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GEOLOGY

The Nature of the Continental Crust of Sikhote-Alin as Evidenced from the Nb Isotopy of Rocks of Southern Primorie

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The study of the Nb isotopy of rocks of the continental crustal is an effective tool for evaluating the nature of mechanisms of crust-forming processes and ages of their manifestation [1]. In the first approximation, the Nd model isotope age characterizes the age of formation of the continental crust from the mantle source or, in other words, transformation from oceanic crust to continental. The Nd isotope systematics of sedimentary rocks of upper levels of the continental crust allows us to estimate the average model age and the possible paleogeographic source areas, as well as to determine the lower age limit of sedimentation if there are no paleontological data. Moreover, the use of two-stage Nd model ages of granitoides along with the geochemical and petrological data obtained allow us to obtain data about the deep levels of the continental crust (levels of generation of the granitic melt). In some cases, the combination of these approaches makes it possible to reconstruct the chemical composition and the nature and mechanisms of formation of the continental crust of separate blocks (terranes) and large fold belts [2].

This work presents the Nd isotope data of sedimentary and igneous rocks of Southern Primorie, including the Mesozoic accretionary structures of the Sikhote-Alin system and adjacent blocks of Precambrian and Early Paleozoic consolidation (Fig. 1).

The Sikhote-Alin system consists of terranes: fragments of Middle Jurassic (Berriasian and Neocomian) accretionary prisms, Early Cretaceous terranes, fragments of turbidite basins, and island arcs (Fig. 1). Accumulation of the terrigenous matrix of accretionary prisms began approximately in the Callovian and ended in the Late Early Cretaceous [3]. The older deposits are represented by Early–Middle Jurassic allochtonous siliceous-clayey formations, as well as Triassic and Paleozoic cherts, basalts, and ophiolitic gabbro-hyperbasites. The tectonostratigraphic sequence observed is evidence that accretionary prisms formed by the oceanic crust subduction in a setting similar to that in the modern deep-sea trenches.

In the Early Cretaceous, deformational processes, caused by the movement of the Tan-Lu fault system along fault zones, began in Sikhote-Alin terranes [3]. As a result, the Jurassic accretionary prism took a distinctive S-curved shape (Fig. 1). Deformation processes resulted in rapid thickening of the primary crust, formation of the granite-metamorphic layer, and formation of the continental crust of 30–40 km thick [3]. Thus, according to the geological data available, the entire process of formation of the continental lithosphere of the Sikhote-Alin system from accumulation of primary volcanogenic–sedimentary strata to formation of the continental crust lasted only 50–60 Ma (Middle Jurassic–Albian).

The Sm and Nd concentrations and isotopic compositions were determined in IPGG RAS (St. Petersburg) and GI KSC RAS (Apatity) using the methods described in [5] and [6], respectively. To calculate the $\varepsilon_{Nd}(t)$ values and the model ages $t_{Nd(DM)}$, the modern CHUR values [7] ($^{143}Nd/^{144}Nd$ = 0.512638, $^{147}Sm/^{144}Nd$ = 0.1967) and DM [8] ($^{143}Nd/^{144}Nd$ = 0.513151, $^{147}Sm/^{144}Nd$ = 0.2136) were used. In order to take into account the possible Sm–Nd fractionation during intracrustal processes, two-stage Nd model ages $t_{Nd(DM\text{-}2)}$ [9] were calculated for the studied rock samples using the average crustal ratio of $^{147}Sm/^{144}Nd$ = 0.12 [10].

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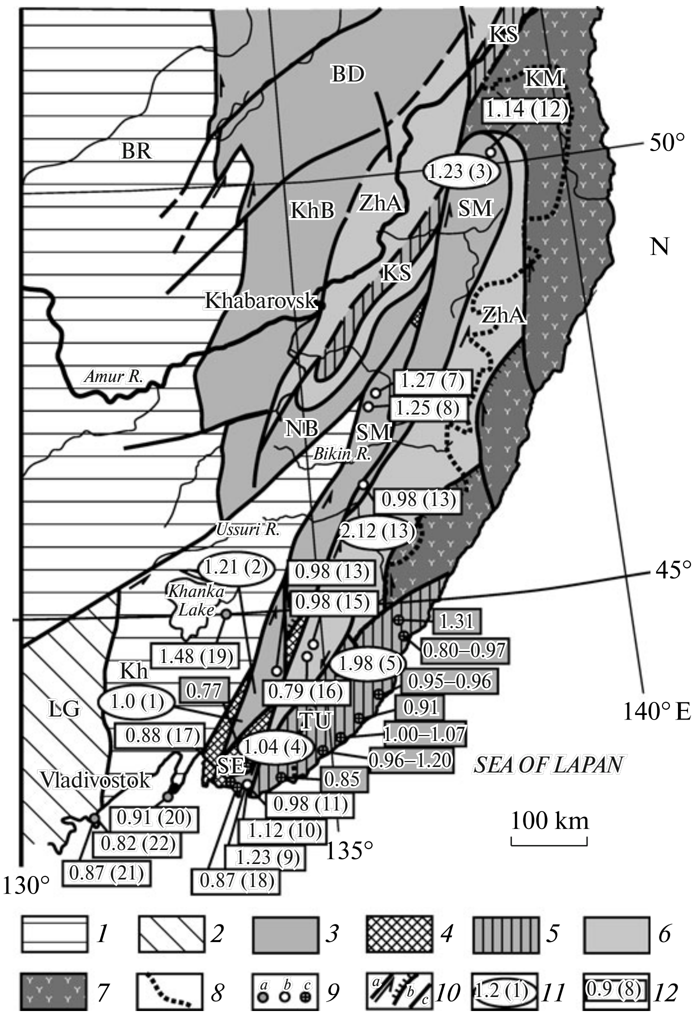

Fig. 1. Geological scheme of Southern Primorie ([3], modified) with the Nd isotope characteristics of rocks of the continental crust. (*1*) Precambrian–Early Paleozoic terranes and superterranes (B, Bureya–Jiamusy; Kh, Khanka); (*2*) Paleozoic terranes (LG, Heilongjiang-Grodekovo); (*3*, *4*) Jurassic terranes: (*3*) accretion prisms (SM–Samarka, NB—Nadanhada-Bikin, KhB—Khabarovsk, B—Badzhal), (*4*) fragments of Precambrian-Early Paleozoic terranes, involved into the structure of the Jurassic accretion prism (SG—Sergeevka); (*5–7*) Cretaceous terranes: (*5*) accretion prisms (TU—Taukhe, KS—Kiselevo-Manoma), (*6*) turbidite basins of the transform continental margin (ZhA–Zhuravlevka-Amur), (*7*) island arcs and/or back-arc basins (KM—Kema); (*8*) the western boundary of distribution of Late Cretaceous subduction-related volcano-plutonic associations of the eastern Sikhote-Alin belt; (*9*) granitoid intrusions (not to scale): *a*—Pre-Cretaceous, *b*—Early Cretaceous, *c*—Late Cretaceous-Paleogene; (*10*) main faults: *a*—faults (arrows show direction of movement), *b*—thrusts, *c*—others; (*11*, *12*) Nd model ages, Ga (*11*—sedimentary rocks, *12*—granitoides: numbers of samples in Table 1 are in brackets). The model ages in gray rectangles are given after [4].

Mesozoic sedimentary rocks of Sikhote-Alin were studied within three terranes: Samarka and Taukhe accretionary prisms and the Zhuravlevka syn-fault turbidite basin. The detailed description of the geological structure and lithology of these terranes is given in [3, 11].

According to the petrochemical composition, sandstones and aleurolites of the turbidite matrix of the Samarka accretion prism correspond mainly to acidic greywackes and clayey shales.

Their Nd model ages $t_{\mathrm{Nd(DM)}}$ (Table 1 (analyses 1–4); Fig. 1) are in the range of 1.0–1.25 Ga. Sandstones of the Taukhe accretionary prism and Zhuravlevka turbidite basin are characterized by more "mature" composition. Arkoses and litites are in predominance. Sandstones have model ages $t_{\mathrm{Nd(DM)}}$ = 2.0–2.1 Ga (Table 1 (analyses 5, 6); Fig. 1).

Cretaceous granitoides of the Sikhote-Alin system were studied within the Samarka and Zhuravlevka terranes. Early Cretaceous granitoides of the Samarka terrane are represented by rocks of aluminiferous and calc-alkali series [3]. Granitoides of aluminiferous series are characterized by $\varepsilon_{\mathrm{Nd}}(t)$ = –3.7...–4.1 and the model ages $t_{\mathrm{Nd(DM\text{-}2)}}$=1.2–1.3 Ga (Table 1(analyses 7–9)). The isotope characteristics of the granitoides of the calc-alkali series varies greatly ($\varepsilon_{\mathrm{Nd}}(t)$ = –0.8...–2.7;

The Sm–Nd isotope data of rocks of the continental crust of Southern Primorie

Serial number	Number of sample	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma_{mod}$)	$\varepsilon_{Nd}(0)$	t, Ma	$\varepsilon_{Nd}(t)$	$t_{Nd(DM)}$	$t_{Nd(DM2)}$
Mesozoic sedimentary rocks of the Sikhote-Alin										
1	8-888/6	3.31	17.2	0.1161	0.512518 ± 5	–2.3	100	–1.3	998	1025
2	8-874	6.26	31.5	0.1201	0.512408 ± 5	–4.5	150	–3.0	1209	1208
3	8-09-18/1	6.70	35.6	0.1139	0.512342 ± 5	–5.8	150	–4.2	1235	1305
4	8-08-18/1	4.59	23.8	0.1167	0.512489 ± 2	–2.9	150	–1.4	1041	1072
5	8-10-13/5	3.36	19.4	0.1047	0.511728 ± 2	–17.8	130	–16.2	1983	2284
6	8-10-12/1	3.60	21.0	0.1038	0.511618 ± 3	–19.9	130	–18.4	2118	2460
Early Cretaceous granitoides of the Sikhote-Alin										
7	8-11-55/1	5.57	28.0	0.1202	0.512367 ± 2	–5.3	125	–4.1	1277	1275
8	C-381g	4.84	23.8	0.1231	0.512386 ± 3	–4.9	125	–3.7	1285	1247
9	8-02-26	3.63	15.6	0.1407	0.512407 ± 2	–4.5	102	–3.8	1553	1233
10	8-08-11	6.06	32.2	0.1136	0.512458 ± 2	–3.5	102	–2.4	1056	1121
11	8-08-6	3.42	18.5	0.1114	0.512546 ± 4	–1.8	102	–0.7	902	976
12	8-09-1/1	5.23	24.4	0.1297	0.512455 ± 2	–3.6	105	–2.7	1262	1143
13	8-871-1	2.96	18.1	0.0987	0.512532 ± 6	–2.1	100	–0.8	821	984
14	8-10-8/1	4.14	22.2	0.1126	0.512544 ± 4	–1.8	100	–0.8	915	979
15	A-117	3.92	20.7	0.1148	0.512546 ± 3	–1.8	105	–0.7	933	979
16	GV-158	2.98	15.1	0.1193	0.512662 ± 4	0.5	105	1.5	790	795
Late Cretaceous granitoides of Sikhote-Alin										
17	8-881/2	2.83	16.2	0.1059	0.512599 ± 4	–0.8	96	0.4	780	882
18	8-02-1	8.04	35.4	0.1374	0.512626 ± 4	–0.2	75	0.3	1048	867
Pre-Cretaceous granitoides of Precambrian and Paleozoic terranes of Southern Primorie										
19	8-10-21/2	4.95	24.4	0.1223	0.512246 ± 4	–7.6	460	–3.3	1507	1481
20	8-11-57/1	3.89	17.1	0.1376	0.512646 ± 4	0.2	490	3.9	1011	913
21	8-10-30/3	5.51	31.3	0.1064	0.512593 ± 2	–0.9	250	2.0	793	872
22	8-10-33/2	2.92	14.3	0.1229	0.512647 ± 4	0.2	250	2.5	847	828

Note: (1)–(4) Samarka accretionary prism, aleuritic sandstones of the turbidite matrix; (5) Taukhe accretionary prism, arkosic sandstones; (6) Zhuravlevka syn-fault turbidite basin, arkosic sandstones; (7) Shivki massif, coarse-grained biotite melanocratic granite; (8) stock of the Lermontov deposit, medium-grained biotite melanocratic granite; (9)–(11) Uspenskii massif: (9) garnet-biotite leucogranite, (10) biotite granodiorite, (11) amphibole-biotite granite; (12) Gobillinsky massif, biotite melanocratic granite; (13) central stock of the Vostok deposit, medium-grained biotite melanocratic granite; (14) Lampokhezskii massif, medium-grained biotite granite; (15) Berezovskii massif, biotite–amphibole monzodiorite; (16) Porubino massif, biotite granodiorite; (17) Wrangel massif, biotite granodiorite; (18) Cape Ovseenko massif, biotite leucogranite; (19) Shmakovka massif, biotite granite; (20) Russian Island massif, amphibole quartz monzodiorite; (21), (22) Gamov massif: (21) biotite–amphibole granodiorite, (22) biotite leucogranite. The ages of granitoid intrusions are given after [10, 12–14] and our unpublished data.

$t_{Nd(DM\text{-}2)}$ = 1.0–1.2 Ga) (Table 1 (analyses 10–14)). Early Cretaceous granitoides of the Taukhe terrane are referred mainly to the moderate alkali series and are characterized by a more radiogenic Nd isotope composition ($\varepsilon_{Nd}(t)$ = 1.5...–0.7; $t_{Nd(DM\text{-}2)}$ = 0.8–1.0 (Table 1 (analyses 15, 16)). The similar Nd isotope composition ($\varepsilon_{Nd}(t)$ = 0.3...–0.4; $t_{Nd(DM\text{-}2)}$ = 0.87–0.88 (Table 1 (analyses 17, 18)) is characteristic of Late Cretaceous granitoides, manifested within the conjunction zone between the extreme southern part of Sikhote-Alin and the surrounding Early Paleozoic units (Fig. 1). Pre-Cretaceous granitoides of the Precambrian–Early Paleozoic units surrounding Sikhote-Alin were studied from the example of the Khanka and Heilongjiang-Grodekovo terranes. The isotopic composition of granitoides varies greatly, depending on the rock types of terranes and the nature of the adjacent units. For example, Ordovician calk-alkaline granitoides of Shmakovka massif in the Khanka terrane are characterized by $\varepsilon_{Nd}(t)$ = –3.3 and $t_{Nd(DM\text{-}2)}$ = 1.5 Ga (Table 1 (analysis 19)).

The coeval alkaline granitoides of the Russian Island are characterized by higher values $\varepsilon_{Nd}(t)$ (+3.9) and a young model age (0.9 Ga) (Table 1 (analysis 20)). Late Paleozoic granitoides of the Heilongjiang-Grodekovo terrane are characterized by a more radio-

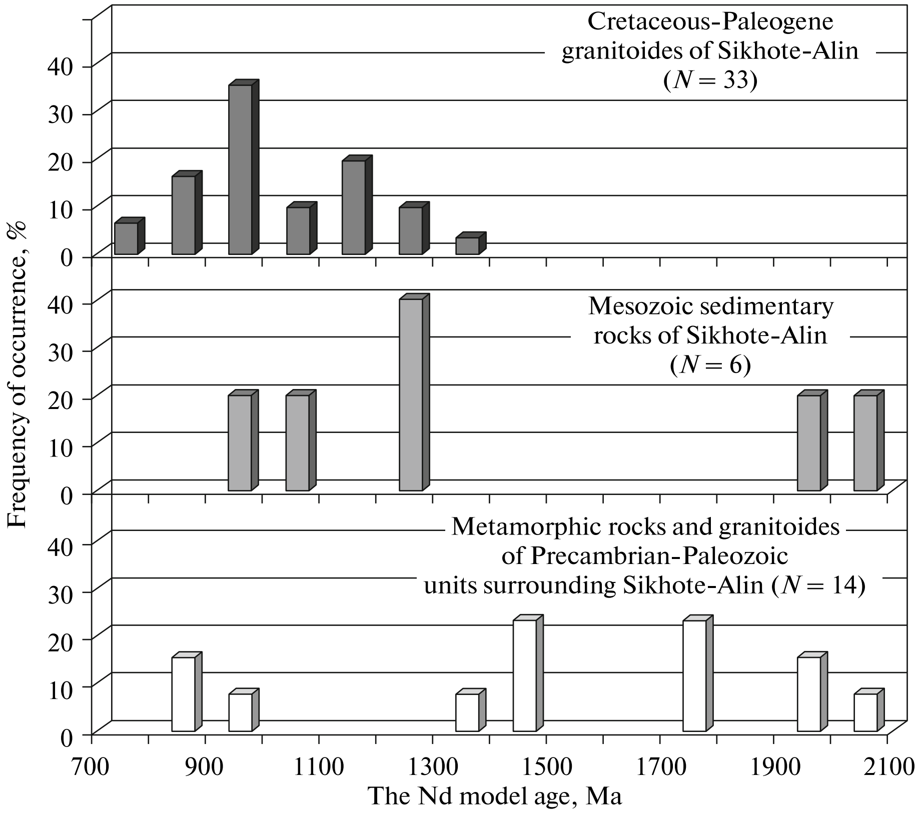

Fig. 2. Histograms of Nd model age distribution for granitoides, metamorphic and sedimentary rocks of Sikhote-Alin, and the Precambrian–Paleozoic surrounding units, based on [4, 15].

genic Nd composition ($\varepsilon_{Nd}(t)$ = 2.0...2.5; $t_{Nd(DM\text{-}2)}$ = 0.83–0.87 Ga) (Table 1 (analyses 21, 22)).

The summary of Nd isotope data obtained for rocks of Southern Primorie given in this article and earlier works [4, 15] allows us to clarify the conclusions made on the basis of geological data [3] and obtain information on the nature and sources of the matter of the accretion crust of Sikhote-Alin.

The results of studying the Nd isotopic composition in rocks of metamorphic complexes of the south of the Far East Region of Russia [15] show that the Precambrian–Early Paleozoic metapelites of the area of study are characterized by model ages $t_{Nd(DM)}$ = 1.5–2.0 Ga, while metabasites are characterized by a model age of 1.3–1.7 Ga. The model ages $t_{Nd(DM\text{-}2)}$ of Paleozoic granitoides that intruded into the ancient units, surrounding Sikhote-Alin $t_{Nd(DM\text{-}2)}$ vary greatly in the range of 0.83–1.5 Ga. As a consequence, if an additional source of juvenile material represented by the island arc basalts existed, the simultaneous erosion of these units could lead to the formation of sedimentary rocks with Nd isotopic characteristics corresponding to the Samarka accretionary prism ($t_{Nd(DM)}$ = 1.0–1.3 Ga). However, arkosic deposits of the Taukhe and Zhuravlevka terranes ($t_{Nd(DM)}$ = 2.0–2.1 Ga) could not be collected due to erosion of these geological complexes (Fig. 2). One can suppose that these rocks formed due to other more "mature" sources of terrigenous material.

Judging by the sharp differences in Early Cretaceous faunistic complexes described in deposits of these terranes (boreal complexes in the Zhuravlevka terrane and Tethian complexes in the Taukhe terrane [3, 11]), the sources of clastic material for these sequences were geographically separated. In the first case, a possible source area of the clastic material could be the eastern margin of the Siberian Craton; in the second case, it could be complexes of the Sino-Korean Craton or its Paleozoic framing.

Comparison of the Nd isotopic composition of Mesozoic granitoides of the Sikhote Alin and sedimentary rocks of the upper continental crust of their host terranes (Fig. 2) shows that the Nd model ages of granitoides correspond to those of upper crustal deposits of the corresponding units (for plumasite granitoides) or these granitoides have younger age values (for calc-alkaline and moderately alkaline series). This is evidence that at deeper levels of the Sikhote-Alin system there is no isotopically more ancient rock substrate. On the contrary, the systematic increase in $\varepsilon_{Nd}(t)$ and rejuvenation of the Nd model age of calc-alkaline granitoides (compared with sedimentary rocks and S-granites of metasedimentary origin) show that sedimentary strata are underlain by complexes enriched in radiogenic Nd of probable juvenile nature.

Thus, the results of isotopic studies confirm conclusions made during detailed geological study of accretionary complexes of Sikhote-Alin, that an ancient pre-Mesozoic basement is absent beneath the folded structures of the Sikhote-Alin.

CONCLUSIONS

(1) Formation of Mesozoic sedimentary strata of Sikhote-Alin was connected with transport of terrigenous material from geological units of different nature. Along with the Precambrian and Paleozoic geological complexes, formations of the eastern part of the Siberian and Sino-Korean cratons could be probable sources of terrigenous material.

(2) Folded structures of Sikhote-Alin are underlain by complexes of the juvenile crust; the Pre-Mesozoic sialic foundation is absent within the area of study.

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