

Isotopic Geochronology of the Archean Posttectonic Association of Sanukitoids, Syenites, and Granitoids in Central Karelia

E. V. Bibikova*, N. A. Arestova**, V. V. Ivanikov***,
S. Claesson****, A. Yu. Petrova*, and O. A. Levchenkov**

*Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences,
ul. Kosygina 19, Moscow, 119991 Russia

e-mail: bibikova@geokhi.ru

**Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences,
nab. Makarova 2, St. Petersburg, 199034 Russia

***Geological Faculty, St. Petersburg State University,
Universitetskaya nab. 7/9, St. Petersburg, 199034 Russia

****Swedish Museum of Natural History, Box 50007, Stockholm, S-10405 Sweden

Received May 20, 2005

Abstract—The U–Pb geochronological study (by the classic technique and on an ion microprobe) of syenites from central Karelia has established their Archean age. The age values obtained for individual massifs are 2735 ± 15 Ma for syenites from the Sjargozero Massif and 2745 ± 10 Ma for syenite from the Khizhjarvi Massif. The syenites are demonstrated to have been emplaced nearly synchronously with sanukitoid massifs in central Karelia, whose average age is 2743 ± 3 Ma (Bibikova *et al.*, 2005). The syenites of the Sjargozero Massif and granodiorites of the Ust-Volomsky Massif were determined to have practically identical ages of 2735 and 2738 Ma, respectively, a fact also corroborating the coeval character of the syenites and granodiorites. Some zircon grains from the Sjargozero syenites contain cores with an age of about 2755 Ma, which suggests that the syenites could have been contaminated with the material of the host volcanic rocks of basaltic and andesitic composition that were metamorphosed at 2750–2760 Ma. The results of the isotopic geochronologic research indicate that the different rock groups composing the Archean postorogenic association of sanukitoids, syenites, and granitoids in central Karelia have been generated in a single stage at approximately 2740 Ma, i.e., 60–70 m.y. after the origin of the syntectonic tonalites. The zircons have elevated Th/U ratios, which is consistent with the mantle genesis of the rocks. Significant crustal contamination was identified in the most acid members of the sanukitoid series: syenites and granitoids. Our data obtained for zircons from the sanukitoids and syenites of the Karelian craton in the Baltic Shield are in good agreement with the results obtained on the sanukitoids of the Canadian Shield.

DOI: 10.1134/S0869591106010048

INTRODUCTION

The term *sanukitoid* was coined by Shirey and Hanson (1984) for a group of posttectonic rocks of elevated alkalinity, including diorites, monzonitoids, and granitoids. The term was proposed because of the chemical similarities between these rocks and magnesian andesites from Japan, which are thought to be derived by the direct melting of peridotites (Tatsumi and Ishizaka, 1982). Since then analogous rocks have been found in all cratons, where they make up a significant part of the Archean crust. In contrast to syntectonic trondhjemites, tonalites, and granitoids (TTG association), the granitoids of sanukitoid complexes are less silicic rocks of dualistic geochemical nature. They are typically highly magnesian ($mg\# > 0.5$), have elevated concentrations of Ni, Cr, and Co (which testify to the mantle genesis of these rocks) and, at the same time, are enriched in Sr, Ba, LREE, and P_2O_5 . The isotopic geochemical signatures of sanukitoids are also contradictory.

Posttectonic sanukitoids and related high-Mg granitoids were actively studied over the past years in the Karelian craton of the Baltic Shield (Chekulaev *et al.*, 2003; Lobach-Zhuchenko *et al.*, 2005; Kovalenko *et al.*, 2005; Samsonov *et al.*, 2004). We conducted an U–Th–Pb isotopic geochemical examination of zircon from sanukitoids sampled at some massifs in Karelia (Bibikova *et al.*, 2005) and demonstrated that these rocks had been produced within two narrow age ranges: 2740 ± 10 Ma in central Karelia and 2715 ± 10 Ma in western Karelia. Except zircons from the most acid rocks (granodiorites and granites), zircons from sanukitoids contain no ancient cores, a fact consistent with the mantle genesis of these rocks. The sanukitoids are usually younger than the syntectonic rocks of the TTG association by at least 50–70 m.y., and this precludes their direct attributing to rocks produced by subduction.

In some areas, including Karelia, sanukitoids are closely associated with syenites. The spatiotemporal relations between sanukitoids and syenites remain still

not fully clear and were interpreted differently (Corfu *et al.*, 1989; Sutcliffe *et al.*, 1990). In the late 1980s and early 1990s, a posttectonic (postcollision) gabbro–monzonite–syenite–granite association was distinguished in Karelian granite–greenstone province. The association comprised, as a single magmatic series, all massifs of rocks of elevated alkalinity (Ivanikov *et al.*, 1987; Grigor'eva *et al.*, 1990). It was ascribed to the Archean, although several researchers were then prone to believe that some of the massifs are Proterozoic, which also pertained to the syenite massifs. Later, based on newly obtained geological and petrographic evidence, V.V. Ivanikov (1997a, 1997b) subdivided this association into two independent magmatic series: clinopyroxenite–syenite and gabbro–monzonite–granite (sanukitoid). They are represented most fully in the Panozero and West Khizhjarvi massifs, respectively. It was also noted that some of the posttectonic granitoids remarkably differ from both syntectonic granite–gneisses and magnesian granites of the sanukitoid type. These studies were conducted simultaneously by means of K–Ar isotopic dating the massifs, but the dates thus obtained were merely approximate because of some features of the method. These dates only confirmed the Late Archean age of the massifs but did not elucidate the relative ages of intrusions of different composition.

GEOLOGICAL AND PETROGRAPHIC OVERVIEW

We examined syenites from the West Khizhjarvi and Sjagozero syenite massifs, granitoids from the Ust-Volomsky Complex, and lamprophyres from a dike cutting both the syenites and granitoids. In addition, our results are discussed with regard for earlier published data on the sanukitoids of the Panozero Massif (Bibikova *et al.*, 2005).

The setting of the massifs among regional geologic structures is illustrated in Fig. 1, and the sampling sites for zircon are shown in a large-scale map of a fragment of central Karelia (Fig. 2), in a detailed plan of a lakeside exposure of the Sjargozero Massif in this area (Fig. 3), and in a geological map of the West Khizhjarvi Massif (Fig. 4).

The territory displayed in Fig. 2 is adjacent to the western lakeside of Segozero Lake and is the most informative for studying the geologic relations between the plutons of the association in question. The southern part of the territory includes the Panozero zonal sanukitoid massif, which consists of various rocks, ranging from ultramafics to granitoids. The massif was studied in detail and thoroughly described by several researchers (Ivanikov, 1997; Chekulaev *et al.*, 2003; Lobach-Zhuchenko *et al.*, 2005; and others).

Sanukitoids of composition close to that of the rocks of the Panozero Massif were found in the northern part of territory, where they compose large differentiated

dikes. The latter are in places cut by the syenites of the Sjargozero Massif and its satellites. The Sjargozero Massif itself is a dike-shaped body that trends from the bank of Sjargozero Lake for 2.5 km to the north-northeast and has a thickness of up to 1 km (Fig. 2). The intrusion cuts across Lopian (Late Archean) green-schists (metamorphosed volcanic rocks), and the syenites are in turn intruded by the granitoids of the Ust-Volomsky Complex, as is shown in Fig. 3. Both the syenites and granitoids are intersected by lamprophyres (Fig. 3).

The following genetic succession of rocks composing the association was reconstructed for the study area: sanukitoids (including their acid derivatives)–syenites–granitoids of the Ust-Volomsky Complex–lamprophyres.

The petrotypical syenite intrusion of Karelia is the West Khizhjarvi Massif (Fig. 4). The massif is hosted by gneiss–granites and Lopian volcanic rocks. In map view, the intrusion has the shape of an oval elongated to the northwest and extending for 7 km at a maximum thickness of 3 km. The massif has a conformable inner structure, and its morphology corresponds to a gently inclined lens. The footwall consists of coarse- and giant-grained syenite with thin (no thicker than 0.5 m) layers of cumulus clinopyroxenites. The latter rocks grade into mostly equigranular leucosyenites toward the center of the massif and its top. The rocks consist of 70–90% anti- and mesoperthitic alkaline feldspar, with interstices between its crystals filled with smaller prisms of diopside that are variably amphibolized. The minor and accessory minerals are quartz, biotite, epidote, andradite, calcite, magnetite, titanite, zircon, and apatite. The reconstructed original composition of the rocks makes it possible to identify them as diopside–anorthoclase syenite.

The Sjargozero syenites, which were initially thought to be metasomatic rocks (Glebova-Kul'bakh *et al.*, 1963), are closely similar to the Khizhjarvi rocks. The similarities, including common geochemical features, leave no doubts that the rocks are magmatic.

The syenites are the richest in Na₂O + K₂O (up to 11.5 wt %) among all rocks of the association. They are moderately alkaline, although their K/(Na + Al) ratio is close to one (up to 0.95). The trace-element composition of the Archean syenites is unusual (Condie, 1981), which also fully pertains to the syenites of the Karelian granite–greenstone province (Ivanikov, 1997b). These rocks are noted for elevated concentrations of Sr and LREE and strongly fractionated REE composition. Analogous geochemical features were identified, as was mentioned above, in the sanukitoids. However, the syenites and sanukitoids show an important difference: the former rocks are significantly less magnesian (mg# < 0.5) and have relatively low Cr and Ni concentrations.

The granitoids of the Ust-Volomsky Complex, which intrude the syenites, are leucocratic biotite granites. These are fine- and medium-grained massive rocks

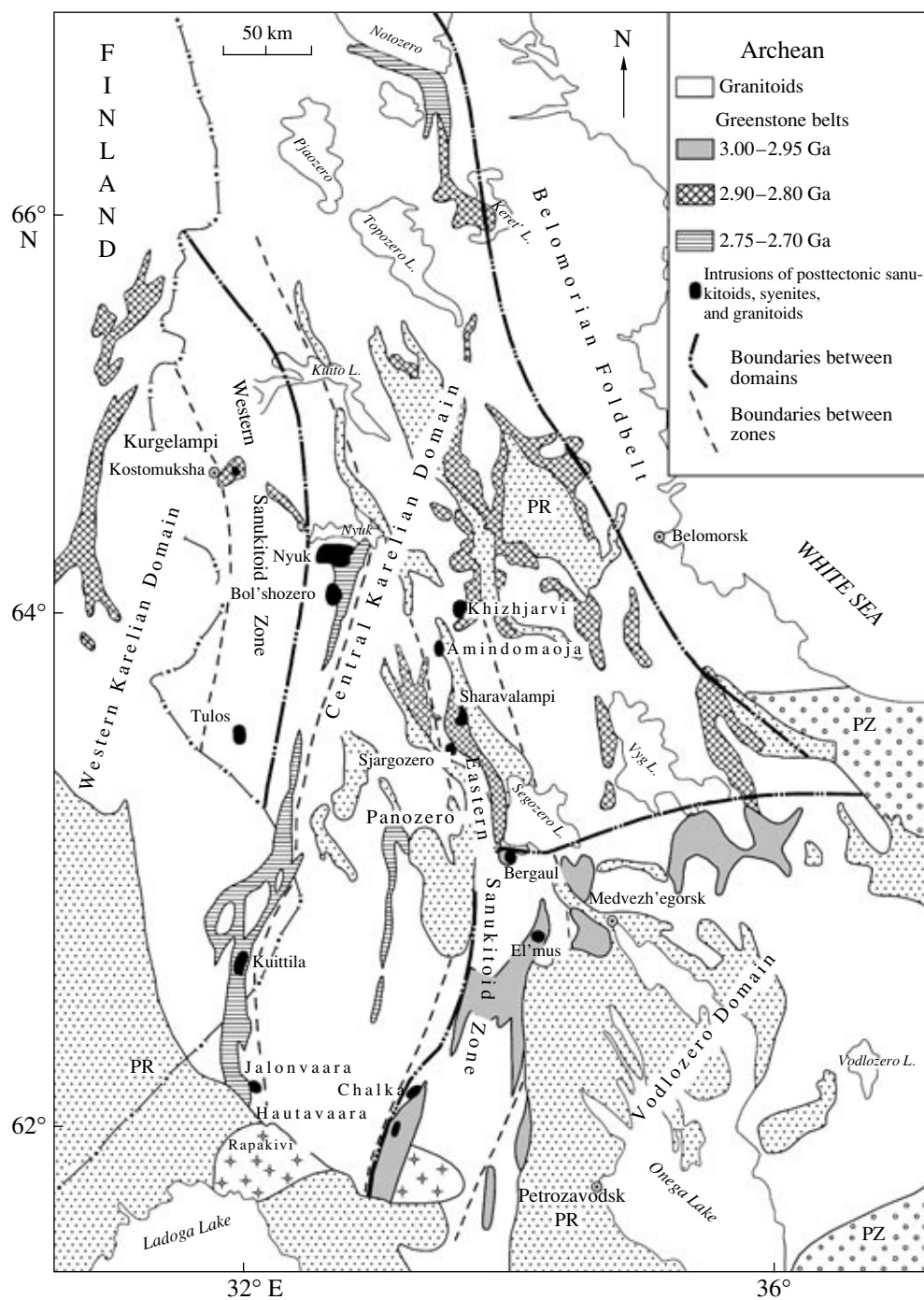


Fig. 1. Geological map of the Karelian granite–greenstone terrane after (Lobach-Zhuchenko *et al.*, 2005). The map displays three Archean domains and Archean sanukitoid and syenite massifs.

with rare microcline and plagioclase phenocrysts. With regard for the amount of phenocrysts, the proportions of the leucocratic minerals of the rock are as follows: 50–60% plagioclase, 15% microcline, and about 20% quartz. The mafic minerals are chloritized biotite and epidote, and the accessories are apatite, titanite, and zircon. Compared with the syntectonic granitoids of the TTG association, the granitoids of the Ust-Volomsky

Complex are notably richer in alkalis, particularly Na_2O , and differ from the sanukitoid granitoids in having much lower mg#.

The dark gray rock of dikes that cut across the syenites and granitoids is strongly sheared along dike contacts and bears completely replaced plagioclase phenocrysts and unrecognizable mafic minerals submerged in a groundmass of tiny grains of feldspars, quartz,

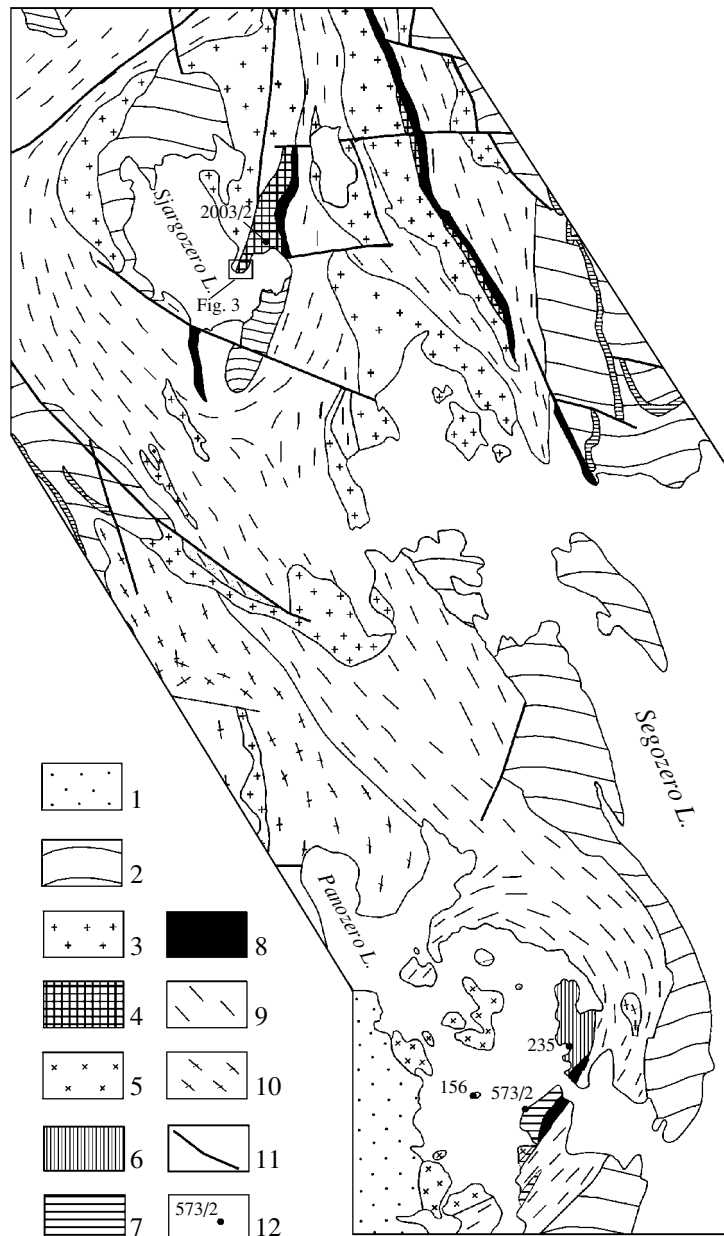


Fig. 2. Geological map of the western bank of Segozero Lake (modified after Ivanikov, 1997a).

(1) Quaternary deposits; (2) Lower Proterozoic volcanic–sedimentary deposits; (3) granitoids of the Ust-Volomsky Complex; (4) syenites of the Sjargozero Massif and its satellites; (5–8) rocks of the sanukitoid complex: (5) quartz monzonites–granodiorites, (6) leucocratic diorites–monzonites, (7) melanocratic monzodiorites, (8) monzogabbro with ultramafic layers; (9) Upper Archean (Lopian) greenschists and metasedimentary rocks; (10) Archean granite-gneisses; (11) faults; (12) sampling sites.

chlorite, epidote, and carbonate. Here we adhere to the original name lamprophyre, which was given to this rock when it was first described (Glebova-Kul'bakh *et al.*, 1963).

ISOTOPIC GEOCHRONOLOGY

Mineralogical samples for zircon separation were taken at exposures with the typical rocks of the massifs.

Leucocratic biotite granodiorite of the Ust-Volomsky Complex was sampled at the bank of Sjargozero lake (sample 2003/1), at a distance of 100 m from the contact between the syenites and granodiorites (Figs. 2, 3). In the same lakeside exposure not far from the contact of the Sjargozero syenite intrusion with Lopian metavolcanic rocks, samples of syenite (sample 100-10) and lamprophyre from a cutting dike (sample 100-8) were taken. Another sample of the Sjargozero syenite (sample 2003/2) was collected in the central part of the massif,

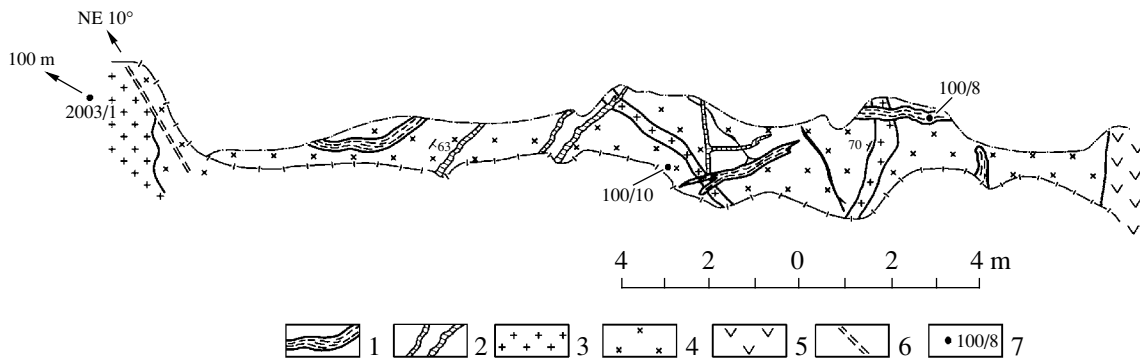


Fig. 3. Sketch map of an exposure in the bank of Sjargozero Lake (modified after Ivanikov, 1997a).

(1) Lamprophyre dikes; (2) aplite dikes; (3) granodiorites of the Ust-Volomsky Complex; (4) syenites of the Sjargozero Massif; (5) Upper Archean metabasites; (6) faults; (7) sampling sites.

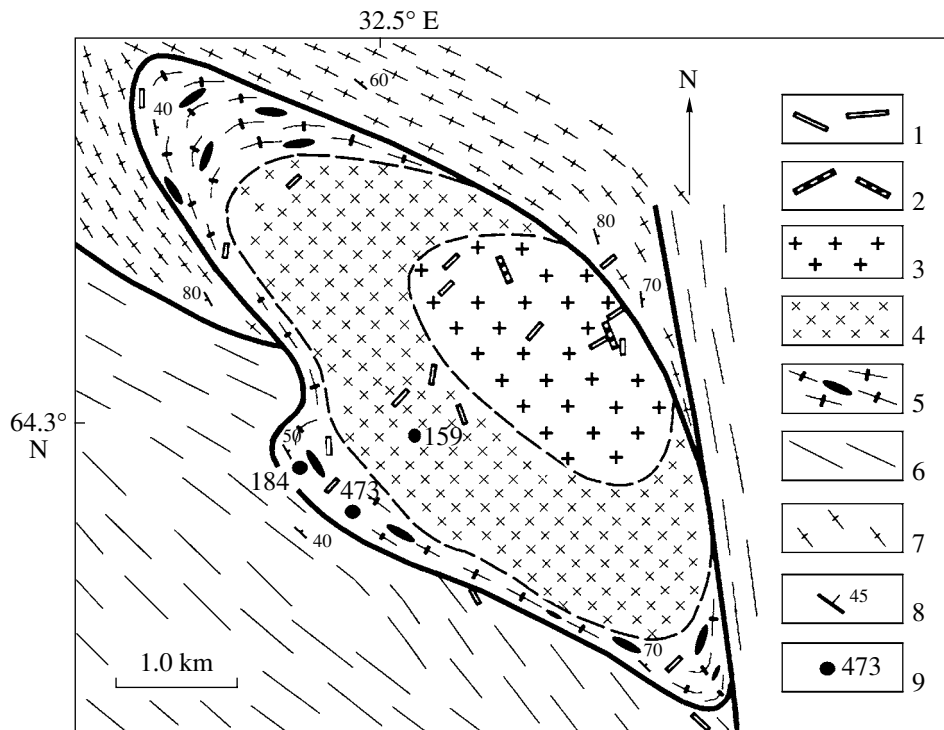


Fig. 4. Geological map of the West Khizhjarvi syenite massif (modified after Ivanikov, 1997a).

(1) Aplite dikes; (2) syenite porphyry dikes; (3) quartz-bearing leucosyenites; (4) equigranular leucosyenites; (5) porphyritic trachytoid mesocratic syenites with pyroxenite layers; (6) Late Archean (Lopian) greenschists; (7) Archean granite-gneisses; (8) strike and dip symbols; (9) sampling sites.

approximately one kilometer northeast of the lakeside exposure.

The West Khizhjarvi Massif was represented by three samples. Sample 473 is inner-contact syenite, which is trachytic and banded, with bands accentuated by alternating layers of more melanocratic and leucocratic varieties. Not far from this sampling site, sample 184 was taken from a pyroxenite layer in the syenite. Sample 159 from the central part of the massif is leucocratic syenite.

Figure 2 additionally demonstrates the sampling sites of samples 573/2, 235, and 156 of the rocks of the Panozero sanukitoid massif, which are, respectively, monzodiorite, monzonite, and quartz monzonite-granitoid of the youngest three intrusive phases. Zircon from these rocks was dated previously (Bibikova *et al.*, 2005).

The chemical compositions of the rocks from which zircon was separated are listed in Table 1.

Zircon dating was conducted by classic U–Pb method at the Vernadsky Institute of Geochemistry and

Table 1. Chemical composition of rocks whose samples were taken for isotopic dating

Component	184 pyroxenite	159 syenite	2003/1 granodiorite	2003/2 syenite	100-10 syenite	100-8 lamprophyre
SiO ₂	51.00	61.94	67.9	60.4	57.42	63.00
TiO ₂	1.14	0.60	0.31	0.74	1.03	0.45
Al ₂ O ₃	7.14	11.88	16.5	16.2	15.38	15.62
Fe ₂ O ₃	9.51	4.30	2.73	5.54	5.26	4.72
MnO	0.25	0.07	0.041	0.101	0.11	0.07
MgO	11.10	1.47	0.79	2.36	3.12	2.16
CaO	12.40	2.38	2.16	4.23	4.51	3.82
Na ₂ O	1.33	6.77	5.89	5.84	5.89	7.20
K ₂ O	1.94	4.05	3.03	4.07	3.97	2.41
P ₂ O ₅	1.16	0.25	0.121	0.45	0.46	0.22
LOI	1.51	0.81	0.42	0.51	1.9	0.49
Rb	48	112	76	79	68	78
Sr	924	1587	1328	1520	1097	1446
Y	33	28			30	30
Zr	117	420	130	95	77	108
Ba	918	1673	1285	1540	2164	1039
Nb	9	17			19	7
Th	7	10	6	9.1	9	9
U			1.8	1.3		
Cr	434	37			43	52
Ni	204	29			36	26

Note: Oxides are given in wt %, elements are in ppm.

Analytical Chemistry, Russian Academy of Sciences, and the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. It was also dated by the U–Th–Pb method on a CAMECA 1270 ion microprobe, NORDSIM, at the isotopic laboratory of the Swedish Museum of Natural History in Stockholm.

For studying on ion microprobe, an epoxy pellet with zircon grains to be analyzed and the standard zircon were prepared and polished until the cores of the crystals were exposed. The inner structure of the zircon grains was preliminarily examined by cathodoluminescence. Preparatory to the analysis, the pellet was sputter coated with gold. The primary ion beam consisted of O₂⁻ and affected an ellipsoidal area 25 × 40 μm. Secondary ions were analyzed at a resolution of 5600,

which enabled the reliable distinguishing of all atomic masses. The analytical method is described in more detail in (Whitehouse *et al.*, 1997, 1999). The accuracy of the measurements was 0.1–0.3% for Pb composition and 1–3% for U–Pb isotopic ratios. The results are summarized in Table 3 and shown in the concordia diagrams of Figs. 6a–6e.

Zircon isotopic dating by the classic method was conducted in compliance with the technique described in (Krogh, 1973), on a TRITON mass spectrometer at the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, and on a Finnigan MAT 261 mass spectrometer at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. The results are listed in Table 2 and demonstrated graphically in concordia diagrams (Figs. 5a, 5b).

Table 2. U–Pb isotopic data on zircon from granodiorite 2003/1, Sjargozero, and syenite 473/1, Khizhjarvi

No.	Size fraction, μm	Sample, mg	Concentrations, ppm		Pb isotopic composition			Isotopic ratios		Age, Ma
			U	Pb	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{207}\text{Pb}$	$^{206}\text{Pb}/^{208}\text{Pb}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$	
granodiorite 2003/1										
1	+125	0.55	172.99	11.32	323.1	4.419	4.064	0.4853	12.656	2734.6 ± 1.2
2	-125+100	0.54	201.08	64.39	348.6	4.447	4.337	0.2453	6.4423	2746.5 ± 1.2
3	-100+75	0.37	281.73	126.54	357.9	4.480	4.579	0.3477	9.094	2739.6 ± 1.1
4	-75	0.11	962.41	351.35	325.9	4.429	4.032	0.2753	7.1735	2733 ± 1.2
5	isr	n.a.	n.a.	n.a.	2870	4.9516	7.248	0.5322	14.527	2809.4 ± 1.2
syenite 473/1										
1	>130	0.56	318	180	2760	5.463	3.0978	0.4295	10.84	2680.7
2	>130	1.05	315	188	3315	5.413	2.956	0.4521	11.52	2695.9
3	>130, aa	1.20	391	228	4395	5.478	3.1601	0.4473	11.26	2676.1
4	100–130	0.24	253	148	3975	5.401	3.026	0.4429	11.33	2699.5
5	100–130, aa	0.87	137	53.6	5615	5.588	3.079	0.4664	11.51	2643.3
6	85–100, isr	n.a.	n.a.	n.a.	3990	5.282	5.426	0.5208	13.59	2736.2

Note: Zircon isotopic study was conducted by the method (Krogh, 1987) for small zircon samples. The U and Pb concentrations were determined by the isotopic dilution technique, using a mixed $^{208}\text{Pb} + ^{235}\text{U}$ tracer. The blank was 0.1 ng for Pb and 0.01 ng for U. The isotopic composition was measured on a TRITON multicollector solid-source mass spectrometer at the isotopic laboratory of the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences (granodiorite 2003/1) and on a MAT-261 mass spectrometer at Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences (sample 473/1). Isotopic ages were calculated by the computer program (Ludwig, 1999). The errors of the U–Pb ratios were 0.5%. The correction for common Pb was introduced for an age of 2740 Ma in compliance with the model (Stacey and Kramers, 1975); isr is the insoluble residue of zircon after its treatment with HF at 200°C for 4 h; aa is air abrasion; n.a. means not analyzed.

Table 3. Isotopic data (ion microprobe) on zircons from sanukitoids and syenites of Karelia

Sample no., analytical spot no.	Concentration, ppm			Th/U	Common ^{206}Pb , %	Isotopic ratios $\pm 1\sigma$		Age, Ma	Discordance, %
	U	Th	Pb			$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{235}\text{U}$		
Sjargozero Massif									
sample 2003/2, syenite									
1	241	162	164	0.633	3.23	0.4947 ± 65	12.998 ± 16	2747 ± 5	-7
2	269	165	172	0.568	2.48	0.5258 ± 65	13.853 ± 16	2710 ± 8	-1
3	150	134	110	0.848	0.27	0.5233 ± 70	13.813 ± 16	2733 ± 5	-2
4	328	408	261	1.261	0.2	0.4689 ± 60	12.048 ± 16	2731 ± 5	-10
5	224	194	169	0.888	0.03	0.5133 ± 65	13.374 ± 17	2751 ± 4	-3
6	184	231	149	1.275	0.03	0.5167 ± 70	13.441 ± 17	2754 ± 4	-2
sample 100-10, syenite									
1	111	147	91	1.331	0.04	0.5264 ± 70	13.730 ± 16	2735 ± 6	-1
2	205	261	164	1.262	0.11	0.5158 ± 70	13.591 ± 16	2752 ± 4	-3
3	70	65	51	0.885	0.39	0.5011 ± 70	13.037 ± 16	2731 ± 9	-5
4	128	230	103	1.445	4.72	0.5039 ± 70	13.042 ± 16	2722 ± 11	-4
5	175	284	145	1.545	0.13	0.5107 ± 70	13.273 ± 16	2729 ± 5	-3
sample 100-8, lamprophyre									
1	188	246	147	1.32	0.14	0.5088 ± 285	13.28 ± 72	2736 ± 7	-4
2	341	220	215	0.65	3.29	0.4370 ± 77	11.67 ± 21	2774 ± 8	-16
4	131	124	97	0.95	0.33	0.4898 ± 88	12.84 ± 25	2743 ± 10	-4
4a	133	112	108	0.85	1.65	0.563 ± 11	14.78 ± 32	2745 ± 12	5
6	215	180	161	0.84	0.15	0.523 ± 10	14.35 ± 29	2817 ± 7	-3
7	1326	289	554	0.22	0.11	0.3258 ± 64	8.98 ± 18	2825 ± 3	-40
Khizhjarvi Massif									
sample 159, syenite									
1	198	171	147	0.840	0.04	0.5218 ± 75	13.692 ± 175	2745 ± 5	-2
2	248	165	179	0.655	0.04	0.5260 ± 75	13.806 ± 175	2745 ± 4	0
3	192	153	143	0.794	0.05	0.5291 ± 75	13.920 ± 178	2749 ± 5	-3
4	107	69	77	0.645	0.06	0.5290 ± 75	13.812 ± 178	2737 ± 8	0
6	188	213	148	1.106	0.03	0.5258 ± 75	13.814 ± 178	2747 ± 5	-1
sample 184, pyroxenite									
1	174	156	129	0.854	0.06	0.5185 ± 70	13.619 ± 175	2747 ± 5	-2
2	56	52	41	0.869	0.23	0.5018 ± 70	13.042 ± 175	2729 ± 10	-5
3	153	121	111	0.741	0.07	0.5169 ± 70	13.557 ± 175	2744 ± 6	-3
4	174	136	125	0.739	0.05	0.5104 ± 70	13.326 ± 175	2737 ± 6	-3
5	203	170	143	0.816	0.08	0.4906 ± 70	12.808 ± 175	2736 ± 4	-7

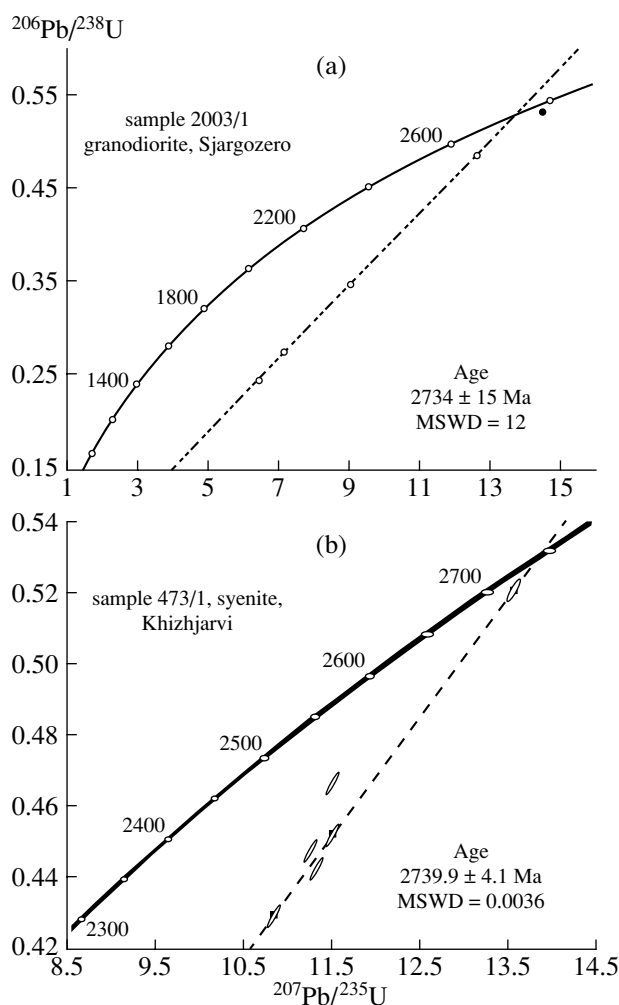


Fig. 5. Concordia diagrams for zircons. (a) Zircon from granodiorite, sample 2003/1; (b) zircon from syenite, sample 473 (classic U–Pb method).

The accessory zircon from granodiorite from the Ust-Volomsky Complex (sample 2003/1) consists of pale brown transparent and semitransparent prismatic subhedral crystals. The mineral was dated by the classic method (Table 2, Fig. 5a).

The zircons contain moderate U concentrations, except the smallest grains, their calculated isotopic ages are discordant (Ludwig, 1999). The selective dissolution of one zircon fraction (Mattinson, 1994) has revealed the presence of a more ancient phase, whose age is no younger than 2809 Ma. The occurrence of two zircon phases can account for the relatively high value of MSWD = 12 and significant errors. The age corresponding to the upper discordia and concordia intercept is 2734 ± 15 Ma (Fig. 5a).

Zircons from syenites of the Sjargozero Massif (samples 2003/2 and 100-1) are very large crystals, more than 1 mm long, and are contained in the samples exclusively in the form of crystal fragments. Judging by

the crystal faceting preserved in these fragments, these crystals were short-prismatic and had elongation coefficients of no more than 1–1.5. The zircon crystals are dark and usually opaque. The inner structure of the crystals was examined by means of cathodoluminescence. Some of the crystals possibly contain cores. The results of the ion-microprobe isotopic dating are presented in Table 3 and Figs. 6a, 6b.

Zircons from the syenites have fairly low U concentrations, which somewhat increase (to 300 ppm) in the cores. Their Th/U ratios are very high, up to 1.5, and their isotopic ages are mildly discordant. The age calculated from the upper intercept of the discordia and concordia is 2738 ± 12 Ma for zircon from samples 2003/2 and 2735 ± 14 Ma for this mineral from sample 100-10. The age of the cores of zircons from sample 2003/2 is 2754 ± 8 Ma. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of one zircon fragment from sample 100-10 was evaluated at 2752 ± 4 Ma.

The lamprophyre from a dike exposed in the bank of Sjargozero Lake (sample 108-8) contains a very heterogeneous zircon population. Many grains possess inner cores, some of which are enriched in U and yield highly discordant ages (Table 3, Fig. 6e). The age of zircon corresponding to the upper intercept of the discordia and concordia is 2742 ± 16 Ma. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages of two cores are 2817 ± 7 and 2825 ± 3 Ma (gray ellipses in Fig. 6e).

Zircons from leucosyenite (sample 159) and pyroxenite (sample 184) from the Khizhjarvi Massif were dated on an ion microprobe; the results are demonstrated in Fig. 3 and concordia diagrams (Figs. 6c, 6d). We also dated zircon from banded trachytoid mesocratic syenite sampled within the inner contact zone (sample 473). Zircons from this sample were dated by the classic U–Pb isochron method at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. The dates are presented in Table 2 and shown in concordia diagrams (Fig. 5b).

Accessory zircons from both the syenites and the pyroxenite have morphologies similar to those of this mineral from the Sjargozero syenites. All of the zircons are dark, usually opaque, homogeneous, and have no inner cores.

The U concentrations in these zircons, as in this mineral from the Sjargozero syenites, are low, particularly in zircon from the pyroxenite (close to 100 ppm), and the Th/U ratios are high. The isotopic ages are almost concordant and are equal to 2744 ± 4 Ma for zircon from the leucosyenite (sample 159), 2748 ± 13 Ma for zircon from the pyroxenite, and 2740 ± 4 Ma for zircon from the mesocratic inner-contact syenite.

The fractions separated from syenite 473/1 consist of variable proportions of amber-yellow to dark brown, more metamict, zircon crystals. This causes the significant dispersion of the data points in the concordia plot (Fig. 5b). The fractions whose data points plot to the left of the regression line are dominated by amber-yellow grains, whereas the point that plots to the right of

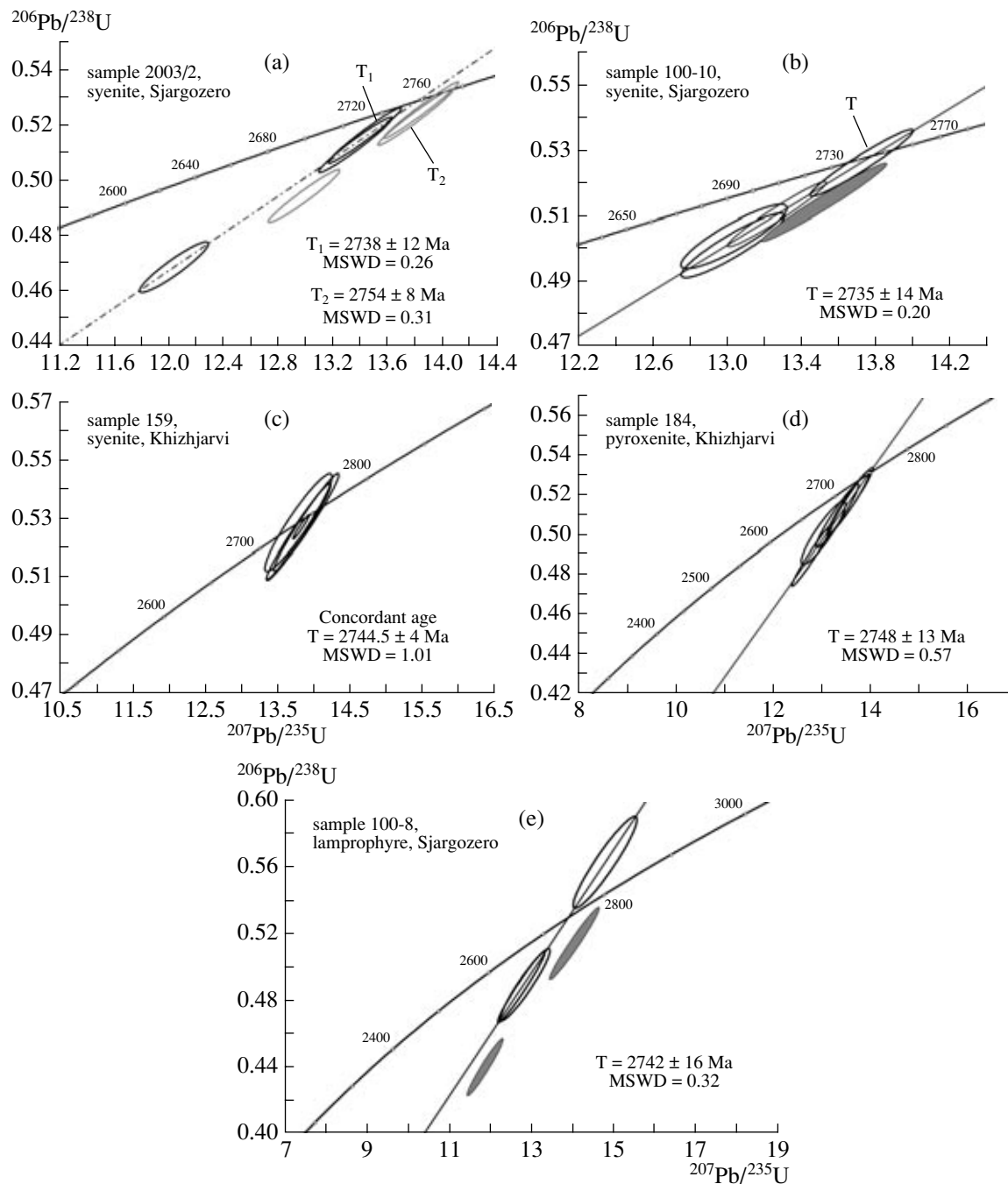


Fig. 6. Concordia diagrams for zircon from various rocks in central Karelia.

(a) Zircon from syenite, sample 2003/2; (b) zircon from syenite, sample 100-10 (gray ellipse corresponds to a xenocryst); (c) zircon from syenite, sample 159; (d) zircon from pyroxenite, sample 184; (e) zircon from lamprophyre, sample 100-8, gray ellipses correspond to xenocrysts that were not included in the calculation of the age values (ion microprobe data).

the regression line corresponds to the fraction dominated by dark brown crystals. These three points were rejected from the calculations of the regression parameters. The isochron is drawn through the points that define the best regression parameters. It corresponds to an age of 2739.9 ± 4.1 Ma.

The earlier dates obtained for the Panozero Massif by the Th–U–Pb method with the use of an ion microprobe are as follows: 2737 ± 11 Ma for monzodiorite (sample 573/2), 2739 ± 11 Ma for monzonite (sample 235), and 2741 ± 8 Ma for quartz monzonite (Bibikova *et al.*, 2005).

CONCLUSIONS

Our isotopic geochemical research has definitely determined that syenites in central Karelia have an Archean age. The dates obtained for individual syenite massifs in Karelia (2735 ± 15 Ma for syenites from the Sjargozero Massif and 2745 ± 10 Ma for syenite from the Khizhjarvi Massif) demonstrate that these massifs are coeval with sanukitoid massifs in central Karelia, whose average age is 2743 ± 3 Ma (Bibikova *et al.*, 2005). The syenites of the Sjargozero Massif and granodiorites of the Ust-Volomsky Massif yield practically identical isotopic ages of 2735 and 2738 Ma, a fact also corroborating their synchronous emplacement. The lamprophyres contain zircon xenocrysts with ages older than 2800 Ma. This is quite typical of dikes, which commonly entrain zircons borrowed from the host rocks. At the same time, some zircon grains from the Sjargozero syenites (sample 159) were determined to contain cores with an age of 2755 Ma. In this situation, we cannot rule out the possibility that the syenite has been contaminated with the host metavolcanics of basaltic and andesite composition, which were metamorphosed at 2750–2760 Ma. This is indirectly confirmed by the fact that this syenite sample is noted for elevated silicity and mg# as compared with all other analyzed rocks from the Sjargozero Massif (Table 1). The earlier study (Kovalenko *et al.*, 2005) of the Sm–Nd isotopic systems of various posttectonic rocks in central Karelia, including syenites, has revealed their positive $\epsilon_{Nd}(T)$ value of about 2, a fact testifying for the mantle genesis of the syenites and for the possibility of only insignificant contamination of these rocks with crustal material.

Sanukitoid and syenite massifs in central Karelia were formed in a single stage, 60–70 m.y. after the origin of the syntectonic tonalites. Zircons from these rocks have an elevated Th/U ratio, which is consistent with the mantle genesis of the rocks. Notable crustal contamination was identified in the most acid members of this rock association of the sanukitoid series: syenites and granitoids. Our data on zircon from the sanukitoids and syenites of the Karelian craton of the Baltic Shield are in good agreement with the results obtained on sanukitoids from the Canadian Shield (Stevenson *et al.*, 1999).

Thus, various rock groups that compose the Archean posttectonic associations of sanukitoids, syenites, and granitoids in central Karelia have similar ages of approximately 2740 Ma. The more detailed mineralogical and geochemical characterization of these rocks and their petrogenetic modeling will be presented in a special publication.

ACKNOWLEDGMENTS

The authors thank M. Whitehouse (Swedish Museum of Natural History) for the possibility of conducting isotopic analyses on the secondary-ion mass

spectrometer in Stockholm. We also thank L. Il'inskii (Swedish Museum of Natural History) and A.V. Kovalenko (Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences) for help with ion-microprobe analyses. The authors thank M.V. Malashin (St.-Petersburg State University) and A.N. Komarov (Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences) for help in the geological and mineralogical study of the rocks and zircons. This study was financially supported by the International Association for the Promotion of Cooperation with Scientists from the New Independent States of the Former Soviet Union (project no. 01-0073) and the Russian Foundation for Basic Research (project no. 03-05-65051) and is Publication 98a of a research conducted under a NORDSIM project, Stockholm, Sweden.

REFERENCES

1. E. V. Bibikova, A. Petrova, and S. Claesson, "NORDSIM U–Th–Pb Isotopic Study of Zircons from Sanukitoids of the Karelian Craton, Baltic Shield," *Lithos* **79**, 129–145 (2005).
2. V. P. Chekulaev, O. A. Levchenkov, V. V. Ivanikov, *et al.*, "Composition, Age, and Sm–Nd Systematics of Archean High-Mg Granitoids (Sanukitoids) of the Panozero Pluton, Karelia," *Geokhimiya*, No. 8, 817–828 (2003) [*Geochem. Int.* **41** (8), 741–752 (2003)].
3. F. Corfu, T. E. Krogh, Y. Y. Kwok, and L. S. Jensen, "U–Pb Zircon Geochronology in the Southwestern Abitibi Greenstone Belt, Superior Province," *Can. J. Earth Sci.* **26**, 1747–1763 (1989).
4. G. O. Glebova-Kul'bakh, S. B. Lobach-Zhuchenko, N. I. Pinaeva, and K. D. Borisova, "Granites of Southern Karelia," *Tr. Lab. Geol. Dokembriya*, No. 15, 161–315 (1963).
5. L. V. Grigor'eva, V. V. Ivanikov, and N. F. Shinkarev, "A Model of the Geodynamic Evolution of the Karelian Granite–Greenstone Terrane," *Geotektonika*, No. 3, 28–38 (1990).
6. V. V. Ivanikov, "Archean Syenites and Monzonites in Karelia, I," *Vestn. St. Peterburg. Univ.*, Ser. 7, No. 1, 11–21 (1997a).
7. V. V. Ivanikov, "Archean Syenites and Monzonites in Karelia, II," *Vestn. St. Peterburg. Univ.*, Ser. 7, No. 4, 3–15 (1997b).
8. V. V. Ivanikov, V. E. Pilatskii, and V. A. Bogachev, "Homologues Series of Granitoid Associations in Karelia," in *Abstracts of Papers of the IV Regional Petrographic Conference "Magmatism, Metamorphism, and Geochronology of East European Platform"* (Petrozavodsk, 1987), pp. 28–30 [in Russian].
9. K. Condie, *Archean Greenstone Belts* (Elsevier, Amsterdam, 1981; Mir, Moscow, 1983).
10. A. V. Kovalenko, J. D. Clemens, and V. M. Savatenkov, "Sm–Nd and Rb–Sr Isotopic Data on the Sanukitoid Intrusions of Karelia, Baltic Shield: Implications for Their Genesis and Lithospheric Evolution," *Lithos* **79**, 147–160 (2005).

11. T. Krogh, "A Low Contamination Method for Hydrothermal Decomposition of Zircon and Extraction of U and Pb for Isotopic Age Determination," *Geochim. Cosmochim. Acta* **37**, 485–494 (1973).
12. S. B. Lobach-Zhuchenko, V. P. Chekulaev, N. A. Arestova, *et al.*, "High-Magnesian Granitoids (Sanukitoids) of the Karelian Terrane in the Baltic Shield: Geology, Geochemistry and Implications for the Origin of Mantle Derived Melts," *Lithos* **79**, 107–128 (2005).
13. K. R. Ludwig, "User's Manual for Isoplot/Ex. Version 2.10: A Geochronological Toolkit for Microsoft Excel," Berkeley Geochronol. Center Spec. Publ., No. 1a (1999).
14. J. M. Mattinson, "A Study of Complex Discordance in Zircon Using Stepwise Dissolution Technique," *Contrib. Mineral. Petrol.* **116**, 117–129 (1994).
15. A. V. Samsonov, E. V. Bibikova, Yu. O. Larionova, *et al.*, "Magnesian Granitoids (Sanukitoids) of the Kostomuksha Area, Western Karelia: Petrology, Geochronology, and Tectonic Environment of Formation," *Petrologiya* **12** (5), 495–529 (2004) [*Petrology* **12** (5), 437–468 (2004)].
16. S. B. Shirey and G. N. Hanson, "Mantle-derived Archean Monzodiorites and Trachyandesites," *Nature* **310**, 222–224 (1984).
17. J. S. Stacey and J. D. Kramers, "Approximation of Terrestrial Lead Isotope Evolution by a Two-stage Model," *Earth Planet. Sci. Lett.* **26**, 207–221 (1975).
18. R. Stevenson, P. Henry, and C. Gariépy, "Assimilation-Fractional Crystallization and Origin of Archean Sanukitoid Suites: Western Superior Province, Canada," *Precambrian Res.* **96**, 83–99 (1999).
19. R. Sutcliff, A. Smith, W. Doherty, and R. Barnett, "Mantle Derivation of Archean Amphibole-Bearing Granitoid and Associated Mafic Rocks: Evidence from the Southern Superior Province, Canada," *Contrib. Mineral. Petrol.* **105**, 255–274 (1990).
20. V. Tatsumi and K. Ishizaka, "Origin of High-magnesian Andesites of the Setouchi Volcanic Belt, Southwest Japan: I. Petrographical and Chemical Characteristics," *Earth Planet. Sci. Lett.* **60**, 293–304 (1982).
21. M. J. Whitehouse, B. S. Kamber, and S. Moorbath, "Age Significance of U–Th–Pb Zircon Data from Early Archean Rocks of West Greenland: A Reassessment Based on Combined Ion Microprobe and Imaging Studies," *Chem. Geol.* **160**, 201–224 (1999).
22. M. Whitehouse, S. Claesson, T. Sunde, and J. Vestin, "Ion Microprobe U–Pb Zircon Geochronology and Correlation of Archean Gneisses from the Lewisian Complex of Gruinard Bay, Northwest Scotland," *Geochim. Cosmochim. Acta* **61**, 4429–4438 (1997).