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GEOLOGY

New Data on the Early Riphean Age (U–Pb, Shrimp-II) of Acid and Basic Effusives of the Gulf of Finland (Sommers Island, Russia)

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Abstract—This work presents data on the age of the volcanites of Sommers Island located to the south of the submarine extension of the Vyborg massif, as potential comagmates of rapakivi granites. The U–Pb system of zircon from Early Riphean volcanics is studied to determine their geochronological age using the SHRIMP-II ion microprobe (VSEGEI). For quartz porphyries composing the southern part of Sommers Island, the oldest age determinations of volcanics (1663 ± 8 Ma) were obtained for the Gulf of Finland area for the first time, which can be assigned to the lower parts of the Hogland series of the Early Riphean. In the northern part of the island, there are various rocks: quartz–feldspar porphyries (rhyodacites), andesibasalts, trachybasalts, and granodiorites. All of them underwent modifications under conditions of greenstone metamorphism in contrast to the relatively fresh rocks in the southern part of the island. The trachybasalts (1591 ± 5 Ma) are older than the quartz–feldspar porphyries (rhyodacite, 1578 ± 14 Ma), and a similar modification from older basic rocks to younger acidic ones is typical of all magmatic occurrences of the anorthosite–rapakivi granite formation in the Gulf of Finland region. The “young” ages of the rocks from the northern part of Sommers Island are likely to represent the presence of a younger massif of rapakivi granites than the Vyborg massif in the center of the Gulf of Finland. In this case, the Riphean trough structure traced eastward from Sommers Island is composed not only of rocks of the Hogland series, but part of it correlates with the bottoms of the Pasha graben section and the Priozerskaya Formation.

Keywords: quartz porphyries, rapakivi granites, U–Pb age, zircon, Early Riphean

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The Riphean formations composing the rift structures are widely distributed in the frame of the Baltic Shield, especially in the northern and eastern parts. Most of them are Middle Riphean (1.2–1.0 Ga), and only the base of many-kilometer sections of the Belomorian paleorift system is assumed to be older [6]. In the southern frame of the Baltic Shield, Early Riphean tectono-magmatic processes were more intense that reflected in the formation of troughs, intrusions of gabbro-anorthosites and rapakivi, dyke swarms, and indicators of seismites, pseudotachylites. The onset of these events in the region is recorded by the bottom of the Hogland series on Gogland Island in the central part of the Gulf of Finland, where quartz conglomerates occur on the migmatized Svecofennian basement. They are overlain by two thin basalt flows, while most of the section is composed of quartz porphyries aged 1.64–1.63 Ga, which is similar to the age the main pulses of magmatic activity of the Vyborg batholite [2]. Younger and also Early Riphean strata of the Priozerskaya Formation compose the bottom of Pasha graben, which is primarily confined to the Lake Ladoga basin (Fig. 1a). The age of sedimentary rocks from this trough is confined within the time from the youngest detrital zircon located on the eastern bank of the lake of Salmi massif (1.55 Ga), found in the sandstones of the Priozerskaya Formation, before the formation of the Valaam sill (1.47 Ga), which intruded Early Riphean deposits [7]. Quartz porphyries on Sommers Island, which are similar to those in the section of the Hogland series on Gogland Island, are also known in the other places of the southern Baltic Shield. They were encountered as dykes in the northern frame of the Vyborg massif and within it, as well as in the dykes

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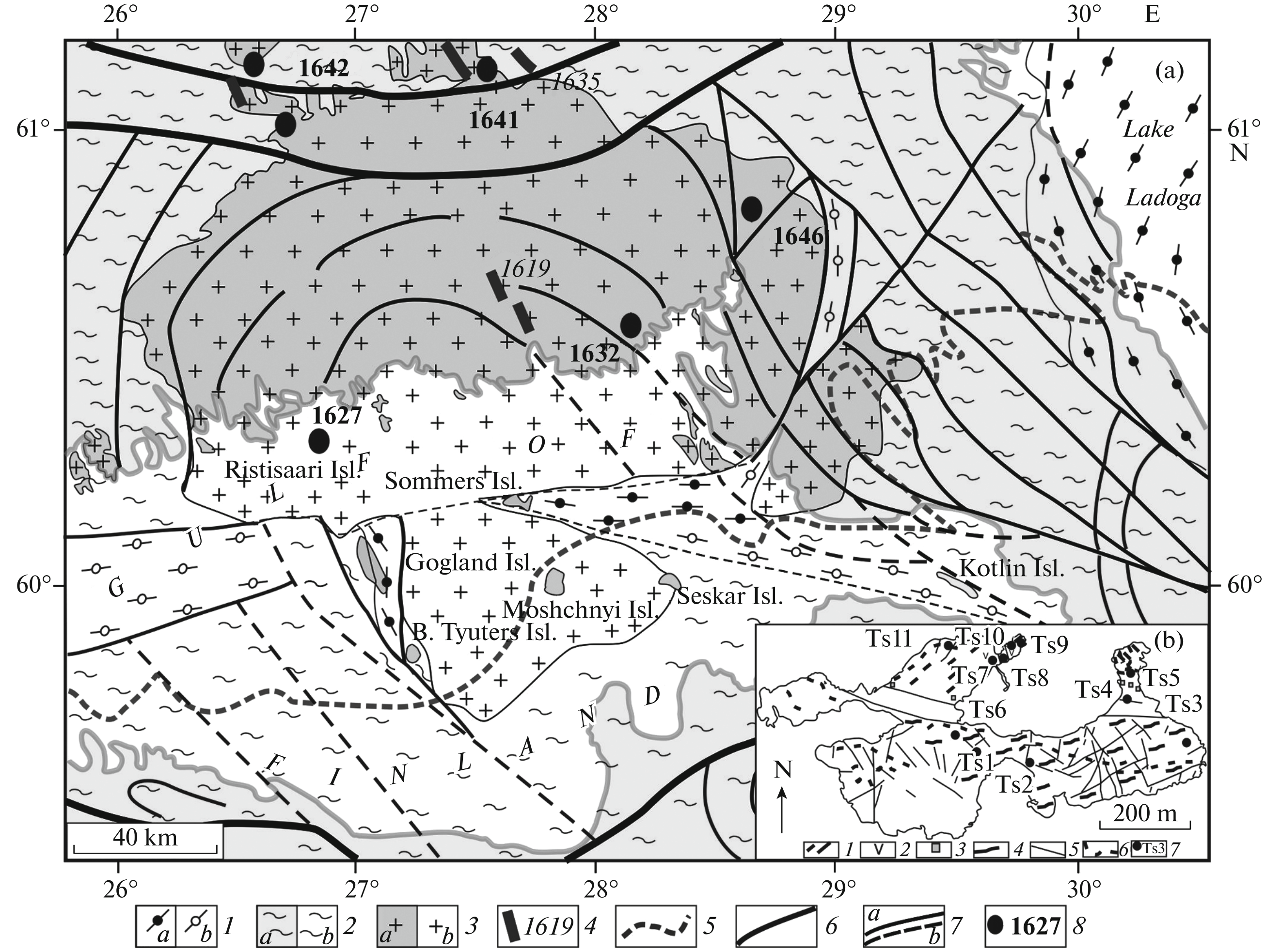

Fig. 1. (a) Structural positions of the Early Riphean formations in the eastern part of the Gulf of Finland: (*1*) Early Riphean deposits (*a*) on the dryland and (*b*) in the water area; Hogland series in the area of Gogland Island; it is likely to be the Priozerskaya Formation in the structure to the east from Sommers Island and the Priozerskaya Formation in the area of Lake Ladoga; (*2*) Paleoproterozoic Svecofennian formations (*a*) on the dryland and (*b*) in the water area; (*3*) rapakivi granites of the Vyborg massif (*a*) on the dryland and (*b*) in the water area; (*4*) dyke swarms of quartz porphyries and their age (from [14]); (*5*) northern border for the distribution of the Vendian deposits; (*6*) marginal faults of the Baltic–Mezen tectonic zone; (*7*) faults: (*a*) proved and (*b*) expected; (*8*) points of geochronological sampling and age (from [14]). In the inset (b), the geological pattern of Sommers Island: (*1*) quartz–feldspar porphyries (rhyodacites) of the northern stratum; (*2*) labradorite porphyries (basalts); (*3*) lava–breccias of quartz porphyries; (*4*) quartz porphyries (rhyolites) of the southern stratum; (*5*) faults; (*6*) predicted borders of lava flows; (*7*) points of sampling.

among the rocks of Salmi and Aland massifs with ages of 1.55 and 1.58 Ga, respectively [5, 12, 14]. Quartz porphyries were described on the small Sommers Island in the Gulf of Finland [12] (Fig. 1). It was assumed that these rocks are similar to the formations of Gogland Island, but their ages were not determined. In addition, based on the results of marine magnetic profiling, they can produce larger bottom areas [12] than was shown in some maps. Since, for a long time, Sommers Island was hard-to-reach for geological research, its position in the regional structure is rather fuzzy. For example, most of the geological maps, including the 1 : 200 000 State Geological Map, show that this island is composed of rapakivi granites of the Vyborg massif. At the same time, 1 : 1 000 000 State Geologicla Map shows the field of Early Riphean deposits. This work is dedicated to determining the age of igneous rocks on Sommers Island.

In contrast to Gogland Island, where the Early Riphean Hogland series consists of quartz conglomerates, only igneous rocks crop out on Sommers Island (Fig. 2). The southern part of Sommers Island is composed of quartz porphyries and rhyolites (samples TS-6, TS-1, TS-2, TS-3; Table 1) being of similar composition with porphyries from Gogland Island [2]. More variegated rocks outcrop in the northern part of the island: trachybasalts (TS-8), andesibasalts (TS-7, TS-10), granodiorites (TS-11), and quartz–feldspar porphyries

Fig. 2. Typical representatives of rocks on Sommers Island: (a) quartz porphyry (sample TS-6); (b) lava–breccia of quartz porphyries; (c) dyke-like body of trachybasaltic composition (sample TS-8); (d) quartz–feldspar porphyry with large crystals of potassium feldspar (sample TS-9). The sample location is marked with a circle.

(TS-5, TS-9). Quartz porphyries in the center of the island were encountered to have a horizon of lava-breccias (TS-4).

The southern part of Sommers Island hosts quartz porphyries of uniform appearance and composition; the sample taken (TS-6) represents this stratum. Samples TS-8 (trachybasalts) and TS-9 (quartz–feldspar porphyry) were brought from the northern part of the island, where the rocks are more variegated, while these samples are the last in the mafic–felsic rock series (Table 1). The U–Pb system was studied for the representative sample of zircon from samples TS-6, TS-8, and TS-9 on a SHRIMP-II ion microprobe (VSEGEI) according to the standard procedure with the selection of analysis points by the cathodoluminescence (CL) images of grains.

Quartz porphyries–rhyolites (sample TS-6) are dark gray porphyry ore with impregnations of potassium feldspar. This rock includes isometric quartz grains and irregular-shaped muscovite and albite segregations. Biotite laminae replaced with chlorite are developed along the cleavage of muscovite.

The groundmass is fully recrystallized and is represented by a fine-grained aggregate of the same minerals and black dust-like crystals of the ore mineral. Zircon from quartz porphyries (sample TS-6) is primarily represented by idiomorphic elongated (K_{elong} 1 : 3–1 : 4 and more) grains with thin-layered oscillation zoning in grey shades, reaching ≥ 300 μm in length (Fig. 3a). In rare cases, the central part of grains is dark gray and nonzonal (point 6). The content of U varies from 37 to 509 ppm at an average value of 117 ppm (Table 2). The content of Th varies within the same ranges (from 19 to 527 ppm; on average, 101 ppm). The Th/U ratio varies from 0.52 to 1.07 at an average value of 0.80, which corresponds to zircon of magmatic origin. All analyzed zircon grains form a concordant cluster with the concordant age of 1663 ± 8 Ma (Fig. 4a).

Quartz-feldspar porphyries–rhyodacites (sample TS-9) are a dark gray rock with bright pink potassium feldspar phenocrysts from 1 to 6 mm in size. This rock contains large, up to 3 mm, isometric segregations of quartz and biotite, which are replaced with yellow parquet-like chlorite–chamosite crystalline aggregates. The groundmass is recrystallized and is represented by elongated skeletal branching crystals of albite, quartz, feldspar, biotite, muscovite, black fine (10–100 μm)

Table 1. Chemical composition (wt %) of representative samples from Sommers Island

Component	Sample										
	TS-1	TS-2	TS-3	TS-4	TS-5	TS-6	TS-7	TS-8	TS-9	TS-10	TS-11
SiO_2	75.20	71.99	73.43	81.52	68.99	74.24	55.33	50.95	72.54	54.84	64.52
TiO_2	0.25	0.29	0.27	0.76	0.54	0.27	2.47	2.62	0.36	2.27	0.61
Al_2O_3	11.64	12.14	12.08	5.13	13.27	11.82	12.97	15.00	12.38	13.90	15.90
Fe_2O_3*	3.24	4.97	4.28	5.83	5.76	4.24	13.75	14.49	4.18	13.02	5.58
MnO	0.04	0.05	0.04	0.06	0.06	0.05	0.13	0.14	0.03	0.14	0.11
MgO	0.16	0.48	0.32	1.23	0.75	0.30	3.06	2.44	0.55	2.70	3.31
CaO	1.35	1.43	0.95	3.01	2.26	1.52	5.07	7.41	0.93	7.49	2.55
Na_2O	1.30	1.95	2.19	1.06	1.92	1.19	3.34	3.14	2.26	2.25	1.87
K_2O	6.14	5.94	5.77	0.68	5.80	5.83	2.41	2.20	5.41	2.04	3.54
P_2O_5	0.03	0.07	0.06	0.22	0.16	0.04	0.72	0.77	0.12	0.72	0.16
LOI	0.65	0.70	0.61	0.51	0.49	0.50	0.74	0.83	1.24	0.64	1.86
Total	100.00	100.10	100.00	100.10	100.00	100.00	99.99	99.99	100.00	100.10	100.10

grains of ore (magnetite, rutile), and large (1–5 mm) oval segregations of ilmenite. Rhyodacites visually contain less quartz than rhyolites by a factor of 1.5–2. The shapes of zircons from quartz–feldspar porphyries and quartz porphyries are similar (Fig. 3b). The difference is that the zircon colors in CL are darker, and the central parts of grains are more often dark gray (e.g., points 1 and 9). The U content varies from 93 to 5720 ppm (in the dark central parts). The recrystallized Th content behaves similarly (from 32 to 2458 ppm); in this respect, the Th/U ratio remains quite consistent from 0.32 to 0.58 at an average value of 0.44, which also corresponds to magmatic zircon. Almost all points of zircon demonstrate reverse discordance and form a compact cluster (Fig. 4b). Regardless of the U content, the points of all grains of the analyzed zircon of sample TS-9 lie on discordia oriented to the zero mark and intersecting concordia at the age of 1578 ± 5 Ma.

Trachybasalts (sample TS-8) are a porphyry dark gray rock with large light grey elongated plagioclase (labradorite) phenocrysts up to 8 mm in size. In addition to plagioclase, the rock contains impregnations of saussuritized potassium feldspar. The fine groundmass is composed of the same elongated crystals of labradorite, potassium feldspar, seladonite, and quartz, which are uniformly distributed in a fully recrystallized glass; there occur numerous dust-like and rare fine black grains of the ore mineral (magnetite) up to 0.5 mm in size, as well as segregations of green and yellow–brown chlorite. The presence of feldspar and seladonite in a rock, which are potassium alkaline minerals, confirms its name, trachybasalt, established by whole-rock chemical analysis. The zircon from trachybasalts (sample TS-8) showed different age values (Table 2). Four elongated grains (1, 4, 7, 8; Fig. 3c) with growth zoning in gray shades in CL images form a concordant cluster with a concordant age value of 1591 ± 14 Ma (Fig. 4c). These grains are characterized by a moderate content of U (from 101 to 256 ppm) and Th (from 65 to 126 ppm) at an average Th/U ratio equal to 0.69. The zircon grain with a young $^{206}Pb/^{238}U$ age of about 600 Ma (3 in Fig. 3c) has a round shape and a light black color in CL. This grain is apparently xenogenic, of unclear genesis. Another group of grains (2, 5, 6, 9, 10; Fig. 3c) is located subconcordantly in the interval of 1750–2000 Ma. These grains have a dark gray color, relics of growth zoning, and a round or isometric shape. The U and Th contents are higher than in other grains, from 583 to 1642 ppm and from 148 to 376 ppm, respectively. For three grains (2, 5, and 9), the Th/U ratio is 0.14, on average, which corresponds more to metamorphic zircon; in other grains of this group (6 and 10), the Th/U ratio is higher, 0.61 and 0.64. This group of older grains can be captured by a dyke from the Svecofennian basement rocks.

The closeness of Sommers Island to the exposed bedrocks of rapakivi granites and to the assumed submarine extension of the Vyborg massif makes it possible to study the geological situation on this island together with the massif of rapakivi granites. Quartz porphyry of this region is considered by the researchers as an effusive comagmate of rapakivi granites or as late dykes of the same massifs [2, 5]. The rocks studied on Sommers Island, including sample TS-6, are close to the similar formations on Gogland Island in terms of the petrogeochemical parameters, being different only in the older age by 20 Ma. The age of 1663 ± 8 Ma estimated for quartz porphyries may correspond to the earliest magmatic activity of the Vyborg massif.

The modern ideas of geochronology for the Vyborg massif are based on the large sample of U–Pb dates

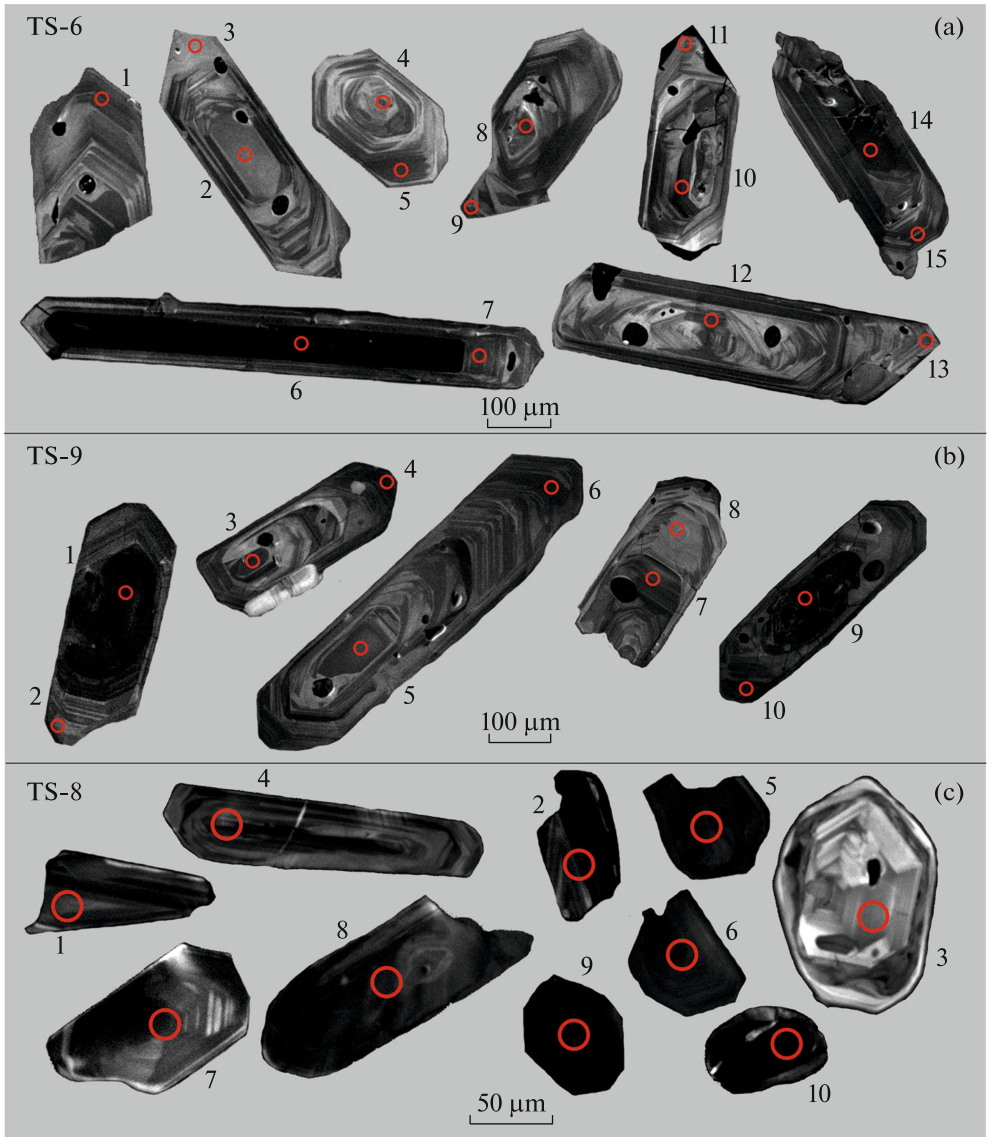

Fig. 3. Cathodoluminiscence images of dated zircon grains from samples (a) TS-6, (b) TS-9, and (c) TS-8. The location of the analytical crater with a diameter of ~20 μm is marked with a circle.

obtained over the past 40 years [13, 15], according to which age of rapakivi granite crystallization is in the range of 1650–1627 Ma [11, 14]. The U–Pb zircon age is 1627 ± 3 Ma (ID-TIMS) from the dark wiborgite on Ristisaari Island and it is the youngest age that has been determined so far for the rocks of the Vyborg batholite. This island is the closest point to Sommers Island.

Based on the published data on the U–Pb age of zircon (from 1.65–1.64 Ga in the north and to 1.627 Ga in the south), we assume that, while the Vyborg batholite was growing, the common magmatic focus could have been displaced southward, with the age of quartz porphyry dykes being even younger though, 1619 Ma [14]. The "young" age of quartz porphyry–rhyodacite from Sommers Island (sample TS-9), which is 1578 Ma, fits well into this tendency of rejuvenation. It is pertinent to note that the center of the Gulf of Finland, where Sommers Island is located is an axial part of the large long-lived tectonic zone, which has different names: the Baltic–Mezen zone, the Polkanov flexure, or the peripheral part of the Baltic ring structure (the nuclear) [4, 10]. This structure is also assigned to other massifs of rapakivi granites, in particular, the Salmi massif with an age of 1.55 Ga [8]. This latitudinal zone is also identified at the bottom of Lake Ladoga, where it controls a sharp increase in the depth of the Pasha graben [1].

The relationship between the granite and gabbro-anorthosite magmas in the Vyborg massif and other massifs in the southern part of the Baltic shield has not been fully clarified. The dominant opinion is that,

Table 2. Results of zircon U–Pb analyses from rocks of Sommers Island

Point number	$^{206}Pb_c$, %	U ppm	Th ppm	$^{232}Th/^{238}U$	$^{206}Pb^*$, ppm	$^{206}Pb/^{238}U$ age, Ma		$^{207}Pb/^{206}Pb$ age, Ma		D %	$^{238}U/^{206}Pb^*$	± %	$^{207}Pb^*/^{206}Pb^*$	± %	$^{207}Pb^*/^{235}U$	± %	$^{206}Pb^*/^{238}U$	± %	Rho
Sample TS-6																			
1	0.04	79.9	50.8	0.66	20.3	1670	± 19	1645	± 31	–1	3.382	1.3	0.1011	1.7	4.123	2.1	0.2957	1.3	0.599
2	0.06	46.9	30.8	0.68	11.9	1668	± 20	1636	± 29	–2	3.387	1.4	0.1007	1.6	4.098	2.1	0.2952	1.4	0.662
3	0.08	37.1	18.7	0.52	9.36	1657	± 21	1666	± 33	1	3.411	1.5	0.1023	1.8	4.134	2.3	0.2932	1.5	0.641
4	0.06	52.1	39.8	0.79	13.4	1692	± 20	1676	± 27	–1	3.332	1.4	0.1028	1.5	4.256	2.0	0.3002	1.4	0.681
5	0.04	98.4	68.0	0.71	24.9	1665	± 19	1632	± 30	–2	3.392	1.3	0.1005	1.6	4.083	2.1	0.2948	1.3	0.615
6	0.01	508	527	1.07	129	1668	± 16	1655	± 10	–1	3.387	1.1	0.1017	0.54	4.14	1.2	0.2953	1.1	0.899
7	0.03	104	69.0	0.69	26.1	1657	± 18	1643	± 19	–1	3.412	1.2	0.1010	1.0	4.083	1.6	0.2931	1.2	0.767
8	0.03	84.2	83.4	1.02	21.5	1679	± 19	1688	± 33	1	3.362	1.3	0.1035	1.8	4.244	2.2	0.2974	1.3	0.581
9	0.04	82.9	51.7	0.64	20.6	1641	± 18	1668	± 21	2	3.449	1.3	0.1024	1.2	4.094	1.7	0.2899	1.3	0.736
10	0.02	146	136	0.96	36.8	1655	± 17	1629	± 26	–2	3.417	1.2	0.1003	1.4	4.047	1.8	0.2927	1.2	0.649
11	0.06	67.5	43.0	0.66	17.0	1654	± 19	1645	± 24	–1	3.418	1.3	0.1012	1.3	4.08	1.8	0.2925	1.3	0.706
12	0.04	79.2	75.3	0.98	20.2	1673	± 19	1673	± 22	0	3.375	1.3	0.1027	1.2	4.195	1.7	0.2963	1.3	0.733
14	0.01	184	176	0.99	47.0	1677	± 17	1639	± 17	–2	3.366	1.2	0.1008	0.94	4.129	1.5	0.2971	1.2	0.783
15	0.03	115	78.5	0.71	29.0	1664	± 18	1668	± 28	0	3.395	1.2	0.1024	1.5	4.158	2.0	0.2946	1.2	0.618
13	0.05	75.0	69.4	0.96	19.4	1694	± 19	1690	± 23	0	3.327	1.3	0.1036	1.2	4.294	1.8	0.3006	1.3	0.720
Sample TS-9																			
1	0.01	1207	564	0.48	306	1667	± 19	1587	± 6	–5	3.390	1.3	0.09801	0.29	3.987	1.3	0.2950	1.3	0.976
2	0.01	294	113	0.40	75.2	1682	± 20	1585	± 11	–6	3.355	1.3	0.09793	0.58	4.025	1.5	0.2981	1.3	0.918
3	0.04	219	123	0.58	54.6	1639	± 20	1581	± 13	–4	3.453	1.4	0.09769	0.71	3.901	1.6	0.2896	1.4	0.889
4	0.02	308	129	0.43	80.2	1706	± 20	1587	± 11	–7	3.300	1.3	0.09802	0.58	4.095	1.5	0.3030	1.3	0.918
5	0.03	168	85.4	0.53	41.7	1635	± 20	1583	± 15	–3	3.464	1.4	0.09782	0.79	3.894	1.6	0.2887	1.4	0.869
6	0.02	427	197	0.48	111	1703	± 20	1566	± 9	–8	3.307	1.3	0.09692	0.49	4.041	1.4	0.3024	1.3	0.939
7	0.07	220	78.1	0.37	50.5	1529	± 19	1580	± 14	3	3.735	1.4	0.09766	0.75	3.605	1.6	0.2677	1.4	0.877
8	0.00	93.4	31.7	0.35	23.4	1650	± 21	1575	± 19	–5	3.429	1.5	0.09740	1.0	3.916	1.8	0.2917	1.5	0.817
9	0.01	5720	2458	0.44	1520	1734	± 20	1574	± 5	–9	3.240	1.3	0.09734	0.24	4.142	1.3	0.3086	1.3	0.982
10	0.03	454	139	0.32	112	1622	± 19	1569	± 9	–3	3.495	1.3	0.09708	0.49	3.83	1.4	0.2861	1.3	0.938
Sample TS-8																			
3	0.00	160	77.8	0.50	13.3	597	± 8	681	± 93	14	10.31	1.4	0.06220	4.4	0.832	4.6	0.0970	1.4	0.305
4	0.15	101	65.1	0.67	24.3	1592	± 20	1566	± 30	–2	3.571	1.4	0.09690	1.6	3.742	2.1	0.2800	1.4	0.661
8	0.03	256	126	0.51	61.8	1597	± 23	1576	± 17	–1	3.557	1.6	0.09744	0.89	3.778	1.8	0.2812	1.6	0.876
1	0.04	178	101	0.59	43.1	1600	± 18	1580	± 20	–1	3.550	1.3	0.09770	1.0	3.794	1.6	0.2817	1.3	0.772
7	0.07	111	108	1.00	27.3	1617	± 20	1605	± 26	–1	3.509	1.4	0.09900	1.4	3.889	2.0	0.2850	1.4	0.707
6	0.02	636	376	0.61	173	1773	± 18	1756	± 9	–1	3.159	1.1	0.1074	0.51	4.689	1.3	0.3166	1.1	0.915
5	0.02	950	148	0.16	279	1896	± 19	1846	± 7	–3	2.924	1.1	0.1129	0.38	5.323	1.2	0.3420	1.1	0.950
9	0.01	1642	188	0.12	483	1897	± 19	1897	± 5	0	2.922	1.1	0.1161	0.29	5.478	1.2	0.3422	1.1	0.968
2	0.27	1361	170	0.13	415	1952	± 25	1952	± 6	0	2.828	1.5	0.1197	0.34	5.839	1.5	0.3537	1.5	0.975
10	0.02	583	361	0.64	185	2022	± 20	1986	± 8	–2	2.715	1.2	0.1220	0.47	6.196	1.3	0.3684	1.2	0.929

Pb_c and Pb* are common and radiogenic lead. The errors in calibration of the standard (0.41% for sample TS-6, 0.37% for sample TS-9, 0.35% for sample TS-8) are not added to the above errors but are required in comparing the data from the different sources. Common lead correction during the age determination by the measured ^{204}Pb. Rho is the coefficient of error correlation. D is discordance, %.

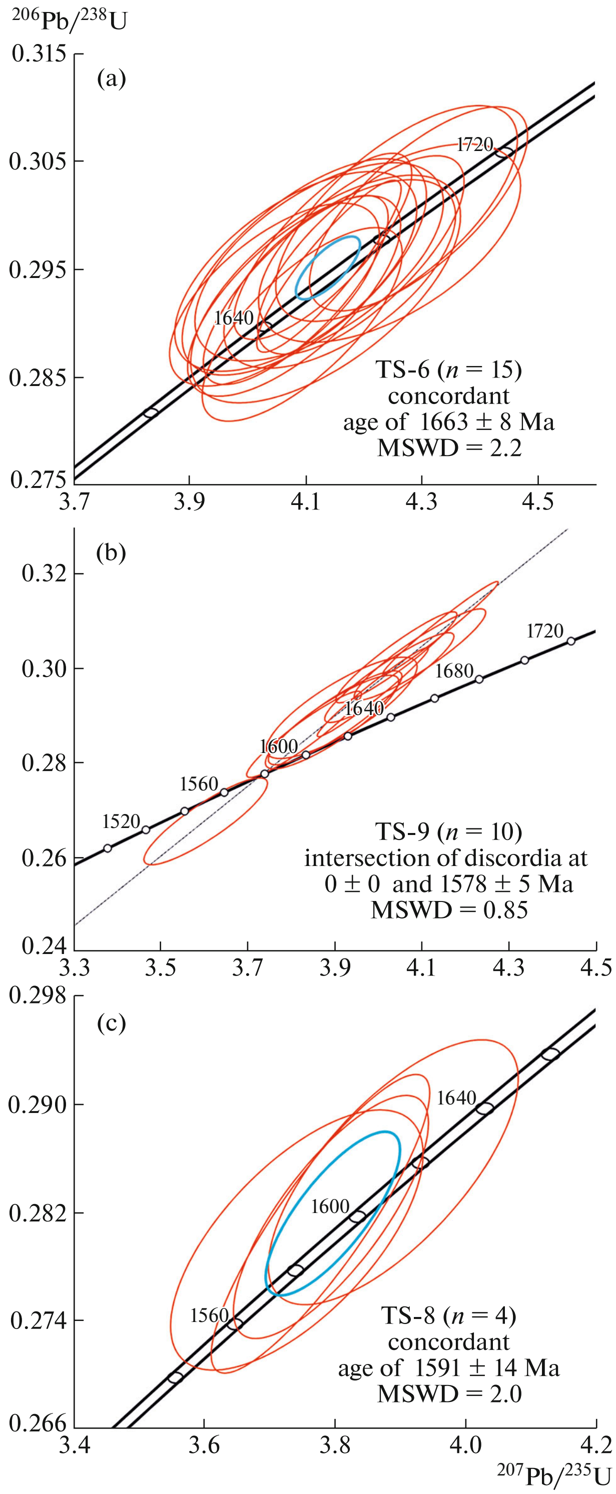

Fig. 4. Concordia diagrams for zircon from samples: (a) TS-6, (b) TS-9, and (c) TS-8. The ellipses and values of concordant age correspond to 2σ, including the error of the disintegration constant.

during the formation of the Vyborg massif, the mafic magma was the earlier and its thermal effect on the felsic crust contributed to the granite melt generation. The data of the geochronological studies point to the older age of gabbro-anorthosites from the Salmi and Vyborg massifs compared to the granites from those massifs [8]. The geological relationship of basalts and quartz porphyries on Gogland Island also indicates the older age of mafic rocks compared to the acidic ones [2]. Our data on trachybasalts (sample TS-8), 1591 ± 14 Ma, and on rhyodacites (sample TS-9), 1578 ± 5 Ma, confirm the regular rejuvenation of the age from mafic to felsic rocks. Presuming that the effusive comagmates were initially located above the future massif, while it was growing, the structure composed of these deposits displaced relative to the massif center and formed ever younger granites nearby, which resulted in the appearance of granites on Ristisaari Island with an age of 1627 ± 3 Ma and quartz–feldspar porphyries on Sommers Island (sample TS-9) of 1578 ± 5 Ma. However, the age of rocks from samples TS-8 and TS-9 (in the interval of 1591–1578 Ma) most likely represents a new cycle of magmatic activity in the area of the Vyborg massif that is superimposed on its main stage with an age of 1660–1630 Ma. In this case, the sample of quartz porphyries TS-6 (1663 ± 8 Ma) belongs to the southern, older, and more uniform stratum, which can be correlated with the earliest manifestations of the Riphean events: the development of the strike–slip zones and the adjacent troughs of a pull-apart type, filled with rocks of the Hogland series. To the north of the lava–breccia horizon (sample TS-4) on Sommers Island rests a younger heterogenous complex 1591–1578 Ma in age. It is likely that the igneous and sedimentary formations of exactly this age compose the sublatitudinal trough extending from Sommers Island to the east. Numerous boulders of conglomerates and quartzite–sandstones along the coasts of Moshchnyi and Seskar islands indicate the occurrence of sedimentary rocks in this structure. The tectonic activity related to the formation of the Early Riphean troughs of this age was also manifested in the formation of the fault zones along the periphery of the Baltic shield, where pseudotachylites 1.59 Ga in age were indicators of seismic events [9].

In conclusion, we note that for quartz porphyries composing the southern part of the Sommers Island, the oldest dates of volcanics (1663 ± 8 Ma) were obtained for the Gulf of Finland area for the first time, which can be assigned to the bottoms of the Hogland series of Early Riphean. In the northern part of the island, various rocks are distributed, such as quartz–feldspar porphyries (rhyodacites), andesibasalts, trachybasalts, and granodiorites. In general, they are altered more strongly than the rocks in the southern part of the island, since they host indicator minerals, including chlorite–chamosite and magnetite, evidencing greenschist facies metamorphism, but they are younger. Here, the trachybasalts (sample TS-8 is 1591 ± 14 Ma) are older than the quartz–feldspar porphyries (rhyodacites, sample TS-9 is 1578 ± 5 Ma). The “young” ages of the feldspar porphyries and the trachybasalts in the northern part of Sommers Island probably reflect the occurrence of a rapakivi granite massif in this area that is younger than the Vyborg massif. In this case, the Riphean trough structure traced to the east from Sommers Island (Fig. 1) may comprise not only the rocks of the Hogland series, but also the part of it that is younger and is correlated with the bottom of the section of the Pasha graben, the Priozerskaya Formation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. V. Amantov, Region. Geol. Metallog., No. 58, 22–32 (2014).
2. A. M. Belyaev, Region. Geol. Metallog., No. 55, 28–36 (2013).
3. *The 1 : 1 000 000 State Geological Map of the Russian Federation, New Ser., Sheet No. R-(35)-37-Petrozavodsk, Explanatory Note* (Karpinsky Russ. Geol. Res. Inst., St. Petersburg, 2000).
4. S. Yu. Kolodyazhny, E. N. Terekhov, A. S. Baluev, A. V. Poleshchuk, and D. S. Zykov, Geotectonics **54** (1), 1–19 (2020).
5. A. A. Konyshev, M. O. Anosova, A. A. Rusak, I. A. Alekseev, A. I. Yakushev, and Yu. B. Shapovalov, Dokl. Earth Sci. **491** (1), 127–131 (2020).
6. N. B. Kuznetsov, A. S. Baluev, E. N. Terekhov, S. Yu. Kolodyazhnyi, E. S. Przhiyalgovskii, T. V. Romanyuk, A. S. Dubenskii, V. S. Sheshukov, S. M. Lyapunov, T. B. Bayanova, and P. A. Serov, Geodynam. Tectonophys. **12** (3), 570–607 (2021). https://doi.org/10.5800/GT-2021-12-3-0540
7. A. V. Kuptsova, A. K. Khudoley, W. Davis, R. H. Rainbird, V. P. Kovach, and I. Yu. Zagornaya, Stratigr. Geol. Correl. **19** (2), 125–141 (2011).
8. A. M. Larin, *Rapakivi Granites and Related Rocks* (Nauka, St. Petersburg, 2011) [in Russian].
9. Yu. A. Morozov, D. S. Yudin, A. V. Travin, A. I. Smul’skaya, A. L. Kulakovskii, and M. A. Matveev, Dokl. Earth Sci. **493** (1), 485–490 (2020).
10. E. N. Terekhov and A. S. Baluev, Stratigr. Geol. Correl. **19** (6), 600–618 (2011).
11. A. Heinonen, O. T. Rämö, I. Mänttäri, T. Andersen, L. K. Heinonen, A. P. Rämö, O. T. Mänttäri, I. T. Andersen, and K. Larjamo, J. Petrol. **58**, 2493–2517 (2017).
12. I. Laitakari, O. T. Ramo, and V. Suominen, M. Niin, K. Stepanov, and A. Amantov, Geol. Surv. Finl. Geol. Spec. Pap. **21**, 59–97 (1996).
13. O. T. Rämö and I. Haapala, Mineral. Petrol. **52**, 129–185 (1995).
14. O. T. Rämö, V. Turkki, I. Mänttäri, A. Heinonen, K. Larjamo, and Y. Lahaye, Bull. Geol. Soc. Finl. **86**, 71–91 (2014).
15. M. Vaasjoki, Tutkimusrap.—Geol. Tutkimuskeskus **135** (1) (1996).

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