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The Sm–Nd Isotopic Systematics of Ophiolites in the Ozernaya Zone (Mongolia)

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Abstract—The Sm–Nd isochron age was defined for rocks from various associations which make up part of the ophiolite assemblage of the Ozernaya zone of the early Caledonides. The age of gabbroids and tholeiite basic rocks of the silica-volcanic sequence in the Seriin-Nuru Range, which were formed under the conditions of an open marine basin, is 527 ± 43 Ma and $\varepsilon_{Nd}(T) = +6.7$. The Geriin–Nuru volcanics are associated with graywackes and were, most likely, generated in an island arc setting. Their age was found to be 522 ± 13 Ma, $\varepsilon_{Nd}(T) = +8.0$. The time of the regional metamorphic reworking of the ophiolites was determined on the basis of metamorphic minerals from rocks of the island-arc affinity of the Khalzan-Buregtei-Ula mountains and defined to be 487 ± 6 Ma with $\varepsilon_{Nd}(T) = +7.8$. The obtained data indicate the age similarity between MORB and island-arc ophiolites, and regionally metamorphosed rocks. They mark the final stage of the early Caledonian paleoocean with rapid change and lateral conjugation of various geodynamic settings.

Key words: *Ophiolites, metamorphism, isotopic age, Sm–Nd systematics.*

INTRODUCTION

Ophiolites have a significant role in the history of the fringing folded structures of the Siberian platform. They occur as basal formations of these structural zones and are commonly considered as the earliest manifestations of crust-forming processes within the region. In most cases, ophiolites are devoid of organic remains; therefore, their age position is defined on the basis of the age of the overlying rock units of the section or, more often, by the similarity of their geological position and composition with other ophiolites. Therefore, any direct evidence about the age of ophiolites is very important for correlating geological processes in the region. The article presents data on the Sm–Nd dating of the Ozernaya zone ophiolites, which is one of the largest in the south Caledonides fringing off the Siberian platform.

GEOLOGICAL CHARACTERISTICS

The ophiolitic Ozernaya zone is a part of the Great Lakes depression in western and southwestern Mongolia (Fig. 1). Abundant ophiolites occur here at the base of the stratified sequences (*Tektonika* ..., 1974). Ophiolite rocks commonly form tectonic blocks. Therefore, the general succession of magmatic events in the Ozernaya zone was reconstructed in the form of a composite section on the basis of the similarity of regularly repeated features (Dergunov, 1989) recorded in different blocks. The lower parts of the ophiolite section are presumably composed of rocks of the melanocratic assemblage (imbricated assemblages, represented by ultramafic rocks, gabbroids, and sheeted dikes). This assemblage is overlain by pillow basalts altered to greenstone. Basaltic lavas and diabase sills give way upsection to lava breccias, hyaloclastites, tuffosiliciliths, tuffites, and siliceous sediments. The carbonate–terrigenous–volcanic sequence, commonly enclosing basalts, andesites, dacites, and plagiorhyolites, occurs above the spilite–diabase complex. The sequence is rich in siliciclastic rocks, olistostromes, and reef-limestones. Recently, blocks of metamorphic rocks (gneisses and amphibolites) were discovered in the lower stream area of the left bank of the Kobdo River (the Ozernaya zone western border); according to data of the medium-scale geological survey, they are conventionally attributed to the Lower–Middle Ordovician, i.e. to the time of the main folding phase in the Ozernaya zone.

The samples we studied are from three levels of the above-mentioned composite section. The spilite–diabase pillow lavas, intercalated with siliceous sediments, the dikes cutting them, and the layered gabbroic sill were studied in the Seriin-Nuru Range, northeast of the Khoitu-Dalai-Nur (*S* in Fig. 1) in the central part of the Ozernaya zone. The tectonically bounded block is exposed here on the southern slope of the range among

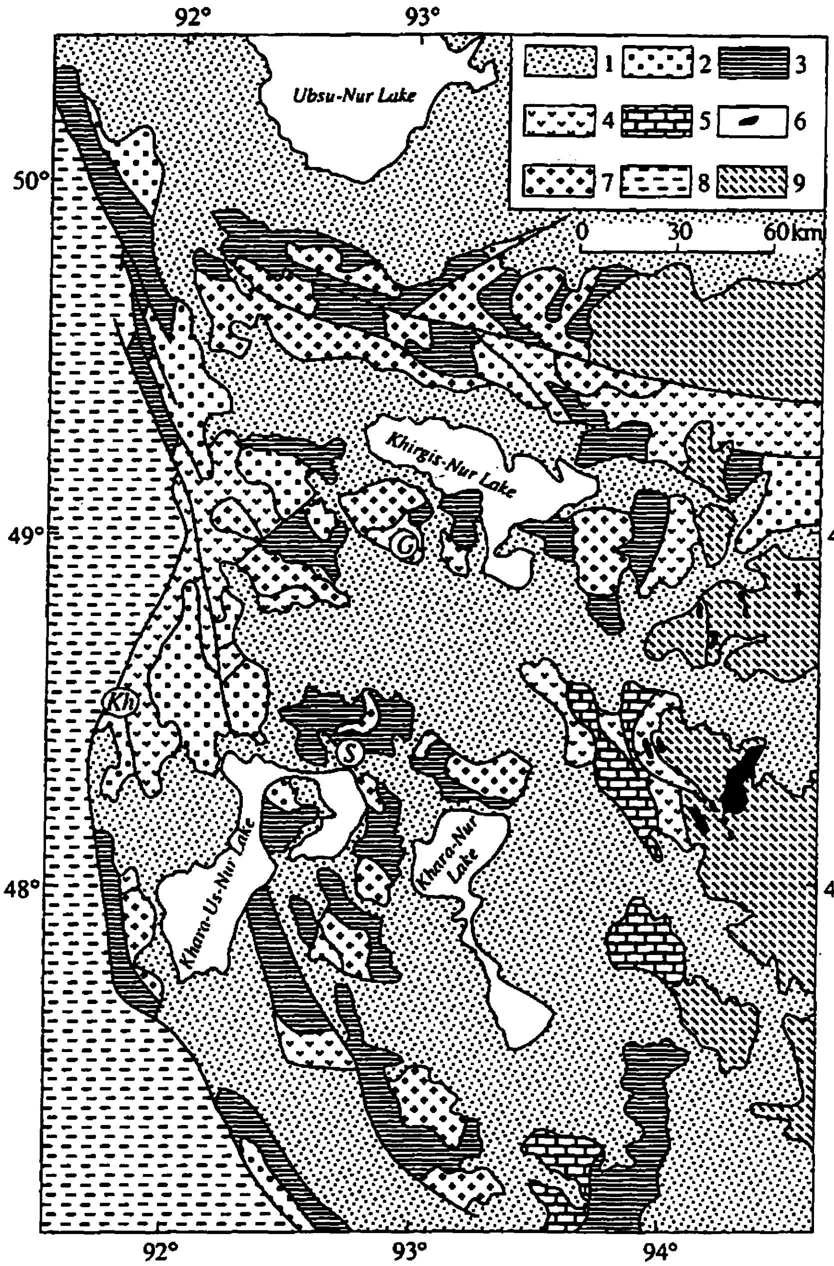

Fig. 1. Scheme of the geological structure of the Ozernaya zone of the early Caledonides in Mongolia complied using published map and scheme of tectonic zonation of Mongolia (*Karta* .... 1989: *Geologicheskie* .... 1995).

(1) Mesozoic–Cenozoic terrigenous complexes: (2) Middle Paleozoic complexes: (3–5) Vendian–Cambrian complexes: (3) ophiolite, (4) carbonate–terrigenous–volcanic, (5) terrigenous–carbonate: (6) allochthonous unltramafic rocks: (7) Early Paleozoic granitoids: (8) Caledonides of the Mongolia–Altai zone: (9) Precambrian crystalline complexes.

The sampling areas are indicate by letter symbols in circles: *S*—Seriin-Nuru, *G*—Geriin-Nuru. *Kh*—Khaldzan-Buregtei.

younger Devonian deposits; it is composed of rocks of the spilite–diabase facies and referred to the Vendian–Early Cambrian on the basis of geological evidence. Two fragments are identified in the block area we studied. They are separated by faults and exposed along the dry river bed near the Ielin-Khuduk Well (Fig. 2). The southern fragment is composed of greenstones after the pillow or massive basalts, interlayered with siliceous rocks, and cut by basite dikes and by the sill of stratified gabbroids. The thickness of lava flows is a few meters, and for sedimentary interlayers, about 0.5 m. The northern fragment of the block is represented by

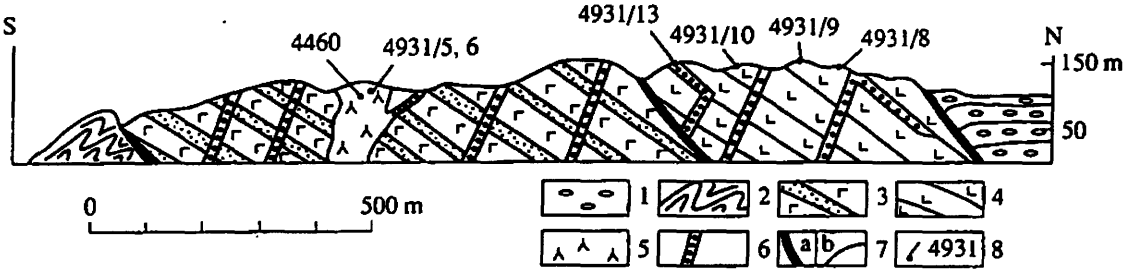

Fig. 2. Section through the ophiolite assemblage at the southern border of the Seriin-Nuru Range.
(1) red molasse (D); (2) sandy–siltstone deposits (D?); (3–7) ophiolite assemblage: (3) basalts, interbedded with siliceous deposits, (4) pillow and massive basalts. (5) layered gabbro. (6) basaltic dikes, (7) faults (a), geological boundaries (b); (8) sampling sites and their numbers.

homogenous pillow lavas enclosing rare thin interlayers of hyaloclastites and siliceous sedimentary rocks. The lavas are cut by basaltic dikes.

Samples for isotopic and geochemical analyses were collected from pillow lavas of the massive part of the section (SN-4931/8–10, Table 1), basaltic dikes (SN-4931/13), and a stratified body of gabbroids (SN-4460, SN-4931/5, 6, Table 1). All of the studied rocks, except gabbroids, correspond to spilites or spilitized basalts bearing albite (An_{17}). In addition to albite, phenocrysts are represented by clinopyroxene ($Wo_{36-43}En_{38-45}Fs_{18-21}$) and serpentinized olivine. The ground mass comprises glass replaced by actinolite and chlorite, plagioclase microlites, occasional round ore mineral segregations, carbonate, and epidote. Gabbroids are composed of plagioclase (from anorthite to andesine), clinopyroxene (Fe-index 0.25–0.31), and occasionally by titanomagnetite. High-Ti amphibole, which substitutes for the titanomagnetite outer rims, is recorded as an accessory and relatively late mineral. The rock texture is gabbroic. The sill layering is expressed as the alternation of more leucocratic (up to anorthosite) and more melanocratic rock layers with obscure boundaries, which are subparallel to the contacts of the body.

The sample GU-4898/5 is from the carbonate–terrigenous–volcanic sequence with basalts, andesites, and dacites. It was collected at the top of Mt. Gelben-Ula, the southern coast of the Khirgiz-Nur Lake (*G* in Fig. 1). Basalts, basaltic andesites and their tuffs with clinopyroxene and amphibole megacrysts are exposed here. In addition to these minerals, other phenocrysts are composed of plagioclase, clinopyroxene, hornblende, olivine, and magnetite. Olivine, clinopyroxene ($Wo_{45-47}En_{45-47}Fs_{7-9}$), and hornblende are mainly unaltered, whereas plagioclase phenocrysts and microlites are locally intensely albitized, and they have a basic composition only in relicts (An_{85}). The ground mass is chloritized and actinolitized, and comprises amygdales composed of epidote, actinolite, and rare quartz.

The schist sample KhBU-IX was collected at the left bank of the Kobdo River, in a dry river bed with the Khara-Yamar-Khuduk Well, west of the Khalzan-Buregtei-Ula (*Kh* in Fig. 1). It characterizes the metamorphic sequence convetionally assigned by the geological data to the Lower–Middle Ordovician. These schists represent the orthorocks which compose the intrusive body in gneisses, and are cut by dikes of amphibolites. The schist sample consists of quartz, plagioclase (An_{30-38}), biotite, muscovite, magnetite, ilmenite, garnet, and sphene. The chemical composition suggests the plagiogranite composition of its premetamorphic protolith (Table 1).

INVESTIGATION METHODS

Mineral fractions (from 40 to 100 mg) for isotopic investigations were hand separated at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry of the Russian Academy of Sciences (IGEM). Minerals were analyzed at the Mineralogisch–Petrographisches Institut, Universität zu Köln, applying the Camebax electron microprobe with accelerating voltage (15 kV), a target current of 20 nA and a measurement time for each element 10 s. The bulk rock composition was studied at IGEM by the wet chemical method. The trace and rare earth elements were studied at the Mineralogisch–Petrographisches Institut, Universität zu Köln using the method of inductively coupled plasma spectrometry (ICPs). The chemical preparation of samples and analytical procedure are described in detail by Roelandts *et al.* (1988).

Sm–Nd isotopic investigations were carried out at the Max-Planck Institut in Mainz using a technique already published (Chauvel *et al.*, 1985), though somewhat modified. The $^{149}Sm + ^{150}Nd$ mixed spike was added to samples before decomposition. The sample powder (100–150 mg) and mineral fractions (50–70 mg) were decomposed in hermetic teflon beakers with the mixture of the $HF + HNO_3$ acids at a temperature of about 120°C during 3–5 days. After decomposition, the dry residue was dissolved in 6 N HCl and was again dried out. The procedure of chemical extraction of total REE, and the separation of Nd from Sm is identical to that described by White and Patchett (1984). The mass spectrometry analysis on Nd and Sm was performed

Table 1. The content of main and trace elements in ophiolitic rocks of the Ozernaya zone

Components	SN-4460	SN-4931/5	SN-4931/6	SN-4931/8	SN-4931/9	SN-4931/10	SN-4931/13	GU-4898/5	KhBU-IX
SiO_2	47.2	43.5	47.5	55.6	49.5	57.2	50.3	54.6	69.3
TiO_2	2.08	2.23	2.14	0.92	1.30	1.07	2.28	1.37	0.92
Al_2O_3	17.3	16.5	18.2	15.4	17.4	14.5	14.4	17.1	13.9
Fe_2O_3	5.20	5.75	2.32	4.63	4.60	7.09	5.93	2.58	0.00
FeO	5.38	5.98	6.70	4.20	7.17	4.37	5.95	5.57	2.65
MnO	0.18	0.22	0.16	0.18	0.19	0.19	0.18	0.13	0.15
MgO	4.10	4.59	4.29	4.81	4.58	3.96	4.46	4.41	1.92
CaO	9.64	10.8	8.87	4.23	3.12	2.23	6.24	7.09	3.12
Na_2O	4.04	2.31	4.14	7.28	6.12	5.54	4.70	4.85	4.19
K_2O	0.65	0.73	1.10	0.61	1.23	0.57	2.20	0.85	2.10
P_2O_5	0.16	0.45	0.39	0.18	0.21	0.15	0.39	0.47	0.15
H_2O	0.39	1.14	0.11	0.00	0.21	0.10	0.36	0.21	0.00
H_2O^+	3.43	5.08	3.32	1.72	4.00	2.60	2.41	0.47	1.21
F	0.09	0.09	0.07	0.16	0.07	0.05	0.09	0.12	0.11
CO_2	0.15	0.38	0.20	0.11	0.55	0.87	0.17	0.11	0.15
Total	99.94	99.72	99.46	99.87	100.25	100.34	100.16	99.92	99.90
Cr		22	16	17	12	2	22	88	3
V		335	300	321	326	379	329	349	27
Co		46	43	32	36	41	51	30	5.8
Ni		22	16	16	12	6	13	42	4
Cu		39	48	66	32	83	43	85	9
Zn		95	78	68	85	123	128	71	91
Zr	127	114	132	74	87	77	189	92	189
Nb	7	6	6	2	3	2	9	6	6
Y	27.0	27.1	29.5	23.2	26.7	26.8	40.8	24.9	28.9
Sc		27	25	33	33	38	32	31	12
Sr	276	332	487	175	378	137	452	440	408
Rb	6	5	11	6	8	5	17	12	18
La		9.94	11.3	4.78	4.57	4.65	19.0	11.7	17.0
Ce		25.4	28.4	12.8	14.0	13.6	44.8	26.3	42.4
Nd		17.7	19.3	9.82	11.0	10.4	27.7	16.1	27.7
Sm		4.77	5.07	3.02	3.37	3.28	6.89	3.90	6.56
Eu		1.60	1.72	1.01	1.17	1.11	2.26	1.34	2.31
Gd		5.14	5.55	3.64	4.06	3.93	7.19	4.40	6.31
Dy		4.84	5.26	3.78	4.41	4.30	7.05	4.27	5.37
Er		2.63	2.85	2.36	2.71	2.71	3.99	2.44	2.97
Yb		2.33	2.62	2.31	2.64	2.61	3.78	2.27	2.94
Lu		0.32	0.36	0.33	0.37	0.36	0.53	0.31	0.42

Note: The content of main components in wt %, trace elements in ppm.

using the Finnigan-MAT 261 under the statistic regime. The correction for Sm–Nd fractionation effects during the measurements was done by normalizing isotopic ratios relative to $^{147}Sm/^{152}Sm$ and $^{146}Nd/^{144}Nd$ = 0.7219. The measurements of the La Jolla Nd-standard isotopic composition during the experimental runs yielded the average result of $^{143}Nd/^{144}Nd = 0.511809 \pm 20$ (one σ; N = 17). The measurement results of the Nd isotopic composition in the samples were corrected with reference to the La Jolla value of $^{143}Nd/^{144}Nd$ = 0.511860 (Jacobson and Wasserburg, 1980, 1984). The calculation of isochron parameters was done by the York method (York, 1966). The error in the $\varepsilon_{Nd}(T)$ initial value was calculated using the Flecher and Rosman method (Fletcher and Rosman, 1982). While calculating the isochron parameters, the following errors were allowed for the isochron diagram coordinates for $^{147}Sm/^{144}Nd$—0.2%, and for $^{143}Nd/^{144}Nd$—the maximum divergence value between the reproducibility error in a series of La Jolla analyses (±0.000020) and the error for individual analyses. Errors in the isochron parameters correspond to a 2σ or 95% confidence interval.

RESULTS AND DISCUSSION

According to the chemical composition (Table 1), the investigated samples of basic rocks are referred to gabbro (massive gabbroids), basalts, and basaltic andesites. Abundant albite in the volcanic rocks, together with their high Na_2O and low CaO contents, suggest that they are spilites or spilitized basalts.

It is not so easy to infer the initial composition of magmatic ophiolite rocks, in spite of numerous publications on methods concerning this problem. In our case, different methods do not bring identical results. The most reliable conclusions are as follows:

(1) Basalts and gabbroids of the Seriin-Nuru Range are associated with siliceous sediments, typical of open marine basins, and are characterized by the accumulation of iron and titanium in more differentiated rock varieties; the latter is typical of the tholeiitic magmatic series. The Geriin-Nuru rocks are weakly differentiated, so the iron distribution does not provide an opportunity to infer the particular petrochemical group of the rocks. The fact that among them there are varieties with amphibole phenocrysts and low-Fe dacites suggest that the rocks belong to the calc-alkaline island-arc series. The association of these rocks with graywacke sandstones and siltstones implies the proximity of the original setting to an island-arc.

(2) The REE distribution patterns for rocks of the Seriin-Nuru Range are of the intermediate type between MORB and island-arc tholeiite series. The Rb, Th, Hf, Zr, Ti, Y, Nb, and REE contents insignificantly (by a factor less than 2) deviate from the average contentrations of these elements in MORB (Sharas'kin, 1992). The island-arc volcanic rocks differ from MORB by the reduced content of Nb and Ta, and to a lesser extent, of Zr and Hf. Basic volcanics of the Seriin-Nuru Range show only Ta-depletion, though less prominent than in island-arc series.

(3) The REE distribution in samples SN-4931/13 and GU-4898/5 greatly differs from that of MORB, though it is similar to that of island-arc calc-alkaline volcanics.

(4) With their values of La/Nb and La/Th ratios, the studied rocks fall within the MORB field (Sharas'kin, 1992), or at the boundary between MORB and island arc rocks.

The obtained data on the REE distribution and geological association of the rocks under study suggests that the Seriion-Nuru basites are similar to MORB and marginal basin tholeiites with certain components of island-arc origin, which is quite typical of magmatic products in spreading zones of marginal basins. Sample GU-4898/5 seems to be close to island-arc calc-alkaline basalts.

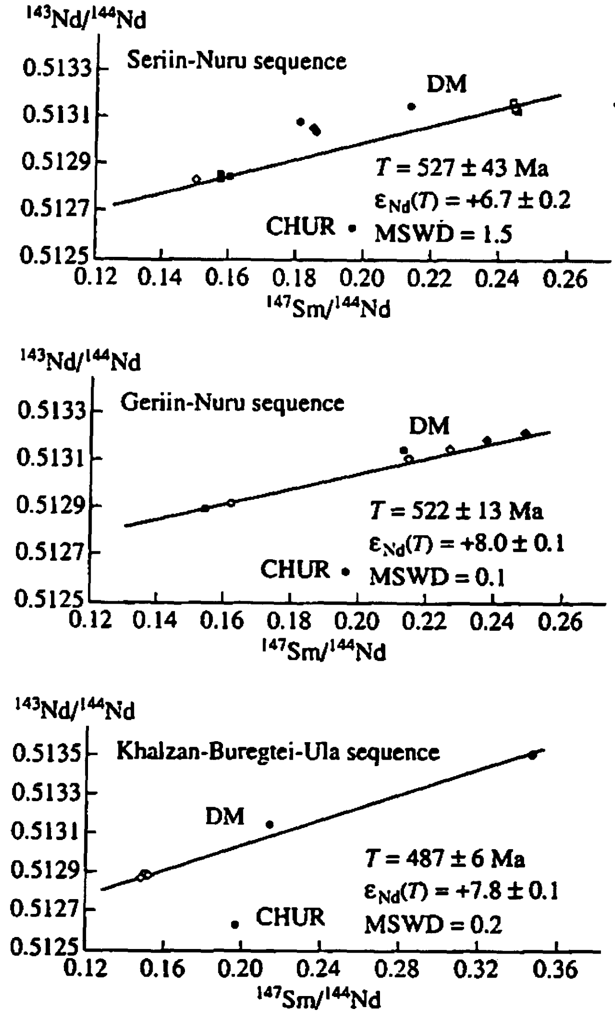

Fig. 3. Sm–Nd evolution diagrams for the Ozernaya zone ophiolites.

The Seriin-Nuru sequence: filled and open squares— whole rock samples and clinopyroxene fractions from gabbro sill; filled and open rhombs—basalts 4931/8–10 and 4931/13 respectively;

The Geriin-Nuru sequence: square—whole rock sample, open circle—olivine, filled and open rhombs—clinopyroxenes and amphiboles respectively;

The Khalzan-Buregtei-Ula sequence: square—whole rock sample, filled and open rhombs—garnet and plagioclase and biotite respectively.

The results of the Sm–Nd isotopic systematics for whole rock samples and mineral fractions from all of the above-discussed sequences (Seriin-Nuru, Geriin-Nuru, and Khalzan-Buregtei-Ula) are shown in Table 2 and in the Sm–Nd evolutionary diagrams (Fig. 3).

The Seriin-Nuru sequence. The data points for whole rock samples gabbro and clinopyroxene fractions fit the isochron age of 527 ± 43 Ma, indicating the emplacement time of sill with a rather high positive value of $\varepsilon_{Nd}(T) = +6.7 \pm 0.2$ (MSWD = 1.5). The isotopic parameters of the basaltic dike sample 4931/13

Table 2. Sm–Nd isotopic data

Sample no.	Rock	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(T)$*
			Seriin-Nuru sequence			
SN-4460 WR	Gabbro	5.173	19.82	0.15779	0.512841 ∓ 8	+6.6
SN-4460 Cpx		4.755	11.74	0.24488	0.513137 ∓ 6	+6.5
SN-4931/5 WR	Gabbro	4.576	17.31	0.15987	0.512851 ∓ 9	+6.6
SN-4931/5 Cpx		4.497	11.15	0.24377	0.513166 ∓ 9	+7.1
SN-4931/6 WR	Gabbro	5.002	19.17	0.15777	0.512862 ∓ 7	+7.0
SN-4931/6 Cpx		4.366	10.80	0.24439	0.513141 ∓ 8	+6.6
SN-4931/8 WR	Basalt	2.955	9.870	0.18096	0.513083 ∓ 25	+9.8
SN-4931/9 WR	Basalt	3.326	10.89	0.18472	0.513055 ∓ 13	+9.0
SN-4931/10 WR	Basalt	3.150	10.26	0.18562	0.513043 ∓ 9	+8.7
SN-4931/13 WR	Basalt	6.643	26.71	0.15035	0.512835 ∓ 7	+7.0
			Geriin-Nuru sequence			
GU-4898/5 WR	Basalt	4.710	18.44	0.15438	0.512902 ∓ 8	+8.0
GU-4898/5 Ol		1.815	6.759	0.16234	0.512928 ∓ 10	+7.9
GU-4898/5 Cpx1**		4560	11.60	0.23771	0.513190 ∓ 17	+8.0
GU-4898/5 Cpx2***		4.465	10.85	0.24893	0.513220 ∓ 13	+7.9
GU-4898/5 Amph1**		1.701	4.788	0.21478	0.513109 ∓ 29	+8.0
GU-4898/5 Amph2***		1.347	3.593	0.22665	0.513156 ∓ 32	+8.1
			Khalzan-Buregtei-Ula sequence			
KhBU-IX WR	Gneiss	7.002	28.12	0.15056	0.512891 ∓ 15	+7.8
KhBU-IX Gar		7.055	12.35	0.34538	0.513510 ∓ 9	+7.8
KhBU-IX Plag		2.925	11.68	0.15141	0.512892 ∓ 18	+7.8
KhBU-IX Bi		1.140	4.627	0.14902	0.512880 ∓ 9	+7.7

Note: * The ε_{Nd} values are recalculated for the isochron age *T* of each sequence. Mineral fractions were treated in 2 N (**) and 4 N HCl (***) respectively. WR, Ol, Cpx, Amph, Gar, Plag, Bi indicate the whole rock and olivine, clinopyroxene, amphibole, garnet, plagioclase, and biotite fractions, respectively.

[$\varepsilon_{Nd}(T)$ = +7.0] approaches those in the investigated massive gabbroids. Pillow lava samples (mostly spilites) from the massive part of the spilite–diabase sequence have much higher values of the Sm/Nd ratios and a more radiogenic Nd isotope composition [$\varepsilon_{Nd}(T)$ value varies from +9 to +10].

The linear approximation of analytical data for the lava sample 4898/5 from the Geriin-Nuru sequence and its clinopyroxene and amphibole fractions yielded the age of 522 ± 13 Ma, i.e. identical to the age of gabbro sill. The Nd isotope composition shows that this rock is intermediate between the gabbro sill and volcanic rocks of the Geriin-Nuru locality with more radiogenic Nd [$\varepsilon_{Nd}(T)$ = +8.0 ± 0.1].

The whole rock sample KhBU-IX from the Khalzan-Buregtei-Ula and metamorphic mineral fractions identify in the Sm–Nd evolutionary diagram the line with the slope, corresponding to the age of 487 ± 6 Ma [$\varepsilon_{Nd}(T)$ = +7.8 ± 0.1].

Geological data do not suggest any age difference between basalts of the spilite–diabase sequence (sample SN-4931/8–10) and gabbroids and basalts of the dike group. The calculated high $\varepsilon_{Nd}(T)$ values of +9 to +10 seem to agree with the geological and geochemical data, which indicate that these rocks were formed under conditions of oceanic spreading. Taking into consideration the lower value of $\varepsilon_{Nd}(T)$ = +7 for gabbro, we have to admit that the island-arc component was involved in the process of magma generation and formation of the spilite–diabase sequence.

The obtained age values for ophiolitic magmatic rocks in the Ozernaya zone are very similar (within the measurements error) to the rocks of the Bayan-Khongor zone (569 ± 21 Ma; Kepezhinskas *et al.*, 1991), but substantially younger than the Bayanur complex of the Daribi Range (695 ± 25 Ma) in the Ozernaya zone (Khain *et al.*, 1995). Therefore, ophiolites in the Ozernaya zone may be different in age, suggesting a long time interval of its evolution.

The Sm–Nd age for the orthogneiss sample KhBU-IX from the Khalzan-Buregtei-Ula sequence corresponds to the time of regional metamorphism at the stage of general collision of the early Caledonides in the southern framing zones of the Siberian platform (Sklyarov, 1994).

Our results suggest that MORB, island-arc, and deeply metamorphosed ophiolite sequences are similar in age. This agrees with an assumption of A.N. Didenko *et al.* (1994) on the concurrent existence and, most likely, spatial conjugation of several spreading zones associated with large enough marginal seas, island arc systems, and zones of intense regional metamorphism within the Ozernaya zone.

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Reviewer E.V. Bibikova

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