ISSN 1028-334X, Doklady Earth Sciences, 2014, Vol. 457, Part 1, pp. 824–830. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © K.A. Dokukina, T.V. Kaulina, A.N. Konilov, L.M. Natapov, E.A. Belousova, K.V. Van, S.G. Simakin, E.N. Lepekhina, 2014, published in Doklady Akademii Nauk, 2014, Vol. 457, No. 1, pp. 74–80.

GEOCHEMISTRY

Mesoarchean Mafic Dykes of the Belomorian Eclogite Province (Gridino Village Area, Russia)

K. A. Dokukina[a, b], T. V. Kaulina[c], A. N. Konilov[a, d], L. M. Natapov[e], E. A. Belousova[e], K. V. Van[d], S. G. Simakin[f], and E. N. Lepekhina[g]

Presented by Academician Yu.G. Leonov, March 16, 2013

Received May 25, 2013

Abstract—Archean processes of eclogitization in the Gridino metamorphic association (the Belomorian eclogite province) developed in mafic dykes, boudins, and acidic rocks of the Archean continental crusts. To determine the U–Pb age of the intrusion of the latest dykes, the geochronological samples were taken from the dyke of ferriferious metagabbro that cross-cuts the dyke of eclogitzed and granulitized olivine gabbronorite. The igneous zircons were dated by the SHRIMP II technique. The zircons showed a concordia age of 2846 ± 7 Ma, which is considered as the time of intrusion of a mafic melt. The younger low-thorium zircon rims of 2.78–2.81 Ga age around the igneous cores are typical formations that appeared under metamorphic conditions in equilibrium with a migmatite melt, and may characterize the time of formation of the granite leucosome under metamorphism, probably of eclogite facies.

DOI: 10.1134/S1028334X14070034

Within the South Kola active margin, along the northwestern boundary of the Belomorian accretion orogen, eclogite bodies formed as a result of Meso–Neoarchean subduction of oceanic and continental crust are located (the Salma and Gridino associations) [1–3]. The oceanic gabbroids of 2.89–2.82 Ga age, in their composition correspond to rocks of the third layer of the slow-spreading Mid Oceanic Ridge, were the protoliths of Salma eclogites [1, 2]. As for the Gridino association, the continental rocks enclosing the acidic gneisses containing the rock fragments of basic and ultrabasic composition and several generations of mafic dykes underwent eclogitic metamorphism [3].

At present, the age of magmatic crystallization, eclogitic metamorphism, and the subsequent retrograde transformations of mafic dykes of the Gridino association are actively debated. Many of the researchers of eclogites of the Gridino area believe that the zircons of ~2.4 Ga in age, occurring sometimes in eclogitized dykes, date the intrusion and igneous crystallization of the mafic melt [4]. Based on this opinion, two stages of eclogitization were distinguished in the history of rock formation in the Gridino area [5]: Archean at the level of 2.72 Ga, related to the dipping of the oceanic plate in the zone of subduction, and Paleoproterozoic associated with the "local" eclogitization of Paleoproterozoic mafic dykes. This latter scenario is under intense discussion.

In contrast to the notion on the Paleoproterozoic age of the intrusion of eclogitized dykes, detailed studies have made the authors conclude that the rocks of the Gridino association were subjected to eclogitic metamorphism 2.7 Ga ago or earlier [3, 6]. The dykes were intruded during the Archean time, and the eclogitization of all the complexes of the Gridino area is related to the Archean subduction and collision along the active margin of the Kola continent. This conclusion is based on the results of field structural, geological, petrological, and geochronological studies of the Gridino dykes. To do this, the classic ID TIMS- and SHRIMP II-dating was carried out for zircons from the high-pressure granite leucosome intersecting the eclogitized dykes, and from the latest dyke.

The event of ~2.4 Ga age registered by individual zircons occurring regularly within the eclogitized mafic rocks was related to the active tectonic and thermal processes in the Early Paleoproterozoic caused by the upwell of a superplume in the mantle area under-

[a] *Geological Institute, Russian Academy of Sciences, Moscow, Russia*
[b] *Moscow State University, Moscow, Russia*
[c] *Institute of Geology, Kola Science Center, Russian Academy of Sciences, Apatity, Murmansk oblast, Russia*
[d] *Institute of Experimental Mineralogy, Russian Academy of Sciences, Chernogolovka, Russia*
[e] *ARC National Key Center, Macquarie University, Sydney, Australia*
[f] *Yaroslavl Branch, Institute of Physics and Technology, Russian Academy of Sciences, Yaroslavl, Russia*
[g] *Karpinskii Russian Geological Research Institute, Russian Academy of Sciences, St. Petersburg, Russia*
e-mail: ksdokukina@gmail.com

lying the eastern Fennoscandian shield [7]. To determine the U–Pb age of the intrusion of the youngest dykes (in view of their intersections), the authors collected a geochronological sample from the dyke of ferriferious metagabbro that intersected the dyke of eclogitized and granulitized olivine gabbronorite at the Cape Gridin (Fig. 1). The zircons were dated using the SHRIMP II and LA–ICP–MS techniques.

Metagabbro, sample d44-4. The rock of the metagabbro dyke has the equilibrium garnet–clinopyroxene–plagioclase mineral assemblage (± amphibole and biotite) that formed under the metamorphism of granulite facies at 700–750°C and 10–12 kbar. Some of the clinopyroxenes retained relic cores with an increased content of Ca–Tschermak end-member (9–14 mol % of CaTs at 13 mol % of Jd). This testifies to higher pressures during the formation of these cores [8]. The minerals of the eclogitic facies in similar dykes of metagabbro were studied on the Vorotnaya Luda Island [3]. The omphacite (Jd content up to 36 mol %, P_{min} = 16 kbar) and kyanite are as inclusions in garnet, and the omphacite is as relics in the orthopyroxene–clinopyroxene–plagioclase symplectites.

Metagabbro is characterized by various concentrations of main elements (wt. %): 47.5–49.5 of SiO_2, 12.6–14.4 of Al_2O_3, 0.98–2.2 of TiO_2, 13.1–15.7 of FeO_{tot}, 0.18–0.24 of MnO, 5.7–7.3 of MgO, 9.9–12.2 of CaO, 2.0–2.7 of Na_2O, and 0.1–0.8 of K_2O and decreased contents of Ba, Rb, Th, and U. These rocks are also unusual for continental intrusion REE pattern depleted in light REE: La_N/Lu_N = 0.59–1.49 and Eu/Eu* = 0.90–1.09). Such REE distributions are similar to N–MORB.

Although metagabbro is characterized by an extremely low content of Zr, a sufficient amount of zircon was separated from the sample and 14 measurements were made using the SHRIMP II technique (Table 1). All zircons are elongate of 150 × 500 μm dimensions, brownish or colorless, and show the cores and rims structure in the cathodoluminescence (CL). Many of zircons exhibit a clear oscillatory zoning and are characterized by medium values of Th/U ratio (0.38–1.39), positive Ce- and negative Eu-anomalies (Ce/Ce* = 2.35–11 and Eu/Eu* = 0.53–0.77), and the enrichment in HREE relative to LREEs (Lu_N/La_N = 213–941, Fig. 2). Some of the CL-dark cores of zircons show the increased U content (351–1321 ppm) with quite a low Th content (46–91 ppm) and, respectively, the low Th/U ratio (0.05–0.18). The REE pattern is characterized by positive Ce- and negative Eu-anomalies (Ce/Ce* = 2–30 and Eu/Eu* = 0.06–0.77) and enrichment in HREE relative to LREE (Lu_N/La_N = 309–6702, Fig. 2). All described zircons exhibit characteristics pointing to their igneous origin [9]. Regardless of the content of uranium and the habit, the zircons have the same Mesoarchean concordia age: 2846 ± 7 Ma, or 2869 ± 41 Ma at a discordia with the upper intercept (Fig. 3).

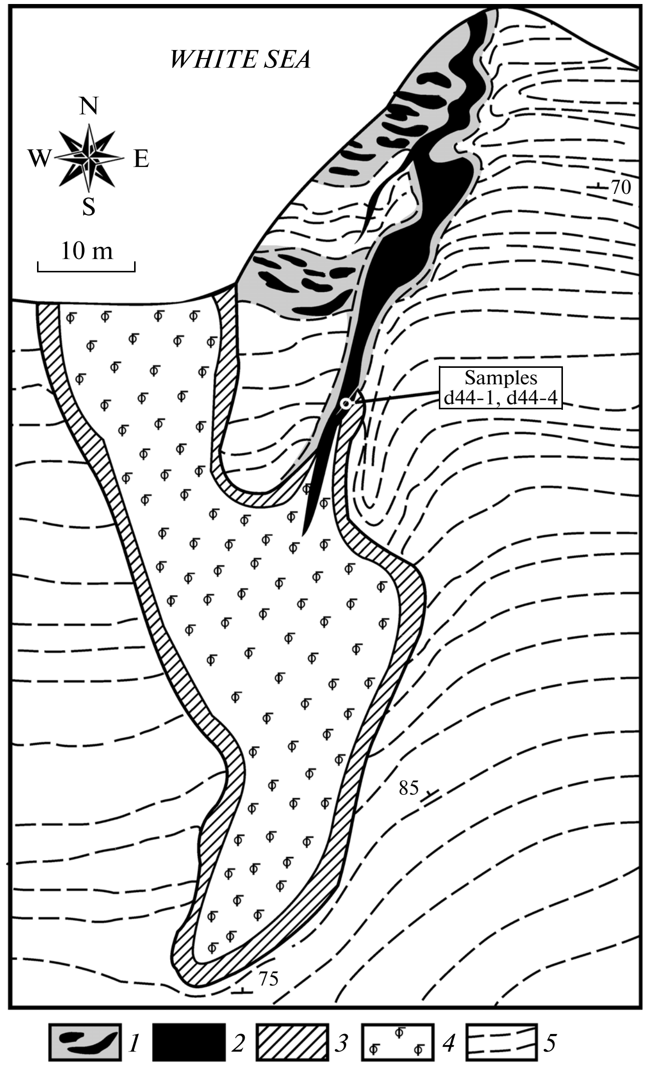

Fig. 1. Geological sketch of Cape Gridin. *1*—granite leucosome with the enclaves of mafic metamorphic rocks; *2*—metagabbro; *3*, *4*—metamorphized rocks of the dyke of olivine gabbronorites (*3*—chilled margin and *4*—the dyke rocks); *5*—gneisses.

Low-uranium colorless rims surrounding individual grains of zircons (Fig. 2) showed a concordia age of 2780 ± 20 Ma, or 2777 ± 67 Ma at a discordia with the upper intercept (Fig. 3). Rims are characterized by varying Th/U ratios of 0.09–0.38 and depleted in all the trace elements excluding Hf, exhibit positive Ce- and negative Eu-anomalies (Ce/Ce* = 1.55–7 and Eu/Eu* = 0.28–0.64, respectively), with relatively flat REE pattern (La_N/Lu_N = 63–940, Lu_N/Sm_N = 12–48, Fig. 2).

Granite leucosome, sample d44-1. The granite leucosome consists of garnet, biotite, plagioclase, potassium feldspar, quartz, epidote, and scapolite. Scapolite is developed around the complicated aggregates of pyrite, chalcopyrite, and pentlandite. Garnet porphyroblasts contain inclusions of quartz, biotite, Ti-bear-

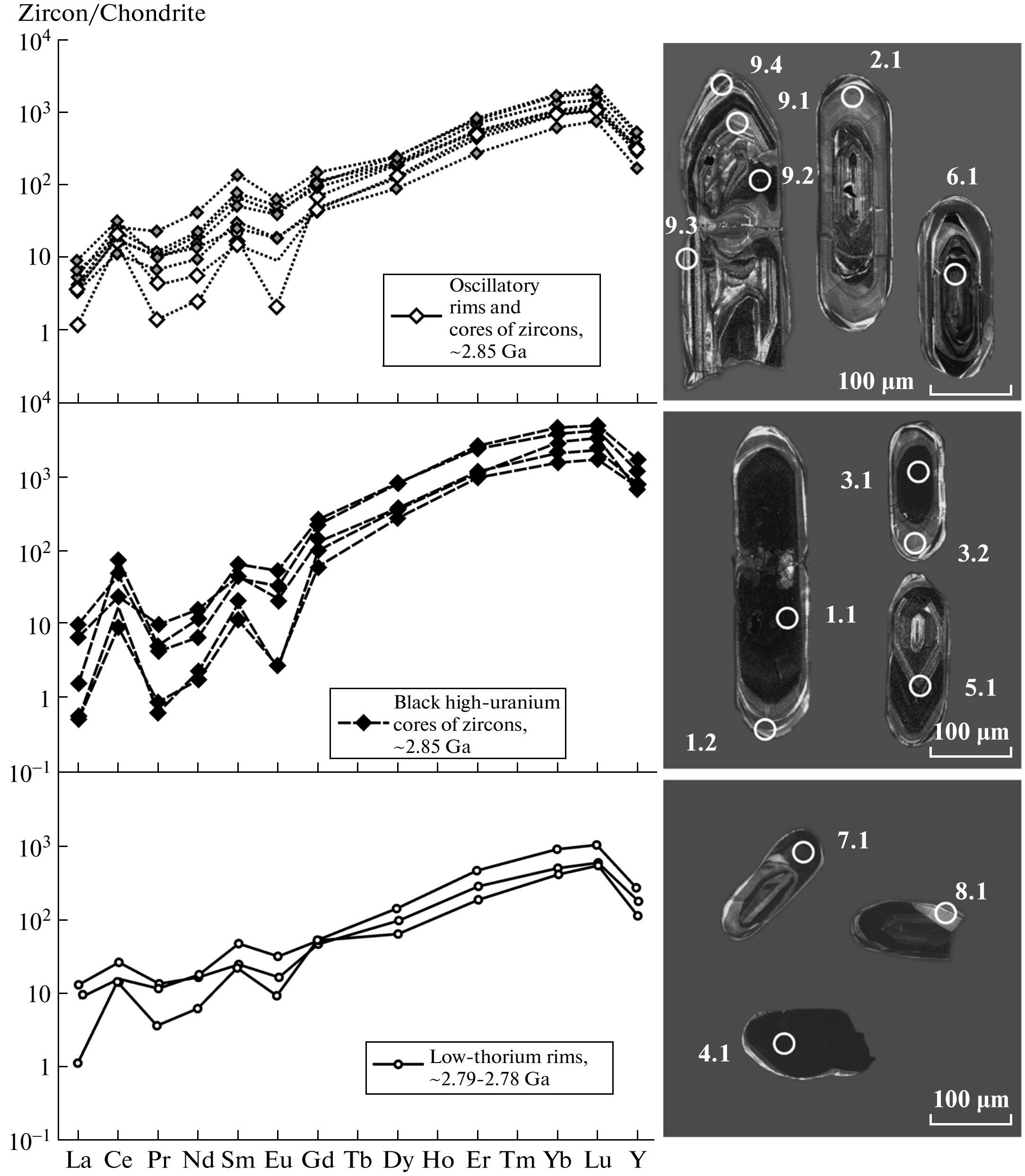

Fig. 2. The images of dated zircons and the distribution of REEs in the analyzed groups of zircons (chondrite by [11]).

ing phengite, epidote, plagioclase, and K-feldspar. A reactionary corona of clinopyroxene is formed around garnet. Formation of mineral paragenesis in the granite leucosome corresponds to conditions of high-pressure granulite facies (700–750°C, 10–12 kbar).

The leucosome is characterized by a granite composition including (in wt. %) 66.3 of SiO_2, 2.83 of Na_2O, 2.69 of K_2O, 13.8 of Al_2O_3, 0.43 of TiO_2, 5.8 of Fe_{tot}, 0.12 of MnO, 3.9 of MgO, and 2.6 of CaO, with the middle content of magnesium #Mg = 0.55. It is considerably enriched in LREE ($La_N/Lu_N = 39$) relative to gneisses and dykes of the Cape Gridin and exhibits a positive Eu-anomaly (Eu/Eu* = 1.39).

Zircons from the leucosome were dated using SHRIMP II at the Russian Geological Research Institute (VSEGEI) in St. Petersburg (Table 1) and of LA–ICP–MS at the ARC National Key Center (Australia, Table 2). Zircons dated by SHRIMP II have Mesoarchean $^{207}Pb/^{206}Pb$-ages from 2926 to 2764 Ma (Fig. 3). A histogram of $^{207}Pb/^{206}Pb$-ages by LA–ICP–MS shows age peaks of 2845 ± 14, 2797 ± 11, and 2720 ± 28 Ma (Fig. 4).

Few zircons were presented by colorless elongate grains light in CL, either with sectorial or oscillatory zoning. These zircons are characterized by a high Th/U ratio (0.55–1.01) and an age of ~3 Ga (Fig. 3).

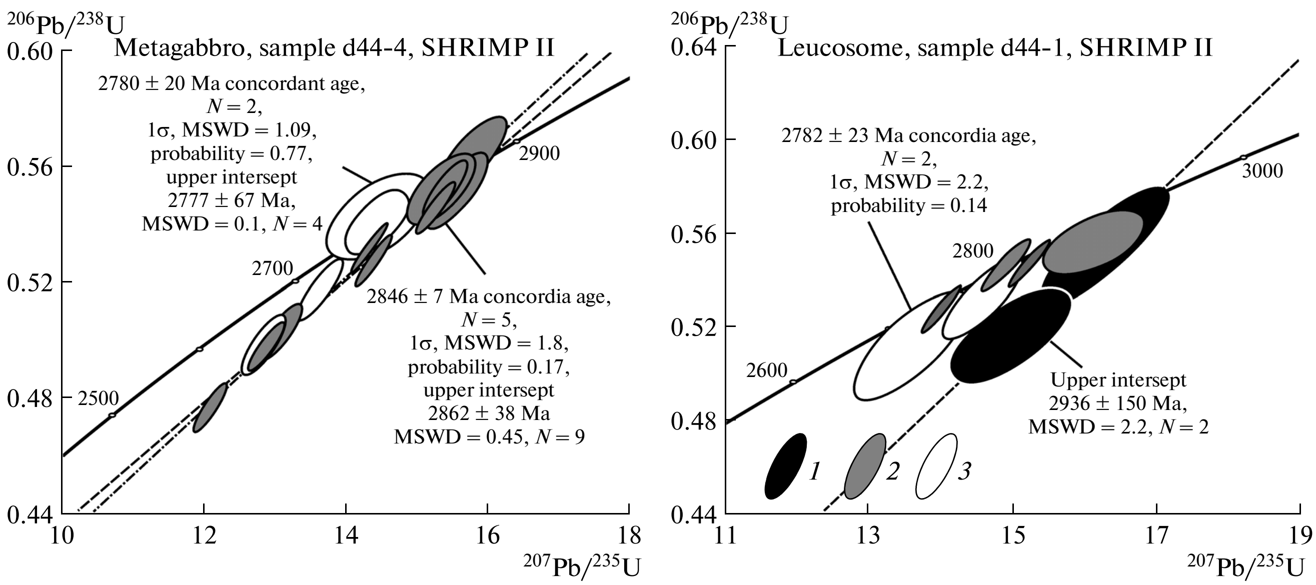

Fig. 3. U–Pb zircon concordia diagrams for zircons dated by SHRIMP II.

The REE distribution is characterized by positive Ce- and negative Eu-anomalies (Ce/Ce* = 8.67 and Eu/Eu* = 0.27, respectively), and enrichment in HREE ($Lu_N/Sm_N = 119$ and $Lu_N/La_N = 4602$).

Zircons of the other group are similar to prevailing zircons from metagabbro (sample d44-4). These are brownish elongate grains of (50–100) × (200–300) μm dimensions, gray in CL, and showing a clear oscillatory zoning. Zircons are characterized by Th/U ratios 0.20–0.46 and by relatively flat REE pattern (Lu_N/Sm_N = 38–41 and Lu_N/La_N = 152–203). This group is well correlated to the first group of zircons from the metagabbro (sample d44-4). Some of the zircons contain black cores. These cores are enriched in uranium (377–1653 ppm) and show Th/U ratios within 0.04–0.45 (Table 1), positive Ce- and negative Eu-anomalies (Ce/Ce* = 1.36–2.92 and Eu/Eu* = 0.29–0.77, respectively), and a small enrichment in HREE (Lu_N/Sm_N = 9–41 and Lu_N/La_N = 97–364). The age of zircons corresponds to the peak of 2845 ± 14 Ma and is synchronous to crystallization time of igneous zircons of the dyke of metagabbro.

Low-uranium colorless rims show an age of 2.78–2.79 Ma (Fig. 3). Younger rims are characterized by Th/U ratios within 0.01–0.48, by small positive Ce- and negative Eu-anomalies (Ce/Ce* = 2 and Eu/Eu* = 0.49, respectively), and by relatively flat REE pattern ($Lu_N/Sm_N = 25$ and $Lu_N/La_N = 47$), and their ages correspond to young low-uranium rims of zircons from the metagabbro dyke (Fig. 2).

DISCUSSION

In both samples, elongate magmatic zircons of Archean age prevail, with an absolute absence of Paleoproterozoic grains and rims. Ancient grains of ~3 Ga age were found within the granite leucosome (Fig. 3), which probably corresponds to the age of formation of the tonalitic protolith of the host gneisses.

The Mesoarchean ages of 2.87–2.85 Ga for elongate igneous zircons from the metagabbro sample d44-4 were also determined in the vein of the granite leucosome d44-1. The authors consider these ages as the time of the formation of mafic intrusions. The crystallization temperatures of these zircons are 710–820°C (Ti in Zrn [12, 13]). The leucosome is developed

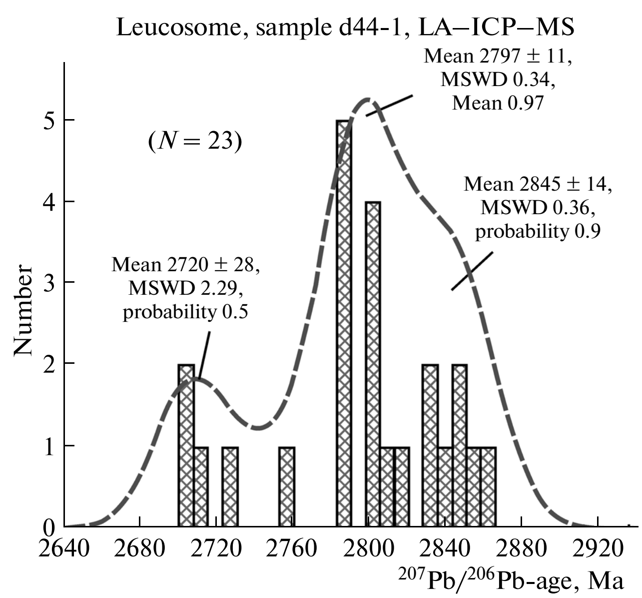

Fig. 4. Histogram of $^{207}Pb/^{206}Pb$ ages of zircon in granite leucosome, dated by LA-ICP-MS. The broken line is relative probability.

Table 1. The SHRIMP II U–Th–Pb-isotope data for zircons from d44-4 metagabbro and d44-1 granite leucosome (the Cape Gridin)

Point	$^{206}Pb_c$, %	U	Th	$^{206}Pb^*$	$\frac{^{232}Th}{^{238}U}$	$\frac{^{206}Pb}{^{238}U}$		$\frac{^{207}Pb}{^{206}Pb}$		D, %	$\frac{^{207}Pb^*}{^{206}Pb^*}$	±%	$\frac{^{207}Pb^*}{^{235}U}$	±%	$\frac{^{206}Pb^*}{^{238}U}$	±%	*Rho*
		ppm				age, Ma											
Late ferriferous metagabbro, sample d44-4																	
d44-4.1.1	0.04	723	54	309	0.08	2603	±30	2722	±13	5	0.1877	0.81	12.88	1.6	0.4975	1.4	0.87
d44-4.1.2	0.25	74	6	34.4	0.09	2784	±35	2775	±32	0	0.1939	2.00	14.44	2.5	0.5401	1.6	0.62
d44-4.2.1	0.66	37	50	17.8	1.39	2832	±41	2840	±29	0	0.2017	1.80	15.34	2.5	0.5517	1.8	0.70
d44-4.3.1	0.01	1321	67	603	0.05	2747	±30	2790	±6.5	2	0.19559	0.40	14.33	1.4	0.5313	1.3	0.96
d44-4.3.2	0.35	37	46	18.1	1.27	2878	±47	2853	±25	–1	0.2033	1.60	15.77	2.5	0.5630	2.0	0.79
d44-4.4.1	0.05	526	91	239	0.18	2730	±31	2809	±8.8	3	0.1979	0.54	14.39	1.5	0.5273	1.4	0.93
d44-4.5.1	0.06	393	274	184	0.72	2805	±33	2850	±9.6	2	0.2029	0.59	15.25	1.5	0.5451	1.4	0.92
d44-4.6.1	0.43	79	17	37.7	0.22	2830	±43	2863	±24	1	0.2046	1.50	15.55	2.4	0.5510	1.9	0.78
d44-4.7.1	0.11	112	1	49.9	0.01	2687	±36	2753	±16	2	0.1912	0.98	13.64	1.9	0.5171	1.7	0.86
d44-4.8.1	0.68	18	6	8.32	0.38	2793	±50	2771	±57	–1	0.1934	3.40	14.46	4.1	0.5420	2.2	0.54
d44-4.9.1	0.14	82	31	38.9	0.38	2831	±34	2845	±15	0	0.2024	0.93	15.39	1.7	0.5515	1.5	0.85
d44-4.9.2	0.11	351	46	144	0.14	2512	±31	2691	±12	7	0.1842	0.73	12.10	1.6	0.4766	1.5	0.90
d44-4.9.3	0.21	177	45	76.8	0.26	2624	±34	2733	±16	4	0.1890	0.98	13.09	1.9	0.5024	1.6	0.85
d44-4.9.4	0.20	134	6	57.6	0.05	2607	±36	2717	±18	4	0.1871	1.10	12.86	2.0	0.4983	1.7	0.84
Granite leucosome, sample d44-1																	
d44-1.1.1	–	14	4	0.32	6.29	2665	±81	2764	±51	4	0.193	3.1	13.6	4.9	0.512	3.7	0.8
d44-1.2.1	–	377	83	0.23	171	2732	±35	2763	±9	1	0.192	0.5	14.0	1.6	0.528	1.6	0.9
d44-1.3.1	0.05	181	35	0.20	84.7	2810	±39	2808	±11	0	0.198	0.7	14.9	1.8	0.546	1.7	0.9
d44-1.4.1	0.02	654	25	0.04	307	2813	±34	2840	±7	1	0.202	0.4	15.2	1.6	0.547	1.5	1.0
d44-1.4.2	–	30	14	0.48	13.8	2751	±59	2815	±30	3	0.199	1.9	14.6	3.2	0.532	2.6	0.8
d44-1.5.1	0.61	15	8	0.55	7.15	2843	±86	2926	±39	3	0.213	2.4	16.3	4.5	0.554	3.7	0.8
d44-1.5.2	0.00	24	23	1.01	10.5	2685	±70	2906	±54	9	0.210	3.4	15.0	4.6	0.517	3.2	0.7
d44-1.6.1	0.11	77	34	0.46	36.6	2851	±46	2908	±48	2	0.210	3.0	16.1	3.6	0.556	2.0	0.6

The measurements on the sample d44-1 were made by A.N. Larionov by SHRIMP II ionic probe at VSEGEI; Pb_c and Pb^* indicate the common and radiogenic portions, respectively; D is discordance.

Table 2. La–ICP–MS U–Th–Pb-isotope data for the zircons from the sample d44-1 of granite leucosome (the Cape Gridin)

Point	$^{206}Pb_c$, %	U	Th	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	*D*, %	$^{207}Pb/^{206}Pb$	1σ	$^{207}Pb/^{235}U$	1σ	$^{206}Pb/^{238}U$	1σ
		ppm		age, Ma								
d44-1-02		88	116	2772 ± 23	2845 ± 18	3.2	0.20230	0.00217	14.98575	0.15956	0.53732	0.00550
d44-1-03		395	94	2682 ± 25	2704 ± 18	1	0.18569	0.00202	13.20727	0.15545	0.51593	0.00584
d44-1-04		175	80	2883 ± 26	2864 ± 19	–0.8	0.20471	0.00238	15.91320	0.19376	0.56392	0.00630
d44-1-06		1000	453	2734 ± 26	2729 ± 21	–0.2	0.18843	0.00239	13.72330	0.18235	0.52830	0.00607
d44-1-07		499	158	2776 ± 24	2802 ± 18	1.1	0.19703	0.00217	14.62286	0.16331	0.53831	0.00565
d44-1-08		1653	318	2786 ± 24	2784 ± 18	–0.1	0.19489	0.00208	14.52300	0.16058	0.54051	0.00574
d44-1-09	0.04	1578	131	2712 ± 23	2798 ± 18	3.7	0.19653	0.00211	14.17307	0.15443	0.52308	0.00544
d44-1-10		254	92	2755 ± 25	2817 ± 19	2.7	0.19887	0.00228	14.62014	0.17401	0.53323	0.00583
d44-1-11		29	9	2778 ± 29	2834 ± 26	2.4	0.20093	0.00313	14.92336	0.24066	0.53872	0.00704
d44-1-12		27	18	2786 ± 24	2800 ± 19	0.6	0.19683	0.00227	14.66895	0.16840	0.54055	0.00571
d44-1-13		415	54	2809 ± 24	2830 ± 18	0.9	0.20046	0.00211	15.09206	0.16590	0.54607	0.00583
d44-1-14		614	158	2764 ± 27	2785 ± 19	1	0.19506	0.00217	14.39223	0.17913	0.53531	0.00636
d44-1-15C		628	260	2735 ± 24	2787 ± 17	2.3	0.19528	0.00201	14.22894	0.15445	0.52850	0.00568
d44-1-15R		383	92	2764 ± 25	2787 ± 18	1	0.19522	0.00214	14.40829	0.16842	0.53534	0.00594
d44-1-19C		180	41	2876 ± 27	2851 ± 18	–1	0.20310	0.00221	15.73824	0.19102	0.56216	0.00658
d44-1-19R		404	6	2662 ± 25	2712 ± 19	2.3	0.18651	0.00209	13.14179	0.16255	0.51124	0.00596
d44-1-22	0.15	105	53	2618 ± 24	2700 ± 18	3.7	0.18519	0.00198	12.78774	0.14737	0.50091	0.00560
d44-1-23		427	135	2844 ± 25	2848 ± 18	0.2	0.20271	0.00215	15.49927	0.17580	0.55461	0.00611
d44-1-24C		171	74	2770 ± 24	2801 ± 18	1.4	0.19693	0.00215	14.57091	0.16483	0.53668	0.00576
d44-1-24R		181	45	2683 ± 26	2755 ± 20	3.3	0.19149	0.00232	13.61806	0.18181	0.51616	0.00623
d44-1-25	0.17	110	84	2709 ± 25	2810 ± 18	4.4	0.19808	0.00211	14.26454	0.16301	0.52240	0.00579
d44-1-26		176	53	2815 ± 24	2838 ± 18	1	0.20142	0.00214	15.20578	0.16369	0.54750	0.00568
d44-1-27	0.36	238	68	2711 ± 26	2789 ± 30	3.4	0.19551	0.00347	14.09118	0.18732	0.52274	0.00614

D is discordance.

exclusively along the boundary of the dyke of metagabbro and tonalitic gneisses, penetrating the metagabbro dyke beyond its contacts to the gabbronorite body (Fig. 1). Evidently, the boundary between gneisses and the metagabbro dyke was most suitable for the migration of fluid, which promoted a partial melting of tonalitic gneisses and involved the dyke rock into this process, providing a capture of zircons from metagabbro in the formed granite leucosome.

Young low-thorium rims of 2.78–2.81 Ga have grown on all ancient zircons and constitute the typical formations appearing under metamorphic conditions in equilibrium with a migmatite felsic melt. The crystallization temperatures of these rims are 700–720°C (Ti in Zrn [12, 13]), which characterizes the formation time of the granite leucosome at metamorphic conditions, probably eclogitic facies.

The histogram of $^{207}Pb/^{208}Pb$ ages of the leucosome (Fig. 4) also shows an age peak about 2.7 Ga. This age corresponds to time of a decompression post-eclogitic metamorphism of the high-pressure granulite facies [3].

The effect of an event of ~1.9 Ga is noticeable in the calculations of ages: the lower intersections of the concordia always show the values of ~1.9 Ga. The superimposed metamorphism of the amphibolites facies and the "final" exhumation of metamorphic complexes which took place 2.0–1.8 Ga ago are related to the collision events at the end of the Paleoproterozoic, which are conventionally correlated to the formation of the Svecofennian accretion orogen directly westwards (in the current coordinates) from the Belomorian province.

CONCLUSIONS

The authors consider the ages of 2.87–2.85 Ga as the time of the intrusion of mafic melt. These ages coincide within error to the age of the oceanic protoliths of Salma eclogites (2.9–2.82 Ga). These data and a general geochemical trend of the distribution of main and trace elements in eclogitized rocks of Gridino and Salma allow us to draw a conclusion about the correlation between the Gridino dykes and the ocean of the Salma [14]. The dykes might either be the derivatives of a slow-spreading ridge dipping into the zone of subduction [14] or forego an opening of the Salma Ocean [3]. The formation of low-thorium rims of 2.78–2.79 Ga was at an increase of temperature and associated with partial melting of the crust. This metamorphic event probably represented the stage of the dipping of continental rocks into the zone of subduction. The submelting of the metagabbro dyke and an injection of leucosome into the dyke rocks caused the saturation of the leucosome in zircons inherited from the dyke.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project nos. 11-05-00492-a and 12-05-00856-a) and by the ONZ-6 Program. The authors are grateful to Dr. M.V. Mints for his continual support, collaboration, and constructive criticism.

REFERENCES

1. M. V. Mints, A. N. Konilov, K. A. Dokukina, et al., Doklady Earth Sci. **434**, 1311 (2010).
2. A. N. Konilov, A. A. Shchipansky, M. V. Mints, et al., in *Ultrahigh Pressure Metamorphism: 25 Years after the Discovery of Coesite and Diamond* (Elsevier, London, 2011), ch. 19, pp. 623–670.
3. K. A. Dokukina and A. N. Konilov, in *Ultrahigh Pressure Metamorphism: 25 Years after the Discovery of Coesite and Diamond* (Elsevier, London, 2011), ch. 18, pp. 591–634.
4. A. I. Slabunov, O. I. Volodichev, S. G. Skublov, and A. V. Berezin, Doklady Earth Sci. **437**, 396 (2011).
5. A. I. Slabunov, S. B. Lobach-Zhuchenko, E. B. Bibikova, et al., Mem. Geol. Soc. London **32**, 627–644 (2006).
6. K. A. Dokukina, T. B. Bayanova, T. V. Kaulina, et al., Doklady Earth Sci. **432**, 671 (2010).
7. K. A. Dokukina, A. N. Konilov, K. V. Van, et al., Doklady Earth Sci. **445** (1), 832 (2012).
8. T. C. McCarthy and A. E. Patiño Douce, J. Metamorph. Geol. **16**, 671–682 (1998).
9. P. W. O. Hoskin and U. Schaltegger, Rev. Mineral. and Geochem. **53**, ch. 2, 27–32 (2003).
10. A. W. Hofmann, Earth Planet. Sci. Lett. **90**, 297–314 (1988).
11. S. S. Sun and W. F. McDonough, Geol. Southern Ocean. London Spec. Pub. **42**, 313–345 (1989).
12. J. M. Ferry and E. B. Watson, Contribs. Mineral. Petrol. **154**, 429–437 (2007).
13. E. B. Watson, D. A. Wark, and J. B. Thomas, Contribs. Mineral. Petrol. **151**, 413–433 (2006).
14. M. V. Mints, K. A. Dokukina, and A. N. Konilov, http://dx.doi.org/10.1016/j.gr.2012.11.010.

Translated by A. Rylova