

Neoproterozoic A-Type Granites of the Garevka Massif, Yenisey Ridge: Age, Sources, and Geodynamic Setting

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Abstract—This paper presents the results of geochemical, isotopic (Sm–Nd), and geochronological (U–Pb and Ar–Ar) investigations of leucogranites from the Garevka massif in the Transangara segment of the Yenisey Ridge. The most distinctive geochemical characteristics of these A-type granitoids are the enrichment in silica, potassium, iron, and fluorine and a considerable depletion in europium. Using U–Pb zircon geochronology, the age of the Garevka leucogranites was estimated as 752 ± 3 Ma, which allowed us to attribute them to a previously established Neoproterozoic tectonic event related to the collision of the Central Angara terrane and the Siberian craton. The parental melts of the granitoids were probably derived by melting of a mixed source composed of continental crustal rocks of Paleoproterozoic and Mesoproterozoic and (or) Neoproterozoic ages. Based on the obtained petrological, geochemical, and geochronological data, the leucogranites of the Garevka massif were assigned to the Neoproterozoic postcollisional Glushikha complex.

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INTRODUCTION

Determining the nature of magma sources and geodynamic conditions of the formation of collisional granitoids, which are characterized by a great diversity of geochemical types, is usually a difficult task (Barbarin, 1999; Frost *et al.*, 2001; Ilbeyli *et al.*, 2004; etc.). Such granitoids are widespread in the Transangara segment of the Yenisey Ridge, where they were related to Neoproterozoic accretion–collision events at the western margin of the Siberian craton (Vernikovskiy *et al.*, 2003). Recent studies have shown that each tectonic stage of the formation of this fold-and-thrust structure was closely associated with the formation of granitoids of distinctive geochemical types and ages (Fig. 1). The oldest collisional granites of this part of the region are represented by the Teya complex with an age of 880–865 Ma (Nozhkin *et al.*, 1999; Vernikovskaya *et al.*, 2002, 2004a). These rocks vary from diorite–plagiogranite to leucogranite, and their geochemical characteristics correspond to transitional I–S-type granites. The next stage of collision events was marked by the formation of syncollisional granites of the Ayakhta complex 760–750 Ma ago and postcollisional leucogranites of the Glushikha complex 750–720 Ma ago (Vernikovskiy *et al.*, 2002, 2003; Vernikovskaya *et al.*, 2002, 2003). The syncollisional complex includes the calc-alkaline

and subalkaline granite series of the Ayakhta massif (S–I-type granites) and the quartz syenites, subalkaline granites, and leucogranites of the Chirimba massif (A-type granites). The postcollisional Glushikha complex (Lendakha, Glushikha, Strelka, and other massifs) are composed of calc-alkaline and subalkaline leucogranites with geochemical features corresponding to A-type granites. The age and origin of granitoids of the Garevka massif in the western Transangara segment of the Yenisey Ridge is still a subject of much debate. According to Volobuev *et al.* (1973), the age of this massif is 1.76 Ga. Because of this, the massif is considered as the independent Garevka complex, similar in age to the Taraka granites of the southern Yenisey Ridge (*Regional Schemes...*, 1999; Nozhkin *et al.*, 2003). Other researchers correlate the Garevka granitoids with the leucogranites of the Glushikha complex of the Transangara region on the basis of geological, petrographic, and geochemical data (Datsenko, 1984; Kachevskii *et al.*, 1998). Therefore, the determination of the age of the Garevka massif and assignment of its rocks to a particular granitoid complex have a bearing on the important regional problem of the presence or absence of Early Precambrian granites in the Transangara part of the Yenisey Ridge and the development of adequate paleogeodynamic models for the formation of the

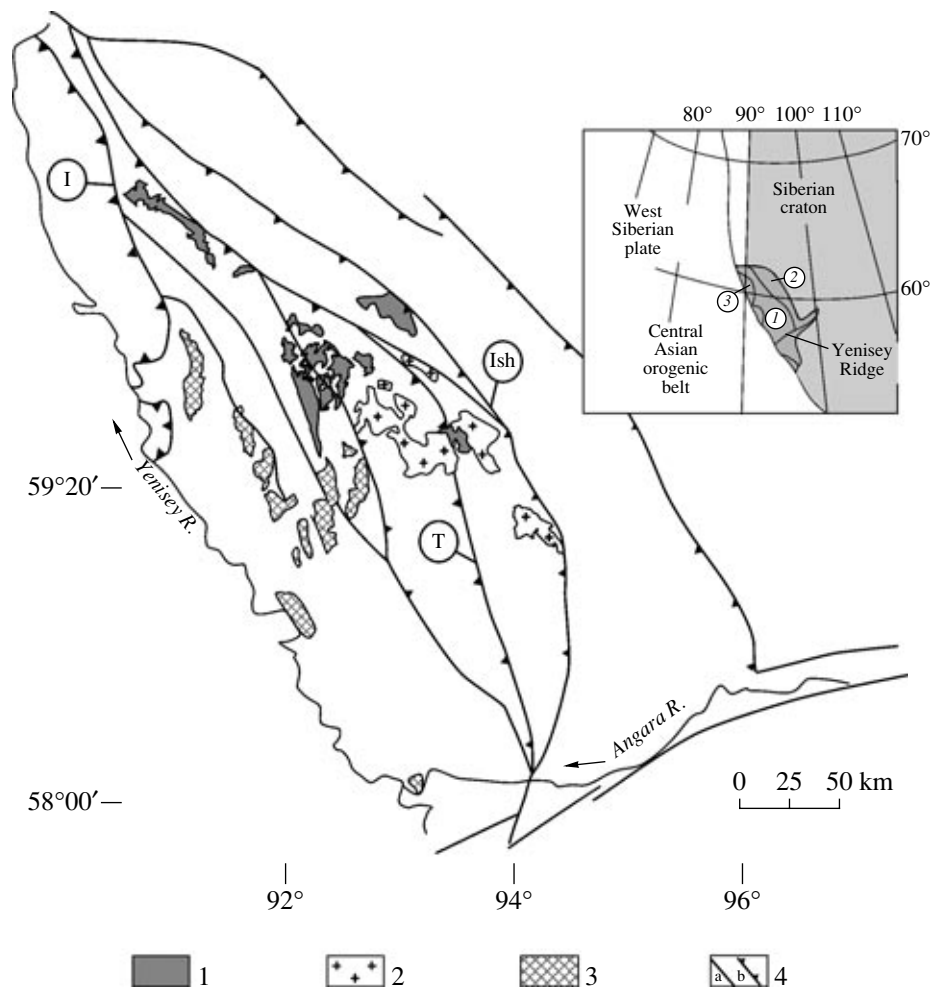


Fig. 1. Neoproterozoic collisional granitoid complex of the Transangara region. (1) Teya (880–865 Ma), (2) Ayakhta (760–750 Ma), and (3) Glushikha (750–720 Ma); (4a) fault and (4b) thrust: Ish, Ishimba; T, Tatarskii, and I, Isakov. Terranes are designated by numbers in circles in the inset: 1, Central Angara; 2, East Angara; and 3, Isakov.

whole Yenisey Ridge, which is a key structure in the western framing of the Siberian craton. To this end, we performed comprehensive geological, geochemical, isotopic, and geochronological investigations of the rocks of the Garevka massif, the results of which are reported in this paper.

GEOLOGIC SETTING

The fold-and-thrust structure of the Transangara segment of the Yenisey Ridge consists of three terranes of different origins (Fig. 1): Isakov, Central Angara, and East Angara (Vernikovskiy *et al.*, 2003). Similar to the majority of granitoid massifs of the region, the Garevka massif is located in the Central Angara granite–metamorphic terrane (Fig. 2). Together with the leucogranite massifs of the Glushikha complex, which were formed 750–720 Ma ago (Vernikovskiy *et al.*, 2002, 2003; Vernikovskaya *et al.*, 2003), the Garevka massif is located in the western granitoid belt of this terrane. The eastern granitoid belt comprises the Teya, Eruda, Kalama,

Chirimba, Ayakhta, and other massifs and was formed in at least two stages, 880–865 and 760–750 Ma ago (Vernikovskaya *et al.*, 2002, 2004a; Vernikovskiy *et al.*, 2003). The Central Angara terrane, which is often referred to as the Central anticlinorium (e.g., Petrov and Reshetova, 1967; *Geology and...*, 1985), is made up of Meso(?)–Neoproterozoic terrigenous, terrigenous–carbonate, and carbonate rocks of the Teya, Sukhopit, and Tungusik groups. The rocks of the Teya Group are metamorphosed under epidote–amphibolite and amphibolite facies conditions. They are represented by andalusite–sillimanite–staurolite, kyanite–sillimanite, and biotite–sillimanite gneisses, quartz–muscovite schists, quartzites, and marbles. Based on the high-grade metamorphism of these rocks, many geologists believed that they are of Early Precambrian (*Regional Schemes...*, 1999; Nozhkin *et al.*, 1999) or even Archean age, if the independent Garevka Group is distinguished (Kachevskii *et al.*, 1998). The granitoids of the oldest Teya complex are located in the northern part of the terrane and hosted by the highest grade metamor-

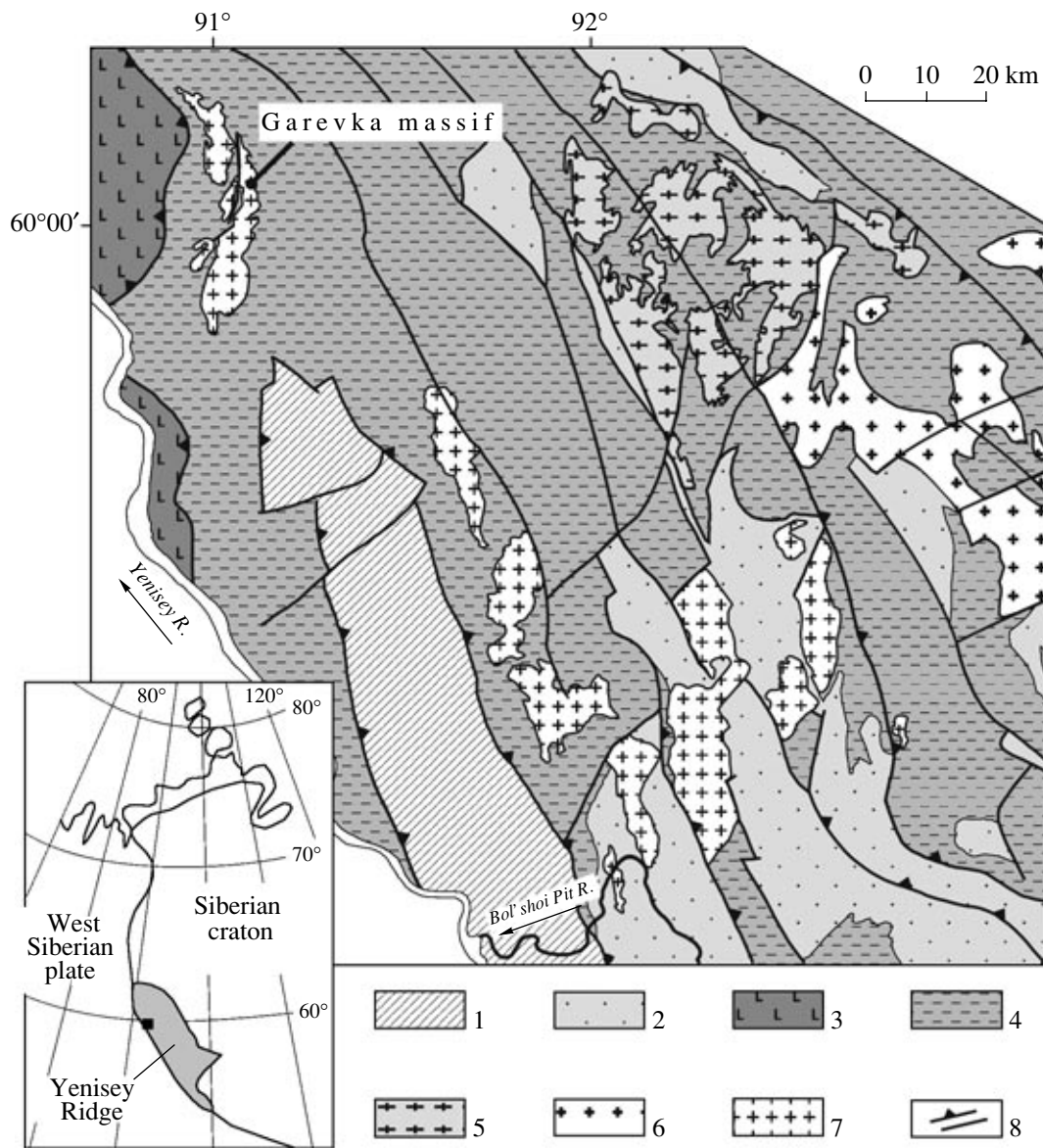


Fig. 2. Geological sketch map for the western part of the Central Angara terrane, compiled after Kachevskii *et al.* (1998). (1) Vendian–Cambrian cover; (2) terrigenous–carbonate deposits, NP₂; (3) Isakov ophiolite complex, NP₂; (4) mainly flyschoid complexes metamorphosed under greenschist to amphibolite facies conditions, including undifferentiated granite gneisses, MP–NP₁?; (5) granitoid of the Teya complex (880–865 Ma); (6) granitoid of the Ayakhta complex (760–750 Ma); (7) granitoid of the Glushikha complex (750–720 Ma); and (8) thrusts and faults.

phic rocks of the Teya Group. Together with the country metapelites, they compose granite–metamorphic tectonic blocks, where the outlines of intrusive bodies are not always distinct and their contact zones are usually represented by areas of gneissic and cataclastic rocks (Nozhkin, 1999; Vernikovskaya *et al.*, 2004a). The granitoids of the Ayakhta complex compose several massifs confined to the Ishimba collisional suture between the Central Angara and East Angara terranes and cut the rocks of both the Teya and Sukhopit groups. The latter is composed of terrigenous–carbonate rocks metamorphosed under greenschist- and epidote-

amphibolite-facies conditions. The rocks of the Ayakhta complex show contact aureoles represented by hornfels zones with andalusite, sillimanite, and cordierite as well as magnesian skarns (Datsenko, 1984; Kozlov and Lepezin, 1995; Likhanov *et al.*, 2001). The postcollisional Glushikha leucogranites are widespread in the western part of the Central Angara terrane, where they form small (20–280 km² in area) massifs with narrow contact aureoles (up to several tens of meters). They cut the terrigenous, terrigenous–carbonate, and carbonate rocks of the Tungusik Group, which were metamorphosed to no more than upper greenschist

facies conditions. Similar to most massifs of the Glushikha complex, the Garevka massif is a roughly N–S striking body traced over a distance of ~30 km at a width of 5–7 km and occupying an area of 170 km² (Fig. 2). Along its eastern boundary, the country rocks are represented by variably migmatized gneisses of the amphibolite facies (Datsenko, 1984). In the western part of the massif, the country rocks are two-mica and biotite gneisses, quartz–actinolite–biotite–epidote–plagioclase schists, which were subjected to regional metamorphism up to the epidote–amphibolite and greenschist facies. Tectonic contacts are most common, and the fault zones are often healed by granite material and injected by aplite veins and quartz veins with fluorite (Kornev *et al.*, 1974).

PETROGRAPHY

The Garevka massif is composed of calc-alkaline and subalkaline leucogranites, including alaskites (*Igneous Rocks*, 1985). The rocks have a pinkish gray color, fine- to medium-grained porphyritic textures, and often a gneissic structure. The major minerals are potassium feldspar (35–45%) and quartz (up to 40%), and the minor phases are plagioclase of albite–oligoclase composition (5–15%) and biotite (1–3%). Muscovite occurs as individual laths but more often, like epidote and chlorite, is a replacement product of iron-rich biotite. Magnetite grains are up to 1–2 mm in size and amount to ~0.5%. Together with ilmenite and titanite, magnetite often occurs as inclusions in biotite. The leucogranites also contain fluorite, apatite, and zircon; Datsenko (1984) documented cassiterite and molybdenite. The phenocrysts of these rocks are represented by potassium feldspar and occasional plagioclase (no. 26–28).

ANALYTICAL METHODS

The concentrations of major elements and fluorine in rocks were determined by X-ray fluorescence and photometric methods, respectively; and REE and other trace elements were analyzed by ICP-MS with relative errors of 5–10%.

The separation of accessory zircon and major rock-forming minerals was performed by standard techniques with heavy liquids. The isotopic analyses of U, Pb, Sm, and Nd were carried out using a Finnigan MAT-261 multicollector mass spectrometer.

The chemical decomposition of zircon and extraction of U and Pb were performed by a modified method after Krogh (1973). The accuracy of U/Pb ratios was 0.5%. The blank levels were no higher than 0.1 ng Pb and 0.005 ng U. The air abrasion treatment of zircon was performed by the method of Krogh (1982). Experimental data were processed using the PbDAT and ISOPLOT programs (Ludwig, 1991, 1999). Ages were calculated on the basis of the universally accepted decay constants of uranium (Steiger and Jager, 1976).

Corrections for common lead were calculated using the model values of Stacey and Kramers (1975).

Sm–Nd isotope analyses were carried out by the method described by Kotov *et al.* (1995). The total blank levels during measurements were 0.03–0.2 ng Sm and 0.1–0.5 ng Nd. The measured ¹⁴³Nd/¹⁴⁴Nd values were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219 and adjusted to ¹⁴³Nd/¹⁴⁴Nd = 0.511860 in the La Jolla standard. The accuracy of determination was ±0.5% (2σ) for Sm and Nd concentrations, ±0.5% for ¹⁴⁷Sm/¹⁴⁴Nd, and ±0.005% for ¹⁴³Nd/¹⁴⁴Nd. The weighted mean ¹⁴³Nd/¹⁴⁴Nd ratio for the La Jolla standard was 0.511862 ± 22 (2σ) from the results of 25 measurements. The calculation of ε_{Nd} values and model ages T_{Nd}(DM) was based on the present-day parameters of the chondritic uniform reservoir (CHUR; Jacobsen and Wasserburg, 1984): ¹⁴³Nd/¹⁴⁴Nd = 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd = 0.1967 and the depleted mantle (DM; Goldstein and Jacobsen, 1988): ¹⁴³Nd/¹⁴⁴Nd = 0.513151 and ¹⁴⁷Sm/¹⁴⁴Nd = 0.2136. In order to take into account possible Sm and Nd fractionation in crustal processes, two-stage model ages, T_{Nd}(DM-2st), were calculated (Liew and Hofmann, 1988).

The Ar–Ar isotopic analysis of biotite was carried out on a Noble gas 5400 mass spectrometer. Mineral fractions with a grain size of no less than 0.15 mm were packed in Al foil and sealed in evacuated quartz ampoules. Irradiation was conducted in a Cd-shielded channel of the VVR-K research reactor of the Tomsk Polytechnic Institute. A charge of MSA-11 biotite sample was placed between each two samples in order to calibrate the neutron flux. The gradient of neutron flux was no higher than 0.5% within the sample size. Argon release was conducted in an externally heated quartz reactor. A blank experiment at 1200°C for 40 min yielded no more than 5 × 10⁻⁹ ncm³ ⁴⁰Ar. The released argon was purified using two-stage Ti and ZrAlSAES getters.

GEOCHEMISTRY

In addition to high SiO₂ (up to 76 wt %) and K₂O contents (up to 6.3 wt %), the Garevka leucogranites show high concentrations of F, Rb, Th, Ta, Nb, Ce, and Sm and K₂O + Na₂O values of up to 9.6 wt % (Table 1). They have relatively small values of the A/CNK index (1.1–1.2) and normative corundum content (2–3%). The Garevka leucogranites show unusually high FeO*¹/MgO (up to 67) and K₂O/Na₂O ratios (up to 2.9) and elevated TiO₂/MgO (up to 6.7) and Ga/Al (up to 4.4). These and a number of other features (strong negative Eu anomalies with Eu* decreasing to as low as –30.2, low CaO, Sr, and Ba concentrations, and distribution patterns of trace and rare earth elements) are similar to those of the leucogranites of the Glushikha complex (Vernikovskaya *et al.*, 2003), which were classed as

¹ FeO* is total iron expressed as FeO.

Table 1. Chemical compositions of rocks from the Garevka massif

Component	00-3	00-4	00-2	00-1	00-10	1529	1517	1519-6	1528	1520	1525	1530
	1	2	3	4	5	6	7	8	9	10	11	12
SiO ₂	74.97	75.04	75.81	75.96	76.08	73.88	74.54	74.99	75.39	75.53	75.24	76.15
TiO ₂	0.24	0.25	0.22	0.20	0.09	0.34	0.28	0.26	0.19	0.16	0.16	0.15
Al ₂ O ₃	13.24	13.34	13.08	12.83	12.80	12.83	12.87	12.49	12.40	12.42	12.33	11.76
Fe ₂ O ₃	2.16	1.90	1.62	2.01	1.65	2.58	1.89	1.89	1.72	2.23	2.11	3.25
MnO	0.11	0.11	0.11	0.12	0.11	0.03	0.04	0.01	0.08	0.01	0.01	0.10
MgO	0.06	0.06	0.04	0.03	0.03	0.14	0.05	0.09	0.09	0.05	0.10	0.18
CaO	0.37	0.50	0.35	0.40	0.94	0.81	0.68	0.40	0.40	0.40	0.57	0.26
Na ₂ O	2.34	2.37	2.35	2.02	2.42	3.10	3.77	3.49	3.10	3.10	3.03	2.69
K ₂ O	5.91	5.71	5.80	5.88	4.95	5.90	5.78	5.78	5.90	5.90	5.78	4.45
P ₂ O ₅	0.03	0.04	0.02	0.03	0.05	0.11	0.04	0.06	0.28	0.02	0.05	0.57
LOI	0.32	0.46	0.41	0.28	0.71	0.68	0.46	0.37	0.44	0.44	0.49	0.62
Total	100.00	100.00	99.99	100.00	100.01	100.47	100.51	99.97	100.13	100.47	100.09	100.33
F	300	400	300	840	4920	–	–	–	–	–	–	–
Li	6.25	8.29	5.38	6.99	5.78	20.00	9.00	1.00	9.00	9.00	–	11.00
Sc	2.40	2.87	2.06	2.14	3.93	6.80	5.80	3.00	5.90	2.60	3.20	4.10
V	1.26	2.27	3.23	<0.02	<0.02	12.00	15.60	2.50	2.20	–	3.90	2.00
Cr	13.80	20.70	17.30	9.17	6.52	–	6.50	6.00	–	–	3.10	–
Co	1.86	1.67	1.29	1.72	1.62	–	3.30	2.60	–	–	–	–
Ni	15.85	10.77	9.69	19.65	20.90	8.10	6.80	5.50	6.20	6.60	1.70	8.90
Cu	5.92	6.18	3.01	9.42	10.10	–	–	–	–	–	–	–
Zn	23.40	32.50	13.10	21.90	12.90	–	–	–	–	–	–	–
Ga	16.40	18.50	16.20	16.50	20.50	17.00	16.00	12.00	16.00	29.00	22.00	17.00
Rb	424	425	369	392	523	295	–	196	278	330	278	330
Sr	19.50	24.70	17.00	18.00	13.00	–	–	–	–	–	–	–
Y	27.60	39.00	28.90	27.30	17.43	–	–	–	–	–	–	–
Zr	183	216	169	191	127	130	–	–	110	320	210	140
Nb	12.20	15.90	13.30	13.10	23.90	12.00	20.00	–	13.00	17.00	–	13.00
Cs	3.84	9.91	2.17	2.70	3.91	13.00	6.00	2.80	4.00	6.00	4.00	4.00
Ba	144	140	110	116	53	250	220	140	98	190	250	170
La	22.30	69.30	41.10	44.80	14.00	59.00	120.00	–	69.00	120.00	83.00	40.00
Ce	67	103	74	87	37	120	160	–	120	240	–	–
Pr	4.90	13.99	8.84	9.36	3.73	–	–	–	–	–	–	–
Nd	15.80	45.00	29.20	31.50	12.50	–	–	–	–	–	–	–
Sm	3.08	7.04	4.64	5.09	2.72	–	–	–	–	–	–	–
Eu	0.24	0.38	0.23	0.24	0.05	–	–	–	–	–	–	–
Gd	3.05	5.72	4.48	4.75	2.45	–	–	–	–	–	–	–
Tb	0.67	1.04	0.82	0.83	0.51	–	–	–	–	–	–	–
Dy	4.40	6.21	4.92	4.76	3.30	–	–	–	–	–	–	–
Ho	1.04	1.37	1.15	1.08	0.67	–	–	–	–	–	–	–
Er	3.12	4.71	3.35	3.38	1.91	–	–	–	–	–	–	–
Tm	0.48	0.75	0.55	0.57	0.33	–	–	–	–	–	–	–
Yb	3.51	4.95	3.76	3.75	2.05	8.00	6.20	–	9.90	20.00	11.00	7.60
Lu	0.53	1.02	0.49	0.61	0.29	–	–	–	–	–	–	–
Hf	6.58	7.05	6.02	6.85	5.59	–	–	–	–	–	–	–
Ta	1.66	2.46	1.94	1.75	3.59	–	–	–	–	–	–	–
Pb	26.60	36.90	20.60	23.70	21.90	47.00	39.00	29.00	38.00	54.00	46.00	36.00
Th	47.10	58.10	53.20	54.90	27.80	–	–	–	–	–	–	–
U	5.94	8.42	10.49	12.55	5.05	3.00	6.00	6.00	8.00	7.00	6.00	6.00
(La/Lu) _{CN}	4.30	7.00	8.70	7.60	4.90	–	–	–	–	–	–	–
Eu*	–13.2	–30.2	–21.9	–23.9	–13.9	–	–	–	–	–	–	–

Note: (1) and (3) alaskites; (2) subalkaline leucogranite; (4) and (5) leucogranites; (6)–(12) analyses of rocks after Datsenko (1984): (6)–(10) subalkaline leucogranites, (11) alaskite, and (12) leucogranite. Concentrations of elements normalized after Evensen *et al.* (1978): $(La/Lu)_{CN}$ and $Eu^* = Eu_{CN} - [Gd_{CN} + Sm_{CN}]/2$. Dashes denote 'no data'. Oxides are in weight percent, and elements are in ppm.

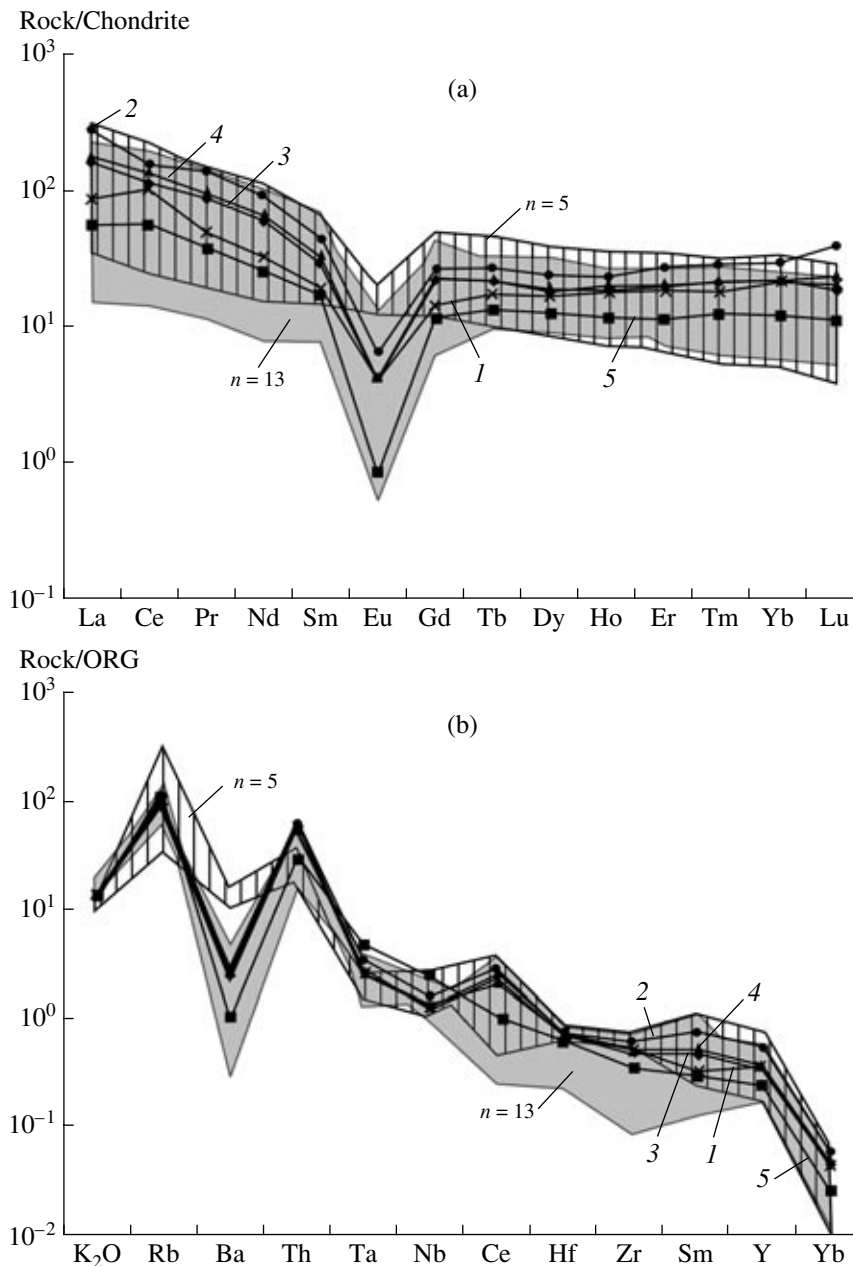


Fig. 3. (a) Chondrite-normalized (Evensen *et al.*, 1978) REE distribution patterns and (b) multicomponent diagram normalized to the average oceanic ridge granite composition (Pearce *et al.*, 1984) for the leucogranites of the Garevka massif, Glushikha complex, and granitoids of the Chirimba massif. The numbers of spectra correspond to the numbers of Garevka granitoid samples in Table 1. The gray field shows leucogranite samples from the Glushikha complex (Vernikovskaya *et al.*, 2003). The hatched field shows subalkaline granitoid samples from the Chirimba massif (Vernikovskaya *et al.*, 2002). n is the number of samples in a set.

rare-metal granites (Kovalenko, 1977) (Figs. 3a, 3b). The rocks of the Garevka massif, as well as other massifs of the Glushikha complex, differ from the quartz syenites and subalkaline granites of the Chirimba massif, which is assigned to the syncollisional Ayakhta complex (Vernikovskaya *et al.*, 2002; Vernikovskiy *et al.*, 2003), in higher SiO_2 , K_2O , Th, and F but slightly lower Zr, Hf, and Nb and very low Ba, Sr, and Eu contents (Figs. 3a, 3b). In the $(Na_2O + K_2O - CaO) - SiO_2$

diagram, which is used to discriminate granitoid series with respect to the alkali-lime index (Frost *et al.*, 2001), the leucogranites fall within the fields of alkali-calcic and calc-alkalic intrusive series, and in most cases their characteristics correspond to those of typical syncollisional complexes, peraluminous S-type leucogranites (Fig. 4a). However, they differ from S-type granites in very high FeO^*/MgO and $FeO^*/(FeO^* + MgO)$ ratios, which is typical of A-type granites (Whalen *et al.*, 1987;

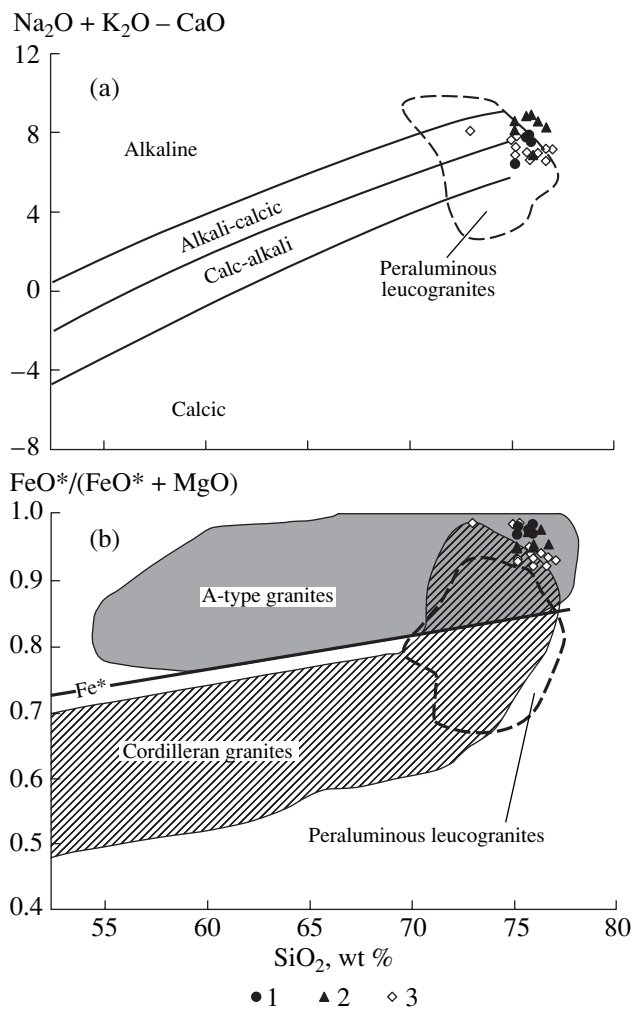


Fig. 4. Geochemical diagrams (a) $(\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}) - \text{SiO}_2$ and (b) $\text{FeO}^*/(\text{FeO}^* + \text{MgO}) - \text{SiO}_2$ (Frost *et al.*, 2001) for the postcollisional leucogranites of the Yenisey Ridge. (1) and (2) rocks of the Garevka massif: (1) nos. 1–5 (Table 1) and (2) nos. 6–12 (Table 1); and (3) rocks of the Lendakha, Glushikha, and Strelka massifs (Vernikovskaya *et al.*, 2003). The line labeled Fe^* separates the trends of (1) iron-rich and (2) magnesium-rich intrusive rocks.

Frost *et al.*, 2001) (Figs. 4b, 5). The $\text{FeO}^*/\text{MgO} - (\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ diagram (Whalen *et al.*, 1987) displays distinct crystal fractionation trends toward an increase in FeO^*/MgO and a decrease in alkalinity for three groups of A-type granites: (1) leucogranites of the Garevka massif; (2) leucogranites of the Glushikha, Lendakha, and Strelka massifs; and (3) quartz syenites, granites, and leucogranites of the Chirimba massif (Fig. 5). The two former trends (in the sequence subalkaline leucogranite–calc-alkaline leucogranites) show a decrease in $(\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$, whereas the latter trend is accompanied by an increase in this parameter (in the sequence quartz syenite–subalkaline granite–calc-alkaline leucogranite). The concentrations of Ta, Yb, Rb, and Nb in the leucogranites suggest that these

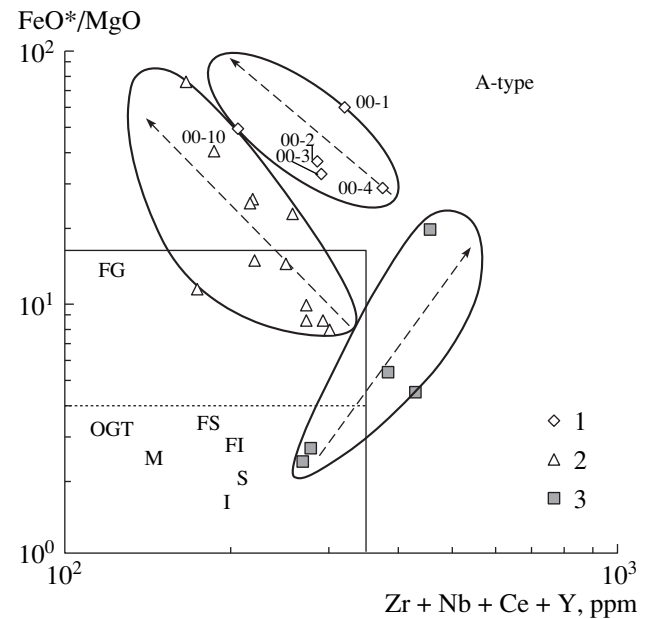


Fig. 5. Geochemical diagram $\text{FeO}^*/\text{MgO} - (\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ (Whalen *et al.*, 1987) for the A-type granites of the Glushikha and Ayakhta complexes. A-type, field of A-type granites; FG, field of fractionated granites; OGT, field of non-fractionated granites of the M-, I-, and S-types; M, I, and S, average values for M-, I-, and S-type granites; FI and FS, average values for the fractionated granites of I- and S-types. Leucogranites of the Glushikha complex from the (1) Garevka, (2) Lendakha, Glushikha, and Strelka massifs; and (3) granitoids of the Ayakhta complex, Chirimba massif. The numbers of samples correspond to those in Table 1. Dashed lines with arrows show the proposed trends of fractional crystallization of subalkaline melts for the fields of the rocks of the Chirimba, Garevka, and Lendakha–Strelka–Glushikha massifs.

rocks were formed in a postcollisional environment (Pearce, 1996). The rocks of the Garevka massif show higher FeO^*/MgO ratios and Zr, Ta, and Nb concentrations (Fig. 3b) compared to other massifs of the Glushikha complex and could be formed from the earliest derivatives of Chirimba-type subalkaline melts. In the Nb–Y–Zr/4 diagram (Eby, 1992), some A-type granites of the Chirimba massif plot within the A_1 field (mantle source), which may be indicative of their derivation from a mixed mantle–crust source, whereas most of the leucogranites plot within the A_2 field and show mainly crustal characteristics (Fig. 6). It should also be noted that, similar to the sources of the Glushikha granitoids, the magma sources of the Garevka massif probably contained a considerable fraction of a pelitic component, which is indicated by low $\text{CaO}/\text{Na}_2\text{O}$ ratios (<0.3) and $\text{FeO}^* + \text{MgO} + \text{TiO}_2$ values (<4) (Sylvester, 1998).

GEOCHRONOLOGICAL AND ISOTOPIC RESULTS

Accessory zircon occurs in the Garevka alaskite (sample 00-3) as translucent or transparent subhedral

crystals, short prismatic in shape (Figs. 7a–7c) and light yellow or reddish in color. Their major crystal faces are those of the {100} prism and {101} and {111} bipyramids. The zircon shows fine internal zoning and is surrounded by low-birefringence fractured rims, often with secondary iron oxides. Relics of metamictized cores were detected in some clouded crystals. The grain size varies from 50 to 300 μm with an aspect ratio of ~ 2.0 .

Five aliquots of the most transparent zircon crystals were separated for U–Pb geochronological investigations from the size fractions 100–85, 85–60, and 60–45 μm (Table 2). Zircons from three aliquots were preliminarily subjected to air-abrasion treatment. As can be seen from Table 2 (nos. 1–3) and Fig. 8, zircons from the fraction 100–85 μm are characterized by uniform isotopic compositions and a slight discordance (degree of discordance of 1.3–2.2%). Zircons from finer fractions (60–45 and 85–60 μm ; nos. 4 and 5, Table 2) have somewhat older ages ($^{207}\text{Pb}/^{206}\text{Pb}$), which is probably related to the presence of an inherited radiogenic lead component. The zircon fraction 100–85 μm (nos. 1–3, Table 2) defines a discordia with an upper intercept age of 753 ± 16 Ma (MSWD = 0.001). The average age ($^{207}\text{Pb}/^{206}\text{Pb}$) of zircon from this fraction is 752 ± 3 Ma (MSWD = 0.17), which can be accepted as the most accurate estimate for the time of alaskite crystallization in the Garevka massif.

Table 3 shows the Sm–Nd isotopic characteristics of Garevka alaskite sample no. 00-3, which was used for U–Pb zircon dating. A comparison of these data with the previously published results of Sm–Nd isotopic investigations for the collisional granitoids of the Transangara region (Vernikovskaya *et al.*, 2002, 2003; Vernikovsky

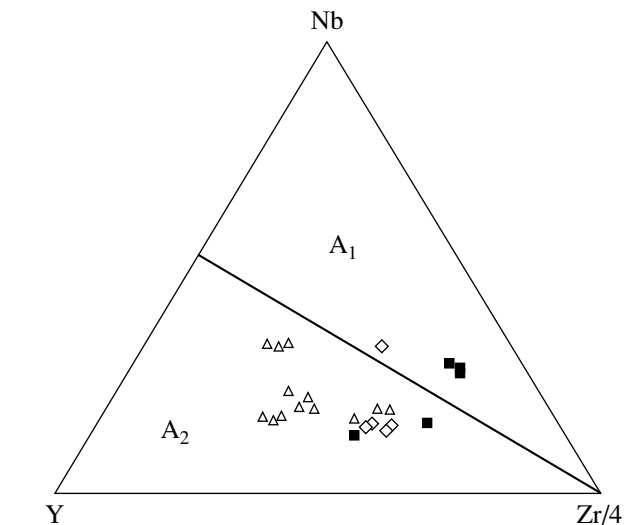


Fig. 6. Geochemical diagram Nb–Y–Zr/4 (Eby, 1992) for the A-type granites of the Glushikha and Ayakhta complexes. A₁, mantle granites and A₂, crustal granites. The symbols are the same as in Fig. 5.

et al., 2003) showed that the leucogranites of the Garevka massif have a higher negative $\epsilon_{\text{Nd}}(\text{T})$ value of -1.9 and a younger Sm–Nd model age, $T_{\text{Nd}}(\text{DM-2st}) = 1.6$ Ga, compared with the postcollisional leucogranites of the Lendakha, Glushikha, and Sterlkovka massifs [$\epsilon_{\text{Nd}}(\text{T})$ between -5 and -8.5 and $T_{\text{Nd}}(\text{DM-2st}) = 1.9$ – 2.2 Ga] as well as the syncollisional granitoids of the Ayakhta and Chirimba massifs [$\epsilon_{\text{Nd}}(\text{T})$ between -6.7 and -8.3 and $T_{\text{Nd}}(\text{DM-2st}) = 2.1$ Ga]. In the $\epsilon_{\text{Nd}}\text{–T}$ diagram (Fig. 9),

Table 2. Results of U–Pb isotopic investigations of zircon from alaskite sample no. 00-3, Garevka massif

No.	Grain size fraction (μm) and its characteristics	Weight, mg	Content, ppb		Isotope ratio		
			Pb	U	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}^*$	$^{208}\text{Pb}/^{206}\text{Pb}^*$
1	–100+85	0.61	144	1128	8595	0.06431 ± 3	0.1502 ± 1
2	–100+85, A 60%**	0.28	59.2	436	896	0.06432 ± 5	0.1578 ± 1
3	–100+85, A 70%	0.51	17.2	130	915	0.06430 ± 10	0.1553 ± 1
4	–60+45	0.42	133	1035	7116	0.06449 ± 2	0.1632 ± 1
5	–85+60, A 20%	0.28	149	1140	1772	0.06517 ± 4	0.1556 ± 1
No.	Grain size fraction (μm) and its characteristics	Isotope ratio		<i>Rho</i>	Age, Ma		
		$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$		$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$
1	–100+85	1.0742 ± 21	0.1211 ± 2	0.96	741 ± 2	737 ± 2	752 ± 1
2	–100+85, A 60%**	1.0824 ± 22	0.1221 ± 2	0.86	745 ± 2	742 ± 2	752 ± 2
3	–100+85, A 70%	1.0687 ± 21	0.1205 ± 2	0.65	738 ± 2	734 ± 2	751 ± 3
4	–60+45	1.0763 ± 22	0.1211 ± 3	0.96	742 ± 2	737 ± 2	758 ± 1
5	–85+60, A 20%	1.0843 ± 22	0.1207 ± 3	0.90	746 ± 2	734 ± 2	780 ± 1

Note: Errors correspond to the last significant digit and reported as 2σ . *Rho* is the correlation coefficient of U–Pb ratios.

* Isotopic ratios are corrected for blank and common lead.

** Fraction of material removed during the air abrasion treatment of zircon.

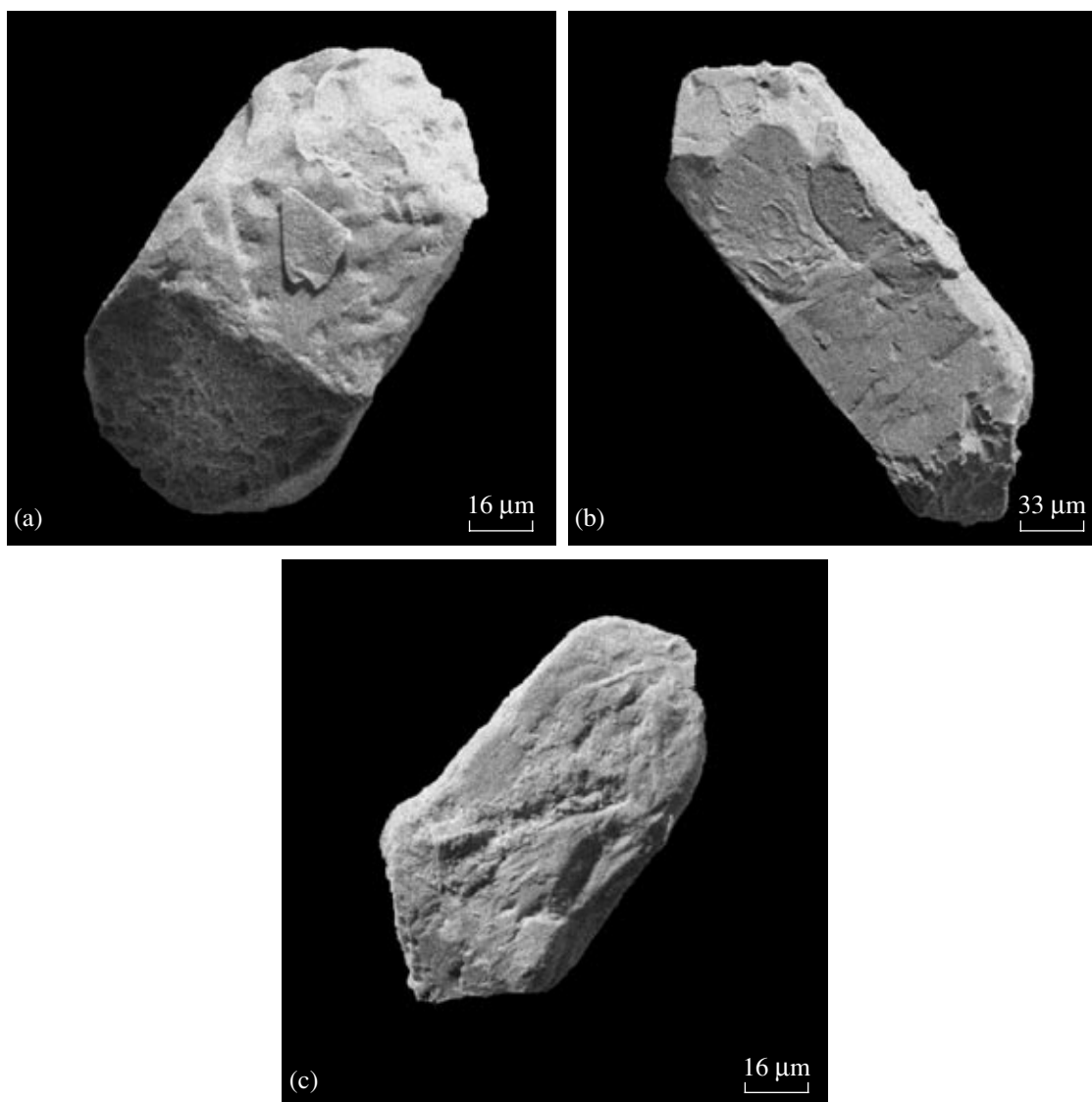


Fig. 7. Photomicrographs of zircons from the alaskite (sample 00-3) of the Garevka massif obtained on an ABT55 scanning electron microscope (accelerating voltage of 20 kV).

the Nd isotopic composition of the Garevka alaskite plots within the field of isotopic evolution of the Mesoproterozoic and Paleoproterozoic continental crust, near its upper boundary. The parental melts of these granitoids were most likely generated by melting of a mixed source composed of continental crustal rocks of Paleoproterozoic and Mesoproterozoic and (or) Neoproterozoic age.

The Ar–Ar isotopic analyses of biotites separated from alaskite sample nos. 00-2 and 00-3 and subalka-

line leucogranite sample no. 00-4 of the Garevka massif yielded discordant $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra (Fig. 10). The low-temperature part of the spectra shows an ascending staircase pattern with apparent ages starting from 380–490 Ma. The plateau ages range from 593 to 518 Ma, which is significantly younger than the U–Pb zircon age obtained for sample no. 00-3. Thus, the Ar–Ar results cannot be interpreted as the age of formation of the massif and are probably related to later events,

Table 3. Bulk-rock Sm–Nd isotopic data for an alaskite sample from the Garevka massif

Sample no.	U–Pb age, Ma	Sm, ppm	Nd, ppm	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}^*$	Error	$\epsilon_{\text{Nd}}(0)$	$\epsilon_{\text{Nd}}(T)$	$T_{\text{Nd}}(\text{DM})$, Ma	$T_{\text{Nd}}(\text{DM-2st})$, Ma
00-3	752	3.62	18.51	0.1183	0.512156	10	–9.4	–1.9	1586	1601

* Error (2σ) of $^{143}\text{Nd}/^{144}\text{Nd}$ is reported in units of the last significant digit.

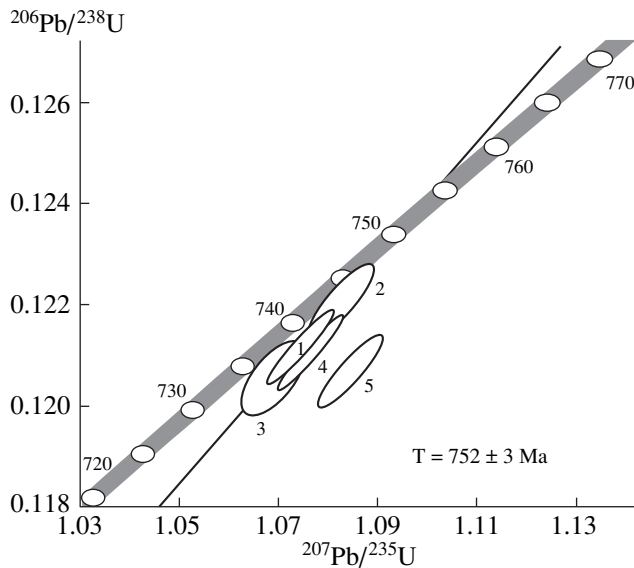


Fig. 8. Concordia diagram for zircon from the alaskite (sample 00-3) of the Garevka massif.

probably to the obduction of ophiolites and island-arcs of the Yenisey belt onto the continental margin (Vernikovskiy *et al.*, 2003). However, the observed shape of the age spectrum indicates that the samples contain at least two components of different age in varying proportion (Yudin *et al.*, 2002). In the current stage of investigations, it can be concluded that the age of the last superimposed event is no older than 490 Ma, which corresponds to the boundary of the occurrence of Early Paleozoic collisional events established in the Angara-Kan terrane of the southern Yenisey Ridge (Vernikovskaya *et al.*, 2004b).

DISCUSSION AND CONCLUSIONS

The results of our petrographic, geochemical, isotopic, and geochronological investigations allowed us to assign the Garevka massif to the Neoproterozoic post-collisional Glushikha leucogranite complex. Similar to other massifs of this complex, the Garevka massif extends in a roughly N-S direction and is part of the western granitoid belt of the Transangara segment of the Yenisey Ridge. The main geochemical characteristics of the rocks of this massif corresponding to A-type granites are the enrichment in silica, potassium, iron, fluorine, and thorium and considerable depletion in europium, barium, and strontium. According to the U-Pb zircon dating of alaskite, the age of formation of the Garevka massif is 752 ± 3 Ma. The parental melts were most likely derived by melting of continental crustal rocks of Paleoproterozoic and Mesoproterozoic and (or) Neoproterozoic age. The rare-metal leucogranites of the Garevka massif were probably produced by fractional crystallization of subalkaline melts geochemically similar to the quartz syenites and subal-

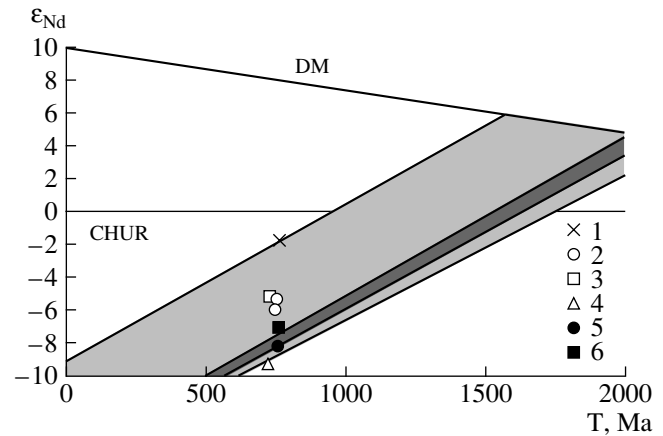


Fig. 9. Diagram ϵ_{Nd} -T for the granitoids of the Central Angara terrane formed during the postcollisional stage, 760–720 Ma ago. Postcollisional leucogranites with ages of 750–720 Ma from the (1) Garevka, (2) Lendakha, (3) Glushikha, and (4) Strelka massifs. Syncollisional granitoids with ages of 760–750 Ma from the (5) Ayakhta and (6) Chirimba massifs. The light gray field shows the Mesoproterozoic and Paleoproterozoic crust (1.6–2.2 Ga) (Vernikovskaya *et al.*, 2003). The dark gray field shows the Paleoproterozoic crust (2.0–2.1 Ga) (Vernikovskaya *et al.*, 2002; Vernikovskiy *et al.*, 2003). CHUR is the chondritic uniform reservoir, and DM is the depleted mantle.

kaline granites of the Chirimba massif, which were derived 761 ± 8 Ma ago from a mantle-crust source with Paleoproterozoic Sm-Nd model ages (Vernikovskaya *et al.*, 2002). In contrast to metaluminous and weakly peraluminous rocks of the Chirimba massif, the Garevka leucogranites are peraluminous and show lower abundances of trace and rare earth elements, especially Ba, Sr, Eu, Zr, Hf, and Nb. Such variations in chemical and mineralogical compositions from syenite-granite to rare-metal leucogranite (including alaskite) suggesting formation by fractional crystallization of a subalkaline or alkaline magma were observed both in anorogenic (rift) environments, for instance in Mongolia, Transbaikalia, and Central Kazakhstan (Heinhorst *et al.*, 2000;

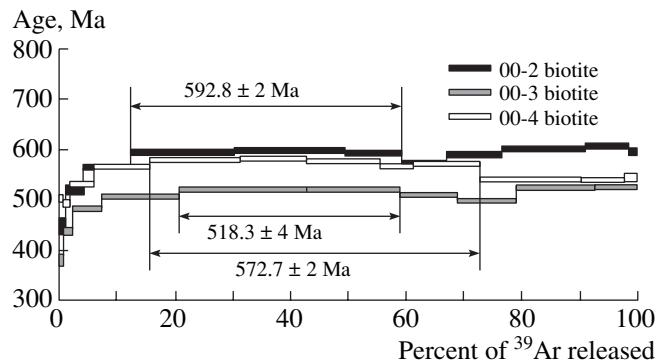


Fig. 10. Ar-Ar age spectrum for biotite from the alaskite (samples 00-2 and 00-3) and subalkaline leucogranite (sample 00-4) of the Garevka massif.

Yarmolyuk *et al.*, 2001; Litvinovsky *et al.*, 2002), and in postcollisional settings, for instance in northern Namibia (Damara belt) and the Swiss Alps (Bonin *et al.*, 1998; Tack and Bowden, 1999). Thus, it is evident that the leucogranites of the Garevka massif are the earliest magmatic rocks of the Neoproterozoic postcollisional event and approximately coeval with the syncollisional granitoids of the Ayakhta complex (Vernikovskaya *et al.*, 2002, 2003; Vernikovskiy *et al.*, 2003).

The ambiguity in the assignment of the Garevka massif to a particular granitoid complex of the Yenisey Ridge was based on the U–Pb geochronological data by Volobuev *et al.* (1973), who estimated the age of the massif as Early Proterozoic. Unfortunately, the results reported by these authors do not meet modern requirements. For instance, isotopic data for both zircon and allanite were used to construct a discordia. Moreover, they did not provide analytical data necessary for the assessment of the reliability of the obtained zircon age. It can only be noted that this zircon is characterized by strongly discordant U–Pb ratios (>2%). In other words, the results reported by Volobuev *et al.* (1973) do not constrain the age of the Garevka massif. Using our new data, the leucogranites of the Garevka massif can be decisively assigned to the Neoproterozoic postcollisional Glushikha complex, which supports the previous inference (Vernikovskiy *et al.*, 2003) on the absence of Early Proterozoic granitoid complexes in the Transangara segment of the Yenisey Ridge.

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REFERENCES

1. B. Barbarin, "A Review of the Relationships between Granitoid Types, Their Origins, and Their Geodynamic Environments," *Lithos* **46**, 605–626 (1999).
2. B. Bonin, A. Azzouni-Sekkal, F. Bussy, and S. Ferrag, "Alkali–Calcic and Alkaline Post-Orogenic (PO) Granite Magmatism: Petrologic Constraints and Geodynamic Setting," *Lithos* **45**, 45–70 (1998).
3. V. M. Datsenko, *Granitoid Magmatism in the Southeastern Framing of the Siberian Platform* (Nauka, Novosibirsk, 1984) [in Russian].
4. G. N. Eby, "Chemical Subdivision of the A-Type Granitoids: Petrogenetic and Tectonic Implications," *Geology* **20**, 641–644 (1992).
5. N. M. Evensen, P. J. Hamilton, and R. K. O’Nions, "Rare Earth Abundances in Chondritic Meteorites," *Geochim. Cosmochim. Acta* **42** (8), 1199–1212 (1978).
6. B. R. Frost, C. G. Barnes, W. J. Collins, *et al.*, "A Geochemical Classification for Granitic Rocks," *J. Petrol.* **42** (11), 2033–2048 (2001).
7. *The Geology and Metallogeny of Yenisey Ore Belt*, Ed. by G. N. Brovko, L. V. Li, and M. L. Sherman (SNIIG-GiMS, Krasnoyarsk, 1985) [in Russian].
8. S. J. Goldstein and S. B. Jacobsen, "Nd and Sr Isotopic Systematics of River Water Suspended Material: Implications for Crustal Evolution," *Earth Planet. Sci. Lett.* **87**, 249–265 (1988).
9. J. Heinhorst, B. Lehmann, P. Ermolov, *et al.*, "Paleozoic Crustal Growth and Metallogeny of Central Asia: Evidence from Magmatic–Hydrothermal Ore Systems of Central Kazakhstan," *Tectonophysics*, No. 328, 69–87 (2000).
10. N. Ilbeyli, J. A. Pearce, M. F. Thirlwall, and J. G. Mitchell, "Petrogenesis of Collision-Related Plutonics in Central Anatolia Turkey," *Lithos* **72**, 163–182 (2004).
11. S. B. Jacobsen and G. J. Wasserburg, "Sm–Nd Isotopic Evolution of Chondrites and Achondrites," *Earth Planet. Sci. Lett.* **67**, 137–150 (1984).
12. L. K. Kachevskii, G. I. Kachevskaya, and Zh. M. Grabovskaya, *1 : 500,000-Scale Geological Map of the Yenisey Ridge*, Ed. by A. K. Mkrtch’yan and M. L. Sherman (Krasnoyarskgeologos’emka, Krasnoyarsk, 1998) [in Russian].
13. T. Ya. Kornev, V. M. Datsenko, and A. V. Bozin, *Riphean Magmatism and Massive Base-Metal Sulfide Mineralization of the Yenisey Ridge* (Nedra, Moscow, 1974) [in Russian].
14. A. B. Kotov, V. P. Kovach, E. B. Sal’nikova, *et al.*, "Stages of Continental Crust Formation in the Central Aldan Granulite–Gneiss Terrain: U–Pb and Sm–Nd Isotopic Data for Granitoids," *Petrologiya* **3** (1), 99–110 (1995) [*Petrology* **3** (1), 87–96 (1995)].
15. V. I. Kovalenko, *The Petrology and Geochemistry of Rare Metal Granitoids* (Nauka, Novosibirsk, 1977) [in Russian].
16. P. S. Kozlov and G. G. Lepezin, "The Petrology, Petrochemistry, and Metamorphism of Rocks in the Angara Region, Yenisey Ridge," *Geol. Geofiz.* **36** (5), 3–22 (1995).
17. T. E. Krogh, "A Low-Contamination Method for Hydrothermal Decomposition of Zircon and Extraction of U and Pb for Isotopic Age Determinations," *Geochim. Cosmochim. Acta* **37**, 485–494 (1973).
18. T. E. Krogh, "Improved Accuracy of U–Pb Zircon by the Creation of More Concordant Systems Using An Air Abrasion Technique," *Geochim. Cosmochim. Acta* **46**, 637–649 (1982).
19. T. C. Liew and A. W. Hofmann, "Precambrian Crustal Components, Plutonic Associations, Plate Environment of the Hercynian Fold Belt of Central Europe: Indication from a Nd and Sr Isotopic Study," *Contrib. Mineral. Petrol.* **98**, 129–138 (1988).
20. I. I. Likhanov, O. P. Polyanskii, V. V. Reverdatto, *et al.*, "Metamorphic Evolution of High-Alumina Metapelites near the Panimba Overthrust, Yenisey Ridge: Mineral Assemblages, P–T Conditions, and a Tectonic Model," *Geol. Geofiz.* **42** (8), 1205–1220 (2001).
21. B. A. Litvinovsky, Jahn Bor-Ming, A. N. Zanvilevich, *et al.*, "Petrogenesis of Syenite–Granite Suites from the

- Bryansky Complex, Transbaikalia, Russia: Implications for the Origin of A-Type Granitoid Magmas,” *Chem. Geol.* **189**, 105–133 (2002).
22. K. R. Ludwig, “ISOPLOT/Ex. Version 2.06: A Geochronological Toolkit for Microsoft Excel,” Berkley Geochronology Center, Spec. Publ. 1a (1999).
 23. K. R. Ludwig, “PbDat for MS-DOS, Version 1.21,” US Geol. Surv. Open-File Rept. 88-542 (1991).
 24. *Magmatic Rocks*, Ed. by O. A. Bogatikov (Nauka, Moscow, 1985), Part 2 [in Russian].
 25. A. D. Nozhkin, “Early Proterozoic Continental-Margin Complexes of the Angara Foldbelt and Their Metallogeny,” *Geol. Geofiz.* **40** (11), 1524–1544 (1999).
 26. A. D. Nozhkin, E. V. Bibikova, O. M. Turkina, and V. A. Ponomarchuk, “Isotopic Geochronology (U–Pb, Ar–Ar, and Sm–Nd) of Subalkaline Porphyry Granites of the Tarak Massif, Yenisey Ridge,” *Geol. Geofiz.* **44** (9), 881–891 (2003).
 27. A. D. Nozhkin, O. M. Turkina, E. V. Bibikova, *et al.*, “Proterozoic Granite–Gneiss Domes of the Yenisey Ridge: Geological Structure and U–Pb Isotopic Age,” *Geol. Geofiz.* **40** (9), 1305–1313 (1999).
 28. J. A. Pearce, “Sources and Settings of Granitic Rocks,” *Episodes* **19** (4), 120–125 (1996).
 29. J. A. Pearce, N. B. W. Harris, and A. G. Tindle, “Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks,” *J. Petrol.*, No. 25, 956–983 (1984).
 30. S. G. Petrov and S. A. Reshetova, “The Geology and Petrography of the Tatarka–Ayakhta and Glushikha Intrusive Complexes, Yenisey Ridge,” in *Proceedings on the Geology and Mineral Deposits of Eastern Siberia* (Nedra, Leningrad, 1967), pp. 108–139 [in Russian].
 31. *Regional Correlation Models for Magmatic and Metamorphic Complexes of the Altai–Sayan Foldbelt*, Ed. by V. L. Khomichev (SNIIGGiMS, Novosibirsk, 1999) [in Russian].
 32. J. S. Stacey and I. D. Kramers, “Approximation of Terrestrial Lead Isotope Evolution by a Two-stage Model,” *Earth Planet. Sci. Lett.* **26** (2), 207–221 (1975).
 33. R. H. Steiger and E. Jager, “Subcommission of Geochronology: Convention of the Use of Decay Constants in Geo- and Cosmochronology,” *Earth Planet. Sci. Lett.* **36** (2), 359–362 (1976).
 34. P. J. Sylvester, “Post-Collisional Strongly Peraluminous Granites,” *Lithos*, No. 45, 29–44 (1998).
 35. L. Tack and P. Bowden, “Post-Collisional Granite Magmatism in the Central Damaran (Pan-African) Orogenic Belt, Western Namibia,” *J. Afr. Earth Sci.* **28** (3), 653–674 (1999).
 36. A. E. Vernikovskaya, V. A. Vernikovskiy, E. B. Sal’nikova, *et al.*, “Yeruda and Chirimba Granitoids, Yenisey Ridge, as Indicators of Neoproterozoic Collisions,” *Geol. Geofiz.* **43** (3), 259–272 (2002).
 37. A. E. Vernikovskaya, V. A. Vernikovskiy, E. B. Sal’nikova, *et al.*, “Neoproterozoic Postcollisional Granitoids of the Glushikha Complex, Yenisey Ridge,” *Petrologiya* **6** (1), 53–67 (2003) [*Petrology* **6** (1), 48–61 (2003)].
 38. A. E. Vernikovskaya, V. A. Vernikovskiy, M. T. D. Wingate, *et al.*, “The Oldest Granitoids in the Transangara Region of the Yenisey Ridge: U–Th–Pb Data on Zircon,” *Dokl. Akad. Nauk* **397** (2), 225–230 (2004a) [*Dokl. Earth Sci.* **397** (5), 616–620 (2004a)].
 39. A. E. Vernikovskaya, V. A. Vernikovskiy, V. M. Datsenko, *et al.*, “Manifestation of Early Paleozoic Magmatism in the Southern Yenisey Ridge,” *Dokl. Akad. Nauk* **397** (3), 374–379 (2004b) [*Dokl. Earth Sci.* **397A** (6), 747–752 (2004b)].
 40. V. A. Vernikovskiy, A. E. Vernikovskaya, E. B. Sal’nikova, *et al.*, “Postcollision Granitoid Magmatism in the Transangara Region of the Yenisey Ridge: An Event 750–720 Ma B.P.,” *Dokl. Akad. Nauk* **384** (2), 221–226 (2002) [*Dokl. Earth Sci.* **384** (4), 362–366 (2002)].
 41. V. A. Vernikovskiy, A. E. Vernikovskaya, A. B. Kotov, *et al.*, “Neoproterozoic Accretionary and Collisional Events on the Western Margin of the Siberian Craton: New Geological and Geochronological Evidence from the Yenisey Ridge,” *Tectonophysics* **375**, 147–168 (2003).
 42. M. I. Volobuev, N. I. Stupnikova, and S. I. Zykov, “The Yenisey Ridge,” in *Geochronology of the USSR* (Nedra, Leningrad, 1973), Vol. 1, pp. 189–202 [in Russian].
 43. J. W. Whalen, K. L. Currie, and B. W. Chappell, “A-Type Granites: Geochemical Characteristics, Discrimination, and Petrogenesis,” *Contrib. Mineral. Petrol.* **95**, 407–419 (1987).
 44. V. V. Yarmolyuk, B. A. Litvinovskii, V. I. Kovalenko, *et al.*, “Formation Stages and Sources of the Peralkaline Granitoid Magmatism of the Northern Mongolia–Transbaikalia Rift during the Permian and Triassic,” *Petrologiya* **9** (4), 351–380 (2001) [*Petrology* **9** (4), 291–301 (2001)].
 45. D. Yudin, A. V. Travin, V. G. Vladimirov, *et al.*, “Age Spectra of Biotite as Indicator of Deformation Rate: Evidence from Microchemical, Structural, Step Heating and Laser $^{40}\text{Ar}/^{39}\text{Ar}$ Analyses,” *Geochim. Cosmochim. Acta.* **6** (15A), A79 (2002).