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GEOCHEMISTRY

Sr and Nd Isotopic Compositions and Sources of Basalts of Southern Primorye

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The paper presents new data on the Sr and Nd isotopic compositions in basalts of southern Primorye (43°30′–47° N and 134°–137° E). Information about this area is missing in the literature devoted to geochemical typification and sources of Cenozoic basalts of eastern Asia [1, 2, and others]. Numerous K–Ar dates have recently been obtained for basalts of this region in the Laboratory of Isotopic Geochemistry and Geochronology, IGEM RAS [3–5]. Taking into consideration these ages and based on geological–geochemical characteristics, we have subdivided Late Jurassic, Cretaceous, and Early Paleogene basalts into three types. The first type comprises alkaline and subalkaline varieties with high concentrations of HFSE (Ti, Zr, Nb, Hf), as well as Ba, K, Rb and LREE. They occur in faulted and thrust slabs of Triassic–Lower Cretaceous siliceous–terrigenous deposits and olistostromes. Volcanics of this type formed periodically in the Late Jurassic–Paleogene interval. The second type includes high-Ti subalkaline varieties depleted in elements with large ionic radii. The varieties began to form in the Early Cretaceous. Together with rocks of the first type, they occur in the same structures. The third type includes Paleocene–Eocene continental basalts that predominate in the study region. The volcanics mentioned above are intraplate (partially, plume) varieties. This inference is consistent with the Nd and Sr isotope data discussed below. Schemes of distribution of volcanics and data on their age and content of major and accessory elements are given in [3–5].

Type 1 volcanics (alkaline rocks with high concentration of Ti and Ba) are widespread in the Sikhote-Alin folded area. They form flat conformable bodies dikes, fissure intrusions, and volcanic pipes in Jurassic–Early Cretaceous (jaspers, cherts, shales, and siltstones), Triassic (limestones), and Jurassic (cherts) olistoplaques of the Valanginian olistostrome. At the present-day section, alkali basalt exposures form belts in tectonic horsts and fault systems. The earliest variety is represented by meimechites of the pipe located near the Settlement of Ariadnoe (kaersutites are dated at 158 ± 6 Ma) and alkali dolerites among Jurassic sandstones of Mt. Bol'nichnaya in the Nezhdanka River valley (160 ± 2, 158 ± 6 Ma). The Kokshar fissure intrusion (17 × 2 km) represents an intrusive analog of type 1 volcanics. It is composed of titanium–augite pyroxenites (with kaersutite, biotite, and apatite) and accompanied by dikes of alkaline rocks and carbonatites. Pyroxenites and nepheline syenites are estimated at 160 ± 7 Ma (K–Ar biotite method). According to data from [6], Nd and Sr isotopic compositions in pyroxenites and carbonatites of the massif are uniform (ε_{Nd}^{T} ranges from +4.2 to +4.3, $(^{87}Sr/^{86}Sr)_0$ = 0.7035–0.7039). In general, K–Ar data have established a series of intrusion pulses for basalts of this type in the Late Jurassic–Paleogene interval. Fissure intrusions, sills and dikes of alkali gabbro-dolerites, basalts, and trachytes in the center of the Dal'negorsk ore field are dated back to the Albian and Late Cretaceous [3, 5]. Most bodies of type 2 basalt are also located there. These subalkaline basalts make up small flat bodies, dikes, ring dikes, fissure intrusions in siltstones, cherts, jaspers of the Gorbushin Group (J_2–K_1), and limestones (T_{2-3}). They are deposited in NE- and NS-trending faults. Relative to type 1 rocks, they are characterized by high contents of TiO_2 (>2%), moderate concentrations of Nb (25–50 ppm), and low contents of LILE and LREE (K, Rb, Ba, La, Ce). Intrusion of these rocks corresponds to the early orogenic stage. According to isotope dates, the emplacement phases fall within time intervals of 116–104, 90–85, and 80–72 Ma. In terms of the Zn/Nb ratio (2–4 in alkali and 4–8 in early orogenic subalkaline basalts), both rock varieties correspond to hot spot melts (OIB) with participation of material of the EMII type.

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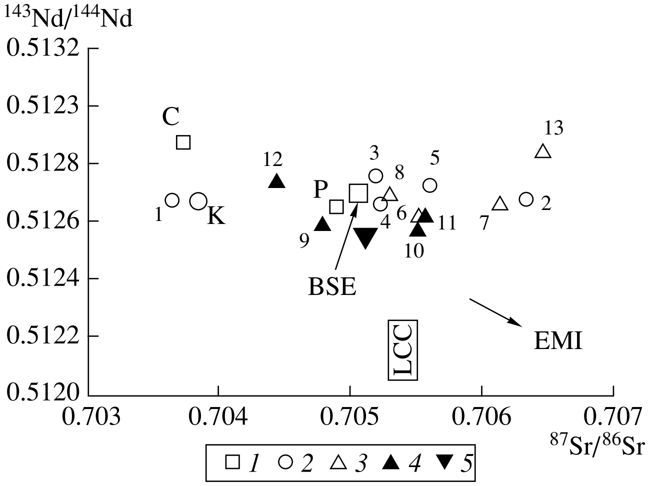
Type 3 is represented by Paleocene and Eocene post-orogenic basalts and basaltic andesites that predominate in the study region. They mainly occur as steep dikes 0.5–2 m thick (in some places, 3–5 m). Clusters of dikes make up NS- and NNE-trending belts up to hundreds of meters wide and a few kilometers long along the strike. The dikes penetrate terrigenous–siliceous deposits of the folded basement, Mesozoic alkali basalts, and Cretaceous–Paleogene acid volcanics and granitoid intrusions. Individual small sheets of basic lava (1.5–2 km across and tens of meters thick) are also found. Type 3 basalts are depleted in Nb (8–12 ppm) and Zr (70–130 ppm). The isotope dating of the earliest bodies of this type yielded 64–58 Ma, and the remaining mass of dikes yielded 54–53, 51–49, and 45 Ma.

Until recently, scanty data on the Nd and Sr isotopic compositions were available only for Mesozoic–Early Cenozoic basalts of the study region, namely rocks of the Kokshar Massif [6], and for Paleogene basalts found near Kavalerovo [1]. Information about Sr^{87}/Sr^{86} ratios available in the literature is summarized in [7]. New data on the Sr and Nb isotopic compositions in our representative specimens are given in the table and the figure.

Preparation of specimens; their chemical decomposition with mixed tracers ^{85}Rb–^{84}Sr and ^{150}Nd–^{149}Sm for determination of the concentration of investigated elements by the isotopic dilution method; and separation of Rb, Sr, Sm, and Nd fractions were carried out using standard procedures and ion-exchange chromatography. The isotopic composition of these elements was established by the Sector 54 Micromass multiple-collector mass spectrograph. The measurement accuracy for the ^{147}Sm/^{144}Nd and ^{143}Nd/^{144}Nd ratios is not worse than ±0.15% and ±0.002%, respectively. The measurement accuracy for the ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios made up ±0.5% and ±0.002%, respectively.

Interpretation of the results obtained is based on the concept of isotopic compositions of BSE global reservoirs [8], which virtually coincide with PRIMA [9]. Point C [9] corresponding to the composition of plumes is shifted to the Nd-depleted area. The area between C and BSE characterizes isotopic compositions of mantle magma sources in different geodynamic environments, such as OIB basalts, hot spots in oceans and continents, rifts in aseismic rises of the ocean floor, continental rifts, continental plateaus, and continental-margin orogens [8–10]. Rocks depleted in radiogenic Nd and enriched in radiogenic Sr (relative to BSE) indicate the participation of enriched sources EMI and EMII [8].

In the rocks studied, we found no compositions corresponding to environments of island arcs and mid-ocean ridges (N-MORB). Nd and Sr isotopic compositions of type 1 plume bodies (Kokshar pyroxenites, [6]) are clustered near point C ("average plume" [9]). Isotopic compositions of other elements make up clusters near BSE (figure), within areas of OIB isotopic compositions (according to [8]), and basalts of active margins [10]. One specimen (no. 73, Early Cretaceous gabbro from fissure intrusion) is characterized by a high degree of crustal contamination. Composition trends within groups are nearly horizontal. Zindler and Hart believe differentiation to be responsible for such a shift toward higher values of the Sr^{87}/Sr^{86} ratio at equal values of the ^{143}Nd/^{144}Nd isotope ratio [8]. Nd and Sr isotopic compositions in the volcanics studied are most similar to compositions of volcanics from the hot spot of the Marquesas Islands [11]. Compositions of Paleogene continental basic rocks correspond to a source slightly enriched in nonradiogenic Nd and are very similar to Eocene basalts (53–49 Ma) of southern Primorye [1], Cenozoic basalts of continental rifts in the Sea of Japan, and plateau basalts of the Columbia River in the United States [12]. The Sr and Nd isotopic compositions in Paleogene basalts are consistent with the inference on their intraplate origin.



Sr–Nd diagram for Late Mesozoic–Paleogene basalts of southern Primorye. (*1*) Average compositions of (C) plumes, (P) primitive mantle, (LCC) lower crust [9]; EMI, EMII, BSE [8]; (*2–5*) rock types: (*2*) type 1 alkali plume basalts, (K) pyroxenite of the Kokshar Massif [6], (*3*) early orogenic subalkaline plume volcanics of type 2 and tholeiites, (*4*) Paleogene continental basalts and basaltic andesites of type 3, (*5*) two specimens of Eocene basalts of southern Primorye (53–49 Ma [1]). Numerals are samples analyzed by the author.

Materials on the Sr and Nd isotopic compositions in Late Cenozoic basalts of eastern Asia in northeastern China, southwestern Japan, islands of the Sea of Japan, and central and northern Sikhote-Alin (both in type and distribution of mantle xenoliths) are available in [1, 2, 15, and others]. The authors of the mentioned works concluded that Cenozoic volcanics in the region were derived from spinel lherzolites of the subcontinental lithospheric mantle, which melted under the influence of an asthenospheric diapir, with the significant role of EMI- and EMII-type materials at different stages of Cenozoic volcanism.

Rb–Sr, Sm–Nd, and K–Ar data for basalts of southern Primorye

Ord. nos.	Speci-men no.	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$ $\pm 2\sigma$	$(^{87}Sr/^{86}Sr)_0$	$^{87}Sr/^{86}Sr$ $\pm 2\sigma$	Nd, ppm	Sm, ppm	$^{147}Sm/^{144}Nd$ $\pm 2\sigma$	$^{143}Nd/^{144}Nd$ $\pm 2\sigma$	$(^{143}Nd/^{144}Nd)_0$	ε^0_{Nd} $\pm 2\sigma$	ε^T_{Nd}	T_{K-Ar}
1	71	92	560	0.49	0.703654	0.704769 ± 13	47	8	0.109	0.512797 ± 9	0.512683	3.1 ± 2	4.9	160 ± 2
2	59	75	545	0.41	0.706333	0.706866 ± 13	40	8	0.122	0.512756 ± 10	0.512683	2.3 ± 2	3.2	92 ± 2
3	38	210	730	0.82	0.705202	0.706102 ± 11	32	6	0.121	0.512829 ± 9	0.512768	3.7 ± 2	4.5	77 ± 2
4	89	180	1000	0.54	0.705242	0.705798 ± 11	87	14	0.094	0.512715 ± 7	0.512670	1.5 ± 1	2.5	72 ± 3
5	2427	25	1060	0.07	0.705623	0.705695 ± 11	80	10	0.0745	0.512771 ± 7	0.512735	2.6 ± 1	3.7	72 ± 4
6	20	14	463	0.088	0.705533	0.705640 ± 13	33	7.0	0.129	0.512703 ± 8	0.512631	1.3 ± 2	2.0	85 ± 3
7	29	34	346	0.29	0.706154	0.706481 ± 13	17	4.3	0.154	0.512753 ± 9	0.512672	2.2 ± 2	2.7	80 ± 4
8	191	4.9	230	0.062	0.705312	0.705393 ± 13	9.0	2.8	0.189	0.512820 ± 9	0.512706	3.6 ± 2	3.6	92 ± 6
9	308	22	770	0.086	0.704810	0.704875 ± 13	13	3.0	0.114	0.512645 ± 10	0.512605	0.1 ± 2	0.69	53 ± 5
10	1936	26	750	0.10	0.705522	0.705594 ± 11	27	6.0	0.128	0.512623 ± 10	0.512580	–0.3 ± 2	0.16	51 ± 2
11	438	33	1520	0.065	0.705582	0.705624 ± 11	20	5.0	0.133	0.512663 ± 6	0.512623	0.5 ± 1	0.86	46 ± 1
12	385	7	560	0.038	0.704454	0.704476 ± 14	26	6.0	0.136	0.512784 ± 9	0.512748	2.9 ± 2	3.2	40 ± 3
13	73	5	609	0.025	0.706479	0.706516 ± 14	19	5.0	0.160	0.512962 ± 8	0.512853	6.3 ± 2	6.8	104 ± 6

Note: (1–5) Type 1 plume rocks and their differentiates: (1) 71/03, alkali dolerite, Nezhdanka River; (2) 59/9, alkali dolerite, Vysokogorskaya River (courtesy of V.P. Simanenko); (3) 38/03, gabbro-dolerite, the Dal'negorsk boron deposit; (4) 89/86, taxitic shonkinite, the same area; (5) 2427/90, sodium trachyte, the Klubnyi Spring, Dal'negorsk; (6–8) type 2 (early orogenic) rocks: (6) 20/03, dolerite, the Malyshev Creek valley; (7) 29/03, gabbro-dolerite, the same area; (8) 191/86, tholeiitic basalt, Mt. Sakharnaya Golova; (9–12) type 3 (Paleogene) rocks: (9) 308/87, hornblende-andesite, dike, the Svetlyi Otvod Spring; (10) 1936/88, basalt, postore dike, the Verkhnee deposit; (11) 438/87, trachybasalt, postgranite dike, the Dal'negorsk boron deposit; (12) 385/85, plagiobasalt, sheet, Plastun Bay; (13) 73/03, gabbro, fissure intrusion, Mt. Sakharnaya Golova.

Our data indicate a minor role of EMII in sources of the Late Mesozoic and Early Cenozoic volcanism in the described segment of the continental margin. In contrast to basalts of northeastern China [15], Mesozoic basalts of Primorye are related to the more depleted and metasomatized substrate, typical of the subcontinental lithospheric mantle. Asthenospheric sources served as the major agent of volcanism since the Early Cretaceous.

CONCLUSIONS

The continental-margin segment located between 43°30′–47° N and 134°–137° E in the Sikhote-Alin folded region and the eastern volcanic belt underwent a prolonged intraplate volcanism in the course of alternating compression and tension in the Late Mesozoic–Paleogene. This period was marked by the formation of alkaline-basaltic melts with high concentrations of Ti, Zr, Nb, La, Ba, and K. Early stages of compression also promoted the emplacement of subalkaline basalts and tholeiites, which were similar in composition to enriched asthenospheric melts developed at hot spots. After the Cretaceous–Paleocene intense acid magmatism in the region, Paleogene basalts formed on the thick continental crust in extended zones. In terms of formation conditions, they correspond to rift-related basalts of the continental margin. Their specific features, for instance, Zr/Nd values, are similar to those in basalts of continental plateaus and rifts. The location of Paleogene basalts was controlled by scattered extension zones.

The inference about the intraplate origin of volcanics in the region is confirmed by the Sr and Nd isotope data that indicate the OIB-type source of melts.

The Sr and Nd isotopic compositions of Late Mesozoic plume volcanics in Primorye are similar to those of Late Mesozoic–Early Cenozoic basalts in western Transbaikalia and Mongolia [13, 14]. This fact and the similarity of geochemical characteristics allowed us to suggest that the periphery of the North Asian plume should have reached in the Late Mesozoic the continental margin, the position of which was close to the present-day position. The scale and duration of plume activity in Far East Russia were much lower. Sources (in particular, involvement of enriched mantle components) were different. Low volumes of volcanics in Primorye indicate the activity of small isolated plume apophyses. In the preorogenic time (Late Jurassic–Early Cretaceous), plume volcanics formed in epicontinental rift-grabens. Active zones in the Cenozoic were only represented by isolated centers of differentiation and channels of fluid effects of plume magma. Plume magmatic and fluid activities were retained and revived in individual tectonic zones in the Late Mesozoic–Eocene period.

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