RUSSIAN JOURNAL OF EARTH SCIENCES, VOL. 5, NO. 3, PAGES 145–163, JUNE 2003

Early Precambrian mafic rocks of the Fennoscandian shield as a reflection of plume magmatism: Geochemical types and formation stages

N. A. Arestova, S. B. Lobach-Zhuchenko, and V. P. Chekulaev

Institute of the Precambrian Geology and Geochronology of the Russian Academy of Sciences, St. Petersburg

E. G. Gus'kova

St. Petersburg Branch of the Institute of the Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (SPbF IZMIRAN), St. Petersburg

Abstract. The analysis of radiometric ages of Early Precambrian basites of the Fennoscandian shield, from the most ancient ones, >3.1 Ga, to 2.40 Ga, resolves five age groups of the basites. Each of these stages is shown to time span interval of 70–80 m.y. The early stages of the high-T mafic magmatism (>3.1 and 2.99–2.91 Ga) are confined to within the oldest core of continental crust in the Fennoscandian shield – the Vodlozero domain with crustal age of 3.2–3.4 Ga. The next stage of mafic magmatism (2.88–2.80 Ga) occurred within the Kola and western Karelian domains with crustal ages of 3.0 and 3.1 Ga and on the north of the younger, central Karelian domain. The last of the Archean stages of high-temperature mafic magmatism with ages of 2.72–2.66 Ga occurs in the north Karelian belts, in the Karelian part of the Belomorian area (the regions of Lake Notozero and the Tupaya Guba Bay of Lake Kovdozero) and possibly, in the western Karelian domain. This magmatism took place also immediately after the subduction processes at the boundary of the Karelian and Belomorian domains. The Early Proterozoic high-T mafic magmatism at 2.50–2.41 Ga was both the most areally extensive and continuos such episode in the Fennoscandian shield. Nearly all the researchers of the high-T basites of this stage attribute this magmatism to the ascent of a deep mantle super-plume. Paleomagnetic data provide further evidence that at 2.5–2.41 Ga a long-lived heat source occupied virtually the entire area of the present day Fennoscandian shield.

Introduction

The last decade witnessed how the previously governing plate tectonic paradigm of the Earth's history gave way to the new theory of the global Earth Tectonics. From the standpoint of this theory, the Earth developed through the processes of core growth, plume tectonics, and plate tectonics, which first operated sequentially and then jointly [*Devias,* 1997; *Kumazava and Maruyama,* 1994; *Maruyama et al.,* 1994; etc.]. In this succession of mechanisms, plume tectonics, whose refinement was contributed to by many studies of the last decade [*Campbell and Griffiths,* 1990, 1992; *Condie,* 2001; *Dobretsov et al.,* 2001; *Grachev,* 1998, 2000; *Maruyama,* 1994; etc.], is thought to have played the leading role at early phases of the Earth's evolution. Studies by a number of workers in the Early Precambrian have shown

Paper number TJE03126.
ISSN: 1681–1208 (online)

The online version of this paper was published 18 July 2003.
URL: http://rjes.wdcb.ru/v05/tje03126/tje03126.htm

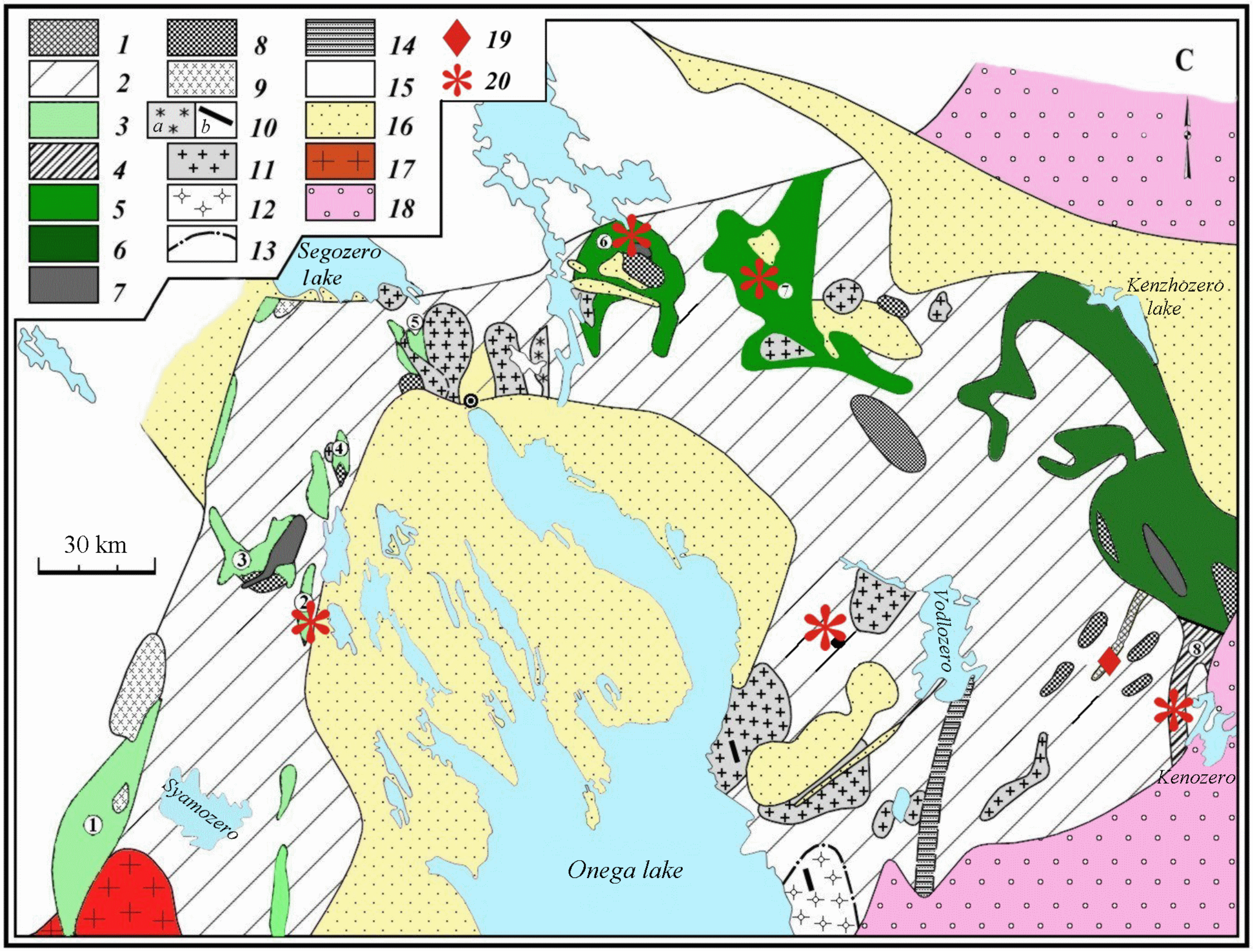


Figure 1. Geologic map showing the Vodlozero domain [*Lobach-Zhuchenko et al.,* 2002].
1 – areas where the oldest rocks of the domain have been dated: KV – mafic volcanics of the Vinela and Chereva rivers, TL – Lairuchei Creek tonalite, GAV – Vodla gneisses and amphibolites, TV – Vyg River tonalite, TPL – Palaya Lamba tonalite; 2 – gneissic tonalite, gneissic granite, and migmatite, undifferentiated; greenstone belts: the most ancient (3.0–2.92 Ga), 3 – with multimodal volcanism, 4 – with bimodal volcanism; 5 – younger (2.9–2.85 Ga), with bimodal volcanism, 6 – with bimodal volcanism, undated; (greenstone belts: 1 = Hautavaara, 2 = Koikary, 3 = Semch, 4 = Palaya Lamba, 5 = Oster, 6 = Shilos, 7 = Kamennoozero, 8 = Kenozero). Intrusions: 7 – gabbronorite, gabbro, gabbro-diorite, diorite; 8 – tonalite, trondhjemite; 9 – high-magnesian granite; 10 – subalkaline rocks: (a) granitoids, (b) mafic and intermediate dikes; 11 – granite; 12 – province of development of overprinted granulite facies metamorphism, including charnockite and enderbite massifs; 13 – boundary of development of the granulite facies assemblage; 14 – Matkalahti zone basites; 15 – central Karelian domain; 16 – Proterozoic rocks, 17 – rapakivi granite; 18 – Paleozoic rocks; 19 – basites dated at >3.1 Ga; 20 – basites dated at 2.99–2.91 Ga.

that the plume-tectonic mechanism was dominant during the Early Precambrian stages of geologic history [*Abbott,* 2001; *Campbell and Griffiths,* 1990, 1992; *Vrevsky,* 2000; etc.].

The most promising approach in unraveling mechanisms that were likely to operate in the Early Precambrian is the study of compositions of basites and ultrabasites, derivatives of mantle melts, to elucidate their source composition, melting conditions, and subsequent melt evolution.

The focus of our work is on Early Precambrian (3.4–2.4 Ga) basites and ultrabasites of the eastern Fennoscandian shield. Our study draws on the recent results regarding the conditions and history of formation of Early Precambrian (Archean) crust in the eastern part of the shield [*Lobach-Zhuchenko et al.,* 1998, 2000b, 2003]. Among these results is the conclusion that, alongside the previously established age heterogeneity of the Archean domains (Fenno-Karelian, Belomorian, and Kola) of the eastern Fennoscandian shield, there exists an age heterogeneity of the shield's largest ancient entity, the Fenno-Karelian granite–greenstone province. The oldest portion of the Fenno-Karelian granite–greenstone province is the Vodlozero domain, whose crust started forming at 3.2–3.4 Ga. Later on, the crust of the western Karelian (3.1–3.0 Ga), Kola, and Belomorian (3.0–2.9 Ga) domains began to form. The crust of the youngest, central Karelian domain is less than 2.85 Ga old. Another approach in scrutinizing mafic-ultramafic magmatism is centered on establishing the principal stages of formation and evolution of Early Precambrian crust of the shield [*Lobach-Zhuchenko et al.,* 2001].

Detailed petrologic and geochemical studies of Early Precambrian komatiites, basalts, and mafic intrusives of the eastern Fennoscandian shield, carried out in recent years [*Arestova and Glebovitsky,* 2003; *Chekulaev et al.,* 2002, 2003; *Lobach-Zhuchenko et al.,* 1998, 2002a, 2003; *Puchtel et al.,* 1997, 1998, 1999; *Vrevsky,* 2000], enabled the researchers to identify (by analogy with modern basites generated in a variety of geodynamic settings) the rocks whose generation was likely related to mantle plumes [*Campbell and Griffiths,* 1992; *Kerr et al.,* 2000; etc.]. Such basites, derived from high-temperature melts, are the focus of this study.

Characteristics of Early Precambrian Basites of the Fennoscandian Shield

Over the past 15 years, a large number of reliable isotope age determinations, most of which are listed in Table 1, have been carried out on Fennoscandian shield basites. These basites fall into five age groups: (1) >3.1 Ga, (2) 2.99–2.91 Ga, (3) 2.88–2.80 Ga, (4) 2.72–2.66 Ga, and (5) 2.50–2.41 Ga. Given below is the analysis of how basites of various age groups are distributed over the area of the Fennoscandian shield and of the geochemical types of the basites constituting these age groups.

Basites With Ages Older Than 3.1 Ga

Mafic rocks with the oldest age determinations (3.4 Ga) are found in the southeastern Vodlozero domain, the oldest in the Fennoscandian shield (Figure 1) [*Kulikova,* 1993; *Puchtel et al.,* 1991]. The basites are represented by the Volotskaya Sequence komatiite–basalt assemblage (Table 2, nos. 1, 2). The peridotites of the Sequence are high-Mg rocks with ca. 27% MgO (no. 1, Table 2). Currently, there is no doubt that peridotitic komatiites with >24% MgO in spinifex-textured varieties are plume derived. Liquidus temperatures for melts initial to such komatiites, as calculated using the formula proposed by [*Nisbet et al.,* 1993], range 1550–1600°C, which corresponds to a mantle temperature of ca. 1800°C and is far in excess of mantle temperatures in the Archean or Early Proterozoic, as calculated by [*Richter,* 1988]. Compositions of the Volotskaya Sequence peridotitic komatiites (27% MgO, 47% SiO_2, CaO/Al_2O_3 = 0.7–1.29, Al_2O_3/TiO_2 = 15–24, 1900–1300 ppm Ni, $\varepsilon_{Nd}(t) = +1.2$)

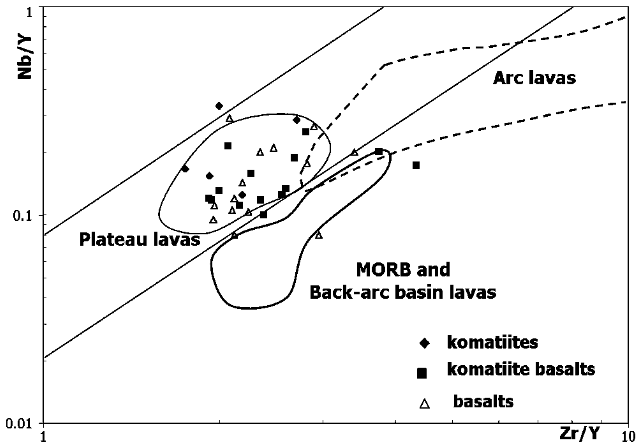


Figure 2. Zr/Y vs. Nb/Y plot for komatiites and basalts of the ancient Volotskaya Sequence of the Vodlozero domain showing fields for basalts from various geodynamic settings, after [*Kerr et al.,* 2000].

suggest that they are derived from high-temperature mantle and are undepleted or slightly depleted in silica. The basalts associated with these komatiites are high in Ni (760–150 ppm) and have Nb/Y and Zr/Y ratios (>0.1 and 2–3, respectively) that place them in the field of rocks generated in oceanic or continental-margin plateaus (volcanic rifted margins; Figure 2) [*Kerr et al.,* 2000; *Marsoli et al.,* 2000]. Although, according to our own geological data, such an old age requires additional validation, it can be safely assumed that high-temperature melts (plume derivatives) first appeared as early as >3 Ga ago.

Basites With 2.99–2.91 Ga Ages

The next (and longest) stage of mafic magmatism takes the time span between 2.99–2.91 Ga. The basites of this stage are widespread within the ancient Vodlozero domain and are represented by intrusions in the central part and by volcanics (komatiites and basalts) in the marginal parts of the domain (Figure 1). This stage, which lasted ca. 75–80 m.y., is divisible into three episodes.

The earliest episode is featured by intrusive magmatism, as exemplified by the Lairuchei layered intrusion (composed of gabbropyroxenite, gabbronorite, anorthosite, and diorite), situated in the central part of the domain and dated at 2.987±11 Ga. Geochemical features of the basites composing the intrusion (Table 2, nos. 3, 4) are: high mg# (0.79–0.68), 22–7% MgO, and high Cr (1000–350 ppm) and Ni (800–200 ppm). According to Campbell and Griffits's data, NiO>600 ppm at 16% MgO may point to a plume provenace for the initial melt. Note, however, that characteristics of high-temperature melts, such as elevated (as compared to Archean komatiites) SiO_2 contents, $(Nb/La)_N = 0.5$, Ti/Zr = 40, an evolved distribution of the rare earth elements ($(La/Yb)_N$ = 5–10) (Figure 3), and $\varepsilon_{Nd}(t) = -0.8$ to -2.5, suggest crustal contamination for the initial melt.

Table 1. Isotope age of Early Precambrian mafic rocks of the Baltic shield

age	method used	occurrence, massif	rock	ε_{Nd}	reference
2410±64	Sm-Nd WR, Opx, Pl	Panikat	layered assemblage	−1.7±0.6	*Huhma et al.*, 1990
2435±7	U-Pb, Zr	Akanvaara	layered assemblage		*Hanski et al.*, 2001
2436±5	U-Pb, Zr	Koilismaa			*Alapieti*, 1982
2439±3	U-Pb, Zr	Koitilainen			*Hanski et al.*, 2001
2439±29	Sm-Nd, WR	Kivaka	gabbro		*Amelin and Semenov*, 1996
2440±10	Sm-Nd, WR	Kovdozero (Puakhta block)	pegmatitic schliere	−1.2±0.3	*Efimov and Kaulina*, 1997
2441±1.2	U-Pb, Zr	Tsipringa	gabbro	−1; −0.5	*Amelin et al.*, 1995
2442±1.4	U-Pb, Zr	Lukkulaisvaara	gabbro	−1.5	*Amelin et al.*, 1995
2443±10	U-Pb, Zr	Tolstik	gabbro	0, −1.5	*Bogdanova and Bibikova*, 1993
2445±2	U-Pb, Zr	Kivaka	gabbro	−1; −0,5	*Amelin et al.*, 1995
2446±5	U-Pb baddeleyite	Lake Pyaozero (western Tikshozero dike assemblage)	gabbronorite		*Vuollo et al.*, 1994
2448±42	Sm-Nd, WR	Vetreny belt	komatiites	−1.2	*Puchtel et al.*, 1997
2449±1.1	U-Pb, Zr	Burakovsky	gabbroids	2 – −2.8	*Amelin et al.*, 1995
2449±35	Sm-Nd, WR, Opx, Pl, Ol	Mt. Golets, Vetreny belt	komatiitic basalts		*Puchtel et al.*, 1997
2430±174	Sm-Nd isochr. WR+Ol+Px	Vinela dike	Peridotites	−1.4±1.0	*Puchtel et al.*, 1997
2450±10	U-Pb, Zr	Kolvitsy	anorthosite		*Mitrofanov et al.*, 1993
2453±					
2406±3	U-Pb, Zr	Main Range	leucogabbro		*Mitrofanov et al.*, 1993
2452±3	U-Pb, Zr	Pyrshin	anorthosite		*Mitrofanov et al.*, 1993
2450±70	U-Pb, Zr	Panajarvi-Tsipringa	Ol-gabbronorites, dikes		*Buiko et al.*, 1995
2457±88	Sm-Nd, WR	North Karelian zone	gabbronorite dikes		*Amelin and Semenov*, 1996
2460±9	U-Pb, Zr	Zhemchuzhny	gabbronorite	−1.3±0.8	*Kudryashov and Balagansky*, 1999
2446±39	U-Pb, Zr	Imandra	gabbronorite		*Bayanova et al.*, 1999
2444±77	Sm-Nd, WR, Opx, Pl, Cpx	Imandra, Umba River massif	gabbronorite		*Bayanova et al.*, 1999
2446±10	U-Pb, Zr	General'skaya	anorthosite	−1.2±0.3	*Bayanova et al.*, 1999
2496±10	U-Pb, Zr	General'skaya	gabbronorite		*Bayanova et al.*, 1999
2491±1.5	U-Pb, Zr	Fedorovo-Panskaya	gabbronorite		*Bayanova et al.*, 1994
2493±7	U-Pb, Zr	Monchegorsk	gabbronorite		*Bayanova and Mitrofanov*, 1999
2668±2	U-Pb, Zr	Tsaga intrusion			*Mitrofanov et al.*, 1993
2692±1.4	U-Pb, Zr	Tupaya Guba Bay, Lake Kovdozero	gabbro		*Lobach-Zhuchenko et al.*, 1993
2694±14	U-Pb, Zr	Guba Mironova Bay, Lake Notozero	gabbro		*Lobach-Zhuchenko et al.*, 1995
2705±7	U-Pb, Zr	Hizovaara belt	dacite cutting komatiites of the upper rock sequence, cutting komatiites		*Shchipansky et al.*, 1999

Table 1. Continued

age	method used	occurrence, massif	rock	ε_{Nd}	reference
2760	U-Pb, Zr	Kuhmo	A mafic sill, cutting komatiites		*Patchet et al.*, 1981
2882±190	Sm-Nd, WR	Uraguba Bay, Polmos-Poros	komatiites	2.8	*Vrevsky*, 2000
2880±10	U-Pb, Zr	Central Belomorian mafic zone	felsic volcanics within basites		*Bibikova et al.*, 1999
2803±35	U-Pb, Zr	Hizovaara belt	dacites cutting komatiites of the lower sequence		*Kozhevnikov*, 1982
2800	U-Pb, Zr	Suomussalmi	granodiorite, cutting rocks of the belt		*Gaal, et al.*, 1976
2843±39	Sm-Nd, WR	Kostomuksha belt	komatiites	2.8	*Puchtel et al.*, 1997
2808±95	Sm-Nd, WR	Kostomuksha belt	komatiites and basalts	2.9	*Lobach-Zhuchenko et al.*, 2000a, 2000b
2840±30	U-Pb, Zr	Palaya Lamba intrusion	Leucogabbro		*Lobach-Zhuchenko and Lavchankov*, 1985
2849±3	U-Pb, Zr	Semch Intrusion	gabbro-diorite	−0.8; −1.5	*Sergeev, Arestova, et al.*, 1983
2916±117	Sm-Nd, WR, isochron	Kamennye Ozera belt	komatiites and basalts	2.7±0.3	*Puchtel et al.*, 1999
2913±30	Sm-Nd, WR, isochron	Shilos structure	basalts	1.6±0.4	*Lobach-Zhuchenko et al.*, 1999
2925±6	U-Pb, zircon	suture between the Murmansk and Kola-Keivy domains	evolved gabbro		*Kudryashov and Gavrilenko*, 2000
2944±170	Sm-Nd, WR, isochron	Koikary belt	komatiites and basalts	1.7	*Svetov and Huhma*, 1999
2960±150	Sm-Nd, WR, isochron	Kenozero belt	komatiites and basalts	2.2	*Sochavanov et al.*, 1991
2987±11	U-Pb, Zr	Lairuchei	gabbro-diorite	−0.6; −2.5	*Lobach-Zhuchenko et al.*, 1993
3128±86	U-Pb, Zr	Vodla River	amphibolite 1		*Lobach-Zhuchenko et al.*, 1993
3320±100	U-Pb, Zr	Vodlozero block	amphibolite		*Sergeev et al.*, 1990
3391±76	Sm-Nd, WR, isochron	Volotskaya Sequence	komatiites and basalts	1.2	*Puchtel et al.*, 1991

Table 2. Contents of major (%), trace, and rare-earth elements (ppm) in representative samples of high-temperature mafic rocks of the >3.1 Ga stage (nos. 1, 2) and the 2.99–2.91 Ga stage (nos. 3–17)

	1	2	3	4	5	6	8	9	10	11	12	13	14	15	16	17
Samp. no.	352 Ar	319 Ar	393 Ar	367 Ar	427-7 Vr	7LZh	2103b Ar	517VB	565 Ar	348a Ar	5-103	11-116	41 Ar	25 Ar	400 Ar	605 Ar
SiO_2	45.86	45.98	52.77	58.75	46.98	50.78	46.23	48.48	45.65	50.43	51.44	51.06	46.38	50.36	45.15	49.79
TiO_2	0.27	0.47	0.29	0.26	0.39	0.65	0.23	1.11	0.23	1.10	0.56	0.76	0.77	1.09	0.29	0.79
Al_2O_3	8.02	10.13	14.81	18.16	7.79	14.77	6.9	14.76	6.3	14.37	12.17	16.70	16.26	16.39	7.62	15.10
FeO	11.08	14.05	8.13	5.13	11.68	9.61	12.73	12.36	12.97	12.25	11.91	10.03	12.25	11.89	9.42	12.06
MnO	0.21	0.22	0.16	0.09	0.16	0.23	0.2	0.20	0.19	0.20	0.18	0.20	0.19	0.20	0.28	0.20
MgO	25.66	17.62	13.55	7.45	28.82	8.15	28.3	6.72	29.19	8.51	16.24	8.7	9.76	6.89	30.32	7.50
CaO	7.77	10.06	7.88	6.67	5.13	12.08	5.16	14.08	4.65	9.56	5.58	9.7	11.26	9.30	5.34	11.04
Na_2O	0.91	1.24	1.77	2.84	0.03	1.60	0.17	1.82	0.11	2.8	0.01	3.08	2.41	2.53	0.04	1.66
K_2O	0.19	0.20	0.31	0.27	0.01	0.17	0.1	0.02	0.02	0.64	0.01	0.05	0.08	0.01	0.07	0.07
P_2O_5	0.03	0.03				0.06		0.13	0.01	0.01	0.02	0.05	0.06	0.08	0.22	0.06
mg#	0.80	0.69	0.75	0.72	0.83	0.60	0.80	0.50	0.81	0.55	0.71	0.61	0.59	0.51	0.85	0.53
Rb	1	13	12	5	0	4	1	3	1	44	2	2	4	7	1	<5
Sr	21	37	210	295	7	102	3	112	30	125	21	99	75	159	3	109
Y	7	16	10	11	6	17	4	18	8	24	14	15	19	22	7	18
Zr	12	33	36	58	19	39	12	67	13	62	26	42	42	64	14	45
Nb	2	2	2	3	1	2.3	2	4	1	4.2	2		2	3.4	1	1.8
Ti	1162	3402	1996	1563	1653	4101	1380	6600	1283	7042	3238	4473	4030	6624	1740	5284
Ba	115	186	118	134	11	53	22	20	90	158	<100	163	<100	<30		<30
Cr	1035	2219	735	542	2170	414	3632	144	4501	366	1271	499	371	281	2527	400
Ni	1344	607	354	224	584	105		97	984	175	300	153	158	112	1437	145
Co	102	7	53	31		39		58	116	49		38				56
V	50	194	101	73		236			128	331		254	298	318		312
La			4.30	8.40	1.58	1.4	2.0	3.8	1.3	4			0.98	4.01	0.42	1.080
Ce			10.0	17.0	3.65	4.8	3.1	8.3		11			3.2	11.0	1.50	4.00
Nd			6.4	11	2.37		2	5.8	0.57	7.6	3.54	5.08	2.7	8.54		
Sm			1.39	1.3	0.75	1.54	0.82	2.0	0.21	2.67	1.09	1.65	1.32	2.85	0.496	1.740
Eu			0.53	0.41	0.19	0.544	0.3	0.67		0.7			0.51	1.04	0.186	0.700
Gd					0.85		1.0									2.58
Tb			0.21	0.19		0.36	0.18	0.49		0.64			0.36	0.71	0.116	0.40
Yb			0.61	0.57	0.7	1.4	0.88	2.2	0.72	2.4			1.3	1.9	0.420	1.62
Ti/Zr	97	103	55	27	86	105	115	99	99	114	125	107	96	104	124	117
Nb/Y	0.29	0.13	0.20	0.27	0.17	0.14	0.50	0.22	0.13	0.18			0.11	0.15	0.14	0.10
Zr/Y	1.7	2.1	3.6	5.3	3.2	2.29	3	3.7	1.6	2.6			2.21	2.91	2.00	2.50
Nb/La			0.47	0.36	0.63	1.64	1.0	1.05	0.77	1.05			2.04	0.85	2.38	1.67

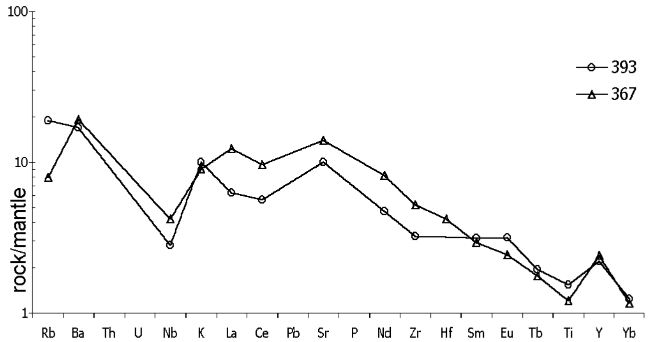


Figure 3. Spidergrams for gabbronorites and gabbrodiorites of the Lairuchei intrusion. Sample numbers on diagrams correspond to those in Table 2.

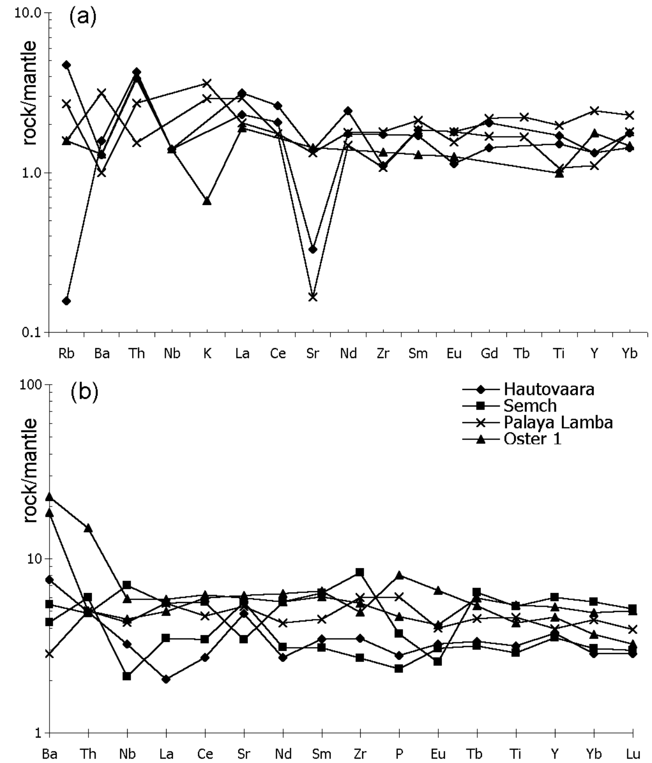


Figure 4. Spidergrams for komatiites (a) and high-temperature basalts (b) from greenstone belts of the western margin of the Vodlozero domain.

Mass balance calculations using major- and trace elements and AFC model calculations based on the (ε_{Nd}–La/Sm) ratio suggest melt generation conditions that involved 15% assimilation of the Lairuchei tonalite by a plume melt with mantle REE abundances [*Arestova,* 1997].

Another episode is represented by mafic–ultramafic volcanics of the western and eastern margins of the Vodlozero domain; it is dated at 2.96–2.94 Ga (Figure 1). Peridotitic komatiites with 24.8–29.6% MgO contents in spinifex textured varieties and 44.4–47.2% SiO_2 are found in all the greenstone belts (Table 2, nos. 5, 7, 9, 11). They belong to the silica-undepleted type (CaO/Al_2O_3 = 0.5–0.9, Al_2O_3/TiO_2 = 15–25) and are high in Ni (950–1450 ppm) and Cr (2000–4000 ppm). The komatiites have unfractionated REE patterns ($(La/Yb)_N = 1\pm0.1$, $(Gd/Yb)_N = 1\pm0.1$) and REE abundances 1.5–4 times the chondritic at $(Nb/La)_N$ of ca. 1 (Figure 4a). Less frequently, the komatiites are depleted in the light REE and have $(La/Yb)_N$ = 0.6–0.7, $(Gd/Yb)_N = 1$, and $(Nb/La)_N$ = 1–1.2. The $\varepsilon_{Nd}(t)$ value in komatiites from the western surroundings of the domain is +1.7, and from the eastern, +2.2. In the Hautavaara belt komatiites (the domain's western margin), Ni contents (650 ppm) are lower than in komatiites from the other belts. The Hautavaara komatiites are enriched in the light REE ($(La/Yb)_N = 1.3\pm0.1$ and $(Gd/Yb)_N = 0.9\pm0.1$) and have $(Nb/La)_N$ ratios of 0.5–0.7 and negative $\varepsilon_{Nd}(t)$ values; this set of evidence suggests crustal contamination for the komatiitic melt (Figure 4a).

Basalts found in the Oster, Palaya Lamba, and Hautavaara belts along the western margin the Vodlozero domain and in the Kenozero belt at its eastern margin, have different geochemical characteristics. Thus, basalts associated with komatiites have mantle Ti/Zr ratios (100–110), unfractionated REE patterns ($(La/Sm)_N$ = 1.0–0.9 and $(La/Yb)_N$ = 1.1–1.2), and REE abundances 7–14 times the chondritic (Table 2, nos. 6, 8, 10, 12; Figure 4b). The high Ni contents (>100–150 ppm), Nb/Y ratios in excess of 0.1, Zr/Y ratios of 2–3, and Nb/La = 0.9–1.11 of this basaltic group, are similar to those of oceanic plateau rocks. The $\varepsilon_{Nd}(t)$ value in high-temperature uncontaminated basalts ranges from +0.5 to +3.2, suggesting source heterogeneity and/or mixing of melts from depleted and undepleted sources.

Geochemical features of the Hautavaara belt komatiites and basalts (reduced Ni contents, La/Yb>1, Nb/La<0.8 (Table 2, nos. 5, 6)) imply that these rocks make part of a plateau generated on continental crust. Komatiites occurring in association with basalts at Palaya Lamba are also likely to represent a fragment of a plateau generated on continental crust. This is evidenced by the surviving low-angle attitudes of volcanic flow units and by the superimposed deformations (high angle schistosity related to the subsequent accretionary phase and, at the same time, conformable to bedding planes, as should be expected in an oceanic plateau obducted onto a continental margin).

Detailed studies performed in the Oster and Semch greenstone belts have shown that alongside basalts similar to those just described, these belts contain basalts whose chemical features and spatial association with andesites suggest an analogy with modern volcanics generated in island-arc and backarc basin settings (Figure 5). Later on, basalts that were generated in various geodynamic settings underwent tectonic juxtaposition, to form a collage.

At the northern margin of the Vodlozero domain, mafic-ultramafic volcanics are dated at 2913–2916 Ma [*Lobach-Zhuchenko et al.,* 1999; *Puchtel et al.,* 1999; *Sochevanov et al.,* 1991]. These volcanics occur in the Shilos and Kamennye Ozera bimodal greenstone belts. Komatiites are only encountered in the Kamennye Ozera belt, where they are

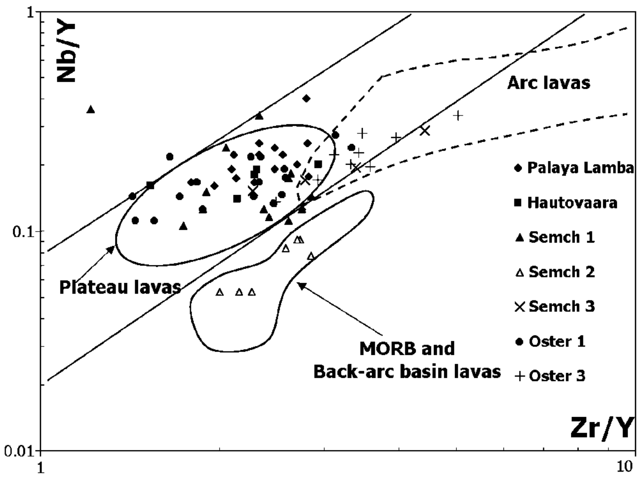


Figure 5. Zr/Y vs. Nb/Y plot for basalts from the western margin of the Vodlozero domain showing fields for basalts from various geodynamic settings, after [*Kerr et al.,* 2000].

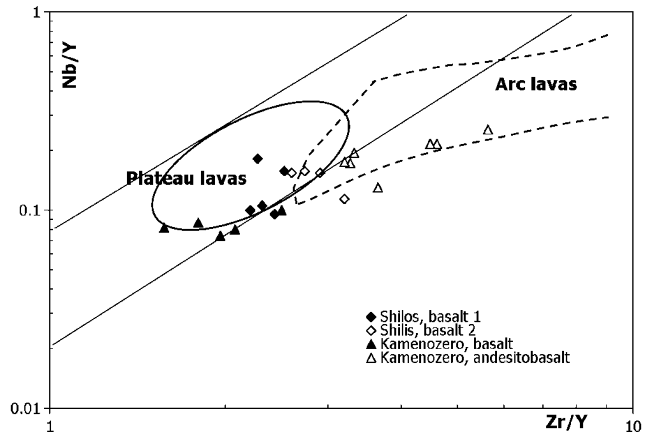


Figure 7. Zr/Y vs. Nb/Y plot for basalts from the northern margin of the Vodlozero domain showing fields for basalts from various geodynamic settings, after [*Kerr et al.,* 2000].

represented by peridotitic varieties that, where spinifex textured, show high MgO, Cr, and Ni contents (Table 2, no. 16). The komatiites are depleted in the light REE ($(La/Yb)_N$ = 0.6–0.7), their medium- and heavy REE contents corresponding to those of primitive mantle (Figure 6). The komatiitic $(Nb/La)_N$ ratio is 0.9–1.0, suggesting lack of crustal contamination of the melts. Geochemical characteristics of the komatiites testify to their having originated from high-temperature plume melts in oceanic or rifted continental margin settings.

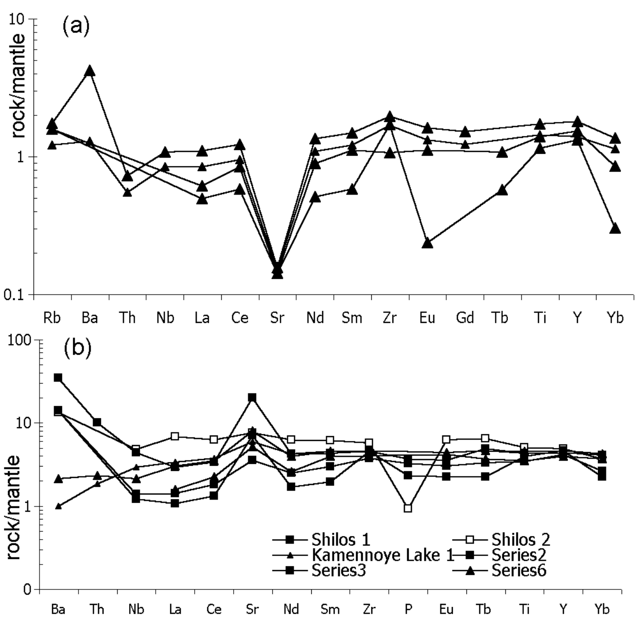


Figure 6. Spidergrams for komatiites (a) and high-temperature basalts (b) from greenstone belts of the northern margin of the Vodlozero domain.

Basalts of the northern margin have a broad range of compositions. In the Shilos belt, two basalt groups are discerned (Table 2, nos. 14, 15, Figure 6b). Both basaltic groups are high temperature rocks, considerable distinctions between them occur in their Ti and Zr abundances and REE enrichment degrees. Group 1 basalts are light REE depleted ($(La/Yb)_N = 0.5$–0.7, $(La/Sm)_N = 0.6$) and slightly HREE depleted ($(Tb/Yb)_N = 1.2$). Their REE contents are 2.5–3.5 times the primitive mantle (Figure 4b). Group 2 basalts have $(La/Yb)_N = 1.9$ and $(La/Sm)_N = 1$ and REE contents 6–8 times the PM values. Both basaltic groups lack evidence of crustal contamination; their $(Nb/La)_N$ ratio ranges of 0.8–1.5. The early stage tholeiites of the Kamennye Ozera greenstone belt (Table 2, nos. 17, 18) fall into groups with distinctive mg# (from 0.62 to 0.53) and high Cr and Ni abundances. These tholeiites are depleted in the light REE and show no crustal contamination, their $(Nb/La)_N$ ratio ranges of 0.8–1.7.

Geochemical characteristics of both basaltic sub-groups of the Shilos belt and early stage basalts of the Kamennye Ozera belt are consistent with those of modern oceanic plateaus or continent margin plateau basalts (Figure 7). The discrepancies in the $\varepsilon_{Nd}(2916)$ values of the Shilos basite isochron (+1.6) [*Sochevanov et al.,* 1991] and those of Kamennye Ozera (+2.7) [*Puchtel et al.,* 1999] are due to different isotope compositions of their initial melts and imply melt derivation from various parts of a heterogeneous source, which is feasible if melting occurs in the plume head.

Basites With 2.88–2.80 Ga Ages

The third episode of mafic magmatism, dated to the 2.88–2.81 Ga time interval, is recorded in various domains of the Fennoscandian shield (Figure 8). During this stage, komatiitic and basaltic eruptions took place in the Kola Peninsula (Polmos-Poros belt, Uraguba, and Korvatundra, dated at 2.88 Ga [*Vrevsky,* 2000]), in northern Karelia (early vol-

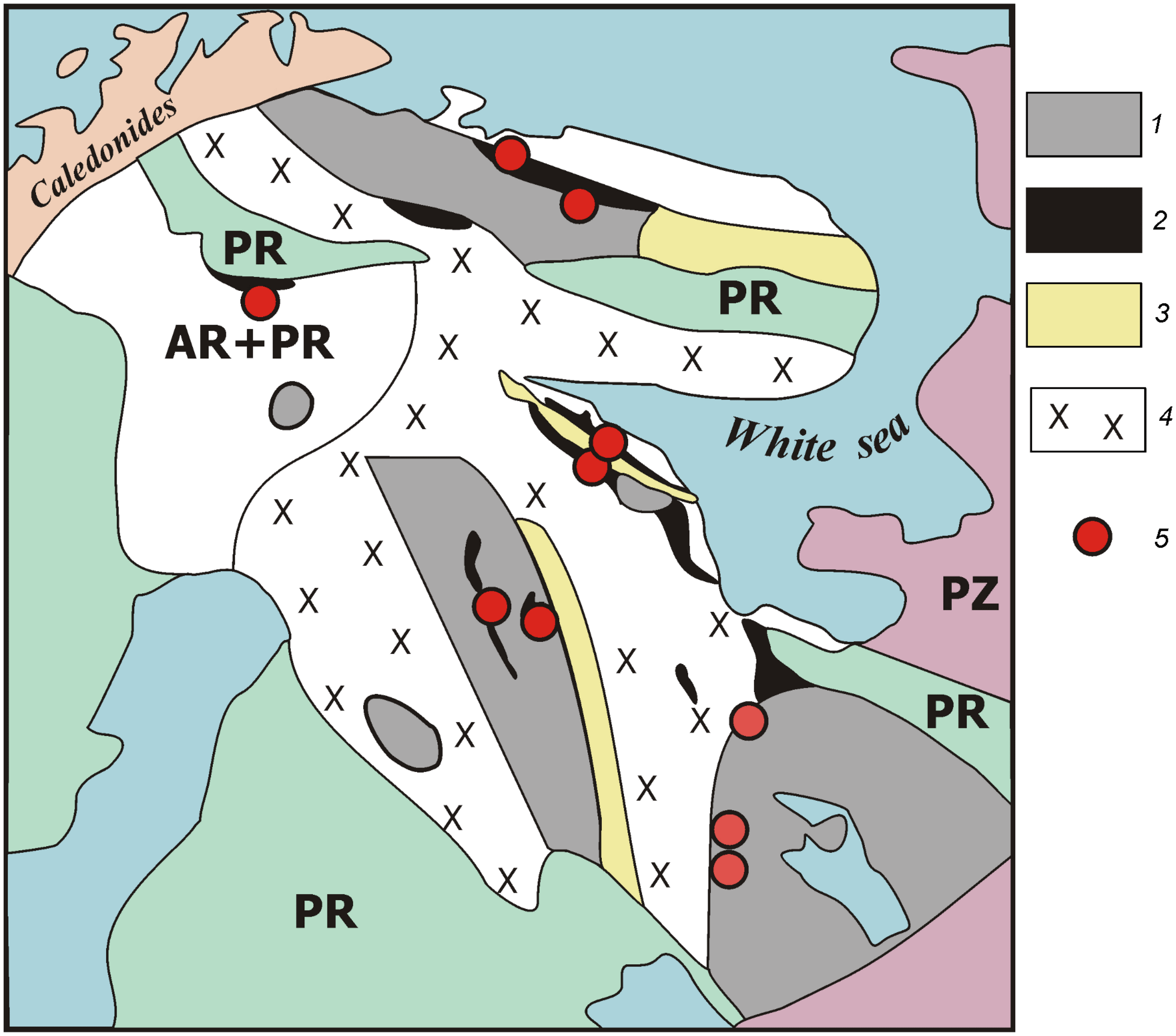


Figure 8. Sketch map of the Fennoscandian shield. 1 – ancient crustal domains with ages older than 2.9 Ga; 2 – greenstone belts with ages of 2.88–2.80 Ga; 3 – paragneissic belts; 4 – newly generated crust with an age of 2.85–2.74 Ga; 5 – basites dated at 2.88–2.80 Ga.

canism of the north Karelian system of greenstone belts, dated at >2.81 Ga [*Kozhevnikov,* 2000]), and in the western Karelian domain (Kostomuksha belt, dated at 2.84–2.81 Ga [*Lobach-Zhuchenko et al.,* 2000a; *Puchtel et al.,* 1998]). High-temperature peridotitic komatiites with 22–31% MgO and 44.4–47.2% SiO_2 (Table 3, nos. 1, 4–6) are present in all the belts of this particular stage. They belong to the undepleted or slightly silica-depleted type (CaO/Al_2O_3 = 0.6–0.9, Al_2O_3/TiO_2 = 15–25) and have high Ni (800–1600 ppm) and Cr (2000–4000 ppm) contents. Komatiites from most belts of this stage have unfractionated REE patterns ($(La/Yb)_N = 1\pm0.1$, $(Gd/Yb)_N = 1\pm0.1$), REE abundances 1.5–3 times the chondritic (Figure 9), and a $(Nb/La)_N$ ratio of ca. 1. Our own detailed study of komatiites from the Kostomuksha belt in the western Karelian domain shows them to be depleted in the light REE ($(La/Yb)_N$ = 0.4–0.6, $(Gd/Yb)_N$ = 1.04–1.16, and $(Nb/La)_N$ = 1–1.2). The $\varepsilon_{Nd}(t)$ value in the komatiites ranges from +2.7 to +2.9, pointing to generation of their initial melts from a depleted source and to lack of crustal contamination. Basalts of greenstone belts of this stage (Table 3, nos. 3, 7–9) have mantle Ti/Zr ratios (100–116), unfractionated REE patterns ($(La/Yb)_N$ = 1.0–0.9), and REE abundances 7–14 times the chondritic (Figure 9). The high Ni contents (75–135 ppm), the ratios of Nb/Y = 0.1 and Zr/Y = 2–2.5 (Figure 10), and Nb/La >1.0 are earmarks of rocks generated in oceanic or continental plateaus in the absence of crustal contamination. However, the basaltic sequence of the Kostomuksha green-

Table 3. Contents of major (%), trace, and rare-earth elements (ppm) in representative samples of high-temperature mafic rocks of the 2.88–2.80 Ga stage

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Samp. no.	576-4	576-6	574-2	737-2	82	91155	44	123	25	90	43	1	868a	1002	849	112
SiO_2	45.41	50.97	50.87	48.12	47.47	45.1	49.82	49.27	49.72	47.44	50.66	47.26	51.72	52.74	53.60	50.93
TiO_2	0.37	0.53	1.36	0.35	0.32	0.41	0.88	0.81	1.00	1.48	1.45	1.36	1.94	0.38	0.40	0.32
Al_2O_3	7.5	13.06	15.28	6.04	6.70	7.01	15.14	13.72	15.89	14.66	14.76	18.11	19.55	18.26	19.09	21.85
FeO	13.66	10.43	12.28	10.14	11.19	12.69	12.86	13.01	12.03	12.14	13.59	12.16	9.87	6.86	5.68	6.07
MnO	0.32	0.24	0.22	0.14	0.14	0.16	0.20	0.19	0.14	0.23	0.21	0.13	0.14	0.22	0.10	0.07
MgO	31.74	10.15	5.86	29.40	27.92	27.20	6.75	7.06	7.31	8.00	6.19	4.82	3.01	6.62	5.80	7.22
CaO	0.52	13.69	10.15	5.62	5.46	5.93	11.95	11.47	9.97	11.69	9.45	9.78	7.05	9.38	9.40	9.38
Na_2O	0.09	0.67	2.56	0.14	0.40	0.02	2.67	3.75	1.79	2.58	3.30	2.86	3.99	2.63	3.12	2.69
K_2O	0.02	0.26	1.23	0.04	0.16	0.02	0.23	0.35	0.20	0.18	0.17	0.72	0.74	0.48	0.51	0.75
P_2O_5	0.35		0.17	0.74	0.05	0.06	0.07	0.07	0.02	0.09	0.11	0.80	0.50	0.06	0.08	0.10
mg#	0.81	0.63	0.46	0.84	0.82	0.79	0.48	0.49	0.52	0.54	0.45	0.41	0.35	0.63	0.65	0.67
Rb	3	8	15		4	1.3	14	10	4	4	6	15	16	16	15	35
Sr	74	97	107		11	13.8	159	140	108	132	170	559	623	381	628	338
Y	5	12	30		8	9.6	20	25	22	29	28	16	22	12	15	13
Zr	19	24	69	20	20	24.5	52	50	55	75	83	69	176	57	60	36
Nb	1		3			0.768	2.5	2.5	3.8	4	3.5	4	10			5
Th	0.05		0.42			0.049	9	23	9							
Ti				2209	1814	2460	6043	4832	6000	7755	8677	7653	11589	2344	2987	2012
Cr	4537	697	262		3184	3812	323	269	274	245	151	37	26	287	178	165
Ni	844	172	75		1627	1167	123	117	135	77	74	13	16	143	84	90
Co	92	62	59		103	113	58	47			51		15			22
V	233	363	339		107	202	405	330			432	265	143	114	86	96
La	0.68		2.80	0.25		0.505	2.5	2.6	2.6	4.7	4.7					7.8
Ce	2.02		8.2	1.32		1.66		7.8	6.5	12	10	52.2	61.8	19.4	14.5	13
Nd	1.78		6	1.043	1.32	1.87	5.9	6.2	4.9	9.2	7.5	25.8	28.7	10.1	7.6	6.6
Sm	0.72		2.2	0.430	0.52	0.81	1.96	2.2	2.13	3.27	2.13	5.18	6.12	2.35	1.72	1.54
Eu	0.123		0.9	0.020		0.27		0.9	0.79	1.12	0.76	2.4	1.66	0.82	0.35	0.69
Gd	1.00		3	0.960		1.21										
Tb				0.130				0.56	0.53	0.79	0.51	0.57	0.73	0.36	0.3	0.32
Yb	0.74		2.3	0.58		0.834		1.69	2.3	3.2	2.2	0.95	1.24	0.84	0.72	0.82
Ti/Zr	98		116	110	91	100	116	97	109	103	105	111	66	41	50	56
Nb/Y	0.2		0.1		0	0.08	0.13	0.1	0.17	0.14	0.125	0.25	0.45			0.38
Zr/Y	3.8	2	2.3		2.5	2.55	2.6	2	2.5	2.59	2.964	4.31	8	4.75	4	2.77
Nb/La	1.47		1.07			1.52	1.0	0.96	1.46	0.85	0.745					0.64

stone belt, alongside uncontaminated basalts (Nb/La >1, $\varepsilon_{Nd}(t) = 2.9$), hosts basalts that probably suffered contamination (Table 3, nos. 10, 11), their $\varepsilon_{Nd}(t)$ value ranging from −3.1 to +0.9 [*Lobach-Zhuchenko et al.,* 2000a]. This implies that basalts of the Kostomuksha greenstone belt are plume-derived melts erupted in a volcanic rifted margin setting.

Intrusive mafic magmatism of the 2.85–2.84 Ga interval is recorded to have taken place on the western and northern margins of the Vodlozero domain, which had been formed through accretion. Mafic intrusives (the Semch, Palaya Lamba, and Shilos massifs; Table 3, nos. 12–16) have rather high SiO_2 contents at elevated (0.5–0.8) mg#, Ti/Zr ratios of 40–80, an evolved REE pattern ($(La/Yb)_N = 5–12$) (Figure 11), negative Nb anomaly ($(Nb/La)_N = 0.8–0.5$), and negative ε_{Nd} values (from −0.8 to −1.5), features that are suggestive of a variable degree of crustal contamination for the initial melts.

Basites With 2.72–2.66 Ga Ages

The Late Archean stage of mafic magmatism was less vigorous as compared to the preceding ones. It spans a ca. 2.72–2.66 Ga time interval. This stage is distinguished by moderate- and low-pressure granulite metamorphism first affecting a number of regions in southwestern and western Karelia (Lake Tulos, Lake Kuito), south-central Finland in the vicinity of Iisalmi (all the structures of the western Karelian domain), and between Lake Kovdozero and Lake Notozero in the Belomorian domain. Basites of this stage are chiefly developed in northern Karelia and the Belomorian region. They are represented by: the late-stage komatiites of the north Karelian group of belts (>2705 Ma) [*Shchipansky et al.,* 1999] and, apparently, of Finland [*Gruau et al.,* 1990; *Jahn et al.,* 1980]; the gabbronoritic and high-Ti, high-

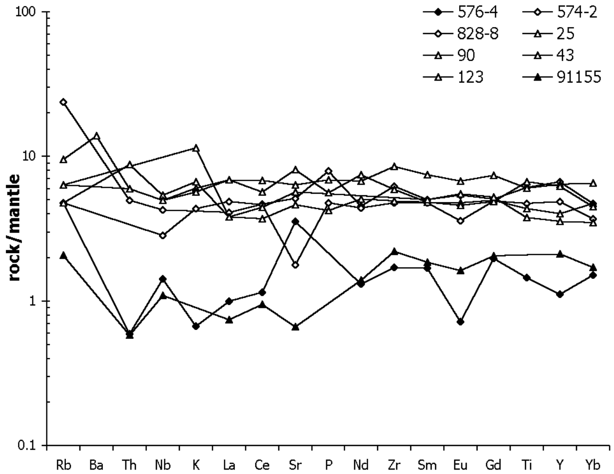


Figure 9. Spidergrams for komatiites and basalts of the 2.88–2.80 Ga stage. Sample numbers on diagrams correspond to those in Table 3.

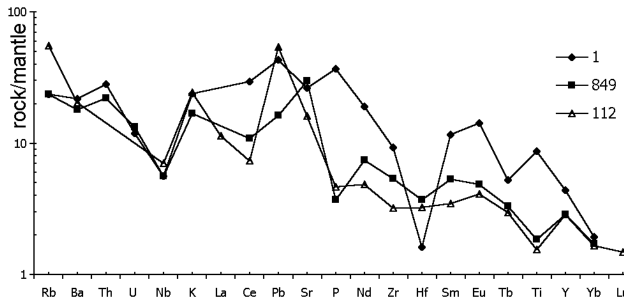


Figure 11. Spidergrams for intrusive basites of the 2.88–2.80 Ga stage.

Fe gabbroic intrusions dated at 2.69 Ga in the regions of Lake Notozero and the Tupaya Guba Bay of Lake Kovdozero [*Lobach-Zhuchenko et al.,* 1993, 1995]; and dikes developed throughout the shield (Figure 12; Table 4, nos. 1–5). Geochemical characteristics of both the volcanic and intrusive rocks alike (in particular, high Ni contents at high mg# of the rocks) testify to a plume related provenance for their initial melts [*Campbell and Griffiths,* 1992], whereas the elevated SiO_2 contents, evolved REE patterns, Ti/Zr ratios of 60–70, and negative Nb anomaly (Nb/La <1) (Figure 13) point to a considerable crustal contamination of initial melts for both the intrusive and volcanic rocks. Evidence for a

Late Archean plume within the Karelian province includes (besides the formation of high-temperature basites) the emplacement (in the 2.70–2.68 Ga time interval) of postorogenic intracratonic granitoid intrusions featured by high contents of HFS elements such as Y, Zr, Ti, and Nb [*Lobach-Zhuchenko,* 2002].

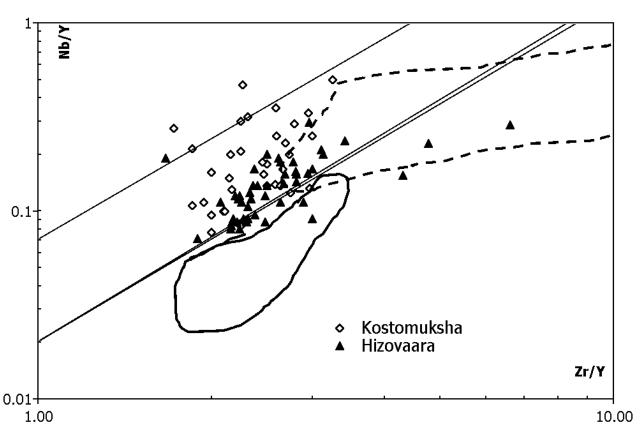


Figure 10. Zr/Y vs. Nb/Y plot for basaltic komatiites and basalts of the 2.88–2.80 Ga stage (Hizovaara and Kostomuksha greenstone belts).

It is open to discussion whether or not this particular age group includes the mafic–ultramafic volcanics from greenstone belts of eastern Finland. Not inconceivably, they belong to the preceding stage. Komatiites of these belts have the following compositional parameters: 22–27% MgO at 0.80–0.77 mg# and 9.5–19.8% MgO at 0.76–0.50 mg#; CaO/Al_2O_3 ratios of 0.72–0.87, Al_2O_3/TiO_2 = 16–17, and Ti/Zr = 110; and Ni contents of 800–1500 ppm and 300–650 ppm [*Gruau et al.,* 1990; *Jahn et al.,* 1980]. In this age group, komatiites make three sub-groups with dissimilar REE patterns: (1) light REE depleted ($(La/Sm)_N$ = 0.3–0.6 and $(Gd/Yb)_N$ of ca. 1.0); (2) with a flat REE pattern or a slight LREE enrichment ($(La/Sm)_N$ of ca. 1 and $(Gd/Yb)_N$ = 1.0–1.32); and (3) with REE abundances 1.5–2 times the mantle values and HREE depletion ($(La/Sm)_N$ = 0.7–0.95 and $(Gd/Yb)_N$ = 1.7–1.4). The basalts are also divisible into three groups: (1) uncontaminated, with Ti/Zr ratios of 100–110, (La/Sm) = 0.62, $(Gd/Yb)_N$ of ca. 1.0, $(La/Sm)_N$ of ca. 1.0–0.96, and $(La/Yb)_N$ of ca. 1.0, and with REE abundances 7–20 times the chondritic; (2) contaminated, with Ti/Zr = 70, $(La/Sm)_N$ of ca. 1.5–2, and $(La/Yb)_N$ of ca. 2–4; (3) subalkaline basalts with a high mg# (0.60), relatively high total alkali abundances (up to 6%) and Rb, and high Zr, P_2O_5, and REE. These rocks also have fractionated REE patterns ($(La/Sm)_N$ of ca. 4 and $(Gd/Yb)_N$ of ca. 4). The existence within the same greenstone structure of such a broad compositional variety of high-temperature volcanics is in good agreement with their plume origin and is not inconsistent with eruptions in a rifted continental margin setting.

Basites With 2.50–2.41 Ga Ages

The next stage of mafic-ultramafic magmatism belongs to the Early Proterozoic period and spans a 2.5–2.43 Ga time interval. Basites of this stage are widespread throughout the Fennoscandian shield and occur as both volcanic and intrusive varieties (Figure 14). These basites are represented by the layered intrusions of the Kola Peninsula, northern Karelia and Finland, Burakovskaya intrusion in southeastern Karelia, numerous drusite intrusions (coronitic gabbronorites) of the Belomorian region, and volcanics of the Vetreny belt and a number of smaller Sumian structures

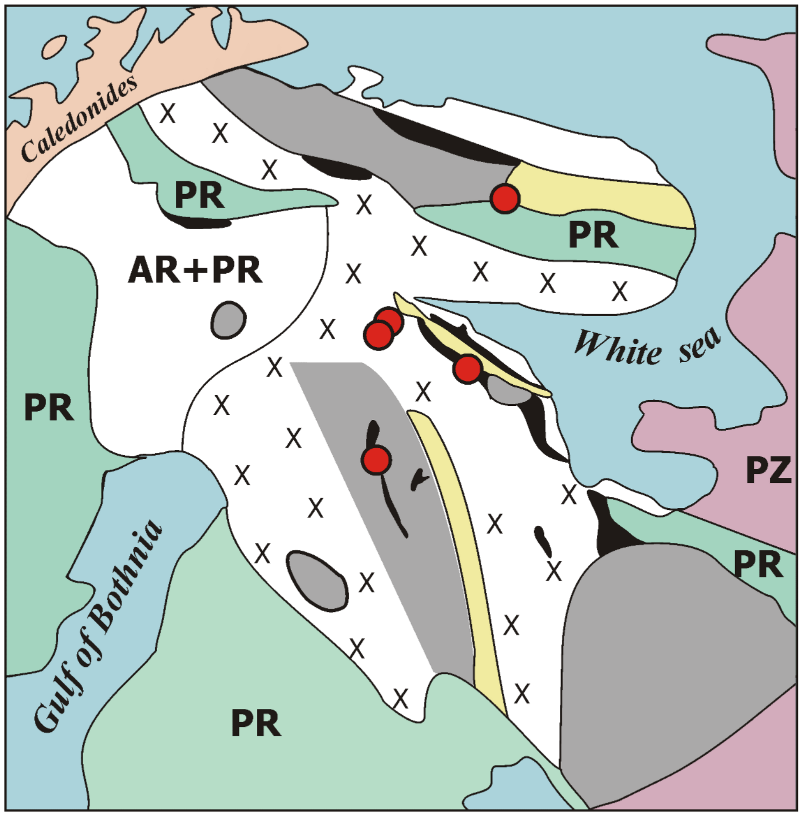


Figure 12. Sketch map of the Fennoscandian shield. Symbols, as in Figure 8. Red circles denote radiometrically dated basites with ages of 2.72–2.66 Ga.

in Karelia and the Kola Peninsula. In terms of geochemical and isotope characteristics, both the volcanic and intrusive basites of this age are closely similar (Table 4, nos. 6–16). All the basites of this group have elevated SiO_2 contents at increased MgO and high Ni abundances. Among all the rocks of this group, our most detailed studies were centered on the Belomorian drusites. Drusite composition plotted on variations diagrams show silica enrichment (SiO_2 2–4% higher than in Archean komatiites and basalts or in their later, Proterozoic counterparts; Figure 15), owing to which their initial melts are not infrequently referred to as being "boninite-like" [*Sharkov et al.,* 1994]. On most variations diagrams, the drusites fall into two suites: magnesian (mg# = 0.81–0.49) and high-Fe (mg# = 0.53–0.29), featured by contrasting differentiation trends. According to their MgO/TiO_2 ratios, the magnesian drusites plot in the komatiitic field, and the high-Fe ones, in the tholeiitic field (Figure 15). Drusites of the magnesian suite are dominant. They are typically high in Zr and have low Ti/Zr (50–80) and a high Zr/Y (3–6) ratios, as compared to the mantle. These rocks are high in Cr (130–3652 ppm) and Ni (up to 1300 ppm). In the high-Fe drusite suite, the Ti/Zr ratio ranges 60–140, and the Zr/Y ratio is similar to that in the magnesian drusites. Drusites of both suites are enriched in the light REE ($(La/Yb)_N$ = 5–10, $(La/Sm)_N$ = 2.5–3.5, and $(Gd/Yb)_N$ =1.2–2.0) (Figure 16), the total REE content in the high-Fe drusites being higher than in the magnesian ones. The drusites of both suites have negative Nb (Nb/La <1) and phosphorus anomalies and positive Pb anomaly, just like the crustal tonalites and gneisses. We interpret the contrasting chemistries of the drusites of the two suites within the same massif as evidence of cryptic layering, which is traceable even in the marginal portions of the massifs, where the drusites are turned to

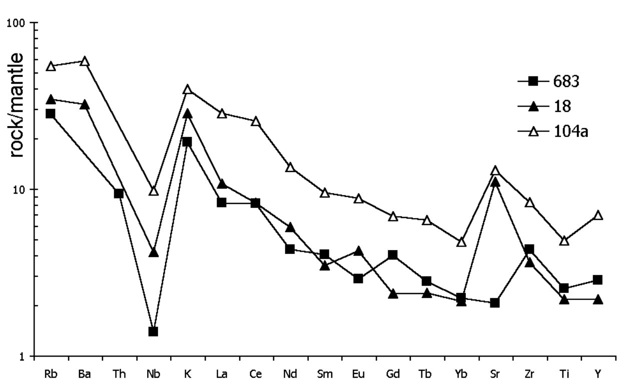


Figure 13. Spidergrams for komatiites and gabbronorites of northern Karelia of the 2.72–2.66 Ga stage. Sample numbers on diagrams correspond to those in Table 4.

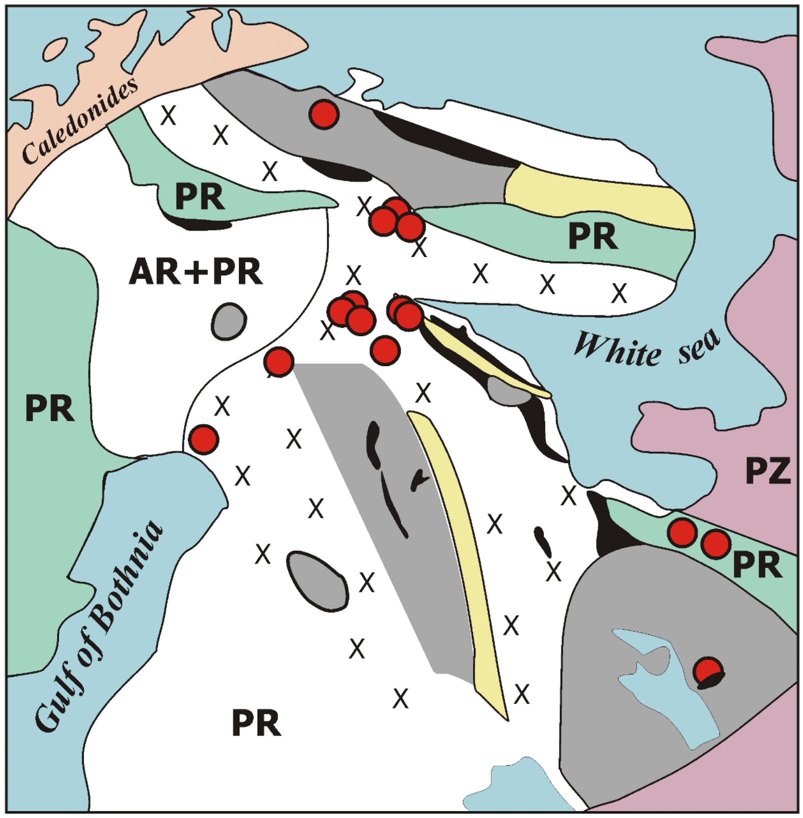


Figure 14. Sketch map of the Fennoscandian shield. Symbols, as in Figure 8. Red circles denote radiometrically dated basites with ages of 2.50–2.41 Ga.

garnet amphibolite. All the basites of this group (drusites, mafic rocks from layered intrusions, and volcanics) have ε_{Nd} values between 0 and −2.5 (Table 1).

Melts initial to the high-Mg rocks with elevated silica contents and low Ti/Zr ratios may have been generated in three ways: (1) melting of water saturated mantle wedge in subduction zones (boninite model), (2) assimilation of felsic crustal material by mantle melt, and (3) mixing of high-temperature plume melts with partial melts of depleted harzburgitic lithospheric mantle. The boninite model for drusite melt generation is at odds with the high TiO_2 contents and the low Al_2O_3/TiO_2 ratio. Besides, oxygen isotope composition data from igneous minerals in the drusites ($\delta^{18}O$ ranging 8–4) testify to their crystallization from dry melts [*Salye et al.,* 1983]. The fact that the drusites are light REE enriched and have high Ni (600 ppm or more) with at least 15% MgO is rather suggestive of a plume nature for their parental melt [*Campbell and Griffiths,* 1992].

We have presented quantitative model calculations that involve contamination of picritic or komatiitic melts by crustal material (Belomorian granite or biotite–garnet gneisses) (Figure 17) and mixing of an EM1 type enriched melt with a high-magnesian, high-silica melt derived from residual harzburgite mantle [*Lobach-Zhuchenko et al.,* 1998]. Mass balance calculations using both major and the rare earth elements allow for both processes. The low Nb/La ratio, assimilation and mixing calculations in the La/Sm – ε_{Nd} reference frame, and the ε_{Nd} variations and values in comparatively small massifs, all suggest that the most likely model is the one that invokes contamination of an undepleted plume melt by Late Archean crustal material.

Conclusions

Analyzing the timing, spatial position, and distribution of Early Precambrian basites throughout the Fennoscandian shield point to a number of regularities. Although it is impossible to establish the duration of the earliest radiometrically dated stage of mafic magmatism, it can be ascertained that each successive stage spans a time interval of 70–80 m.y. The early stages of high-temperature mafic magmatism (>3.1 and 2.99–2.91 Ga) are confined to the most ancient core of continental crust on the Fennoscandian shield; namely, the Vodlozero domain with crustal age of 3.2–3.4 Ga. The first long-lasting stage of mafic magmatism (2.99–2.91 Ga) took place following a pattern that is classical to a number of modern plumes, and in which the first occurrences of high-temperature plume magmatism emerge in

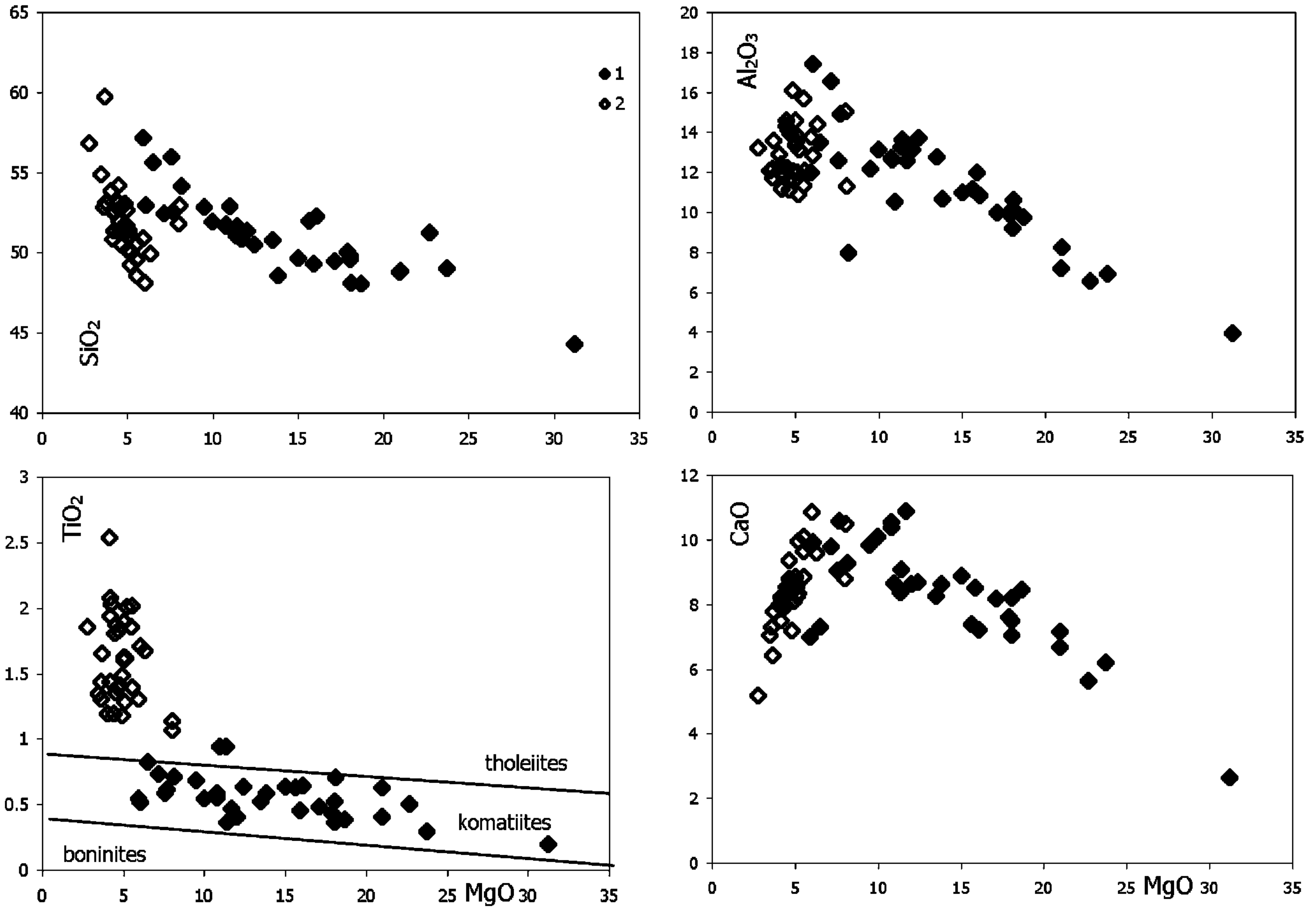


Figure 15. SiO_2 vs. MgO, TiO_2 vs. MgO, Al_2O_3 vs. MgO, and CaO vs. MgO variation diagrams for Belomorian basites (drusites) with ages of 2.50–2.41 Ga. 1 – drusites of the magnesian suite; 2 – drusites of the high-Fe suite.

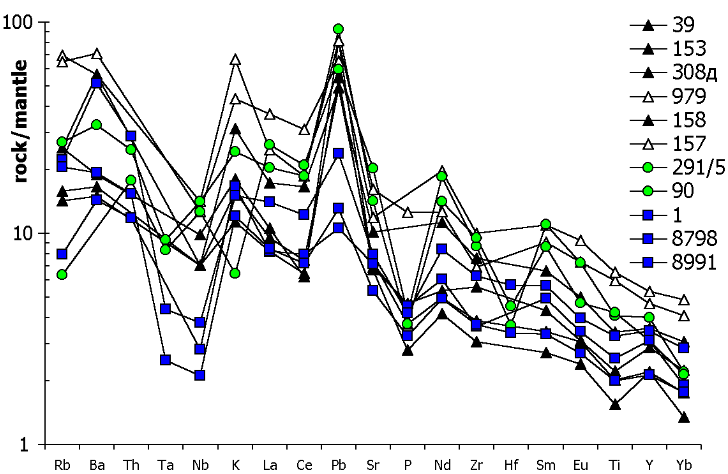


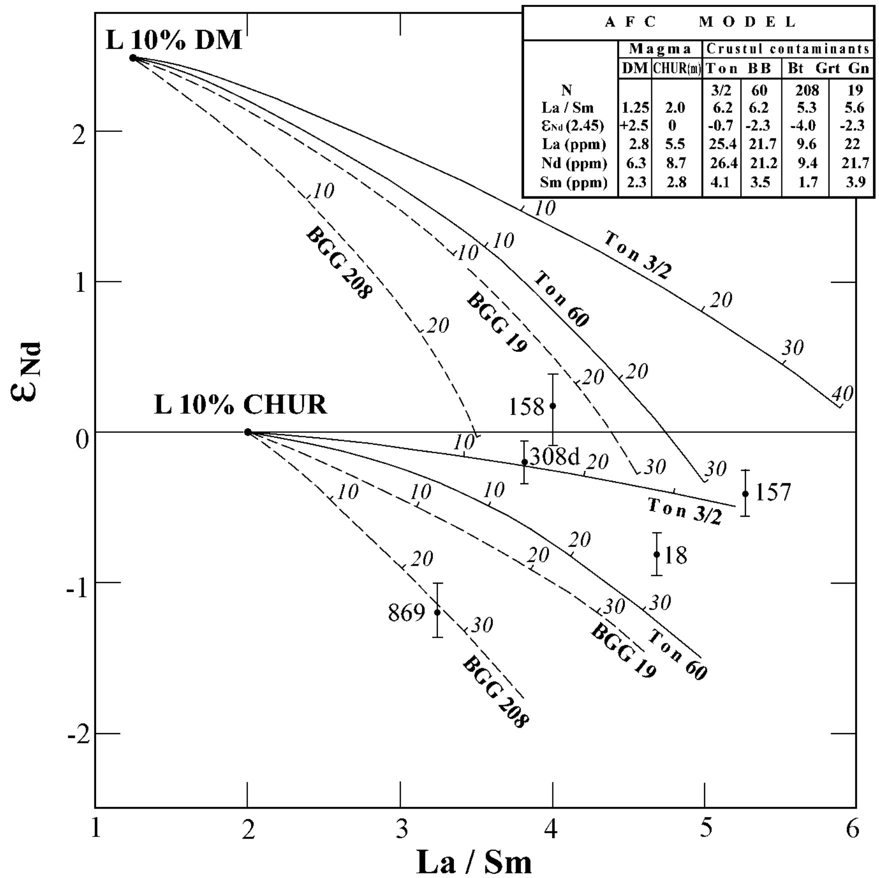
Figure 16. Spidergrams for 2.50–2.41 Ga komatiites and gabbronorites. Sample numbers on diagrams correspond to those in Table 4.

Table 4. Contents of major (%), trace, and rare-earth elements (ppm) in representative samples of high-temperature mafic rocks of the 2.72–2.66 Ga (1–5) and 2.50–2.41 Ga (6–16) stages

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Samp. no.	683 VK	18	104a	3v	212	238	39	153	308d	979	158	157	1	5	291-5	91
SiO_2	49.35	51.66	51.86		53.27	44.31	49.04	49.36	49.5	49.6	55.65	54.9	49.66	51.58	52.98	55.64
TiO_2	0.57	0.37	1.07		0.6	0.2	0.3	0.46	0.49	1.4	0.83	1.35	0.55	0.64	0.88	1.32
Al_2O_3	9.95	13.67	15.08		13.85	3.97	6.92	12.03	10.00	15.70	13.50	12.10	11.46	12.71	10.24	12.90
FeO	10.39	8.50	10.70		9.21	11.32	10.23	7.26	10.32	8.73	11.19	14.22	10.36	9.74	9.75	12.12
MnO	0.24	0.14	0.09		0.14	0.20	0.14	0.16	0.16	0.10	0.15	0.16	0.19	0.19	0.17	0.19
MgO	20.36	11.40	8.00		9.57	31.45	23.72	15.87	17.10	5.50	6.47	3.45	14.24	12.05	8.90	6.09
CaO	7.82	9.08	8.80		8.35	2.65	6.20	8.53	8.20	10.10	7.30	7.07	9.00	8.89	11.25	5.48
Na_2O	1.00	2.31	2.85		2.31	0.40	1.22	1.71	1.60	3.40	2.55	3.03	1.34	2.11	2.63	4.74
K_2O	0.23	0.86	1.20		0.63	0.29	0.34	0.47	0.54	2.00	0.95	1.48	0.51	0.39	0.20	1.39
P_2O_5	0.09	0.08	0.17		0.12	0.11	0.06	0.08	0.10	0.27	0.01	0.01	0.06	0.07	0.09	0.14
mg#	0.78	0.71	0.57		0.65	0.83	0.81	0.80	0.75	0.53	0.51	0.30	0.71	0.69	0.62	0.47
Rb	18	22	35	14	21	6	9	10	16	44	16	41	5		4	30
Sr	44	234	274	388	232	17	141	155	145	339	213	249	150		427	109
Y	13	10	23	16	13	3	10	10	13	21	16	24	14		18	15
Zr	49	41	94	97	51	22	34	43	62	77	85	111	40		97	140
Nb	1	3	7	7	3	7	5	5	7	10	5	9	2	2	7	10
Th	0.8	12	13	<5	<5	16	10	9	15	15	9	12			1.5	3
Ti	3420	2860	6416	13856	3781	980	2004	2604	2883	7729	4400	8418	3300	3840	5280	7032
Ba		226	413	134	452	50	104	115	132	393	333	494			226	221
Cr	2252	344	156	49	195	3652	2751	1730	1659	97	197	54	1600	1700	550	107
Ni	509	292	107	43	47	1289	1005	489	659	92	59	15	386	403	298	57
Co	78	50	43	304	128	100	90	63	63	35	75	51	47	56	43	43
V	209	138	226			41	109	136	147	200	290	494	210			201
La	5.7	7.42	19.6			2.45	5.6	6.5	7.2	17	11.8	25.9	5.7	8.52	18	
Ce	14.6	14.8	45.8			5.62	11.4	13.19	11.00	33.00	29.3	54.9	14	18	37	
Nd	5.9	8.03	18.2			3.2	5.6	6.65	7.20	17.00	15.1	26.6	2.1		25	
Sm	1.8	1.55	4.24			0.64	1.2	1.51	1.90	4.00	2.93	4.84	2.18	2.5	4.85	
Eu	0.49	0.72	1.48			0.21	0.4	0.51	0.52	1.22	0.83	1.55	0.57	0.84	1.21	
Gd	2.4	1.42	4.1			0.64	1.19	1.3			2.4	4.4		3.2	3.9	
Tb		0.26	0.71			0.09	0.11	0.22	0.31	0.65	0.38	0.71	0.405	0.44	0.51	
Yb	1.1	1.05	2.39			0.4	0.66	0.86	1.10	2.00	1.5	2.38	0.88	0.62	1.07	
Ti/Zr	70	70	68	143	74	45	59	61	47	100	52	76	83		54	50
Nb/La	0.18	0.40	0.36			2.86	0.89	0.77	0.97	0.59	0.42	0.35	0.35	0.23	0.39	

the central part of the continent, and subsequent ones, in its marginal parts. In the case in point, such first occurrence is the Lairuchei intrusion (2.99 Ga, in the central part of the Vodlozero domain) with the subsequent komatiite and high-temperature basalt volcanism along the western and eastern margins of the domain (2.94–2.96 Ga) and, possibly, at its northern margin (2.91 Ga). In all likelihood, beneath the Vodlozero domain there existed a deep seated plume (super-plume, or a first order plume, to use the terminology of Dobretsov and co-workers) that was rising from the interface between the core and the lower mantle. This particular inference is favored by the fact that the Nd isotope characteristics of a number of komatiites and mafic intrusions are explicable assuming mixing of melts derived from undepleted and depleted mantle sources or contamination of an undepleted mantle melt by crustal material. The rising mantle plume generated rift structures near the boundary and at the margins of the Vodlozero domain. Brittle deformations that caused rifting related to the rising mantle plume did not result in breakup of the newly formed continental crust. The dominant values of model Nd ages (T_{DM}) in the 2.9–3.0 Ga time interval, obtained from rocks derivative from basalts that make up the younger domains [*Lobach-Zhuchenko et al.,* 2000a, 2000b], suggest that basalts of this age were developed over a significant area outside the Vodlozero domain.

The next stage of high-temperature mafic magmatism (2.88–2.80 Ga) is expressed within the Kola and western Karelian domains with crustal ages of 3.0 and 3.1 Ga and on the north of the younger, central Karelian domain. Generation of komatiites and high-temperature tholeiite lavas in these domains provides evidence of a super-plume that ascended within these domains. The ascent of this plume initiated rifts beneath the continental crust of the Kola and western Karelian domains and beneath the oceanic plateau



	Magma		Crustul contaminants			
	DM	CHUR(m)	Ton	BB	Bt Grt	Gn
N			3/2	60	208	19
La / Sm	1.25	2.0	6.2	6.2	5.3	5.6
ε_{Nd} (2.45)	+2.5	0	-0.7	-2.3	-4.0	-2.3
La (ppm)	2.8	5.5	25.4	21.7	9.6	22
Nd (ppm)	6.3	8.7	26.4	21.2	9.4	21.7
Sm (ppm)	2.3	2.8	4.1	3.5	1.7	3.9

Figure 17. AFC model [*DePaolo,* 1981] in the La/Sm–$\varepsilon_{\rm Nd}$. plane. The calculations assume (A) 10% melt assimilating depleted mantle with $\varepsilon_{\rm Nd}(2.45) = +2.5$ and (B) 10% CHUR melt assimilating crustal rock. Contaminants are Belomorian tonalite samples with a 2.75 Ga zircon age and Chupa Formation gneiss samples the with a 2.85 Ga zircon age. Geochemical characteristics of the samples are given in [*Lobach-Zhuchenko et al.,* 1998].

in the northern part of what is now the central Karelian domain. According to [*Vrevsky,* 2000], the higher liquidus temperatures for the komatiites from greenstone belts of the Kola domain and the greater depth of generation of their initial melts, as compared to the liquidus temperatures for the older komatiites from the Vodlozero domain, should imply a higher ascent for the early plume.

As the deep mantle plume ascended beneath the northern to northwestern part of the shield, its south-southeastern part (namely, the northwest margin of the Vodlozero domain) provided the stage for extensive development of mafic magmatism and granitoids with ages of 2.85–2.80 Ga, whose generation is attributed to underplating [*Lobach-Zhuchenko et al.,* 1999]. These facts suggest the existence, in parallel to the superplume, of another plume that may have been less deep seated, and that was initiated at the interface between the lower mantle and the upper mantle, inasmuch as this magmatism immediately postdated the termination of subduction processes at the western margin of the Vodlozero domain. The ascent of this mantle plume may have been triggered by mantle slab sinking to the interface between the lower mantle and the upper mantle.

The last of the Archean stages of high-temperature mafic magmatism with ages of 2.72–2.66 Ga occurs in the north Karelian belts, in the Karelian part of the Belomorian area (the regions of Lake Notozero and the Tupaya Guba Bay of Lake Kovdozero) and, possibly, in the western Karelian domain. This magmatism took place also immediately after the subduction processes at the boundary of the Karelian and Belomorian domains. Accordingly, the mantle plume that ensured generation of high-temperature mafic melts, rose from the interface between the lower mantle and the upper mantle immediately following the end of the subduction processes. The majority of high-temperature melts, of both volcanic and plutonic provenance alike, suffered crustal contamination, which points to the existence of thick continental crust.

Early Proterozoic high-temperature mafic magmatism at

2.50–2.41 Ga was the most extensive areally and the longest lasting on the Fennoscandian shield. Nearly all the researchers of high-temperature basites of this stage attribute this magmatism to the ascent of an extensive deep superplume [*Amelin and Semenov,* 1996; *Arestova and Lobach-Zhuchenko,* 1996; *Hanski et al.,* 2001; *Lobach-Zhuchenko et al.,* 1998; *Puchtel et al.,* 1997; etc.]. Circumstantial evidence for the existence, in the 2.5–2.41 Ga time interval, of a long lived heat source that occupied virtually the entire area of what is now the Fennoscandian shield may be provided by paleomagnetic data. Nearly all the Archean basites measured yielded an additional magnetic component, whose age is estimated at 2.5–2.45 Ga [*Arestova et al.,* 1999, 2000]. A hallmark of the mafic rocks of this stage is that all the volcanic and plutonic varieties without exception show varying degrees of crustal contamination, which is a further evidence that by the beginning of the Early Proterozoic there had been formed a thick continental crust, probably continuous beneath the entire eastern (Archean) part of the Fennoscandian shield.

Our analysis of the spatial position, timing, distribution, and geochemical characteristics of the high-temperature Early Precambrian basites of the Baltic shield suggests the following conclusions:

1. In the Early Precambrian of the Baltic shield (3.4–2.4 Ga), established are five stages of high-temperature mafic–ultramafic magmatism, most of which is attributable to the action of the plume-tectonic mechanism that ensured the inflow of lower mantle material and heat to cause melting in the upper mantle and crust.

2. The plume-derived high-temperature komatiitic melts, showing no crustal contamination and originating from depleted sources, are heterogeneous in terms of their Nd isotope compositions; accordingly, they either are derivatives from second-order plumes or result from mixing of plume material and plume-entrained portions of depleted upper mantle.

3. The plume-derived melts intruded both the newly formed continental crust and surviving oceanic crust, giving rise to deep-seated intrusions in the rather thick continental crust and to volcanics in continental and oceanic plateau settings. As a rule, intraplate rifting occurred in marginal parts of the sialic domains.

4. The process of interaction between initial mafic melts and crustal material (plume-crustal interaction) is established starting from the second recorded stage of mafic–ultramafic magmatism.

5. With increasing thickness of the continental crust of the Baltic shield, the degree of crustal contamination of mafic melts became progressively higher, to reach a maximum at the end of the Archean and beginning of the Proterozoic, during the fourth and, especially, the fifth stage of magmatism.

Acknowledgments. This work was supported by the Russian Foundation for Basic Research (project nos. 01-05-64930 and 02-05-65052).

References

Abbot, D., Plumes and hotspots as sources of greenstone belts, *Lithos, 37,* 113–127, 2001.

Abbott D. Plumes and hotspots as sources of greenstone belts, *Lithos 37,* 113–127, 2001

Alapieti, T., The Koilismaa layered igneous complex, Finland — its structure, mineralogy and geochemistry, with special emphasis on the distribution of chromium, *Geol. Surv. Finl. Bull., 319,* 1–116, 1982.

Amelin, Yu. V., and V. S. Semenov, Neodymium isotopic geochemistry of mafic layered intrusions in the eastern Baltic Shield: Implications for the evolution of Paleoproterozoic continental mafic magmas, *Contrib. Mineral. Petrol., 124,* 255–272, 1996.

Amelin, Yu. V., L. M. Heaman, and V. S. Semenov, U–Pb geochronology of layered mafic intrusions in the eastern Baltic Shield: implication for the timing and duration of Palaeoproterozoic continental rifting, *Precambrian Res., 75,* 31–46, 1995.

Arestova, N. A., Petrology of the Archean Lai-ruchei Creek layered mafic intrusion, Vodlozero block (SE Karelia), in *The Precambrian of Northern Eurasia,* Abstracts, St. Petersburg, Institute of Precambrian Geology and Geochronology, 4, 1997.

Arestova, N. A., E. G. Gooskova, and A. F. Krasnova, Palaeomagnetic study of the Palaeopreterozoic (2.4–2.5 Ga) basites of the Baltic Shield and some geotectonics conclusions, *Docl. RAS 366,* (6), 781–784. 1999

Arestova, N. A., and V. A. Glebovitsky, Mafic rocks of the 2.46–2.41 Ga stage. The Belomorian block, in *Early Precambrian of the Baltic shield,* edited by V. A. Glebovitsky, St. Petersburg, 2003 (in press).

Arestova, N. A., and S. B. Lobach-Zhuchenko, Comparison of Early Proterozoic (2.4–2.5 Ga) basites from various Archean segments of the Baltic shield and certain petrogenetic implications, in *Correlation of Fennoscandian Geologic Assemblages,* Abstract of the 1st International Conference, 2–3, St. Petersburg, 1996.

Arestova, N., E. Gus'kova, and A. Krasnova, Paleomagnetism of rocks of the Shilos structure of the Southern Vygozero greenstone belt, eastern Karelia (in Russian), *Fiz. Zemli, 5,* 70–75, 2000.

Bayanova, T. B., and F. P. Mitrofanov, Duration and timing of ore-bearing Paleoproterozoic intrusions of Kola province, in *Early Precambrian: genesis end evolution of continental crust,* Abstract of an International Conference, 10–12, 1999.

Bayanova, T. B., N. V. Levkovich, and L. V. Ivanova, U–Pb age of the Imandra layered intrusion, Kola Peninsula, Materials of the IX scientific conference of young scientists, in *Geology of the Baltic shield and other Precambrian provinces of Russia,* pp. 25–29, Apatity, 1995.

Bayanova, T., V. Smol'kin, N. Levkovich, and G. Ryunganen, U-Pb age of the Mt. General'skaya layered intrusion, Kola Peninsula (in Russian), *Geokhimiya, 1,* 3–13, 1999.

Bibikova, E., A. Slabunov, A. Bogdanova, V. Stepanov, and E. Borisova, Early magmatism of the Belomorian mobile belt, Baltic shield: Lateral zonation and isotope age (in Russian), *Petrologiya, 7,* 115–140, 1999.

Bogdanova, S. V., and E. V. Bibikova, The "Saamian" of the Belomorian mobile belt: new geochronological constraints, *Precambrian Res., 64,* 131–152, 1993.

Buiko, A., O. Levchenkov, S. Turchenko, and E. Drubetskoi, Geology and radiometric dating of the Early Proterozoic Sumian–Sariolian assemblage of northern Karelia (Panajarvi–Tsipringa structure) (in Russian), *Stratigr. Geol. Korrelyatsiya, 3,* (4), 16–30, 1995.

Campbell, T. H., and R. W. Griffiths, Implication of mantle plume structure for the evolution of flood basalts, *Earth Planet. Sci. Lett., 99,* 79–93, 1990.

Campbell, T. H., and R. W. Griffiths, The changing nature of mantle hotspots through time: implication for the chemical evolution of the mantle, *J. Geol., 100,* 497–523, 1992.

Chekulaev, V., S. Lobach-Zhuchenko, N. Arestova, N. Guseva, A. Kovalenko, and I. Krylov, Archean magmatism of the northwestern margin of the ancient Vodlozero domain, the region of Lake Oster, Karelia (Geology, geochemistry, petrology) (in Russian), *Petrologiya, 10,* (2), 146–164, 2002.

Chekulaev, V. P., N. A. Arestova, A. V. Kovalenko, and A. I. Slabunov, Karelian granite-greenstone region. Central Karelian domain, *The Early Precambrian of the Baltic Shield* (in Russian), Ed. V. A. Glebovitsky, Nauka, St. Petersbug, 2003.

Condie, C. K., *Mantle plumes and their record in Earth history,* 306 pp., Cambridge University Press, 2001.

DePaolo, D. J., 1. Trace element and isotopic effect of combined wallrock assimilations and fractional crystallization, *Earth Planet. Sci. Lett., 53,* 189–202, 1981.

DePaolo, D. J., *Neodymium isotope geochemistry,* 187 pp., Springer-Verlag, Berlin, 1988.

Devias, G. F., The mantle dynamical repertoire: plates, plumes, overturns and tectonic evolution, *J. Austral. Geol. Geophys., 17,* (1), 93–99, 1997.

Dobretsov, N. L., A. G. Kirdyashkin, and A. A. Kirdyashkin, *Deep Seated Geodynamics,* 410 pp., Siberian Division of the Russian Academy of Sciences, Novosibirsk, 2001.

Efimov, A. A., and T. V. Kaulina, Geologic features and U-Pb dating (pioneering data) of rocks of the southeastern part of the Lake Kovdozero gabbro–peridotite assemblage, in *The Belomorian Mobile Belt: Geology, Geodynamics, Geochronology,* p. 31, abstracts of an International Conference, Inst. Geol., Karelian Sci. Center, Petrozavodsk, 1997.

Gaal, G., A. Mikkola, and B. Soderholm, Evolution of the Archaean crust of Finland, *Precambrian Res., 6,* 199–215, 1976.

Grachev, A., The Khamar-Daban Range: A hot spot of the Baikalian rift (Evidence from chemical geodynamics) (in Russian), *Fiz. Zemli, 3,* 3–28, 1998.

Grachev, A., Mantle plumes and the issues of geodynamics (in Russian), *Fiz. Zemli, 4,* 3–37, 2000.

Gruau, G., C. Chauvel, N. T. Arndt, and J. Cornichet, Aluminium depletion in komatiites and garnet fractionation in the early Archaean mantle: hafnium isotope constraints, *Geochim. Cosmochim. Acta, 54,* 3095–3101, 1990.

Hanski, E., R. J. Walker, H. Huhma, and I. Suominen, The Os and Nd isotopic systematics of c. 2.44 Ga Akanvaara and Koitelainen mafic layered intrusions in northern Finland, *Precambrian Research, 109,* 73–102, 2001.

Huhma, H., R. A. Cliff, V. Perttunen, and M. Sakko, Sm-Nd and Pb isotopic study of mafic rocks associated with early Proterozoic continental rifting: the Peraphja schist belt in Northern Finland, *Contrib. Mineral. Petrol., 104,* 369–379. 1990.

Jahn, B. M., B. Auvray, S. Blais, R. Capdevila, J. Cornichet, F. Vidal, and J. Hameurt, Trace element Geochemistry and Petrogenesis of Finnish Greenstone Belts, *J. Petrol., 21,* (2), 201–244, 1980.

Kerr, A. C., R. V. White, and A. D. Saunders, LIP reading: recognizing oceanic plateaux in the geological record, *J. Petrol, 41,* (7), 1041–1055, 2000.

Kozhevnikov, V. N., *The forming conditions of the structure-methamorphic paragenesis of precambrian rocks,* 184 pp., Nauka, Leningrad, 1982.

Kozhevnikov, V. N., *Archean Greenstone Belts of the Karelian Craton,* 223 pp., Karel. Sci. Center, Russ. Acad. Sci., 2000.

Kudryashov, N. M., and V. V. Balagansky, Age of the Zhemchuzhnyi drusite massif, Belomorian region, Russia: U-Pb isotope data and geologic implications, in *Rifting, Magmatism, and Metallogeny of the Precambrian,* Correlation of Fennoscandian Geologic Assemblages, Materials of an International Conference, pp. 78–79, Inst. Geol. Karel. Sci. Center, Russ. Acad. Sci., Petrozavodsk, 1999.

Kudryashov, N. M., and B. V. Gavrilenko, Geochronology of the Kolmozero–Voronya greenstone belt and its surroundings (Kola Peninsula), in *Isotope Dating of Geologic Processes: New Methods and Results* (abstract), Inst. Geol. Ore Deposits, Moscow, 196–198, 2000.

Kulikova, V. V., *The Volotskaya Formation: The Stratotype of the Lower Archean of the Baltic Shield,* 254 pp., Karel. Sci. Center, Petrozavodsk, 1993.

Kumazava, M., and S. Maruyama, Whole earth tectonics, *J. Geol. Soc. Japan, 100,* (1), 81–102, 1994.

Lobach-Zhuchenko, S. B., *Tectonics and Geophysics of the Lithosphere,* pp. 26–42, 302–305, Moscow, 2002.

Lobach-Zhuchenko, S. B., and O. A. Levchenkov, New data on the geochronology of Karelia, in *Isotope Methods and the Issues of Geology of the Precambrian of Karelia,* pp. 5–26, Petrozavodsk, 1985.

Lobach-Zhuchenko, S., E. Bibikova, G. Drugova, B. Belyatsky, T. Gracheva, T. Amelin, and V. Matrenichev, Geochronology and petrology of the Tupaya Guba Bay magmatic assemblage, northwestern Belomorian region (in Russian), *Petrologiya, 1,* (6), 657–677, 1993.

Lobach-Zhuchenko S. B., V. P. Chekulaev, S. A. Sergeev, O. A. Levchenkov, and I. N. Krylov, Archaean rocks from southeastern Karelia (Karelian granite greenstone terrain), *Precambrian Research, 62,* 375–397, 1993.

Lobach-Zhuchenko, S., E. Bibikova, G. Drugova, O. Volodichev, V. Chekulaev, I. Krylov, T. Grachev, and V. Makarov, Archean magmatism of the Lake Notozero region, northwestern Belomorian domain: isotope geochronology and petrology (in Russian), *Petrologiya, 3,* (6), 593–621, 1995.

Lobach-Zhuchenko, S. B., N. A. Arestova, V. P. Chekulaev, L. K. Levsky, E. S. Bogomolov, and I. N. Krylov, Geochemistry and petrology of 2.40–2.45 Ga magmatic rocks in the north-western Belomorian Belt, Fennoscandian Shield, Russia, *Precambrian Research, 92,* 223–250, 1998.

Lobach-Zhuchenko, S., N. Arestova, V. Chekulaev, O. Levchenkov, I. Krylov, L. Levsky, E. Bogomolov, and A. Kovalenko, Evolution of the southern Vygozero greenstone belt, Karelia (in Russian), *Petrologiya, 7,* (2), 156–173, 1999.

Lobach-Zhuchenko, S., N. Arestova, R. Milkevich, O. Levchenkov, and S. Sergeev, The stratigraphic section of the Kostomuksha structure, Karelia (Upper Archean): Reconstructions based on geochronology, geochemical, and isotope data (in Russian), *Stratigr. Geol. Korrelyatsiya, 8,* (4), 2000a.

Lobach-Zhuchenko, S., V. Chekulaev, N. Arestova, L. Levsky, and A. Kovalenko, Archean terranes of Karelia: A geologic and isotope geochemical validation (in Russian), *Geotektonika, 6,* 26–42, 2000b.

Lobach-Zhuchenko, S. B., N. A. Arestova, A. B. Vrevsky, V. P. Chekulaev, Formation of the ancient (3.20–2.85 Ga) terranes of the Baltic Shield, Materials of scientific. Conference (in Russian), *Supercontinents in geological development of Precambrian,* pp. 140–143, Irkutsk, 2001.

Lobach-Zhuchenko, S. B., N. A. Arestova, and A. V. Kovalenko, Karelian granite–greenstone region: Vodlozero domain, in *The Early Precambrian of the Baltic Shield,* edited by V. A. Glebovitsky, St. Petersburg, 2002 (in press).

Marzoli, A., E. M. Piccirillo, P. R. Renne, G. Bellieni, M. Iacumin, J. B. Nyobe, and A. T. Tongwa, The Cameroon volcanic line reversed: petrogenesis of continental basaltic magmas from lithospheric and asthenospheric mantle sources, *J. Petrol., 41,* (1), 87–109, 2000.

Maruyama, S., M. Kumasazawa, and S-i Kawakami, Towards a new paradigm on Earth's dynamics, *J. Geol. Soc. Japan, 100,* (1), 1–3, 1994.

Maruyama, S., Plume tectonics, *J. Geol. Soc. Japan, 100,* (1), 24–49, 1994.

Mitrofanov, F., V. Balagansky, Yu. Balashov, L. Ganiball, V. Dokuchaeva, L. Nerovich, and G. Ryunganen, U-Pb age of gabbro-anorthosites of the Kola Peninsula, *Dokl. Ross. Akad. Nauk, 331,* 95–97, 1993.

Morgan, W. J., Convection plumes in the lower mantle, *Nature, 230,* 42–45, 1971.

Nisbet, E. G., M. J. Cheadle, N. T. Arndt, and M. J. Bickle, Constraining the potential temperature of the Archaean mantle: A review of the evidence from komatiites, *Lithos, 30,* (3–4), 291–307, 1993.

Patchett, P. J., O. Kouvo, C. E. Hedge, and M. Tatsumoto, Evolution of continental crust end mantle heterogeneity: evidence from Hf isotopes, *Contrib. Mineral. Petrol., 78,* 279–297, 1981.

Puchtel, I., D. Zhuravlev, V. Kulikova, A. Samsonov, and A. Simon, Komatiites of the Vodlozero block (Baltic shield) (in Russian), *Dokl. Akad. Nauk SSSR, 317,* (1), 197–202, 1991.

Puchtel, I. S., K. M. Haase, A. W. Hofmann, C. Chauvel, V. S. Kulikov, C.-D. Garbe-Schonberg, and A. A. Nemchin, Petrology and geochemistry of crustally contaminated komatiitic basalts from the Vetreny Belt, southeastern Baltic Shield: Evidence for an early Proterozoic mantle plume beneath rifted Archean continental lithosphere, *Geochim. Cosmochim. Acta, 61,* 1205–1222, 1997.

Puchtel, I. S., A. W. Hofman, A. W. Mezger, K. R. Jochum, A. A. Shchipansky, and A. V. Samsonov, Oceanic plateau model for continental crustal growth in the Archaean: A case study from the Kostomuksha greenstone belt, NW Baltic Shield, *Earth Plan. Sci. Lett., 155,* 57–74, 1998.

Puchtel, I. S., A. W. Hofman, Yu. V. Amelin, C.-D. Garbe-Schonberg, A. V. Samsonov, and A. A. Shchipansky, Combined mantle plume–island arc model for the formation of the 2.9 Ga Sumozero-Kenozrero greenstone belt, SE Baltic Shield: isotope and trace element constraints, *Geochim. Cosmochim. Acta, 63,* (21), 3579–3595, 1999.

Richter, F. M., A major change in the thermal state of the Earth at the Archean-Proterozoic boundary: consequences for the nature and preservation of continental lithosphere, *J. Petrol. Spec. Lithosphere Iss.,* 39–52, 1988.

Salye, M. E., D. P. Vinogradov, and L. M. Gavrilina, *Fractionation of Oxygen Isotopes in Polymetamorphosed Assemblages,* Nauka, Leningrad, 1983.

Sergeyev, S., N. Arestova, O. Levchenkov, and S. Yakovleva, An isotope U–Pb age of the Semchensky gabbro-diorite intrusion, Karelia (in Russian), *Izv. Akad. Nauk SSSR, Ser. Geol., 11,* 15–21, 1983.

Sergeev, S., E. Bibikova, O. Levchenkov, S. Lobach-Zhuchenko, S. Yakovleva, G. Ovchinnikova, L. Neimark, and A. Komarov, Isotope geochronology of the Vodlozero gneiss assemblage (in Russian), *Geokhimiya, 1,* 73–83, 1990.

Sharkov, E., V. Lyakhovich, and G. Ledneva, Petrology of the Early Proterozoic Belomorian drusite assemblage on Pezhostrov Island, northern Karelia (in Russian), *Petrologiya, 2,* (5), 511–531, 1994.

Shchipansky, A., A. Samsonov, M. Bogina, A. Slabunov, and E. Bibikova, High-Mg and low-Ti quartz amphibolites of the Hizovaara greenstone belt, northern Karelia: Archean metamorphosed analogues to boninites? (in Russian), *Dokl. Ross. Akad. Nauk, 365,* (6), 817–820, 1999.

Sochevanov, N., N. Arestova, V. Matrenichev, and S. Lobach-Zhuchenko, The first data on Sm–Nd age for Archean basalts of the Karelian granite–greenstone province (in Russian), *Dokl. Akad. Nauk SSSR, 318,* (1), 175–180, 1991.

Sun, S., and W. F. McDonough, Chemical and isotopic systematic of oceanic basalts: implications for mantle composition and processes, in Magmatism in the Ocean Basins, edited by A. D. Saunders and M. J. Norry, *Geol. Society Spec. Publ., 42,* 313–345, 1989.

Svetov, S., and H. Huhma, The geochemistry and Sm–Nd isotope study of Archean komatiite–tholeiite assemblages of the Vedlozero–Segozero greenstone belt, central Karelia (in Russian), *Dokl. Ross. Akad. Nauk, 369,* 261–263, 1999.

Vrevsky, A., The petrology of komatiites (in Russian), *Doctoral thesis,* 37 pp., St. Petersburg, 2000.

Vuollo, J., V. Nykanen, J. Liipo, and T. Piiranen, Mafic dyke swarms from 2.44 Ga to 1.97 Ga in eastern Fennoscandian Shield, Precambrian crustal evolution in the North Atlantic Regions, Abstracts, *Terra Nova, 6,* (2), 21–22, 1994.

(Received 1 July 2003)