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GEOCHEMICAL SIMILARITY OF CAMBRIAN ALKALINE AND SUBALKALINE MAGMATISM (KUZNETSK ALATAU OROGEN, SIBERIA): A NEW DATA SYNTHESIS

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Abstract. This is a synthesis of recent geochemical evidence from Cambrian granitic, gabbro-monzonitic, and few small gabbro-foidolitic intrusions in the Early Paleozoic Kuznetsk Alatau orogen (western Central Asian Orogenic Belt, Siberia). Their origin is attributed to late- and post-orogenic regional magmatism which produced different rock types sharing basic similarity in isotope systematics and trace-element compositions. The $\varepsilon_{Nd}(t)$ values of ~2 to 8.7 in main igneous lithologies record the extent of interaction between depleted and enriched mantle. Concurrent increase of initial $^{87}Sr/^{86}Sr$ (0.7039–0.7058) ratios and $\delta^{18}O$ values (6.5–13 ‰) in rocks and minerals, as well as ^{207}Pb enrichment ($^{207}Pb/^{204}Pb(t)$ = 15.5–15.7), indicate crustal contamination of mantle melts. Trace-element patterns in the rocks correspond to a mixed IAB + OIB source. The alkaline and subalkaline rocks of the Kuznetsk Alatau area share trace element and isotopic similarity and apparently emplaced almost synchronously late during a regional-scale tectonic event. The synthesized data show that Cambrian magmatism in the area involved mixed mantle and continental crust melt components and acted in a complex tectonic setting of the former active margin of the Paleo-Asian Ocean impacted by a mantle plume.

Keywords: *Cambrian magmatism, trace-element and isotope geochemistry, mantle plume, continental margin, Paleo-Asian Ocean, Kuznetsk Alatau orogen*

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ГЕОХИМИЧЕСКОЕ СХОДСТВО КЕМБРИЙСКОГО ЩЕЛОЧНОГО И СУБЩЕЛОЧНОГО МАГМАТИЗМА (КУЗНЕЦКИЙ АЛАТАУ, СИБИРЬ): СИНТЕЗ НОВЫХ ДАННЫХ

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Аннотация. Обобщены последние геохимические данные по кембрийским гранитоидным, габбро-монцонитовым и габбро-фойдолитовым интрузивам каледонид Кузнецкого Алатау в западной части Центрально-Азиатского орогенического пояса (Сибирь). Их происхождение связано с развитием поздне- и посторогенного регионального магматизма, в результате которого образовались различные изверженные породы, сходные по микроэлементному и изотопному составу. Значения $\varepsilon_{Nd}(t)$ ~ 2–8,7 в главных интрузивных разновидностях отражают степень взаимодействия между деплетированной и обогащенной мантией. Одновременное увеличение первичных отношений $^{87}Sr/^{86}Sr$ (0,7039–0,7058) и значений $\delta^{18}O$ (6,5–13 ‰) в породах и минералах, а также обогащение ^{207}Pb ($^{207}Pb/^{204}Pb(t)$ = 15,5–15,7) указывают на коровую контаминацию мантийных расплавов. Соотношения редких рассеянных элементов в плутонах соответствуют смешанному IAB + OIB источнику. Щелочные и субщелочные породы Кузнецкого Алатау обладают сходством по микроэлементам и изотопам и, по-видимому, сформировались почти синхронно во время позднего регионального тектогенеза. Синтез данных показывает, что кембрийский магматизм происходил при смешении в расплаве компонентов мантии и континентальной коры в сложной геодинамической обстановке воздействия сублитосферного плюма на ранее сформированную активную окраину Палеоазиатского океана.

Ключевые слова: *Кембрийский магматизм, геохимия редких рассеянных элементов и изотопов, мантийный плюм, континентальная окраина, Палеоазиатский океан, Кузнецкий Алатау*

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Introduction

Multiple events of alkaline and subalkaline intraplate magmatism in the geological history of the Central Asian Orogenic Belt (CAOB) have been attributed to the action of mantle plumes [Ernst, 2014; Yarmolyuk, Kuzmin, Ernst, 2014]. Most of Paleozoic intrusions are located in the western flank of the orogenic belt, in the regions of Kuznetsk Alatau, Minusa, Altai-Sayan, Lake Baikal, southeastern Tuva, western Transbaikalia, and northern Mongolia [Yashina, 1982; Nikiforov, Yarmolyuk, 2007; Sklyarov et al., 2009; Yarmolyuk, 2010; Doroshkevich et al., 2012, 2018; Vrublevskii et al., 2012, 2014, 2016a, 2016b, 2018a, 2019, 2020 a, 2020b; Vrublevskii, 2015; Izbrodin et al., 2017; Vrublevskii, Kruk, 2018; Salnikova et al., 2018; Vorontsov et al., 2021; Vrublevskii, Gertner, 2021].

The Early Paleozoic (Caledonian) Kuznetsk Alatau orogen is an island arc terrane within CAOB that formed along the Paleo-Asian active margin. The collisional and accretionary processes were associated with closure of the Paleo-Asian Ocean which, together with the Protopacific ocean, opened as a result of the plume-induced break-up of the Neoproterozoic Rodinia supercontinent about 900–800 Ma ago [Şengör, Natal'in, Burtman, 1993; Khain, 2003; Dobretsov, Buslov, Vernikovsky, 2003; Windley et al., 2007; Li et al., 2008; Kheraskova et al., 2010; Wilhelm, Windley, 2015; Wan et al., 2018].

The regional-scale event of late- and post-orogenic magmatism, which spanned an interval from ~510 to 490 Ma, produced granitic, gabbro-monzonitic, and mafic alkaline rocks with the respective U-Pb, Sm-Nd, and Rb-Sr ages. It is important to identify the mantle sources of parent melts that produced the diverse subalkaline and alkaline plutonic rocks of the Kuznetsk Alatau terrane [Vrublevskii et al., 2014, 2015, 2016a, 2016b, 2018a].

The aim of this paper is to bring together previously published [Vrublevskii et al., 2016a, 2018a; Vrublevskii, Gertner, 2021] but dispersed geochemical results for specific intrusions within the Kuznetsk Alatau terrane, which are nearly coeval but compositionally different. The synthesized trace-element and isotopic data from the Cambrian igneous rocks of the area reveal several components in parent magmas that represent an active margin setting and an effect of a mantle plume. The geochemical and geochronological proximity of different igneous lithologies suggests similarity of their magma sources and almost synchronous emplacement in the conditions of a possible plume impact on the lithospheric complexes of a former island arc. The model of regional-scale Cambrian magmatism is new for the Kuznetsk Alatau area. The chronology and evolution trends of the Cambrian magmatism have implications for exchange and/or recycling of material at convergent plate boundaries.

Geological background

The Kuznetsk Alatau accretionary-collisional terrane borders the Minusa and Kuznetsk rift basins in the west and east, respectively (Fig. 1), and has a complex tectonic framework. It comprises abundant Early Paleozoic oceanic and island arc complexes with fragments of the Precambrian basement and small superimposed Devonian graben-like basins [Kungurtsev et al., 2001], as well as deformed Neoproterozoic-Cambrian volcanics and clastic-carbonate sediments, Middle Paleozoic subcontinental volcano-sedimentary deposits, Late Precambrian ophiolites, and Cambrian plutons. Less abundant Devonian and Permian intrusions appear most often as small mafic alkaline stocks and dikes [Vrublevskii, Gertner, 2021]. The general tectonic style of the Kuznetsk Alatau terrane, like the whole Central Asian Orogenic Belt, records the history of its collisions with other terranes during the Paleo-Asian Ocean closure [Dobretsov, Buslov, Vernikovsky, 2003; Yarmolyuk et al., 2003].

The Cambrian plutons of different compositions discussed in this paper are located in the northern (Mariinsk segment) and eastern (Batenev segment) slopes of the Kuznetsk Alatau Range, where they intrude metamorphosed volcanic and carbonate sediments (Fig. 1 b, 2).

Mafic alkaline magmatism occurs as the Upper Petropavlovka and University small (~0.8–3 km^2) gabbro-foidolite intrusions cut by foyaite and few calcite carbonatite dikes and veins in the Mariinsk segment.

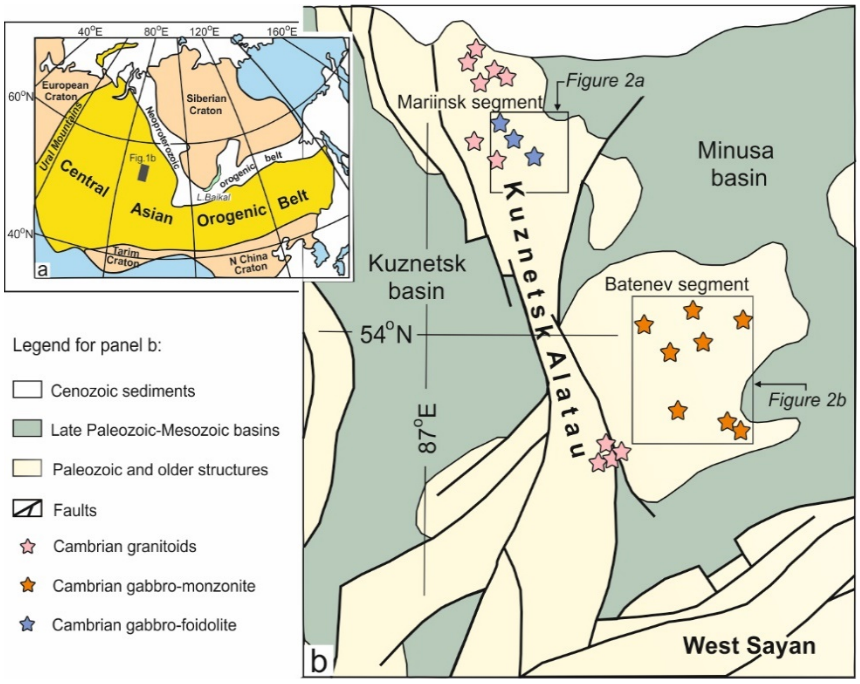

Fig. 1. (a) Location map of the Kuznetsk Alatau area in the Central Asian Orogenic Belt, simplified after [Şengör, Natal'in, Burtman et al., 1993; Jahn, Wu, Chen, 2000]; (b) tectonic framework of the Kuznetsk Alatau terrane and clusters of Cambrian magmatism, after [Vrublevskii et al., 2016a; Vrublevskii et al., 2018a; Vrublevskii, Gertner, 2021]

Рис. 1. (а) Схема размещения Кузнецкого Алатау в Центрально-Азиатском орогеническом поясе, по [Şengör, Natal'in, Burtman et al., 1993; Jahn, Wu, Chen, 2000]; (b) тектоническая схема террейна Кузнецкого Алатау и проявлений кембрийского магматизма, по [Vrublevskii et al., 2016a; Vrublevskii et al., 2018a; Vrublevskii, Gertner, 2021]

The foidolite and carbonatite rocks have Sm-Nd isochron ages of ~510–500 Ma [Vrublevskii, 2015; Mustafaev et al., 2020]. Gabbro-monzonite plutons of similar ages (~490–505 Ma, U-Pb) cluster among Early Paleozoic granitoids of the Batenev segment. The structural and compositional frameworks of large (~40 to 200 km^2) plutons correspond to a two-phase history [Dovgal', Shirokikh, 1980; Vrublevskii et al., 2018a]. The Cambrian (~490–510 Ma, U-Pb) plutons reaching sizes of 60–70 to 500 km^2 consist mainly of granodiorite-tonalite and later granites [Vrublevskii et al., 2016a]. Coeval granitoids in the Mariinsk segment form up to 300–500 km^2 batholiths composed of diorite-tonalite, plagiogranite, and granite, as well as quartz syenite and granosyenite [Rudnev, 2013].

Compositions of main igneous lithologies

Various aspects of chemistry and isotope systematics of the Kuznetsk Alatau igneous rocks were detailed in numerous earlier publications [Rudnev, 2013; Vrublevskii, 2015; Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020; Vrublevskii, Gertner, 2021]. Main features of different rock types are summarized as selected analyses in Tables 1 and 2 and illustrated by trace-element and Nd and Sr isotope patterns in Figures 3 and 4.

Major- and trace-element chemistry.

The Kuznetsk Alatau *gabbro-foidolite* intrusions typically have low silica (~44–53 wt. % SiO_2), high calcium (to ~10–15 wt. % CaO), and elevated aluminum (to 18–22 wt. % Al_2O_3) and alkali (to 9–12 wt. % ($Na_2O + K_2O$), $Na_2O/K_2O \approx 2–7$) contents. Compared to gabbro, the later foyaite and foidolite have lower MgO# (0.5–0.1) and compatible elements (529–4 ppm Cr, 112–3 ppm Ni, 200–8 ppm V, 48–2 ppm Co), but higher LILE and HFSE reaching ~10 to 90 ppm Rb, ~2000 ppm Ba, 540 to 1180 ppm Sr, 0.4 to 7 ppm Th, 0.3 to 5.4 ppm U, 46 to 240 ppm REE, ~100 to 280 ppm Zr, and ~10 to 50 ppm Nb). The patterns of REE ($La/Yb_N \approx 6–11$; Eu/Eu* ≈ 1) and other trace elements in these intrusions look like those of average ocean island basalts (OIB) but bear additional island-arc basalt (IAB) signatures. The IAB contribution appears in multi-element spectra with distinct Nb-Ta and Zr-Hf depletion.

The *gabbro-monzonitic* intrusions of the area contain moderate amounts of alkalis (~3–10 wt. % $Na_2O + K_2O$) and show large ranges of silica (~43 to 65 wt. % SiO_2) and alumina (~15–20 wt. % Al_2O_3), while Fe# is about 0.5. Some of the rocks have relatively high K_2O contents of ~5–6 wt. % (K_2O/Na_2O from 0.2–0.7 to 0.5–1.5), along with quite low TiO_2 (~2.2 to 0.5 wt. %). The concentrations of compatible elements decrease markedly in the series from gabbro to monzodiorite and monzonite: 436 to 12 ppm Cr, 182 to 9 ppm Ni, 574 to 32 ppm V, and 56 to 5 ppm Co, whereas LILE and HFSE become times higher: ~3 to 134 ppm Rb, ~100 to 2900 ppm Ba, ~0.2 to 31 ppm Th, ~0.4 to 37 ppm Nb, and ~60 to 336 ppm REE (Eu/Eu* ≈ 0.7–1.3); Sr reaches ~1400 to 2500 ppm. The REE (La/Yb_N ≈ 7–30) and other trace-element patterns in gabbro are similar to the average IAB composition, with typical minimums in Nb-Ta and Zr-Hf. The LILE and HFSE concentrations in more strongly fractionated (La/Yb_N ≈ 14–34) monzonites approach or even exceed the OIB average but the general shapes of the spectra remain as in IAB.

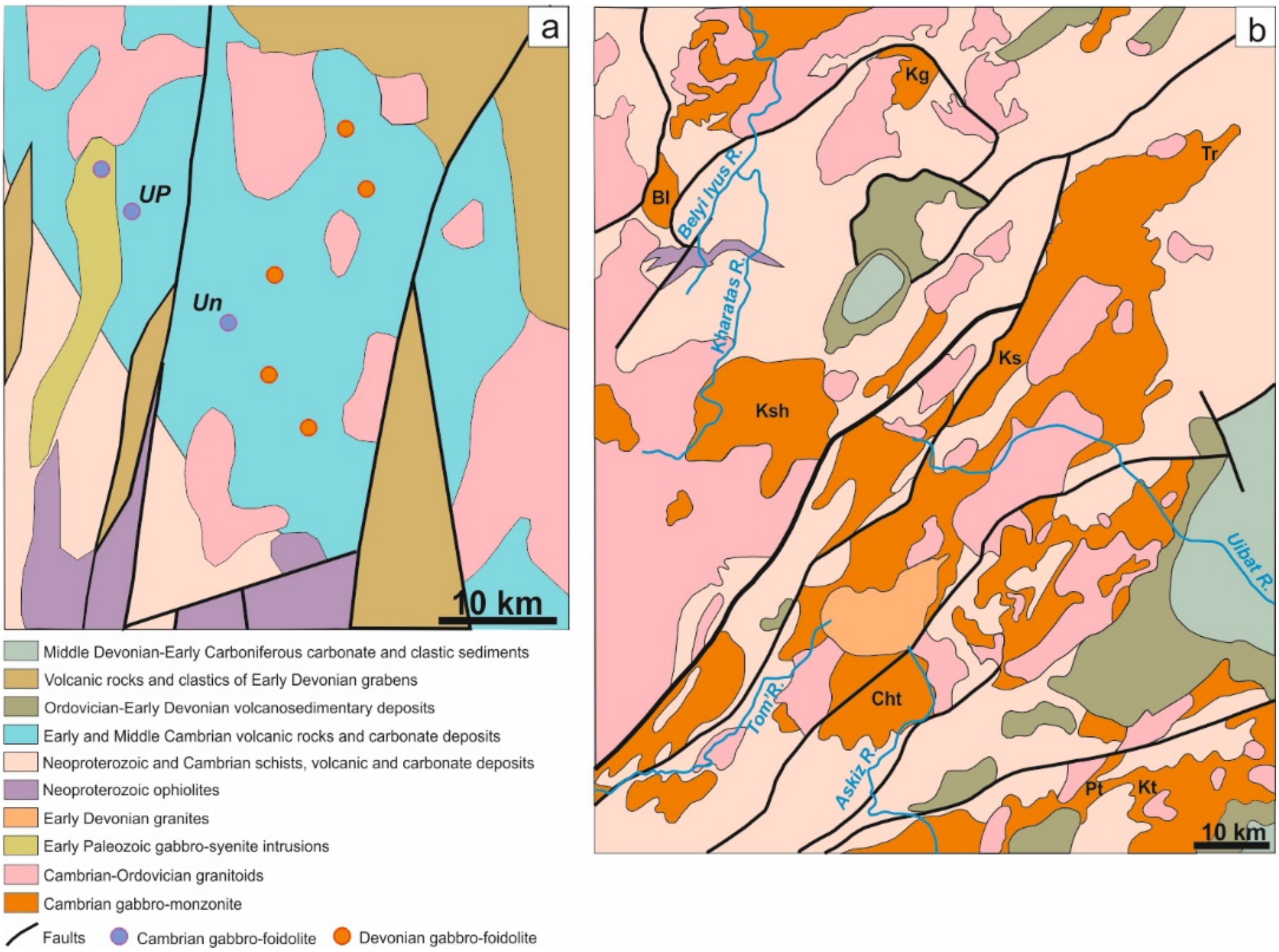

Fig. 2. (a) Location map of gabbro-foidolite plutons (not to scale) and (b) granitoids in the Mariinsk segment, after [Rudnev, 2013; Vrublevskii et al., 2014; Vrublevskii, Gertner, 2021]

Gabbro-foidolite intrusions: UP = Upper Petropavlovka, Un = University; (b) Geological framework of gabbro-monzonitic and granitic intrusions in the Batenev segment, after [Dovgal', Shirokikh, 1980; Vrublevskii et al., 2016a, 2018a]. Gabbro-monzonite intrusions: Kg = Kogtakh, Bl = Balakhcha, Ksh = Kashpar, Ks = Kiskach, Cht = Chas-Taiga, Pt = Pistag, Kt = Karatag

Рис. 2. (a) Локализация габбро-фойдолитовых плутонов (вне масштаба) и (b) гранитоидов в Мариинском сегменте, по [Vrublevskii et al., 2014; Vrublevskii, Gertner, 2021; Rudnev, 2013]

Габбро-фойдолитовые интрузивы: UP = Верхнепетропавловский, Un = Университетский; (b) Геологическая карта габбро-монцонитовых и гранитных интрузивов в Батеневском сегменте, по [Dovgal', Shirokikh, 1980; Vrublevskii et al., 2016a, 2018a]. Габбро-монцонитовые интрузивы: Kg = Когтахский, Bl = Балахчинский, Ksh = Кашпарский, Ks = Кискачинский, Cht = Частайгинский, Pt = Пистагский, Kt = Каратагский

Table 1

Selected analyses of the Kuznetsk Alatau Cambrian granitic, gabbro-monzonitic, and gabbro-foidolitic rocks

Таблица 1

Выборка анализов кембрийских гранитоидов, габбро-монцонитов и габбро-фойдолитов Кузнецкого Алатау

Intrusion	Gabbro-foidolite			Gabbro-monzonite			Granitoids					
Rock type	SG	AG	I	SG	MD	M	Tn	Tn	GD	S	GS	Gr
SiO_2, wt, %	44,98	46,46	44,38	44,77	53,47	58,90	64,04	65,72	67,85	63,14	68,60	70,76
TiO_2	0,95	1,27	0,91	1,57	0,89	1,01	0,43	0,41	0,32	0,60	0,32	0,17
Al_2O_3	15,11	14,71	18,57	14,31	18,89	17,59	16,28	15,09	15,26	17,26	16,65	15,54
Fe_2O_3	11,20	11,34	10,68	14,83	7,83	6,51	5,00	5,82	3,84	3,69	2,88	2,03
MnO	–	–	0,22	0,14	0,12	0,10	0,12	0,10	0,11	0,08	0,06	0,08
MgO	8,93	6,92	2,34	8,12	4,42	3,41	4,12	2,33	1,33	0,51	0,81	0,76
CaO	14,63	10,53	11,42	12,52	7,44	4,67	3,01	4,24	2,46	3,15	2,55	1,35
Na_2O	2,96	4,23	7,22	2,25	4,55	4,06	4,53	1,65	5,07	7,42	4,19	5,55
K_2O	0,95	2,43	2,44	0,96	1,96	2,58	1,94	1,64	2,25	3,38	3,20	3,35
P_2O_5	0,09	0,50	0,69	0,21	0,53	0,33	0,07	0,09	0,05	0,22	0,05	0,06
LOI	1,13	1,26	1,18	0,41	0,13	0,30	0,43	1,82	0,71	0,24	0,12	0,17
Total	*100,93*	*99,65*	*100,05*	*100,09*	*100,23*	*99,46*	*99,98*	*98,91*	*99,25*	*99,70*	*99,43*	*99,82*
Cr, ppm	224	56	28	57	49	35	96	–	51	38	–	40
Ni	56	7	22	86	16	15	32	–	16	7	–	8
V	155	12	81	274	159	125	–	–	–	–	–	–
Co	49	12	21	56	26	17	15	–	10	4	–	5
Sc	24	0,9	5,8	53	19	12	11	–	6	1,6	–	2,4
Pb	–	–	5,4	–	13	11	7	–	9	11	–	14
Cs	0,8	1	0,5	0,6	0,7	1,6	0,9	–	0,4	0,2	–	0,8
Rb	24	42	34	13	69	83	51	44	62	94	64	85
Ba	303	726	1802	231	1105	1076	658	531	1024	1110	1030	785
Sr	538	893	869	720	1407	1336	648	401	809	979	442	745
Nb	9	42	12	4,6	19	21	11	2,4	19	16	14	22
Ta	0,6	2,5	0,7	0,24	1,1	1,5	0,8	0,4	1,4	1	1,3	1,7
Zr	124	279	144	71	157	368	23	23	47	76	209	42
Hf	2,7	4	2,6	1,9	2,6	4,7	0,8	1,2	1,6	2,2	6,5	1,4
Y	22	45	27	15	31	18	10	19	15	11	10	11
Th	2,7	7	3	1,7	6,7	8,9	2,7	2,2	7,5	4,2	4,9	5
U	1,9	5,5	2	0,53	1,5	1,8	1,2	0,8	1,3	0,8	2,6	1,8
La	21	49	32	13	52	49	22	11	47	31	31	35
Ce	45	101	63	29	115	125	43	23	84	60	52	63
Pr	5,2	9,1	7,3	4,4	13	14	5	2,2	8,3	6	6,2	6,4
Nd	21	44	28	20	45	55	19	10	30	20	20	24
Sm	4,6	8,5	5,3	3,9	7,4	9,8	3,3	2,2	4,7	3,1	2,9	3,7
Eu	1,3	2,6	1,8	1,2	2,4	2,3	1	0,72	1,2	0,75	1	0,87
Gd	4,4	8,1	4,8	3,6	6,6	9,1	3,2	2,3	4,5	2,4	2,2	3,4
Tb	0,7	1,3	0,7	0,51	0,8	1,2	0,45	0,4	0,63	0,37	0,36	0,5
Dy	4,3	8,2	4,2	2,9	3,8	6,4	2,1	2,6	3	1,7	2	2,3
Ho	0,9	1,8	0,9	0,57	0,77	1,3	0,4	0,6	0,57	0,35	0,4	0,43
Er	2,4	5,1	2,5	1,5	2,1	3,4	1,1	1,9	1,6	0,98	1,1	1,2
Tm	0,4	0,8	0,4	0,2	0,3	0,53	0,15	0,35	0,22	0,15	0,21	0,17
Yb	2,2	4,8	2,6	1,3	1,8	2,3	1	2,1	1,6	1	1,4	1,1
Lu	0,3	0,7	0,4	0,18	0,27	0,35	0,15	0,29	0,24	0,16	0,18	0,17
ΣREE	114	245	155	82	251	280	102	59	188	128	121	142
LREE/HREE	6,3	7	8,3	6,8	14,5	10,2	10,7	5	13,7	16,1	14,3	14,7

Note. SG = subalkaline gabbro, AG = alkaline gabbro, I = feldspar ijolite, MD = monzodiorite, M = monzonite, Tn = tonalite, GD = granodiorite, S = quartz syenite, GS = granosyenite, Gr = subalkaline granite. (–) is not detected. Major and trace elements and REE in rocks were analyzed by XRF and ICP–MS, respectively, under standard operating conditions. Data after [Rudnev, 2013; Vrublevskii, 2015; Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020].

Примечания. SG = субщелочное габбро, AG = щелочное габбро, I = полевошпатовый ийолит, MD = монцодиорит, M = монцонит, Tn = тоналит, GD = гранодиорит, S = кварцевый сиенит, GS = граносиенит, Gr = субщелочной гранит. (–) не обнаружено. Петрогенные, редкие и редкоземельные элементы в породах анализировались методами XRF и ICP–MS соответственно, в стандартных условиях. Данные по [Rudnev, 2013; Vrublevskii, 2015; Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020].

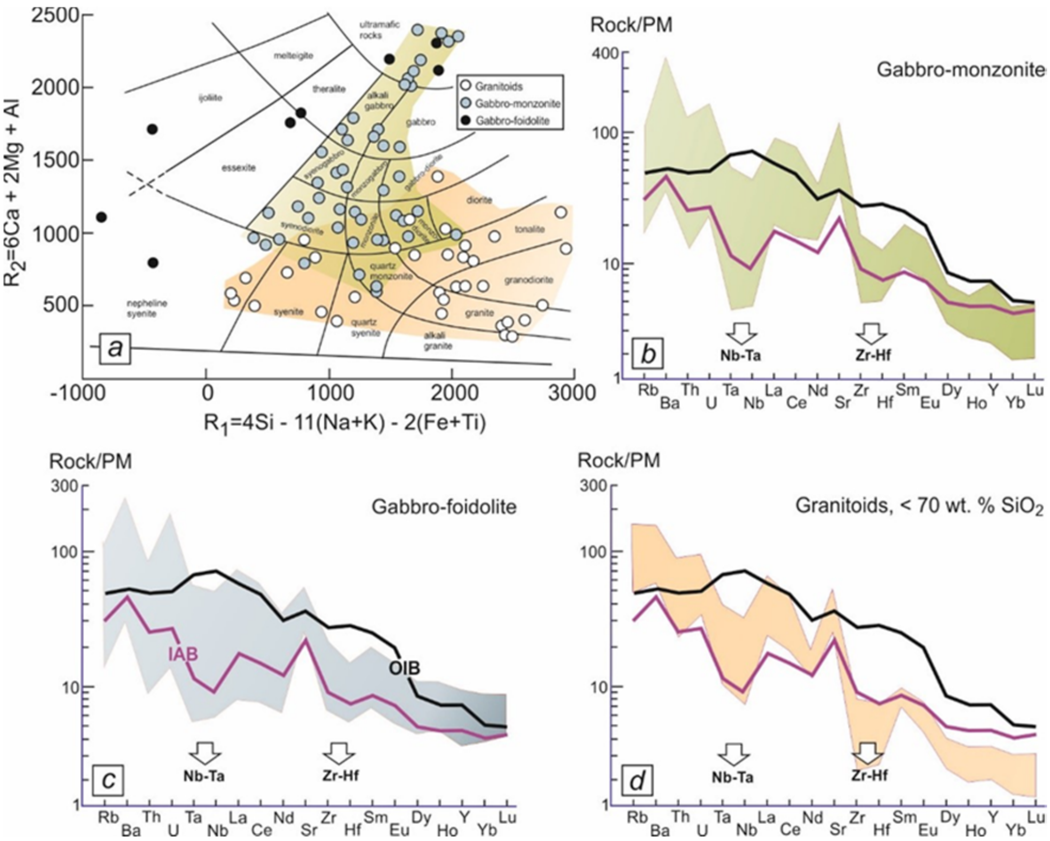

Fig. 3. Chemical classification and compositions of the Kuznetsk Alatau Cambrian igneous rocks
a – R1–R2 diagram [De la Roche et al., 1980]; **b–d** – Primitive mantle-normalized [Sun, McDonough, 1989] multi-element spectra. All diagrams include selected analyses (Table 1) and published data from [Rudnev, 2013; Vrublevskii, 2015; Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020; Vrublevskii, Gertner, 2021]. Average ocean island basalt (OIB) and island-arc basalt (IAB) compositions are after [Sun, McDonough, 1989; Kelemen, Hanghøj, Greene, 2003], respectively

Рис. 3. Химическая классификация и состав кембрийских изверженных пород Кузнецкого Алатау
a – диаграмма R_1–R_2 [De la Roche et al., 1980]; **b–d** – мультиэлементные спектры (нормализация по составу примитивной мантии [Sun, McDonough, 1989]). На диаграммах нанесены табличные (табл. 1) и литературные данные по [Rudnev, 2013; Vrublevskii, 2015; Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020; Vrublevskii, Gertner, 2021]. Средние составы базальтов океанских островов (ocean island basalt = OIB) и островных дуг (island-arc basalt = IAB) по [Sun, McDonough, 1989; Kelemen, Hanghøj, Greene, 2003] соответственно

Most of the Kuznetsk Alatau granitoids are subalkaline, alkaline or less often peralkaline varieties (~58–76 wt. % SiO_2; ~3–13 wt. % ($Na_2O + K_2O$); K_2O/Na_2O ~0.2–1.7) with a relatively low Al saturation index (ASI ≤1.1; suprasubduction granitoids) and Fe# ≤0.8. The REE concentrations are quite low (~50–230 ppm; La/Yb_N ~ from 3–8 to 15–37) while the HFSE distribution corresponds to the average IAB composition with Nb-Ta and Zr-Hf minimums. Some granitoids show above-OIB enrichment in several trace elements that reach ~140 ppm Rb, ~1110 ppm Ba, ~1100 ppm Sr, ~8 ppm U, and ~40 ppm Th.

Isotope systematics (Nd-Sr-Pb-O).

The gabbro-foidolite intrusions of the area show notable variations of initial Nd and Sr isotope ratios, $^{143}Nd/^{144}Nd(t)$ = 0.512245–0.512438 ($\varepsilon_{Nd}(t)$ ~5–8.7) and $^{87}Sr/^{86}Sr(t)$ = 0.7041–0.7058, as well as the ~7–13 ‰ $\delta^{18}O_{V\text{-}SMOW}$ values and the ^{207}Pb enrichment ($^{207}Pb/^{204}Pb(t)$ 15.53–15.71, $^{206}Pb/^{204}Pb(t)$ 17.92–20.65) in rocks and minerals [Vrublevskii, Gertner, 2021].

The gabbro-monzonitic plutons have less radiogenic Nd and Sr isotope compositions ($^{143}Nd/^{144}Nd(t)$ = 0.512174–0.512273; $\varepsilon_{Nd}(t)$ ~3.5–5.4; $^{87}Sr/^{86}Sr(t)$ = 0.7039–0.7052). Their Nd isotope heterogeneity is more prominent than in the gabbro-foidolite rocks. On the other hand, the $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{V\text{-}SMOW}$ (6.5–8.8 ‰) values are concordantly high [Vrublevskii et al., 2018a]. The granitoids of the area share isotopic similarity with the gabbro-monzonitic rocks: $^{143}Nd/^{144}Nd(t)$ = 0.512098–0.512346; $\varepsilon_{Nd}(t)$ ~2–4.8; $^{87}Sr/^{86}Sr(t)$ ~0.7047–0.7052 [Rudnev, 2013; Vrublevskii et al., 2016a]. The isotopic heterogeneity of the igneous rock associations may record participation of different magma sources in the parent melts.

Table 2

Sr-Nd isotopic composition of the Kuznetsk Alatau Cambrian granitic, gabbro-monzonitic, and gabbro-foidolitic rocks

Таблица 2

Sr-Nd изотопный состав кембрийских гранитоидов, габбро-монцонитов и габбро-фойдолитов Кузнецкого Алатау

Rock series	Rock-type	Sm, ppm	Nd, ppm	$^{143}Nd/^{144}Nd$	$^{143}Nd/^{144}Nd(t)$	$\varepsilon_{Nd}(t)$	Rb, ppm	Sr, ppm	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr(t)$
Gabbro-foidolitic	SG	3,42	15,3	0,512808	0,512365	7,25	19	583	0,70620	0,70553
	“	1,77	7,46	0,512907	0,512438	8,67	14	745	0,70520	0,70483
	“	2,74	9,43	0,512937	0,512362	7,19	8,6	709	0,70452	0,70414
	AG	5,98	31,38	0,512766	0,512389	7,71	44	964	0,70649	0,70557
	NS	9,45	50,77	0,512727	0,512432	6,03	207	539	0,71266	0,70495
	I	5,18	27,5	0,512618	0,512245	4,90	19	1365	0,70566	0,70538
	C	2,97	11,9	0,512740	0,512247	4,94	3	1000	0,70590	0,70584
Gabbro-monzonitic	SG	7,84	36,90	0,512627	0,512206	4,14	7,24	1626	0,70414	0,70405
	“	4,91	26,67	0,512538	0,512174	3,52	51,2	961	0,70576	0,70469
	“	9,15	41,78	0,512661	0,512227	4,55	9,7	1164	0,70539	0,70522
	MD	7,88	46,93	0,512511	0,512179	3,61	72,3	1278	0,70551	0,70437
	“	6,21	38,78	0,512513	0,512196	3,95	45,1	1179	0,70561	0,70484
	“	10,79	63,43	0,512538	0,512201	4,04	52,5	2180	0,70450	0,70402
	M	6,27	36,04	0,512586	0,512241	4,82	67,3	733	0,70704	0,70519
	“	3,13	21,02	0,512568	0,512273	5,45	62,8	1092	0,70587	0,70472
	“	6,08	40,36	0,512494	0,512196	3,95	41,3	3073	0,70413	0,70386
Granitic	GD	4,09	24,5	0,512563	0,512226	4,83	42,4	886	0,70576	0,70478
	S	3,88	24,9	0,512543	0,512240	4,59	44,6	1118	0,70557	0,70478
	Gr	3,65	22,9	0,512429	0,512121	2,26	73,2	804	0,70693	0,70514

Note. NS = nepheline syenite, C = carbonatite. Isotopic data after [Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020; Vrublevskii, Gertner, 2021]. The isotope analyses were carried out using the standard techniques and instruments.

Примечания. NS = нефелиновый сиенит, C = карбонатит. Данные по [Vrublevskii et al., 2016a, 2018a; Mustafaev et al., 2020; Vrublevskii, Gertner, 2021]. Изотопные анализы проводились с использованием стандартных методик и оборудования.

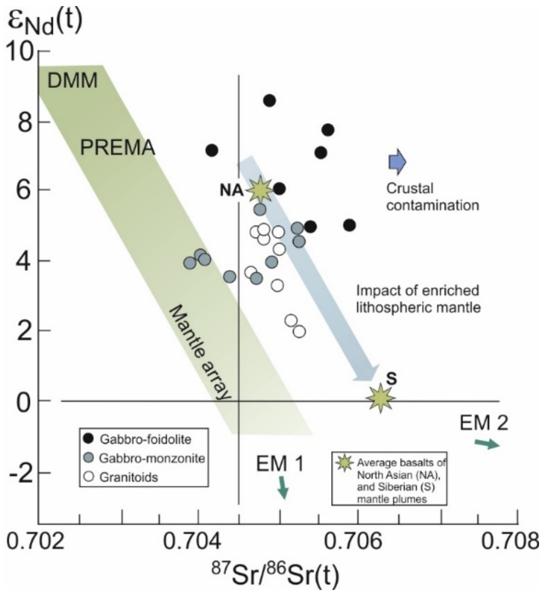

Fig. 4. $\varepsilon_{Nd}(t)$ vs. $^{87}Sr/^{86}Sr(t)$ plot for the Kuznetsk Alatau Cambrian igneous rocks

Average basalt compositions are after [Yarmolyuk, Kovalenko, 2003] for the Altai-Sayan fold area (NA = North Asian plume) and [Lightfoot et al., 1993] for the Siberian Trap Province (S = Siberian plume). Mantle array, DMM (depleted MORB mantle), PREMA (prevalent mantle), EM 1 (enriched mantle 1) and EM 2 (enriched mantle 2) mantle reservoirs are according to [Zindler, Hart, 1986; Salters, Stracke, 2004]

Рис. 4. Диаграмма $\varepsilon_{Nd}(t)$–$^{87}Sr/^{86}Sr(t)$ для кембрийских изверженных пород Кузнецкого Алатау

NA (North Asian plume) = средний состав базальтов Алтае-Саянской складчатой области, по [Yarmolyuk, Kovalenko, 2003] S (Siberian plume) = средний состав базальтов Сибирской трапповой провинции, по [Lightfoot et al., 1993]. Мантийная последовательность (Mantle array), резервуары DMM (depleted MORB mantle), PREMA (prevalent mantle), EM 1 (enriched mantle 1) and EM 2 (enriched mantle 2) мантии, по [Zindler, Hart, 1986; Salters, Stracke, 2004]

Discussion

Major-element chemistry of Cambrian intrusions and its implications.

The discussed plutonic complexes differ markedly in petrography and major-element chemistry. The low-silica (~43–47 wt. % SiO_2) rocks have mainly sodic alkalinity (~ 0.9–6.5 wt. % $Na_2O + K_2O$, $Na_2O/K_2O \geq 1$), which is common to rift-related mantle alkaline magmatism. The higher-SiO_2 (~58–76 wt. %) varieties, including granitoids and most of monzonites, have higher total alkalis (~10–13 wt. % $Na_2O + K_2O$) and variable K_2O/Na_2O ratios from ~0.2 to 1.7. The K_2O contents in some monzonite samples are relatively high (~5–6 wt. % and K_2O/Na_2O up to ~1.5) and, along with low TiO_2 (~ 0.3–2.2 wt. %), may represent continental-margin material at the source. The Al_2O_3 contents of ~12–18 wt. % and relatively low ASI values (≤1.1) in most of the granitoids correspond to *I*-type granite compositions inconsistent with purely collisional environments. Thus, the observed whole-rock chemistry features provide implicit evidence for a complex tectonic setting of magmatism.

Sources of Cambrian plutonic magmatism in the Kuznetsk Alatau orogen

The Cambrian (~510–490 Ma) gabbro-foidolitic, gabbro-monzonitic, and granitic intrusions in the Kuznetsk Alatau orogen emplaced synchronously with magmatic events in the Western CAOB Early Paleozoic large igneous province (LIP) [Izokh et al., 2008; Vrublevskii et al., 2012; Yarmolyuk, Kuzmin, Ernst, 2014]. The Nd isotope composition of rocks reveals a mantle contribution to the parent magma generation. The large $\varepsilon_{Nd}(t)$ range from 8.7 to 2 may result from mixing and homogenization of the depleted (PREMA-like) and enriched (EM-like) lithospheric mantle components.

The gabbro-foidolite rocks are derived from the most depleted mantle, while the share of the EM component is greater in the gabbro-monzonitic and granitic rocks (Fig. 4). Isotopic heterogeneity of this kind in roughly coeval igneous complexes is possible within even a small field of magmatism [Bell, Tilton, 2001]. A similar $\varepsilon_{Nd}(t)$ range of ~1 to 7 is common to Cambrian alkaline plutons elsewhere in the LIP (Russian Altai, SE Tuva, Western Transbaikalia), which have a proven mantle origin [Doroshkevich et al., 2012; Vrublevskii et al., 2012, 2020a]. These Kuznetsk Alatau intrusions, as well as other occurrences of Early Paleozoic magmatism in the Altai-Sayan region, may result from the activity of the North Asian PREMA superplume [Yarmolyuk, Kovalenko, 2003; Kuzmin, Yarmolyuk, Kravchinsky, 2010].

On the other hand, the concurrently increasing $^{87}Sr/^{86}Sr(t) = 0.7039–0.7058$ (Fig. 4) and $\delta^{18}O_{SMOW}$ ~ to 6.5–13 ‰ values in the Kuznetsk Alatau igneous rocks may result from crustal contamination of the parental melts. The interaction of the melts with continental crust is further supported by enrichment in radiogenic lead, with the initial $^{207}Pb/^{204}Pb$ 15.71 and $^{206}Pb/^{204}Pb$ 20.65 ratios typical of those in orogenic areas [Vrublevskii, Gertner, 2021]. Note that many Paleozoic-Mesozoic volcano-plutonic complexes in the Western CAOB share signatures of additional upper crustal ^{87}Sr and ^{18}O inputs [Pokrovskii et al., 1998; Nikiforov et al., 2002; Vrublevskii et al., 2003, 2005, 2012, 2015, 2016a, 2016b, 2018a, 2018b, 2019, 2020a, 2020b; Doroshkevich et al., 2012, 2018; Baatar et al., 2013; Krupchatnikov, Vrublevskii, Kruk, 2018; Vrublevskii, Gertner, Chugaev, 2018; Vrublevskii, Gertner, 2021].

Post-accretion continental margin magmatism under a plume impact.

Despite the enrichment in some LILEs and HFSEs till the OIB level, the trace-element patterns of gabbro-foidolitic, gabbro-monzonitic, and granitic rocks generally show IAB affinity (Fig. 3 b–d). Therefore, magma generation involved mixed OIB-like (within-plate plume) and IAB-like (subduction) components. This mixing is consistent with the idea that the Kuznetsk Alatau accretionary orogen evolved on the former active margin of the Paleo-Asian Ocean [Kungurtsev et al., 2001; Dobretsov, Buslov, Vernikovsky, 2003], which was exposed to the impact of a plume.

Different contributions of the IAB and OIB components to the melts show up in LILE and HFSE variations observed in the analyzed samples, with Th, Ta, Nb, Yb, and Y ranges corresponding to OIB/E-MORB-type sources of enriched mantle (Fig. 5 a–b, f). At the same time, island arc material includes continental crust components, which may be partly responsible for the degree of Nb depletion and its correlation with Zr, as well as for the U, Ba, Rb, and Sr enrichment of the Kuznetsk Alatau igneous rocks (Fig. 3, 5 c–e). Although the εNd(t) values are mostly in the ~3–6 range typical of rocks derived from moderately depleted mantle, the Ce/Pb, Ce/Nb, and Th/Nb ratios vary markedly (Fig. 4, 6), possibly, because the mantle melts were more or less strongly contaminated with island arc material.

Thus, the trace-element patterns of the Kuznetsk Alatau gabbro-foidolitic, gabbro-monzonitic, and granitic rocks record the source heterogeneity, as well as a complex tectonic setting of their emplacement. The geochemical similarity of the Cambrian intrusions in the Kuznetsk Alatau orogen may be due to Early Paleozoic activity of the PREMA/OIB-superplume [Yarmolyuk, Kovalenko, 2003], which impinged on the lithosphere beneath the former active margin of the Paleo-Asian Ocean.

The $\varepsilon_{Nd}(t)$ behavior records variations of depleted and enriched material in the parent mantle domain and is concordant with the general isotopic evolution trend of magma sources from the Early Paleozoic (North Asian plume) through earliest Mesozoic (Siberian plume) time (Fig. 4).

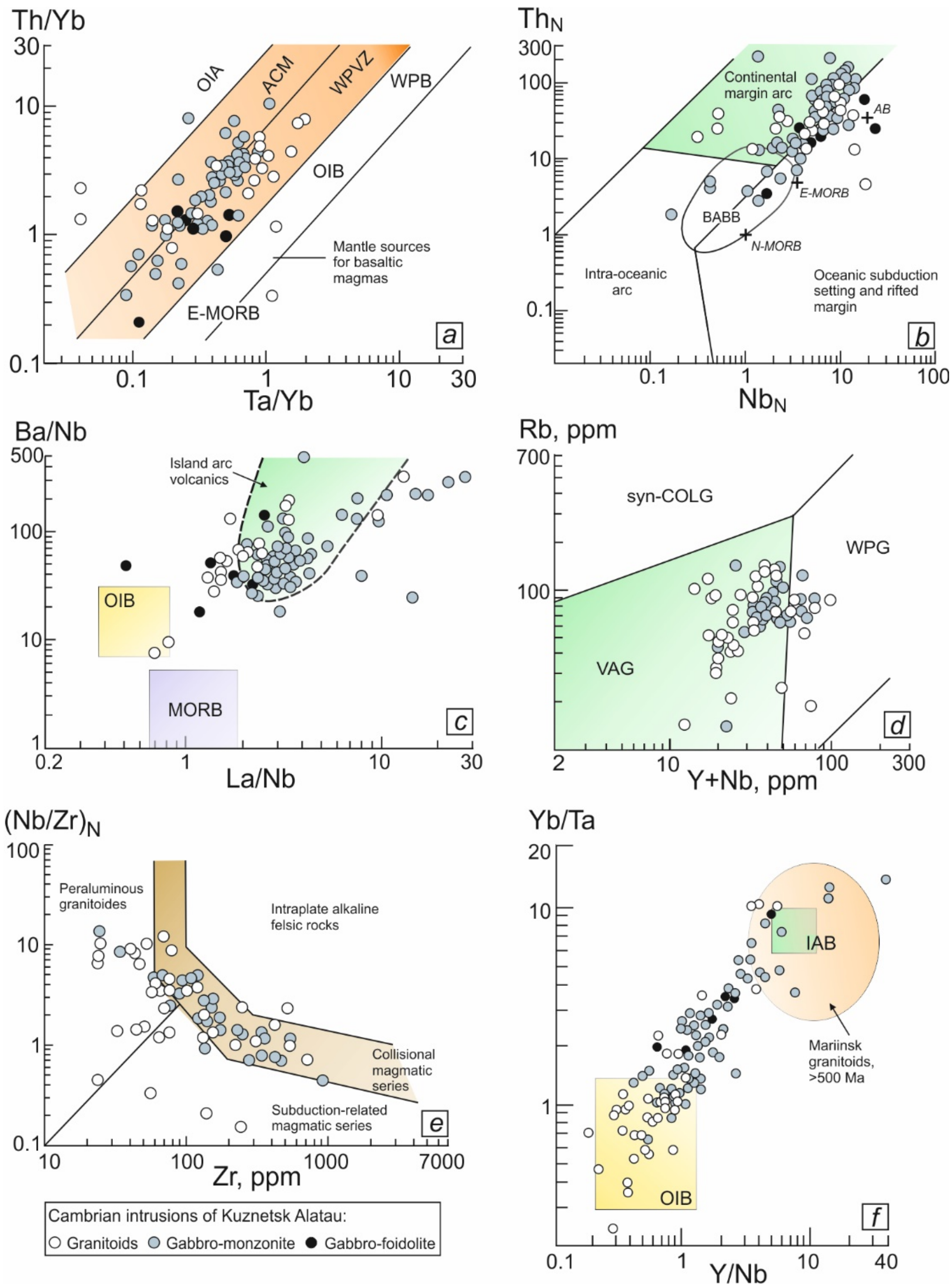

Fig. 5. Trace-element contents and their ratios in the Kuznetsk Alatau Cambrian igneous rocks

a – Th/Yb–Ta/Yb diagram [Gorton, Schandl, 2000]: OIA = oceanic island arc, ACM = active continental margin, WPVZ = within-plate volcanic zone, E-MORB = enriched mid–ocean ridge basalt; WPB = within-plate basalt; **b** – ThN–NbN diagram [Saccani, 2015]: AB = alkaline basalt, BABB = back-arc basin basalt; N-MORB-normalized [Sun, McDonough, 1989] Th and Nb; **c** – Ba/Nb–La/Nb diagram [Bi et al., 2015]; **d** – Rb–(Y + Nb) diagram [Pearce, Harris, Tindle, 1984]: syn-COLG = syncollisional granite, VAG = volcanic arc granite; WPG = within plate granite; **e** – (Nb/Zr)N–Zr diagram [Thièblemont, 1999]: BSE-normalized [Hofmann, 1988] Nb/Zr; **f** – Yb/Ta–Y/Nb diagram [Eby, 1990]. Diagrams in panels d and e include only granitic and monzonitic compositions

Рис. 5. Соотношения микроэлементов в кембрийских изверженных породах Кузнецкого Алатау

а – диаграмма Th/Yb–Ta/Yb [Gorton, Schandl, 2000]: OIA = океанская островная дуга (oceanic island arc), ACM = активная континентальная окраина (active continental margin), WPVZ = внутриплитная вулканическая зона (within-plate volcanic zone), E-MORB = обогащенный базальт срединно-океанического хребта (enriched mid–ocean ridge basalt); WPB = внутриплитный базальт (within-plate basalt); **b** – диаграмма Th$_N$–Nb$_N$ [Saccani, 2015]: AB = щелочной базальт (alkaline basalt), BABB = базальт задугового бассейна (back-arc basin basalt); содержание Th и Nb нормализовано по N-MORB [Sun, McDonough, 1989]; **c** – диаграмма Ba/Nb–La/Nb [Bi et al., 2015]; **d** – диаграмма Rb–(Y + Nb) [Pearce, Harris, Tindle, 1984]: syn-COLG = синколлизионный гранит (syncollisional granite), VAG = островодужный гранит (volcanic arc granite); WPG = внутриплитный гранит (within plate granite); **e** – диаграмма (Nb/Zr)$_N$–Zr [Thièblemont, 1999]: Значения Nb/Zr нормализованы по BSE (Bulk Silicate Earth) [Hofmann, 1988]; **f** – диаграмма Yb/Ta–Y/Nb [Eby, 1990]. На панелях «d» и «e» нанесены составы только гранитов и монцонитов

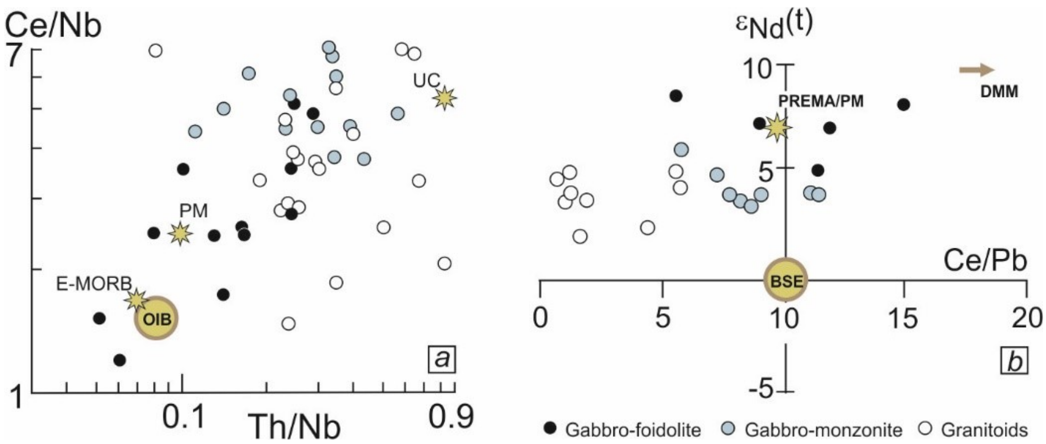

Fig. 6. Ce/Nb–Th/Nb (a) and ε_{Nd}(t)–Ce/Pb (b) diagrams for the Kuznetsk Alatau Cambrian igneous rocks
Compositions of primitive (PM) and depleted (DMM) mantle, E-MORB, OIB, PREMA, BSE (bulk silicate Earth), and UC (upper crust) are after [Zindler, Hart, 1986; Sun, McDonough, 1989; Rudnick, Gao, 2003; Salters, Stracke, 2004]

Рис. 6. Диаграммы Ce/Nb–Th/Nb (a) и ε_{Nd}(t)–Ce/Pb (b) для кембрийских изверженных пород Кузнецкого Алатау
Составы примитивной (PM) и деплетированной (DMM) мантии, E-MORB, OIB, PREMA, BSE и UC (upper crust = верхняя кора), по [Zindler, Hart, 1986; Sun, McDonough, 1989; Rudnick, Gao, 2003; Salters, Stracke, 2004]

Meanwhile, some trace-element and isotopic dissimilarity of the rocks may result from their emplacement among compositionally and structurally heterogeneous accretionary-collisional complexes. Signatures of such plume-lithosphere interaction were reported from different areas of the Paleo-Asian active margins [Dobretsov, 2011; Vrublevskii et al., 2012, 2016a, 2018a; Gordienko, Metelkin, 2016; Gordienko, 2019; Vrublevskii, Gertner, 2021].

The subcontinental lithospheric mantle (SCLM) apparently played a subordinate role in the process, as a mantle wedge effect. Any significant involvement of SCLM components was hardly possible, given the island arc origin of the Kuznetsk Alatau terrane and the Nd isotope composition of the analyzed rocks corresponding to moderately depleted mantle.

Conclusion

Cambrian magmatism in the Kuznetsk Alatau orogen produced granitic, gabbro-monzonitic, and gabbro-foidolitic intrusions within the ~510 to 490 Ma time span and terminated the collisional processes along the Early Paleozoic Paleo-Asian active margin. The observed Sm-Nd isotopic patterns in main igneous lithologies indicate parentage of the magma sources and involvement of PREMA-type and EM-type mantle components in the magma generation. The existence of the prevalent mantle (PREMA) reservoir was possibly maintained by the activity of the North Asian superplume, which induced the Early Paleozoic magmatism of the Western CAOB.

The trace-element compositions of igneous rocks record possible mixing of IAB- and OIB-like components in the source magma, whereas relatively high Sr, Pb and O isotope ratios record crustal contamination of the melts. The revealed geochemical similarity of the Kuznetsk Alatau Cambrian igneous complexes is not fortuitous but may be due to their emplacement in the former active margin exposed to the impact of a mantle plume.

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