

Mantle–Crustal Nature of Early Paleozoic Alkaline Intrusions in Central Sangilen, Tuva (from Nd, Sr, Pb, C, and O Isotope Data)

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Abstract—The Paleozoic foidolite–foyaite plutons of the Sangilen upland (Bayan-Kol, Dakhu-Nur, Chik, and Kharly ones) might have formed in the Late Cambrian–Early Ordovician (~490–500 Ma, Sm–Nd and U–Pb); they are the result of the oldest alkaline magmatism in southeastern Tuva. The intrusion was accompanied by the formation of high-temperature (up to ~600–900 °C) endogenous carbonate rocks containing calcite, alkali pyroxene, Na–Ca amphibole, biotite, fluorapatite, microcline, and nepheline. Silicate and carbonate derivatives were produced, most likely, from genetically related heterogeneous sources with $\epsilon_{Nd}(T)$ varying from 3.0 to 6.3 and from –0.5 to 6.5, respectively, which might be due to the mixing of the depleted (PREMA) and enriched (EM) mantle materials. Initial ratios $^{207}Pb/^{206}Pb \approx 0.89$ and $^{208}Pb/^{206}Pb \approx 2.15$ in K-feldspar from calcitic rocks are close to those of EM 1. The correlation between the stable-isotope ratios ($\delta^{18}O \sim 7.2$ – 19.5 , $\delta^{13}C$ from –6.0 to –1.4‰) and the high $^{87}Sr/^{86}Sr(T)$ ratio (0.7057–0.7076) indicates a significant crustal contamination of magma in the upper horizons of the lithosphere and a minor impact of a meteoric fluid. The assumed synchronous formation of the studied plutons and other alkaline rock complexes of the Early Paleozoic Large Igneous Province in the west of the Central Asian Orogenic Belt as well as their isotope similarity do not rule out that the intrusion took place in the plume–lithosphere interaction setting.

Keywords: alkaline magmatism, isotope geochemistry and geochronology, plume–lithosphere interaction, Sangilen upland, Central Asian Orogenic Belt

INTRODUCTION

Formation of the Central Asian Orogenic Belt (CAOB) was accompanied by the repeated alkaline magmatism in the Neoproterozoic, Paleozoic, and Mesozoic (Andreeva, 1968; Kononova, 1976; Konev, 1982; Yashina, 1982; Samoilov and Kovalenko, 1983; Andreeva et al., 1984; Chernyshova and Morikiyo, 1999; Frolov and Belov, 1999; Nikiforov et al., 2002; Vrublevskii et al., 2003a,b, 2012, 2014a,b, 2016; Nikiforov and Yarmolyuk, 2007; Sazonov et al., 2007; Vernikovskiy et al., 2008; Doroshkevich et al., 2012, 2018; Romanova et al., 2012; Vrublevskii, 2015; Izbrodin et al., 2017; Vrublevskii et al., 2018c). It is believed that the generation and chemical evolution of parental magmas were much due to the plume activity and the geodynamic settings of their intrusion. Sometimes, the mantle nature of volcano-plutonic complexes is indicated by carbonatites, which usually result from differentiation of alkaline ultrabasic melts in the platform setting (Samoilov, 1984; Bell, 1989; Sokolov, 1993; Bell et al., 1998). Carbonatites are less typical derivatives of alkaline magmatism in fold–block areas, including

the CAOB (Kuznetsk Alatau, Gorny Altai, Sayans, western Transbaikalia, and Mongolia), and inherit the heterogeneous composition of their sources (Nikiforov et al., 2002, 2006; Ripp et al., 2009; Doroshkevich et al., 2012; Vrublevskii et al., 2012; Nedosekova et al., 2013; Vrublevskii, 2015).

A feldspathoid province of the Sangilen upland (southeastern Tuva) in the west of the CAOB is an example of the above-mentioned petrographic association. There are 20 small (<5 km²) differentiated plutons with still smaller satellites in this magmatic area. They are united into a series of aegirine–hedenbergite foyaites, juvites, and ijolite–urtites (Yashina, 1982; Andreeva et al., 1984). Alkaline rock bodies are accompanied by vein rocks similar to carbonatites (Kononova, 1957; Dergachev, 1973). The available K–Ar dates for intrusions are not always reliable and fall mostly in the range 300–400 Ma (Yashina, 1982). Recently, however, the first evidence for alkaline magmatism at the Cambrian/Ordovician boundary has been obtained (Nikiforov et al., 2014). The U–Pb and Ar–Ar age of alkali rare-metal granites of the Ulug–Tanzek massif in the north of the Sangilen upland, the youngest rocks in the study region, is 294–302 Ma (Yarmolyuk et al., 2010).

We obtained isotope data on the Bayan-Kol, Kharly, Chik, and Dakhu-Nur foidolite–foyaite plutons in Central

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Sangilen, which suggest the early phase of evolution of regional alkaline magmatism in the Early Paleozoic and point to the specific geodynamic settings of its manifestation and the heterogeneous composition of its sources.

GEOLOGIC AND PETROGRAPHIC OUTLINES

The Sangilen middle massif with the alkaline province under study is a large structural block of the Precambrian Tuva–Mongolian microcontinent (Kuz'michev, 2004). Its basement seems to be composed predominantly of Neoproterozoic schists, gneisses, marbles, and quartzites, and its cover is formed by continent-marginal complexes of Late Riphean–Vendian and Cambrian metamorphosed carbonate, terrigenous, and volcanic rocks. The geologic evolution of the Sangilen massif was much governed by nappe and fold formation accompanied by metamorphic processes (Belyaev and Terleev, 1990; Gibsher and Terleev, 1992; Gibsher et al., 2000). According to isotope dates, there were two main stages of tectonic and metamorphic events at the Precambrian/Paleozoic boundary, ~535 and ~495 Ma. These events took place in accretion–collision settings (Kozakov et al., 2001; Vladimirov et al., 2005). The age of detrital zircons found in the basement gneisses (Moren and Erzin complexes), 0.7–0.8 Ga, probably marks the time of formation of the protoliths of metamorphic complexes, which coincides with the initial stages of the opening of the Paleasian Ocean. Modeling (Vladimirov et al., 2005) showed that the Early Caledonian folded structure of the Sangilen upland was the result of the accretion of the Tannu-Ola island-arc system to the Tuva–Mongolian microcontinent and of the change of transpression (570–490 Ma) by transform fault extension (490–430 Ma). Tectogenesis strongly governed the evolution of regional magmatism. The plutonic facies of magmatism is dominated by Late Precambrian and Early Paleozoic ultrabasic, gabbroid, and granitoid complexes.

The alkaline plutons under study (in Central Sangilen) intrude Neoproterozoic marbles and metacarbonate and metaterrestrial-carbonate deposits of the Naryn complex in the Late Riphean–Vendian nappe (Fig. 1a). All these deposits are similar to derivatives of marl–limestone association of epicontinental seas and outer oceanic shelf (Gibsher and Terleev, 1992; Gonikberg, 1997). In places, the sedimentary section includes more deep-water Vendian–Cambrian volcanoterrigenous-carbonate rocks. The plutons are confined to a long (~200 km) N–S striking deep-fault zone of the basement, which controls most of the manifestations of heterochronous alkaline magmatism in Sangilen (Khomichev et al., 2009).

The Bayan-Kol pluton (50°36' N, 96°40' E) is formed by two stock-like bodies, ~7 km² in total area, separated by the valley of the Bayan-Kol Brook (Kononova, 1962; Yashina, 1982). The largest body, localized on the left bank of the brook, is composed predominantly of basic feldspathoid syenites (aegirine–hedenbergite foyaites) with primary lay-

ering (alternation of melanocratic- and leucocratic-rock layers) (Fig. 1c). The other body has a rather homogeneous composition and is made up of essentially nepheline rocks—juvites (feldspathic urtites). There are also melteigites and ijolites at the pluton endocontact.

The Kharly pluton (50°34' N, 96°32' E) lies in the valley of the Kharly Brook, a left tributary of the Tarbagatai River, and forms a large stock (9.2 km²) of zonal structure related to contact reaction processes (Fig. 1e) (Yashina, 1982). The pluton core is composed of trachtyoid aegirine–hedenbergite foyaites with units of magmatic-flow structures. The endocontact zone includes ijolites and ijolite-urtites separated from nepheline syenites by a narrow (≤60 m) band of hybrid juvites. The exocontact marbles contain numerous layer-by-layer injections of foidolites and foyaites and are transformed into nepheline–pyroxene calciphyres.

The Dakhu-Nur pluton (50°21' N, 96°45' E) is localized on the southern slope of Mt. Dakhu-Nur at 5 km to the northeast from Lake Dakhu-Nur. It consists of two closely located steeply dipping bodies of ultrabasic foidolites (jacupirangite–melteigites, ijolites, ijolite–urtites, and urtites), ~1.5 km² in area, and associated nepheline syenites (Fig. 1b) (Kononova, 1957). Foidolites with primary nepheline–clinopyroxene paragenesis have pegmatoid and metasomatized sites with abundant calcite, shorlomite, and zeolite. Nepheline syenites have high contents (up to ~20–25%) of amphibole and biotite and a weak banded texture.

The Chik pluton (50°09' N, 96°43' E) is a set of four separate small plate-like bodies of ultrabasic foidolites, ~2 km² in area (Fig. 1d), in the lower reaches of the Chik River, a right tributary of the Balyktyg-Khem River. The igneous rocks of the largest body form a subvertical schlieren-banded complex with alternating ijolite–urtites, ijolites, and melteigites (Kononova, 1957). Shorlomites and carbonate-enriched rocks occur in the southeast of the complex. Marbles at the exocontact and in xenoliths are transformed into calciphyres.

Carbonatite-like rocks in the Sangilen alkaline intrusions form cutting thin (0.2–1 to 5–10 m) veins and lenses, often with xenoliths of nepheline syenites. They have an essentially calcitic composition and a medium- to coarse-grained holocrystalline texture. In addition to predominant carbonate, the carbonatite-like rocks contain porphyritic microcline segregations (up to 20%; Kharly, Dakhu-Nur, and Bayan-Kol plutons), spotty and banded apatite grains (up to 20–25%), and, less often, individual crystals or clusters of crystals of biotite, amphibole, clinopyroxene, and nepheline (up to 10–15%), indicating high-temperature conditions of formation. Fluorite and magnetite are sporadic.

ISOTOPE RESEARCH METHODS

The Sm–Nd and Rb–Sr isotope composition of rocks and minerals was studied on Finnigan MAT-262 and MI 1201-T mass spectrometers in the static regime (Bayanova, 2004)

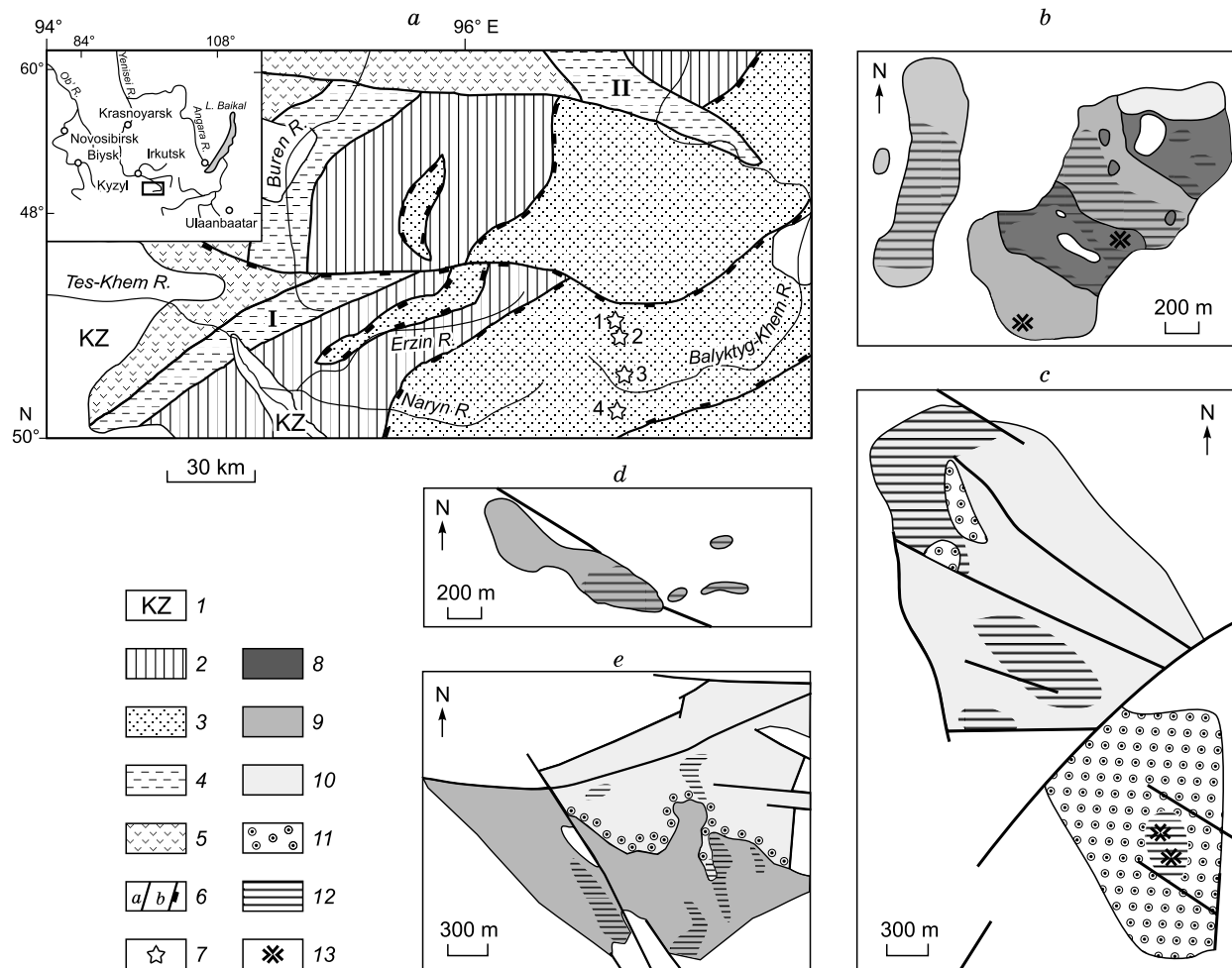


Fig. 1. Geologic position and internal structure of intrusive alkaline massifs of the Sangilen upland. *a*, Fragment of a schematic map of the geologic structure of Western and Central Sangilen, after Gibsher et al. (2000). Inset shows the geographic location of the region; *b–e*, schematic geological maps of the Dakhu-Nur (*b*), Bayan-Kol (*c*), Chik (*d*), and Kharly (*e*) plutons (Kononova, 1957, 1962, 1976; Yashina, 1982; Andreeva et al., 1984; Vrublevskii et al., 2014b). *1*, Cenozoic superposed basins; *2*, Neoproterozoic complexes of metamorphic rocks (schists, gneisses, marbles, and quartzites) in the basement of the Tuva–Mongolian microcontinent; *3*, continent-marginal complexes of Late Riphean–Vendian and Cambrian metamorphosed carbonate-terrigenous and volcanic rocks of Central Sangilen; *4*, Vendian–Early Cambrian tectonic fragments (I, Agardag zone, II, Kaa-Khem zone) of back-arc basins, composed of pillow lavas, siliceous and turbidite deposits with serpentinite melange, and cutting gabbro-plagiogranites; *5*, Vendian–Cambrian island-arc complexes (calc-alkalic volcanics, carbonate deposits, and gabbro-tonalite–plagiogranite intrusions) of the East Tannu-Ola structural-formation zone and intruding Late Cambrian–Ordovician collisional granitoid batholiths; *6*, faults (*a*) and borders of nappe structures (*b*), *7*, location of alkali massifs (1, Kharly, 2, Bayan-Kol, 3, Dakhu-Nur, 4, Chik), *8–13*, igneous rocks: *8*, jacupirangite–melteigites, *9*, ijolites, ijolite-urtites, and urtites, *10*, nepheline syenites (foyaite), *11*, juvites (feldspathic urtites), *12*, zones of carbonatization and endogenous carbonate rocks; *13*, sites of pegmatoid alkaline rocks.

and on a Sector 54 mass spectrometer in the multidynamic regime at the Geological Institute of the Kola Science Center, Apatity, and at the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Moscow. The contents of chemical elements were determined by the isotope dilution method with an accuracy of 1% for Rb and Sr and 0.5% for Sm and Nd. The analytical error (2σ) does not exceed 0.5 rel.% for $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{147}\text{Sm}/^{144}\text{Nd}$, 0.05 rel.% for $^{87}\text{Sr}/^{86}\text{Sr}$, and 0.005 rel.% for $^{143}\text{Nd}/^{144}\text{Nd}$. The average $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the La Jolla standard sample was 0.511833 ± 15 ($N = 15$, normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$), and the average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the SRM-987 standard

sample was 0.710238 ± 16 ($N = 11$, normalized to $^{88}\text{Sr}/^{86}\text{Sr} = 8.37521$). The initial isotope ratios (ϵ_{Nd} and ϵ_{Sr}) were calculated for an isochron age of 490 Ma (present-day CHUR— $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$, $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$; UR— $^{87}\text{Sr}/^{86}\text{Sr} = 0.7045$, $^{87}\text{Rb}/^{86}\text{Sr} = 0.0827$). Isochron was constructed by the York (1966) method, using the ISOPLOT/EX program (Ludwig, 1999).

The Pb isotope composition of K-feldspar from carbonatites of the Kharly pluton was determined on a MC-ICP-MS Neptune (Thermo Scientific, Germany) mass spectrometer at the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Moscow, following the

standard technique (Chernyshev et al., 2007). After the digestion of the 10–15 mg sample in the HCl + HNO₃ mixture, Pb was separated in HBr on chromatographic columns filled with the Bio-Rad AG 1 × 8 anion exchange resin. Before an isotope analysis, the solution of Pb in 3% HNO₃ was traced with a Tl isotope material with a known ²⁰⁵Tl/²⁰³Tl ratio. The sample was introduced into the atomizing quartz chamber of the mass spectrometer (wet plasma regime). The measured Pb isotope ratios were normalized to ²⁰⁵Tl/²⁰³Tl = 2.3889 ± 2. The accuracy and reliability of measurements were estimated from the results of parallel analyses of standard USGS samples: AGV–2 (²⁰⁶Pb/²⁰⁴Pb = 18.871 ± 5; ²⁰⁷Pb/²⁰⁴Pb = 15.621 ± 4; ²⁰⁸Pb/²⁰⁴Pb = 38.548 ± 10; n = 5) and BCR–1 (²⁰⁶Pb/²⁰⁴Pb = 18.822 ± 6; ²⁰⁷Pb/²⁰⁴Pb = 15.640 ± 4; ²⁰⁸Pb/²⁰⁴Pb = 38.737 ± 12; n = 10). The error of measurements (2σ) was ±0.04 %.

Analysis of carbon and oxygen isotopes in carbonates was performed on a Delta V Advance mass spectrometer with a Gas-Bench II (ThermoFisher) system at the Geological Institute, Moscow. The samples under study and the reference samples KH–2, C–O–1, and NBS–19 were decomposed in H₃PO₄ at 50 °C. The values of isotope ratios

(±0.2‰) are given relative to the V–SMOW standards for δ¹⁸O and the V–PDB standards for δ¹³C. The oxygen isotope composition in rock-forming apatite, nepheline, K-feldspar, and Fe–Mg silicates (biotite, amphibole, and clinopyroxene) was determined on a Finnigan MAT-253 gas mass spectrometer equipped with a MIR 10-30 laser ablation system with a vacuum line at the Geological Institute, Ulan–Ude. Samples were prepared by laser fluorination in the presence of BrF₅. During the measurement period, the δ¹⁸O_{V-SMOW} value of the NBS-28 standard (quartz) was 9.6 ± 0.2.

THE SYSTEMATIC ISOTOPE AND AGE OF ALKALINE INTRUSIONS

Neodymium, strontium, and lead. The ⁸⁷Sr/⁸⁶Sr(*T*) and ¹⁴³Nd/¹⁴⁴Nd(*T*) values in the studied alkaline rocks are within 0.70570–0.70733 ($\epsilon_{\text{Sr}}(T) \approx 25–48$) and 0.512153–0.512328 ($\epsilon_{\text{Nd}}(T) \approx 2.9–6.3$), respectively (Table 1). The carbonatite-like rocks have a similar isotope composition (¹⁴³Nd/¹⁴⁴Nd(*T*) = 0.512123–0.512982; $\epsilon_{\text{Nd}}(T)$ from +6.5 to –0.5; ⁸⁷Sr/⁸⁶Sr(*T*) = 0.70567–0.70762, $\epsilon_{\text{Sr}}(T) \approx 25–53$). This suggests that the

Table 1. Isotope composition of Nd and Sr in alkaline and carbonatite-like rocks of the Sangilen upland

Sample	Mas-sif	Rock, mineral	Sm	Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	±2σ	¹⁴³ Nd/ ¹⁴⁴ Nd(<i>T</i>)	$\epsilon_{\text{Nd}}(T)$	Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr	±2σ	⁸⁷ Sr/ ⁸⁶ Sr(<i>T</i>)	$\epsilon_{\text{Sr}}(T)$
			ppm					ppm								
249/1	Dkh	Jacupirangite	6.68	34.6	0.11660	0.512591	14	0.512217	+4.10	19.9	1902	0.02947	0.70691	19	0.70670	+39.5
243/1	Dkh	Ijolite	6.44	33.8	0.11511	0.512626	8	0.512257	+4.88	20.4	1939	0.02966	0.70754	14	0.70733	+48.4
250	Dkh	Ijolite***	3.15	14.2	0.13436	0.512759	10	0.512328	+6.27	27.3	1956	0.0404	0.70713	5	0.70685	+41.6
244	Dkh	Foyaite	5.88	25.2	0.14136	0.512777	15	0.512323	+6.17	44.3	1233	0.10130	0.70790	18	0.70719	+46.4
252	Dkh	Carbonatite*	2.87	12.4	0.14020	0.512789	14	0.512339	+6.48	13.4	2743	0.01381	0.70692	15	0.70682	+41.2
257	BK	Foyaite	2.42	11.4	0.12864	0.512581	7	0.512168	+3.14	44.8	832	0.15195	0.70676	15	0.70570	+25.2
257/1	BK	Juvite	1.15	5.60	0.12370	0.512583	8	0.512186	+3.50	73.5	1018	0.20370	0.70782	17	0.70640	+35.2
262/5	BK	Carbonatite*	30.3	176	0.10437	0.512521	5	0.512186	+3.50	3.29	8802	0.00105	0.70636	15	0.70635	+34.5
256/2	BK	Carbonatite*	9.30	60.9	0.09232	0.512278	12	0.512982	–0.49	9.82	5176	0.00535	0.70646	16	0.70642	+35.5
950	Khr	Ijolite	2.36	10.7	0.13306	0.512587	10	0.512153	+2.86	–	–	–	–	–	–	–
265	Khr	Foyaite ***	4.18	18.2	0.13838	0.512607	10	0.512163	+3.05	34.6	396	0.2526	0.70809	6	0.70633	+34.2
265	Khr	Titanite***	92.3	382	0.14585	0.512632	10	0.512156	–	–	–	–	–	–	–	–
265	Khr	Pyroxene***	2.29	9.51	0.14553	0.512632	10	0.512156	–	–	–	–	–	–	–	–
267	Khr	Foyaite	2.22	9.73	0.13767	0.512603	17	0.512161	+3.01	73.9	734	0.28398	0.70770	7	0.70572	+25.5
268/10	Khr	Carbonatite*	15.4	93.8	0.09932	0.512480	10	0.512161	+3.01	54.2	5779	0.02644	0.70585	16	0.70567	+24.9
498/2	Khr	Carbonatite*	15.2	79.7	0.11524	0.512493	14	0.512123	+2.27	1.31	2252	0.00164	0.70763	18	0.70762	+52.5
270/1	Chk	Ijolite	1.55	6.45	0.14481	0.512709	18	0.512244	+4.63	31.3	457	0.19305	0.70776	17	0.70641	+35.3
270/2**	Chk	Ijolite ***	23.2	64.7	0.21637	0.512965	10	0.512271	+5.16	22.4	837	0.0775	0.70701	12	0.70647	+36.2
270/2**	Chk	Apatite***	85.3	485	0.10639	0.512607	10	0.512266	–	–	–	–	–	–	–	–
270/2**	Chk	Garnet***	46.3	81.4	0.34367	0.513367	10	0.512264	–	–	–	–	–	–	–	–
272/4	Chk	Carbonatite*	25.1	121	0.12530	0.512704	16	0.512302	+5.72	8.31	4051	0.00579	0.70692	16	0.70688	+42.0

Note. Plutons: Dkh, Dakhu-Nur, BK, Bayan-Kol, Khr, Kharly, Chk, Chik.

*Carbonatite = carbonatite-like rock (sample 252, feldspar–calcite rock; sample 262/5, apatite–calcite rock; sample 256/2, feldspar–clinopyroxene–calcite rock; sample 268/10, microcline–calcite rock; sample 498/2, apatite–calcite rock; sample 272/4, clinopyroxene–nepheline–apatite–calcite rock).

**Sample 270/2, garnet-containing ijolite (Sal'nikova et al., 2018).

***Isotope analyses were carried out at the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Moscow.

Table 2. Isotope composition of Pb in microcline from calcite veins of the Kharly pluton

Sample	U	Th	Pb	$(^{206}\text{Pb}/^{204}\text{Pb})_m$	$(^{207}\text{Pb}/^{204}\text{Pb})_m$	$(^{208}\text{Pb}/^{204}\text{Pb})_m$	$(^{206}\text{Pb}/^{204}\text{Pb})_{in}$	$(^{207}\text{Pb}/^{204}\text{Pb})_{in}$	$(^{208}\text{Pb}/^{204}\text{Pb})_{in}$	$(^{207}\text{Pb}/^{206}\text{Pb})_{in}$	$(^{208}\text{Pb}/^{206}\text{Pb})_{in}$	
	ppm											
268/10	0.10	0.094	1.6	17.626	15.418	37.297	17.282	15.399	37.205	0.891	2.153	

Note. Isotope ratios: m, measured, in, initial (calculated for an age of 490 Ma).

rocks of the two types are of comagmatic genesis. The above similarity of isotope parameters is often interpreted as a result of the mixing of the depleted-mantle (PREMA) and enriched-mantle (EM) material with components of the upper continental crust. The involvement of EM-1 in the magma genesis is evidenced from the Pb isotope composition ($^{206}\text{Pb}/^{204}\text{Pb} = 17.28$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.40$; $^{208}\text{Pb}/^{204}\text{Pb} = 37.21$) of K-feldspar from calcite veins of the Kharly pluton (Table 2).

The isotope dates for alkaline magmatism in Central Sangilen show a wide variation (within ~100 Myr), from Middle through Late Paleozoic. The constructed Sm–Nd isochrons for the Chik and Kharly plutons yield a more ancient age of ~490–500 Ma (Fig. 2), which is confirmed by a synchronous U–Pb date (492 ± 2 Ma) for rock-forming garnet in ijolites of the Chik intrusion (Sal'nikova et al., 2018). The much younger age of biotite (~330 Ma) in foyaites of the Dakhu-Nur pluton (Vrublevskii et al., 2014b) and in carbonatites of the Bayan-Kol pluton (Prokopyev et al., 2018) might be due to the heating and low-temperature transformation of the K–Ar isotope system of mica as a result of Late Carboniferous alkali-granitoid magmatism in this part of the CAOB (Yarmolyuk et al., 2010, 2017).

Oxygen and carbon. The $\delta^{18}\text{O}$ value in the studied alkaline rocks and their minerals (clinopyroxene and nepheline) varies from 7.8 to 13.4‰ (Table 3). Similar $\delta^{18}\text{O}$ values are established for apatite, microcline, biotite, amphibole, clinopyroxene, and nepheline from carbonatite-like rocks (7.2–13.9‰). The only exception is ijolite of the Kharly pluton

(sample 950), with inversion of isotope fractionation expressed as a significant ^{18}O depletion of nepheline relative to the coexisting pyroxene. Similar transformation of the oxygen systems under the impact of heated meteoric waters with $\delta^{18}\text{O} < 0$ is detected in foidolite recrystallization zones of alkaline intrusions in Kuznetsk Alatau (Pokrovskii et al., 1998; Vrublevskii, 2015).

The rock-forming calcite shows a weak positive correlation between $\delta^{13}\text{C}$ (–4.0 to –1.4‰) and $\delta^{18}\text{O}$ (12.4–19.5‰) in the range of values between those of the fields of primary igneous carbonatites and normal sedimentary carbonates (Table 3, Fig. 3a). This correlation usually indicates mixing of endogenic CO_2 with isotopically heavy CO_2 of sedimentary genesis or Rayleigh fractionation of high-temperature (600–800 °C) carbonatitic melt (Kuleshov, 1986). A similar variation in isotope composition ($\delta^{13}\text{C}$ from –6 to –2‰; $\delta^{18}\text{O} = 13.0$ –17.5‰) is observed in calcite grains in the host alkaline rocks. Most of the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values fall in the composition field ($\delta^{13}\text{C}$ from –6 to –2‰; $\delta^{18}\text{O} = 12$ –18‰; Fig. 3a) proposed for the identification of carbonatites of mixed mantle–crustal nature (Vrublevskii, 2017; Vrublevskii et al., 2018c).

DISCUSSION

The age and petrogenesis of the intrusions. The U–Pb and Sm–Nd isotopic ages of rocks of the Chik and Kharly plutons (~490–500 Ma) suggest the Late Cambrian occur-

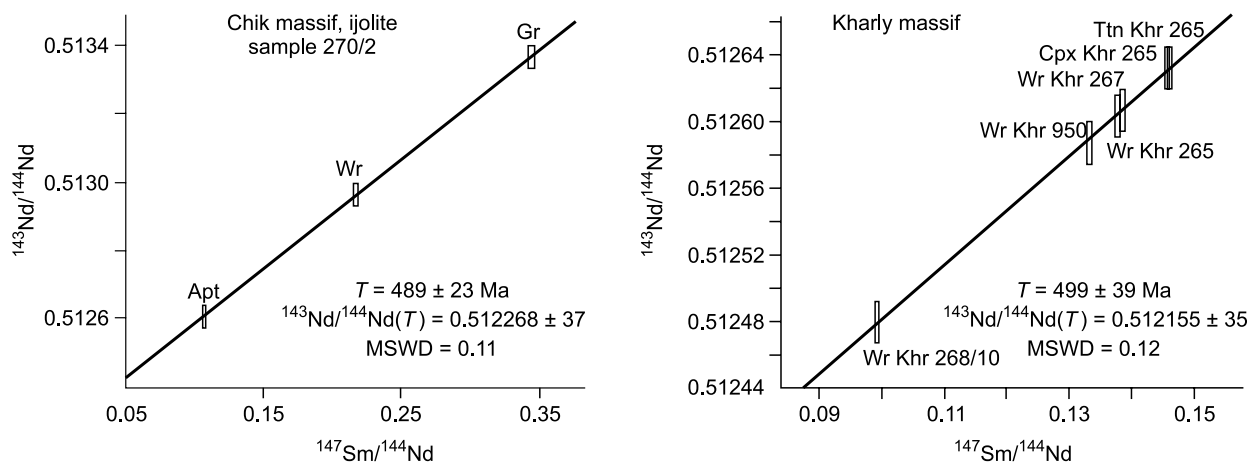


Fig. 2. Sm–Nd isochrons constructed over minerals from rocks of the Chik and Kharly plutons. Sample numbers follow Table 1. WR, whole-rock composition, Apt, apatite, Gr, garnet, Ttn, titanite, Cpx, clinopyroxene.

Table 3. Isotope composition of carbon and oxygen in alkaline and carbonatite-like rocks of the Sangilen upland

Sample	Massif	Rock	Material	$\delta^{13}\text{C}$, ‰	$\delta^{18}\text{O}$, ‰	T , °C
950	Khr	Ijolite	Wr	N.d.	9.7 ^d	N.d.
950		Ijolite	Nepheline	N.d.	7.8	N.d.
950		Ijolite	Pyroxene	N.d.	13.4	N.d.
950		Ijolite	Calcite	-2.2	16.9	N.d.
267		Foyaite	Wr	N.d.	13.0 ^d	N.d.
1084 ^a		Foyaite	Calcite	-5.0	13.0	N.d.
2540		Carbonatite-like rock	Calcite	-2.7	15.2	N.d.
2540		Carbonatite-like rock	Apatite	N.d.	11.9	423, 535 ^c
498/2		Carbonatite-like rock	Calcite	-2.3	16.4	N.d.
498/2		Carbonatite-like rock	Apatite	N.d.	13.9	527, 645 ^c
268/10		Carbonatite-like rock	Calcite	-2.6	15.0	N.d.
268/10		Carbonatite-like rock	Microcline	N.d.	7.2 ^d	N.d.
1179 ^a		Carbonatite-like rock	Calcite	-4.0	16.0	N.d.
1190 ^a		Carbonatite-like rock	Calcite	-3.8	14.0	N.d.
908 ^a		Carbonatite-like rock	Calcite	-3.4	16.6	N.d.
1186 ^a		Carbonatite-like rock	Calcite	-3.9	17.1	N.d.
268/11		Carbonatite-like rock	Calcite	-2.3	19.5	N.d.
2843/35		Calcite vein	Calcite	-0.5	17.3	N.d.
2843/35		Calcite vein	Nepheline	N.d.	11.9	N.d.
2843/31		Calcite vein	Calcite	-0.6	17.5	N.d.
961 ^a		Marble	Wr	-0.5	22.3	N.d.
257/1	BK	Juvite	Wr	N.d.	11.5 ^d	N.d.
00296 ^b		Juvite	Calcite	-4.6	13.8	N.d.
257		Foyaite	Wr	N.d.	12.2 ^d	N.d.
00187 ^b		Foyaite	Calcite	-2.8	13.8	N.d.
00240 ^b		Foyaite	Calcite	-2.7	15.3	N.d.
262/5		Carbonatite-like rock	Calcite	-2.4	13.9	N.d.
262/5		Carbonatite-like rock	Apatite	N.d.	9.3 ^d	317, 360 ^c
BK-40 ^c		Carbonatite-like rock	Calcite	-3.5	14.1	N.d.
BK-40 ^c		Carbonatite-like rock	Apatite	N.d.	9.4 ^d	311, 340 ^c
BK-40 ^c		Carbonatite-like rock	Pyroxene	N.d.	12.6 ^d	984
BK-35 ^c		Carbonatite-like rock	Calcite	-2.1	15.4	N.d.
BK-35 ^c		Carbonatite-like rock	Biotite	N.d.	12.9 ^d	585
BK-2 ^c		Carbonatite-like rock	Calcite	-2.4	15.4	N.d.
BK-2 ^c		Carbonatite-like rock	Amphibole	N.d.	12.5 ^d	700
256/2		Carbonatite-like rock	Calcite	-3.2	12.4	N.d.
0058 ^b		Marble	Wr	-2.5	24.1	N.d.
249/1	Dkh	Jacupirangite	Wr	N.d.	9.7 ^d	N.d.
249/1		Jacupirangite	Calcite	-6.0	17.5	N.d.
243/1		Ijolite	Wr	N.d.	10.4 ^d	N.d.
8-982 ^b		Ijolite	Calcite	-2.9	13.5	N.d.
244		Foyaite	Wr	N.d.	10.9 ^d	N.d.
252		Carbonatite-like rock	Calcite	-1.4	16.2	N.d.
252		Carbonatite-like rock	Microcline	N.d.	9.3 ^d	N.d.
243/2		Marble	Calcite	-0.5	24.8	N.d.
270/1	Chk	Ijolite	Wr	N.d.	12.1 ^d	N.d.
2683 ^b		Ijolite	Calcite	-2.0	16.4	N.d.
272/4		Carbonatite-like rock	Apatite	N.d.	10.1 ^d	N.d.
2693 ^b		Marble	Calcite	N.d.	23.2	N.d.

Note. Plutons: Khr, Kharly; BK, Bayan-Kol; Dkh, Dakhu-Nur; Chk, Chik; Wr, whole-rock composition. ^a (Kuleshov, 1986; Vrublevsky et al., 1999). ^b (Andreeva et al., 1984). ^c (Oral report by A.G. Doroshkevich, Institute of Geology and Mineralogy, 2017). ^d (Laser ablation data). Isotope temperature was calculated by formulas: $1000 \ln \alpha (\text{calcite-apatite}) = 1.6 \times 10^6/T^2$ (Fortier and Lutge, 1995); $1000 \ln \alpha (\text{calcite-pyroxene}) = 2.37 \times 10^6/T^2$ (Chiba et al., 1989); $1000 \ln \alpha (\text{calcite-biotite}) = 1.84 \times 10^6/T^2$ (Fortier et al., 1994); $1000 \ln \alpha (\text{calcite-amphibole}) = 0.13 \times 10^6/T^2 + 3.90 \times 10^3/T - 1.59$ (Zheng, 1993). ^c Calculated after Alberti et al. (1999). N.d., not determined.

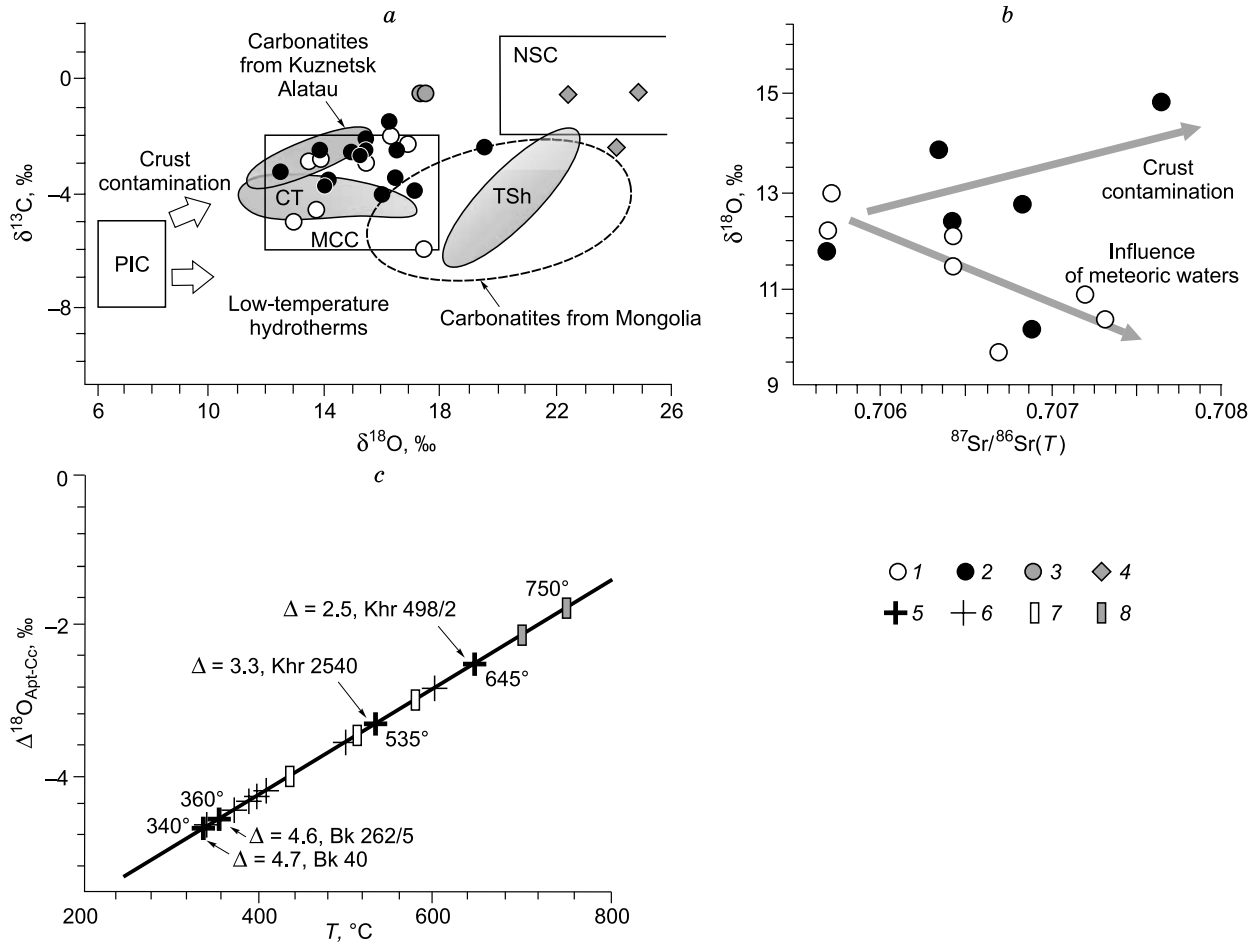


Fig. 3. Carbon and oxygen isotope composition of rocks of alkaline complexes and the host metacarbonate deposits. *a*, $\delta^{13}\text{C}$ – $\delta^{18}\text{O}$ diagram: PIC, domain of primary magmatogene carbonatites (Conway and Taylor, 1969); NSC, marine sedimentary carbonates (Pokrovskii, 2000). Arrows show the influence of crustal contamination and low-temperature hydrotherms (Demény et al., 1998). MCC, assumed field of mantle–crustal carbonatites (Vrublevskii, 2017). Gray fields mark predominant calcite/dolomite compositions in carbonatites of Kuznetsk Alatau, Central Tuva (CT), and Turkestan–Alai segment of the Tien Shan (TSh) (Nikiforov et al., 2006; Vrublevskii, 2015; Vrublevskii et al., 2018c). Mongolian carbonatites are represented by dikes, veins, breccias, and tuffs of the Mushgai Hudag and Ulgei Hiyd complexes (Kuleshov, 1986). *b*, $\delta^{18}\text{O}$ – $^{87}\text{Sr}/^{86}\text{Sr}(T)$ diagram. *c*, Fractionation of oxygen isotopes between calcite and apatite in carbonatites and carbonatite-like rocks. For calculation of equilibrium temperatures see Notes to Table 3. Apt, apatite, Cc, calcite. Data on carbonatites of Brazil, Angola, Siberia, and the South Tien Shan are after Santos and Clayton (1995), Alberti et al. (1999), Vrublevskii and Gertner (2005), and Vrublevskii et al. (2018c). Sangilen upland: 1, calcite of alkaline rocks, 2, carbonatite-like rocks, 3, hydrothermal veins of calcite, 4, limestones and marbles. Temperatures of apatite–calcite isotope equilibrium: 5, carbonatite-like rocks of Sangilen, 6, carbonatites of Angola, 7, carbonatites of Siberia and the South Tien Shan, 8, carbonatites of Brazil (Jacupiranga).

rence of feldspathoid magmatism in southeastern Tuva. The above dates fall in the time interval of the formation of many volcanoplutonic associations of the western CAO (–470–510 Ma) that are united into an Early Paleozoic Large Igneous Province (LIP) (Izokh et al., 2008). Most of these associations formed, most likely, from a mantle plume source. A close age was established for intraplate granitoids in Tuva (~490 Ma) (Kozakov et al., 2003; Kuznetsova and Shokal'skii, 2011) and for complexes of subalkalic gabbroids, gabbro-monzonites, granitoids, alkaline rocks, and carbonatites in the adjacent East Sayan, Cisbaikalia, Transbaikalia, Kuznetsk Alatau, and Gorny Altai regions (~480–520 Ma) (Shokal'skii et al., 2000; Vladimirov et al., 2001; Nikiforov

and Yarmolyuk, 2007; Sklyarov et al., 2009; Doroshkevich et al., 2012; Vrublevskii et al., 2012, 2014a, 2016, 2018a). This indicates similar and synchronous mantle processes in the above areas at the Early Paleozoic stage of the CAO evolution.

The specifics of the alkaline plutons in Central Sangilen is the late formation of vein bodies similar in composition to carbonatites. The assemblage of predominant calcite and subordinate clinopyroxene, amphibole, mica, microcline, and apatite corresponds to the high-temperature paragenesis of the K-feldspar and albite–calcite facies (Samoilov, 1984), which is accompanied by metasomatism of the host alkaline rocks with the formation of wollastonite, vesuvianite, and

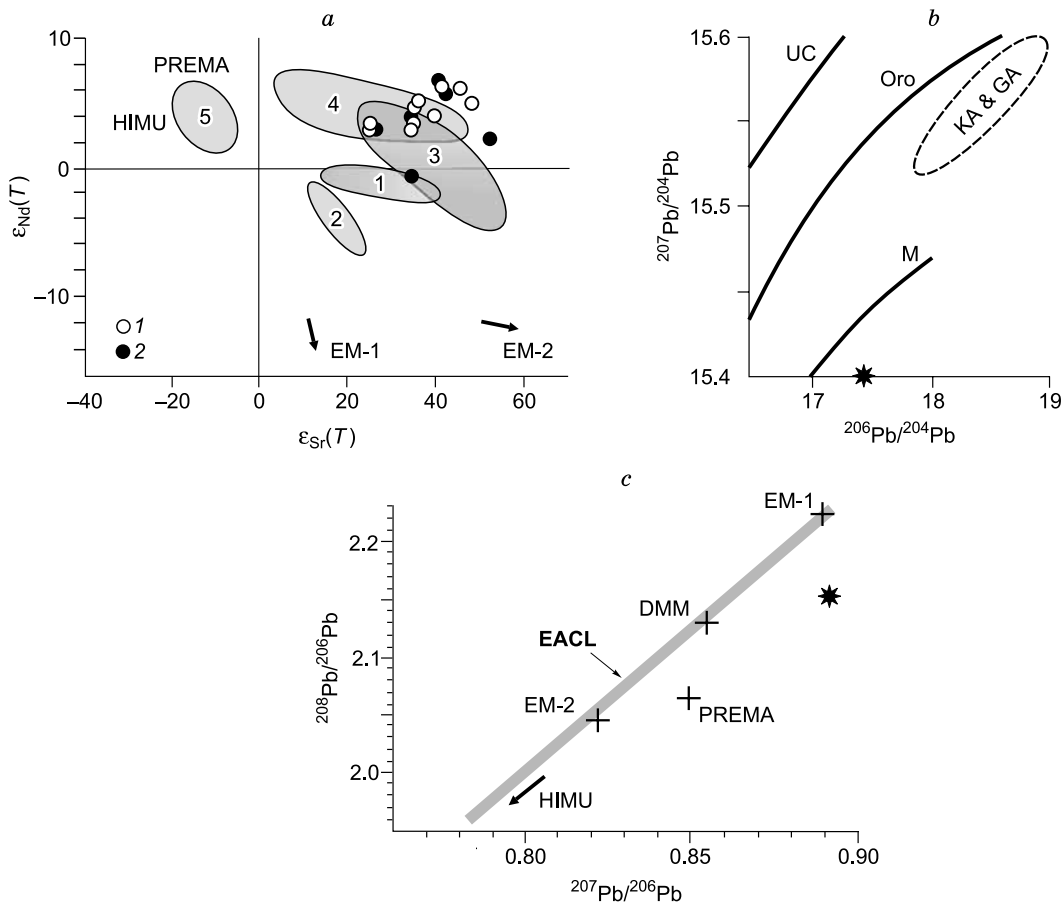


Fig. 4. Nd–Sr–Pb isotope composition of alkaline and carbonatite-like rocks of the Sangilen upland. *a*, $\epsilon_{Nd}(T)$ – $\epsilon_{Sr}(T)$ diagram. For comparison, the predominant compositions (gray fields) of igneous rocks of alkaline and carbonatite complexes of the CAOB (Mesozoic: 1, southern Mongolia, 2, western Transbaikalia; Paleozoic: 3, Vitim province of western Transbaikalia and northern Mongolia, 4, Kuznetsk Alatau) and the Precambrian Siberian, European, and North American Cratons (5) are shown (Nikiforov et al., 2002; Vrublevskii et al., 2003b; Vladykin, 2005; Vrublevskii and Gertner, 2005 (and references there); Sazonov et al., 2007; Doroshkevich et al., 2012; Vrublevskii, 2015). Localization of the PREMA, HIMU, EM 1, and EM 2 reservoirs is given in accordance with their present-day isotope parameters (Zindler and Hart, 1986; Stracke et al., 2005). Rocks: 1, alkaline, 2, carbonatite-like. *b*, *c*, Primary $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ (*b*) and $^{208}\text{Pb}/^{206}\text{Pb}$ – $^{207}\text{Pb}/^{206}\text{Pb}$ (*c*) ratios in microcline (black asterisk) from calcite veins of the Kharly pluton. The average composition of the mantle components PREMA, HIMU, DMM, EM-1, and EM-2, plumbotectonics model, and Pb isotope evolution (UC, upper crust, Oro, orogeny, M, mantle) (Stacey and Kramers, 1975; Zartman and Doe, 1981; Zindler and Hart, 1986; Hart et al., 1992; Stracke et al., 2005; Armienti and Gasperini, 2007) are shown; EACL, East African carbonatite line (Bell and Tilton, 2001); KA&GA, alkaline rocks and carbonatites of Kuznetsk Alatau and Gorny Altai in the western CAOB (Vrublevskii et al., 2017, 2018b).

garnet. Similar minerals are produced at the exocontact of fassaite–montichellite–magnetite–apatite carbonatite (~600–900 °C) veins in Kuznetsk Alatau (Vrublevskii, 2015). Fractionation of oxygen isotopes between rock-forming calcite and apatite in the Kharly and Bayan-Kol plutons corresponds to high equilibrium temperatures ($\Delta^{18}\text{O} = 2.5$ – 4.7% , $T \approx 320$ – 600 °C; Table 3, Fig. 3c) suggesting salt melt crystallization of the minerals. The same is evidenced by the parameters of the isotope equilibrium between carbonate and Fe–Mg silicates (~590–980 °C; Table 3). A similar degree of fractionation is established in mineral assemblages in contaminated carbonatites of Brazil, Angola, Siberia, and the South Tien Shan.

Mantle–crustal sources of alkaline magmas. Alkaline and carbonatitic magmatism is usually related to the mantle

plume activity, with the HIMU/FOZO reservoirs and EM 1 being the main sources of material (Bell and Tilton, 2001). Rocks of the Dakhu-Nur and Chik plutons have a more radiogenic isotope composition of Nd than these sources and are enriched in ^{87}Sr ($\epsilon_{Nd}(T) \sim 4.1$ – 6.5 , $\epsilon_{Sr}(T) \sim 35$ – 48 ; Fig. 4a). This suggests the contribution of the depleted mantle PREMA in the magma generation and its nonuniform mixing with the material of both the enriched mantle EM and the continental crust. During the formation of nepheline syenites and carbonatite-like rocks of the Bayan-Kol and Kharly plutons, the portion of the EM component in the melts seems to increase considerably, whereas the degree of crustal contamination varies insignificantly ($\epsilon_{Nd}(T) = +3.5$ to -0.5 , $\epsilon_{Sr}(T) \sim 25$ – 52). The initial ratios $^{208}\text{Pb}/^{206}\text{Pb} = 2.153$ and $^{207}\text{Pb}/^{206}\text{Pb} = 0.891$ in microcline from carbonate veins

Table 4. Isotope parameters of Neoproterozoic marbles at the exocontact of alkaline intrusions of the Sangilen upland

Sample	Pluton	Rb	Sr	⁸⁷ Rb/ ⁸⁶ Sr	⁸⁷ Sr/ ⁸⁶ Sr
		ppm			
243/2*	Dakhu-Nur	0.46	2412	0.00054	0.70820
261	Bayan-Kol	—	—	—	0.70851
273/1	Chik	—	—	—	0.70823
268/26	Kharly	—	—	—	0.70790

Note. Dash, no data.

* Data of Sm–Nd isotope analysis (Sm = 0.13 ppm, Nd = 0.69 ppm; ¹⁴⁷Sm/¹⁴⁴Nd = 0.11789, ¹⁴³Nd/¹⁴⁴Nd ± 2σ = 0.511547 ± 363, ¹⁴³Nd/¹⁴⁴Nd(T) = 0.510697, ε_{Nd}(T) = –19.04; T = 750 Ma).

of the Kharly pluton testify to a predominance of the EM 1 material but are not consistent with the general trend of Mesozoic carbonatite magmatism (Table 2, Fig. 4b, c). Isotope studies of carbonatite–nepheline volcanoes of the East African Rift (Bell and Tilton, 2001) show that such inconsistency is possible even in closely spaced magmatic centers.

The observed isotope-geochemical similarity of alkaline and carbonatite-like rocks in Tuva confirms their cogenetic nature. Similar Paleozoic alkaline plutonic complexes (~520–400 Ma) in the adjacent regions of the western CAO (Kuznetsk Alatau, northern Mongolia, and Vitim province of western Transbaikalia) (Fig. 4a) seem to have the same evolution. This suggests a genetic relationship between the sources of their material and the occurrence of magmatism under plume–lithosphere interaction.

The content of ⁸⁷Sr in the Central Sangilen intrusions might be related not only to the scale and mechanism of magma contamination by the material of the mature continental crust but also to the varying composition of the crust. This is evidenced by the higher oxygen and carbon isotope ratios in the minerals (δ¹⁸O = 7.2–19.5, δ¹³C = –6 to –1.4‰) as compared with the mantle (δ¹⁸O = 5.5 ± 0.5‰ SMOW (Taylor and Sheppard, 1986)). In calcite, there is a direct relationship between δ¹⁸O and δ¹³C (Figs. 3 and 5). Most of the composition points of calcite, along with the points of magmatogene carbonates of other alkaline complexes of the

CAOB, fall in the field of carbonate minerals of carbonatites of mantle–crustal genesis (Fig. 3a). According to the earlier estimates (Kuleshov, 1986; Nikiforov et al., 2000), the initial isotope composition of endogenous carbonates in alkaline igneous complexes of folded areas varies in a still narrower interval of values: δ¹³C ≈ –6.0 to –4.5, δ¹⁸O ≈ 9–11‰. Taking into account the established heavy isotope composition of hydrothermal calcite veins and the host Neoproterozoic marbles (δ¹³C = –2.5 to –0.5, δ¹⁸O = 17.3–24.8‰; Table 3, Fig. 3a) and their high ⁸⁷Sr/⁸⁶Sr ratios (~0.7080–0.7085) and extremely low ε_{Nd}(T) value (–19) (Table 4), we admit a strong crustal contamination of the Central Sangilen feldspathoid intrusions.

A positive correlation between the δ¹⁸O and ⁸⁷Sr/⁸⁶Sr(T) values, a sign of the involvement of the upper-crustal sedimentary material in magmatic processes, is observed mostly for the carbonatite-like rocks (Fig. 3b). Calcite in the alkaline rocks shows a weak negative correlation between these parameters because of the slight decrease in ¹⁸O/¹⁶O under the action of heated meteoric waters. In the Sangilen intrusions, meteoric waters usually exert no effect on the oxygen isotope equilibrium among most of rock-forming minerals. The mutual enrichment of paragenetic silicates, apatite, and calcite in ¹⁸O due to the accumulating capacity of their crystal lattices suggests crustal contamination at the stage of the melt generation. This might cause additional carbonatization of alkaline magma and its subsequent liquation with separation of a carbonatitic liquid.

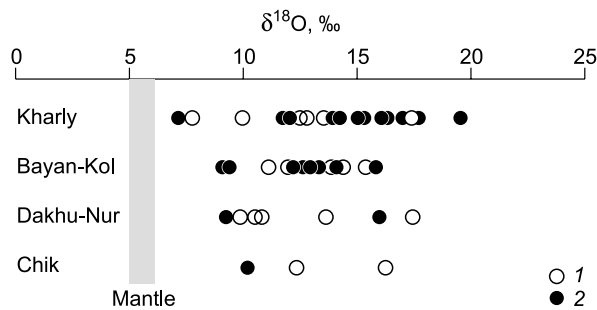


Fig. 5. The range of δ¹⁸O values for minerals and rocks of alkaline plutons of the Sangilen upland. The “mantle” range values (δ¹⁸O_{SMOW} = 5.5 ± 0.5‰) are given after Taylor and Sheppard (1986). Designations follow Fig. 4.

CONCLUSIONS

Based on the performed studies, we have drawn the following conclusions: (1) The plutonic association of foidolites, nepheline syenites, and carbonatite-like rocks of the Sangilen upland in southeastern Tuva might have formed in the Cambrian at ~490–500 Ma. This gives grounds to consider it a derivative of the Early Paleozoic Large Igneous Province located in the western CAO; (2) the variations in Nd and Pb isotope composition in the plutons indicate the heterogeneous composition of their comagmatic sources, which is related to different degrees of the partial mixing of

the PREMA and EM 1 materials. The established radiogenic isotope composition of Sr and the high $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of rocks and minerals are apparently due to the crustal contamination of melts in the upper lithospheric horizons. The provoked carbonatization might have stimulated the liquation of alkaline silicate magma, which resulted in a high-temperature liquid salt melt.

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