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SHORT COMMUNICATIONS

Age of the Magmatic and Metamorphic Processes in the Vodlozero Complex, Baltic Shield: An Ion Microprobe (SHRIMP II) U–Th–Pb Isotopic Study of Zircons

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Ancient cores older than 3.5 Ga were found by isotope–geochronological methods in practically all Archean cratons. Over a few past decades, attempts were made to find such a core (or cores) in the Baltic shield.

Trondhjemite gneisses in Central Finland with 3.7 Ga-old zircon cores are the only old rocks found as of yet in the Baltic shield [1]. The areas promising for the discovery of ancient zircons are located in the Vodlozero domain [2]. The Vodlozero gneisses were previously dated by the conventional U–Pb zircon method at 3115 ± 17 Ma (two-point isochron on early zircons) and 2873 ± 15 Ma (late zircon) [2–4], while K–Ar and Pb–Pb dates on amphiboles and plagioclases varied from 2850 to 2650 Ma, reflecting later superimposed events. No reliable ages were obtained by dating of early zircons on SHRIMP I in Canberra. The dates thus obtained were discordant, which is difficult to interpret during ion microprobe zircon dating [5].

The early stages of the onset and development of continental cores are reconstructed primarily with high-precision isotope age determinations. Given the intricate structural–metamorphic nature of this region, additional U–Pb isotope studies were carried out on zircons from gneisses with reliable correlation with the local structural scale.

Gneissic exposures (Vodlozero gneissic complex) were found and studied at the southeastern Baltic shield, where they extend over a distance of about 10 km along the Vodla River bank (Fig. 1). The Vodlozero Complex consists of gneisses and amphibolites with tonalite–trondhjemite veins. The rocks underwent multiple structural reworking and metamorphic transformations [4].

The least altered rocks retain their early textures (D_{n+1}), such as banding and schistosity, and compose small lenses a few dozen centimeters in size. Gneissic samples 18k and 45b were taken from a lens consisting of two layers of biotite–amphibole gneisses and one amphibolite layer. Sample 18g was taken from a small amphibolite lens. Small deformed amphibolite and gneissic lenses are related to the late deformation zones (D_{n+2}, Fig. 1, inset). The amphibolites retaining early textures belong to the calc-alkaline series, unlike the younger amphibolites in this area. In the south, the metamorphic rocks are cut by the Kubov granites with an age of 2680 ± 40 Ma [3]. Zircons were preliminarily studied by microscopic and cathodoluminescent methods.

Cathodoluminescent images are shown in Fig. 2. In amphibole–biotite gneisses (sample 18k), the early zircon generation was preserved only in crystal cores. It consists of short-prismatic flattened crystals with sharp zoning (Fig. 2, grains 1.4 and 2.2). The second generation comprises brown prismatic unzoned grains (Fig. 2, grain 2.1). Two sharply distinct zircon generations were found in gneiss (sample 45b) affected by late magnetization (K_2O content reaches 1%). The old generation is composed of short-prismatic crystals with smoothed outlines (Fig. 2, grains 2.3, 2.4, 2.6). The young generation includes dipyramidal crystals with sharp edges and well expressed zoning (Fig. 2, grains 1.3, 1.1). Two main zircon generations were also found in amphibolite (sample 18g). The old generation consists of small flattened weakly zoned crystals (Fig. 2, grains 1, 4, 7), while the young generation is significantly larger prismatic crystals with distinct zoning (Fig. 2, grains 12, 15, 16, 17).

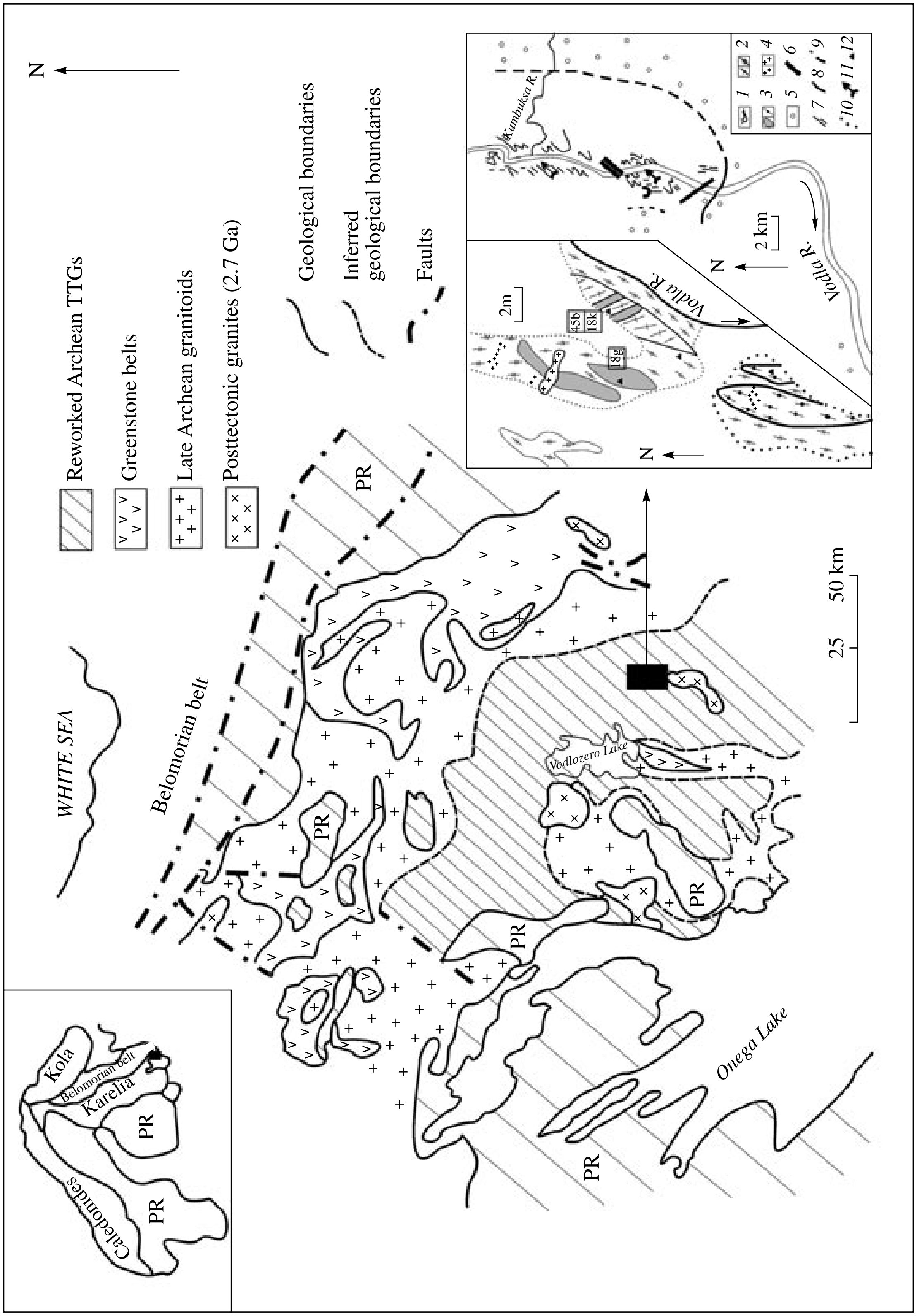

Fig. 1. Position of gneisses of the Vodlozero Complex (inset) in the schematic geological map of the Vodlozero block. Inset: (*1*) gneisses, (*2*) gneisses with early schistosity (*a*) and (*b*) gneisses with schistosity S-2; (*3*) amphibolites 1(*a*) and 2(*b*); (*4*) trondhjemite veins [(*a*) early, (*b*) late]; (*5*) late kinematic granites; (*6*) mafic dikes; (*7*) blastomylonites; (*8*) geological boundaries; (*9*) inferred boundaries; (*10*) exposures; (*11*) fold axes; (*12*) sample numbers used in the work for age determination.

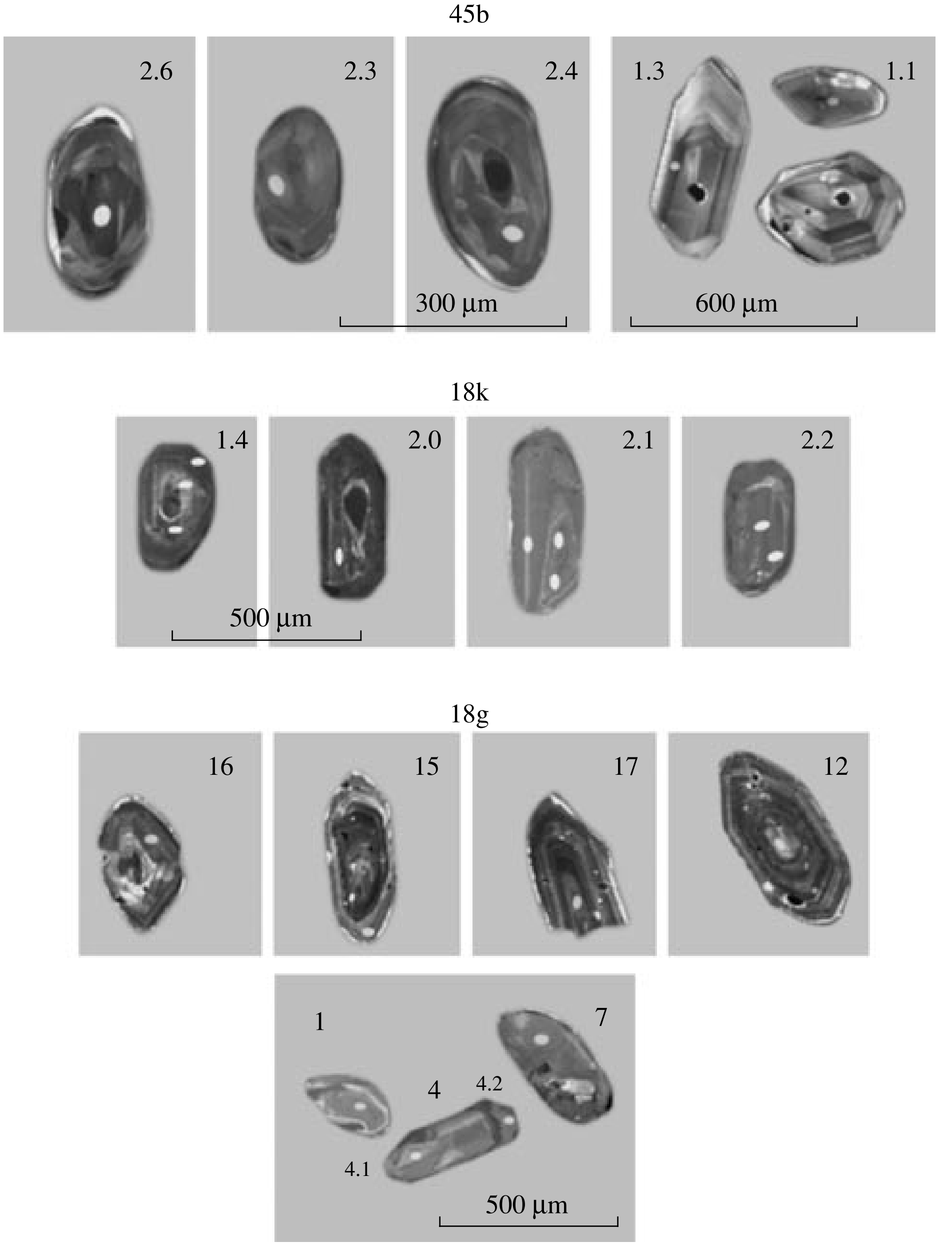

Fig. 2. Cathodoluminescent image of zircons from various gneiss and amphibolite samples (see text).

U–Pb zircon dating was conducted on a high-resolution secondary ion microprobe (SCHRIMP-II) at the Center of Isotopic Research, Karpinskii All-Russia Research Institute. The U–Pb isotope ratios were analyzed on a SHRIMP-II mass spectrometer using the technique [6]. The intensity of the primary beam of negative molecular oxygen ions was 5 nA, the diameter of the spot (crater) was 25 µm in size. The obtained data were treated with the SQUID program [7]. The U–Pb ratios were normalized to 0.668 in the TEMORA standard zircon corresponding to an age of 416.75 Ma [8]. The uncertainty of individual analyses (ratios and ages) was given at a 1-σ level, the uncertainties of the calculated concordant ages and concordia intercepts are given at 2σ. The concordia diagrams were plotted using the ISOPLOT/EX programs [9].

U–Th–Pb isotope zircon study on SHRIMP II ion microprobe showed that the zircons have distinct geochemical nature and isotope ages. The results of the isotopic studies are shown in table and concordia diagrams (Figs. 3–5).

The oldest zircons in gneisses have about 100 ppm U content, 0.9 Th/U, and an age of 3240 ± 15 Ma. They

U–Th–Pb isotope study of zircons on SHRIMP II ion microprobe

Sample, point	Content, ppm			^{232}Th/^{238}U	206 common %	^{206}Pb/^{238}U	±%	^{207}Pb /^{235}U	±%	Corr. coeff.	^{206}Pb/^{238}U Age ±1σ	^{207}Pb/^{206}Pb Age ±1σ	Discord. %
	^{206}Pb, p	U	Th										
18-k, amphibole–biotite gneiss													
1	2	3	4	5	6	7	8	9	10	11	12	13	14
18k.1.1	90.3	170	206	1.25	0.26	0.6148	1.9	20.86	2.0	0.95	3089 ± 46	3160 ± 10	2
18k.2.1	156.2	291	317	1.13	0.25	0.6240	1.8	21.24	1.9	0.96	3126 ± 45	3165 ± 8	1
18k.3.2	202.8	382	95	0.26	0.31	0.6158	1.8	21.29	1.8	0.97	3093 ± 44	3189 ± 7	3
18k.4.2	355.5	671	81	0.12	0.23	0.6152	1.8	20.74	1.8	0.98	3090 ± 43	3150 ± 5	2
18k1.1.1	62.5	115	106	0.95	0.28	0.6333	5.7	22.57	6.8	0.83	3162 ± 42	3237 ± 59	2
18k1.2.1	213.7	408	361	0.91	0.15	0.6088	1.8	20.89	1.8	0.97	3065 ± 43	3177 ± 7	4
18k1.3.1	62.8	111	71	0.66	0.48	0.6527	2.0	23.03	2.1	0.92	3238 ± 50	3221 ± 13	–1
18k1.3.2	63.4	116	72	0.64	0.31	0.6335	1.9	22.84	2.1	0.93	3163 ± 49	3255 ± 12	3
18k1.4.1	112.3	240	126	0.54	0.22	0.5423	1.8	15.11	1.9	0.95	2792 ± 41	2843 ± 10	2
18k1.4.2	297.9	580	110	0.20	0.21	0.5969	1.8	19.79	1.8	0.98	3017 ± 42	3123 ± 6	3
18k1.4.3	52.1	94	76	0.83	0.57	0.6405	2.3	22.50	2.4	0.94	3190 ± 57	3215 ± 13	1
18k2.1.1	99.0	186	96	0.53	0.49	0.6156	1.9	21.10	2.0	0.94	3092 ± 46	3176 ± 10	3
18k2.1.2	370.2	772	98	0.13	0.77	0.5537	1.8	18.19	1.9	0.94	2840 ± 40	3109 ± 10	9
18k2.1.3	91.0	176	215	1.26	0.28	0.6003	1.9	20.42	2.0	0.94	3031 ± 45	3164 ± 11	4
18k2.2.1	131.0	242	279	1.19	0.16	0.6286	1.8	22.56	1.9	0.96	3144 ± 46	3249 ± 8	3
18k2.2.2	95.5	185	178	1.00	0.29	0.5992	1.9	21.65	2.0	0.95	3026 ± 45	3259 ± 10	7
18k2.3.1	148.5	271	345	1.32	0.18	0.6378	1.8	21.55	1.9	0.96	3180 ± 46	3153 ± 8	–1
18k1.3.3	633.1	1412	212	0.16	0.04	0.5216	1.7	14.11	1.7	0.98	2706 ± 38	2795 ± 5	3
18k.2.2	433.5	932	60	0.07	0.05	0.5410	1.7	13.97	1.8	0.98	2787 ± 39	2718 ± 6	–3
18k.5.1	51.9	93	89	0.99	0.69	0.6441	2.0	21.63	2.2	0.91	3205 ± 51	3143 ± 15	–2
18k.6.1	394.0	690	939	1.41	0.01	0.6646	1.7	23.65	1.8	0.98	3285 ± 45	3235 ± 5	–2
18k.3.3	720.5	1473	259	0.18	0.09	0.5687	1.7	15.84	1.8	0.96	2902 ± 40	2842 ± 8	–2
45, gneiss													
1	2	3	4	5	6	7	8	9	10	11	12	13	14
45.1.1.1	25.2	53	37	0.73	0.66	0.5532	1.5	15.55	2.1	0.73	2839 ± 34	2858 ± 23	1
45.1.3.1	31.7	66	91	1.43	0.01	0.5579	1.4	15.59	1.9	0.74	2858 ± 32	2848 ± 21	–1
45.1.4.1	36.8	76	107	1.47	0.28	0.5650	1.2	15.56	1.6	0.74	2887 ± 28	2824 ± 18	–2
45.1.5.1	6.9	14	10	0.71	2.42	0.5440	2.7	14.76	4.7	0.57	2800 ± 61	2800 ± 63	0
45.2.1.1	272.1	513	32	0.06	0.30	0.6152	0.6	21.20	0.8	0.77	3091 ± 15	3184 ± 8	3
45.2.1.3.	55.9	101	101	1.03	0.18	0.6445	1.1	23.30	1.3	0.81	3206 ± 26	3260 ± 12	3
45.2.2.1	41.5	74	49	0.69	0.12	0.6521	1.2	22.19	1.5	0.81	3236 ± 30	3164 ± 14	0

Table. (Contd.)

45, gneiss

1	2	3	4	5	6	7	8	9	10	11	12	13	14
45.2.2.2	58.6	107	95	0.92	0.32	0.6374	1.1	21.82	1.3	0.78	3179 ± 26	3174 ± 13	0
45.2.3.1	33.1	59	40	0.70	0.13	0.6490	1.3	23.50	1.6	0.81	3224 ± 33	3262 ± 15	2
45.2.4.1	40.3	71	53	0.78	0.03	0.6643	1.4	23.74	1.6	0.85	3284 ± 35	3241 ± 14	–2
45.2.5.1	149.2	275	94	0.35	0.07	0.6312	0.7	21.17	0.9	0.84	3154 ± 18	3142 ± 7	–1
45.2.5.2	46.8	83	67	0.83	0.52	0.6516	1.2	23.23	1.4	0.80	3234 ± 29	3238 ± 14	0
45.2.6.1	58.8	105	111	1.09	0.30	0.6499	1.0	22.81	1.3	0.81	3227 ± 26	3213 ± 12	–2
45.2.7.1	28.0	52	35	0.69	0.59	0.6188	1.5	21.48	1.9	0.76	3105 ± 36	3196 ± 20	1
45.2.1.2	42.8	76	60	0.82	0.65	0.6560	1.2	22.87	1.6	0.79	3252 ± 32	3202 ± 15	–1

18-g, amphibolite

1	2	3	4	5	6	7	8	9	10	11	12	13	14
18G.1.1	92.8	170.8	208.3	1.3	0.04	0.632	1.6	22.67	1.7	0.94	3158 ± 41	3247 ± 9	3
18G.2.1	75.0	140.9	147.6	1.1	0.20	0.6184	1.0	21.87	1.2	0.82	3104 ± 24	3225 ± 11	4
18G.3.1	122	233.9	91.7	0.4	0.15	0.6065	0.8	21.02	1.0	0.83	3056 ± 20	3193 ± 9	4
18G.4.1	53.3	94.1	92.0	1.0	0.18	0.6582	1.2	23.43	1.4	0.82	3260 ± 29	3236 ± 13	–1
18G.4.2	374	1089.7	150.3	0.1	0.10	0.3986	0.6	8.326	0.70	0.82	2163 ± 10	2363 ± 7	8
18G.5.1	38.9	85.5	66.4	0.8	0.29	0.5286	1.2	14.70	1.6	0.76	2736 ± 27	2840 ± 17	4
18G.6.1	138	246.5	194.7	0.8	0.05	0.6501	0.8	23.40	0.9	0.84	3228 ± 20	3253 ± 8	1
18G.7.1	107	192.7	254.0	1.4	0.07	0.6480	0.9	23.15	1.0	0.84	3220 ± 22	3241 ± 9	1
18G.8.1	90.1	177.0	211.8	1.2	0.02	0.5928	0.9	19.17	1.1	0.81	3001 ± 22	3084 ± 10	3
18G.9.1	55.0	98.4	82.6	0.9	0.13	0.6503	1.1	23.13	1.4	0.82	3229 ± 29	3234 ± 13	0
18G.10.1	87.3	156.7	210.3	1.4	0.04	0.6483	0.9	23.10	1.1	0.84	3222 ± 24	3237 ± 10	0
18G.11.1	289	550.3	372.6	0.7	0.05	0.6115	0.6	21.40	0.8	0.83	3076 ± 15	3209 ± 7	4
18G.12.1	51.9	113.4	51.7	0.5	0.03	0.5325	1.7	15.99	2.0	0.88	2752 ± 39	2964 ± 15	7
18G.13.1	64.3	132.4	72.5	0.6	0.04	0.5651	1.0	16.88	1.3	0.79	2888 ± 23	2956 ± 13	2
18G.14.1	46.8	92.8	23.8	0.3	0.11	0.5872	1.2	17.85	1.5	0.80	2978 ± 28	2984 ± 14	0
18G.15.1	82.7	165.7	53.4	0.3	0.00	0.5810	1.6	17.45	1.7	0.93	2953 ± 38	2965 ± 11	0
18G.16.1	70.5	140.9	44.3	0.3	0.13	0.5818	1.0	17.52	1.3	0.80	2956 ± 24	2968 ± 12	0
18G.17.1	121	248.1	72.9	0.3	0.06	0.5661	0.8	17.04	1.0	0.82	2892 ± 19	2968 ± 9	3
18G.18.1	95.5	187.6	155.2	0.9	0.08	0.5924	0.9	18.14	1.1	0.82	2999 ± 22	2996 ± 10	0
18G.19.1	51.1	98.4	45.9	0.5	0.21	0.6029	1.2	19.16	1.5	0.80	3041 ± 28	3056 ± 14	0
18G.20.1	170	329.7	280.3	0.9	0.17	0.5988	0.7	19.16	0.9	0.84	3025 ± 18	3066 ± 8	1
18G.21.1	116	210.8	252.8	1.2	0.02	0.6426	0.8	23.05	1.0	0.85	3199 ± 21	3248 ± 8	1
18G.22.1	63.6	135.2	75.5	0.6	0.32	0.5460	1.0	18.62	1.3	0.76	2809 ± 22	3167 ± 13	11

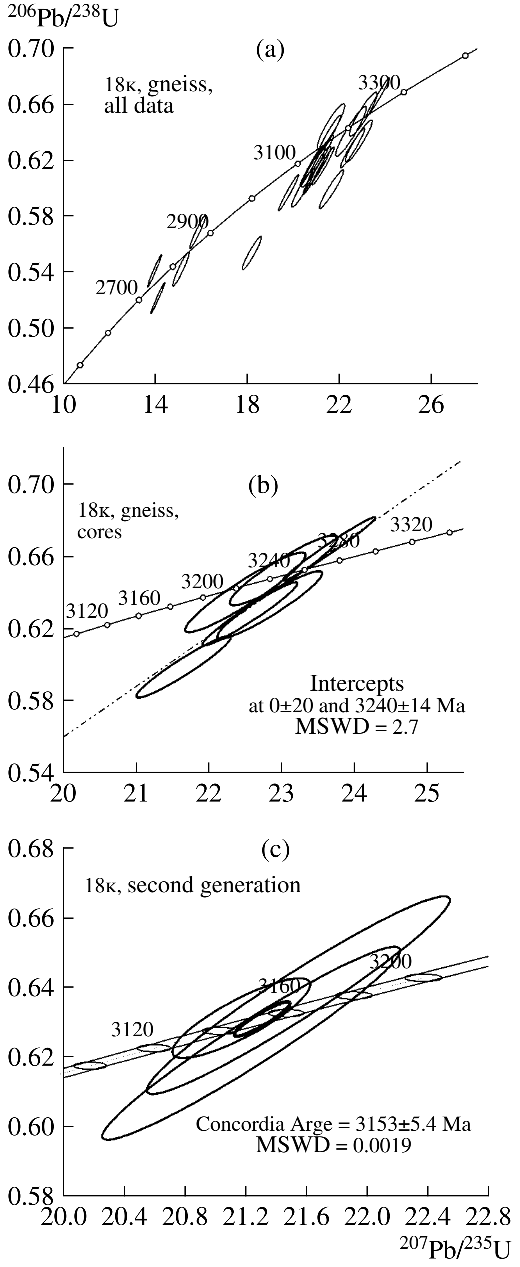

Fig. 3. Concordia diagram for zircons from amphibole–biotite gneiss 18k.

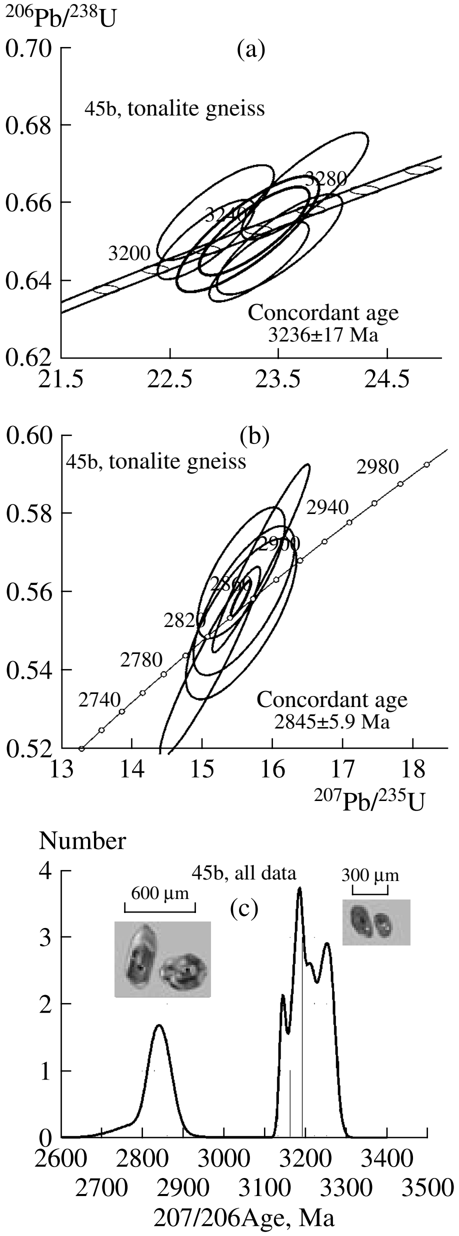

Fig. 4. (a, b) Concordia diagrams and (c) distribution of ages determined by the $^{207}Pb/^{206}Pb$ isotope ratio in zircons from gneiss 45b.

compose grain cores in sample 18k and individual crystals in sample 45b. The second generation of zircons in the gneisses contains about 300 ppm U, occasionally up to 700 ppm, with a Th/U ratio of 0.66. The age of this generation is 3153 ± 5 Ma. The late zircon generation was found only in gneiss (sample 45b). The zircons have a very low U content of ~50 ppm, a Th/U ratio about 1.0, and an age of 2845 ± 6 Ma.

Early zircon from the amphibolites (sample 18g) contains about 130 ppm U, with a Th/U ratio of 0.5. The age of this generation is 3240 ± 10 Ma. The late zircon contains about 150 ppm U, at Th/U ratio of 1.0, and is dated at 2980 ± 12 Ma.

The obtained dates and geochemical characteristics of the zircons reflect the intricate metamorphic evolution of the region. The earliest zircon from both the gneisses and the amphibolites has an age of 3240 Ma, which presumably is the protolith age. This is confirmed by available Sm–Nd isotope data on these rocks [10], whose positive εNd_t values from +1.5 to +1.8 testify to a juvenile source.

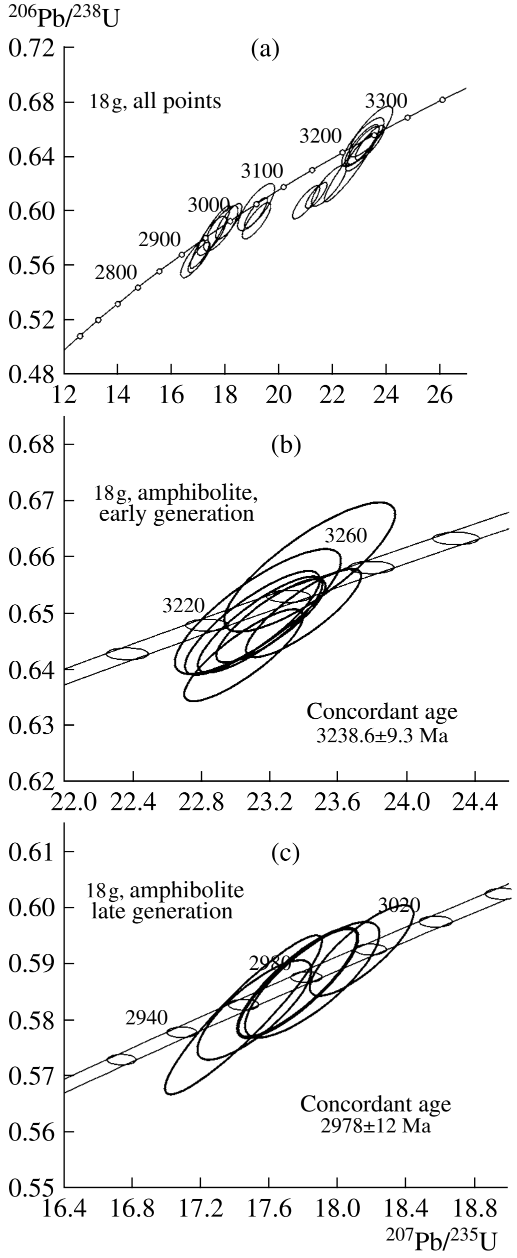

Fig. 5. Concordia diagram for zircons from amphibolite 18g.

However, early zircons from the gneiss (sample 45b) and amphibolite have distinct morphologies. The gneisses were presumably formed after quartz diorites, while zircons from amphibolite are morphologically similar to those from volcanic rocks. Zircons from amphibolite are partially dissolved (Fig. 2, grains 1, 4), suggesting their entrapment from the host rocks. This assumption is consistent with variable age of metamorphic zircon in these rocks.

The evolution of the Vodlozero gneisses and amphibolites can be represented in the following form:

Calc-alkaline juvenile magmatism occurred at 3240 Ma.

At 3150 Ma, the Vodlozero Complex underwent early metamorphism, which was responsible for the crystallization of a new zircon generation in the gneisses and for the formation of a metamorphic shell around early zircons. Tonalite intrusions were concurrently emplaced in the central part of the Vodlozero domain [2, 5, 11]. The rocks of this age were formed in the lower crust, as follows from Nd isotope data on crustal granites [11]. The wide spatiotemporal spread of these processes is evident from detrital zircons in the sediments of the Matkalakhta belt in the southern part of the Vodlozero domain. Zircons accounting for 40% of the detrital fractions have an age of 3160–3100 Ma [12], Th and U contents, and Th/U ratios similar to those in the simultaneous zircons from the Vodlozero gneisses.

Mafic dikes of generation I were emplaced in the Vodlozero gneisses at 2980 Ma and induced the growth of magmatic zircons in the amphibolites. At this time, felsic and mafic magmatism widely occurred in the Vodlozero block: tonalites and granodiorites were emplaced in its northern part and gabbrodiorites in the central part. The mafic dikes were emplaced concurrently with greenstone mafic volcanics in the structures surrounding the Vodlozero domain [11].

Mafic dikes of generation II were formed at 2860–2900 Ma. The mafic magmatism of this stage was widespread beyond the Vodlozero domain.

The plagiomigmatization of the Vodlozero Complex at 2845 Ma led to the formation of a new zircon generation in relicts of ancient gneisses. Mafic and felsic intrusive magmatism of this time took place in greenstone belts at the periphery of the Vodlozero blocks (tonalities of the Shilos greenstone belt and gabbro and gabbrodiorites of the Semch and Palaya Lamba greenstone belts) [11].

The emplacement of posttectonic granites at 2670 Ma did not lead to the growth of zircons in the gneisses and exerted no effect on the U–Pb isotopic system of these zircons.

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