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Formation of the Archean Crust of the Ancient Vodlozero Domain (Baltic Shield)

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Abstract—The available geological, petrological, and isotopic data on Archean rocks of the Baltic shield are used to analyze the formation of the crust of the ancient Vodlozero domain. This made it possible to reveal the succession of endogenic processes in different parts of the domain and correlate them between each other. Several stages of magmatic processes reflecting changes in magma-generation environments are definable in the crust formation. The earliest stages of magmatism (3.24 and 3.13–3.15 Ga) are mostly represented by rocks of the tonalite–trondhjemite–granodiorite association. The next stage of endogenic activity (3020–2900 Ma) was marked by the formation of volcanics of the komatiite–basalt and andesite–dacite associations constituting greenstone belts in marginal parts of the Vodlozero domain and basic dikes accompanied by layered pyroxenite–norite–diorite intrusion in its central part. These basic bodies crossing earlier tonalities were formed in extension settings related to the formation of the mantle plume, which is confirmed by the rock composition. This stage culminated in the formation of trondhjemites at margins of greenstone structure. The next stage of endogenic activity commenced at 2890–2840 Ma by the emplacement of high-magnesian gabbro and diorite dikes in the western margin of the domain, where they cross rocks of the tonalite–trondhjemite association. This stage was marked by the formation of intermediate–acid subvolcanic bodies and dikes as well as basite intrusions including the layered and differentiated Semch intrusion, the largest one in the Vodlozero domain. The stage culminated at approximately 2850 Ma in the emplacement of tonalities of the limited distribution being represented by the Shilos massif in the north of the domain and Shal'skii massif on the eastern shore of Lake Onega. The important stage in the geological history of the Vodlozero domain is the formation of the intracratonic Matkalakhta greenstone belt at approximately 2.8 Ga, which includes arenite quartzite and graywackes and polymictic conglomerates developed in the Lake Oster area in addition to volcanics. These rocks indicate a stable tectonic regime, which resulted in deep erosion of the crust. The emplacement of sanukitoids (2.73–2.74 Ga) as well as subsequent two-feldspar granites (2.68–2.70 Ga) and basite dikes (2.61–2.65 Ga) may be considered as resulting from the plume influence on the relatively stabilized sialic crust of the Baltic shield.

Keywords: Baltic shield, Vodlozero domain, isotopic age of rocks, geodynamics

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INTRODUCTION

The formation of cratons at early stages of the Earth's evolution is one of the most important fundamental problems of geology. Two main geodynamic models are now debatable: the amalgamation of small different-age blocks into large cratons and disintegration of large structures into smaller fragments. The basic method used in paleotectonic reconstructions is temporal and lateral correlation of processes responsible for the formation of particular rock complexes and their geodynamic identification. The specific methods used for estimating the age of rocks based on the study of single zircon grains, which resulted in the discovery of relicts of old rocks among younger complexes, contributed much to development of Early Precambrian geodynamic models. Owing to these methods, Lower Archean rocks are now documented practically in all the Precambrian cratons.

In the Baltic shield, the Lower Archean rocks constitute both individual outcrops and significant areas (Lobach-Zhuchenko et al., 2000; *Rannii*..., 2005). In addition, the presence of old rocks is locally established on basis of the occurrence of ancient xenogenic and detrital zircons. The widest distribution of Paleo- and Mesoarchean rocks is characteristic of the Vodlozero domain located in the eastern part of the Baltic shield (Lobach-Zhuchenko et al., 2000).

MAIN STAGES IN MAGMATIC ACTIVITY

The Vodlozero domain representing a large Paleo- to Mesoarchean fragment of the Archean crust of the Baltic shield (Lobach-Zhuchenko et al., 2000; *Rannii*..., 2005) is an element of the Fenno–Karelian province (granite–greenstone segment). The domain corresponds to its southeastern part being characterized by

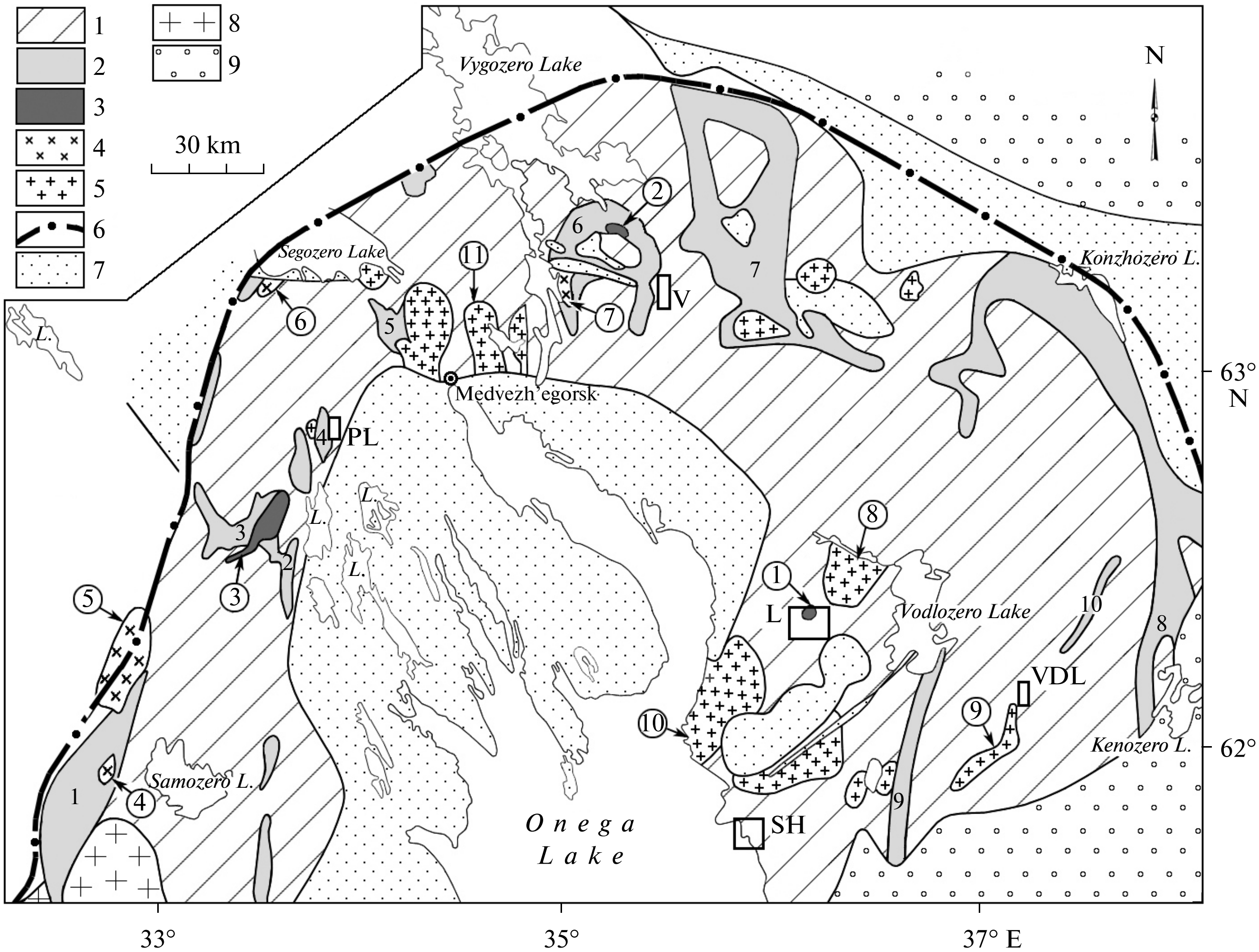

Fig. 1. Geological map of the Vodlozero domain, after (*Rannii...*, 2005) modified. (1) Tonalite–trondhjemite–granodiorite association (rectangles show areas with dates for TTG associations): (L) Lairuchei River, (V) Vyg River, (VDL) Vodla River, (SH) Shal'skii settlement, (PL) Lake Palaya Lamba; (2) greenstone structures (numbers in the gray background): (1) Khautavaara, (2) Koikar, (3) Semch, (4) Palalamba, (5) Oster, (6) Shilos, (7) Kamennoe Ozero, (8) Kenozero, (9) Matkalakhta, (10) Chereva–Vinela; (3) intrusions of basic rocks (encircled numbers): (1) Lairuchei, (2) Shilos, (3) Semch; (4) intrusions of subalkaline rocks (encircled numbers): (4) Khautavaara, (5) Chalka, (6) Bergaul, (7) Konzhozero; (5) intrusions of granites (encircled numbers): (8) Okhtomozero, (9) Kubovo, (10), Tuborechensky (11) Khizhozero; (6) assumed boundary of the Vodlozero domain; (7) Proterozoic formation; (8) rapakivi granite; (9) Paleozoic rocks.

wide development of rocks with zircon ages (U–Pb) exceeding 3.0 Ga and neodymium model ages $T(Nd)_{DM}$ ranging from 3.3 to 3.4 Ga (*Rannii...*, 2005; Sergeev et al., 2007, 2008; Chekulaev et al., 2009a; Arestova et al., 2012a) (Fig. 1). The central part of the domain is composed of rocks of the tonalite–trondhjemite–granodiorite (TTG) association largely represented by tonalities, trondhjemites, and migmatites; subordinate granodiorites and basic to intermediate rocks are developed after the last rocks. Marginal parts of the domain are occupied by different-age greenstone belts. New geological, petrological, and isotopic data combined with available geological information make it possible to analyze the formation of the Archean crust of the domain based on the established succession of endogenic and exogenic processes and their correlation through the latter.

The table presents practically all the available geochronological data obtained for objects with a proven geological position. The data are grouped in accordance with the regional principle for the central, western, northern, and eastern parts of the Vodlozero domain (table). The structure of most areas is considered elsewhere (*Rannii...*, 2005). Several stages of magmatic activity that reflect evolution of magma generation environments are definable in the formation of the domain crust.

The rocks of the first stage of the TTG magmatism older than 3.2 Ga are established in the Lairuchei River and middle reaches of the Vyg and Vodla river basins (central part of the domain), where they are represented by tonalites, trondhjemites, granodiorites, and tonalite–gneisses with inclusions of amphibolites. Judging from the Nd isotope composition and zircon

Correlation of Archean events in the evolution of the Vodlozero domain

Ma	Center		West		North		East	
	Lairuchei River, Vodla River, Shal'skii settlement, Matkalakhta settlement		Khautavaara settlement, Semch River, Lake Palaya Lamba, Lake Oster		Vyg River, Lake Shilos, Lakes Kamennye		Lake Kenozero, Chereva–Vinela rivers	
2600	Gabbronorite (dike)	Nd 2608 ± 56[14]	Gabbro dikes	?				
	Subalkaline amphibolites	Zr 2650 ± 50[1]			Subalkaline amphibolites	SH 2680 ± 13[7]		
2700	Okhtomozero and Kubovo massifs	Zr 2703 ± 30[1], 2680 ± 40[1]	Post-folding granites	SH 2674 ± 35[6] Zr 2684 ± 30[1]	Telekino massif	SH 2705 ± 9[11]		
			Gabbro-pyroxenite	?				
	K rhyolites		Sanukitoids: Khautavaara Chalka El'mus	 SH 2742 ± 23[9] Zr 2745 ± 5[1] Zr 2730 ± 17[1]	Syenites Konzhozero	SH 2743 ± 15[11] 2762 ± 9[11]		
2800	Trondhjemites	SH 2766 ± 22[9]			TT porphyries	SH 2785 ± 15[1]		
2830			Andesites, dacites, Pl porphyries	Zr 2804 ± 31[10] Zr 2830 ± 40[1]	Andesites, rhyolites, porphyries	2804 ± 12[11] Zr 2807 ± 12[1] SH 2832 ± 9[11]		
2840	Arenites, graywackes, and metavolcanics of the Matkalakhta belt	SH < 2821 ± 15[5]	Conglomerates, graywackes of the Lake Oster area					
	Tonalites	SH 2845 ± 6[9] SH 2850 ± 24[9]			Tonalite intrusion	2857 ± 13[11] Zr 2859 ± 29[1]		
	Amphibolites	Zr 2860 ± 20[1]	Gabbro-diorites, anorthosites	Zr 2840 ± 30[1] Zr 2849 ± 40[1] SH 2860 ± 9	Gabbro granodiorites	SH 2869 ± 12[12]	Gabbro	Zr 2841 ± 3[13]
			Rhyolite-porphyries	Zr 2854 ± 14[1] Zr 2862 ± 35[1] SH 2866 ± 11[8]	Andesite-rhyolites	SH 2857 ± 14[11] 2875 ± 50[11]	Andesites, diorites	
2900			Mg gabbro and diorites	SH 2892 ± 9[9]			Basalts, komatiites	Nd 2850 ± 84[10] R 2878 ± 81[10]
	Granodiorite, Kal'ya	Zr 2907 ± 38[1]	Trondhjemite	SH 2903 ± 22[6] SH 2906 ± 14[9]				↓ ?
			Andesites, dacites	SH 2919 ± 14[6] Zr 2935 ± 20[1] Zr 2945 ± 18[1] SH 2959 ± 7[8]				
	Amphibolites of dikes	SH 2967 ± 16[7]	Basalts, komatiites, gabbro	Nd 2944 ± 170[1] SH 3020 ± 14[6]	Basalts, komatiites	Nd 2913 ± 30[1] 2916 ± 117[1]	Basalts, komatiites	Nd 2960 ± 150[1]
3000	Layered basite intrusion	Zr 2978 ± 12[1] Zr 2987 ± 11[1]			Rhyodacite dike?	Zr 3015 ± 20[1]		
			Tonalite	SH 3141 ± 10[6]	TTG	SH 3146 ± 25[4]		
3200								
	Amphibolites (dikes?)	SH 3240 ± 10[3]			Leucosome of migmatites	Zr 3210 ± 15[1]		
3300	TT series	SH 3213 ± 32[2] 3240 ± 11[2,3]	Tonalites	SH 3222 ± 21[6]			Tonalites	?
	Detrital zircons	SH 3334 ± 11[5]						

Ages are from the following works: (1) *Rannii…*, 2005, (2) Chekulaev et al., 2009a, (3) Sergeev et al., 2007, (4) Sergeev et al., 2008, (5) Kozhevnikov and Skublov, 2100, (6) Arestova et al., 2012a, (7) Chekulaev et al., 2009b, (8) Svetov et al., 2010, (9) Arestova et al., 2012b, (10) Puchtel et al., 2007, (11) Myskova et al., 2012, (12) Zhitnikova et al., 2012, (13) Salnikova et al., 2008, (14) Mertanen et al., 2006. Abbreviation in front of the age value means the measuring method: (Zr) Zr–U–Pb on zircon, classical; (SH) U–Pb on zircon, SHRIMP-II; (Nd) Sm–Nd whole-rock; (R) Re–Os method.

Age values without footnotes indicate this work. Color designations: (light gray) tonalites, trondhjemites; (gray) andesites, dacites, diorites, sanukitoids; (dark gray) basalts, komatiites, gabbro.

data obtained by the method of thermoion emission (TIEM), the rocks of the tonalite–trondhjemite (TT) association constituting the eastern part of the domain (Vinela and Chereva river basins in the Arkhangelsk oblast), which are compositionally similar to their counterparts in the Lairuchei area, were likely formed at the same time. Most amphibolite inclusions are represented by fragments of dikes comparable in composition and age with metabasalts of greenstone structures, which are described below. At the same time, amphibolites of the Vodla River area dated back to 3.24 Ga and some amphibolites cropping out in the Lairuchei and Vyg river areas exhibit a different composition; they are considered in (Lobach-Zhuchenko et al., 1995, 2009; Vrevskii et al., 2010) as a probable source for old TT series of the domain. The finding of acid granulite inclusions in zircon grains from the Vyg River area allow an assumption that tonalities could have originated from granulites (Abraham et al., 2013).

The next stage of TTG plutonism at 3130–3150 Ma is represented by tonalities cropping out in the Vyg River area in the northern part of the domain and in the Lake Palaya Lamba area in its western part, i.e., in marginal parts of the domain near surrounding greenstone belts. Several geochemical features, which make these tonalities different from rocks of the TTG association characteristic of the previous stage, indicate different formation environments.

The next stage of endogenic activity (3020–2900 Ma) was characterized by the formation of the rock association, which is widespread through the entire domain. In its marginal parts, the stage is represented by volcanics of the komatiite–basalt and andesite–dacite association constituting greenstone belts. Volcanics of the komatiite–basalt association take part in the structure of all the greenstone belts. Komatiites are present in most sections, although their share never exceeds 3–5% of constituting rocks. The upper parts of the komatiite members contain relicts of primary spinifex, pillow, and breccia textures, which are best preserved in the Palalamba and Kamennoe Ozero structures. The dominant rocks are basalts represented by compact massive varieties with relict pillow structures. The geochronological study of komatiites and basalts by the Sm–Nd method yielded ages ranging with significant errors from 2913 to 2960 Ma (table).

Basic dikes within tonalities in the Palaya Lamba area and in the Lairuchei and Vyg river basins are complete geochemical and age analogs of these basalts. The measured age of these dikes is 3020 ± 14 and 2967 ± 16 Ma (Chekulaev et al., 2009b; Arestova et al., 2012a). The presence of dikes close in composition and age to basalts of greenstone structures among tonalities older than 3.1 Ga provides grounds for assuming that mafic magmatism took place through the entire domain at this stage. The formation of the layered pyroxenite–norite–diorite intrusion within tonalites–trondhjemites of the Lairuchei area in the central part of the domain, which is dated at 2989 ± 11 Ma (Lobach-Zhuchenko et al., 1993), occurred at the stage under consideration as well.

Volcanics of the andesite–dacite association developed in greenstone structures of the western margin of the Vodlozero domain (Khautavaara, Semch, Palalamba, and Oster structures) are dated at 2960–2919 Ma and form thrusts and sills among metabasalts and komatiites as well as dikes in tonalities at the base of the section. For example, the age of the andesite dike in tonalities of the Palaya Lamba area is estimated to be 2919 ± 14 Ma. This age corresponds to that of andesite from the dike in komatiites of the Palalamba structure (Arestova et al., 2012a).

This stage was crowned by the formation of trondhjemites at the boundary between the Semch and Palalamba greenstone structures. In the Palaya Lamba area, tonalites 3141 ± 10 Ma old represent a paleosome of migmatite. Trondhjemite from the leucosome of these migmatites is 2903 ± 22 Ma in age. In the Suna and Semch river basins located in the peripheral part of the Semch greenstone structure, an age of 2906 ± 14 Ma is obtained for tonalities compositionally similar to the substrate of migmatites from the Palaya Lamba area; i.e., this estimate needs additional testing.

The next stage commenced at 2890–2840 Ma with the emplacement of high-magnesian gabbro and diorite dikes 2892 ± 9 Ma old in the western part of the domain, where they intrude rocks of the TT association. This event was followed by the formation of subvolcanic bodies and dikes of the intermediate–acid composition (from andesites to rhyolites) along the entire margin of the Vodlozero domain. In contrast with volcanics of the previous stage, these rocks never form volcanic flow units. Andesites from the western margin of the domain are estimated to be 2866–2830 Ma in age (table). In structures of the northern margin, dacite–rhyolite dikes are dated back to 2875–2804 Ma. It should be noted that dikes 2866–2830 Ma old in greenstone structures of the western margin of the domain reflect the second phase of the andesite–dacite magmatism, whereas coeval dikes in northern structures were generated during the first phase of acid magmatism.

Basite bodies observable in most marginal parts of the domain were emplaced approximately during the same period. These intrusions are dated by different methods within a narrow interval of 2869–2840 Ma. They include the Semch gabbro-diorite intrusion, the largest one in the Vodlozero domain (approximately 120 km^2), gabbro–anorthosite bodies in the Lake Oster area, intrusions and dikes of gabbro of the Shilos massif, leucogabbro of the Palaya Lamba area, and dikes of gabbro in the Chereva–Vinela structure. Intrusions and dikes of this stage intrude deformed and metamorphosed volcanics of earlier stages, indicating the probable change in the tectonic regime and implying the presence of a substantial gap between the formation of volcanics and intruded dikes.

According to geochronological measurements, komatiites and basalts of the Chereva–Vinela structure located in the eastern margin of the domain were formed during the stage under consideration. Their age was previously determined by the Sm–Nd whole-rock method to be 3.39 Ga (Puchtel et al., 1991). Subsequently, geochronological investigations of rocks from this sequence by the Sm–Nd whole-rock and Re–Cs methods yielded age values of 2850 ± 84 and 2878 ± 81 Ma, respectively (Puchtel et al., 2007). The upper age limit of the sequence is determined by age of the gabbro dike, which is dated at 2841 ± 3 Ma (Salnikova et al., 2008). The dike intrudes metamorphosed and deformed komatiite–basalt and andesite volcanics. Taking into consideration these geological data and an estimated error in dating (approximately 80 Ma), the assumption that volcanics of the komatiite–basalt association in the Chereva–Vinela structure were formed at the earlier magmatic stage cannot be ruled out.

This stage culminated in the emplacement of tonalities approximately 2850 Ma old, which are characterized by a limited distribution being represented by the Shilos massif in the northern part of the domain and massif in the Shal'skii settlement area (eastern shore of Lake Onega) in its southeastern part.

The next important stage in the geological evolution of the Vodlozero domain is reflected in the formation of the intercratonic Matkalakhta greenstone belt at approximately 2.8 Ga. This belt includes, in addition to volcanics, arenite quartzites and graywackes (Kozhevnikov et al., 2006; Kozhevnikov and Skublov, 2010), which belong to the platformal association and indicate the stable tectonic regime responsible for deep erosion of the crust. The age of rocks in the Matkalakhta belt is derived from the presence of younger detrital zircons in arenites dated at 2821 ± 15 Ma, in addition to its older grains (Kozhevnikov et al., 2006). The formation of polymictic conglomerates developed in the Lake Oster area, which contain pebbles of different composition and ages, corresponds likely to the stage in question. The youngest rocks among pebbles are represented by gabbro–norites 2860 ± 9 Ma old.

Subvolcanic and dike bodies of the intermediate–acid composition in marginal greenstone structures and intrusive trondhjemites in the eastern coast and islands of Lake Onega were formed approximately during the same period.

The subsequent endogenic processes are reflected in the emplacement of subalkaline sanukitoid bodies (Khautavaara, Chalka, Elmus, and Bergaul massifs), which are located within greenstone structures or at their boundaries in the western part of the Vodlozero domain, 2.73–2.74 Ga in age. In its northern part, this magmatic stage is reflected in the formation of the Konzhozero syenite massif.

The stage at 2705–2680 Ma is readily recognizable through the entire Vodlozero domain owing to a system of granite intrusions (Kubovo, Okhtomozero, Telekino, and Khizhozero massifs). The formation of abundant granite veins and migmatites should also be attributed to this stage. The Archean history of the Vodlozero domain culminates in the emplacement of subalkaline gabbro–amphibolite dikes, local metamorphism of the high-temperature amphibolites facies observable on the eastern coast of Lake Onega and in the Vodla River basin, and development of gabbro and gabbro–norite dikes.

COMPOSITION OF ROCKS AND GEODYNAMIC EFFECT

The correlation table and data discussed in the previous section show that old TTG rocks are developed through the entire Vodlozero domain. Two stages in the formation of these rocks are definable: 3.24 and 3.13–3.15 Ga. The TTG rocks of the earlier stage are characterized by high Sr/Y and $(La/Yb)_n$ values (approximately 70 and >60, respectively) indicating significant depths of magma generation. Tonalites of the second stage are distinguished from their earlier counterparts by elevated K_2O, Rb, Y, and HREE concentrations and lower Sr/Y and $(La/Yb)_n$ values (Fig. 2), which may reflect both the different composition of a source and shallower depths of the melt formation. Amphibolites of the same age observable among TTG rocks differ substantially from basalts of greenstone belts in their enrichment with some lithophile elements, slightly differentiated REE distribution, negative Nb anomaly, lower Sm/Nd values (0.19–0.22), and ε_{Nd} evolution similar to that in TTG rocks (Vrevskii et al., 2010). Consequently, amphibolites of this stage represent derivatives of the Nd-enriched mantle (Fig. 3). The analysis of the Nd isotope composition in basic and TTG rocks of both the Vodlozero domain and other ancient cratons reveals the genetic relation between TTG rock and such amphibolites (Lobach-Zhuchenko et al., 2009; Vrevskii et al., 2010).

In contrast with old amphibolites, most metabasalts and metakomatiites from greenstone structures formed at the stage of 3.02–2.92 Ga are characterized by a flat REE distribution or demonstrate depletion in light REE (Fig. 3).

According to the Nb–Zr–Y–Th classification (Condie, 2005), volcanics of the komatiite–basalt association as well as compositionally similar amphibolite dikes in tonalities are located above the ΔNb line ($\Delta Nb > 0$), falling into the field of plume sources; thus, the formation of primary melts corresponds to plateau settings (Arestova, 2008). The presence of amphibolite dikes, which intrude old rocks of the TT association in different parts of the Vodlozero domain and are analogous in their composition and age to basalts of greenstone belts (Fig. 3), provides grounds for assuming that the first of them served as conduits for volcanics, which were characterized by a wider distribution than is observed now. This fact argues against the model of obduction of oceanic plateaus onto the continental crust in marginal parts of the craton, as is assumed by some researchers (Puchtel et al., 1999; Svetov, 2005; etc.), indicating rather the probable formation of primary melts of basalts from greenstone belts in extension settings related to the formation of the mantle plume.

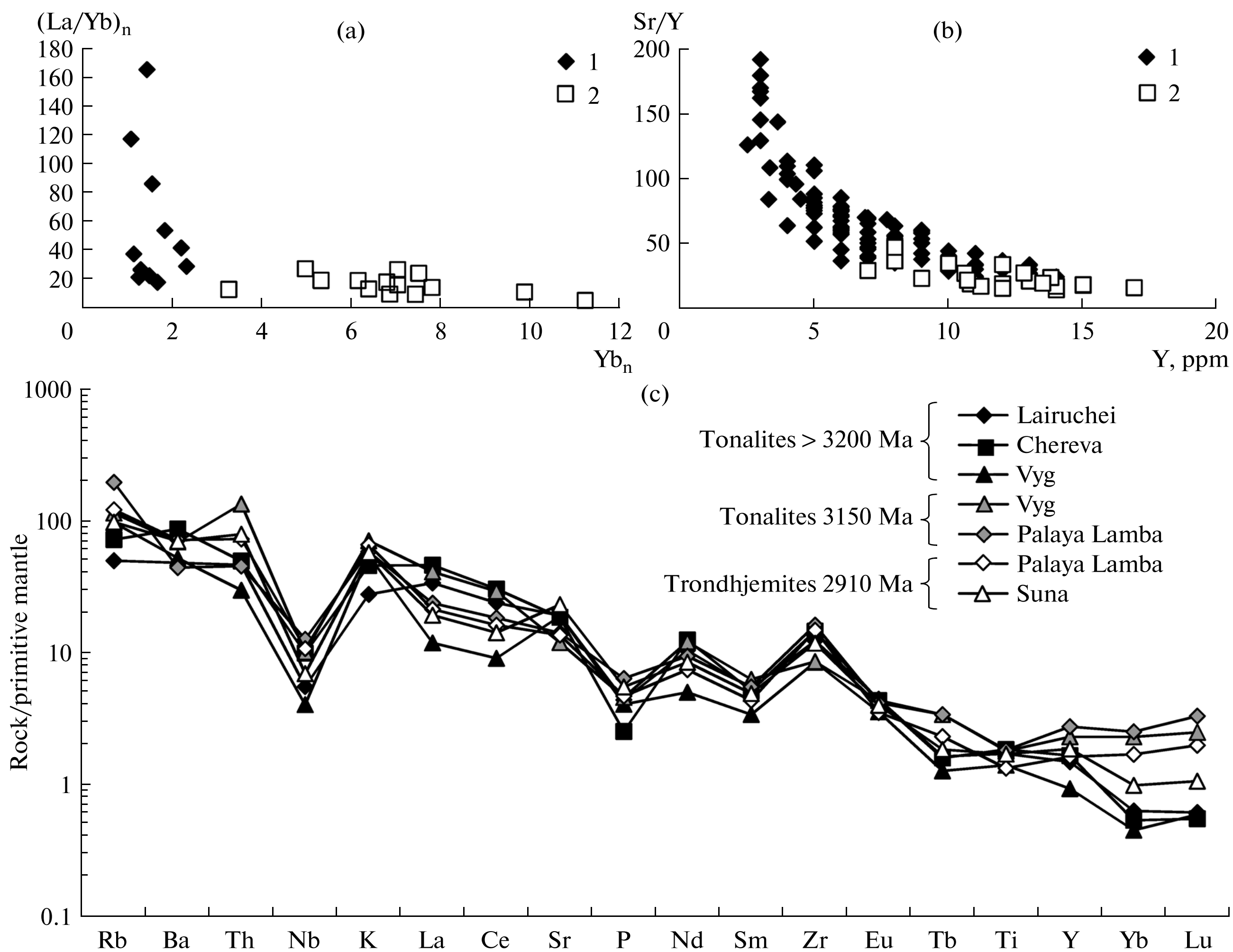

Fig. 2. Diagrams (a) $(La/Yb)_n$–Yb_n and (b) Sr/Y–Y for tonalities dated at (1) ca. 3240 and (2) ca. 3150 Ma and (c) spidergrams normalized to the primitive mantle (Sun and McDonough, 1989) for tonalities >3200, 3150, and 2910 Ma old.

According to geochronological data, the layered pyroxenite–norite–diorite intrusion located in the central part of the Vodlozero domain (Lairuchei River area) was formed simultaneously with volcanics of the komatiite–basalt association in the marginal parts of the domain and mafic dikes. The petrogenic model developed for the formation of the primary intrusion melt based mainly on rare and rare earth elements implies a multistage process that includes generation of the komatiite melt (F = 20–23%) at pressures exceeding 4 GPa, subsequent fractionation of orthopyroxene and olivine, and 20% assimilation of tonalities of the crust (Arestova, 1997). Thus, the composition of the intrusion indicates its belonging to the komatiite series similar to coeval volcanics and, consequently, their melts represent derivatives of the plume. It means that the stage of basite magmatism in the period of 3.02 to 2.92 Ga should be considered as reflecting the first phase of plume activity established in the Vodlozero domain.

Volcanics of the andesite–dacite association of this stage dated at 2.96–2.92 Ga are present in greenstone structures surrounding the Vodlozero domain in the west, where they are divisible in two groups. As compared with similar rocks of its northern structures (Palalamba and Oster), andesites in southern structures (Khautavaara and Semch) are characterized by higher Mg, Cr, Ni concentrations and $(La/Yb)_n$ and $(Gd/Yb)_n$ values. At the same time, all the andesites demonstrate insignificant negative Eu, Nb, and Ti anomalies (Figs. 4a, 4b). These differences between compositions of basalts imply different melt sources, which were likely represented by mantle peridotites for andesites in southern structures and mafites of the lower crust for andesites of northern structures. The formation of such volcanics in subduction zones is the most popular explanation for the simultaneous existence of these sources. At the same time, as is shown above, the presence of diorite dikes, which correspond in composition and age to early volcanics of the andesite–dacite association, among rocks of the TTG asso-

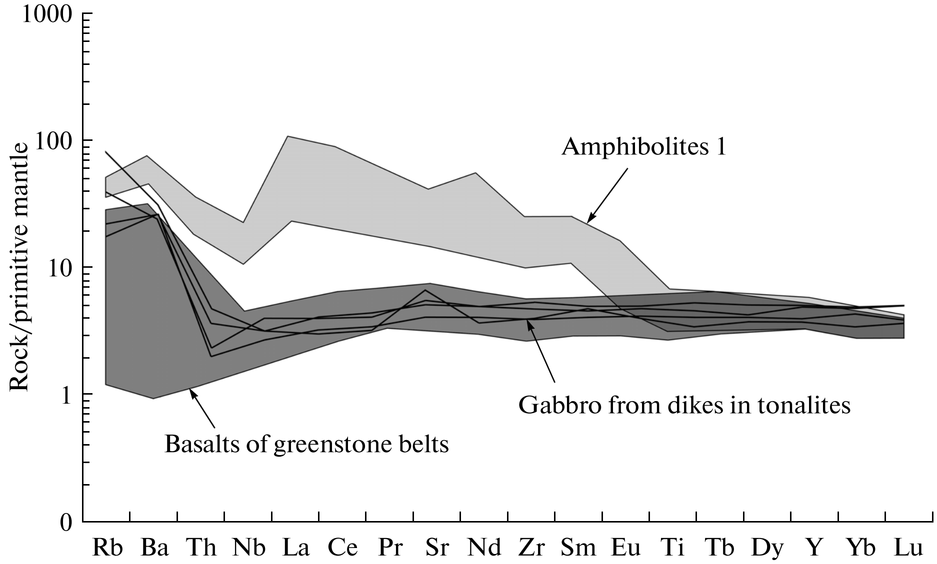

Fig. 3. Spidergram illustrating similarity and difference between early mafites (amphibolites 1, Vodla River area), basalts from greenstone belts, and gabbro from tonalities in the Vodlozero domain. Hereinafter in Figs. 4, 6–8, concentrations of element are normalized to the primitive mantle after (Sun and Donough, 1989). When compiling this and subsequent diagrams, we used original analytical data and data from (Myskova et al., 2012; *Gosudarstvennaya*..., 2013) for rocks of Shilos structure, from (Svetov et al., 2005) for rocks of the Khautavaara structure, and from (Puchtel et al., 1999) for rocks of the Kamennoe Ozero structure.

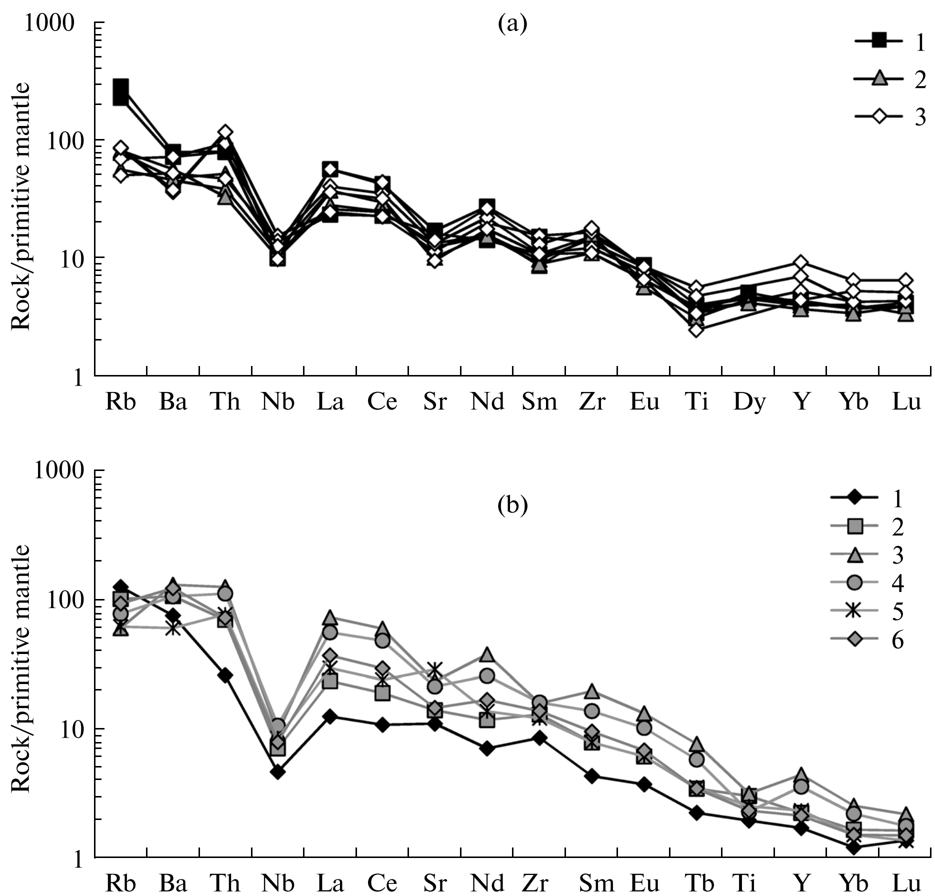

Fig. 4. Spidergrams for andesites from greenstone belts in the western margin of the Vodlozero domain. (a) Northern part: (1) dikes in tonalites of the Palaya Lamba area, (2) dikes and sills in basalts of the Palalamba greenstone structure, (3) volcanic flows in the Oster structure; (b) southern part: (1–5) Khautavaara structure, (6) Semch structure.

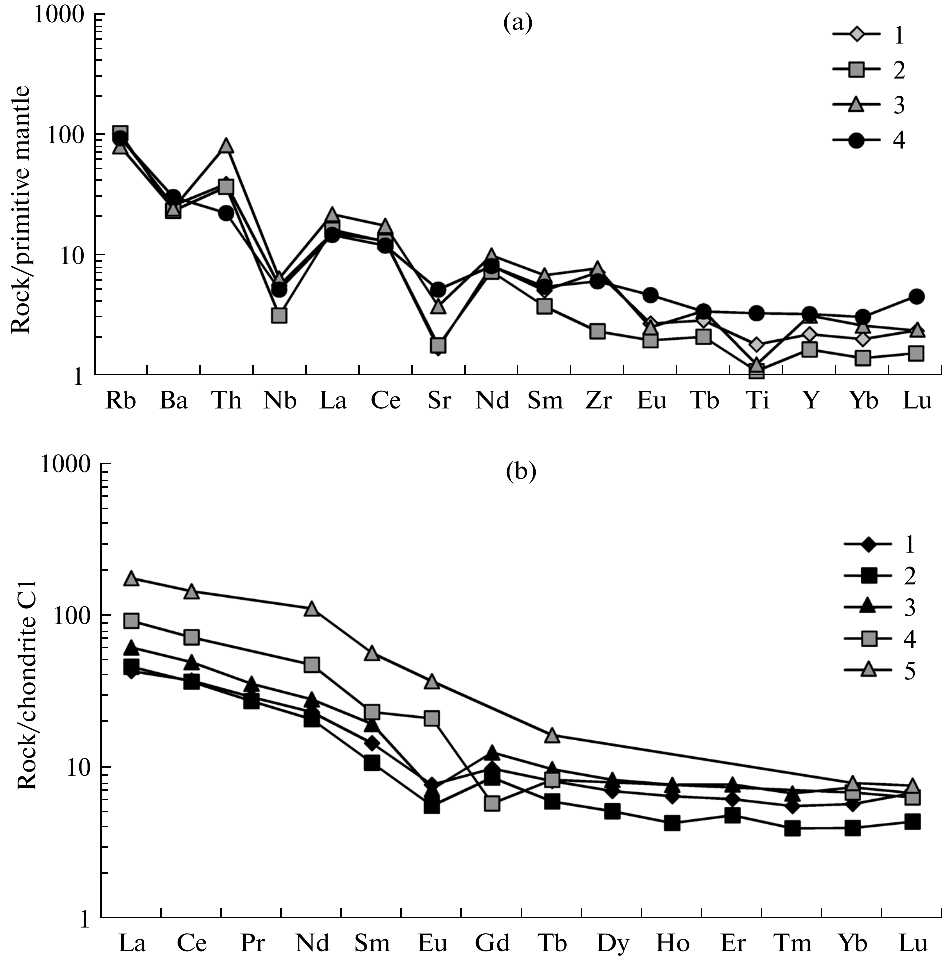

Fig. 5. (a) Primitive mantle normalized spidergram for high-magnesian diorites (1–3) and gabbro (4) from dikes dated at ca. 2.89 Ga from the Palaya Lamba area and (b) chondrite C1 normalized (Sun and Donough, 1989) REE distribution in high-magnesian diorites from dikes in the Palaya Lamba area dated at 2.89 Ga (1–3) and monzodiorites from the Panozero sanukitoid intrusion dated at 2.73 Ga (4, 5).

ciation is inconsistent with the formation mechanism of their melts in island arc settings and their subsequent accretion. The recent investigations (Babushkina et al., 2009) revealed that the concentration of water in the mantle and, especially, lower crust could have been sufficient for andesite magma melting from hydrated areas of the mantle or basalts of the lower crust (Vrevskii, 2009). The indirect argument in favor of such relations in the situation under consideration is represented by the model age $T(Nd)_{DM}$ obtained for andesite melt in the Palaya Lamba area, which is estimated to be 3020 Ma and corresponds to that available for metabasalts in the latter.

The composition of trondhjemites dated at 2903–2917 Ma (Fig. 2) implies their formation due to melting of tonalities of the basement, which is confirmed by geological observations and also by the Nd isotope composition, according to which the rock source is 3130–3150 Ga old, and by the presence of xenogenic zircon in trondhjemites similar in its morphology and composition to that in tonalites.

The dikes of high-magnesian gabbro and diorites formed at the stage of 2892–2840 Ma are characterized by an elevated Mg concentration (mg# = 0.60–0.75), which indicates generation of the primary melt from the melted relict magma of the harzburgite composition, and by a fractional REE distribution with $(La/Yb)_n = 7$ and low negative Eu, Nb, and Ti anomalies, which implies the substantial role of water fluids in melting (Fig. 5). Some researchers compare the formation of high-magnesian diorite melts with that of sanukitoids (Kamei et al., 2004). However, Archean sanukitoids of Karelia are characterized by lower Mg concentrations, higher Al_2O_3 and total alkali contents, and higher REE fractionation (Lobach-Zhuchenko et al., 2005).

Contrary to structures in the western margin of the domain (Khautavaara, Semch, Oster), the subvolcanic bodies and dikes of the intermediate–acid composition (from andesites to rhyolites) dated back to 2875–2854 Ma (table) in structures of its northern margin are petrologically more diverse. In northern structures, three compositionally different groups of

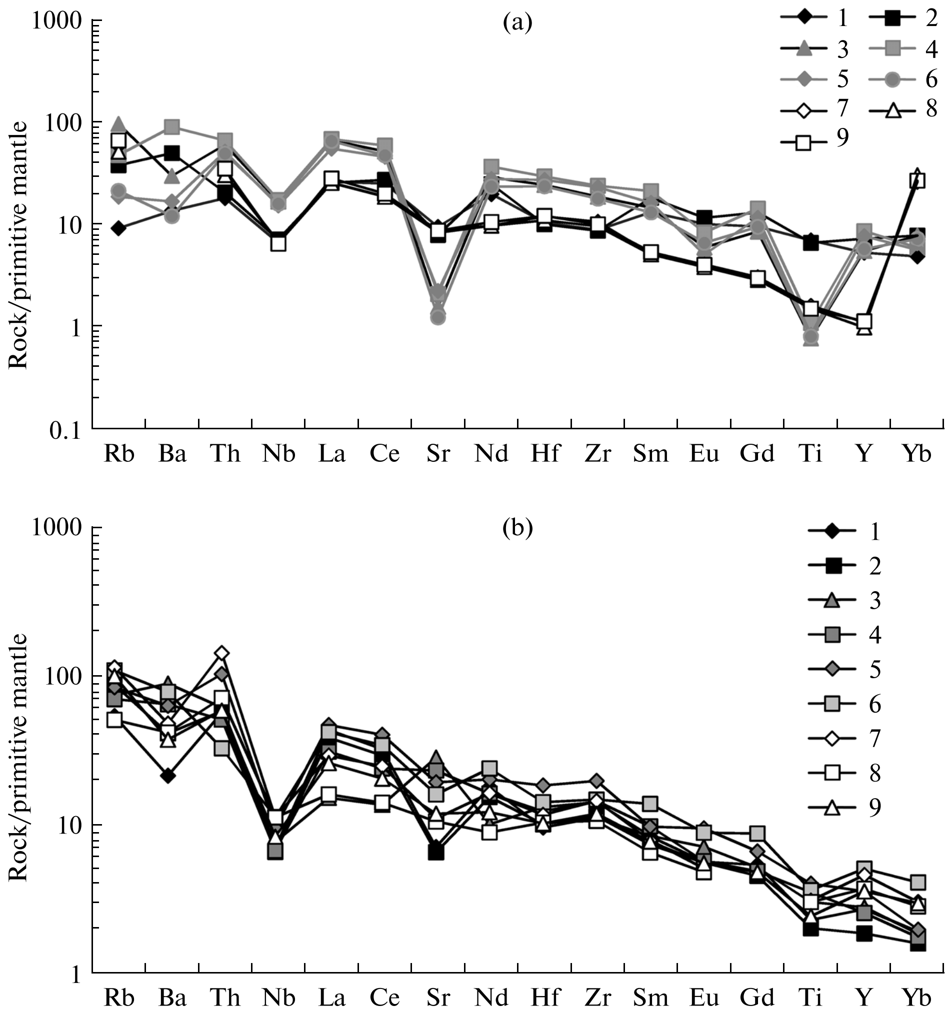

Fig. 6. Spidergrams for andesites 2.86–2.80 Ga old from (a) the northern margin (Shilos Ozero and Kamennoe Ozero structures) and (b) the western margin of the Vodlozero domain. (a): (1, 2) Andesites of the first group, (3–6) andesites of the second group, (7–9) andesites of the third group; (b): (1–5) andesites of the Khautavaara (1, 2) and Chalka (3–5) areas of the Khautavaara structure, (6) andesites of the Semch structures, (7, 8) andesites of the Oster structure.

volcanics are definable (Figs. 6a, 6b). Moreover, volcanics from structures of the western margin of the domain are compositionally similar only to their counterparts from the third group of its northern margin (Figs. 6a–6c). It should be noted that practically simultaneous emplacement of andesite and rhyolite dikes with moderate and low Mg contents within the same structure implies simultaneous melting of amphibolites of the lower crust and mantle sources under the influence of the thermal pulse.

The basite intrusions formed at 2.87–2.84 Ma are represented by gabbro and gabbro–anorthosites. Gabbro is subdivided into magnesian (mg# = 0.63–0.72) and ferruginous (mg# = 0.35–0.40) varieties, which either form autonomous massifs or constitute together the large layered Semch intrusion. The gabbro intrusions in the western and northern margins of the domain are compositionally different (Figs. 7a, 7b). The composition of gabbro intrusions in the western margin with $(La/Yb)_n$ = 10–20 and Mb/La = 0.3–0.5 indicate contamination of their primary melt with crustal tonalities, whereas primary melts of gabbro from the northern margin with $(La/Yb)_n$ = 1 and Mb/La = 1 are free of crustal material (Figs. 7a, 7b). The primary melts of all large and small intrusions are derivatives of komatiite and high-temperature basalt sources and the diversity of all subsequent compositions is determined by contamination processes and liquid and crystallization differentiation. As at the stage of 3.02–2.92 Ga, generation of komatiite and high-temperature basalt melts was possible under the availability of an additional heating source in the Archean mantle. Therefore, wide development of basite intrusions dated at 2.87–2.84 Ga could have been related to the second phase of plume activity.

Tonalites dated back to approximately 2850 Ma (Shilos and Shal'skii massifs) are compositionally close to TTG rocks about 3150 Ma old (Fig. 8),

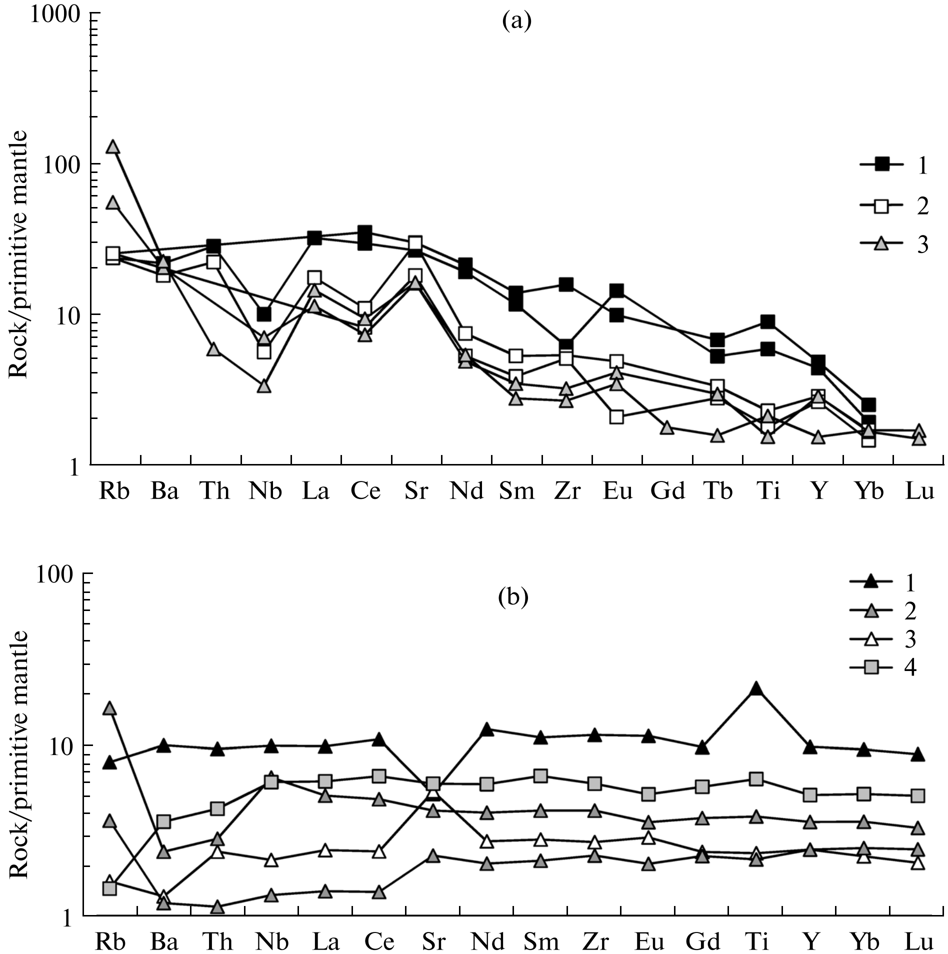

Fig. 7. Spidergrams for gabbro from intrusions in (a) the western margin and (b) the northern margin of the Vodlozero domain (2.86–2.84 and 2.87–2.82 Ga, respectively). (a): (1) Ferrogabbro from the Semch intrusion, (2) magnesian gabbro from the Semch intrusion, (3) gabbro from the Oster intrusion; (b): (1) Kumbuksa intrusion, (2–4) Shilos intrusions.

although their Nd isotope composition indicates a younger (<3 Ga) source.

The formation of the intracratonic Matkalakhta greenstone belt at 2.8 Ga with arenite quartzites (Kozhevnikov et al., 2006; Kozhevnikov and Skublov, 2010), which belong to the platformal association, and polymictic conglomerates developed in the Lake Oster area indicate a stable tectonic regime of the crust in the Vodlozero domain at that time.

Sanukitoid magmatism that took place in the period of 2.73–2.74 Ga is represented by quartz-monzonite–diorite and syenite massifs. Some massifs include mafic rocks. The primary melt for the rocks of this association is estimated to be gabbro–monzonite in composition. The metasomatized mantle, melting of which was determined by plume magmatism (Lobach-Zhuchenko et al., 2005, 2007), served as a source for rocks of such a composition.

The formation of granites 2705–2680 Ma old through the entire domain is explained by partial melting of older TTG series, which is consistent with the data on their composition and model age T(Nd)DM (*Rannii*..., 2005).

The dikes of subalkaline gabbro and normal-alkalinity gabbro–norites, which were emplaced at 2680–2610 Ma, represent a product of the latest phase in Archean magmatic activity. It is conceivable that they were resulted from diminishing activity of the last plume.

CONCLUSIONS

The Archean geological history of the Vodlozero domain is traceable for a period exceeding 600 Ma beginning from 3.24 Ga. The data on detrital zircons (Kozhevnikov and Skublov, 2010) indicate that the domain includes also older rocks dated back to 3.33 Ga. The formation of silaic crust resulted from alternating development of plutonic TTG series and volcano-plutonic associations of variable composition.

The analysis of rocks belonging to the TTG association indicate that the intensity of their formation distinctly decreased with time, which could be explained

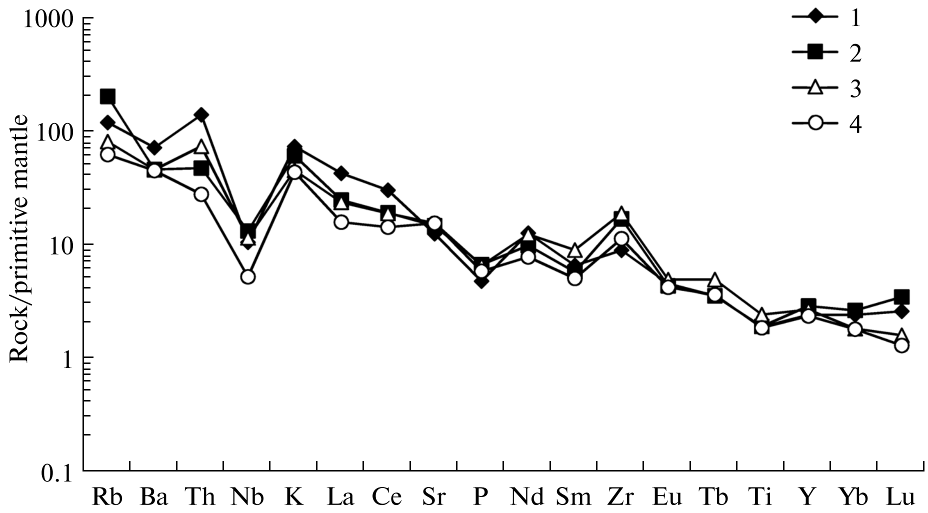

Fig. 8. Spidergram for tonalites (1, 2) 3150 and (3, 4) 2850 Ga old.

by the gradual transition to a more stable regime of the crust reflected in subsequent magmatic and sedimentary series.

In activity of mafic–ultramfic mantle magmatism, two stages are definable: 3.02–2.92 and 2.87–2.84 Ga. The analysis of compositions of volcanics and primary melts of intrusions reveals that they represent products of plume magmatism.

The distribution of mafics through the domain and their geological relationships with host rocks imply that they were emplaced into the sialic crust of variable thickness.

The formation of intracratonic rocks such as arenite quartzites of the Matkalakhta greenstone structure and intraformation conglomerates of the Lake Oster area reflect stabilization of the crust at 2.80–2.83 Ga.

The emplacement of sanukitoids (2.73–2.74 Ga) as well as subsequent two-feldspar granites (2.68–2.70 Ga) and basite dikes (2.61–2.65 Ga) may be considered as resulting from the plume impact on the relatively stabilized sialic crust of the Vodlozero domain.

Results of studying geological and geochemical features of igneous rocks show that the majority of rocks resulted from melting of mantle material within the plumes or more ancient crystal rocks under the influence of plumes.

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