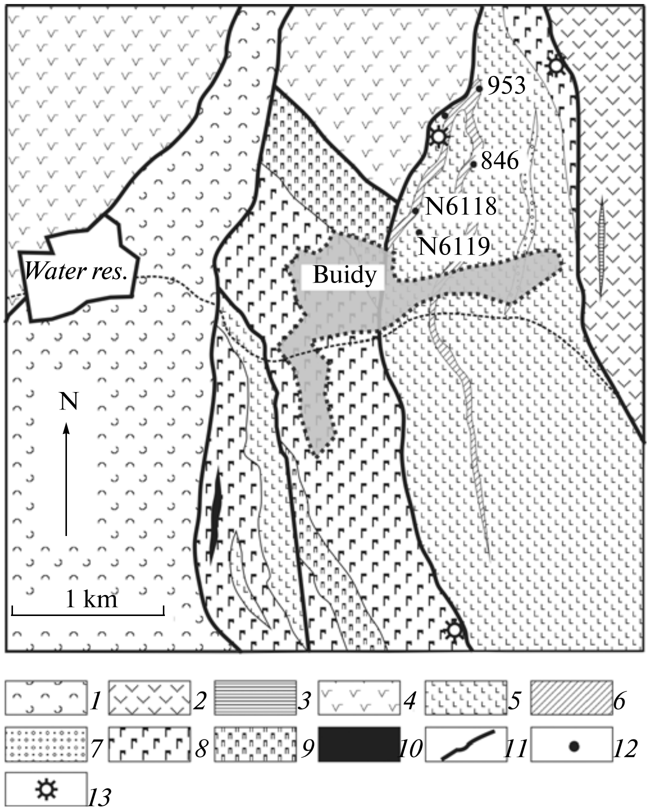

Fig. 8. Geological scheme of the vicinity of Buidy Village. (*1*) Givetian–Frasnian Ulutau Formation, acid tuff and tuffite; (*2, 3*) Eifelian Karamalytash Formation: (*2*) basalt and (*3*) dacite; (*4*) Eifelian Irendyk Formation, basaltic andesite and basaltic tuff and lava breccia; (*5–7*) Emsian Buidy Sequence: (*5*) basalt, tuff, and cherty tuffite; (*6*) chert, and (*7*) siliciclastic gravelstone; (*8*) sheeted dike complex; (*9*) banded complex, wehrlite, websterite, and pyroxenite; (*10*) listvenitized ultramafic rocks; (*11*) fault; (*12*) find of conodonts and its number; (*13*) small granitoid body.

of the basalt and dolerite have a slight positive slope characteristic of MORB. The REE patterns and compositional trends of the dikes and volcanic rocks in the Harker diagrams are parallel, indicating that these rocks are comagmatic. In the discriminant geochemical diagrams, the compositions of the granitoid and volcanic rocks fall into the fields of island-arc rocks.

The West Magnitogorsk Zone (Buidy site)

The Buidy site near the village of the same name is located in the northern part of the West Magnitogorsk Zone (Fig. 1). Ophiolites occur in the core of the narrow meridional anticline that complicated the Magnitogorsk Synform (Fig. 8). In the east and west, the anticline is separated from the Early and Middle Devonian island-arc volcanic complexes by meridional faults. The restite complex is almost completely absent in the section. Small fragments of it occur locally as listvenite lenses. The banded complex of alternating wehrlite, websterite, and clinopyroxenite is widespread. Taxitic gabbro is noted in the upper part of the section. The banded complex gives way to the sheeted dike complex. The aphyric and plagiophyric dikes correspond to basalt and basaltic andesite in composition. The dike-in-dike packets reach 600 m in width. The screens between individual dikes are composed of pyroxenite or fragments of volcanic section, where basalts are intercalated by cherts. The dikes are largely vertical and strike in the NW and NNW directions. The plagiogranite porphyry and granodiorite veins up to 5–10 m into thickness are associated with dike and volcanic complexes.

The volcanic section consists of aphyric basalts intercalated by a member of gray chert, cherty tuffite, and tuffaceous conglobreccia. According to drilling results, this member is 60 m thick [67]. In the eastern part of the exposed section, basalts are overlapped by siliciclasti gravely breccia up to 40 m thick. The volcanic sequence was metamorphosed under conditions of greenschist facies. The degree of deformation increases eastward, where small isoclinal faults are observed in small quarries. The quartz veins in the basalts are also deformed into small isoclinal folds.

Early Devonian conodonts have been collected from the sedimentary member and cherts at three observation points (here and hereafter, conodonts were determined by V.A. Aristov and S.V. Dubinina from the Geological Institute, Russian Academy of Sciences). In particular, these are *Ozarkodina* ex. gr. *remcsheidensis* (Ziagler), *Belodella* sp., *B. striata* Kozur (OP N6118/1); Emsian conodonts *Pandorinellima* cf. *steinhornensis miae* (Bultynck) from cherty tuffite intercalating basalt (OP 846), and *Hamarodus brevirameus* (Walliser), *Perodon* cf. *grandis* (Ethington), *Protopanderodus liripipus* Kennedy et al., and *Ansella* cf. *A. erecta* (Rhodes et Dineley) pertaining to the upper Caradocian–Ashgillian (OP N6119/1 in a small lens of silicified chert between dolerite dikes).

The complexes corresponding to the evolution of the ensimatic arc, which are traced along the entire West Magnitogorsk Zone, occupy a higher structural position relative to the ophiolites. In the north of the Buidy site, this is the Lower–Middle Devonian Irendyk Formation of pyroxene–plagioclase and plagioclase basaltic andesites. In the east, the ophiolite section is separated from aphyric and porphyritic lavas and dacite porphyry dikes of the Eifelian Karamalytash Formation by faults. The Givetian–Frasnian Ulutau Formation of intercalating tuffstone, siltstone, chert, and silicic tuff occurs in the west (Fig. 8).

The dikes and associated volcanic rocks of the Buidy site are close in geochemistry (Figs. 5, 6). They correspond to basalt and basaltic andesite of normal alkalinity (3–4 wt % $Na_2O + K_2O$, wt %) belonging to the tholeiitic series (sodic type). MgO and SiO_2 are inversely correlated in the range of 20.2 wt % MgO at 45.8 wt % SiO_2 to 4.7 wt % MgO at 54.6 wt % SiO_2. The TiO_2 and Al_2O_3 contents vary in the ranges of 0.5–

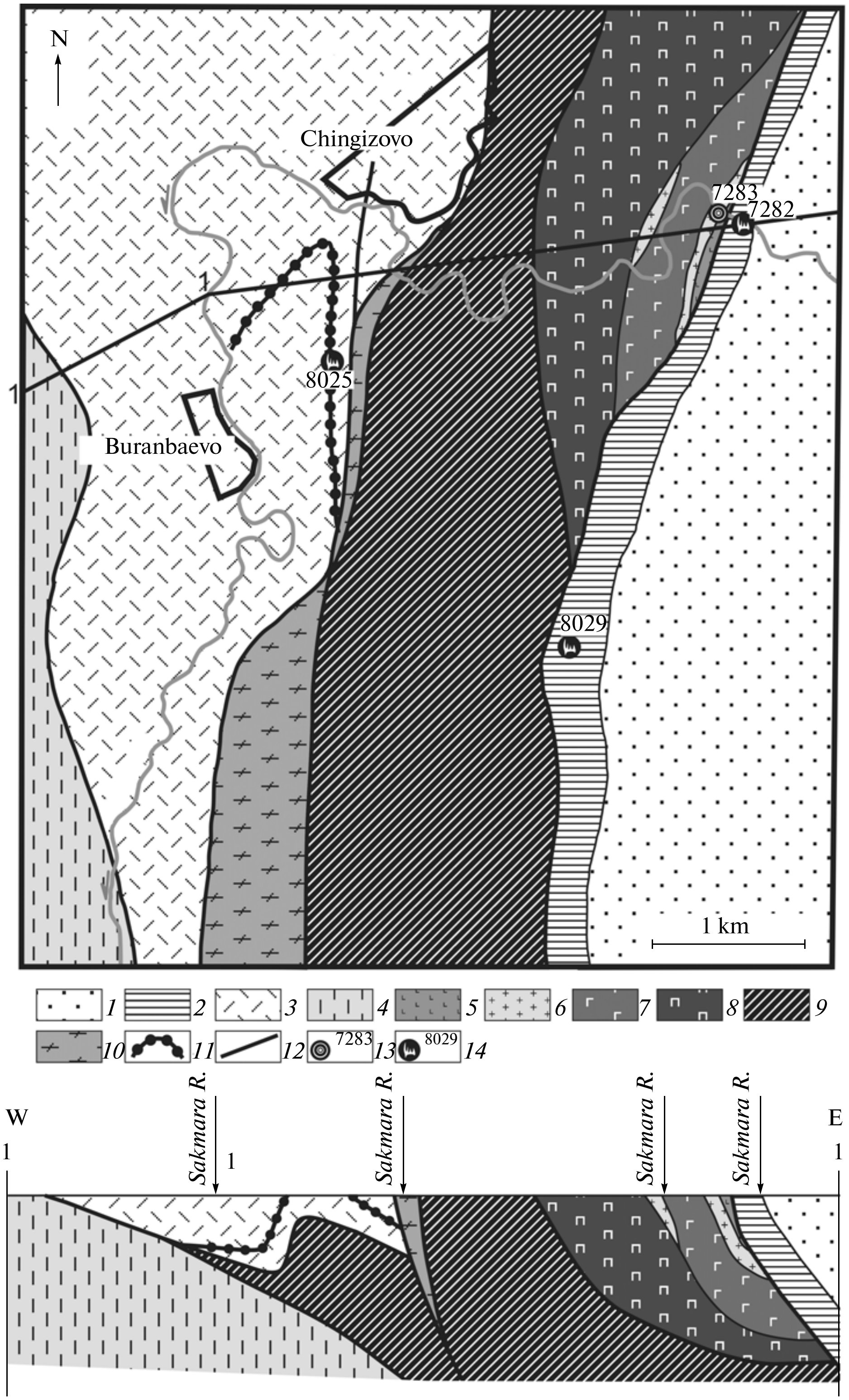

Fig. 9. Chingizovo ophiolite massif in the Cis-Sakmara–Voznesenka Zone. (*1*) graywacke of the Famennian Zilair Formation; (*2*) Lower Devonian–lower Famennian cherty sequence; (*3*) Early Devonian subvolcanic rhyolite bodies; (*4*) quartzitic schist of the Ulutau Zone; (*5–9*) ophiolites: (*5*) basalt, (*6*) granitoids, (*7*) sheeted dike complex, (*8*) pyroxenite and gabbro of banded complex, (*9*) dunite–harzburgite complex; (*10*) amphibolite; (*11*) chert unit; (*12*) fault; (*13*) location of zircon samples; (*14*) location of conodont finds.

1.0 wt % and 9–15 wt %, respectively. The spectra of microelements normalized to the primitive mantle composition are similar to the E-MORB spectra but distinguished by slight negative Th, Ta, Nb, and Zr and positive Ba, K, Sr, and Pb anomalies. The chondrite-normalized REE patterns are nearly horizontal (La/Yb = 0.8–2.4). The REE patterns and compositional trends of the dikes and volcanic rocks in the Harker diagrams are parallel, indicating that these rocks are comagmatic.

The Central Part of the Cis-Sakmara–Voznesenka Zone

In the central part of the Cis-Sakmara–Voznesenka Zone, ophiolites make up a series of tectonic sheets to the east of the Uraltau (Fig. 1). The most complete section is observed along the banks of the Sakmara River near Chingizovo Village to the west of Baimak settlement (Fig. 9). The Uraltau Zone composed of quartzitic schists is overthrust in the east by a sheet of basalt and subvolcanic rhyolite metamorphosed under conditions of greenschist facies. The chert interbeds in the basalts contain Early Devonian conodonts *Belodella* sp. To the east, the tectonic sheet consists of the ophiolitic Chingizovo massif, including a dunite–harzburgite complex (1000 m), banded complex (300 m), dike complex (500 m), and variolitic basalt (100 m). The ophiolites are underlain by an amphibolite sheet and overlain by a tectonic nappe of Devonian chert and Famennian graywacke. The banded complex in its lower part is composed of finely intercalating wehrlite and pyroxenite and pyroxenite alone in the upper part. Sporadic dolerite dikes appear upsection. Sheets of isotropic fine-grained gabbro and fine-to-medium-grained tonalite 5–10 m thick occur between the banded and dike complexes. The dike-in-dike complex extends parallel to the general stratification dipping to the east at angles of 60–70°. A sill of fine-to-medium grained quartz diorite (5–6 m) with dolerite xenoliths occurs near the roof of the dike complex. Plagioclase, quartz, hornblende, and K-feldspar (up to 5–7 vol %) are the major minerals of the quartz diorite; zircon and apatite are accessory minerals; the secondary minerals are albite, chlorite, epidote (pistacite), and quartz. At OP 7283 (52°38′59.6″ N and 58°02′35.8″ E), zircon grains were picked out from the quartz diorite; their concordant U–Pb (SHRIMP II) age is 775.9 ± 2 .3 Ma. These zircons probably are xenogenic. Taking into account the similar sections of ophiolites in the Chingizovo, Khabarny, and Buidy massifs and the similar composition of the crustal elements of these sections, the Early Devonian age of the dike complex and cherty–volcanic sequence of the Chingizovo massif is accepted.

The dikes correspond to basaltic andesite and andesite of normal alkalinity in composition (3.8–6.8 wt % $Na_2O + K_2O$) and belong to the slightly fractionated calc-alkaline series (Figs. 5, 6). The Mg number is 60–67%; the iron mole fraction is 0.3–0.4%; and the MgO content varies from 5.8 to 10.1 wt %. The rocks contain 7.1–9.6 wt % FeO_{tot}, 13.7–15.5 wt % Al_2O_3, and 0.2–0.6 wt % TiO_2. The spectra of microelements normalized to the primitive mantle composition are similar to the E-MORB spectra but reveal a slight negative Nb anomaly and positive U, K, and Pb anomalies. The chondrite-normalized REE patterns are nearly horizontal (La/Yb = 1.0–2.6). In general, the spectra are similar to that of E-MORB but are two–three units lower throughout the spectrum.

The volcanic rocks that overlie the dike complex belong to the fractionated tholeiitic basaltic andesite series and are correlated with the lower sequence of the Baimak–Buribai Formation. MgO and SiO_2 are inversely correlated in the range of 18 wt % MgO at 48.8 wt % SiO_2 to 8.7 wt % MgO at 62.0 wt % SiO_2. The Mg # is 67–68%; the iron mole fraction is 0.30–0.35. The rocks contain 8–13 wt % FeO_{tot}, 11–15 wt % Al_2O_3, and 0.2–0.7 wt % TiO_2. The spectra of microelements and REE patterns are similar to those of the dike complex, coincide with or are parallel to them, indicating that the compared rocks are comagmatic.

The volcanic rocks located to the west and separated by metamorphic rocks from the ophiolite association significantly differ from the former and are conventionally correlated with the upper sequence of the Baimak–Buribai Formation in the Buribai ore district. These volcanics make up contrasting basalt–basaltic andesite–rhyolite calc-alkaline series (3.4–6.8 wt % $Na_2O + K_2O$); the MgO content varies from 1.1 to 10.1 wt %. The Mg number ranges from 40 to 70%. In general, the volcanic rocks are characterized by low contents of TiO_2 (0.1–0.7 wt %), Al_2O_3 (13.8–17.2 wt %), and FeO_{tot} (2–10 wt %). In one sample with 49.5 wt % SiO_2, the TiO_2 content reaches 2.4 wt % and FeO_{tot} is 13.4 wt %. The trends of data points in the Harker diagrams show that rocks with various SiO_2 contents are comagmatic.

DISCUSSION

The Early Devonian ophiolites of the southern Urals described above were formed in the suprasubduction setting. This is confirmed by the occurrence of rocks pertaining to boninite series or having attributes close to boninites in the upper crustal part of the ophiolite complex consisting of sheeted dikes and volcanic rocks. The rocks of the boninite series amount to 30% of all analyzed dikes and volcanics, which are close in geochemistry to one another and differ in composition from Ordovician ophiolites. Most rocks from the upper parts of the ophiolite associations correspond to low-Ti and high-Mg basalt and basaltic andesite. The igneous rocks belong to series of normal alkalinity with Mg # ~ 50–70 and low Ti and high Mg contents. The rocks of the boninite series are characterized by prevalence of low-Ca varieties with $CaO/Al_2O_3 < 0.6$.

The behavior of LILE, Ta, and Nb reflects the contribution of the suprasubduction component. Flat REE patterns with low La/Yb ratio are evidence for lack of contribution of products of partial melting of the slab to magma generation. Most likely, a mantle wedge slightly enriched in volatile components was the source of the melts.

The Early Devonian age of the crustal complexes pertaining to the ophiolite associations is proved by paleontological and isotopic geochronological data.

According to our data and the evidence obtained by Pushkarev [43], the age of the plagiogranite coeval to the sheeted dikes in the Khabarny massif is 394–400 Ma. The age of the plagiogranite from the Kalkan massif (399 ± 15 Ma) is consistent with these data, although the estimate of 464 Ma (Middle Ordovician) should be noted. Older dates were obtained for the Khabarny plagiogranite as well. Only ancient dates (~770 Ma) are established for the granitoids of the Chingizovo massif. These results require additional verification and interpretation. The occurrence of older zircons probably reflects a heterogeneous medium where melts were being formed.

In addition to isotopic geochronological data, we collected Emsian conodonts from the chert interbeds in the volcanic sequences that crown the ophiolite section. The cherty–volcanic section is built up by Early–Middle Devonian island-arc volcanics.

A number of rock complexes in the southern Urals furnish evidence of Early Devonian convergent processes.

Some of them characterize the lithosphere of the suprasubduction wedge altered during the formation of crustal elements of the Early Devonian ophiolites. Such complexes were established in the West Magnitogorsk, Cis-Sakmara–Voznesenka, and Sakmara zones. Primarily, these are harzburgite-type massifs. Harzburgites of the Kalkan, Khalilovo, Khabarny, and Kempirsai massifs host dunite veins often making up stockworks and containing chromitite bodies. Dunites and chromitites are regarded as products of interaction of harzburgites with percolating mafic melts [60, 88 and references therein]. The Sm–Nd age of the harzburgite, pyroxenite, and gabbro in the northwestern part of the Kempirsai massif (Fig. 1) is estimated at 420–400 Ma [88]. The concordant U–Pb zircon age from the pyroxenite veins containing phlogopite and amphibole is 420 ± 10 Ma [88]. In the southeastern part of the massif, the Ar/Ar and Rb–Sr ages of the pargasite coeval with fluid inclusions in the chromite are 365–384 Ma. This indicates that mantle rocks underwent metasomatism under suprasubduction conditions during percolation of mafic melts. The aforementioned dates correspond to the time when the Early Devonian subduction-related ophiolites were formed. At the crustal level, this process was manifested in the upper part of the ophiolite section.

Some rock complexes of the southern Urals occurred in the Early Devonian directly above the subduction zone, e.g., the Polyakovka cherty–basaltic complex, lherzolite massifs, and amphibolites at the base of the Early Devonian ophiolite sections.

The Ordovician Polyakovka cherty–basaltic complex and related dikes are overlapped with stratigraphic unconformity by the Lower–Middle Devonian island-arc rocks [55]. Thus, the Polyakovka Complex occurred in the Early Devonian above the subduction zone, probably, in the accretionary wedge. The basalts of the Polyakovka Complex and associated dikes varying from picrite to trachyandesite in composition bear attributes indicating their relationship to an enriched mantle source. In REE contents and patterns they are similar to OIB. At the Llanvirnian level, the basalts correspond to N-MORB in composition [55]. At the same time, all rocks reveal Ta and Nb minimums.

The mafic–ultramafic lherzolite-type massifs are products of multiple transformation of the lithospheric material and many authors assume that the peridotites were derived from the subcontinental lithosphere [24, 42]. The accompanying serpentinite melange contains blocks of garnet ultramafic rocks and garnet amphibolite. The garnet ultramafic rocks underwent high-pressure and high-temperature metamorphism dated at 416–400 Ma [42, 58, 59, 94]. The mafic–ultramafic complexes are assumed to be fragments of the basement of the oceanic plateau. In our opinion, the metamorphism of the lherzolite massifs is related to their plunging into the Early Devonian subduction zone. The same interpretation was given in [81]. Shortly before 400 Ma ago, metamorphic and ultramafic rocks were exhumed at the crustal level. In the Early Devonian (400 Ma), the ultramafic rocks were intruded by amphibole gabbro and gabbrodiorite and cut through by dike swarms and stockworks composed of low-Ti dolerites.

Metamorphism close in parameters and age (415 Ma) developed at the base of the Khabarny Allochthon [39 and references therein]. The rocks of the metamorphic sole comprise not only orthoamphibolites and greenschists but also metasedimentary rocks, including graywacke and quartz sandstone. Metasedimentary rocks with garnet and cordierite occur as blocks in the melange of the Sakmara Zone. According to our data, the schists of the largest block near Psyanchino Village north of Mount Kuvandyk were metamorphosed 394 ± 2 Ma ago (determined with U–Pb method for rutile) [18]. The mafic–ultramafic rocks of the East Khabarny Complex were emplaced synchronously with metamorphism [45]. Analogues of this complex are widespread in the Kempirsai massif [61, 92]. As suggested from the geochemical data, the intrusions of the Ural Platinum Belt comparable with the East Khabarny Complex [44] were emplaced in the suprasubduction setting [36]. Thus, it may be supposed that both emplacement of this complex and metamorphism were confined to subduction zone. The East Khabarny intrusions that have intrusive contacts with harzburgite and metamorphic rocks mark the time of their convergence. The high-gradient inverted metamorphic zoning is referred to the effect of the East Khabarny Complex at a depth corresponding to 5–7 kbar [4]. It can be suggested that the metamorphic sole of the Kempirsai massif was formed in a geodynamic setting similar to those established for the metamorphic rocks of the Khabarny Allochthon. At the same time, only metaplutonic rocks of the ophiolite section are known in the sole of the Kempirsai massif. They reveal zoning with transition from garnet amphibolite and relics of eclogite to zoisite amphibolite and greenschists [61]. The occurrence of eclogite indicates that these rocks were exhumed from a deeper level of the subduction zone.

The Khabarny metamorphic rocks were removed above the subduction zone to the level of the sheeted dike complex and associated rocks dated at ~400 Ma. Sheeted dikes similar in composition are localized in both the upper part of the ophiolite section and the underlying amphibolite.

The available data allow us to conclude that the formation of the Early Devonian (Emsian) ophiolites was predated by subduction, concomitant metamorphism, and intrusive magmatism.

MODEL OF NONSTATIONARY SUBDUCTION IN THE PALEOZOIDES OF THE SOUTHERN URALS

The distinguishing feature of the above-described ophiolites is the occurrence of boninite-series rocks in the crustal part of the section. In the opinion of most researchers, boninites are formed in intraoceanic convergent zones [77, 79, 84, 90 and references therein]. It is assumed that the formation of boninites requires melting of repeatedly depleted refractory harzburgite at a temperature higher than 1480°C. Melting proceeds with the participation of aqueous fluid at a depth of 35–50 km. According to the publications cited in [79], such conditions are real in the suprasubduction wedge under conditions of nonstationary subduction. According to the definition given in [79], the nonstationary subduction regime is characterized by variable parameters of kinematic, seismic, and thermal processes proceeding in both plunging and overlapping lithospheric plates. The nonstationary subduction regime develops when intraoceanic tectonic elements having greater thickness and buoyancy in comparison with normal oceanic crust approach the zone of convergence. Mid-ocean ridges, aseismic ridges, oceanic plateaus, oceanic islands marking plume activity, and microcontinents are regarded as such tectonic elements.

On the basis of the aforesaid, we offer a reconstruction of the structural elements and processes responsible for the formation of the suprasubduction ophiolites in the southern Urals.

As follows from the data considered in the preceding section, the formation of the Early Devonian suprasubduction ophiolites in the southern Urals was predated in the very beginning of the Early Devonian by the development of a convergent margin characterized by HT–HP metamorphism, which, in particular, resulted in the formation of the metamorphic sole of the ophiolitic massifs.

To trace the evolution of nonstationary subduction, the history of the Paleozoides in the southern Urals should be considered from the Ordovician.

Middle and Upper Ordovician complexes formed in the island-arc and backarc settings occur in the Sakmara and Cis-Sakmara–Voznesenka zones [55, 83]. The Ordovician "normal" oceanic crust in the Kempirsai massif comprises a dike complex and Early–Middle Ordovician basalts comparable to N-MORB in composition [13, 61, 65, 88, 92]. According to our data, fragments of the Ordovician ophiolites in the Ramazanovo melange of the Sakmara Zone are composed of sheeted dike complex (Fig. 1). The associated plagiogranite dikes in two outcrops have U–Pb (SHRIMP II) zircon age of about 456 Ma (the beginning of Late Ordovician) [55 and new data]. Fragments of anomalous oceanic crust are known from the Ordovician Polyakovka Complex. Some of the volcanics pertaining to this complex, as well as the sheeted dike complex, were formed with the participation of a mantle plume. The chondrite-normalized REE patterns of these rocks correspond to MORB and OIB [55]. Fragments of microcontinent underlain by lherzolite-type subcontinental mantle occur in serpentinite melange in the northern Cis-Sakmara–Voznesenka Zone. Metavolcanic and metasedimentary rocks transformed into amphibolites make up the crust of this microcontinent.

Deepwater carbonaceous cherty slates occur in all of the above-considered zones of the southern Urals from the upper part of the Lower Silurian to the Lochkovian, inclusive.

The island-arc volcanics developed more completely in the Tagil Zone, where they comprise the stratigraphic interval from the Upper Ordovician to the Lower Devonian, inclusive [5, 10, 19, 33, 80]. The Early Devonian volcanic rocks are alkaline and subalkaline. Volcanic rocks of elevated alkalinity close in age and composition locally occur in the southern Urals as well [6, 21, 22]. As in the southern Urals, the Upper Silurian limestone was deposited in some structural units of the Tagil Zone.

It may be suggested that the Ordovician and Silurian sections of the southern Ural and Tagil Zone are fragments of a single tectonic unit subsequently displaced along a large strike-slip fault. This unit marked a convergent margin, where the Tagil arc, as well as the island-arc and backarc complexes of the southern Urals, developed above the continuous subduction zone. In the Late Silurian, when island-arc volcanism in the Tagil Zone was characterized by the formation of alkaline and subalkaline igneous rocks, the steady evolution of the subduction zone was disturbed. At that time, intraoceanic tectonic units with anomalously thick and buoyant crust (oceanic islands, microcontinents, etc.) probably approached the subduction zone. Partial consumption of these units resulted in deceleration of the subduction rate and flattening of the subduction zone. This type of subduction is designated as low-angle and warm; the subduction zone beneath Shikoku island is an example [86, 87]. It is assumed that under such conditions, the slab's rocks are transformed into zoisite eclogite via garnet amphibolite; basalt is transformed into eclogite at a shallower depth than under conditions of stationary steep and cold subduction.

The metamorphic sole of the Khabarny and Kempirsai massifs were probably formed during this rearrangement of the subduction zone, as well as mafic and ultramafic intrusions of the Platinum Belt, their counterparts in the southern Urals, and volcanics of elevated alkalinity.

Such development of the subduction zone in ophiolites of fold regions is interpreted in terms of a dying-off island arc or subduction zone [93]. The high-temperature metamorphic sole of the ophiolites in Oman (Semail Allochthon), Greece (Vourinous), and Pakistan (Muslim Bagh) are examples. It is noted that the subduction of anomalous oceanic crust can be accompanied by obduction. The tearing-off of slab and ascent of asthenospheric heat in the originated window are suggested at this stage.

The supply of additional heat is manifested in the formation of mafic and ultramafic intrusions of the Platinum Belt, East Khabarny Complex, and its analogues in the Kempirsai massif. The additional heat ensured high-temperature metamorphism in the sub-Khabarny allochthons and lherzolite massifs. By the end of the Early Devonian, the metamorphic rocks were displaced to the crust.

A new stage of subduction was related to the change of geodynamic setting determined by the active development of the Mugodzhary spreading basin in the second half of the Early Devonian. The ophiolites reflecting the evolution of this basin mostly occur in the Western Mugodzhary [20, 25, 27]. The volcanics and the rocks pertaining to the dike complex are distinguished by moderate and elevated Ti contents and are close in composition to MORB. The sheeted dikes, which are the most representative in the Shuldak River basin, are persistent in orientation and differ in this respect from those described above. The latter are characterized by variable orientation due to the nonstationary extension setting. In the Sakmara and Cis-Sakmara–Voznesenka zones, the cherty–volcanic complexes similar in age and composition are dated at the Emsian–Eifelian from conodonts and occur as narrow tectonic lenses and nappes. The crust of this basin resembles the complexes typical of the slow-spreading zones of the present-day Central Atlantic at intersections with the transform fracture zones. These are ophiolithoclastic breccia and ophicalcites widespread in the Sakmara Zone and in the south of the Cis-Sakmara–Voznesenka Zone. The chert interbeds in these sequences contain Early Devonian and early Eifelian conodonts [57].

It cannot be ruled out that the subduction zone has changed its position relative to that which existed previously. The development of the Emsian convergent margin was accompanied by suprasubduction extension, melting of harzburgite in the hanging wall, and formation of crustal complexes of suprasubduction ophiolites. The additional heat necessary for the formation of boninites at this stage was provided, in particular, by the subduction and mantle plume of the preceding stage. Various metamorphic complexes reflecting the evolution of the subduction zone during the preceding stage were localized in the suprasubduction plate.

Beginning from the late Emsian, the subduction zone developed in a relatively stationary regime. The younger Upper Tanalyk and Irendyk formations are composed of differentiated volcanic series [23].

The formation of the Early Devonian ophiolites was controlled by the nonstationary subduction regime at the intraoceanic convergent plate boundary, which existed, at least, from the Middle Ordovician.

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