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GEOCHEMISTRY

Composition and Isotopic Evolution of Potassic Volcanic Rocks from the Southeastern Gorny Altai

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In the geodynamic evolution of the Gorny Altai, high-K magmatism was manifested repeatedly in several spatially limited areas. In the southeastern area of the region, the youngest rocks of this process are represented by the Early Jurassic association of Li–F granites at the Kalguty rare metal deposit [1] and the Triassic mica lamprophyres (minettes) of the Chuya Complex [2, 3] comparable in age with traps of the Siberian Craton [4]. The Middle Ordovician Edelveis Complex of K-alkaline basic rocks and carbonatites [5] and the Devonian Aksai trachyandesite–dacite–rhyolite complex studied by the authors of this communication were formed in the Paleozoic. The derivatives of the latter complex are known in the closely located Aksai and Kalguty volcanotectonic depressions situated at the border with the Mongolian Altai (Fig. 1). The conditions of the active continental margin that existed during the Emsian–early Givetian stage of the evolution of the Gorny Altai Terrane are considered to be the most preferential geodynamic model for formation of these volcanics [7, 8]. New data on rare element contents and Nd, Sr, and O isotopic compositions of the rocks belonging to the Aksai Complex presented in this communication also suggest its formation in the continental-margin setting and bear information on mantle–crust interaction in the course of origination and transportation of subduction-related potassic magmas.

The Kalguty and Aksai volcanotectonic depressions are located at the southeastern margin of the Kholzun–Chuya anticlinorium and are superimposed upon the Cambrian–Ordovician metaturbidite sequences of the Gorny Altai Group (Fig. 1). In both depressions, the volcanic rocks are spatially associated with Silurian–Devonian carbonate–terrigenous sequences and the Late Mesozoic lamprophyres and granitoids. In contrast to the Kalguty Depression where the Aksai complex is largely made up of subvolcanic intrusions, lavas and pyroclastic rocks are predominant in the Aksai Depression [6]. The older basaltic trachyandesites, trachyandesites, andesites, dacites, and trachydacites give way to the rhyolites, trachyrhyolites, and ultrapotassic rhyolites, which prevail in the upper part of the effusive section and are exposed as separate flows without obvious evidence for superimposed potassic metasomatism [6]. The subvolcanic magmatic rocks make up dikes and stocks composed of rhyolites, rhyodacites, granodiorites, quartz syenites, leucogranite porphyries, and equigranular leucogranites of variable alkalinity. The poorly fractionated rock series of high-Na basaltic trachyandesites, trachyandesites, and andesites (lavas and tuffs), as well as sporadic basaltic and dacitic lavas (Oyum paleovolcano), are localized at the northwestern margin of the Aksai Depression, indicating the heterogeneous character of volcanic activity.

The chemical compositions of the rocks of the Aksai Complex vary widely in both silica contents and level of alkalinity (Table 1). Except for the sodic Oyum sequence, the volcanic rocks should be defined as potassic calc-alkaline series with a stable $K_2O/Na_2O > 1$ (up to 60 in leucogranites and ultrapotassic rhyolites). Approximately 30 vol % of the Oyum paleovolcano belongs to rocks with high values of the Mg index (mg# 50–69) and indicator ratios (Ni/Cr ~0.9, La/Yb ~20, Rb/La ~0.4, and Ca/Sr ~115). These parameters are comparable with those of adakites from continental margins [6]. Volcanics of the Aksai Complex have broadly similar rare element patterns irrespective of their facies and degree of fractionation. In comparison with the primitive mantle (PM) composition, they are 20–300 times enriched in most LILE and HFSE, except Sr, P, and Ti, whose contents are close to those in the PM (Fig. 2). The magma-generating sources were presumably localized in the lower lithosphere. This conclusion also follows from high REE concentrations in

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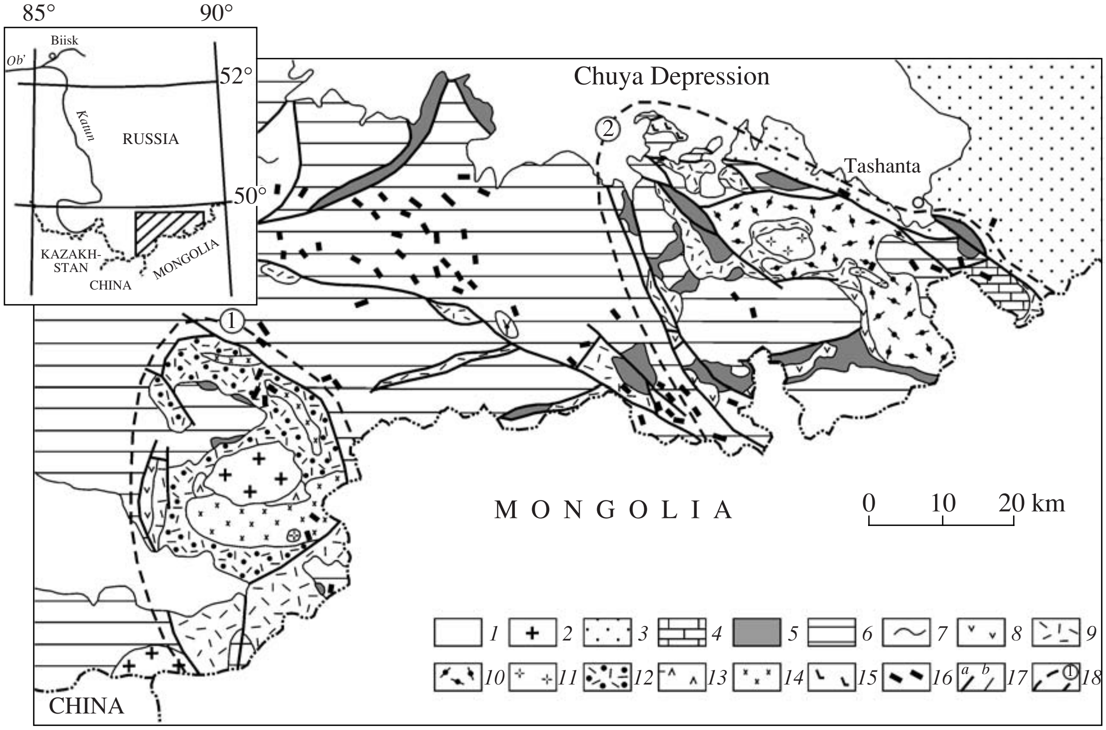

Fig. 1. Geological sketch map of the southeastern Gorny Altai, modified after [6]. (*1*) Cenozoic sediments; (*2*) Mesozoic granitic rocks; (*3–6*) Paleozoic carbonate and terrigenous rocks: (*3*) Middle–Upper Devonian, (*4*) Lower Devonian, (*5*) Lower Silurian–Lower Devonian, (*6*) Middle Cambrian–Lower Ordovician; (*7*) Paleozoic metamorphic rocks; (*8–15*) Aksai volcanic complex: (*8*) trachyandesite, basaltic trachyandesite, and basalt (lavas); (9) rhyodacite and rhyolite, (*10*) trachyrhyolite, (*11*) subvolcanic and hypabyssal subalkali leucogranite, (*12*) rhyolite, (*13*) hypersthene dacite, (*14*) granodiorite porphyry, (*15*) intermediate and basic volcanic rocks of the Oyum paleovolcano; (*16*) Early–Middle Triassic lamprophyres and lamproites of the Chuya Complex; (*17*) faults (*a*) and geological boundaries (*b*); (*18*) contours of volcanotectonic depressions: (1) Kalguty, (2) Aksai.

volcanic rocks of the Aksai Complex. The negative Eu anomaly (Eu/Eu* = 0.1–0.9, see Fig. 2) in combination with a deficiency in Sr is caused by plagioclase fractionation. Judging from the level of enrichment in rare elements (Table 1) and their ratios (La/Yb ~4–20, Ba/La ~5–27, Ba/Nb ~10–55, Th/Ta ~8–16, Th/Yb ~1.2–4.8), the Aksai Complex was formed in the subduction-related setting with involvement of crustal material in processes of melting and participation of the slab-derived fluid (Figs. 3a, 3b). The Rb–Sr isochron calculated from five whole-rock samples of andesite, trachyandesite, dacite, rhyolite, and trachyrhyolite (Table 2, samples Zhu-1, Zhu-4, Ul-1, Ul-7, and Bsh-3) yielded an age of 370 ± 4.2 Ma (MSWD = 1.21; I_{Sr} = 0.707515), which is consistent with the suggested timing (Emsian–early Givetian) of the active continental margin evolution [8].

The comparative analysis of isotopic compositions of volcanic rocks of the Aksai Complex shows that magmatic sources were heterogeneous as in other cases of subduction-related magmatism. Despite the obvious presence of the mantle material of the MORB or PM (PREMA) type, the distinct positive correlation of $\delta^{18}O$ (from +9.3 to +12.8 ‰) and $^{87}Sr/^{86}Sr_{(T)}$ (from 0.7065 to 0.7088) demonstrates large-scale involvement of crustal material in magma formation (Table 2, Fig. 3c). Issuing from the parameters of the Late Devonian continental crust ($^{87}Sr/^{86}Sr_{(370)}$ ~ 0.718 and $\delta^{18}O$ ~ +25‰) and the depleted mantle ($^{87}Sr/^{86}Sr_{(370)}$ ~ 0.7023 and $\delta^{18}O$ ~ +5.7‰), the degree of crustal contamination is no less than 30%. In contrast to compositionally similar volcanic rocks from the Andean margin, southeastern Spain, and central Java [11–14] with the Sr–O isotopic evolution characterized by a mixed line (basalt + ancient crust), the compositions of the rocks of the Aksai Complex appreciably deviate toward the mixing line of mantle material and pelagic sediments (Fig. 3c). This fact indicates that the subduction-related fluid could serve as an additional factor of the mantle–crust interaction. The suggested involvement of the crustal material in processes of melting is also supported by the proportions of the Nd and Sr isotopes (Table 2). The $\varepsilon_{Nd}(T)$ values (from –1.5 to +1.6) of volcanic rocks of the Aksai Complex are close to the BSE range with appreciable shift of isotopic compositions away from the mantle array toward enrichment in radiogenic Sr ($\varepsilon_{Sr}(T)$ from +34 to +67‰). These values are typical of the upper continental crust (Fig. 3d). At the same time,

Table 1. Representative chemical compositions of volcanic rocks of the Aksai Complex

Component	1 (503)	2 (Oyu-5)	3 (Ul-7)	4 (Ul-1)	5 (Zhu-1)	6 (Zhu-4)	7 (Ul-5)	8 (BSh-3)
SiO_2	53.78	55.05	62.59	63.39	64.64	74.45	74.51	74.54
TiO_2	2.69	0.99	0.96	1.04	1.10	0.31	0.18	0.19
Al_2O_3	13.45	15.56	14.32	13.77	14.81	12.51	12.94	13.56
Fe_2O_3	15.67	10.17	11.05	8.33	7.19	2.54	2.31	1.37
MnO	0.28	0.04	0.12	0.06	0.11	0.03	0.03	0.03
MgO	1.92	5.16	1.77	1.12	1.85	0.42	0.10	0.32
CaO	4.97	1.17	0.91	1.38	2.67	0.58	0.17	0.08
Na_2O	3.45	6.65	1.11	4.53	2.30	3.12	2.35	0.60
K_2O	2.44	1.07	2.91	4.14	3.25	4.47	6.83	7.56
P_2O_5	1.39	0.40	0.29	0.34	0.27	0.08	0.03	0.02
LOI	1.02	4.20	3.92	1.91	1.26	1.50	0.68	1.77
Total	101.12	100.49	100.00	100.07	99.41	100.01	100.03	100.05
Cr	13	56	6	67	17	5	10	6
Ni	44	50	20	45	41	6	12	28
V	195	165	43	57	88	20	7	8
Co	22	26	11	10	14	3	2	2
Cs	24	1	5	2	7	3	5	4
Rb	177	17	146	113	114	167	216	253
Ba	328	265	446	676	650	527	283	629
Sr	209	72	37	69	186	89	38	21
Nb	13.1	10.8	14.7	18.2	17	9.5	27.5	21.3
Ta	1	0.8	1.8	1.7	1.2	1	2.9	2.1
Zr	259	142	304	370	491	169	256	235
Hf	6	5	10	10	12	5	10	7
Y	65	18	56	57	63	33	81	78
Th	7.8	10.8	16.9	13.5	17.8	11.5	23.8	18.2
U	2.1	1.8	3.9	3.4	3.7	2.4	5	5.7
REE (total)	245	217	235	172	298	140	351	197

Note: (1–8) Rocks of the Aksai Depression (samples Oyu-5, Ul-1, Ul-5, Ul-7, Bsh-3) and Kalguty Depression (samples 503, Zhu-1, Zhu-4): (1, 2) basaltic trachyandesite, (3) andesite, (4) trachyandesite, (5) hypersthene dacite, (6) rhyolite, (7) trachyrhyolite, (8) ultrapotassic trachyrhyolite. Major oxides (wt %) and rare elements (ppm) were determined with XRF and ICP MS at the United Institute of Geology, Geophysics, and Mineralogy in Novosibirsk (N.M. Glukhova, analyst) and the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements in Moscow (D.Z. Zhuravlev, analyst).

the model age $T(\mathrm{Nd})_{DM}$ of 1.3–1.5 Ga testifies to the direct participation of the Riphean lower crust in magma generation. A similar protolith age ($T(\mathrm{Nd})_{DM}$ ~1.2–1.4 Ga) is noted for the spatially related Early Jurassic granitic rocks of the Kalguty ore-magmatic system ($\varepsilon_{Nd}(T)$ from –1.5 to –5.1) [1], as well as for the Triassic lamprophyres and lamproites ($T(\mathrm{Nd})_{DM}$ ~1.2 Ga, $\varepsilon_{Nd}(T)$ from –2.5 to –3.3, $\varepsilon_{Sr}(T)$ from +61 to +67) of the Chuya subvolcanic complex of the southeastern Gorny Altai (Figs. 1, 3d). These lamprophyres are interpreted as products of mixing of the material of the thermally activated and enriched lithospheric mantle and the continental crust [3]. Therefore, one cannot rule out that the EM1 mantle source together with depleted mantle and crustal components participated in the generation of the parental magma for volcanics of the Aksai Complex. The comparison of $\varepsilon_{Nd}(T)$ of the Paleozoic and Mesozoic high-K rocks (Fig. 3d) sug-

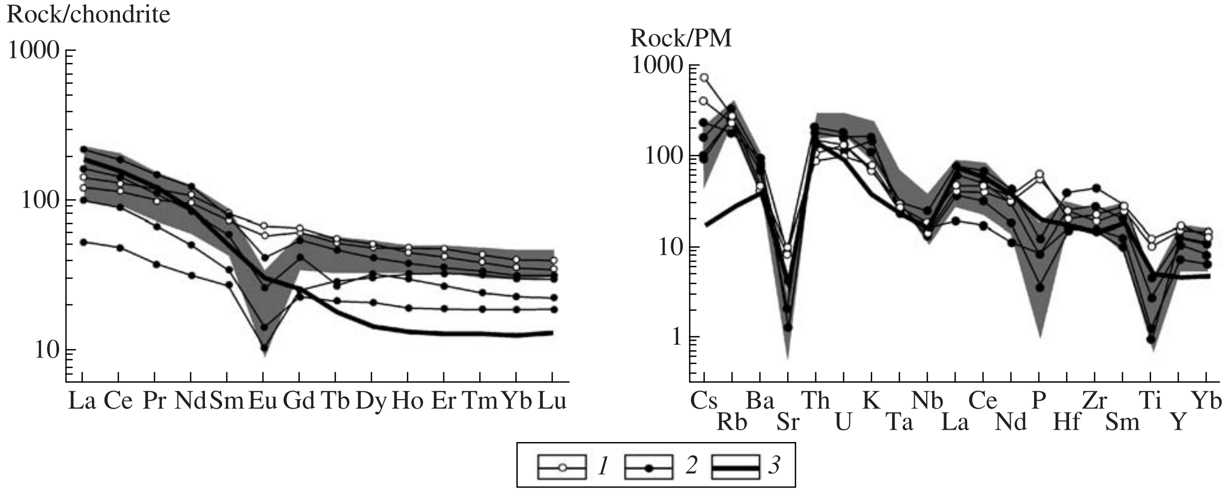

Fig. 2. Distribution of rare elements in volcanic rocks of the Aksai Complex. (*1, 2*) Rocks of the Kalguty Depression: (*1*) basaltic trachyandesite, (*2*) subvolcanic dacite, rhyodacite, and rhyolite; (*3*) basaltic andesite of the Oyum paleovolcano. The field of volcanic rocks of the Aksai Depression is gray. (PM) Primitive mantle.

gests that the potassium content in igneous rocks increased with thickening of the continental lithosphere.

The obtained geochemical data lead to the following conclusions:

(1) The Aksai volcanic complex was formed at the active continental margin that existed during the Middle Devonian history of the Gornyi Altai. Chemical features of rocks of the volcanic complex suggest its affiliation to various formations.

Table 2. Nd, Sr, and O isotopic compositions of volcanic rocks of the Aksai Complex

Sample	Rock	Sm, ppm	Nd, ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$(^{143}Nd/^{144}Nd)_T$	$\varepsilon_{Nd}(T)$	$T(Nd)_{DM}$
503	TAB	10.95	44.2	0.1498	0.512523 ± 6	0.512164	−0.04	1493
Ul-7	A	8.16	36.6	0.1348	0.512409 ± 4	0.512086	−1.54	1429
Ul-1	TA	6.92	30.3	0.1382	0.512517 ± 5	0.512185	+0.37	1276
Oyu-5	TAB	6.82	37.7	0.1094	0.512510 ± 7	0.512247	+1.58	935
Zhu-1	D	11.5	53.7	0.1295	0.512445 ± 6	0.512134	−0.63	1275
Zhu-4	R	5.24	24.4	0.1300	0.512453 ± 4	0.512141	−0.49	1268
Bsh-3	TR	7.12	30.8	0.1395	0.512524 ± 7	0.512189	+0.45	1284
Sample	Rock	Rb, ppm	Sr, ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_T$	$\varepsilon_{Sr}(T)$	$\delta^{18}O_{SMOW}$
503	TAB	247.0	293.0	2.443	0.721663 ± 7	0.708781	+67.0	+9.3
Ul-7	A	143.4	38.47	10.77	0.764106 ± 12	0.707360	+46.81	+11.9
Ul-1	TA	110.0	66.7	4.78	0.732341 ± 5	0.707135	+43.62	+11.8
Oyu-5	TAB	17.48	75.88	0.667	0.709990 ± 10	0.706475	+34.24	+11.1
Zhu-1	D	109.6	180.1	1.762	0.717314 ± 5	0.708023	+56.23	+12.1
Zhu-4	R	162.8	86.1	5.48	0.736170 ± 3	0.707273	+45.58	+12.8
Bsh-3	TR	235.0	19.4	35.6	0.895680 ± 12	0.707965	+55.41	+12.3

Note: (TAB) Basaltic trachyandesite, (A) andesite, (TA) trachyandesite, (D) dacite, (R) rhyolite, (TR) trachyrhyolite. Samples 503, Zhu-1, and Zhu-4 were taken from the Kalguty Depression; samples Oyu-5, Ul-1, Ul-5, Ul-7, and Bsh-3, from the Aksai depression. Concentrations of elements were determined with an accuracy of ±0.5%. Uncertainties (2σ] for $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ are not higher than 0.5 and 1.0%, respectively; and for $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$, not higher than 0.005 and 0.1%, respectively. The parallel measurements showed the following results: for La Jolla, $^{143}Nd/^{144}Nd = 0.511839 \pm 7$ ($N = 13$, normalized to $^{146}Nd/^{144}Nd = 0.7219$); for SRM-987, $^{87}Sr/^{86}Sr = 0.710283 \pm 21$ ($N = 9$, normalized to $^{88}Sr/^{86}Sr = 8.37521$). Initial isotope ratios and $\varepsilon_{Nd}(T)$ and $\varepsilon_{Sr}(T)$ values for 370 Ma were calculated using present-day CHUR values ($^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{144}Nd = 0.1967$) and UR values ($^{87}Sr/^{86}Sr = 0.7045$, $^{87}Rb/^{86}Sr = 0.0827$). The model Nd age $T(Nd)_{DM}$ was calculated on the basis of present-day values for the depleted mantle: $^{143}Nd/^{144}Nd = 0.51315$, $^{147}Sm/^{144}Nd = 0.2137$. $\delta^{18}O$ values are given relative to SMOW with an accuracy of ±0.2‰. The isotopic compositions of Sr, Nd, and O were measured on a Finnigan MAT-262 mass spectrometer at the Institute of Precambrian Geology and Geochronology, St. Petersburg, and the Geological Institute, Moscow (V.P. Kovach and B.G. Pokrovsky, analysts).

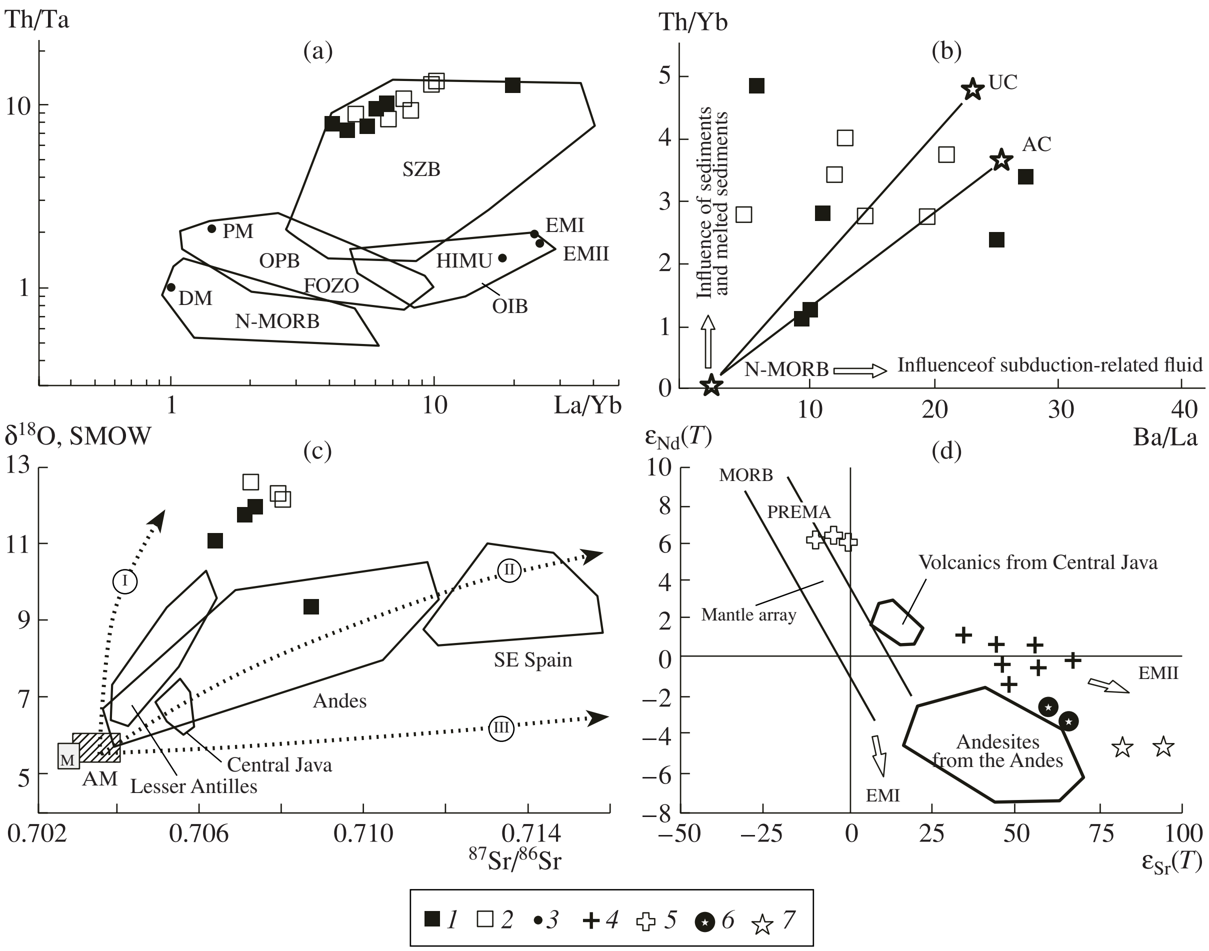

Fig. 3. Isotopic-geochemical parameters of volcanic rocks of the Aksai Complex. (*1*) Basaltic trachyandesite, trachyandesite, and andesite; (*2*) dacite, trachydacite, rhyodacite, rhyolite, and trachyrhyolite; (*3*) parameters of mantle sources; (*4–7*) Nd and Sr isotopic compositions of rocks: (*4*) Middle Devonian volcanics of the Aksai Complex, (*5*) Middle Devonian alkaline rocks and carbonatites of the Edelveis Complex [5], (*6*) Early–Middle Triassic lamproites of the Chuya Complex [3], (*7*) Early Jurassic kalgutite and elvan of the Kalguty ore–magmatic system [1]. (a) Th/Ta–La/Yb discriminant diagram: (N-MORB) mid-ocean ridge basalt; (OPB) oceanic plateau basalt; (SZB) subduction-related basalt; (FOZO) basalts of focal zone; mantle sources [9]: (HIMU) source with high U/Pb ratio; (EM1 + EM2) enriched mantle; (DM, PM) depleted and primitive mantle, respectively. (b) Th/Yb–Ba/La discriminant diagram [10]: values of N-MORB, UC (average upper crust), and AC (average continental crust) are given after Rollinson (1993); (c) Sr–O isotope compositions of the primitive mantle (M), mantle beneath island arcs (AM), and mixing lines I–III (dotted), after [11]: (I) basalt + young crust and pelagic sediments; (II) basalt + ancient crust; (III) mantle + ancient subduction-related sediments (contamination of source); fields of volcanic rocks from the Lesser Antilles Islands, southeastern Spain, Andes (andesites), and central Java (medium- and high-K basalts and basaltic andesites) are contoured after the data from [11–14]. (d) Positions of mantle array and present-day MORB, PREMA, EM1, and EM2 reservoirs are adjusted to present-day parameters [15].

(2) Effusive rocks of this complex are derived from heterogeneous sources due to processes of subduction. In the course of subduction, the heterogeneous materials of the depleted mantle, continental crust, pelagic sediments, and EM1-type substrate were involved in melting and evolution of the parental magmatic melt.

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