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GEOLOGY

Early Paleozoic Age and Geodynamic Setting of the Botogol and Khushagol Alkaline Massifs in the Central Asian Foldbelt

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The Altai–Sayan foldbelt, the southwestern sector of the Early Caledonian framework of the Siberian Platform, includes abundant magmatic complexes with alkaline rocks (alkaline gabbroids, nepheline syenites, alkaline syenites, granites, and their volcanic analogues) that are indicators of within-plate magmatism in the region. On the basis of K–Ar studies, these rocks were traditionally attributed to Devonian rifting. However, recent Rb–Sr and Sm–Nd data showed that alkaline magmatism also occurred here at earlier stages [1–3 and others]. However, the number of these datings is obviously insufficient to reconstruct reliably the geodynamic model of the formation of Caledonides in the Central Asian foldbelt (CAFB). According to [4], the CAFB is related to the accretion of Vendian–Cambrian structures of the Paleoasian Ocean (island-arc and back-arc basin complexes) and Precambrian crustal terranes to the Siberian Platform. According to [5, 6], terranes of the Caledonides were formed beyond the Siberian Platform owing to the collision of the structures mentioned above with a system of oceanic islands controlled by hot spots of the mantle. This concept is based on the involvement of within-plate rocks (high-Ti gabbro, OIB basalts, alkaline granites, and others) in pre-, syn-, and postaccretionary igneous complexes. We present Rb–Sr and Ar–Ar geochronological data on the Botogol and Khushagol alkaline massifs and show that their timing is correlated with pre- and synaccretionary stages, respectively.

These alkaline massifs are located in the Oka lithostructural zone of the northern Tuva–Mongolia Massif (Terrane), the largest Precambrian microcontinent among the CAFB Caledonides.

The *Botogol Massif*, 10 km^2 in area, intrudes Late Cambrian marbleized carbonate rocks intercalated with siliceous shales and quartzites. The massif consists mainly of two rock types. The central sector is made up of predominant nepheline syenites and less common ijolites, while the marginal sector is composed of pyroxene syenites. These typical medium- and coarse-grained massive or trachytic igneous rocks have a monotonous mineral composition. Mafic minerals are represented by hedenbergitic clinopyroxene (10–35 vol %), which is occasionally replaced by amphibole or biotite. Leucocratic minerals are represented by K–Na-feldspar (40–85 vol %) and nepheline (20–50 vol %) in nepheline syenites and feldspathic ijolites and by K–Na-feldspar (60–75 vol %) and oligoclase (*n*%) in syenites. Alkaline feldspar typically contains microperthitic albite lamellae. Titanite occurs in significant amounts (up to few percent). Apatite and Ti-magnetite are accessory minerals. The rocks universally contain graphite and calcite. The latter often forms poikilitic intergrowths in major rock-forming minerals. Secondary alterations produced albite, chlorite, saussurite, prehnite, epidote, spreustein, cancrinite, and sodalite.

The Rb–Sr isochron dating of the Botogol Massif was carried out on mineral fractions additionally separated into density fractions with bromoform and acetone. Sample Bat-2/5 was chosen for this purpose because no petrographic evidence of secondary alterations was observed in the rock. In terms of mineral and chemical composition, the rock is classed as melanocratic nepheline syenite–feldspathic ijolite. The major minerals are nepheline (30–35%), K–Na-feldspar (30%), ferroaugite (30–35%), titanite (<0.5%) and feldspar-hosted rare apatite grains. The rock has a medium- to coarse-grained structure. Nepheline, feldspar, and pyroxene grains are 0.5 mm in size. Titanite grains are 0.1–0.3 mm in size, while apatite is 0.02 × 0.1 mm in size. All minerals have distinct regular boundaries. In thin sections, evidence of postmagmatic alteration is seen only in K–Na-feldspar, which is occasionally replaced at margins by thin lamellae of perthitic albite. Pyroxene in this sample is unaltered, though it is often replaced by amphibole and biotite in the massif.

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Table 1. Rb and Sr Isotopic compositions of minerals and whole-rock samples of rocks from the Botogol and Khushagol massifs

Sample	Density (g/cm^3)	Rb, ppm	Sr, ppm	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
Botogol Massif (feldspathic ijolite, sample Bat-2/5)					
Whole-rock sample	–	46	1292	0.1042	0.707272
Titanite	>2.879	1.6	340	0.0166	0.706649
Pyroxene	>2.879	1.3	248	0.0194	0.706657
K–Na-feldspar	2.79–2.75	73	465	0.4548	0.709743
The same	2.67–2.63	75	487	0.4434	0.709651
Nepheline	2.67–2.63	107	3843	0.0804	0.707188
The same	2.63–2.59	108	3977	0.0790	0.707125
Khushagol Massif (riebeckite syenite, sample Bat-3/1)					
Whole-rock sample	–	226	19	34.87	0.921809
Fluorite	>2.88	5.8	744	0.0226	0.709230
Alkaline amphibole	>2.88	100	52	5.51	0.768559
Intergrowths of alkaline feldspar and albite	2.74–2.88	391	1.2	936.2	5.46568
The same	2.74–2.70	327	1.2	779.1	4.72424
"	2.70–2.63	274	1.3	602.6	3.78666

Note: Minerals were hand picked under binocular microscope from 0.1–0.25 mm fractions obtained by sample separation in a bromoform–acetone mixture. The isotope studies were performed in the Laboratory of Isotope Geology and Geochronology of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry using the standard technique [7, 8]; the Rb and Sr isotope ratios were measured with a Sector-54 mass spectrometer; the ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr ratios were determined with accuracy no worse than 1 and 0.01%, respectively.

The results of Rb–Sr dating are listed in Table 1, while isochron is shown in Fig. 1a. Variations in the ^{87}Rb/^{86}Sr ratio in the rock-forming minerals are no more than 0.45. The ^{87}Rb/^{86}Sr ratio is similar, but the Sr isotopic compositions of density fractions of nepheline are slightly different (Table 1). However, these values coincide within the measurement error of ^{87}Rb/^{86}Sr. Pyroxene and titanite have virtually the same Sr isotopic composition. Minerals and whole-rock sample yielded the Rb–Sr isochron with $T = 492 \pm 11$ Ma (MSWD = 1.12, $(^{87}Sr/^{86}Sr)_{492} = 0.706557 \pm 36$). Based on the MSWD value, the Rb–Sr isochron age can confidently be taken as the timing of feldspathic ijolite of the Botogol Massif. It is noteworthy that the obtained value is close to K–Ar biotite ages (521 and 492 Ma) of nepheline syenites from the Botogol Massif [1].

The *Khushagol Massif* located at the adjacent ridge is composed of two rock associations. The northeastern sector shows exposures of alkaline pyroxene syenites and small bodies of nepheline syenites, which are correlated with the corresponding rocks of the Botogol Massif [11]. The southwestern sector of the ridge is composed of riebeckite and riebeckite–pyroxene syenites and granosyenites (nordmarkites), which were sampled for geochronological studies. We did not see interrelations between rocks of the northeastern and southwestern sectors. According to R.V. Lobzova, contact between these sectors represents a fault. As was mentioned in [10], the alkaline syenites and nordmarkites are separated by a limestone interbed 35–40 m thick.

Rocks from the southwestern sector of the Khushagol Massif have a monotonous mineral composition. Mafic minerals are represented by aegirine-rich clinopyroxene (aegirine-hedenbergite) and amphiboles (hastingsite and riebeckite). Mafic minerals account for up to 30 vol %. In addition, the rocks always contain a few percents of aenigmatite and scarce laths supposedly of astrophyllite. Leucocratic minerals are represented by quartz (up to 10–15%), K-feldspar (cross-hatched microcline) and K–Na-feldspar (up to 80 vol %). The latter mineral includes a great amount of morphologically diverse albite perthites (up to 70%). Albite also forms prismatic crystals and banded replacement perthites. Graphite, calcite, and fluorite are accessory minerals.

Since the studied rocks of the Khushagol Massif bear evidence of secondary alterations, Rb–Sr isochron (minerals) and Ar–Ar (rock-forming amphibole) methods were used for their dating.

Riebeckite syenite (sample Bat-3/1) taken for age determination is represented by massive medium-grained rocks consisting of tabular K–Na-feldspar and microcline (~70%), separate albite crystals (~10%), and riebeckite (~20%). K- and K–Na-feldspars consist of tabular crystals (0.2–0.4 mm in size) with numerous albite perthites of diverse morphology (up to 60–70%). Albite occurs as small tabular crystals 0.1–0.2 mm in

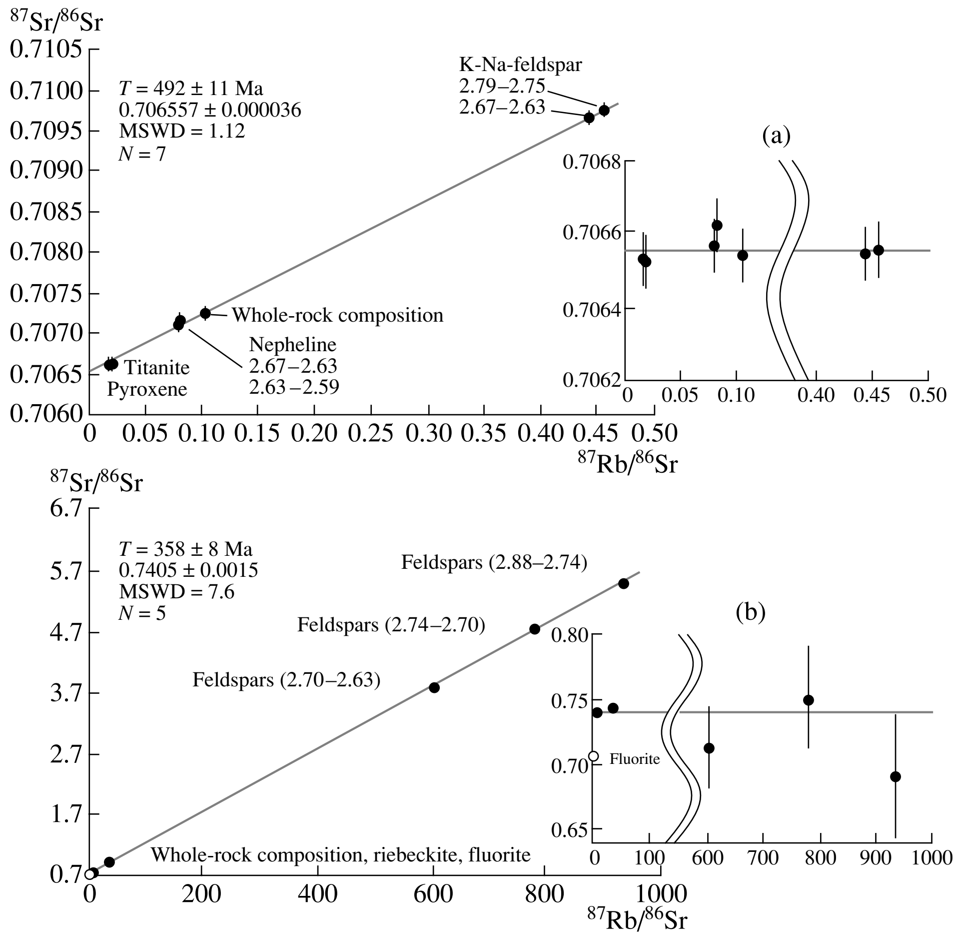

Fig. 1. Rb–Sr isochron relationship in (a) minerals and whole-rock samples of feldspathic ijolites from the Botogol Massif and (b) riebeckite syenites from the Khushagol Massif. Isochron parameters were calculated with ISOPLOT/Ex. Version 2.06 software, model 1 [9].

size. Riebeckite is represented by elongated splinter-shaped crystals up to a few millimeters long. The rock, in addition, contains small grains of aegirine-hedenbergite, fluorite, ore minerals, and rare astrophyllite laths.

The Rb–Sr isotope characteristics of major minerals from riebeckite syenites of the Khushagol Massif differ sharply from those of the Botogol Massif (Table 2). The $^{87}Rb/^{86}Sr$ ratio varies from 0.023 to 940. The obtained isotopic composition of minerals and whole-rock samples suggests disequilibrium of the Rb–Sr system (Fig. 1b). The mismatch is mainly caused by fluorite. However, the correlation does not fit the value required for isochrons (MSWD = 8.5) even when fluorite is omitted. The disturbance of the isotope system can be explained by superposition of secondary processes. In our case, the rock bears signs of intense albitization, such as decomposition of K–Na-feldspar, the presence of albite fringes and lamellae after the microcline, and formation of individual albite grains (Fig. 2). Therefore, the slope of the isochron based on feldspar fractions, the whole-rock sample, and riebeckite presumably corresponds to the timing of albitization (358 ± 8 Ma). Let us recall that fluorite was omitted from calculations, although there is no ground to ascribe it to secondary minerals. Fluorite grains (~0.1 mm in size) occur inside mafic minerals or between tabular feldspars. We did not observe corrosion of rock-forming minerals by fluorite.

The age of riebeckite syenites of the Khushagol Massif was estimated by the Ar–Ar amphibole dating. The results shown in Table 2 and Fig. 3 indicate that almost all steps of the spectrum (99% ^{39}Ar) are older than 500 Ma, and 50% of released Ar is dated at ~521 ± 2 Ma. On the whole, the steps of the spectrum show some discordance probably owing to the compositional heterogeneity, on the one hand, and the Ar redistribution during albitization, on the other hand. However, the obtained value can be taken as the closure time of the Ar–Ar system in amphibole, and hence, as the minimum timing of the riebeckite syenites of the Khushagol Massif.

Thus, the data obtained indicate that the Khushagol and Botogol massifs were formed 521 and 492 Ma ago.

Table 2. Ar isotopic composition of rock-forming riebeckite from syenites of the Khushagol Massif

Step no.	Age, Ma	$^{40}Ar/^{39}Ar$	$^{38}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	Cumulative ^{39}Ar, %
1	537.3 ± 13.3	87.0 ± 1.7	0.087 ± 0.0022	0.011 ± 0.0036	0.072 ± 0.0041	5.6
2	578.8 ± 9.3	76.2 ± 1.4	0.086 ± 0.0013	0.007 ± 0.0003	0.015 ± 0.0003	21.9
3	577.6 ± 4.3	77.9 ± 0.6	0.088 ± 0.0008	0.007 ± 0.0014	0.022 ± 0,000·	32.1
4	511.1 ± 7.9	64.2 ± 1.1	0.075 ± 0.0017	0.008 ± 0.0003	0.007 ± 0.0005	52.1
5	512.0 ± 7.1	66.3 ± 1.0	0.078 ± 0.0012	0.008 ± 0.0008	0.014 ± 0.0003	64.5
6	512.9 ± 9.4	67.0 ± 1.3	0.078 ± 0.0016	0.010 ± 0.0004	0.016 ± 0.0007	75.1
7	516.2 ± 8.9	70.7 ± 0.7	0.078 ± 0.0010	0.012 ± 0.0016	0.027 ± 0.0037	79.2
8	534.1 ± 4.3	69.0 ± 0.6	0.080 ± 0.0010	0.015 ± 0.0006	0.013 ± 0.0004	86.3
9	532.5 ± 5.9	67.8 ± 0.8	0.078 ± 0.0013	0.024 ± 0.0004	0.009 ± 0.0005	95.5
10	505.9 ± 5.4	67.0 ± 0.7	0.075 ± 0.0035	0.025 ± 0.0031	0.019 ± 0.0013	99
11	483.2 ± 7.6	78.0 ± 0.5	0.078 ± 0.0036	0.018 ± 0.0039	0.067 ± 0.0032	100

Note: Studies were performed at the Joint Institute of Geology, Geophysics, and Mineralogy (Novosibirsk) using the standard technique [12].

In the evolution of Caledonides, these dates correspond to preaccretionary and late accretionary stages of the foldbelt evolution. Accretionary processes took place within a narrow time range between 500 and 490 Ma [6]. This age range includes the formation of the main structures, regional metamorphism, and synaccretionary granitoid magmatism [13]. These processes were developed not only in fold zones, but also in marginal zones of median massifs (Precambrian terranes), including the Tuva–Mongolia Massif. The structure of fold zones is defined by tectonic fragments of island arcs, accretionary prisms, back-arc basins, and oceanic islands formed 570–500 Ma ago. Formation of these structures was confined to the Paleoasian Ocean sector controlled by the activity of hot spots of the mantle. This is indicated, for example, by the presence of OIB-type basalts (probably fragments of ocean islands) in ophiolite complexes and the discovery of alkaline associations, e.g., gabbro, theralites, phoidolites, and foyaites with carbonatites in Kuznetsk Alatau (509 Ma [3]) and island arc-related gabbrosyenite massifs (Berkhin Massif, 500 Ma [14]). The age of 521 Ma suggested in this work for the rocks of the Khushagol alkaline massif indicates that Precambrian terranes, in particular, the Tuva–Mongolia Massif, were also affected by within-plate magmatic sources during the preaccretionary stage.

The accretionary processes presumably exerted no influence on the interaction of the Caledonide lithosphere with mantle hot spots. These processes were concurrent with formation of the aforementioned nepheline syenites of the Botogol Massif, alkaline syenites of the Dzhargalant Massif (494 Ma), granosyenites and alkaline granites of the Teskhem Massif [13], nepheline syenites of the Tazheran Massif, and gabbrosyenite massifs in Caledonides [15]. We suggest that such a combination of accretionary and within-plate processes could only occur in a zone affected by hot mantle–lithosphere interaction. The absence of significant breaks during pre-, syn-, and postaccretionary stages of the Caledonide evolution indicates that the within-plate activity was controlled by the same hot spot (or a group of converged hot spots) recorded in oceanic islands, whose fragments are present practically at all exposures

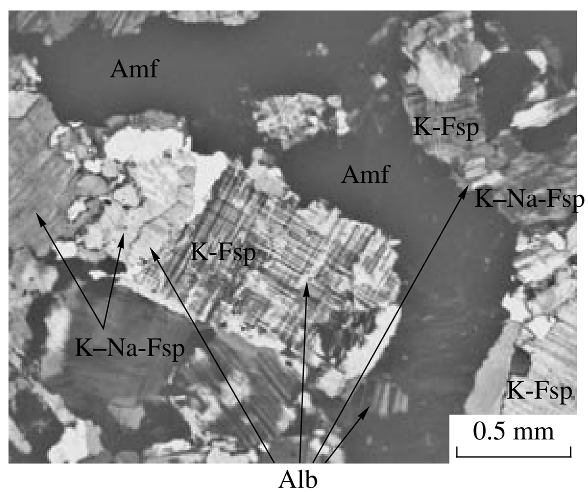

Fig. 2. Images of thin sections of riebeckite syenite (sample Bat-3/1, cross-polarized light). (K-Fsp) microcline, (K–Na-Fsp) K–Na-feldspar, (Alb) albite, (Amp) riebeckite.

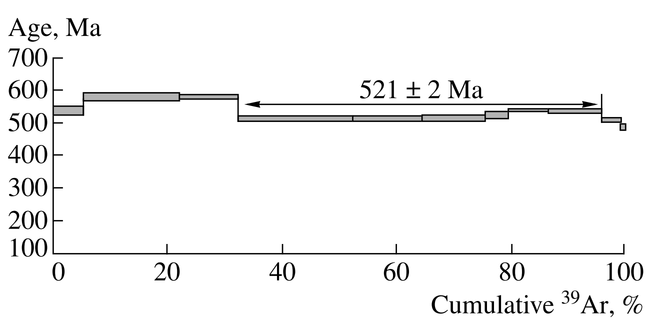

Fig. 3. ^{40}Ar–^{39}Ar- age spectrum of riebeckite from syenites of the Khushagol Massif.

of ophiolite complexes. In our opinion, all these facts indicate that the formation of Caledonides is related to the collision of different structures of the Paleo-Asian Ocean (island arcs, Precambrian terranes, and back-arc basins) with a system of ocean islands controlled by mantle hot spots.

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REFERENCES

1. Yu. A. Kostitsyn, E. N. Altukhov, and N. P. Filina, Geol. Geofiz. **39**, 917 (1998).
2. A. G. Rublev, Yu. P. Shergina, and G. S. Shkorbatova, Otechest. Geol., No. 3, 42 (1994).
3. V. V. Vrublevskii, I. F. Gertner, D. Z. Zhuravlev, and N. A. Makarenko, Dokl. Earth Sci. **391**, 832 (2003) [Dokl. Akad. Nauk **391**, 378 (2003)].
4. I. V. Gordienko, Geol. Geofiz. **47**, 53 (2006).
5. V. I. Kovalenko, V. V. Yarmolyuk, V. P. Kovach, et al., J. Asian Earth Sci. **23**, 605 (2004).
6. V. V. Yarmolyuk, V. I. Kovalenko, V. P. Kovach, et al., Dokl. Earth Sci. **389**, 311 (2003) [Dokl. Akad. Nauk **389**, 354 (2003)].
7. D. Z. Zhuravlev, I. V. Chernyshev, A. A. Agapova, and N. I. Serdyuk, Izv. Akad. Nauk SSSR, Ser. Geol., No. 12, 23 (1983).
8. I. V. Chernyshev, N. I. Serdyuk, D. Z. Zhuravlev, et al., in *Mass Spectrometry and Isotope Geology* (Nauka, Moscow, 1983), pp. 30–43 [in Russian].
9. K. R. Ludwig, Berkley Geochronol. Center. Spec. Publ., No. 1a, 2001.
10. V. P. Kostyuk and T. Yu. Bazarova, *Petrology of Alkaline Rocks from the Eastern Sector of East Sayan* (Moscow, Nauka, 1966) [in Russian].
11. R. V. Lobzova, *Graphite and Alkaline Rocks of the Botogol Massif* (Nauka, Moscow, 1975) [in Russian].
12. V. A. Ponomarchuk, Yu. N. Lebedev, A. V. Travin, et al., Geol. Geofiz. **39**, 55 (1998).
13. I. K. Kozakov, V. P. Kovach, V. V. Yarmolyuk, et al., Petrology **11**, 444 (2003) [Petrologiya **11**, 491 (2003)].
14. *Structural and Tectonic Correlation across the Central Asia Orogen Collage: North-Eastern Segments,* Ed. by E. V. Sklyarov (IEC SO RAN, Irkutsk, 2005].
15. A. G. Vladimirov, A. S. Gibsher, A. E. Isokh, and S. N. Rudnev, Dokl. Earth Sci. **369**, 1268 (1999) [Dokl. Akad. Nauk **369**, 795 (1999)].