The Neoproterozoic and Early Paleozoic geological history of the Ural-Kazakhstan margin of the Paleoasian Ocean using new isotopic and geochronological data obtained for the Polar Ural region

E. V. Khain[1], A. A. Fedotova[1], E. V. Bibikova[2], E. B. Salnikova[3], A. B. Kotov[3], K.-P. Burgat[4], V. P. Kovach[3], and D. N. Remizov[5]

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[1] The presence of pre-Paleozoic ophiolites in the Polar Ural region has been a matter of debate for a long time. In order to solve this problem rock samples were collected from the Enganepe Ridge and the Kharbei metamorphic rock complex to carry out their isotope and geochemical study. The U-Pb method was used to study the zircons from the plagiogranites of the ophiolite rocks from the Enganepe Ridge and from the granite and granite gneiss samples collected from the Kharbei complex. The Enganepe plagiogranite samples showed the concordant age values of 670±5 million years. The data obtained for the Kharbei metamorphosed volcanic and sedimentary rocks suggest that some of them had accumulated in pre-Vendian time (about 640 Ma) and were metamorphozed at 460±10 million years. These data suggest the same scenario for the evolution of the Paleoasian ocean, including its Ural margin, and the margins of the Paleoatlantic Ocean. *INDEX TERMS:* 1040 Geochemistry: Radiogenic isotope geochemistry; 3040 Marine Geology and Geophysics: Plate tectonics; 3042 Marine Geology and Geophysics: Ophiolites; *KEYWORDS:* ophiolite, plagiogranite, isotopic geochronological studies, Polar Ural, granite gneiss.

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Introduction

[2] One of the most characteristic features of the Polar Ural region is the wide development of ophiolites which occupy different structural positions and seem to be of different ages and origins. The problem of their age and geodynamic origin has long been a subject of hot discussion. As far back as the early sixties, views were proposed about the geosynclinal origin of the late Riphean igneous activity in this region [*Moldavantsev and Perfiliev,* 1963; *Sirin,* 1962, to name by a few]. Later, after the publication of *Ivanov* [1977], many papers were published, the authors of which advocated the platform-type rift related origin of this igneous activity. This contradiction still exists at the present time, when some authors advocate the view that the Paleoural oceanic basin began to form as late as the Ordovician time, the other group of the authors suggests the existence of some older Vendian and even Late Riphean paleooceanic rocks in the Ural region. Yet, there are no direct data on the age of these rocks in the Polar Ural area. *Dushin* [1989, 1997] classified the mafic and ultramafic rock complexes of the Polar Ural region, which occupy the lowest structural position (Kharbei and Kharamatalou) and are highly discordant with the general Ural northwestern strike, as well as the rock complexes in the west of the Sob Uplift, resting under the fauna-bearing Late Cambrian (?) and Ordovician rocks, as the elements of the Precambrian and Early Paleozoic ophiolite rock association. To solve this disputable problem we carried out a special study including the collection of samples for our isotopic-geochronological and geochemical studies at three objects of study, such as the Enganepe Ridge, the Kharbei metamorphic rock high, and the Voikar-Synya Massif (Figure 1).

[1] Geological Institute, Russian Academy of Sciences, Moscow, Russia
[2] Vernadski Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia
[3] Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg, Russia
[4] Federal Department of Geoscience and Natural Resources, Hannover, Germany
[5] Institute of Geology, Komi Research Center, Ural Division of the Russian Academy, Syktyvkar, Russia

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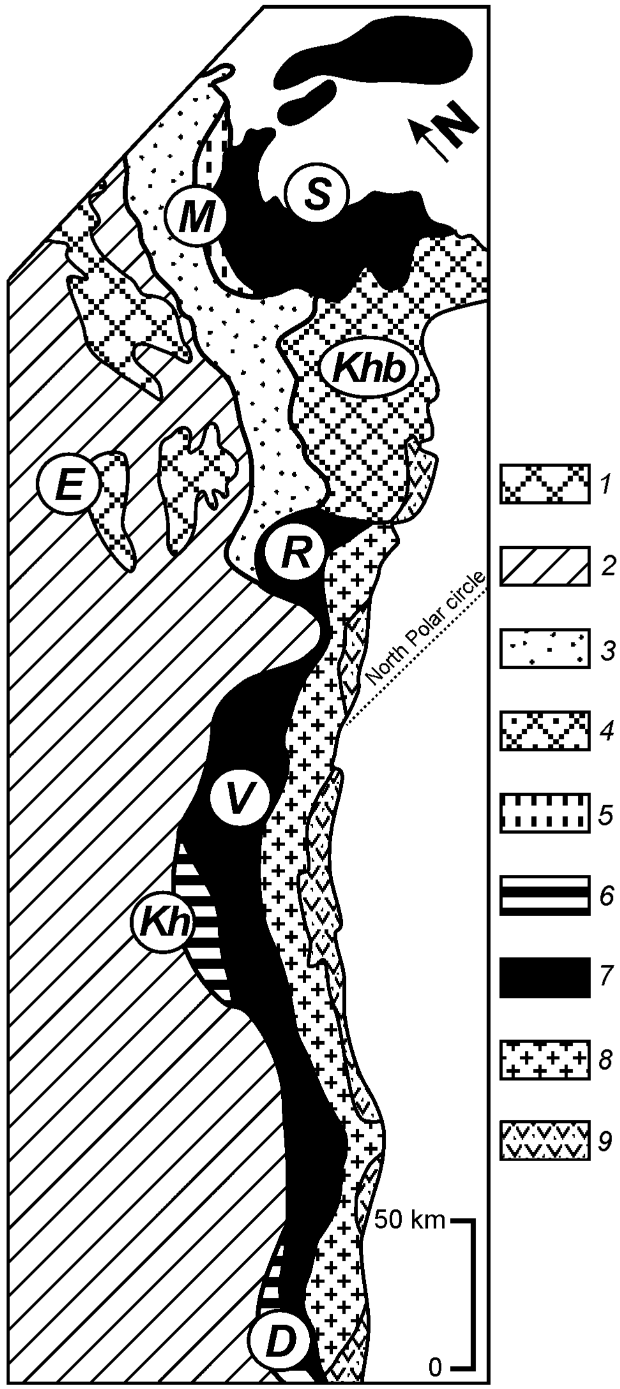

Figure 1. Schematic tectonic map of the Polar Ural region after [*Didenko et al.,* 2001] modified after [*Shishkin,* 2005]: (1) the autochthon of the Western Ural zone, composed of Riphean-Cambrian metamorphic rocks and the protoUral rocks of the East Ural zone; (2) the para-autochthon and allochthon of the West Ural Zone, composed of Paleozoic stratified rocks; (3–4) the Central Ural Zone: (3) the Orang subzone, composed of Paleozoic and Late Paleozoic stratified rocks; (4) the Kharbei subzone, preordovician rocks including Late Paleozoic stratified rocks; (5–9) the East Ural Zone: (5) the Marunkeu subzone, high-pressure metamorphic rocks; (6) the Khord-Yus-Delayus subzone composed mostly of metamorphic mafic rocks, (7) the Syumkeu-Payera (VoikarRai-Iz) subzone of the mafic-ultramafic rock belt; (8–9) the Minor-Ural subzone of Devonian and Carboniferous granites (8)and the volcanic rocks (9) associated with them. The protoUral rocks occur as the Enganepe (E) and Kharbei (Khb) complexes; the metabasic rocks have been classified as the Marunkeu (M), Khord-Yus (Kh), and Dzelayu (D) complexes; the mafic-ultramafic rocks have been classified as the massifs of the mafic-ultramafic rock belt known as the Syumkeu (S), Rai-Iz (R), and Voikar-Synya massifs.

Enganepe Ridge

[3] This ridge (Figure 2) is a unique geologic object for the Polar Ural region, where the erosion window shows the highly dislocated flyschoid volcanic sediments and rocks including fragments of ophiolitic rocks. The contact shows an abrupt structural and metamorphic unconformity. The conglomerates of the Cambrian-Ordovician basement contain pebbles of serpentinite and volcanic rocks. The pre-Paleozoic structure of the Enganepe Ridge shows several tectonic sheets inclined WSW and broken by subvertical faults of a northwest strike. Most of the outcrops of the ophiolite rocks are restricted to the Manyukyus tectonic zone in the northern segment of the Enganepe Ridge (Figure 2). This zone intersects at a low angle almost the whole of the exposed part of the Sob Uplift from the western side of the Enganepe Ridge to the middle coarse of the Sob River in the southeast extending in the NW direction for more than 70 km. Over its entire length it includes lenticular bodies of metaultramafic rocks (Enganepe Complex) ranging from a few dozens to hundreds of meters and to a few kilometers along their long axes.

[4] One of the largest bodies in the northern part of the Enganepe Ridge is the outcrop of serpentinite melange (see Figures 2 and 3), which is exposed in the thalweg of the Yanas-Keu-Lek-Talba Creek flowing to the Bolshaya Usa River from the right. The width of the outcrop is about 300 m; some outcrops were traced as far as 5 km along the strike (Figure 2). The matrix of the serpentinite melange is composed of highly tectonized chrysotile-lizardite serpentinite. The blocks in the melange range from a few decimeters to 50 m (Figure 3). The left side of the Yanas-Keu-Lek-Talba Creek shows several large blocks. One of them is composed of ophicalcite, a carbonatized product of the weathering of the ultramafic rocks in underwater conditions. The ophicalcite includes fragments of carbonatized dunite and harzburgite; its weathered surface often shows fragments of metamorphic structures which preserve the deformations of the rocks of the dunite-harzburgite complex (lineation and striation). Some blocks in the melange were found to be composed of gabbroids. At a distance of 250 m from the ophicalcite outcrop, the opposite bank of the creek includes a large block showing a gradual transition from the gabbro-amphibolite to plagiogranite via amphibolized quartz diorite. This block shows intersecting brecciated diabase dikes (sills) as wide as 1.5–2 m (Figure 3b). A large plagiogranite Sample (no. 2114) was collected for a complex isotopic-geochronological study.

[5] The gabbro amphibolite and quartz diorite are composed of elongated prismatic crystals of bluish green amphibole and of tabular plagioclase crystals wholly replaced by saussurite or by an aggregate of epidote, zoisite, sericite, and quartz grains. The quartz diorite contains large granulated quartz grains with amphibole accounting for 30% of the rock volume. These rocks have a relict subhedral structure. The schistosity planes are marked by the aggregates of secondary chlorite and quartz grains. The main minerals of the plagiogranites are quartz and plagioclase, the latter being slightly altered or wholly replaced by epidote, chlorite, and sericite. The accessory minerals are sphene, zircon, and apatite.

[6] The zircon of Sample 2114 is represented by the perfect crystals showing predominantly hyacinth habitus. The crystals are translucent and slightly brownish. Many grains are highly fractured. The morphology of the zircons suggests their magmatic origin. The U-Pb isotope study of the accessory zircons from the rocks of the Polar Ural region was carried out using the Krogh method [*Krogh,* 1973] and the zircon microspecimens. The uranium and lead concentrations were determined using a mixed $^{235}U+^{208}Pb$ tracer. The isotope composition was measured using a TSN-206A solid-phase mass spectrometer of the Cameca production. The resulting ages were corrected for the common lead admixture using the model reported by *Stacey and Kramers* [1975]. The ages were calculated using the PBDAT program [*Ludwig,* 1991] and the commonly used uranium decay constants. The results are presented here in Table 1.

[7] The results of our U-Pb study, presented in Table 1, prove the low content of uranium, which agrees with the rock genesis. Concordant age values were obtained for two large zircon fractions within the error range (Figure 4). The small-size zircon fraction showed some loss of radiogenic lead, yet, the age derived using the $^{207}Pb/^{206}Pb$ ratio coincided with the concordant age values obtained for the other fractions. As a result of our study, the zircon from the plagiogranite was dated 670$\pm$5 million years. The same sample was examined using the Sm/Nd method for the rock as a whole. For the age of 670 Ma the $\varepsilon_{\rm Nd}$ characteristic was found to be +1.7, the model age of the sample being 1.6 Ga (Table 2). The trace-element spectrum of this sample, measured using the method of isotope dilution, also proved that the study rock block belongs to some ophiolitic suite (Table 3).

[8] The mapping of the area including serpentinite melange, carried out by [*Dushin et al.,* 1997] proved that the melange blocks resided in the field of some sedimentary rock sequence consisting of highly schistose sandstone and siltstone with gradation layering, including numerous blocks of serpentinite, tectonized volcanomictic sandstone, and conglomerates. This creates the impression that we deal with a relatively deep-sea rock sequence including olistostrome horizons, as well as the melanged rock blocks of some disintegrated ophiolite rock complex, occurring as olistoliths and tectonic lenses.

[9] In the west of this region the sedimentary rock sequence borders, along a steep tectonic contact, the undifferentiated sequence of tholeiite basalts (Figure 2). A tectonic sheet, composed of volcanogenic sedimentary rocks, is thrust over the sedimentary rocks. Mapped at the base of this sheet are aphyric basalts, altered to green schists, and overlain by a layer of pillow lava injected by diabase dikes. The width of the exposed volcanic rocks is about 800 m. Above follows a cherty volcanic rock unit (200 m thick) composed of the interbedded layers of aphyric and occasional porphyritic basalts and dark grey cherts and siltstones. Associated with the cherts are aphyric rocks with ovoidal parting and variolite layers. Boninites were reported from the volcanic rocks of this sheet [*Dushin,* 1989].

[10] To sum up, the Enganepe Ridge includes a series of tectonic sheets which were superposed in pre-Late Cambrian

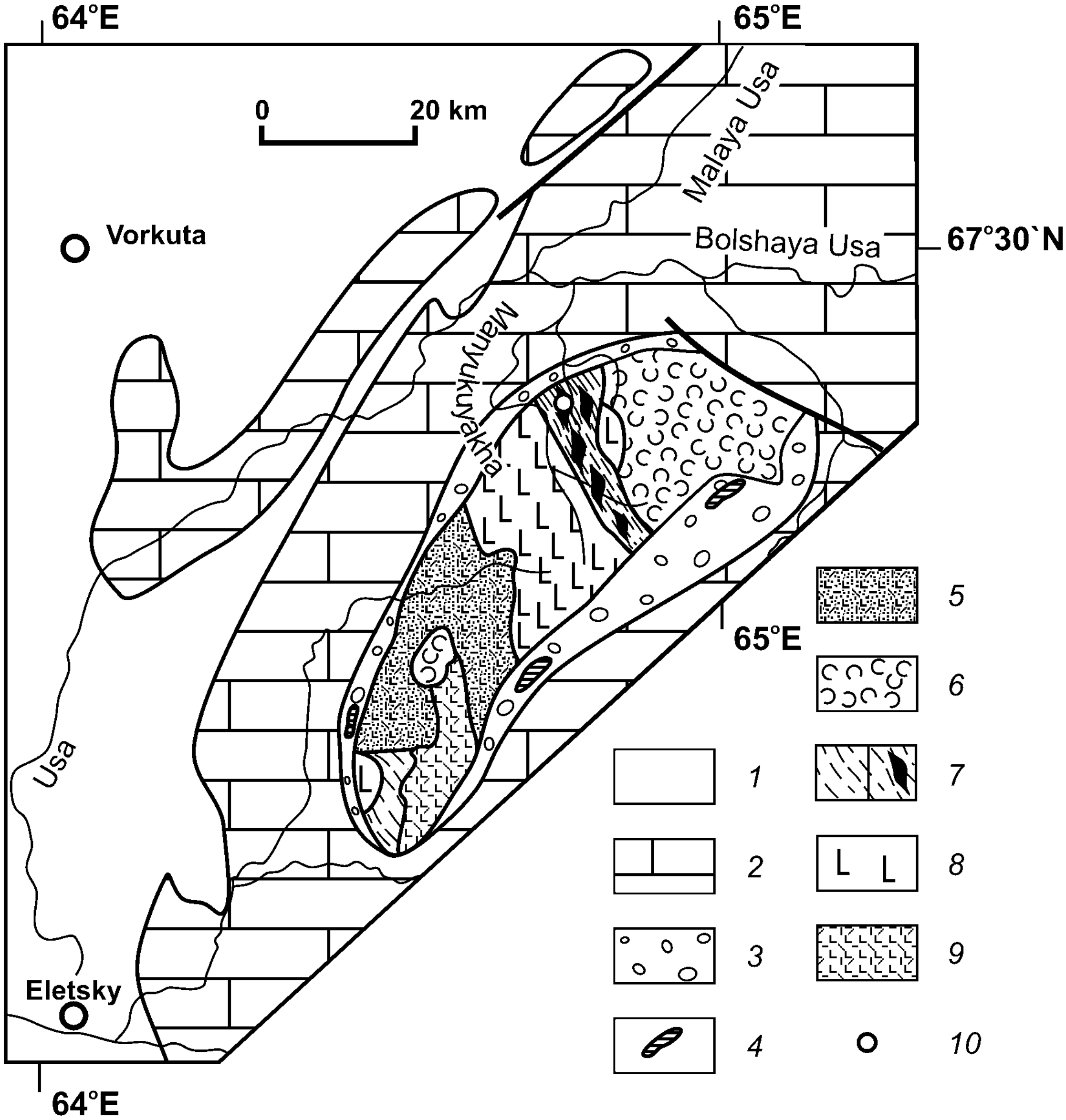

Figure 2. Schematic map of the Enganepe Range structure: (1) undifferentiated Permian rocks; (2) undifferentiated Ordovician-Cambrian terrigenous-carbonate rocks; (3)$\in_3$(?) to O_1 sandstones and conglomerates; (4) alkaline volcanic rocks; (5–9) pre-Ordovician rocks: (5) tuffaceous sedimentary rocks, (6) basalt and rhyolite, (7) a schists-olistostrome sequence with tectonic sheets and olistoliths, (8) undifferentiated tholeiitic basalt sequence, (9) a basalt-andesite-dacite complex, and (10) the position of the serpentinite melange area which was examined in detail in this study.

time. These sheets include the fragments derived from volcanic arcs and their slopes, as well as the fragments of the crust of the adjacent basins. In some places the floors of these basins were composed of ultramafic rocks which were subjected to underwater weathering. The isotopic geochronological data obtained in this study suggest that all of these structural features might have existed at the end of the late Riphean (Neoproterozoic).

Kharbei Block

[11] Similar data were obtained in our study for the Kharbei metamorphic rock complex. The ultramafic rocks and gabbroids, developed in this block, are localized in the deposits of the Nyarovei, Nemyuryugan, and partly Khanmenkhoi formations, where most of them are localized

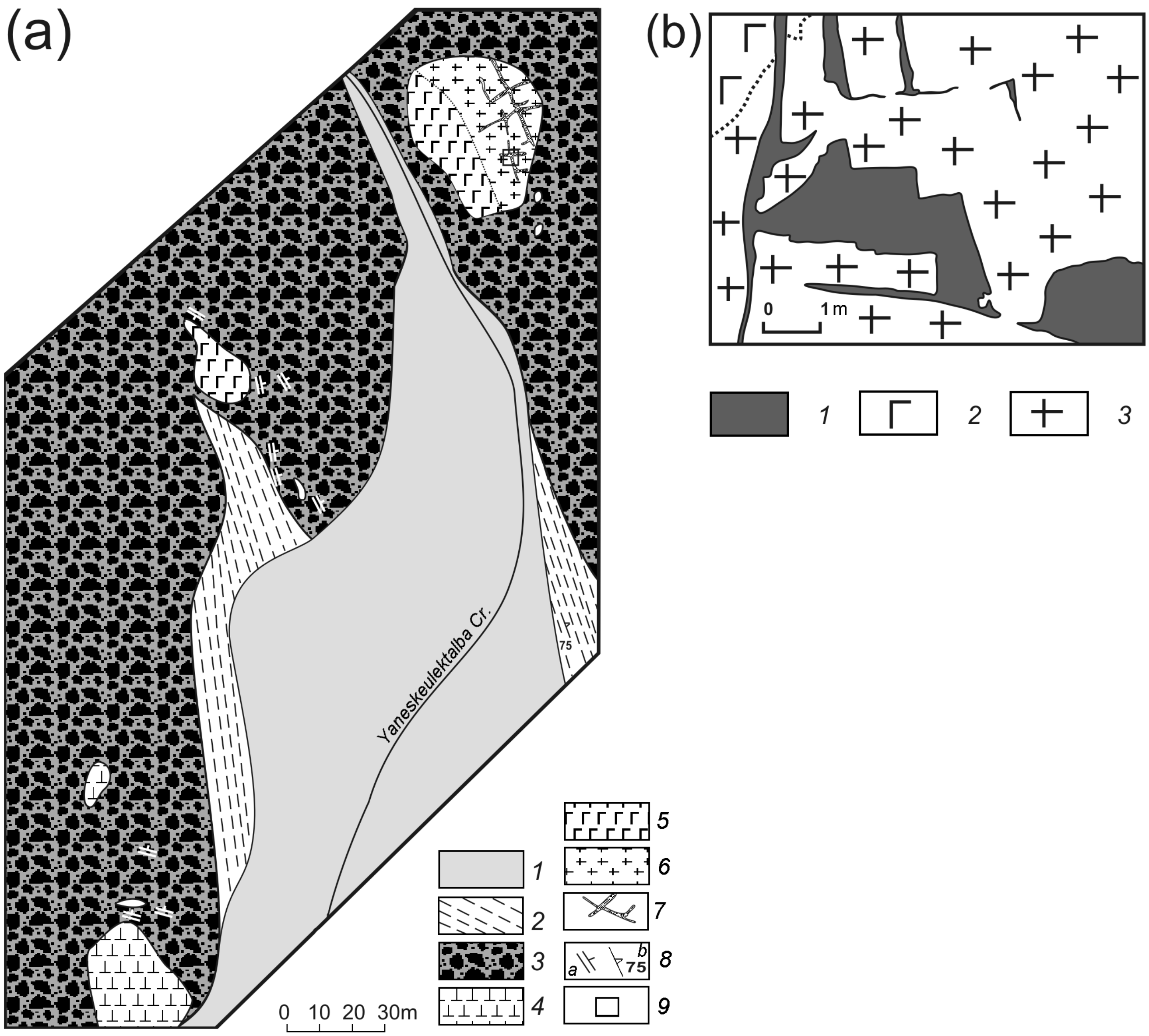

Figure 3. (a) The structure of the serpentinite melange area in the thalweg of the Yanas-Keu-Lek-Talba Creek: (1) alluvial deposits; (2) schistose siltstone and sandstone; (3) serpentinite melange; (4) ophycalcite; (5) gabbro, gabbro amphibolite; (6) quartz diorite and plagiogranite; (7) stepwise intersecting diabase dikes (sills); (8) dips and strikes: schistosity in the serpentinized melange (a) and in the sedimentary rocks (b); (9) the position of the area shown in Figure 3b. (b) A segment of the melange block composed of gabbro-amphibolite grading via amphibolized quartz diorite to plagiogranite, one can see the intersections of thin diabase dikes and sills: (1) diabase, (2) gabbro and gabbro amphibolite, (3) amphibolized quartz diorite and plagiogranite.

in the northern part of this structural feature, mostly in the large fault sutures (Figure 5).

[12] The Khanmenkhoi Formation is represented there as a monotonous sequence of alternating albite amphibolite, chlorite-micaceous, biotite, and amphibole-micaceous schists, and paragneiss. Three tectonic sheets were mapped in the rocks of the Nyarovei and Nemyuryugan formations. The lower sheet is composed of volcanic and terrigenous, often poorly sorted, rocks. The volcanic rocks were identified by their petrochemical characteristics as metamorphosed high-Ti basalts [*Dushin,* 1987]. The upper tectonic sheet is composed mostly of metamorphic flyschoid terrigenous rocks.

[13] Of particular interest are the rocks of the intermediate sheet including the largest number of ultramafic rock and gabbroid bodies. The basis of this sheet is composed of metamorphic carbonaceous-siliceous schists sequence, saturated with tholeiitic metabasalt dikes and sills. The up-

Table 1. U-Pb isotope ages of the zircons from the Polar Ural rocks

Grain size, μm	Sample weight, mg	Concentration, ppm		Pb isotope composition			Atomic ratios and ages, Ma		
		U	Pb	$^{206}Pb/^{204}PB$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{206}Pb$	207Pb/^{235}U	$^{206}Pb/^{238}U$
Plagiogranite of Sample 2114									
+90	2.1	176.9	23.31	425	10.427	4.344	674.0±37	0.9528 679.6	0.1114 681.3±4.0
−90+60	1.0	287.6	31.51	2900	15.024	9.009	661.5±6	0.9321 669	0.1097 670±3.5
−60	1.6	137.0	14.58	1800	14.329	8.745	668±9	0.9003 652	0.1056 647±3.2
Gneisse of Sampe 2127									
+10	2.7	233.6	20.36	1000	13.984	4.147	492.8±17	0.6006 477.6	0.0764 474.5
−100+90	2.7	254.8	24.43	311	9.480	3.235	475.5±61	0.580 464.7	0.0744 462.6
−90+75	2.4	343.1	28.34	2315	15.470	4.807	545.7±12	0.6072 481.8	0.0754 468.5
−75+60	3.0	494.4	43.52	950	13.407	4.515	581.6±17	0.636 500	0.0776 482.1
Gneisse of Sampe 2128									
Gneiss mixture	1.4	305.7	36.13	650.6	12.189	2.809	597.9±25	0.7739 582	0.0938 577.9
+45	1.1	389.1	39.6	2300	15.283	3.931	573.8±7.5	0.7336 558.6	0.0899 554.9
−45	2.4	406.0	41.43	1000	15.637	3.666	562.9±17	0.705 541.8	0.0868 536.7

Note: The error of $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ is 0.5%.

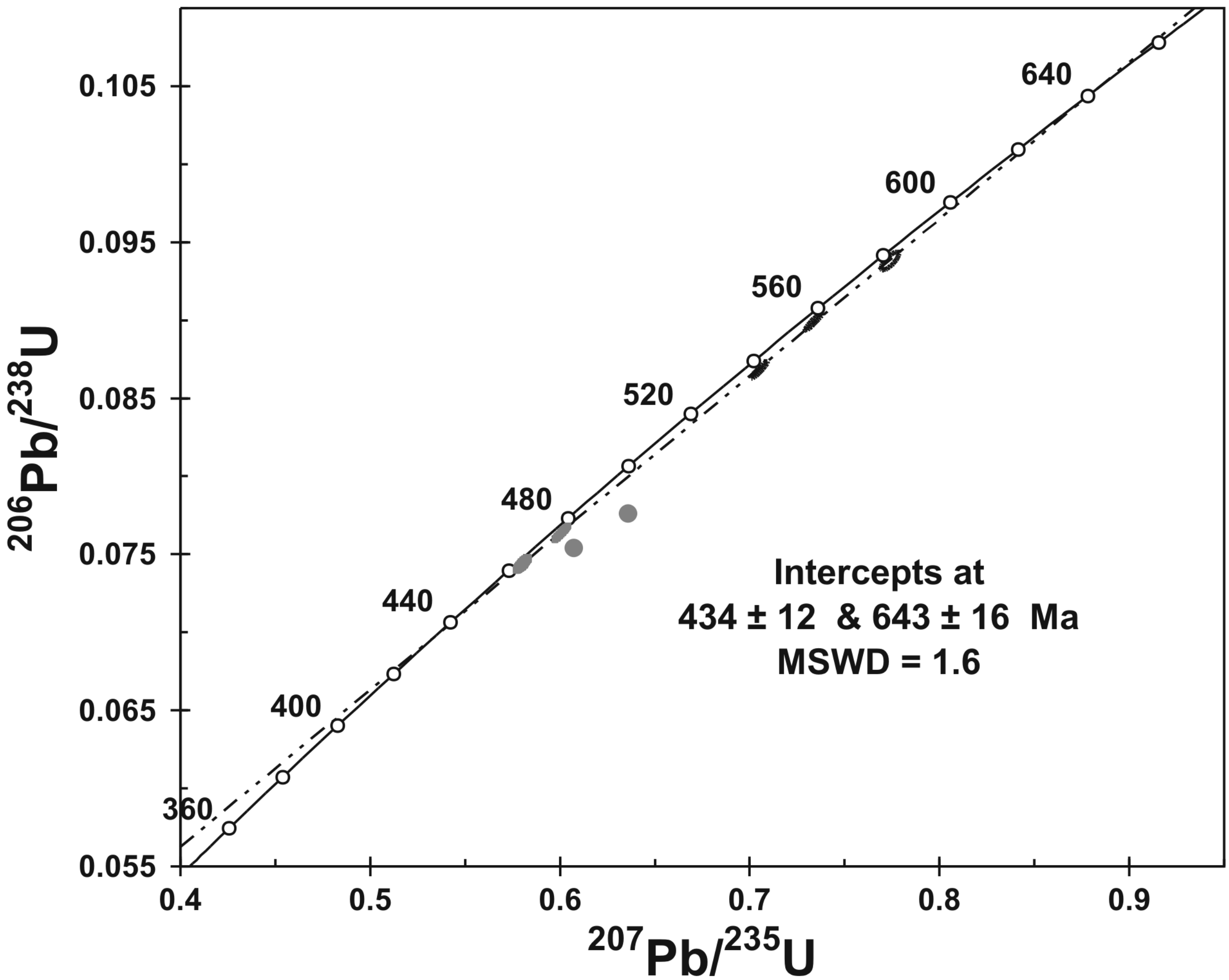

Figure 4. A diagram with a concordia for the isotope composition of the zircons collected from the gneiss (Sample 2127, grey ellipses) and gneissic granite (Sample 2128, black ellipses), collected from the Kharbei metamorphic rock complex.

per part of this sheet is composed of a metamorphosed volcanogenic sedimentary rock sequence represented by chlorite schists, epidote-chlorite schists, chlorite-magnetite schists, and amphibole schists, alternating with metasiltstones and metapelites. This rock sequence seems to be composed of metamorphosed volcanogenic sedimentary rock complex with lavas, tephraturbidites, volcanomictic sandstones, and shales. Our study revealed that the bodies of the ultramafic rocks and gabbroids were restricted to the area composed by the sedimentary rocks of this rock sequence, or occupy a position as a chains of outcrops at the contacts of the rock members with different types of the rock sequences.

[14] In the area of the upper reaches of the Mollybdenite Creek, the left tributary of the Bolshoi Kharbei River, a

Table 2. Sm-Nd isotope data for the plagiogranites of the Enganepe Ridge and for the gneisses and gneissic granites of the Kharbei Block

Sample	Sm	Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	$\varepsilon_{\mathrm{Nd}}$ (670 Ma)	T_{DM}, Ga
plagiogranite of Sample 2114	0.941	3.68	0.1547	0.512540±7	+1.7	1.57
gneisse of Sample 2127	2.27	11.2	0.1220	0.512391±8		1.26
granite gneiss of Sample 2128	8.71	39.8	0.1322	0.512523±6		1.17

Note. The average ^{143}ND/^{144}Nd value of 0.511840±15 ($t_{\mathrm{N}-1} \times \sigma_{\mathrm{av}}$. N=25) was obtained from measuring the La Jolla standard. The concentrations are given in $\pm\mu$g g^{-1}, the accuracy was ±1% (rel) The accuracy of measuring the ^{143}Sm/^{144}Nd ratios was ±2% (rel).

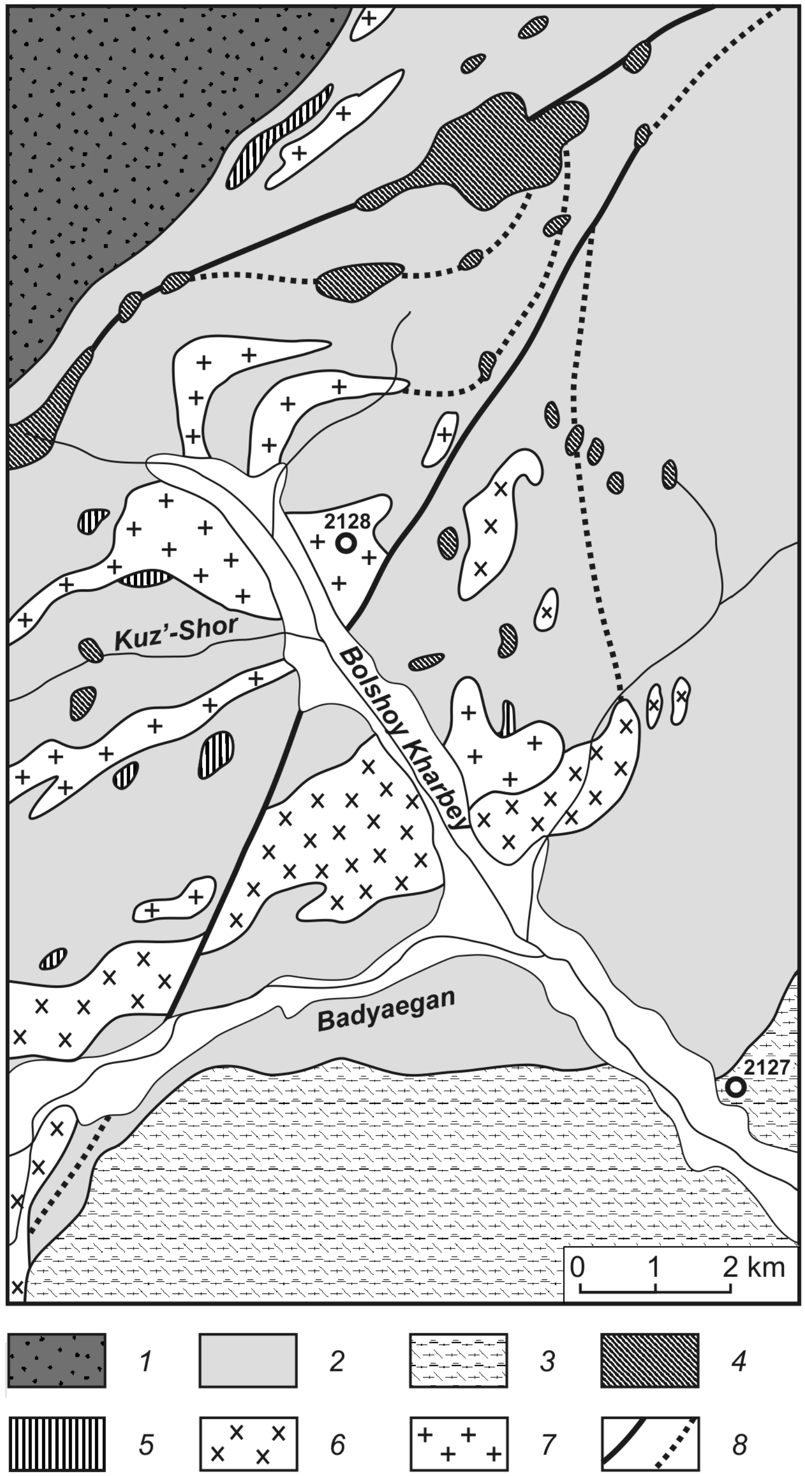

Figure 5. The structure of the northern part of the Kharbei Block and the positions of the sites where Samples 2127 and 2128 were collected for the isotopic and geochronology geochemical studies. (1) the Orang zone, Ordovocoan sedimentary rocks, (2–7) the Kharbei Block complexes: (2) schists and amphibolite, (3) gneiss and amphibolite, (4) ultramafic rocks, (5) gabbroids, (6) diorite, (7) granite, (8) faults and proposed faults.

fragment of an ophiolite allochthon composed of dunite at the base, which is followed by a layred dunite-wehrlite-clinopyroxenite complex with taxite gabbroids at the top was mapped by [*Dushin,* 1987]. The base of the allochthon is granitized. Its contact shows metasomatically altered ultramafic rocks. The average composition of the antigoritized ultramafic rocks agrees with that of harzburgite. The structural position of this allochthone is not quite clear, except for the fact that it is thrust over the schistsose metamorphic sandstone and siltstone.

[15] In the area of the Kuz-Shor Creek, which is the right tributary of the Bolshoi Kharbei River, the structural position of the ultramafic and gabbroid rocks was found to be more obvious. The ultramafic rocks and gabbroids occur as olistoliths in the olistostrome units inside the sedimentary rocks of the volcanic-sedimentary sheet. They also occur as tectonic lenses at the contacts of the sedimentary and volcanic rock members, see Figure 5. An outcrop at a distance of 3 km from the Kuz-Shor Creek shows an olistostrome sequence with a schistose and metamorphic sedimentary and volcanic matrix and elongated rounded olistoliths, completely enclosed in the matrix. The talc-bearing serpentinized ultramafic rocks, including antigorite serpentinite, compose olistoliths, 0.5 m to 5 m in size, the maximum thickness of the gabbroids being 3 m. The lenticular serpentinite bodies, often composed of smaller block accumulations with foliated serpentinite at the contacts, extend over hundreds of meters.

[16] For the purpose of dating the volcanogenic sedimentary rocks and their metamorphism large samples were collected from the paragneisses of the highest-grade metamorphic rocks of the Khanmenkhoi Formation and also from the metamorphic and, hence, gneissic quartz diorite localized in the intermediate sheet composed of volcanic and sedimentary rocks. These diorites were expected to mark the youngest age of the volcanic and sedimentary rock sequence.

[17] The zircons from Sample 2127 of the Khanmenkhoi Formation rocks were represented by prismatic to isometric crystals with a corroded surface. Some of the grains were found to be perfectly shaped, translucent, and brownish in color. The translucent and well-shaped grains, supposed to be of magmatic origin, were selected for the analysis.

[18] The zircons from Sample 2128 had a small size (below 60 μm), a prismatic form with the well developed prism faces, and almost colorless, possibly being of magmatic origin.

[19] The ages obtained for the zircons of both samples are highly discordant (Table 1). It appears that the gneiss of Sample 2127 represents some metasedimentary rock. Proceeding from the metamorphic origin of the zircons from Sample 2127, all zircons contain an admixture of some older radiogenic lead, this precluding the exact dating of the metamorphism. The diagram with a concordia (Figure 4) shows that data points of zircons from sample 2128 (black ellipses) define a regression line with concordia intercepts about 640 and 435 Ma with large error, which may corresponds with ages of zircon crystallisation and their metamorphic transformation. The regression line for data points of zircons from from sample 2128 and for two less discordant data points of zircons from sample 2127 (grey ellipses) define a regression line (MSWD=1.6) with concordia intercepts at 643±16 Ma and 434±12 Ma. These data suggest that the gneiss of Sample 2128 represents some orthorock with an age of about 640 Ma, which experienced metamorphism in Late Ordovician-Early Silurian.

Table 3. The REE contents in the Enganepe plagiogranites obtained using the method of isotope dilution at the IDEM Laboratory of isotope geology, analyst D. Z. Zhuravlev

Sample	La	Ce	Nd	Sm	Eu	Gd	Dy	Er	Yb
Plagiogranite	3.29	7.54	3.91	1.01	0.34	1.16	1.34	0.90	0.99

[20] To conclude, the metamorphism of these two rock samples can be dated 434±12 million years.

[21] The isotopic-geochronologic data obtained in this study suggest that the metamorphic volcanogenic sedimentary rocks of the Kharbei Complex originated in pre-Vendian time. The fragments of the rocks of ophiolite origin occur as olistoliths inside the olistostrome units and seem to be even older. The rocks of the Kharbei Complex were transformed to metamorphic rocks in Late Ordovician-Early Silurian.

Voikar-Synya Massif

[22] The world-largest mafic-ultramafic belt of the Polar and Sub-Polar Ural region, as long as 400 km, includes the Voikar-Synya, Rai-Iz, and Syumkeu massifs (Figure 1). In the west, this belt borders the allochthonous rock complexes of the West Ural Zone, composed of the sedimentary and volcanogenic sedimentary rocks of Paleozoic age, and the chain of the Dzelayu, Khord-Yus, and Marunkeu metamorphic blocks (Figure 1), which are interpreted by some authors as an independent zone, or as the lower sheet of a mafic-ultramafic allochthon by the others. These blocks of metamorphic rocks include mafic-ultramafic rock bodies of different sizes and different metamorphic grades. The most reliable geochronological data are available for the Dzelayu rock complex: U-Th-Pb method of single zircon grain analysis, showed the crystallization of the Dzelayu gabbroids was 578±9 million years [*Remizov and Pease,* 2005]. Along the eastern contact of the Voikar-Synya and Rai-Iz massifs a granitoid belt extends, the two different phases of which were dated Devonian and Carboniferous [*Andreichev,* 2004].

[23] The rock massifs of the mafic-ultramafic belt were characterized by Sm-Nd and Ar-Ar isotopic geochronological data, which placed the rocks into a large Ordovician to Devonian age range. Sm-Nd study of the whole-rock samples of the Voikar-Synya Massif yielded an age of 387±34 million years [*Sharma et al.,* 1995]. In terms of the dating method used, this value seems to be doubtful, because it was made using the samples collected from different parts of the ophiolite complex. The study of the gabbroids and diabase of the Syumkeu Massif using the Ar-Ar method yielded the data corresponding to a large time interval, namely from 491 Ma to 419 Ma. In the case of the gabbroids and dikes of the Voikar-Synya Massif the resulting ages varied from 497 Ma

to 426 Ma [*Kurenkov et al.,* 2002]. In our study we dated the rocks of the dikes from the Voikar-Synya Massif, using their geological and isotopic-geochemical studies for the purpose of dating the ophiolite rock association of the Voikar-Synya Massif.

[24] Developed in the study area are three voluminous rock complexes. In the NW-SE direction these rocks are (1) the dunite-harzburgite complex of mantle tectonites, (2) dunite-pyroxenite-gabbro, and (3) the intrusive gabbro complex. Found in subordinate volumes was the diabase of the parallel dikes, which had been undoubtedly associated with the origin of the ophiolite gabbroids.

[25] The rocks of the dunite-harzburgite complex (1) composing the water-shed area of the Polar Ural segment were studied in detail and described in the literature [*Bogdanov,* 1978; *Savelieva,* 1987; *Sobolev and Dobretsov,* 1977, to name by a few]. As a result of our study we obtained new information about the structure of the second and third rock complexes mentioned above and their relationships. Proceeding from their relationships, we identified a complex of intrusive gabbroids, differing from the complex that had been identified earlier in terms of its volume and rock types.

[26] The ophiolite complex of mafic-ultramafic rocks (2) includes dunite, pyroxene-bearing dunite, the layered sequence of rocks ranging from verlite to leucocratic gabbroid, as well as the isotropic gabbro and gabbro-diabase complex of parallel dikes. The dunite was found to be associated with massive coarse-grained pyroxenite via gradual transitions. Another characteristic feature of these rocks is the banded alternation and the reticular and spotty relationships between the dunite and massive pyroxenite bodies. These rocks also compose bodies as large as a few kilometers, located mostly in the watershed area of the Lagortayu and Trubayu rivers. The rock bodies of this type are believed to be characteristic of mantle-crust transition zones or are interpreted as the upper parts of the mantle rock complexes in the well-known ophiolite rock sequences. The layered rock complex includes the rhythmically alternating sequence of wehrlite, pyroxenite, and gabbroid bands, ranging from their melanocratic to leucocratic varieties. These bands, ranging from a few millimeters to some decimeters, usually measuring 1–1.5 cm in width, seem to be of the primary, magmatic origin, yet, the orientation of the mineral grains suggests that these rocks experienced some metamorphic transformation which was responsible for the folds deforming their primary banding. The layered wehrlite-pyroxenite-gabbro sequence, and also the isotropic gabbro associated with the diabase, are known to be typical of the ophiolite association, which is confirmed by geochemical data [*Bogdanov,* 1978; *Kurenkov et al.,* 2002].

[27] Exposed in the Right Payera River basin is a zone of massive gabbro to diabase transition, the structure of which proves that these rocks belong to the same rock complex. This zone is composed of numerous gabbroid screens localized between diabase body packets and individual diabase bodies, some of them showing a stepwise configuration. A specific feature of this zone is the presence of small gabbro-pegmatite bodies, devoid of any chill zones, which cut across both the older gabbro and diabase bodies. The diabase and gabbroids of the transition zone are cut by a series of leucocratic rock veins, composed of felsite, plagioclase rocks, amphibole-plagioclase pegmatoid rocks, and plagiogranite, which include igneous rock breccias with gabbro and diabase fragments. The rocks developed in the direction toward the contact with the ultramafic rocks along the Right Payera River are gabbroids and the less developed rocks of the wehrlite-pyroxenite-gabbro association, which show distinct doubling marked by a serpentinite zone. The rocks of a parallel double complex are also developed in the area of the Lagortayu R. Canyon. The specific feature of this rock sequence is the wide development of serpentinized ultramafic rocks in the form of screens in the dike complex.

[28] The rocks of the reconstructed dunite-pyroxenite-gabbro association (Complex 2) occur as a large geologic body of complex structure and configuration. Its largest outcrop, not less than four kilometers wide, was found at the latitude of the Right Payera River.

[29] The rocks of this association (2) contact mantle tectonites (1) in the west and large intrusive gabbroid bodies (3) in the east, some small gabbroid bodies being also restricted to the planes of tectonic displacement in the area underlain by the rocks of Complex 2. Their relations with the rocks of Complex 3 control the complex configuration of the geological body composed of the rocks of the dunite-pyroxenite-gabbro complex.

[30] The intrusive bodies of the gabbro norite and olivine gabbroids (3) occupy the significant volume of the Voikar-Synya mafic-ultramafic rock complex. The large bodies of these rocks, being tens of kilometers long, are expressed very well in the topography of the eastern slope of the Polar Ural Ridge and compose an isolated mountain ridge between the water-divide area of the Polar Ural Mountain Range and its eastern piedmont. These bodies extend in the north-eastern direction along the strikes of most of the contacts, along the boundaries of the mantle ultramafic rock bodies, and along the contacts inside the dunite-pyroxenite-gabbro complex. We studied one of the largest gabbro-norite and olivine gabbroid bodies which occupies the significant part of the watershed area of the Lagortayu and Trubayu rivers, and also some smaller bodies in this area. We discovered some relatively smaller intrusions of the same complex in the upper reaches of the Right Payera River.

[31] The body of the gabbro-norite and olivine gabbroid, located in the water-shed area of the Lagortayu and Trubayu rivers was found to be about 4 km wide and more than 10 km long. In the northwest this body borders banded gabbroid and pyroxene-bearing dunite. In terms of their grain size the rocks were found to vary gradually from their coarse-grained varieties (Norite Creek area) to medium-grained varieties in the left bank of the Lagortayu River between the Norite Creek and the next large tributary of this river in its upper course. Discovered in the area west of this tributary was a chill zone in the gabbro-norite massif. Associated with the exocontact zone of the gabbro-norite massif are pegmatoid rock bodies. The pegmatite located in the vicinity of the exocontact zone of the gabbro-norite massif was found to contain amphibole crystals as large as 0.5 in size. At a distance of a few hundred meters from the contact zone the banded pyroxenite and gabbroid were found to include a body of pegmatoid gabbro norite and pyroxenite with crys-

tals 1–2 cm in size, some of them being as large as 10–15 cm. At a distance of about 5 km along the strike of the exocontact zone, the left side of the Trubayu River valley includes another outcropping body of characteristic gabbro norite. The southeastern contact of this body is exposed in the right side of the Trubayu River valley, where the gabbroids contact a large lenticular dunite body, 0.5×5 km in size, elongated along the general strike of the contacts. Here, the endocontact zone of the massif is composed of gabbro and pegmatite with oriented pyroxene and plagioclase crystals amounting to a few centimeters in length.

[32] The area of the Right Payera River does not expose any intrusive gabbro-norite bodies of Complex 3. This seems to have been responsible for the good preservation of the rock sequence enclosing the mafic rocks the ophiolite complex. This explains its classification as the Payera Sheet [*Saveliev and Savelieva,* 1977]. However, in the course of studying the banded rocks of the ophiolite association in the vicinity of the surface of their tectonic doubling we discovered a series of gabbro-norite and websterite veins (3) with distinct chill zones, bordering the layered gabbroids (2) and the rocks of a dunite-harzburgite complex (1). The rocks enclosing them contain large pyroxene and plagioclase crystals which seen to have been impregnated during the intrusions of new mafic magma portions into the ophiolites along some weak zones.

[33] To sum up, the new data available for the geologic structure of the Voikar-Synya rock complex confirm the previously offered view about the presence of two ophiolite and intrusive rock associations in it. However, its intrusive rock association is reported here to have a new volume and a new rock composition. Proceeding from our new data, we conclude that the wide development of intrusive gabbro bodies seems to explain some specific features of the Voikar-Synya ophiolite association, such the absence of an effusive-sedimentary rock sequence and the subordinate development of diabase complexes. It can be assumed that the rocks of the upper part of the ophiolite sequence were intruded by new magma portions from some intermediate-depth magma chambers, which were responsible for the formation of gabbro-norite and olivine gabbroids massifs existing in the present-day structure. It is possible that these rocks can be found as skialiths or xenoliths in these rock massifs in the course of their more detailed study.

[34] At the present time a special study is carried out to examine the compositions of the rocks and minerals, as well as of the distribution of trace and rare earth elements in them to verify the above conclusions which were base thus far mainly on the geological data available.

[35] In terms of our geochronological study a particular attention was given to studying the series of the parallel dyke complex (2) in the vicinity of its contact with the gabbroids of the same complex, where the plagiogranite bodies of the ophiolite association could be expected. In the rocks exposed by the Lagortayu River, plagiogranites were found at two sites: in the gabbroids residing at a distance of several tens of meters west of the contact with the dike complex and also among the parallel dikes at a distance of 1.5 km this contact (Site 2570).

[36] A plagiogranite sample was collected at this site from a vein 20 cm wide, which intersected the early generations of diabase and plagioclase porphyries of the parallel dike series, and was intruded by mafic dikes of the later generation (Figure 2). Thus, the plagiogranite had been sealed up inside the dike complex, this allowing one to date the upper age boundary of the ophiolite formation.

[37] The accessory zircon derived from the plagiogranite (Sample 2570) was found to be represented by subidiomorphic nontransparent colorless semimetamictic crystals with intensively corroded surfaces. Some grains showed metamictic cores of irregular form. Accounting for not more than 20% of the total sample volume were idiomorphic and subidiomorphic, translucent colorless or light yellow crystals of prismatic or short-prismatic form of zircon habit, which were used for dating the rocks. Some grains showed slightly corroded surfaces. Characteristic of the internal structure of the zircon crystals was the presence of "fine" magmatic zones and sectors, also of solid-phase mineral inclusions. The crystal size varies from 50 μm to 250 μm, the elongation of the crystals ranging from 1.6 to 2.0.

[38] The U-Pb isotope studies were carried out using three zircon samples collected from the size fractions ranging from $-100+60$ μm to >60 μm. The zircons larger than 60 μm were subject to preliminary air abrasion [*Krogh,* 1982]. As follows from Table 1 and Figure 4, the zircon used in this study showed insignificant discordance, its data points producing a discordia, whose intersection with the concordia corresponded to the age of 489±20 million years, the lower intersection being almost zero (MSWD=0.4). The average age value calculated using the $^{207}Pb/^{206}Pb$ ratio for the three fractions of the examined zircon was found to be 490±7 million years (MSWD=0.21) and coincided with the age obtained using the upper intersection of the discordia. Taking into account the fact that the morphologic features of the studied zircons suggested their magmatic origin, the age value of 490±7 million years can be taken as the most exact dating of the plagiogranite crystallization in the Voikar-Synya Massif (E. V. Khain et al., in press, 2006).

[39] The resulting age of the plagiogranite from the ophiolites of the Voikar-Synya Massif (490±7 Ma) corresponds roughly to the Cambrian-Ordovician boundary of the modern scale. Consequently, the ophiolite of this massif can be dated late Cambrian or somewhat older. The problem of dating its gabbro-norite complex remains to be solved.

Discussion

[40] This study proved that the Polar Ural region exposes the ophiolite fragments dated about 670 million years. Some ophiolites mapped in the largest ophiolite allochthons were dated Cambrian (about 490 Ma) or somewhat older. The results of our study and the geochemical data obtained by *Dushin* [1989, 1997] and by *Scarrow et al.* [2001] suggest that the oldest structural features of the Polar Ural region contain the relics of encialic volcanic arcs and their slopes, as well as those of the bottoms of marginal sea basins. The presence of the volcanic rocks of different compositions, including adakite and boninite, suggests that these rocks are not purely supersubduction products but are also the prod-

ucts of some atypical subduction which had been accompanied by the collision of the spreading ridges with the arc, by the sealing of the subduction zone, and by the origin of asthenospheric windows. The paleomagnetic data obtained by A. N. Didenko and the authors of this paper [*Didenko et al.,* 2001] suggest that the Enganepe volcanic arc was located at that time not far from the edge of the Baltic plate and might have been connected with the Kadoma volcanic arc.

[41] Our isotopic and geochronological data suggest that the metamorphic volcano-sedimentary rocks of the Kharbei Block had accumulated in pre-Vendian time. The fragments of the rocks of the ophiolitic suite occur as olistoliths in the olistostrome layers and seem to be even older. The rocks of the Kharbei High transformed to metamorphic rocks in the time interval of 460±10 million years , which corresponds to the Middle Ordovician. That time witnessed the widespread Finmark or Early Caledonian orogeny in the Scandinavian caledonides, the obduction of the ophiolites, granite formation, and metamorphism. This time was extremely characteristic of the Central Asian Belt as a whole. That was the time of the ophiolite obduction, granite formation, and metamorphism. This time was extremely typical of the Central Asian Belt as a whole. It witnessed the ophiolite obduction and the mass formation of granite gneiss domes in West Mongolia, in the Baikal, Altai-Sayan, Sangilen, and other regions. The data obtained in this study confirm the existence of the Vendian and Late Riphean ophiolites, as well as of the rocks of the volcanic arcs and marginal basins, associated with them, in the Polar Ural region. It appears that the structural features of the active continental margin were surrounded in Late Riphean and Vendian time by the oceanic basin which might connect the paleooceanic formations of the Paleoatlantic ocean (Yapetus) and those of the Paleoasian ocean. The age of the metamorphism of the metamorphic rock complexes in the Polar Ural area suggests that part of the nappe structure of this region had been formed as early as the pre-Middle Ordovician time, and that the Cadomian and Early Caledonian, as well as the Late Caledonian (Hercynian) are brought to contact one another.

[42] The schematic tectonic map of the region (see Figure 1) shows that the pre-Devonian rock complex does not include the rocks emplaced during the formation of the mature continental crust, except for some rock complexes of the Kharbei Block; this contradicts the view of the Early Ordovician destruction of the older continental basement and justifies the model of the continuous development of the paleooceanic region.

[43] The ophiolites dated Cambrian-Early Ordovician, similar to the Voikar-Synya ophiolites, were found in the Scandinavian Caledonides (in the areas of the Karmøy, Bomlo, and Stord islands and in the areas of the Bergen, Solund, Stavfegen, and Scalvaier island arcs) and in the Appalachian Mountains (the Humber Arm and Hei Bei allochthons of the Newfoundland Island), that is in the structural features of the Paleoatlantic (Yapetus) Ocean. It should be noted that the episodes of collision, obduction, and granite formation in the listed regions coincide in many respects with the epochs reconstructed for the eastern part of the modern Siberian margin of the Paleoasian Ocean [*Khain,* 1989; *Khain et al.,* 2003]. On the other hand, some Cambrian-Early Ordovician ophiolites are known in the structural features of the western (in modern coordinates) Ural-Kazakhstan margin of the Paleoasian Ocean, namely, in the North Kazakhstan and North Tien Shan areas, as the Maikain-Kyzyltass and Kirgiz-Terskei ophiolite zones. All of these data suggest one scenario for the development of the Paleoasian Ocean, including the Ural-Kazakhstan margin and the margin of the Paleoatlantic Ocean.

[44] The evolution history of the Paleoasian ocean shows some differences in the evolution of its western and eastern segments (in modern coordinates). Its western (Tarim-Kazakhstan) margin remained passive throughout the Neoproterozoic time, some rifting environments having been reconstructed for it, too. Active continental margins began to develop in the eastern part of the ocean (present day reference frame) as far back as the beginning of the Neoproterozoic. This is proved by the fact that the Siberian continent and the central Mongolian microcontinent are surrounded by the Late Riphean-Vendian ophiolite belts. The new data suggest the ophiolite rock complexes dated 1000, 830, 700-670, and 570 million years, the fragments of which occur now as allochthons or are exposed from under the younger sedimentary cover [*Khain et al.,* 2002, 2003; *Pfänder et al.,* 2002]. Associated with the ophiolite complexes are the island-arc volcanics and the sedimentary rocks of back-arc basins. The existence of this Circum-Siberia Belt proves that the Siberian Continent was separated from the other continents by some oceanic space or by a strait, the Paleoural Ocean might have acting as this potential strait. The Paleoasian and Paleoatlantic oceans (Yapetus) might have been connected in Neoproterozoic time by the Polar Ural suture.

[45] The important period of the ocean formation was the time interval of 650–510 million years. This period of time was characterized by the high complication of the structure of ocean margins. This time witnessed the dying off of the large system of volcanic arcs, the closure of the sea basins associated with them, and the accretion of the resulting segments to the edges of the continents and microcontinents, and the obduction of the early ophiolites. All of these events took place at the background of the generation of new subduction zones and the opening of new marginal basins. Two main periods of this activity were dated 590–570 Ma and 530–540 Ma. As the result of these processes the Paleoasian ocean was transformed at the mid-Cambrian to the intricate system of basins with the oceanic crust, island-arc systems, and microcontinents with a terrigenous-carbonate rock cover. At that time the structure of both parts of the paleoocean was similar to the modern situation east and north of Australia.

[46] The period of time from the end of the Cambrian to the beginning of the Ordovician was marked by the opposite processes in the development of the different segments of the Paleoasian Ocean.

[47] During the Late Cambrian and Ordovician the western part of the Paleoatlantic ocean was represented by the active margin of the West Pacific ocean, where the opening of basins with oceanic crust took place, and systems

of volcanic arcs were formed. In the east that time was marked by the collision of the island arcs and microcontinents and by the closure of the interarc basins. These processes resulted in the origin of two types of regions: amagmatic subduction-accretion regions with flyschoid sedimentation (Gornyi and Mongolian Altai and West Sayan) and collision-obduction regions (Tuva, the Eastern Sayan region, West and North Mongolia, and the Baikal region), distinguished by the maximum concentration of microcontinents. Throughout the Late Cambrian to Early Ordovician time, these regions experienced the collisions of their median ridges and volcanic arcs with the microcontinents and continents, which were accompanied by the obduction of their ophiolites, by the intensive crustal and crustal-mantle magmatism, high-temperature metamorphism, and shear deformation.

[48] The new data obtained recently in the Polar Ural region confirm the existence of the long-lived Paleoasian ocean which had existed there at least from the time of 1100 million years. Throughout this long history its western Ural-Kazakhstan and eastern Siberian-Mongolian margins (present day reference frame) developed in different ways, yet having some similar periods in their geologic histories. In the light of the new data, the Ural Mountain Belt seems to be a heterogeneous building. Its southern and intermediate segments evolved following the western, Kazakhstan, evolution version, whereas the evolution history of its Polar Ural segment was similar to that of the Mongolia-Sayan-Yenisei segment of the Asiatic Belt.

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E. V. Bibikova, Vernadski Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow, Russia

K.-P. Burgat, Federal Department of Geoscience and Natural Resources, Hannover, Germany

A. A. Fedotova, E. V. Khain, Geological Institute, Russian Academy of Sciences, 7 Pyzhevskii Lane, Moscow, 119017 Russia

A. B. Kotov, V. P. Kovach, E. B. Salnikova, Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg, Russia

D. N. Remizov, Institute of Geology, Komi Research Center, Ural Division of the Russian Academy of Sciences, Syktyvkar, Russia