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Petrology of the Europe-Largest Burakovka early Paleoproterozoic layered pluton (Southern Karelia, Russia)

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Abstract. The Burakovka layered pluton of basic and mafic rocks is the largest intrusive massif in the Baltic Province composed of Si- and Mg-rich boninite-like rocks. The pluton consists of two individual bodies, each having its own internal structure, and contacting each other in their apical parts, known as the Aganozero and Shalozero–Burakovka bodies. Both bodies have a similar rock sequence including five differentiated zones (upward): mafic rocks, pyroxenite, gabbro norite, pigeonite gabbro norite, and magnetite gabbro diorite (the latter found only in the Shalozero–Burakovka Body). Being generally similar to each other, these bodies differ notably in the styles of their cumulate stratigraphy and, to a lesser extent, in composition. The pluton is distinguished by the presence of markers – singular interlayers of high-temperature mafic cumulates emplaced in the sequence of lower-T formations. Their origin is believed to have been associated with the intrusion of fresh magma portions into the crystallizing magma chambers. The same mechanism is believed to have been responsible for a macrorhythmic pattern found in the southeastern portion of the Shalozero–Burakovka intrusive body. Using chemical and mineralogical data, it is shown that the bodies discussed were derived from similar high-Si and high-Mg magmas, except that the Aganozero Body was emplaced 50 million years later than the Shalozero–Burakovka intrusion: the former was dated (Sm–Nd isochron) 2372±22 Ma ($\varepsilon_{\rm Nd} = -3.22 \pm 0.13$), and the latter, 2433±28 Ma ($\varepsilon_{\rm Nd} = -3.14 \pm 0.14$). It is concluded that the Burakovka Pluton was a long-lived magma center which developed above a local mantle plume, the origin of which had been associated with the activity of a megaplume which had been responsible for the existence of the Baltic province throughout a period of 200 million years.

Introduction

The Europe-largest Burakovka Early Paleoproterozoic layered pluton of basic and mafic rocks (Figure 1), also known in literature as the Aganozero–Burakovka and Burakovka–Aganozero pluton, is located east of Lake Onega in an area almost wholly covered by Quaternary sediments. It was discovered in the early 1950s by drilling in the area of a high magnetic anomaly. Since 1964 extensive geological exploration and geophysical measurements have been made in the area under the guidance of V. A. Ganin, N. G. Grinevich, and V. N. Loginov (Karelian Geological Survey) for the purpose of the thorough study of the massif and the assessment of its ore potential. Along with these field operations, extensive research was done by geologists, petrologists, and geochemists in the Leningrad (St. Petersburg) and Moscow universities, in the Leningrad Mining Institute, and in many research institutes of the Russian Academy of Sciences, lo-

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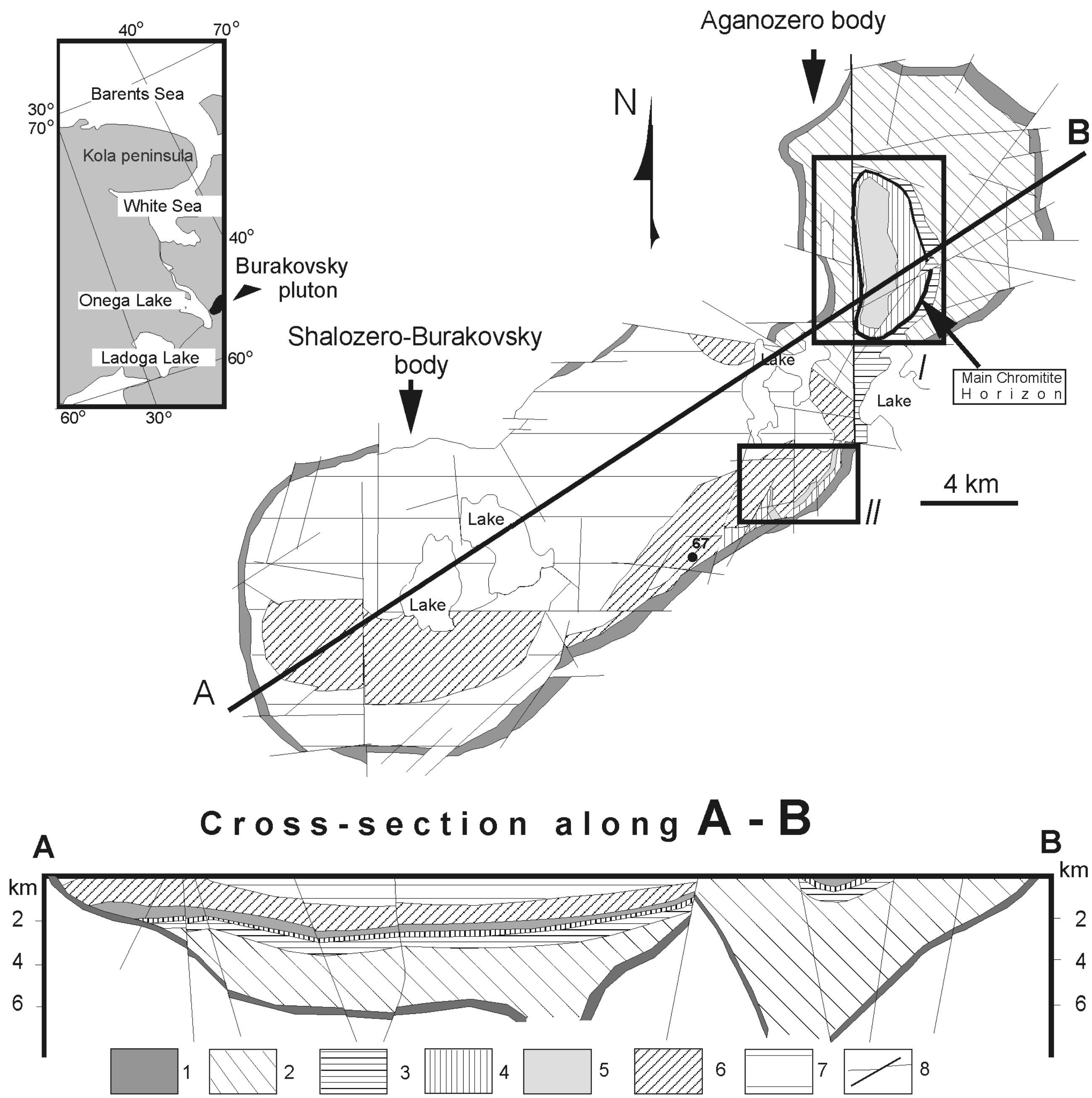
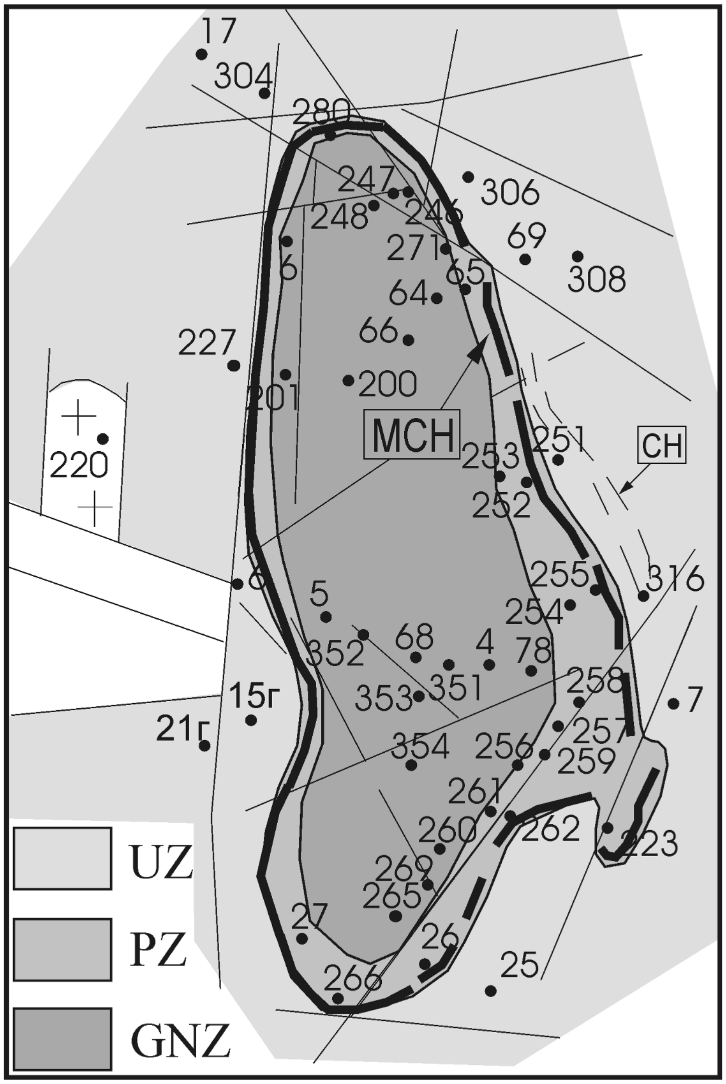


Figure 1. Schematic geological map of the Burakovka Pluton showing a marginal zone (1) and layered zones: 2 and 3 – dunite and peridotite zones of the ultrabasic zone, 4 – pyroxenite zone, 5 – gabbronorite zone, 6 – pigeonite gabbronorite zone, 7 – magnetite gabbronorite zone; 8 – faults; 9 – hole sites. The inset maps I, II, and III show the locations of the hole sites and profiles of study.


UZ
PZ
GNZ
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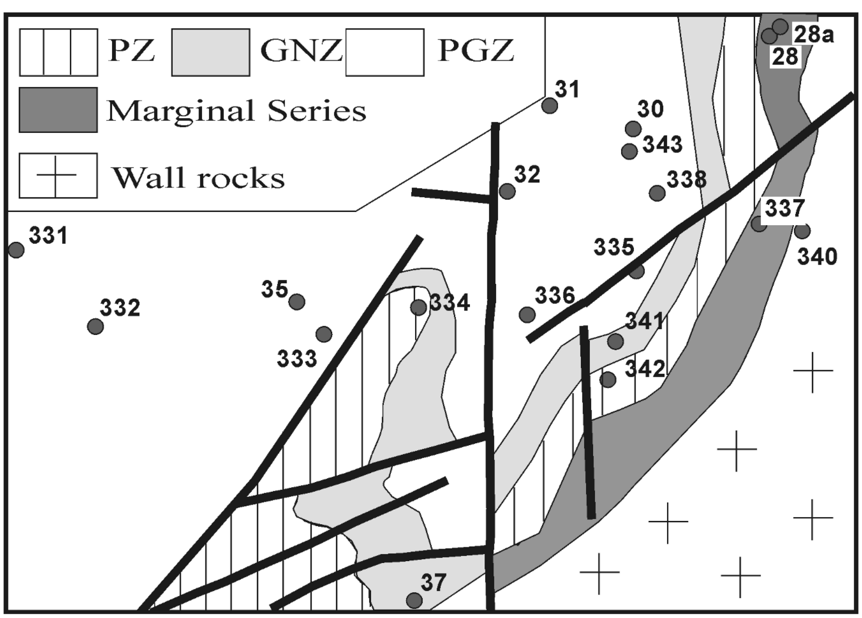
I


PZ
GNZ
PGZ
Marginal Series
Wall rocks
28a
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31
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343
338
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332
341
333
342
37

II

Table 1. Representative chemical analyses of rocks from the Layered series of the Agonozero Body (wt %)

Sample	20/945.5	68/701.8	9/174	68/611	68/449	68/365	68/80	354/21
	1	2	3	4	5	6	7	8
SiO_2	40.12	36.05	35.73	53.50	53.00	45.80	53.77	–
TiO_2	0.02	0.06	0.39	0.20	0.24	0.12	0.23	–
Al_2O_3	0.57	0.10	4.19	1.23	3.35	2.35	20.12	–
Fe_2O_3	1.97	6.56	9.60	1.07	2.91	4.72	1.45	–
FeO	8.03	5.53	4.42	7.10	4.92	7.48	4.12	–
MnO	0.14	0.14	0.14	0.19	0.23	0.22	0.09	–
MgO	45.97	38.31	24.63	21.10	23.02	28.58	5.72	–
CaO	0.73	1.94	4.48	13.97	12.38	3.10	9.34	–
Na_2O	0.05	0.05	0.30	0.05	0.43	0.16	3.65	–
K_2O	0.01	0.01	0.05	0.01	0.03	0.02	0.39	–
LOI	1.98	9.66	8.88	0.84	2.40	6.66	0.90	–
NiO	0.45	0.39	0.22	0.081	0.12	0.17	0.015	–
CoO	0.022	0.019	0.013	0.01	0.013	0.017	0.004	–
CuO	0.0140	0.0046	0.0068	0.0023	0.0063	0.0023	0.025	–
Cr_2O_3	0.12	1.07	6.98	0.37	0.10	0.42	0.00	–
Total	100.19	99.79	100.03	99.72	99.58	99.82	99.82	–
Sc, ppm	4	7	11	37	37	19	15	9
Rb	<1	<1	2	<1	<1	<1	4.3	2.1
Ba	100	–	115	100	100	100	193	147
Sr	24	–	49	32	54	37	279	86
Nb	<1	<1	<1	<1	<1	<1	1.2	<1
Zr	1.7	1.3	14	3.5	10	3.2	21	5.7
Y	1.3	<1	2.2	4.8	5.9	3.0	3.8	1.3
La	0.3	0.29	2.6	0.58	1.6	4.7	–	2.8
Ce	<1	<1	6.0	2.1	4.4	9.1	–	7.5
Nd	<1	<1	<1	1.9	3.1	4.5	–	2.9
Sm	0.07	0.12	0.77	0.65	0.96	0.92	–	0.40
Eu	0.03	0.06	0.27	0.24	0.28	0.55	–	0.25
Tb	0.02	0.04	0.10	0.16	0.21	0.20	–	0.08
Yb	0.08	0.09	0.33	0.38	0.53	0.52	–	0.26
Lu	0.01	0.01	0.07	0.06	0.08	0.08	–	0.04

1 – dunite from the UZ, 2 – peridotite from the UZ, 3 – chromite-bearing peridotite from the MCH, 4 – Pig+Pig-Aug clinopyroxenite from the PZ, 5 – Pig-Aug clinopyroxenite from the PZ, 6 and 8 – peridotites from marking horizon of the GNZ, 7 – gabbronorite-anorthosite from the GNZ. Hereafter – sample: borehole number in numerator and depth – in dominator. – = not determined.

cated in Moscow, St. Petersburg, and Petrozavodsk.

However, in spite of this extensive field work and laboratory research the Burakovka Pluton remains to be not enough thoroughly known. The papers available [*Berkovskii et al.,* 2000; *Chistyakov et al.,* 2000; *Nikolaev et al.,* 1995; *Sharkov et al.,* 1995a, 1995b] give but a general idea of the structure and composition of the Burakovka Pluton. This especially concerns its cumulate stratigraphy and the resultant vagueness of its structure and relationships among its different portions. The new data obtained in this study help to revise many views on the petrology of the massif, which is the subject of this paper.

Geologic structure of the Burakovka pluton

The Burakovka layered pluton is localized in the southeast of the Baltic Shield in the Vodlozero block of the Karelian granite–greenstone province. This block is composed mainly of Archean tonalite gneissic granite ("grey gneiss") with an irregular network of greenstone belts. Some relict areas of the block include the oldest rocks of the Baltic Shield, namely tonalite gneiss with a model Sm–Nd age of ca. 3.54 Ga [*Sergeev et al.,* 1990] and fragments of greenstone belts with an age of 3.45 Ga [*Pukhtel et al.,* 1993].

The Burakovka Pluton has an irregular oval form, curved in map view, and is elongated in the NE direction. It is 50 km long, 13–17 km wide, and is as great as 630 km^2 in area. According to geophysical data, its thickness ranges between 5–7 and 10 km [*Sobolev,* 1993]. Earlier [*Garbar et al.,* 1977], the massif was believed to be one intrusive body, and its present-day structure was interpreted as the result of the rejuvenation of tectonic activity in Late Proterozoic time, when the central and eastern parts of the intrusive massif had been raised stepwise along combined normal and strike-slip faults mainly of a roughly N-S strike. As a result of this faulting, the massif was broken into three main tectonic blocks: Burakovka, Shalozero, and Aganozero. The inferred magnitude of displacement between the latter two blocks was 1–2 km. In the previous reconstructions of the internal structure of the pluton and its generalized cross-section, the Aganozero “block” was interpreted as the lower part of the once united whole massif, and the Shalozero and Burakovka blocks, as its middle–upper parts.

At the same time, the geophysical sections (Figure 1) revealed that the Aganozero “block” was an independent funnel-shaped body. The Shalozero and Burakovka “blocks” are divided by a system of small faults with insignificant vertical displacements and constitute one body of a lopolith form. Each of these bodies has its own internal structure and orientation in space: the Aganozero block is elongated in a roughly S-N direction, whereas the Shalozero–Burakovka block strikes NE. This evidence suggests that the pluton consists of two independent intrusive massifs, Aganozero and Shalozero–Burakovka, which contact each other in the region of their upper parts and occur as one massif at the level of the pre-Quaternary erosion [*Berkovskii et al.,* 2000; *Chistyakov et al.,* 2000].

These new findings called for a more comprehensive investigation of the massif’s structure. As has been mentioned above, the massif is almost wholly covered by Quaternary sediments, this hindering the study of its internal structure. The main evidence of the latter was provided by the results of drilling comparatively shallow holes (usually drilled to depths of 200–300 m, occasionally, to a depth of 500 m, very few being drilled to depths of 1200–1500 m). Until recently, the sections across different parts of the pluton were correlated using mainly geochemical data [*Nikolaev et al.,* 1995; *Sharkov et al.,* 1995a, 1995b]. This approach failed to provide accurate results, because it is based on the methods of mathematical statistics and fails to account for thin layering and for the real structure of the rocks (in particular, for relations between cumulus and intercumulus phases). Accordingly, where the compositionally close intrusive massifs are correlated, this approach can provide a very general pattern, similar not only for the pluton discussed but also for the other Early Proterozoic layered intrusive massifs of the Baltic Shield [*Sharkov and Smolkin,* 1998]. For this reason, we undertook a special study of the cumulate stratigraphy of the Aganozero and Shalozero–Burakovka intrusive bodies, which revealed significant differences between them. The representative analyses of their main cumulates are given in Tables 1 and 2.

The best known now is the Aganozero Body (AB) which is composed mainly of ultramafic rocks. This is a funnel-shaped body with its western side cut off by N-striking faults. The central part of the body is composed of gabbroids and has a trough-shaped form elongated in the northern direction. According to the geophysical data, the magma feeder of this intrusive body was located in its SW part.

The *Shalozero–Burakovka Body (SBB)* has a U-shaped form with the steeper southern sides and consists mainly of basic rocks in the pre-Quaternary section, although the drilling data suggest its rocks to be generally similar to those of the Aganozero Body. Judging by the geophysical and scanty drilling data, the basic rocks are underlain there by a thick unit (more than half of the body’s total thickness) of ultrabasic rocks. The location of a magma feeder for this body remains to be uncertain.

Each of the bodies has its central (layered) series and a marginal zone composed of the rocks of the marginal border group. The rocks of the upper marginal zone seem to be demolished by erosion, and those of the lower zone have not been reached by drill holes. As follows from the drilling data, the contacts between the lateral marginal rocks and the Archean basement dip toward the centers of the bodies and are usually steep. The contact surfaces dip at angles of 60–70° in the southern surroundings of the Shalozero–Burakovka Body, at 35–40° in its southern surroundings, and at 50–60° in the Aganozero Body, the layering in the marginal border groups being conformable with the contact surface. As follows from the low-angle layering and trachytoid texture of the rocks from the central series (30° in the peripheral parts of the intrusions to 10° and less in their central parts), both bodies have internal structures independent of their contacts.

Comparison of the Sections Across the Aganozero and Shalozero–Burakovka Bodies

As mentioned above, the Burakovka Pluton was believed earlier to be one body. The composite section of its layered series, based on the correlation of the geological, petrographic, and geochemical data [*Ganin et al.,* 1994; *Nikolaev et al.,* 1995; *Sharkov et al.,* 1995a, 1995b], was believed to consist of the following five zones (upward): an zone of ultrabasic rocks, a pyroxenite zone, a gabbronorite zone, a zone of pigeonite gabbronorite, and a zone of magnetite gabbronorite–diorite, the latter being found only in the Shalozero–Burakovka Body. The location of the boundaries between these zones and the correlation of their sections were based mainly on the petrochemical classification of rock samples using a cluster analysis. It was demonstrated that the petrochemical clusters were generally close to a set of cumulate phases in the layered rocks and can be used for stratigraphic purposes with a certain degree of convention, disregarding the possibility of varying relations between the cumulus and intercumulus minerals in particular samples. Our study showed that generally this structural model was valid for both the Aganozero and Shalozero–Burakovka bod-

Table 2. Representative chemical analyses of rocks of the Shalozero–Burakovka Body (wt %)

	338/234	334/301.5	341/154.5	338/188	338/168.7	338/133	31/383	46/78	123/253.5	28a/204.6	28a/199.7
Zone	UZ	UZ	UZ, MCH	PZ	PZ	PZ	PGNZ	MGDZ	MGDZ	Marginal Series	
SiO_2	38.70	–	–	52.35	52.70	55.05	54.56	51.42	54.83	56.24	52.72
TiO_2	0.23	–	–	0.25	0.24	0.42	0.59	2.25	1.07	0.29	0.31
Al_2O_3	2.89	–	–	18.25	17.90	7.30	16.96	15.12	15.69	17.11	20.82
Fe_2O_3	5.10	–	–	3.98	0.63	0.92	1.75	3.58	2.92	0.91	0.63
Cr_2O_3	0.86	–	–	0.033	0.034	0.085	–	–	–	0.12	–
FeO	5.93	–	–	1.64	5.28	8.46	6.70	10.84	7.54	7.59	4.03
MnO	0.12	–	–	0.098	0.097	0.17	0.13	0.17	0.14	0.12	0.13
MgO	31.93	–	–	8.19	8.48	16.55	5.29	3.30	3.63	4.81	5.42
CaO	1.22	–	–	11.34	10.85	7.76	8.53	7.50	8.57	6.60	9.51
Na_2O	0.24	–	–	3.02	3.02	1.62	3.59	4.30	3.74	4.11	4.10
K_2O	0.17	–	–	0.35	0.34	0.42	0.83	0.83	1.18	0.34	0.51
NiO	0.40	–	–	0.088	0.089	0.048	0.012	0.001	0.015	0.16	0.06
CuO	0.12	–	–	0.089	0.087	0.017	0.030	0.004	0.032	0.48	0.12
CoO	0.025	–	–	0.006	0.007	0.009	0.005	0.001	0.007	0.01	–
H_2O	11.26	–	–	0.52	0.54	0.61	0.66	0.72	0.70	1.04	1.1
CO_2	0.54	–	–	0.11	0.09	0.13	–	–	–	–	–
Total	99.21	–	–	100.22	100.31	99.47	99.64	100.04	100.06	99.18	99.47
Sc, ppm	–	–	–	–	–	21	26	22	–	–	–
Cr	–	–	–	–	–	23	11	16	–	–	–
Rb	–	–	–	–	–	21	14	34	–	–	–
Sr	–	–	–	–	–	226	263	227	–	–	–
Y	–	–	–	–	–	9.9	8.9	13	–	–	–
Zr	–	–	–	–	–	67	46	110	–	–	–
Nb	–	–	–	–	–	3	1.2	5.1	–	–	–
Ba	–	–	–	–	–	310	304	373	–	–	–
La	3.99	1.9	11.1	2.57	–	6.93	13	8	17	–	–
Ce	8.10	3.5	18.2	5.13	–	13.7	24	18	35	–	–
Pr	0.93	0.47	1.41	0.65	–	1.64	–	–	–	–	–
Nd	3.55	2.09	4.88	2.51	–	6.19	12	7.3	15	–	–
Sm	0.65	0.50	1.02	0.62	–	1.35	2.7	1.7	2.8	–	–
Eu	0.17	0.16	0.33	0.34	–	0.38	0.84	0.86	1	–	–
Gd	0.62	0.48	0.95	0.75	–	1.50	–	–	–	–	–
Tb	0.08	0.07	0.14	0.10	–	0.22	0.35	0.33	0.47	–	–
Dy	0.48	0.41	0.80	0.68	–	1.37	–	–	–	–	–
Ho	0.10	0.08	0.15	0.14	–	0.29	–	–	–	–	–
Er	0.25	0.23	0.42	0.4	–	0.78	–	–	–	–	–
Tm	0.04	0.03	0.06	0.06	–	0.10	–	–	–	–	–
Yb	0.23	0.16	0.34	0.36	–	0.75	0.96	0.90	1.3	–	–
Lu	0.03	0.03	0.06	0.06	–	0.10	0.13	0.14	–	–	–

Note: – = not determined.

ies (Figure 2), even though there are substantial differences between them in some details (Figures 3–5).

Ultrabasic zone (UZ) compose the lower units of the layered series in both bodies. As indicated by geophysical data, the total thickness of this zone in the Aganozero Body is about 6000 m, whereas in the Shalozero–Burakovka Body this zone is as thick as ca. 2 km. At the pre-Quaternary erosion level, this zone is most complete in the Aganozero Body, especially in its southern part. The holes drilled in the SBB penetrated merely the top of this zone. The ultrabasic zones have fairly distinct upper contacts which in most holes drilled through both bodies coincide with the major chromite horizons (see below). As follows from the drilling data, all rocks of this zone in the AB are serpentinized to different extents, at least to a depth of 700–900 m below the modern erosion level.

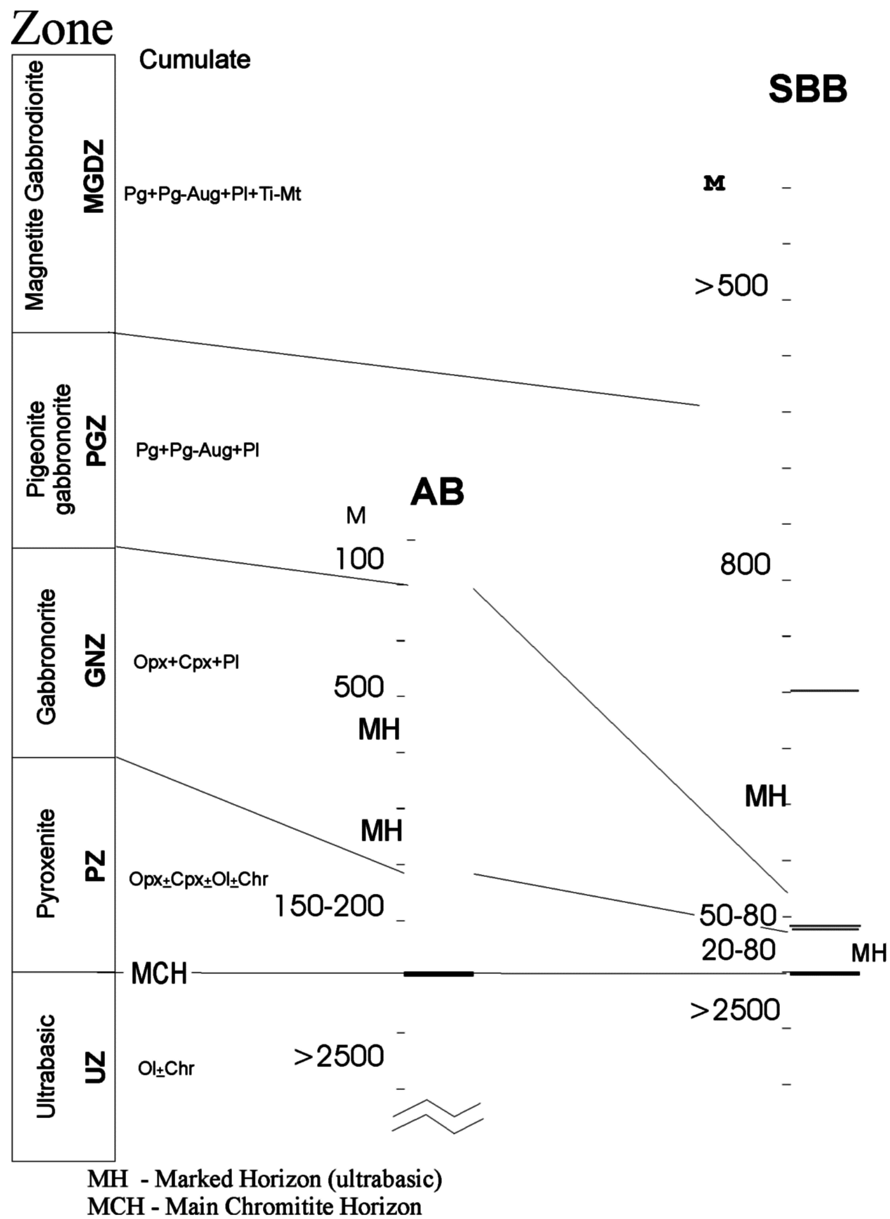

Figure 2. Structure of the layered series of the Aganozero and Shalozero bodies showing major cumulate assemblages and the thicknesses of the individual zones.

The internal structure of the ultrabasic zones is distinguished by a relatively invariable mineral composition of the rocks consisting mainly of olivine (Ol)–chromespinel (Chr) cumulates. Based on the ratio between the cumulus and intercumulus phase minerals, two subzones were distinguished in the Aganozero Body: the lower dunite subzone (2500–3000 m thick) consisting of dunite and olivinite, which are often devoid of intercumulus, and the upper peridotite subzone (200–400 m thick) composed mainly of poikilitic peridotite with intercumulus pyroxene and plagioclase amounting to 30–40 vol.%. The dunite subzone includes a few indistinct rhythms ranging between a few tens and a few hundreds of meters in thickness. The lower parts of the rhythms (75% of their thicknesses) are composed of dunite consisting of cumulate olivine (95–98 vol.%) and a small amount of cumulate chromite (1–2 vol.%), whereas the upper parts of the rhythms consist of interstitial pyroxene and some plagioclase and phlogopite (10–15 vol.%). In the peridotite subzone, the amount of poikilitic peridotite increases upward with the total growth of interstitial pyroxene (mainly clinopyroxene) up to 20–45 vol.% and plagioclase up to 10 vol.% with a decline of cumulate olivine to 50 vol.%. The two-member implicit rhythmic pattern is characteristic of this zone, too, except that its dunite interlayers have a minimum thickness here.

The upper sequence of this zone includes several chromespinel ore units ranging between 0.5 and 4.5–7 m in thick-

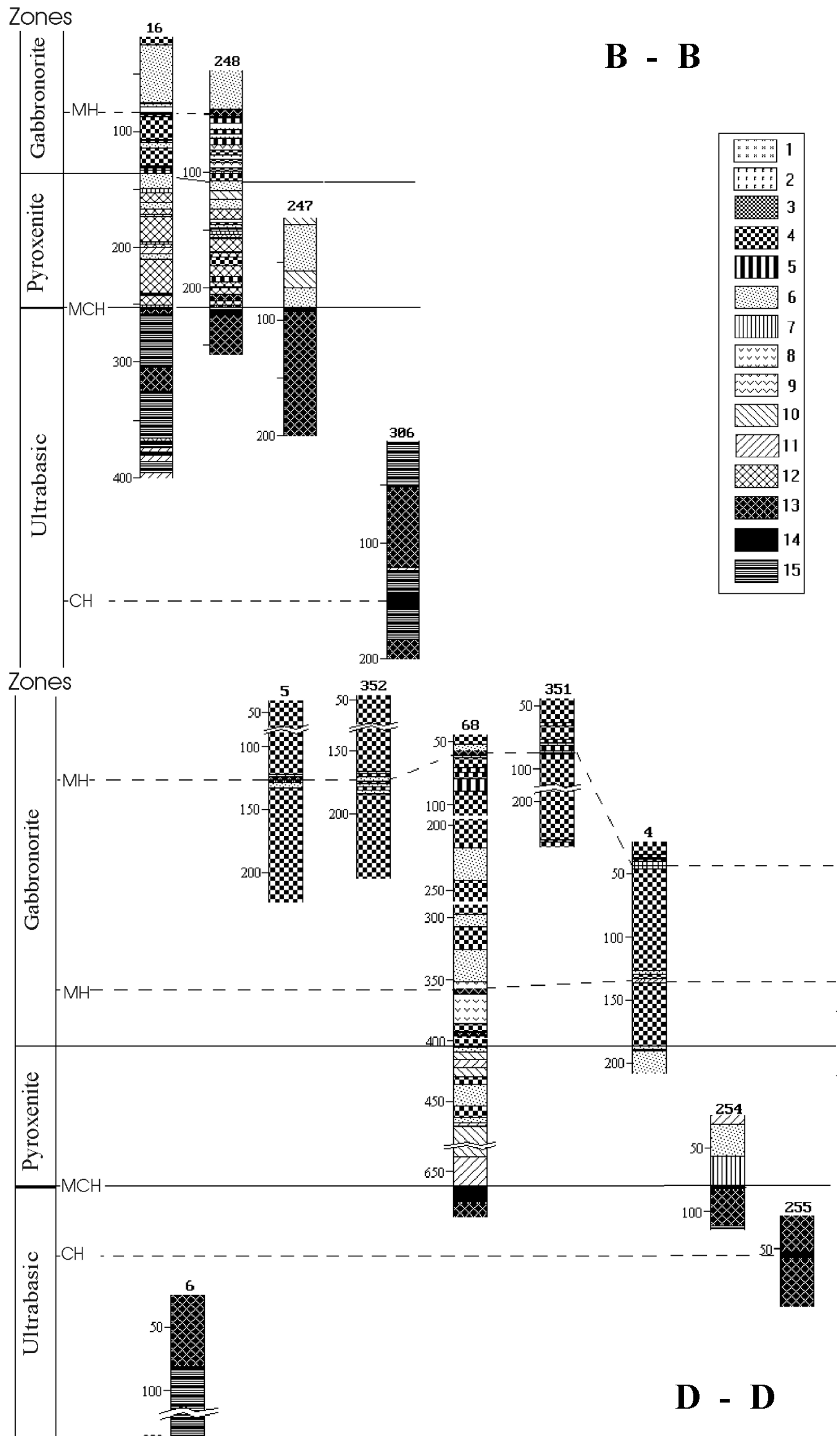

Figure 3. Schematic correlation of the holes along profiles B and D of the Aganozero body: 1 – quartz–feldspar rocks, 2 – pigeonite gabbronorite, 3 – magnetite gabbronorite, 4 – gabbronorite, 5 – gabbronorite–anorthosite, 6 – websterite, 7 – olivine websterite, 8 – orthopyroxenite, 9 – olivine orthopyroxenite, 10 – clinopyroxenite, 11 – olivine clinopyroxenite, 12 – wehrlite, lherzolite, and harzburgite; 13 – poikilitic peridotite, 14 – chromitite, 15 – dunite.

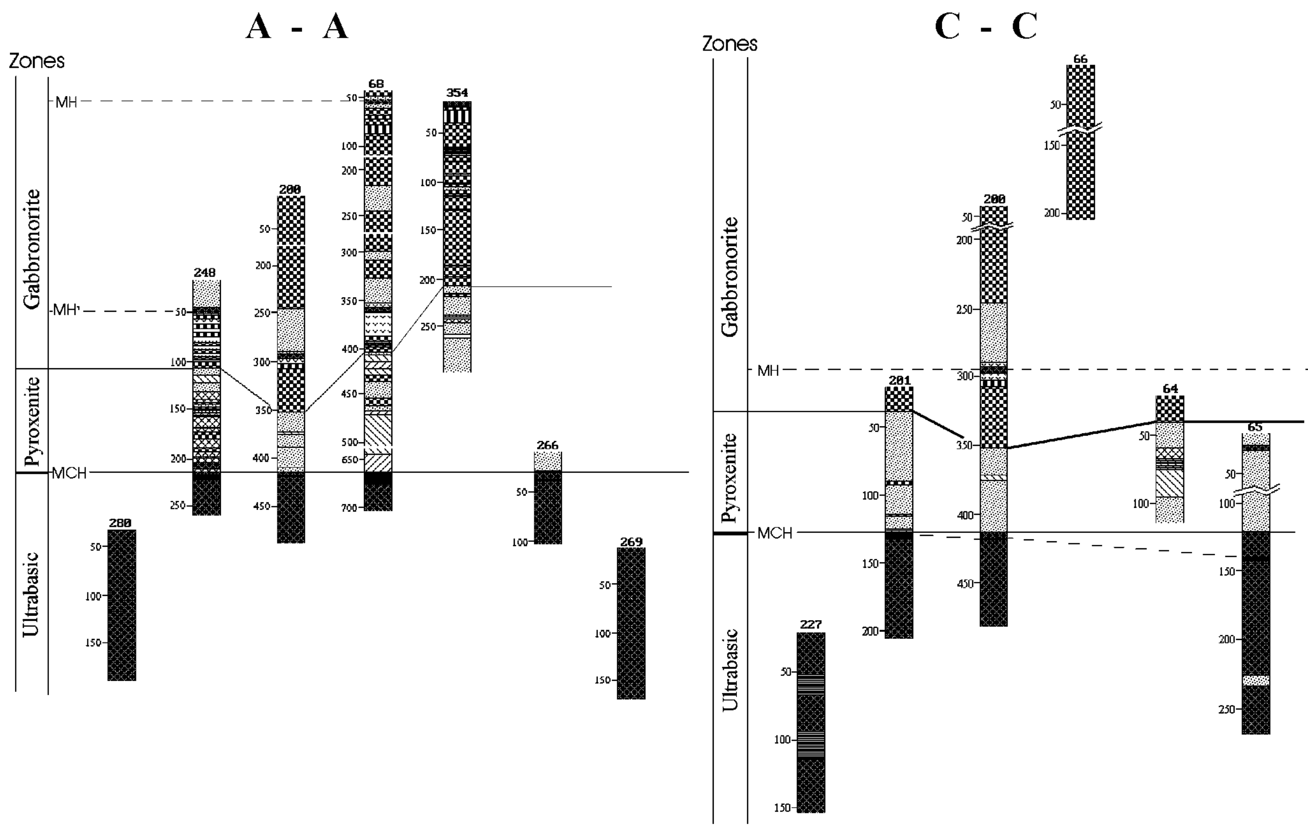

Figure 4. Correlation of holes along profiles A and B of the Aganozero Body.

ness, where the chrome-spinel content is as high as 50–75 vol.%. The thickest of them (Major Chromitite Horizon, MCH) was traced in the very top of the zone and often coincides with the contact of the overlying pyroxenite zone. This unit varies greatly in thickness and is lacking in some holes. It has a maximum thickness (5–6 m) in the central segment of the Aganozero intrusive body, where it was recorded in all holes drilled through this segment of the body, and also traced in the pre-Quaternary erosion surface in the form of occasional outcrops.

The internal structure of the main chromite unit is characterized by a frequent intercalation of peridotite, chromitite, and occasional dunite interlayers. The compositions of its dark-color minerals vary toward the growing Mg content. The contents of chrome-spinel in some layers vary from 10–15 to 60–70%. Grains ranging between the first fractions of mm and 1–2 mm in size occur as numerous accumulations among intercumulate pyroxenes and plagioclase, and in some rare cases as inclusions in olivine. In the chromite ore proper, chrome-spinels occur as veinlets, commonly restricted to contacts between the grains of interstitial pyroxenes or to cracks in the latter.

A layer combining several closely spaced thin chromitite interlayers, known as the Yakozero Unit, was found in the eastern segment of the Aganozero intrusive body in the peridotite subzone below the Main Chromite Unit (MCU).

Only the uppermost interval of the Ultrabasic zone, composed of poikilitic peridotite <300 m thick, was investigated in the Shalozero–Burakovka intrusive body. Here, a poorly expressed intercumulus-based rhythmicity was observed, with orthopyroxene dominating at the bases of the rhythms, and plagioclase and phlogopite, at their tops (Figure 6). The rhythms grow thicker from 5–10 to 30–35 m toward the top of the zone.

Most of the holes showed a chromite ore layer, 5–7 m thick, in the top of the Ultrabasic zone (analog of the MCH of the Aganozero intrusive body).

To conclude, the main distinctive feature of the Ultrabasic zone in the SBB is the predominant development of poikilitic peridotite with the high contents of interstitial minerals, dominated by orthopyroxene and plagioclase, with the ubiquitous presence of phlogopite.

Pyroxenite zone (PZ) with a thickness of 190–200 m is exposed in the pre-Quaternary erosion surface of the Aganozero intrusive body and occurs merely as fragments in the Shalozero–Burakovka intrusive body, where its thickness is as small as 20–80 m. The upper contacts of these zones are marked by the ubiquitous occurrence of cumulate plagioclase.

In the *Aganozero Body*, this zone is composed predominantly of clinopyroxenite, websterite, and their olivine varieties with individual interlayers and patches of lherzolite, hartzburgite, and orthopyroxenite. This zone was studied most thoroughly in the holes drilled in the central part of

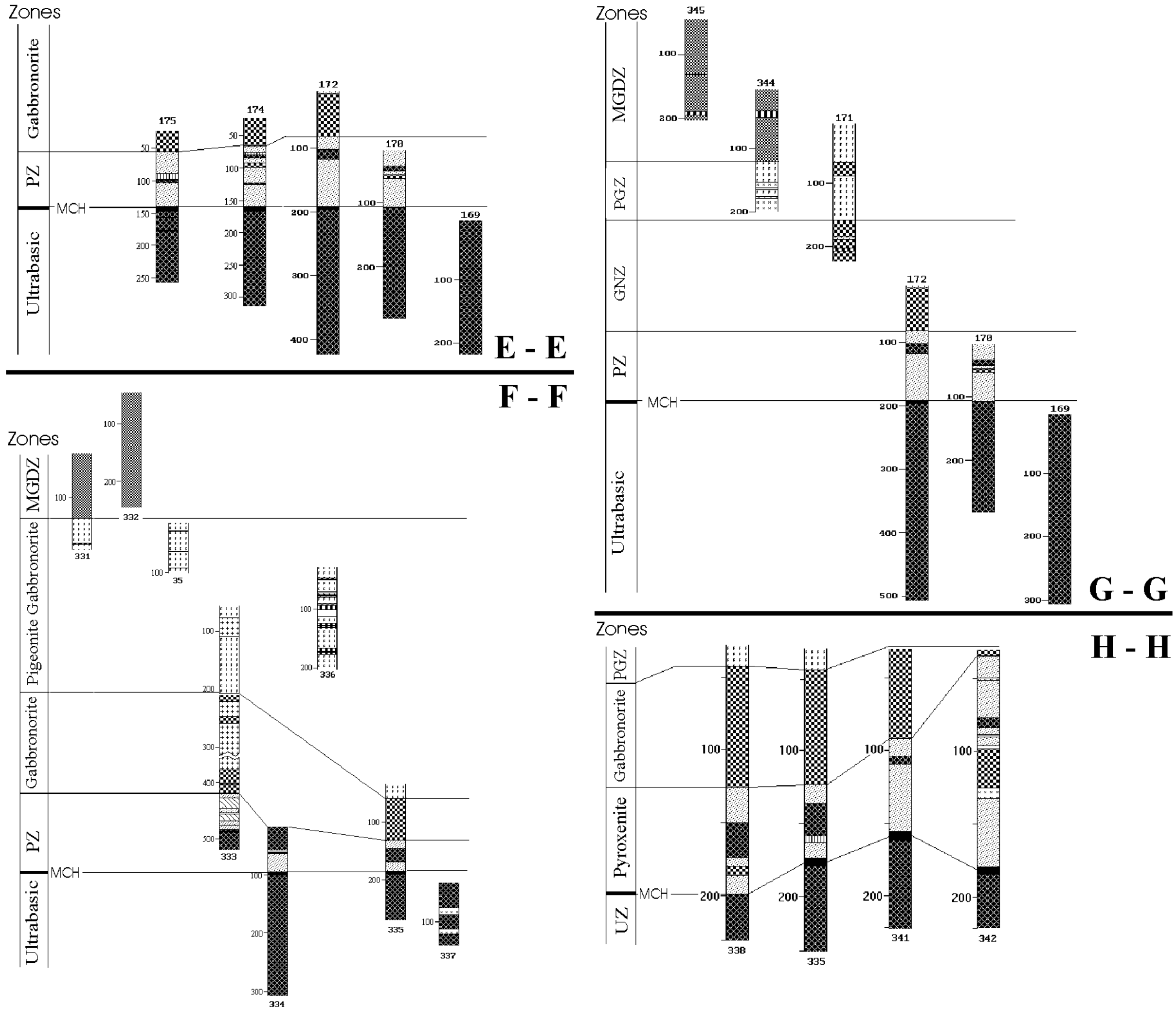

Figure 5. Correlation of holes along profiles E, F, G, and H of the Shalozero–Burakovka Body.

the AB (Figure 7), where it is distinguished by extremely unstable structures and textures with a great development of coarse-grained to pegmatoid varieties. Judging by the petrographic data, the typical cumulate textures are rare with a wide development of metasomatic granoblastic, serrate textures. The most widespread mineral of this zone is inverted pigeonite–augite (Pig–Aug) with a peculiar "tweed" solid-solution texture produced by a system of fine orthopyroxene lamellas intersecting at right angles. This pigeonite-augite replaced (corroded) the earlier cumulate phases (olivine, augite, and orthopyroxene) with the formation of almost monomineral clinopyroxenite. The clinopyroxene matrix of the inverted Pig–Aug and the relict cumulate clinopyroxene are almost identical in composition (see below). The clinopyroxenite is almost entirely devoid of chrome-spinels with magnetite commonly developed instead of them.

The data available suggest that the minerals that underwent replacement there were olivine–chromite, orthopyroxene, and two-pyroxene cumulates. Some boreholes revealed a peculiar transition zone, 5–10 m thick, along a contact between the pyroxenite and the underlying ultrabasic zone, where the peridotite cumulates are seen to be actively replaced by a clinopyroxenite aggregate with the formation of peculiar mottled rocks with relict spots of peridotite composition (Figure 8). Another distinctive feature of the rocks from this zone is the presence of numerous usually round isolated inclusions, mainly of a quartz–carbonate composition, ranging between fractions of mm and 2–3 mm in size, usually located inside clinopyroxene (rarely in orthopyroxene) grains, and also in the interstices between them. Moreover, the clinopyroxenes with a "tweed" solid-solution texture were found to contain quartz–carbonate inclusions, having the form of negative crystals, the feature typical of primary inclusions (data provided by I. P. Solovova). These "microamygdaloidal" clinopyroxenites are a specific feature of this zone and have not been found in any other parts of this intrusive body.

In contrast to the Aganozero intrusive body, the Pyrox-

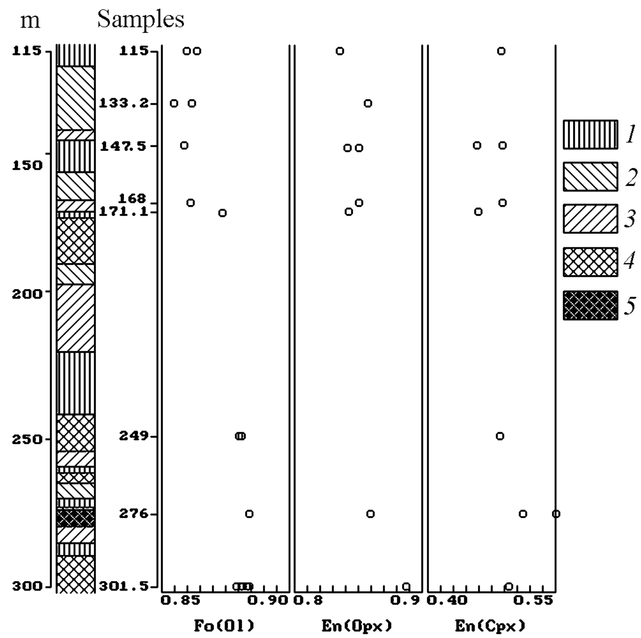

Figure 6. Structure of the ultrabasic zone and compositional variations of olivine and pyroxenes across the ultrabasic zone of the Shalozero Body. Ol+Chr cumulates are represented by 1 – Opx+Cpx+Pl±Bt, 2 – Opx+Pl+Bt, 3 – Pl+Bt, 4 – Cpx+Pl+Bt, 5 – Opx+Cpx±Bt.

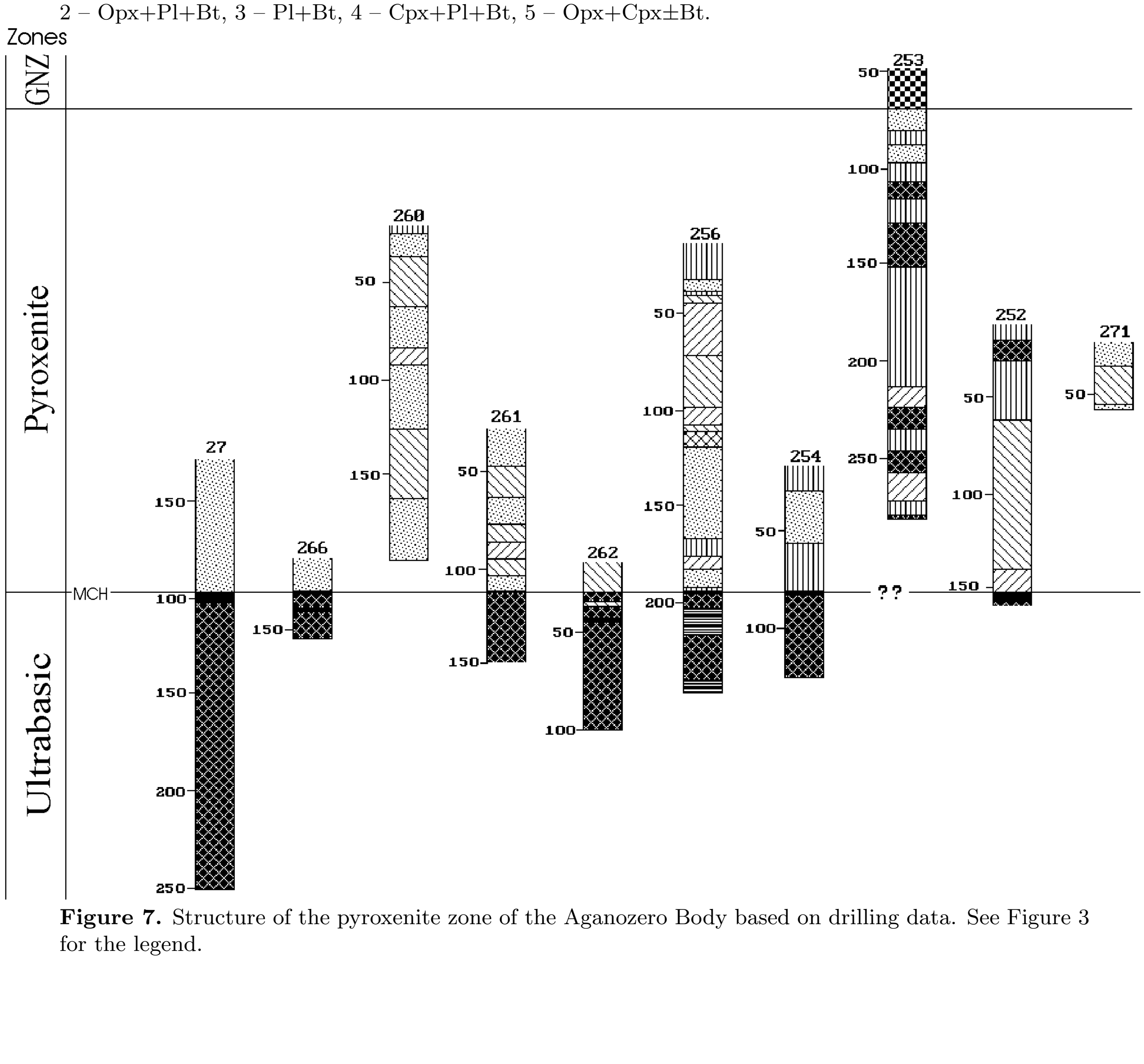

Figure 7. Structure of the pyroxenite zone of the Aganozero Body based on drilling data. See Figure 3 for the legend.

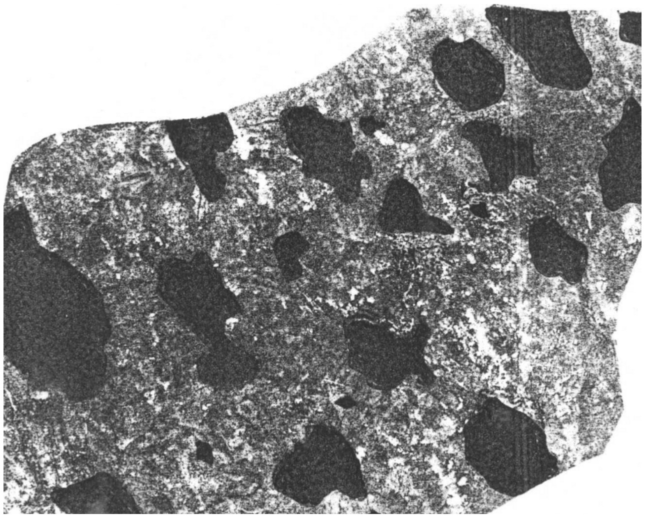

Figure 8. Relic sites of peridotite (dark) in a pigeonite augite aggregate from the base of the pyroxenite zone in the Aganozero Body.

enite zone of the SBB has a small thickness and consists of cumulate pyroxenite. As follows from drilling data, it has a three-member structure (Figure 9). Its lower part, 20–50 m thick, is dominated by websterite and olivine websterite (Aug+Opx±Ol cumulates), whereas its upper part with a maximum thickness of 25 m is composed of orthopyroxenite (Opx cumulate) and websterite.

The middle section of the pyroxenite zone includes a peridotite marker horizon, whose thickness grows from a few meters in the margins of the intrusion to a few tens of meters in its middle (see Figure 9). The marker usually consists of Ol+Chr cumulates with 70–75 vol.% of olivine in its middle and of Ol+Chr+Opx cumulates with 50–55 vol.% of olivine in the top and base.

Gabbronorite zone (GNZ) is best developed in the central part of the Aganozero intrusive body, where it has a maximum thickness (500 m), and was also recorded at the periphery of the Shalozero–Burakovka Body. The lower contact of this zone is defined by the stable development of cumulate plagioclase, and the upper, by the absence of orthopyroxene and the appearance of inverted cumulate pigeonite in the overlying rocks.

Aganozero intrusive body. In the central part of this body the gabbronorite zone has been subdivided into two subzones: the lower or banded subzone, 200–250 m thick, and the upper subzone having a roughly similar thickness.

The lower (layered) subzone is distinguished by the interlayering of websterite (Cpx+Opx±Ol±Chr cumulate), orthopyroxenite (Opx±Ol±Chr), norite (Pl+Opx), gabbronorite (Pl+Opx+Cpx), gabbro (Pl+Cpx), and gabbro-anorthosite (Pl). Based on the ratios of the cumulate minerals in the sequence, we distinguished several rhythms ranging from 20 to 185 m in thickness and having indistinct contacts between them. The base of each rhythm is dominated by Cpx. The olivine and chrome spinel that are also present there vanish toward the top of the subzone, where the dominant mineral in the gabbronorite is orthopyroxene. The tops of the rhythms were found to be enriched in sulfides and platinum-group minerals (PGM).

The lower part of this subzone contains a marker horizon, composed of interbedded poikilitic peridotite and olivine pyroxenite, varying within 3–5 m in thickness (see Figure 1). Another thinner marker horizon was found in the top of the sequence. It consists of poikilitic peridotite, bronzitite, and websterite containing up to 10–15 vol.% of chrome spinel in the top. These rock units are distinguished by the most magnesian compositions of their pyroxenes compared to the other rocks of the gabbronorite zone. The olivine from the rocks of the lower marker horizon occurs in isometric grains <1.5 mm in size, whereas that of the upper marker is represented by very small (commonly a few fractions of mm), almost round grains. In some sites the marker-horizons rocks were found to contain Cu–Ni sulfide.

The upper subzone is composed mainly of gabbronorite including gabbronorite–anorthosite interlayers. A coarse layering was observed expressed in the alternation of meso- and leucocratic gabbronorite varieties and occasional anorthosite layers. The cumulate minerals are plagioclase (65–78 vol.%), augite (7–14 vol.%), and orthopyroxene (5–20 vol.%).

In the *Shalozero–Burakovka intrusive body*, the Gabbronorite zone has a thickness of <100 m and is composed mainly of gabbronorite with interlayers of anorthosite, norite, and gabbro and resembles the upper gabbronorite subzone from the Aganozero Body. Orthopyroxene is seen to dominate in the total content of pyroxene in the rocks upward. The amount of cumulate plagioclase varies within 55–70 vol.%. The interstitial minerals are quartz, magnetite, and apatite, as well as some poor pentlandite–pyrite–chalcopyrite sulfide mineralization.

To sum up, the distinctive features of the Gabbronorite zone in the SBB are (1) its small thickness, (2) the absence of a different cumulate layered unit in the lower part of the zone (that is, the absence of any analog of this subzone of the Aganozero gabbronorite zone), (3) the absence of any distinct rhythmic zoning, (4) the absence of peridotite markers, and (5) a relative enrichment in sulfides.

Pigeonite Gabbronorite Zone (PGZ) was observed mainly in the Shalozero–Burakovka intrusive body and is poorly developed in the central part of the Aganozero body.

This zone is composed of gabbronorite with reversed pigeonite (Pig) and pigeonite–augite (plagioclase–two pyroxene and less common plagioclase cumulates). The northeastern segment of the Shalozero–Burakovka intrusive body showed a poorly expressed layering produced by the alternation of the layers of meso- and leucocratic gabbronorite varieties ranging between 1.5 and 10 m in thickness. Almost all of the studied samples were found to contain interstitial quartz, biotite, and K-feldspar in the amounts of <5 vol.%, and also magnetite and apatite. The pyroxenes are often amphybolized. The gabbronorite is often seen to be cut by plagiomicrocline granite bodies ranging between 0.5 and 50 m in thickness (see below).

Several boreholes revealed a plagioclase harzburgite marker horizon (Ol+Opx+Chr cumulus) varying from 0.6 to 2.2 m in thickness in the gabbronorite of this zone's top.

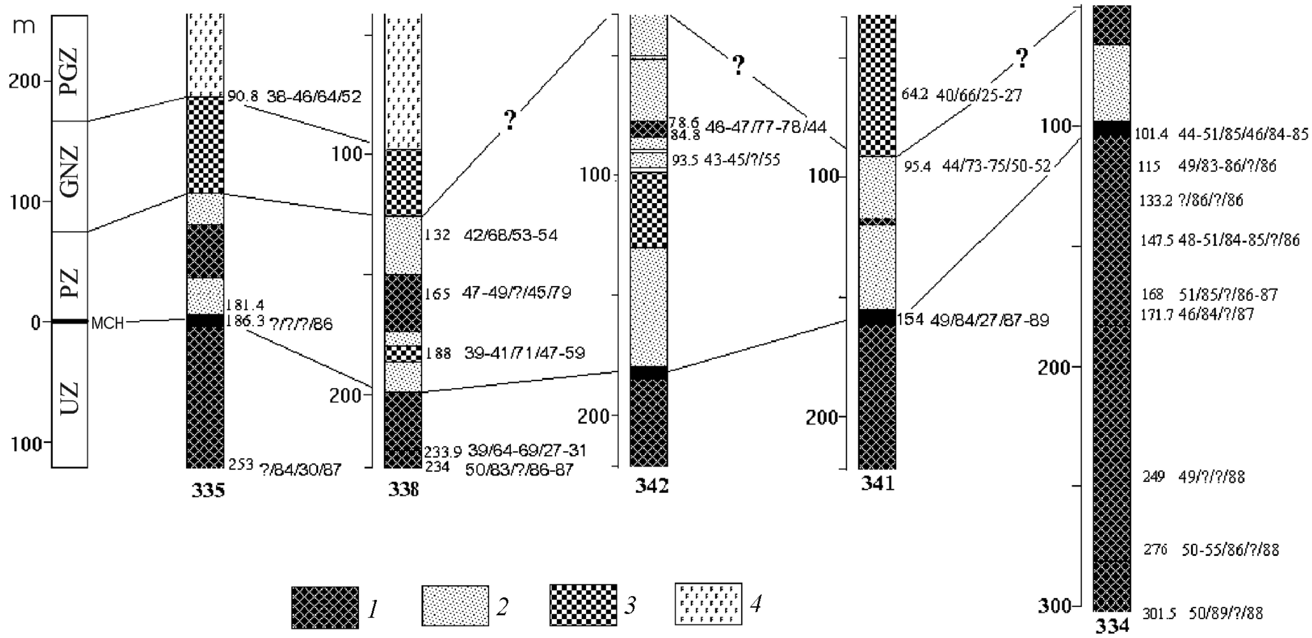

Figure 9. Structure of the pyroxenite zone from the holes drilled in the Shalozero–Burakovka Body. Shown in the figure are the numbers of core samples and the compositions of the main mineral phases: Cpx(En)/Opx(En)/Pl(An)/Ol(Fo). See Figure 3 for the legend.

As to the central segment of the Aganozero Body, only the tops of the borehole sections were found to contain gabbronorite with the cumulate grains of inverted pigeonite, which could be attributed to the pigeonite gabbronorite zone.

Magnetite Gabbronorite–Diorite Zone (MGDZ) is the uppermost zone in the sequence of the layered-series rocks in the Shalozero-Burakovka intrusive body and is absent in the Aganozero body. The cumulus consists of inverted pigeonite-augite (10–29 vol.%) and pigeonite (9–22 vol.%), titanomagnetite (3–12 vol.%), and plagioclase (oligoclase–andesine) (42–75 vol.%); interstitial K-feldspar and quartz, as well as apatite, were found occasionally in the top of the zone.

The rocks of this zone show a vague rhythmic pattern produced by the alternation of melanocratic and mesocratic rocks. The former were found to contain as much as 10–12% cumulate magnetite and as much as 51% pyroxene. The content of magnetite declines to 1–5% and that of pyroxene, to 20–35%, in the latter. Anorthosite interlayers were recorded in the tops of the rhythms.

Geologic section of Hole 67. This is the deepest hole of those drilled in the Shalozero–Burakovka Body. It crossed its eastern segment in the direct vicinity of the marginal-series rocks (see Figure 1). The rocks penetrated by this hole are generally comparable with the pluton's rocks elsewhere, yet show some specific features, the principal of them being the occurrence of two thick layers of Ol+Chr cumulates at the bases of two megarhythms with pigeonite-bearing gabbronorite in the top (Figure 10). Both megarhythms show a cumulate succession typical of the Burakovka Pluton (and common for most of the Early Paleoproterozoic layered intrusions of the Baltic Shield): Ol+Chr → Ol+Chr+Opx → Opx+Chr → Opx → Opx+Cpx → Opx+Cpx+Pl → Pig+Pig–Aug+Pl. In spite of the similar structure of the megarhythms, our study revealed that olivine and orthopyroxene in the peridotites of the lower megarhythm differ by their higher Mg contents (Fo_{86-87} and En_{87}, respectively) from the similar rocks in the upper megarhythm (Fo_{84-85} and En_{81-84}) (see Figure 10). This fact suggests that here we deal with two independent megarhythms instead of the doubling of the sequence along a fault.

Concluding the description of the cumulate stratigraphy of the Burakovka Pluton, it should be mentioned that both intrusive bodies show the following succession of the main typomorphic cumulates: Ol±Chr (Ultrabasic zone) → Opx±Cpx±Ol±Chr (Pyroxene zone) → Opx + Cpx + Pl±Ol (Gabbronorite zone) → Pig + Pig–Aug + Pl (Pigeonite gabbronorite zone) → Pig + Pig–Aug + Pl + Mag (Magnetite gabbronorite zone which is absent in the Aganozero body, where its seems to have been eroded). In this respect the Burakovka Pluton does not show any differences from most of the Early Paleoproterozoic layered intrusions of the Baltic Shield, and also from the classical massifs, such as Bushveld (South Africa) and Stillwater (North America).

The Marginal Border Group is represented in both intrusive bodies by a group of contact rocks which usually occur as a band <200–400 m wide along the periphery of the massif. Three zones can be distinguished in the sequence of the marginal rocks: a zone of direct contact, an outer (banded) zone, and an inner zone.

In the southern surroundings of the Shalozero–Burakovka intrusive body, the *zone of direct contact* is composed of microgabbronorite enriched in accessory sulfides of a pentlandite–pyrite–chalcopyrite assemblage and in titano-

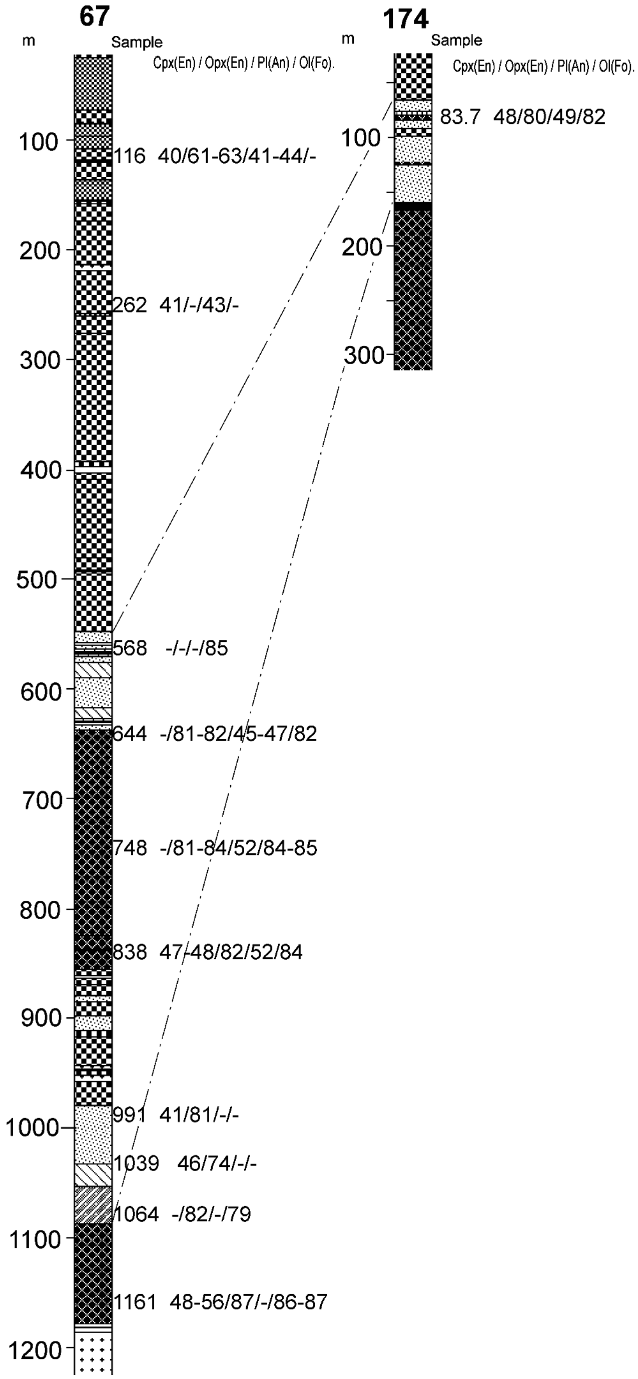

Figure 10. Sections of Holes 67 and 174 drilled in the SW and N segments of the Shalozero–Burakovka Body, respectively. The figure shows the numbers of the core samples and the compositions of the major minerals (see Figure 9). See Figure 3 for the legend.

magnetite (totaling 5–10%) and ranging between 0.4 and 0.9 m in thickness. In the Aganozero Body, the contact gabbroids are represented by amphibolized quartz-bearing norite and gabbronorite, roughly 120 m thick (Hole 196), sometimes porphyritic, containing large (up to 2 mm long) plagioclase (An_{44-63}) crystals, often normally zoned, in a fine- and medium-grained plagioclase–pyroxene groundmass with small (<1 mm) veinlets and fine-grained patches of irregular form. The rock includes single sulfide and magnetite grains everywhere. There are occasional pyroxene and anorthosite interlayers and also fragments of a quartz–feldspar rock, which can be interpreted as the xenoliths of the host tonalite granite gneiss. A similar sequence was observed in the northeastern surroundings of the Shalozero–Burakovka intrusive body.

The outer (banded) zone, 10 to 210 m thick, occurs in the surroundings of the Shalozero–Burakovka intrusive body. It is composed mainly of fine- to medium-grained usually leucocratic gabbronorite (clinopyroxene $Wo_{47}En_{38}Fs_{15}$, orthopyroxene $Wo_5En_{65}Fs_{30}$, plagioclase An_{47}) with interlayers of plagioclase websterite where ortho- and clinopyroxene grains are enclosed in plagioclase oikocrysts. The outer zone is mostly absent in the Aganozero body, where the near-contact gabbroids are replaced abruptly by the peridotites of the inner zone. The exception is Hole 177 drilled in the south of this body, where the rocks of the outer zone occur as a 20-meter layer of medium-grained plagioclase websterite which is changed by contact gabbroid closer to the contact.

The inner zone, 20 to 170 m thick, is present in both bodies and consists of chrome-spinel-bearing (1–5%) poikilitic serpentinized peridotite with occasional interlayers of plagioclase websterite in the Aganozero intrusive body and with those of websterite and less common peridotite in the Shalozero–Burakovka Body. The data available suggest that this difference in the structure of the internal zones depends on the type of the layered-series rocks, with which they are in contact. For instance, in the AB, the inner zone contacts the ultramafic rocks, whereas in the SBB, it contacts the mafic rocks in the west and the ultramafic rocks of the layered series in the east. The olivine from the peridotite samples collected in Hole 28a showed a magnesian number which was found to be the lowest for the rocks of the pluton (Fo_{52}), the ortho- and clinopyroxenes yielded $En_{78.5}$ and $En_{46.6}$, respectively, and the interstitial plagioclase, An_{34-38}. In the inner zone, the contents of SiO_2, TiO_2, Al_2O_3, FeO, Na_2O, and K_2O grow toward the contact with a decreasing MgO content caused by the enrichment of the marginal peridotite in interstitial plagioclase.

Therefore, the differences recorded in the structure of the marginal series can be associated with the composition of the adjacent rocks of the layered series. The most complete sequence of the rocks was observed in the Shalozero–Burakovka Body where we recorded a transition from the near-contact fine-granular gabbronorite via fine- to coarse-granular gabbronorite to plagioclase websterite and further, via its olivine variety, to the rocks of the layered series.

Cryptic Layering

The compositions of minerals were determined throughout the sequences of the layered series of the Aganozero and Shalozero–Burakovka bodies. Measurements were made at IGEM RAN using an MS-46 Cameca microprobe with the

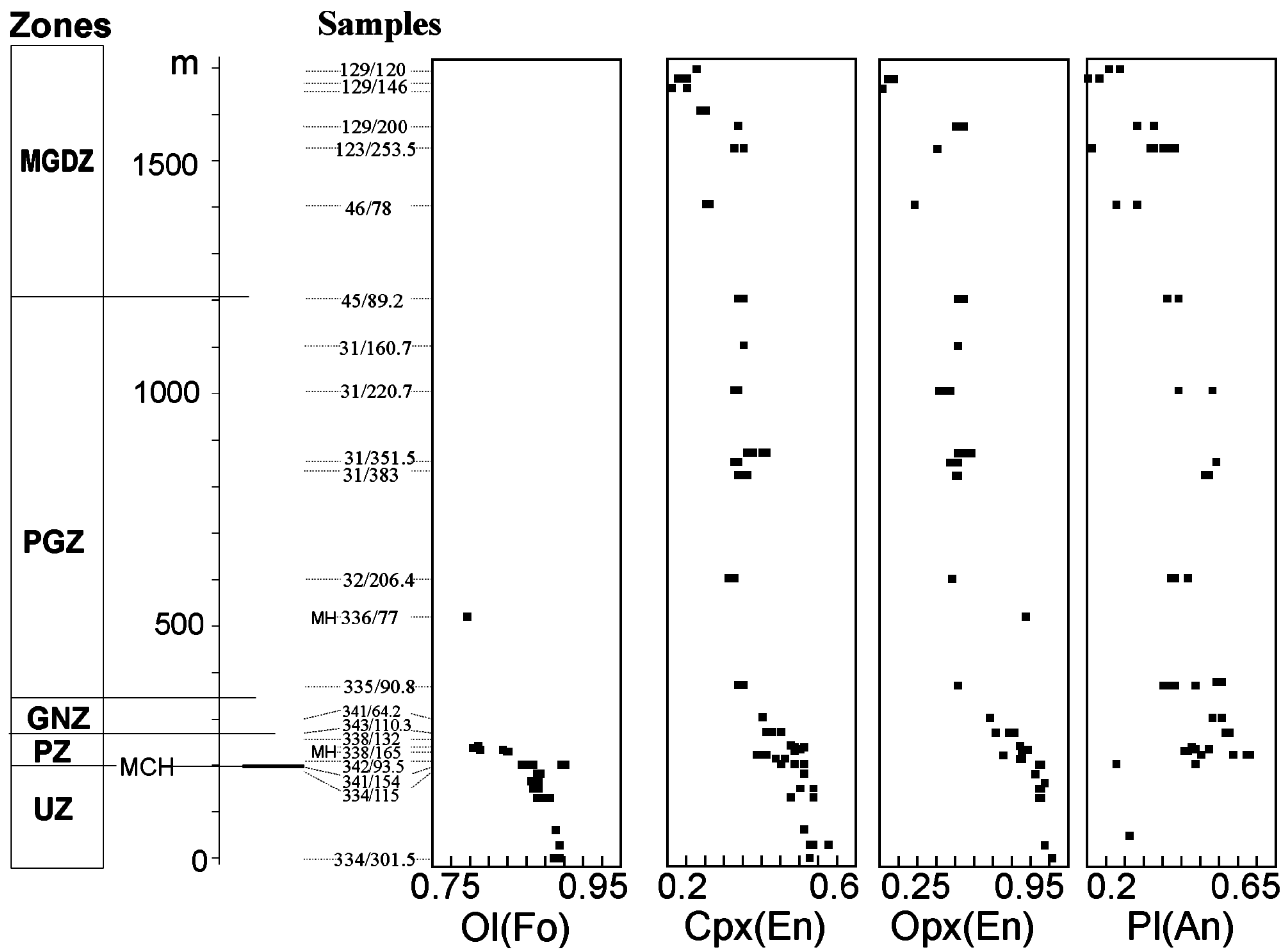

Figure 11. Compositional variations of olivine, pyroxenes, and plagioclase across the layered series of the Shalozero–Burakovka Body. The figure shows the numbers of core samples.

experimental conditions of 15 kV and 50 mA. The time of measuring each element was 70 s.

The rocks of the layered series in both intrusive bodies of the Burakovka Pluton are characterized by cryptic layering expressed in the regular compositional variations of the major rock-forming minerals (olivine, pyroxene, and plagioclase) from the bottom to the top of the body. Our study revealed obvious variations in the compositions of the mineral phases against the general trend of the declining Mg content in the olivines and pyroxenes, and the Si content in the plagioclases (Tables 3–10, Figures 11–12)

Olivine is the main cumulate mineral in the ultrabasic zones and in the overlying peridotite marker horizons. In a 200-meter section examined in the top of the ultrabasic zone in the *Shalozero–Burakovka Body*, the Mg content of olivine declines up the section from Fo_{88} to Fo_{84} and increases again to 86–89% Fo in the Main Chromite Horizon, with the NiO content in the olivine varying between 0.45 and 0.55% and tending to decline up the zone. In the peridotite marker horizon of the Pyroxenite zone, olivine is more ferrous (Fo_{79-80}) with the NiO content varying between 0.37 and 0.43%. Therefore the olivine composition varies from Fo_{88} to Fo_{79}.

In the Ultrabasic zone of the *Aganozero Body*, the Mg content of olivine declines upward from 90 to 86% Fo, increasing again to Fo_{88} in the MCH. The relict olivine grains in the pigeonite–augite clinopyroxenite from the Pyroxenite zone showed a comparatively constant composition (Fo_{82-83}). At the base of the Gabbronorite zone the olivine gabbronorite contains olivine with 80% Fo, its composition being similar to that of olivine in the lower peridotite marker horizon (Fo_{80-81}). In the upper marker, olivine is more ferroan (Fo_{76}). Therefore the Mg content of olivine varies from Fo_{90} to Fo_{76} up the section of the Aganozero Body.

Almost all of the olivine grains analyzed in the Burakovka massif are devoid of silica and Ca oxide, the olivine always containing isomorphous NiO (0.3 to 0.56 wt.%).

Low-Ca pyroxene is represented by orthopyroxene and pigeonite in the rocks of the Burakovka Pluton. In terms of the content of a wollastonite end member (4–6%) the pyroxenes occupy a boundary position with the pyroxenes of a pigeonite series (Figure 13). In the ultrabasic zones and

Table 3. Chemical composition of olivines from the Shalozero–Burakovka Body (wt %)

Sample	SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	NiO	Sum	Fo
				Ultrabasic zone					
334/301.5	40.31	0.06	11.58	0.17	47.36		0.51	99.99	0.88
334/249	39.79		11.89	0.14	48.72	0.04	0.47	101.05	0.88
334/168	40.22	0.02	13.17	0.21	45.62	0.03	0.55	99.82	0.86
334/147.5	40.16	0.06	13.59	0.19	45.27	0.04	0.52	99.83	0.86
334/133.2	38.85		13.80	0.23	45.72		0.46	99.06	0.86
334/115	39.19		13.23	0.14	47.03	0.04	0.48	100.11	0.86
334/101.4	37.65	0.06	15.23	0.23	47.41	0.03	0.45	101.06	0.85
338/234	39.61		13.49	0.18	46.57	0.03	0.48	100.36	0.86
				Main Chromitite Horizon					
341/154	40.26		10.88	0.14	48.13		0.51	99.92	0.89
335/186.3	39.61		14.17	0.19	47.34	0.04	0.46	101.81	0.86
				Marking horizons					
338/165	37.95		19.72	0.28	42.18	0.03	0.37	100.53	0.79
338/165	38.63		19.25	0.26	42.01	0.04	0.43	100.62	0.80
174/83.7	39.41		16.86	0.25	44.45		0.34	101.31	0.82
336/77	39.02		20.04	0.35	41.46	0.03	0.57	101.47	0.79
				Hole 67					
67/644-3	37.74		16.48	0.27	43.10	0.06	0.34	97.99	0.82
67/748-3	39.92		14.43	0.21	45.54	0.04	0.38	100.52	0.85
67/838	39.28		15.15	0.21	43.65	0.04	0.38	98.71	0.84
67/1161-3	39.60		12.77	0.19	47.19	0.03	0.53	100.31	0.87
				Marginal Border Group					
28a/175	38.67		17.34	0.26	42.06	0.04	0.43	98.80	0.81

Remarks: Absence of value denotes the contents below the detection limit.

Table 4. Chemical composition of olivines from rocks of the Aganozero Body (wt %)

Sample	SiO_2	FeO	MnO	MgO	CaO	NiO	Sum	Fo
				Ultrabasic zone				
20/1627	39.85	14.21	0.23	45.61	0.07	–	99.97	0.85
20/1541.1	39.28	12.65	0.21	47.28	0.10	0.46	99.98	0.87
20/945.5	40.83	10.88	0.17	46.72	0.13	0.47	99.20	0.88
68/701.8	40.71	12.83	0.18	45.89	0.00	0.52	100.13	0.86
				Main Chromitite Horizon				
68/674	40.62	13.29	0.21	45.78	0.00	0.41	100.31	0.86
				Pyroxenite zone				
16/159	38.50	18.02	0.26	43.66	0.03	0.36	100.83	0.80
262/10	39.81	15.25	0.22	43.64	0.00	0.43	99.35	0.84
68/449	40.13	16.20	0.23	44.09	0.00	0.42	101.07	0.83
68/426.9	38.34	18.65	0.30	42.73	0.04	0.38	100.44	0.80
				Marking horizons				
68/365	39.57	18.04	0.25	42.31	0.15	0.42	100.74	0.81
354/241.3	39.83	19.34	0.27	39.76	0.06	0.39	99.65	0.79
5/124	38.01	22.07	0.28	38.47	0.00	0.56	99.39	0.76
354/21.9	38.44	21.97	0.34	38.86	0.03	0.41	100.05	0.76
				Marginal Border Group				
196/20	39.08	15.44	0.25	42.98	0.00	0.51	98.26	0.84

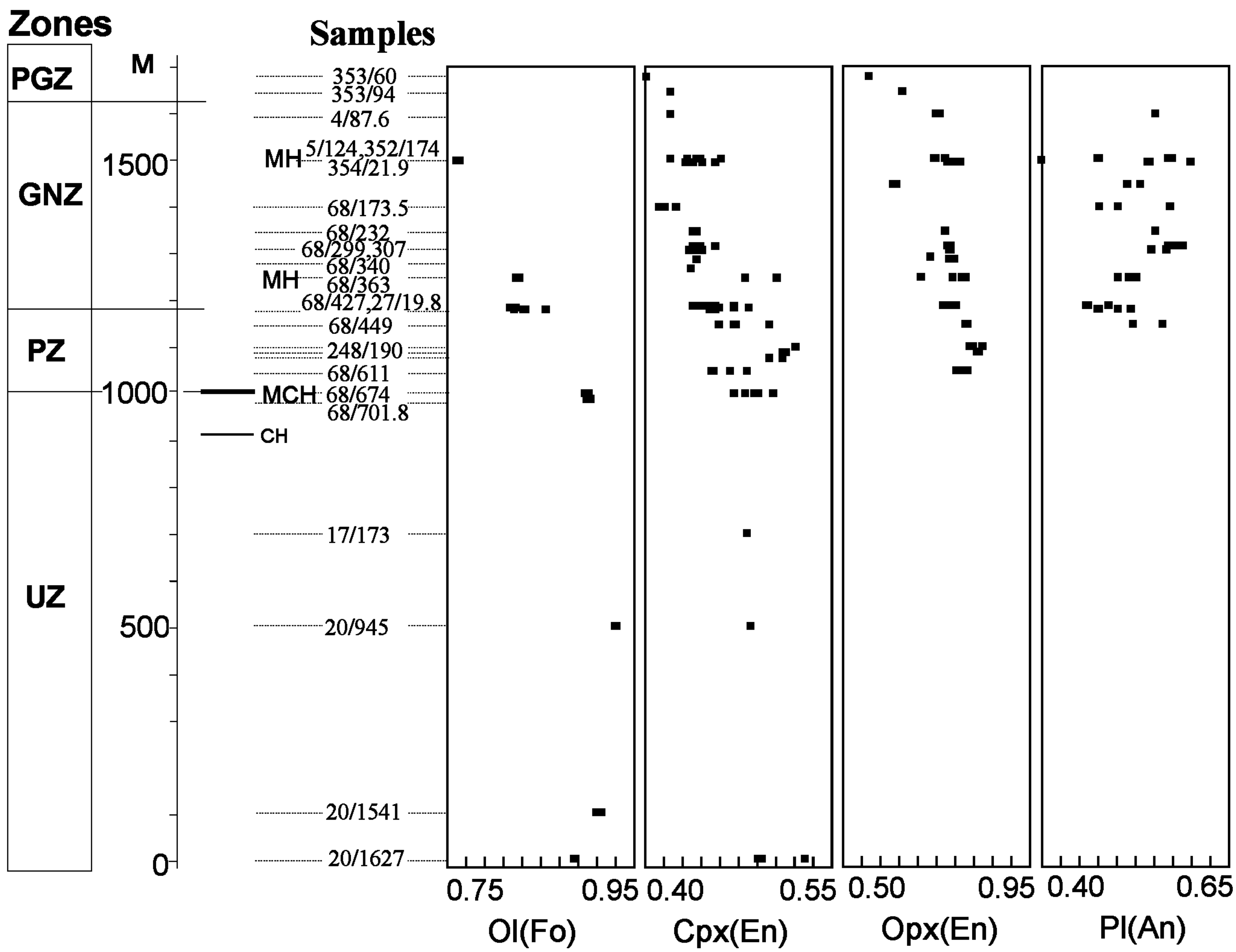

Figure 12. Compositional variations of olivine, pyroxenes, and plagioclase across the layered series of the Aganozero Body. Shown in the figure are the numbers of core samples.

peridotite marker horizons, Opx is a usual constituent of the intercumulus and is represented mainly by cumulate crystals in the overlying rocks. The orthopyroxene compositions are presented in Tables 5 and 6.

In the Ultrabasic zone of the *Shalozero–Burakovka Body*, the Mg content of the orthopyroxenes declines upward along a 200-meter section from En_{86} to En_{83}, increasing again to 85–86% En in the main chromite unit. In the Pyroxenite zone, orthopyroxene has a $Wo_4En_{78}Fs_{18}$ composition in the websterite below the marker and is more ferroan ($Wo_{5-6}En_{73-75}Fs_{21-22}$) above it. In the gabbronorite interlayer of the Lower Pyroxenite horizon orthopyroxen has a $Wo_3En_{71}Fs_{26}$. In the peridotite marker horizon, Opx contains 4–5% Wo with 77–78% En. Orthopyroxene has a composition of $Wo_4En_{66}Fs_{30}$ in the Gabbronorite zone.

The pyroxene from the Pigeonite gabbronorite zone is represented by pigeonite (Pig) and pigeonite–augite (Pig–Aug). Orthopyroxene ($Wo_{1.5-5}En_{51-54}Fs_{43-44}$) occurs as lamellas in the inverted Pig–Aug and as a matrix in the inverted Pig with a normal zoning: $Wo_{1-3}En_{54-58}Fs_{41-44}$ in the cores and $Wo_2En_{46-54}Fs_{44-52}$ in the margins. Therefore the lamellas in Pig–Aug and the matrix in the inverted pigeonite have almost the same composition. In the upper marker horizon, the orthopyroxene composition ($Wo_4En_{79}Fs_{17}$) is close to that of the marker in the Pyroxenite zone. The composition of the orthopyroxene matrix of the inverted pigeonite from the magnetite gabbronorite zone varies upward from $Wo_{2-5}En_{54-56}Fs_{40-44}$ to $Wo_4En_{38}Fs_{59}$. Therefore the total variation in the Opx composition, including the exsolution texture compositions of the inverted Pig and Pig–Aug upward the layered series in the Shalozero–Burakovka Body, is $Wo_4En_{86}Fs_{10}$ to $Wo_4En_{38}Fs_{59}$.

In the *Aganozero Body*, Opx appears later than Cpx in the form of single interstitial grains in the rocks of the Ultrabasic zone. Orthopyroxene occurs as a cumulate mineral above this zone. In the Pyroxenite zone the quantity of this mineral is also subordinate to that of Cpx which occurs as scarce cumulate crystals, often highly corroded by the adjacent pigeonite–augite grains. The orthopyroxene has a $Wo_3En_{76}Fs_{21}$ composition. In the lower intervals of the Py-

Table 5. Chemical composition of orthopyroxenes from rocks of Shalozero–Burakovka Body (wt %)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	Sum	En	Wo	Fs
Ultrabasic zone and the MCH														
334/115	52.82	0.23	1.83	8.67	0.22	32.65	2.21	–	0.63	0.15	99.41	0.83	0.04	0.12
334/133.2	53.95	0.27	0.66	9.02	0.18	34.21	0.91	–	0.26	0.14	99.60	0.86	0.02	0.13
334/147.5	53.80	0.20	1.44	9.06	0.22	34.11	1.27	–	0.45	0.10	100.65	0.85	0.02	0.13
334/168	54.17	0.33	1.57	8.17	0.21	33.96	1.87	0.04	0.51	0.17	101.00	0.85	0.03	0.11
334/171.7	55.11	0.15	1.32	8.16	0.19	32.02	1.99	0.08	0.44	0.17	99.63	0.84	0.04	0.12
334/276	51.64	0.12	1.15	7.50	0.17	34.79	2.06	–	0.48	0.10	98.01	0.86	0.04	0.1
338/234	52.68	0.18	1.23	8.37	0.17	32.05	2.53	–	0.92	0.13	98.26	0.83	0.05	0.12
341/154	55.60	0.13	1.00	7.38	0.19	32.60	2.81	–	0.60	0.13	100.44	0.84	0.05	0.11
Pyroxenite zone and marking horizons														
174/83.7	55.65	0.45	1.23	11.07	0.22	29.88	1.59	–	0.29	0.09	100.47	0.80	0.03	0.17
338/132	51.56	0.17	1.21	18.51	0.32	25.74	2.31	0.02	0.05	0.06	99.95	0.68	0.04	0.27
338/188	51.24	0.15	1.61	18.17	0.34	27.63	1.47	–	0.09	0.13	100.83	0.71	0.03	0.26
341/64.2	51.77	0.17	1.45	20.16	0.36	24.51	2.15	0.08	0.04	0.08	100.77	0.66	0.04	0.30
341/95.4	51.58	0.25	1.25	13.55	0.26	27.53	2.50	0.08	0.25	0.09	97.34	0.75	0.05	0.21
342/93.5	51.43	0.20	1.57	12.75	0.26	30.28	1.97	–	0.37	0.13	98.96	0.78	0.04	0.18
342/78.6	54.42	0.13	1.78	11.98	0.27	28.43	2.35	–	0.58	0.13	100.07	0.77	0.05	0.18
342/84.8	55.21	0.20	1.53	11.85	0.26	28.60	2.21	0.07	0.38	0.20	100.51	0.78	0.04	0.18
333/475	56.02	0.10	1.34	11.03	0.18	27.71	2.14	0.05	0.56	0.06	99.19	0.78	0.04	0.17
336/77	52.50	0.35	1.61	11.42	0.31	30.23	2.34	0.07	0.26	0.14	99.23	0.79	0.04	0.17
Pigeonite-Gabbronorite zone														
31/136	51.83	0.07	0.49	26.77	0.52	18.55	0.83	–	–	–	99.06	0.54	0.02	0.44
31/335	53.60	0.10	0.59	25.46	0.46	20.18	0.59	–	–	–	100.98	0.58	0.01	0.41
31/351.5	52.20	0.20	0.57	28.07	0.56	19.37	1.09	–	–	–	102.06	0.54	0.02	0.44
31/383	52.50	0.18	0.68	26.23	0.54	18.92	1.61	–	–	–	100.66	0.54	0.03	0.42
32/206.4	52.58	0.23	0.72	26.62	0.58	17.31	1.08	–	0.03	0.06	99.21	0.52	0.02	0.45
333/109	53.15	0.27	0.91	26.96	0.49	16.36	3.12	–	–	0.05	101.31	0.49	0.07	0.45
333/247	49.97	0.25	0.76	26.1	0.48	22.32	0.92	–	–	0.08	100.88	0.59	0.02	0.39
343/110.3	51.76	0.32	0.74	27.26	0.58	19.05	1.11	–	0.04	0.06	100.92	0.54	0.02	0.44
Zone of Magnetite Gabbronorit-Diorites														
45/89.2	52.92	0.07	0.76	25.82	0.50	19.28	0.78	–	–	–	100.13	0.56	0.02	0.42
123/253.5	49.46	0.18	0.45	31.27	0.62	16.23	2.07	–	–	–	100.31	0.46	0.04	0.50

Table 6. Chemical composition of orthopyroxenes from rocks of the Aganozero Body (wt %)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Cr_2O_3	NiO	Sum	En	Wo	Fs
Pyroxenite zone													
27/19.8	54.69	0.20	1.30	12.75	0.23	27.46	1.64	0.13	–	98.40	0.77	0.03	0.20
68/449	54.99	0.12	1.70	11.45	0.25	28.82	1.11	0.20	0.09	98.73	0.80	0.02	0.18
68/611-1m	55.40	0.10	0.60	12.03	0.27	30.72	1.13	0.16	0.09	100.50	0.80	0.02	0.18
Gabbronorite zone													
4/87.6	53.58	0.28	1.17	16.49	0.36	26.33	1.05	0.04	0.08	99.38	0.72	0.02	0.25
68/80	52.73	–	1.10	21.45	0.37	22.35	2.21	0.16	–	100.37	0.62	0.04	0.33
68/232	51.96	0.22	1.04	14.87	0.32	28.31	1.76	–	0.09	98.57	0.74	0.04	0.22
68/299	52.19	0.15	1.27	13.98	0.26	28.95	1.62	–	–	98.42	0.76	0.04	0.20
68/307	54.82	0.23	0.79	14.09	0.34	28.27	1.44	0.06	–	100.04	0.76	0.03	0.21
68/340	52.93	0.17	1.36	13.02	0.27	28.80	2.83	0.25	0.08	99.71	0.75	0.05	0.20
Marking horizons													
68/363	52.67	0.08	1.59	10.87	0.25	28.92	3.67	0.48	0.13	98.66	0.77	0.07	0.16
68/365	54.70	0.15	1.60	11.04	0.23	30.10	2.52	0.51	0.10	100.95	0.79	0.05	0.16
354/241.3	54.69	0.13	1.83	12.11	0.28	27.62	2.45	0.54	0.13	99.78	0.76	0.05	0.19
354/21.9	55.87	0.35	2.04	13.46	0.30	26.15	1.72	0.28	0.08	100.25	0.75	0.04	0.21
Pigeonite-Gabbronorite zone													
353/76.9	50.39	0.17	0.94	23.37	0.50	23.63	0.90	–	–	99.90	0.63	0.02	0.35

Table 7. Chemical composition of clinopyroxenes from rocks of the Shalozero–Burakovka Body (wt %)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	Sum	En	Wo	Fs
Ultrabasic zone and the MCH														
334/104.4	52.04	1.00	2.66	6.82	0.18	17.91	18.68	0.55	0.92	0.08	100.84	0.51	0.38	0.11
334/104.4	52.46	0.97	2.89	4.21	0.12	15.09	23.02	0.62	1.02	0.08	100.48	0.44	0.49	0.07
334/115	52.09	0.72	2.78	4.39	0.13	17.06	21.60	0.70	1.13	0.10	100.70	0.49	0.44	0.07
334/147.5	51.96	0.17	1.93	4.08	0.13	19.19	22.30	0.69	1.27	0.18	101.90	0.51	0.43	0.06
334/168	53.55	0.32	2.59	4.37	0.13	17.59	20.51	0.75	1.27	0.09	101.17	0.51	0.42	0.07
334/276	52.05	0.25	1.78	4.36	0.12	19.52	18.78	0.61	1.37	0.08	98.92	0.55	0.38	0.07
334/276	53.15	0.18	1.89	3.62	0.14	18.56	21.86	0.65	1.35	0.09	101.49	0.51	0.43	0.06
334/301.5	53.93	0.27	2.32	6.02	0.15	21.69	14.83	0.70	1.39	0.09	101.39	0.61	0.30	0.09
334/301.5	53.56	0.22	2.27	3.62	0.12	17.40	21.84	0.75	1.37	0.08	101.43	0.50	0.45	0.06
334/171.7	53.45	0.85	2.34	4.08	0.14	15.99	22.96	0.65	1.13	0.06	101.65	0.46	0.47	0.07
338/234	53.67	0.27	1.98	4.76	0.13	17.06	19.89	0.47	1.36	0.06	99.65	0.50	0.42	0.08
341/154	53.20	0.23	1.60	2.96	0.10	16.60	23.80	0.74	1.40	0.06	100.69	0.47	0.48	0.05
Pyroxenite zone and marking horizon														
338/132	52.39	0.37	2.15	7.64	0.21	14.31	23.17	0.39	0.26	0.05	100.94	0.41	0.47	0.12
338/165	52.62	0.25	2.63	5.17	0.14	15.93	21.10	0.55	1.24	0.05	99.68	0.47	0.45	0.09
338/188	52.91	0.45	1.61	9.35	0.21	13.73	22.99	0.38	–	0.13	101.76	0.39	0.47	0.15
341/95.4	54.40	0.70	1.44	6.41	0.14	14.96	21.48	0.42	0.48	0.03	100.46	0.44	0.45	0.11
342/93.5	52.84	0.37	2.72	5.87	0.18	15.32	23.95	0.44	0.64	0.09	102.42	0.43	0.48	0.09
342/78.6	52.20	0.22	2.61	5.47	0.18	16.30	22.52	0.61	1.24	0.09	101.44	0.46	0.46	0.09
342/84.8	51.89	0.50	2.74	5.77	0.18	16.53	21.19	0.50	0.95	0.09	100.34	0.47	0.44	0.09
174/83.7	53.33	0.33	2.68	4.84	0.14	16.63	21.73	–	1.23	0.08	100.99	0.48	0.45	0.08
Pigeonite-Gabbronorite zone														
31/220.7	52.83	0.22	1.13	11.92	0.25	12.50	22.30	0.39	–	–	101.54	0.35	0.46	0.19
31/351.5	50.91	0.47	1.88	12.16	0.24	12.12	22.63	0.40	–	–	100.81	0.34	0.46	0.19
31/383	52.40	0.25	1.83	11.30	0.27	12.17	22.15	0.15	–	–	100.52	0.35	0.46	0.18
32/206.4	49.03	0.55	1.95	11.74	0.27	11.44	22.44	0.55	–	0.05	98.02	0.33	0.47	0.19
333/109	51.06	0.18	0.94	13.47	0.27	11.06	21.36	0.46	–	0.05	98.85	0.33	0.45	0.22
343/110.3	50.29	0.45	1.30	12.48	0.34	12.05	21.92	0.42	0.07	0.06	99.38	0.35	0.45	0.20
Zone of Magnetite Gabbro-Diorites														
45/89.2	52.02	0.40	1.76	11.35	0.19	12.09	22.24	0.43	–	–	100.48	0.35	0.46	0.18
47/83.9	52.30	0.20	1.21	22.18	0.44	9.80	15.05	0.04	–	–	101.22	0.30	0.33	0.38
47/83.9	50.27	0.43	1.32	16.94	0.34	10.00	21.03	0.28	–	–	100.61	0.29	0.44	0.27

roxenite zone, the pyroxenite contains, along with inverted metasomatic pigeonite–augite, inverted pigeonite showing exsolution textures in the form of coarse lamellas parallel to (001) and small augite grains of irregular form. The composition of the orthopyroxene matrix is $Wo_2En_{80}Fs_{18}$, and that of the augite lamellas, $Wo_{45-47}En_{45-47}Fs_8$.

The cumulate Opx has a composition of $Wo_3En_{76}Fs_{21}$ in the lower part of the Gabbronorite zone, and $Wo_4En_{62}Fs_{34}$ in the upper. There are orthopyroxenite interbeds where orthopyroxene has a composition of $Wo_3En_{65}Fs_{32}$. The interstitial Opx in the peridotite marker horizons is more magnesian: $Wo_4En_{80}Fs_{16}$ in the lower unit, and $Wo_{3.5}En_{75}Fs_{21.5}$ in the upper.

Some holes drilled in the central part of the Aganozero Body intersected gabbronorite containing inverted pigeonite with an orthopyroxene matrix having a composition of $Wo_2En_{63}Fs_{35}$, this pigeonite being the most ferrous one in the AB.

To conclude, the widest Opx variation range in the layered series of the Aganozero Body is $Wo_3En_{80}Fs_{17}$ to $Wo_2En_{63}Fs_{35}$.

High-Ca pyroxenes are represented by augite and pigeonite–augite, the latter being usually inverted. Some samples were found to contain uninverted pyroxene grains. The clinopyroxene compositions are presented in Tables 7 and 8 and displayed in Figure 13. In the *Shalozero–Burakovka Body* Cpx is present throughout the section of study. In the Ultrabasic zone, augite is among the main intercumulus phases, and its En content declines upward from En_{51} to En_{44} with some small variations throughout the section. In the main chromite unit, augite has a more magnesian composition, similar to bronzite. Single Pig–Aug grains ($Wo_{38}En_{51-55}Fs_{7-11}$) were found in the ultrabasic zone. In the Pyroxenite zone, augite is substantially more ferroan, $Wo_{46-48}En_{43-45}Fs_9$, in the pyroxenite below the peridotite marker horizon – $Wo_{47}En_{40}Fs_{12}$ and in the gabbronorite interlayer – $Wo_{47}En_{40}Fs_{12}$; the composition of intercumulus augite is $Wo_{42-46}En_{46-49}Fs_{9-10}$ in the peri-

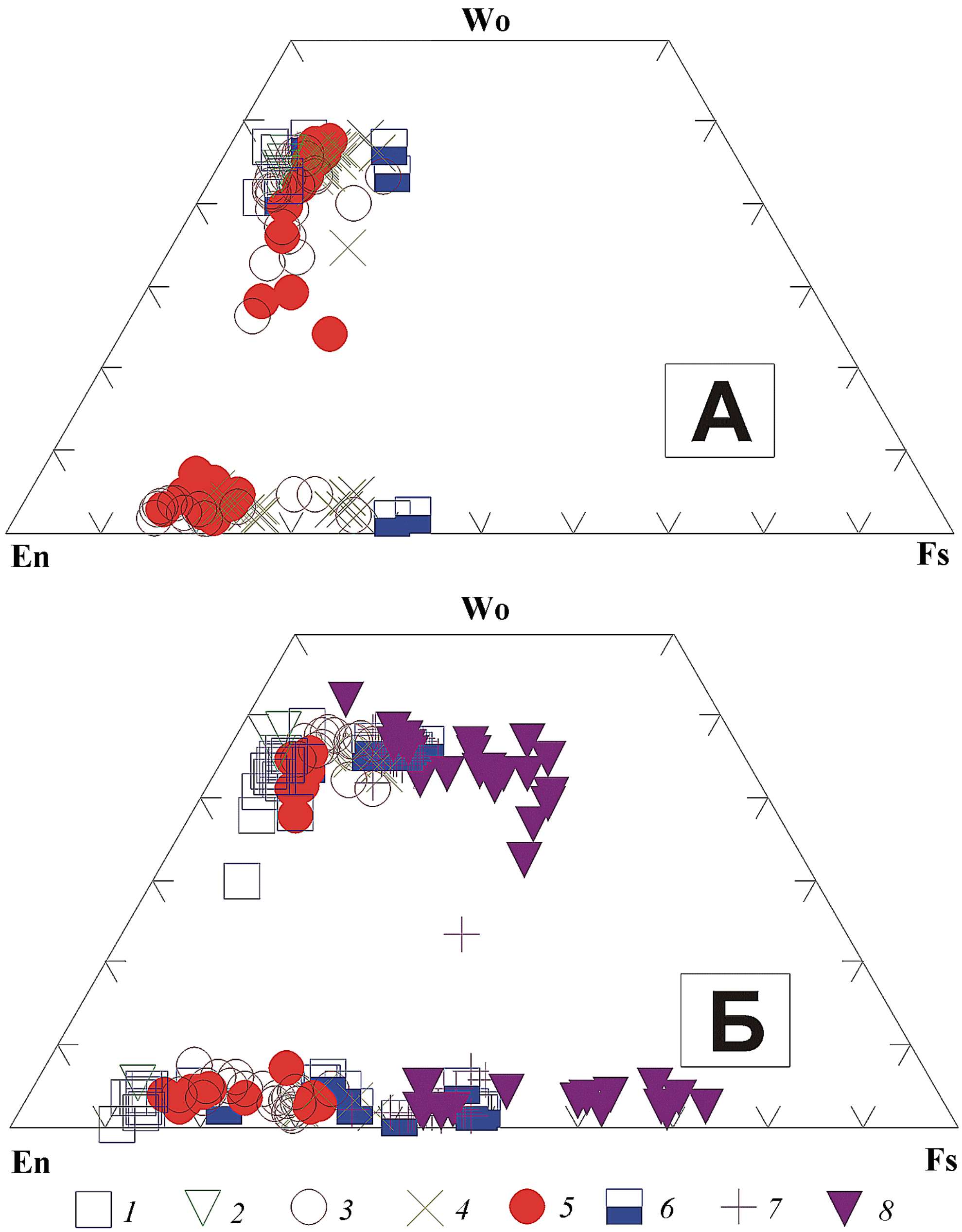

Figure 13. En–Wo–Fs diagram showing the compositions of pyroxenes from the rocks of the Aganozero (A) and Shalozero (B) bodies. 1 to 7 are pyroxenes from the layered series (1 – ultrabasic zone, 2 – main chromite unit, 3 – pyroxenite zone, 4 – gabbronorite zone, 5 – peridotite marker, 6 – pigeonite gabbronorite zone, 7 – magnetite gabbronorite zone); 8 is pyroxene from the marginal series.

dotite, and $Wo_{47-48}En_{41-42}Fs_{10-12}$ in the upper pyroxenite layer. Augite has a composition of $Wo_{46}En_{40}Fs_{14}$ in the Gabbronorite zone.

In the zone of Pigeonite gabbronorite, the composition of the augite matrix in the inverted pigeonite–augite varies from $Wo_{45-46}En_{34-36}Fs_{18-19}$ in the cores of the grains to $Wo_{43-45}En_{35-36}Fs_{20-21}$ in their rims, the composition of the inverted pigeonite lamellas being $Wo_{44-47}En_{40}Fs_{16-19}$. In the Magnetite gabbrodiorite zone, the iron content of the augite matrix in the inverted Pig–Aug grows steadily up the section from $Wo_{46-47}En_{35-36}Fs_{17-18}$ to $Wo_{16}En_{28}Fs_{26}$. Some samples (e.g., 47/83.9) were found to contain pigeonite-augite with a composition of $Wo_{33}En_{30}Fs_{38}$. Thus, the total variation of the augite composition across the layered series was found to be $Wo_{43}En_{51}Fs_{6}$ in the ultrabasic zone to $Wo_{46}En_{28}Fs_{26}$ in the zone of Magnetite gabbrodiorite.

In the *Aganozero Body*, Cpx is also among the main rock-forming minerals. It occurs as angular interstitial grains in

Table 8. Chemical composition of clinopyroxenes from rocks of the Aganozero Body (wt %)

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	Cr_2O_3	NiO	Sum	En	Wo	Fs
Ultrabasic zone and MCH														
20/1627	52.11	0.33	1.66	4.03	0.14	19.07	20.45	0.49	1.02	–	99.30	0.53	0.41	0.06
20/945.5	52.90	0.68	2.48	4.68	0.12	16.93	20.72	0.94	0.54	–	100.83	0.48	0.47	0.05
17/173	53.58	0.37	2.63	3.45	0.13	16.78	22.29	1.73	1.33	0.03	102.32	0.48	0.46	0.06
68/674	54.69	0.13	1.19	4.23	0.15	17.33	21.87	0.49	1.10	–	101.18	0.49	0.44	0.07
Pyroxenite zone														
16/159	52.00	0.32	2.00	5.85	0.17	17.70	21.62	0.60	0.73	0.06	101.05	0.48	0.42	0.10
27/19.8	53.54	0.37	1.91	8.61	0.19	18.55	16.38	0.46	0.19	–	100.20	0.53	0.34	0.14
27/19.8	52.60	0.43	1.81	6.62	0.18	15.77	20.89	0.43	0.20	–	98.93	0.46	0.44	0.11
68/449	53.71	0.40	1.28	7.04	–	19.61	15.99	0.46	0.83	–	99.32	0.56	0.33	0.11
68/449	53.11	0.25	1.96	4.89	–	16.28	22.89	–	0.66	–	100.04	0.46	0.46	0.08
68/611	52.96	0.17	1.17	7.22	0.21	18.59	17.85	0.30	0.34	0.05	98.86	0.52	0.36	0.11
262/10	52.56	0.32	1.83	4.72	0.14	16.50	22.57	0.84	0.76	0.08	100.32	0.47	0.45	0.08
Gabbronorite zone														
68/426.9	51.75	0.23	2.57	5.48	0.17	16.47	22.93	0.46	0.54	0.06	100.66	0.46	0.45	0.09
68/340	52.88	0.38	2.12	5.90	0.17	15.36	22.78	0.54	0.58	0.06	100.77	0.44	0.47	0.09
68/340	52.93	0.17	1.36	13.02	0.27	28.80	2.83	–	0.25	0.08	99.71	0.75	0.05	0.20
68/307	52.02	0.38	2.06	6.41	0.18	15.54	22.85	0.35	0.19	–	99.98	0.44	0.46	0.10
68/299	53.06	0.40	2.14	6.83	0.18	15.62	21.69	0.30	–	–	100.22	0.44	0.45	0.11
68/299	52.19	0.15	1.27	13.98	0.26	28.95	1.62	–	–	–	98.42	0.76	0.04	0.20
68/232	52.34	0.57	2.06	6.57	0.18	16.07	23.38	0.34	–	–	101.51	0.44	0.46	0.10
68/173.5	52.58	0.42	2.17	7.41	0.21	14.71	23.17	0.34	–	–	101.01	0.41	0.47	0.12
4/87.6	50.44	0.53	2.23	6.95	0.19	15.17	23.55	0.40	0.07	0.06	99.59	0.42	0.47	0.11
Peridotite marking horizons														
5/124	50.93	0.37	2.82	6.13	0.14	14.29	22.51	0.89	0.92	0.08	99.08	0.42	0.48	0.10
68/363	51.56	0.17	2.31	6.05	0.18	16.98	20.69	0.44	0.99	0.09	99.46	0.48	0.42	0.10
68/363	52.91	0.18	1.95	8.08	0.23	21.19	13.99	0.30	0.61	0.06	99.50	0.59	0.28	0.13
354/23.6	49.37	0.55	2.25	8.48	0.22	13.43	23.41	0.38	–	–	98.09	0.38	0.48	0.14
354/241.3	51.56	0.32	2.80	6.02	0.17	16.02	20.72	0.74	1.14	–	99.49	0.47	0.43	0.10
Pigeonite-Gabbronorite zone														
353/76.9	50.45	0.67	2.04	9.52	0.26	14.18	23.74	0.30	0.12	–	101.27	0.39	0.46	0.15

the dunite of the ultrabasic zone, and as large oiko-crystals in the peridotite from the top of the zone. The Cpx composition in the ultrabasic zone corresponds to augite with a low iron content, minimal for the marginal rocks, which generally grows up the section from 4.5 to 7.8% Fs.

In the Cr-bearing peridotite of the Main Chromitite Horizon, clinopyroxene is slightly more magnesian ($Wo_{43-46}En_{47-50}Fs_{6-7}$) and shows an elevated Cr_2O_3 content (up to 1.0–1.2 wt.%).

Clinopyroxene is more ferroan in the Pyroxenite zone. The clinopyroxene matrix in the inverted Pig–Aug from the metasomatic clinopyroxene and websterite has a $Wo_{45-47}En_{44-47}Fs_{8-9}$ composition. The primary composition of pigeonite–augite, obtained with a defocused beam, was found to be $Wo_{36.2}En_{52.4}Fs_{11.4}$, which is generally close to the $Wo_{33}En_{53}Fs_{14}$ composition found for the undecomposed portion of one of the grains. The cumulate augite was found to be $Wo_{47}En_{44}Fs_9$. In the wehrlites (Sample 16/159) augite is more magnesian – $Wo_{45-47}En_{44-46}Fs_{8-9}$. Analyses of individual pyroxene grains did nor reveal any zoning, but showed some heterogeneity expressed in the compositional variations (mainly in terms of a Fe/Mg ratio) in some regions of the grains. All clinopyroxenes from the ultramafic part of the sequence were found to contain 0.12–0.8% Cr_2O_3 and <0.08% NiO.

Above the Pyroxenite zone, augite occurs mainly as a cumulate mineral in a plagioclase–two pyroxene assemblage. In the Gabbronorite zone, Cpx is more ferroan ($Wo_{45-46}En_{41-44}Fs_{10-13}$). Its Cr_2O_3 content is not higher than 0.1% and that of NiO, 0.09%, the most common values being 0–0.06% and 0.05%, respectively. In the peridotite marker horizons, the interstitial clinopyroxene has a composition of $Wo_{44}En_{47}Fs_{10}$, this composition being most magnesian for the Gabbronorite zone. In the Pig-bearing gabbronorite from the top of the layered series, clinopyroxene has the highest iron content and a $Wo_{45-46}En_{40}Fs_{14-15}$ composition.

To conclude, viewed along the section of the layered series in the Aganozero Body, the clinopyroxene composition varies from $Wo_{47}En_{48.5}Fs_{4.5}$ at the bottom to $Wo_{45-46}En_{40}Fs_{14-15}$ in the upper pigeonite-bearing gabbronorite.

Plagioclase is widely developed in the intercumulus of

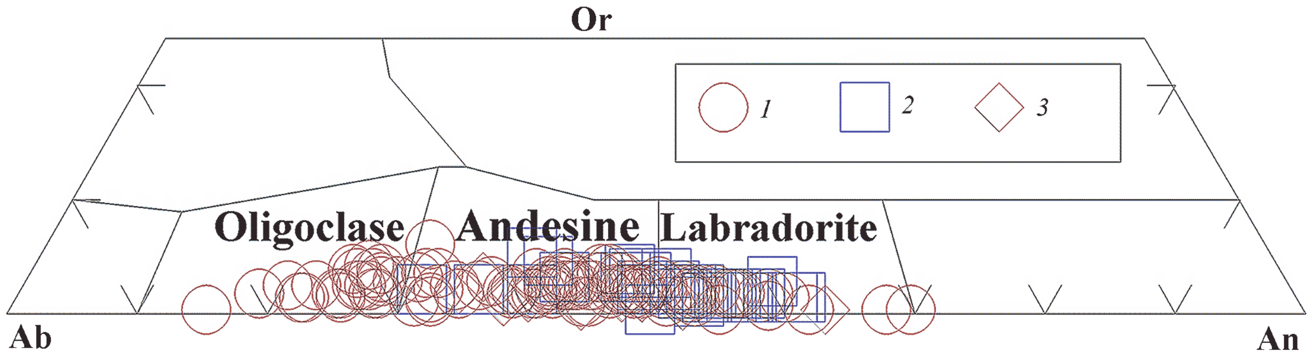

Figure 14. Ab–An–Or diagram showing the compositions of plagioclases from the rocks of the layered series in the Shalozero (1) and Aganozero (2) bodies and also from the rocks of the marginal series (3).

the ultrabasic and pyroxenite zones and is the main cumulate phase in the overlying zones. Variations in its composition are plotted in Figure 14 and listed in Tables 9 and 10.

In the Ultrabasic zone of the Shalozero–Burakovka Body, plagioclase is highly chloritized. As a result, we were able to examine merely two of the single grains: one of labradorite $Or_3Ab_{51}An_{46}$, the other of oligoclase-andesine $Or_3Ab_{66}An_{30}$. In the MCH, the interstitial plagioclase is represented by even more silicic oligoclase $Or_1Ab_{84}An_{15}$. Intercumulate plagioclase has a composition of $Or_{2-3}Ab_{42-43}An_{55}$ in the Pyroxenite zone below the marker horizon and is represented by labradorite $Or_2Ab_{44}An_{53-54}$ and scarce oligoclase ($Or_{2-4}Ab_{71}An_{25-27}$) above it. Plagioclase has a labradorite composition ($Or_4Ab_{45}An_{51}$) in the rocks of the marker horizon.

Plagioclase is a cumulate mineral in the rocks above the Pyroxenite zone. In the Gabbronorite zone it is almost wholly unzoned and has a composition of $Or_{2-4}Ab_{46-48}$ An_{50-52}. Plagioclase is slightly normally zoned in the Pigeonite gabbronorite zone, where its composition varies rather widely ($Or_{2-3}Ab_{46-58}An_{40-51}$). However, because this zone was poorly studied, we did not find any systematics in these variations. Some plagioclase grains showed inverse zoning, from An_{42} in the core to An_{59} in the margin. We believe this pattern to have been caused by the roiling of the settling crystals by fresh magma portions [*Higgins et al.,* 1997]. In the Magnetite gabbrodiorite zone the composition of plagioclase varies from andesine $Or_{3-4}Ab_{55-57}An_{39-42}$ to $Or_2Ab_{66}An_{32}$. The total variation of the cumulate plagioclase across the layered series was found to be An_{50} to An_{32} (without taking into account the interstitial phases of the Ultrabasic and Pyroxenite zones).

In the Ultrabasic zone of the *Aganozero Body*, the composition of interstitial plagioclase varies from $Or_1Ab_{47}An_{52}$ to $Or_2Ab_{54}An_{44}$. In the Pyroxenite zone, the composition of the interstitial plagioclase is variable too ($Or_{1-3}Ab_{38-48}$ An_{50-60}). It is only in the Gabbronorite zone that plagioclase occurs as the main cumulate phase, growing more silicic up the sequence, from $Or_1Ab_{42}An_{57}$ to $Or_3Ab_{35}An_{42}$. Some grains are normally zoned with the An component declining by 3–4% from the cores to the margins of the grains. Reversed zoning is less common. The plagioclase composition is $Or_{0.5-5.5}Ab_{50-63}An_{39-49}$ in the peridotite of the markers.

To sum up, our study of the cryptic layering in the Aganozero and Shalozero–Burakovka bodies of the Burakovka Pluton revealed the following variations in the mineral compositions up the sequences of the layered rocks (see Figures 11 and 12): in the latter, Fo_{88} declines to Fo_{79} in olivine, En_{86} to En_{38} in low-Ca pyroxene, En_{51} to En_{28} in augite, and An_{50} to An_{32} in plagioclase; in the former, $Fo_{88.5}$ declines to Fo_{76} in olivine, En_{80} to En_{63} in low-Ca pyroxene, $En_{48.5}$ to En_{40} in clinopyroxene, and An_{60} to An_{39} in plagioclase. Comparing these data, one can see that the olivine and pyroxenes have similar compositions in the ultramafic rocks of the layered sequences in both bodies. In the Shalozero–Burakovka Body, the clinopyroxene is more ferroan toward the top of the sequence, this possibly being accounted for by the more complete sequence of a gabbroid portion in its layered series.

Chrome-spinels are typomorphic accessory minerals in the rocks of the ultrabasic and pyroxenite zones and in the peridotites of the peridotite marker horizons. Their compositions are presented in Tables 11 and 12.

Accessory chrome spinelids are represented in the ultramafic zones mainly by subferrialuminochromite and are distinguished by high Mg and Cr contents, which grow up the zones (Figure 15). Chrome-spinel from the ultrabasic zone of the Shalozero–Burakovka Body is distinguished by high vanadium, nickel, and zinc contents.

Chrome-spinel is represented by subferrialuminochromite also in the chromite ore units of both bodies, ore varieties with higher Mg and Cr contents (subferrichromite) occurring also in the Aganozero Body. The chrome-spinels found in the Yakozero Unit are distinguished by Cr_2O_3 as high as 56.81 wt.% (the maximum value for the Burakovka Pluton).

A special study of chromites in the Main Chromite Horizon in the Aganozero Body revealed the presence of numerous fine Ru–Os sulfide crystals ranked with a laurite-erlichmanite group [*Smirnova and Dmitrienko,* 1994]. Neither accessory chromite nor chromitites from the Shalozero–Burakovka Body have been studied in this respect.

Chrome-spinel grains were found to account for 3–5 to 20–30% in the peridotite marker horizons of the Gabbronorite zone of the AB and in the Pyroxenite zone of the SBB. The chrome-spinel was identified as subalumoferrichromate or subferrialumochromite. Magnetite was found in rims around

Table 9. Composition of plagioclases from rocks of the Shalozero–Burakovka Body (wt %)

Sample	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	Sum	An	Ab	Ort
Ultrabasic zone and the MCH										
341/154	61.33	24.36	0.10	5.95	8.42	0.60	100.76	0.27	0.69	0.04
341/171	58.45	25.94	0.12	9.11	7.48	0.30	101.40	0.39	0.59	0.02
341/154.9	61.55	20.88	0.09	3.47	10.82	0.22	97.03	0.15	0.84	0.01
335/253	59.22	25.30	0.14	6.70	8.01	0.63	100.00	0.30	0.66	0.04
Pyroxenite zone and Marking Horizon										
174/83.7c	54.80	29.39	0.18	10.63	5.85	0.51	101.36	0.49	0.48	0.03
174/83.7r	55.16	28.69	0.22	10.34	6.36	0.57	101.34	0.46	0.51	0.03
333/432.8	53.60	27.52	0.15	10.66	5.24	0.16	97.33	0.52	0.47	0.01
333/475	53.52	29.14	0.08	10.56	7.23	0.49	101.02	0.44	0.54	0.02
338/132-1	53.10	28.68	0.22	11.50	5.31	0.34	99.15	0.53	0.44	0.02
338/132-2	52.93	29.17	0.23	11.87	5.26	0.31	99.77	0.54	0.44	0.02
338/165	56.68	29.56	0.12	8.87	5.53	0.51	101.27	0.45	0.51	0.04
338/188-1	51.86	30.17	0.24	13.04	4.80	0.25	100.36	0.59	0.39	0.02
338/188-2	54.40	27.81	0.26	10.06	6.04	0.35	98.92	0.47	0.51	0.02
341/95.4r	60.07	23.79	0.19	5.74	8.26	0.28	98.33	0.27	0.71	0.02
341/95.4c	60.31	24.30	0.14	5.47	8.69	0.69	99.60	0.25	0.71	0.04
341/64.2	53.57	29.65	0.30	11.08	5.31	0.33	100.24	0.52	0.45	0.02
342/84.8	55.56	28.10	0.10	10.48	6.87	0.59	101.70	0.44	0.53	0.03
342/93.5-r	52.65	29.42	0.19	12.13	5.28	0.29	99.96	0.55	0.43	0.02
342/93.5-c	53.44	29.57	0.23	12.13	5.15	0.34	100.86	0.55	0.42	0.02
Pigeonite-Gabbronorite zone										
31/220.7-c	55.29	28.05	0.10	10.21	5.54	0.40	99.59	0.50	0.48	0.02
31/220.7-r	56.66	27.25	0.09	9.21	6.81	0.45	100.47	0.42	0.56	0.02
31/383-c	56.40	26.20	0.12	10.69	6.27	0.40	100.08	0.48	0.50	0.02
31/383-r	59.10	24.70	0.14	8.79	7.80	0.37	100.90	0.49	0.60	0.02
32/206.4-r	56.70	26.42	0.18	9.19	7.13	0.54	100.16	0.40	0.57	0.03
32/206.4-c	57.47	26.72	0.19	9.71	6.58	0.42	101.09	0.44	0.54	0.02
333/247.6-r	55.75	27.02	0.27	9.23	7.10	0.42	99.79	0.41	0.57	0.03
333/247.6-c	54.25	28.04	0.26	10.28	6.25	0.39	99.47	0.46	0.51	0.03
335/90.8	54.75	29.25	0.27	11.11	5.55	0.34	101.27	0.51	0.46	0.02
Zone of Magnetite Gabbro-Diorites										
45/89.2-1	57.11	26.61	0.14	8.49	6.93	0.65	99.95	0.39	0.57	0.04
45/89.2-2	57.54	26.88	0.12	8.77	6.51	0.60	100.42	0.42	0.55	0.03
47/83.9-c	60.62	25.70	0.17	7.27	8.14	0.40	102.30	0.32	0.66	0.02
47/83.9-r	61.13	23.78	0.13	6.10	8.99	0.46	100.59	0.27	0.71	0.02
129/146	59.83	24.48	0.03	5.41	9.99	0.47	100.21	0.75	0.22	0.03
129/120	59.74	24.95	0.04	5.88	9.48	0.27	100.36	0.73	0.25	0.02
129/174-c	52.20	29.00	0.28	13.32	5.30	0.27	100.37	0.41	0.57	0.02
129/174-r	53.30	28.50	0.27	12.56	6.30	0.24	101.17	0.47	0.52	0.01
123/253.5-r	55.60	27.20	0.14	9.29	7.50	0.29	100.02	0.58	0.40	0.02
123/253.5-r	57.20	26.00	0.12	8.19	8.30	0.28	100.09	0.64	0.35	0.02
123/253.5-2	60.50	23.00	0.13	5.43	10.9	0.33	100.29	0.77	0.21	0.02

Note: c– center of grain, r – rim.

some grains and is also developed in the cracks of the latter. In some places ilmenite lamellas were found. The chrome-spinel was found to contain less Cr and more Fe.

To sum up, the chrome-spinels tend to be lower in Cr up the section of the layered series in both bodies of the Burakovka Pluton with Cr $\rightarrow$ Fe^{+3}+Al being the leading isomorphism for chrome-spinels in the course of their formation (Figure 16). The chrome-spinels of the ore units in both bodies are distinguished by the higher Mg and Cr contents compared with the accessory chromite in the dunites and peridotites of the ultrabasic zones, where more aluminiferous varieties are developed, and also by the higher Mg content of the coexisting dark-colored silicate minerals. This suggests the higher temperature of the formation of the ore units, which was reported to be 1300–1200°C [*Nikolaev,* 1997].

Summarizing the results of studying cryptic layering in

Table 10. Chemical composition of plagioclases from rocks of the Layered series of the Aganozero Body (wt %)

Sample	SiO_2	Al_2O_3	FeO	CaO	Na_2O	K_2O	Sum	Ab	An	Or
				Pyroxenite zone						
27/19.8-1	55.08	27.27	0.14	10.44	5.57	0.60	99.10	47.5	49.2	3.4
27/19.8-2	57.20	27.90	0.19	9.89	5.92	0.67	101.77	50.1	46.2	3.7
284/139-1	55.42	26.61	0.26	10.23	5.51	0.39	98.42	48.2	49.5	2.2
284/139-2c	53.18	30.07	0.36	13.08	4.58	0.22	101.49	38.3	60.5	1.2
284/139-2r	55.29	28.31	0.27	11.15	5.41	0.16	100.59	46.3	52.8	0.9
68/449-1	52.83	29.54	0.14	12.74	5.30	0.25	100.80	42.4	56.3	1.3
				Gabbronorite zone						
68/426.9	53.08	28.30	0.58	10.17	5.92	0.37	98.42	50.2	47.7	2.1
68/340	56.11	27.85	0.17	9.09	6.74	0.59	100.55	55.5	41.3	3.2
68/307-1c	53.73	29.14	0.31	12.73	5.23	0.24	101.38	42.1	56.6	1.3
68/307-1r	55.14	28.78	0.31	12.27	5.35	0.27	102.12	43.5	55.1	1.4
68/307-2	54.82	28.86	0.26	12.14	5.37	0.30	101.75	43.7	54.7	1.6
68/299-2c	52.20	29.49	0.28	12.27	4.60	0.25	99.09	39.8	58.7	1.4
68/299-2r	52.80	28.17	0.28	12.61	4.74	0.25	98.85	39.9	58.7	1.4
68/299-3	52.87	29.40	0.24	12.56	5.04	0.24	100.35	41.5	57.2	1.3
68/232-1c	52.70	30.36	0.26	12.15	5.18	0.37	101.02	42.7	55.3	2.0
68/232-1r	52.46	29.36	0.26	11.33	5.36	0.45	99.22	45.0	52.5	2.5
68/173.5-2c	53.85	28.63	0.31	11.88	4.64	0.39	99.70	40.5	57.3	2.2
68/173.5-2r	53.00	27.91	0.28	11.04	5.66	0.52	98.41	46.8	50.4	2.8
68/80-2c	54.74	25.87	0.39	11.26	5.59	0.40	98.25	46.3	51.5	2.2
68/80-2r	57.58	25.87	0.37	9.50	7.01	0.58	100.91	55.5	41.5	3.0
354/23.6	54.80	27.44	0.33	11.74	6.15	0.37	100.83	47.7	50.4	1.9
4/87.6-1c	54.99	29.28	0.32	12.37	5.34	0.30	102.60	43.2	55.2	1.6
4/87.6-1r	55.40	28.88	0.28	11.68	5.32	0.33	101.89	44.4	53.8	1.8
352/172-1c	51.89	28.39	0.19	12.51	5.01	0.30	98.29	41.3	57.0	1.6
352/172-1r	53.92	26.89	0.19	11.22	5.82	0.45	98.49	47.3	50.3	2.4
352/172-2	52.77	27.84	0.17	12.49	4.74	0.49	98.50	39.6	57.7	2.7
				Marking horizons						
352/176.1-1c	54.50	27.92	0.19	11.74	5.96	0.35	100.66	47.0	51.2	1.8
352/176.1-1r	55.02	27.82	0.22	11.04	6.39	0.37	100.86	50.2	47.9	1.9
352/178-1c	54.25	28.61	0.18	12.10	5.45	0.31	100.90	44.2	54.2	1.6
352/178-1r	53.77	29.11	0.15	12.02	5.41	0.25	100.71	44.3	54.4	1.4
354/21-1c	55.98	26.31	0.10	8.76	7.17	0.35	98.67	58.6	39.5	1.9
354/21-1r	56.56	26.21	0.06	8.10	7.91	0.39	99.23	62.6	35.4	2.0
354/21.3	54.63	27.80	0.12	11.29	6.39	0.06	100.29	50.4	49.2	0.3
354/241.3	54.37	26.99	0.19	10.83	6.54	0.59	99.51	50.7	46.3	3.0
5/124.2-1c	56.66	26.82	0.14	9.26	7.27	0.92	101.07	56.0	39.4	4.7
5/124.2-1r	57.73	26.78	0.15	8.87	7.35	1.07	101.95	56.7	37.8	5.4
68/363-1	54.85	28.74	0.18	11.14	5.61	0.25	100.77	47.0	51.6	1.4
68/363-2c	54.75	29.00	0.22	11.19	5.42	0.22	100.80	46.1	52.6	1.2
68/363-2r	55.17	28.80	0.19	10.76	5.70	0.25	100.87	48.3	50.3	1.4
68/365	57.42	27.00	0.21	8.40	6.71	0.63	100.37	57.0	39.5	3.5

See remark to Table 9.

the Burakovka Pluton, we can state that the character and variation range of its main typomorphic minerals is similar to those in the other large layered plutons, such as Bushveld (South Africa), the Great Dike in Zimbabwe, and others. For instance, in the Great Dike, the Mg content of olivine varies up the sequence from Fo_{94} to Fo_{85}, and the compositions of cumulate clino- and orthopyroxene vary from En_{51} to En_{38} and from En_{92} to En_{58}, respectively [*Layered Intrusions,* 1996]. In the west of the Bushveld Massif the composition of olivine varies from Fo_{89} to Fo_{83}, and of orthopyroxene from En_{89} to En_{30} [*Layered Intrusions,* 1996]. In the Stillwater massif the total changes of the composition of olivine vary through the section from Fo_{91} to Fo_{81}, that of clinopyroxene, from En_{52} to En_{42}, and that of orthopyroxene, from En_{83} to En_{58} [*Wager and Brown,* 1970]. However, in contrast to other intrusive massifs, the Burakovka Pluton

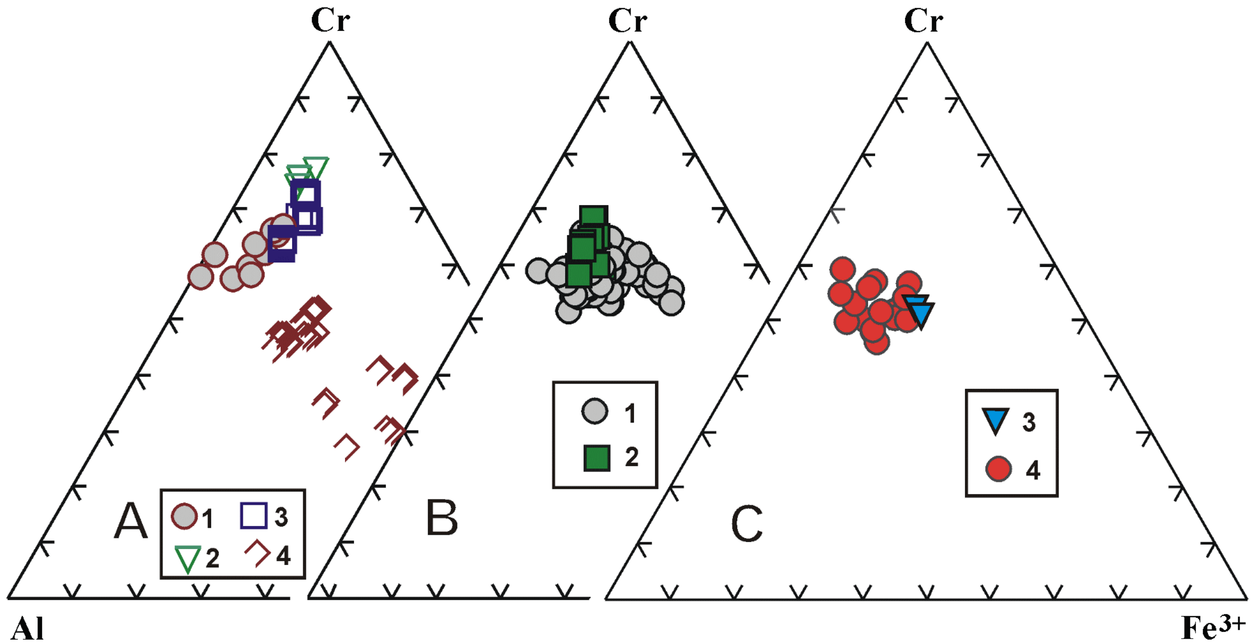

Figure 15. Al–Cr–Fe^{3+} diagram for the chrome spinels from the rocks of the Burakovka Pluton. A – Aganozero Body (1 – ultrabasic zone, 2 – Yakozero unit, 3 – main chromite unit, 4 – peridotite marker from the gabbronorite zone); B and C – Shalozero Body (1 – ultrabasic zone, 2 – main chromite unit, 3 – pyroxenite zone, 4 – peridotite marker).

is distinguished by its more silicic plagioclase, the composition of which varies up the layered rock sequence from An_{60} in the Aganozero Body to An_{32} in the Shalozero–Burakovka Body.

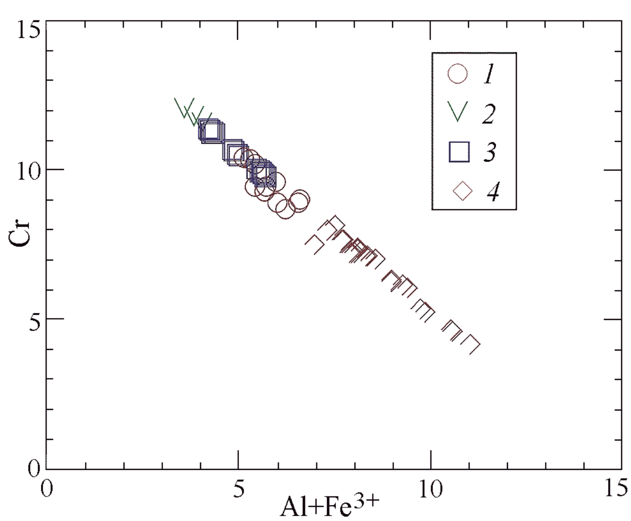

Figure 16. Cr/Al+Fe^{3+} diagram for chrome spinels (calculated for 3 oxygen atoms) from the rocks of the layered series in the Aganozero Body: 1 – accessory chrome spinels from the rocks of the ultrabasic zone, 2 – chrome spinels from the ore-bearing layer in the Yakozero Body, 3 – from the main chromite unit, 4 – from a peridotite marker in the rocks of the gabbronorite zone.

Vein Rocks

Vein rocks are especially widely developed in the Shalozero –Burakovka Body, where they occur as compositionally various veins ranging from a few meters to a few dozens of meters in thickness, their dominating rocks being microgabbronorite, gabbronorite-pegmatite, granophyre, and potassic granite. Vein rocks are scarce in the Aganozero intrusion.

The vein-shaped bodies of microgabbronorite seem to have been feeders that channeled fresh magma portions into the crystallizing intrusive chambers, while the gabbronorite-pegmatite bodies were local accumulations of residual magma in the cumulate rocks.

Of particular interest are *vein granites*. These rocks are widely developed in the northeastern part of the Shalozero–Burakovka Body, where they occur mainly in the Pigeonite Gabbronorite Zone. The granites are gray or light gray, massive, mainly fine- and medium-grained rocks which occur as cross-cutting veins ranging from 0.5 cm to a few dozens of meters in thickness. They vary in composition from biotite leucogranodiorite to K-granite. The granite veins usually have distinct, rectilinear or angular contacts with the host gabbronorite and occasionally include small fragments of the latter. Neither chill zones nor any low-temperature alterations of the host rocks were observed. The isotopic and geochemical characteristics of the granites [*Bogina et al.,* 2000] preclude their formation by way of the basement rock melting and suggest the same source of origin, common for the granites and their host mafic rocks. The geological, petrologic, and isotopic–geochemical data available suggest that the granites originated synchronously with the

Table 11. Chemical composition of chrome-spinels from the Aganozero Body (wt %)

Sample	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	MgO	NiO	ZnO	V_2O_5	Sum	Al	Cr	Fe^3
Ultrabasic zone														
20/1541	2.00	14.10	45.03	6.72	23.69	0.10	7.78	0.19	–	0.34	99.61	4.41	9.45	1.34
20/1541	2.70	15.91	41.86	6.49	24.83	0.10	7.63	0.25	–	0.37	99.77	4.94	8.71	1.29
20/945.5	1.00	19.58	48.71	1.06	18.72	0	11.36	0.13	–	0.21	100.56	5.78	9.65	0.20
17/173	1.32	18.84	44.69	5.21	21.03	0.25	9.91	0.18	–	0.18	101.42	5.60	8.91	0.99
68/701.8	0.78	12.55	48.35	6.52	26.29	0	5.39	0.14	–	0.20	100.02	4.00	10.35	1.33
68/701.8	1.05	11.66	49.14	7.37	22.86	0	7.63	0.20	–	0.18	99.91	3.68	10.41	1.49
Yakozersky Chromitite Horizon														
255/55.8	0.83	8.43	56.59	6.14	17.48	0	10.81	0.20	–	0.16	100.49	2.63	11.82	1.22
255/55.8	0.78	6.69	56.49	7.29	16.34	0	10.98	0.20	–	0.18	98.77	2.13	12.07	1.48
Main Chromitite Horizon														
68/674	1.12	9.20	49.34	9.07	25.61	0.31	5.45	0.15	0.14	0.18	100.39	2.97	10.69	1.87
68/678	0.98	8.64	54.61	8.14	16.97	0.28	11.15	0.19	0.02	0.16	100.97	2.67	11.33	1.61
9/173	1.19	12.63	49.00	8.24	18.88	0.30	10.38	0.20	0.04	0.13	100.86	3.87	10.06	1.61
Marking peridotite horizons														
354/241.3	3.44	11.57	34.31	15.31	30.25	0.26	3.86	0.28	–	–	99.36	3.79	7.53	3.20
354/21.9	1.28	15.67	19.37	29.00	32.28	0.23	1.91	0.41	–	–	100.48	5.08	4.21	6.00
5/124.2	1.83	11.08	20.47	31.99	30.38	0.30	2.24	0.51	–	0.61	98.79	3.73	4.62	6.87
68/365	0.82	13.47	38.49	16.18	23.80	0.21	6.80	0.24	–	0.29	100.30	4.15	8.16	3.38
352/178	1.30	16.10	33.86	16.21	27.74	0.28	4.89	0.25	–	–	100.63	5.07	7.15	3.26
352/178.3	1.52	14.06	36.04	16.02	27.01	0.09	5.32	0.31	–	–	100.37	4.46	7.67	3.25
352/178.3	1.47	13.63	35.86	16.59	27.03	0.08	5.21	0.28	–	–	100.15	4.35	7.67	3.38

Note: – = not determined; 0 – below the level of sensitivity.

Table 12. Composition of chrome-spinels from the Shalozero–Burakovka Body (wt %)

Sample	TiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	MnO	MgO	NiO	ZnO	Sum	Al	Cr	Fe^3
Ultrabasic zone													
334/249	1.70	9.88	43.67	12.69	25.81	0.36	5.46	0.31	0.19	100.07	0.40	1.18	0.33
334/171.7	0.45	15.53	41.07	12.28	24.68	0.10	6.45	0.20	0.25	101.01	0.60	1.07	0.30
334/168	1.37	9.37	41.04	15.98	26.05	0.18	4.97	0.31	0.30	99.57	0.38	1.13	0.42
334/104.4	2.05	13.83	39.35	11.94	28.00	0.18	4.88	0.25	0.32	100.80	0.55	1.05	0.30
334/301.5	1.33	12.11	45.86	9.56	25.90	0.20	5.79	0.22	0.30	101.27	0.48	1.21	0.24
334/276.1	1.00	11.64	46.39	11.13	21.54	0.07	8.39	0.27	0.12	100.56	0.46	1.22	0.28
334/115	1.80	11.07	41.11	14.20	27.41	0.16	4.88	0.33	0.31	101.27	0.44	1.10	0.36
334/133.2	2.07	7.09	37.94	20.88	28.83	0.15	3.65	0.39	0.21	101.20	0.29	1.05	0.55
335/253	1.50	12.94	41.54	13.63	24.68	0.10	6.92	0.34	0.16	101.81	0.50	1.08	0.34
341/171	2.09	12.81	38.73	15.17	22.72	0.25	8.06	0.46	0.16	100.45	0.50	1.02	0.38
Pyroxenite zone and Marking horizon													
67/748	1.50	18.59	36.85	9.69	25.54	0.35	6.32	0.19	0.27	99.30	0.72	0.96	0.24
67/838	3.39	16.48	37.61	6.69	31.53	1.04	2.95	0.18	0.55	100.42	0.66	1.00	0.17
174/83.7	1.08	17.22	35.72	13.78	27.54	0.37	5.09	0.18	0.00	100.98	0.67	0.93	0.34
338/165	2.22	16.31	35.55	11.45	29.39	0.30	4.08	0.18	0.34	99.83	0.65	0.95	0.29
342/93.5	1.74	12.02	36.60	16.40	29.38	0.21	3.52	0.24	0.20	100.31	0.49	1.00	0.43
342/84.8	1.58	14.08	40.70	9.98	28.36	0.10	4.39	0.22	0.00	99.41	0.57	1.10	0.26
342/78.6	3.52	12.76	34.21	14.57	27.88	0.08	5.49	0.31	0.00	98.82	0.52	0.93	0.38
Main Chromitite Horizon													
335/186.3	0.78	10.30	49.91	8.32	22.02	0.22	7.55	0.20	0.11	99.41	0.41	1.34	0.21
335/186.3	1.82	13.62	41.14	9.97	27.48	0.85	4.56	0.25	0.11	99.80	0.55	1.11	0.26
341/154	1.08	13.79	43.92	10.28	23.57	0.25	7.25	0.22	0.10	100.46	0.54	1.15	0.26
341/159	1.08	12.34	46.11	10.50	23.25	0.35	7.43	0.22	0.11	101.39	0.48	1.20	0.26
341/154.9	1.20	11.83	48.60	8.16	20.08	0.27	9.25	0.25	0.06	99.71	0.46	1.27	0.20
341/154.9	0.80	10.98	50.76	7.32	19.38	0.22	9.29	0.25	0.07	99.06	0.43	1.34	0.18

gabbroids *in situ* within the zone of Pigeonite gabbronorite. It is believed that these granites were derived from the residual interstitial silicic melt that was retained in the almost solidified cumulates of this zone. Where the process of contraction was operating, this magma must have been sucked into shrinkage cracks under the resulting vacuum effect.

The Shalozero–Burakovka Body also includes widely developed late gabbroid dikes which are believed to be the late Paleoproterozoic formations of the Pudozhgora submeridional dike belt.

Geochemistry of the Burakovka Rocks

To study the compositions of the rocks typical of the Burakovka Pluton samples were collected from the zones identified in the Aganozero and Shalozero–Burakovka bodies, which had been least subject to secondary alteration, and also a few samples from the rocks of the Marginal Border Group.

Methods of Geochemical Study. The bulk compositions of the rocks were determined using a conventional chemical analysis in the Central Chemical Laboratory of the Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), Russian Academy of Sciences. The contents of trace elements were determined by X-ray fluorescence analysis. Several methods were used to determine REE contents. Some REE were determined by neutron activation analysis, with the radiochemical separation of "noise" elements, in the Geological Institute, Russian Academy of Sciences, using a method proposed by *Lyapunov et al.* [1980]. The convergence of the analytical results was estimated using a BCR-1 standard. Most of the samples were analyzed by ICP-MS in the IGEM Central Laboratory. Analyses were made using a quadrupole Plasma Quad PQ2+Turbo mass spectrometer, a VG Instruments product. The correct use of the technique was checked using certified standard solutions and an AGV international standard sample.

Results. The representative analyses of the rocks are presented in Tables 1 and 2. Many rocks were marked by the combination of high Mg, Cr, and Ni contents with high SiO_2 concentrations and low contents of Ti, alkalies, HREE, Nb, Y, etc. Satisfactory correlation trends were observed for some of the major elements with MgO: negative for the alkali sums and Al_2O_3 (Figure 17) and positive for Ni (Figure 18).

Figure 19 shows the compositions of the Burakovka rocks, normalized to mid-oceanic tholeiites (MORB). Compared with the latter, all rocks of the pluton are enriched in lithophyle elements (Rb, Ba, Sr), and the gabbroids are also enriched in LREE with the lower contents of HREE and Ti, the contents of the latter being significant only in the gabbronorite containing cumulate titanomagnetite from the Shalozero–Burakovka body. The curve of the distribution of REE and trace elements in the rocks of the pluton (Figure 20), normalized to the primitive mantle composition after *Hofmann* [1988], showed the enrichment of the rocks in Rb, Sr, and Ba with the relatively low contents of metallic elements such as Ni, V, and Cr. The contents of the latter were found to be significantly higher in the rocks of the ore-bearing chromitite layers.

In spite of some insignificant differences, all rocks of the pluton showed a generally similar REE distribution trend. The total REE concentrations grow normally from the mafic cumulates at the bottoms of both bodies to the gabbronorite in their tops (Table 13). In the case of the Shalozero–Burakovka body the REE content grows from 10 ppm in poikilitic peridotite to 72.8 ppm in magnetite gabbronorite, this variation range being 2.5 to 20.6 ppm in the Aganozero Body. The rocks also show a successive enrichment in LREE: the Ce/Yb ratio grows from 13.7 to 49.2 ppm in the SBB and from 1.5 to 4.5 in the AB.

The results of our study revealed a significant enrichment in REE and LREE of the Shalozero–Burakovka rocks relative to the same rocks in the Aganozero body (Figure 21), and also the high REE contents in the peridotite of the markers relative to the rocks of the Ultrabasic Zone, this suggesting the enrichment of their parental magmas which are interpreted as later intrusions.

The REE distribution patterns in both bodies of the pluton are similar to the patterns observed in similar layered intrusions in the Baltic and other shields, and also in the high-Mg basalts of the same age from the Vetreny Belt. All rocks studied in the Burakovka Pluton yielded similar REE distribution patterns, characterized by the growth of REE concentrations up the rock sequence with the growing LREE contribution suggesting the accumulation of the latter in the residual melt during the directional solidification of the intrusions. The higher REE enrichments of the SBB rocks relative to the same rocks of the Aganozero Body suggest the relative enrichment of the primary magma (or magmas) parental for the former.

To sum up, the geochemical features characteristic of the rocks from both bodies of the pluton suggest that they were produced by the intrusion of siliceous high-Mg (boninite-like) magma. This is supported by the composition of the gabbronorite from the contact the SBB (Sample 28a/218), which is similar to the B1-type boninite-like parental magma of the Bushveld Complex [*Sharpe and Hulbert,* 1985] (Figure 22). Its REE distribution pattern is close to that of the chilled endocontact rocks from the other layered intrusions of the Baltic Shield, combined into one large igneous province of a siliceous high-magnesian rock series (SHMS) (see below). Magmas of this type constitute a specific feature of igneous activity during the Early Proterozoic, and the rocks they produced are abundant in all Precambrian shields. [*Bogatikov et al.,* 2000; *Sharkov et al.,* 1997].

Isotopic Studies

The isotopic studies of our rock samples were carried out in the Institute of Precambrian Geology and Geochemistry, Russian Academy of Sciences, St-Petersburg. For this purpose we collected samples along the sections across the layered series of both bodies (see Figure 2), which contain all major rock types, least subject to secondary alteration. The methods of Sm–Nd and Rb–Sr studies are described in

Table 13. Concentration of the rare-earth elements (ppm) in rocks of layered and marginal series of the Aganozero and Shalozero–Burakovka bodies

	Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Sum	Ce/Yb	Ce/Sm	La/Nd
	Ultrabasic zone																		
	Shalozero–Burakovka Body																		
1	174/204	2.3	4.2	0.47	1.80	0.38	0.17	0.34	0.05	0.3	0.06	0.19	0.03	0.18	0.03	10.50	23.33	11.05	1.28
2	334/301.5	1.9	3.5	0.47	2.09	0.50	0.16	0.48	0.07	0.41	0.08	0.23	0.03	0.16	0.03	10.01	21.88	7.00	0.91
3	334/115	2.0	3.9	0.51	2.20	0.50	0.17	0.54	0.08	0.44	0.09	0.25	0.04	0.24	0.04	11.00	16.25	7.80	0.91
4	338/234	3.99	8.1	0.93	3.55	0.65	0.17	0.62	0.08	0.48	0.10	0.25	0.04	0.23	0.03	19.22	35.22	12.46	1.12
	Aganozero Body																		
5	20/945.5	0.30	<1	–	<1	0.07	0.029	–	0.020	–	–	–	–	0.076	0.013	2.50	13.16	14.29	0.30
6	200/444	0.49	1.39	–	1.02	0.3	0.10	0.31	0.05	0.33	0.07	0.17	0.02	0.16	0.02	4.43	8.69	4.63	0.48
7	68/701.8	0.29	<1	–	<1	0.12	0.056	–	0.037	–	–	–	–	0.090	0.014	2.60	11.11	8.33	0.29
	Main Chromitite Horizon																		
	Shalozero–Burakovka Body																		
8	334/100.5	1.7	4.14	0.54	2.2	0.49	0.16	0.5	0.07	0.43	0.08	0.23	0.03	0.22	0.03	10.82	18.82	8.45	0.77
9	341/154.5	11.1	18.2	1.41	4.88	1.02	0.33	0.95	0.14	0.80	0.15	0.42	0.06	0.34	0.06	39.86	53.53	17.84	2.27
	Aganozero Body																		
10	9/174	2.6	6.0	–	–	0.77	0.27	–	0.10	–	–	–	–	0.33	0.066	10.10	18.18	7.79	–
	Pyroxenite zone																		
	Shalozero–Burakovka Body																		
11	338/133	6.93	13.7	1.64	6.19	1.35	0.38	1.50	0.22	1.37	0.29	0.78	0.10	0.75	0.10	35.30	18.27	10.15	1.12
12	338/181.7	15.3	37.6	5.28	22.80	5.67	1.20	6.28	0.94	5.92	1.17	3.18	0.43	2.74	0.42	108.9	13.72	6.63	0.67
13	338/188	2.57	5.13	0.65	2.51	0.62	0.34	0.75	0.10	0.68	0.14	0.40	0.06	0.36	0.06	14.37	14.25	8.27	1.02
14	174/147.4	11.9	10.3	1.44	6.2	1.56	0.45	1.71	0.25	1.48	0.29	0.75	0.11	0.62	0.09	37.15	16.61	6.60	1.92
	Aganozero Body																		
15	354/215	0.92	2.05	–	1.43	0.42	0.27	0.47	0.07	0.47	0.09	0.26	0.05	0.23	0.02	6.75	8.91	4.88	0.64
16	354/245	1.51	3.57	–	2.31	0.6	0.24	0.59	0.1	0.68	0.13	0.36	0.05	0.38	0.05	10.57	9.39	5.95	0.65
17	354/279	0.48	1.77	–	2.00	0.76	0.25	0.81	0.16	1.00	0.18	0.48	0.06	0.39	0.05	17.32	4.54	2.33	0.24
18	68/611	0.58	2.1	–	1.9	0.65	0.24	–	0.16	–	–	–	–	0.38	0.057	6.10	5.53	3.23	0.31
19	68/449	1.6	4.4	–	3.1	0.96	0.28	–	0.21	–	–	–	–	0.53	0.080	11.20	8.30	4.58	0.52
20	248/190	0.92	2.4	–	1.76	0.54	0.17	0.53	0.09	0.6	0.11	0.31	0.04	0.25	0.03	7.75	9.60	4.44	0.52
21	248/200.1	0.91	2.3	–	2.1	0.81	0.22	–	0.15	–	–	–	–	0.33	0.04	6.90	6.97	2.84	0.43
	Gabbronorite zone																		
	Shalozero–Burakovka Body																		
22	174/45.5	11.0	5.7	0.75	3.0	0.72	0.31	0.79	0.13	0.81	0.16	0.46	0.06	0.43	0.06	24.38	13.26	7.92	3.67
23	338/98	6.2	12.6	1.58	6.2	1.42	0.50	1.51	0.23	1.42	0.28	0.78	0.12	0.71	0.10	33.65	17.75	8.87	1.00
	Aganozero Body																		
24	353/60	5.59	12.1	–	5.31	1.19	0.57	1.22	0.2	1.22	0.22	0.62	0.08	0.56	0.08	28.96	21.61	10.17	1.05
25	353/94	4.08	9.58	–	5.49	1.44	0.52	1.48	0.25	1.61	0.30	0.86	0.12	0.76	0.10	26.59	12.61	6.65	0.74
26	353/160	3.4	6.77	–	2.97	0.65	0.38	0.65	0.1	0.63	0.12	0.33	0.04	0.32	0.04	16.40	21.16	10.42	1.14
27	353/397	1.2	2.74	–	1.60	0.41	0.27	0.40	0.06	0.38	0.07	0.20	0.03	0.16	0.01	7.53	17.13	6.68	0.75
28	354/172	1.43	3.46	–	2.30	0.67	0.36	0.71	0.12	0.76	0.14	0.37	0.05	0.35	0.04	10.76	9.89	5.16	0.62
29	354/207	1.76	4.58	–	3.29	0.97	0.26	1.03	0.19	1.18	0.21	0.63	0.09	0.56	0.08	14.83	8.18	4.72	0.53
30	68/80	4.7	9.1	–	4.50	0.92	0.55	–	0.20	–	–	–	–	0.52	0.080	20.6	17.50	9.89	1.04
31	4/87.6	2.3	6.6	–	4.10	0.88	0.45	–	0.13	–	–	–	–	0.46	0.064	15.0	14.35	7.50	0.56
	Pigeonite-Gabbronorite zone																		
	Shalozer0–Burakovka Body																		
32	31/160.7	8.2	15.6	1.86	7.2	1.56	0.70	1.59	0.24	1.46	0.29	0.81	0.11	0.70	0.10	40.42	22.28	10.00	1.14
33	31/383	13.0	24	–	12	2.7	0.84	–	0.35	–	–	–	–	0.96	0.13	54.0	25.00	8.89	1.08
34	32/206.4	6.9	13.4	1.6	6.4	1.35	0.62	1.55	0.22	1.4	0.28	0.78	0.10	0.73	0.10	35.43	18.36	9.93	1.08
35	333/247.6	7.0	14.1	1.71	6.7	1.45	0.58	1.52	0.23	1.37	0.26	0.75	0.10	0.68	0.09	36.54	20.74	9.72	1.04

Table 13. Continued

	Sample	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Sum	Ce/Yb	Ce/Sm	La/Nd
Zone of Magnetite Gabbronorite-Diorites																			
Shalozero–Burakovka Body																			
36	45/53.5	7.0	11.8	1.22	4.1	0.72	0.52	0.62	0.09	0.51	0.10	0.27	0.04	0.24	0.03	27.22	49.17	16.39	1.71
37	46/78	8.0	18	–	7.3	1.7	0.86	–	0.33	–	–	–	–	0.90	0.14	37.20	20.00	10.59	1.10
38	123/253.5	17	35	–	15	2.80	1.00	–	0.47	–	–	–	–	1.30	0.20	72.80	26.90	12.50	1.13
Marking horizons of peridotites																			
Shalozero–Burakovka Body																			
39	333/480	4.9	11	–	4.0	0.80	0.20	–	0.14	–	–	–	–	0.43	0.049	21.50	25.58	13.75	1.23
40	174/83.7	4.0	7.6	0.91	3.5	0.74	0.20	0.77	0.11	0.67	0.13	0.36	0.06	0.31	0.05	19.41	24.52	10.27	1.14
41	338/168.7	3.7	7.69	0.98	3.82	0.93	0.27	1.11	0.17	1.08	0.22	0.64	0.09	0.59	0.09	21.38	13.03	8.27	0.97
42	336/77	7.6	15.6	1.9	7.1	1.49	0.45	1.42	0.22	1.39	0.28	0.81	0.12	0.80	0.12	39.30	19.50	10.47	1.07
Aganozero Body																			
43	354/21	2.8	7.5	–	2.9	0.40	0.25	–	0.082	–	–	–	–	0.26	0.042	14.20	28.85	18.75	0.97
44	68/365	0.69	1.6	–	<1	0.27	0.14	–	0.087	–	–	–	–	0.21	0.032	4.00	7.62	5.93	0.69
Marginal Border Group of the Shalozero–Burakovka Body																			
45	28/223	5.8	13.2	–	6.64	1.47	0.39	1.27	0.20	1.13	0.20	0.54	0.06	0.47	0.06	12.18	28.08	8.98	0.87
46	28a/218	17	25	–	12	2.50	0.96	–	0.42	–	–	–	–	0.92	0.15	58.90	27.17	10.00	1.42

Note: – = not determined.

[*Amelin and Semenov,* 1996], and the results are summarized in Table 14.

Sm–Nd isochrons were plotted for individual minerals (Pl, Cpx, and Opx) and whole rocks (Figure 23) using two rock samples collected from the tops of the layered series in both bodies (gabbronorite–anorthosite from the Aganozero Body and magnetite gabbronorite from the SBB). The isochron slope for the Aganozero sample yielded an age of 2372±22 Ma ($\varepsilon_{\rm Nd} = -3.22 \pm 0.13$), and the Sm–Nd isochron age for all Aganozero samples, including the bulk samples and monomineral fractions, was found to be 2374±29 Ma ($\varepsilon_{\rm Nd} = -3.03 \pm 0.19$), this value fitting the value given by the mineral isochron within analytical error. The sample from the Shalozero-Burakovka Body yielded an Sm–Nd isochron age of 2433±28 Ma ($\varepsilon_{\rm Nd} = -3.14 \pm 0.14$), which coincides, within error, with the age of 2449±1.1 Ma found earlier for the gabbro from the Shalozero-Burakovka Body by the U–Pb method using zircon [*Amelin and Semenov,* 1996].

At the same time the isotopic ratio values in the rocks of both intrusive bodies are fairly close (see Table 14). Also close are the model ages of the rocks in these bodies: 2935 to 3065 Ma (Shalozero) and 3007 to 3033 Ma (Aganozero). This suggests that large amounts of the crustal rocks of Archean age were involved in melting to produce basic magma which crystallized as the tops of the intrusions, as follows from the model proposed earlier for the origin of magma parental for the rocks of the siliceous high-Mg series [*Sharkov et al.,* 1997]. At the same time the rocks of the Shalozero Body showed a wider variation of isotope characteristics, the evidence suggesting some differences in the compositions of the melting rocks which contributed to the formation of the parental magmas for the bodies concerned. The same is indicated by Pb isotopes (Table 15, Figure 24). However, in spite of minor differences, all of our isotopic and geochemical data suggest the same type of parental magmas for the intrusive bodies discussed.

The intrusion of each body was apparently accompanied by the injections of new magma portions into the solidifying chambers, the evidence of this being the emplacement of peridotite marker horizons (see below). These new magma injections are characterized by lower $^{87}Sr/^{86}Sr(T)$ ratios (0.7019 for Shalozero and 0.7032 for Aganozero) and by higher $\varepsilon_{\rm Nd}(T)$ values (−1.32 for Shalozero and −2.35 for Aganozero). The pigeonite-augite clinopyroxenite from the Aganozero body (Sample 273/5.4) showed an abnormally high $^{87}Sr/^{86}Sr(T)$ value (0.7060) and a low $\varepsilon_{\rm Nd}(T)$ value (−3.58). On this basis we interpret it as a product of subsolidus metasomatism. This isotopy seems to suggest that crustal fluids were involved in the process of its formation.

Discussion

Individual Features of the Structure and Composition of the Burakovka Pluton

Our study revealed that along with the material and structural characteristics common to the other large Early Paleoproterozoic layered intrusions of the Baltic Shield, the Burakovka Pluton has its own particular features which call for a special discussion. The most important among them are differences between the rock sequences, compositions, and ages of its individual bodies, as well as the origin of

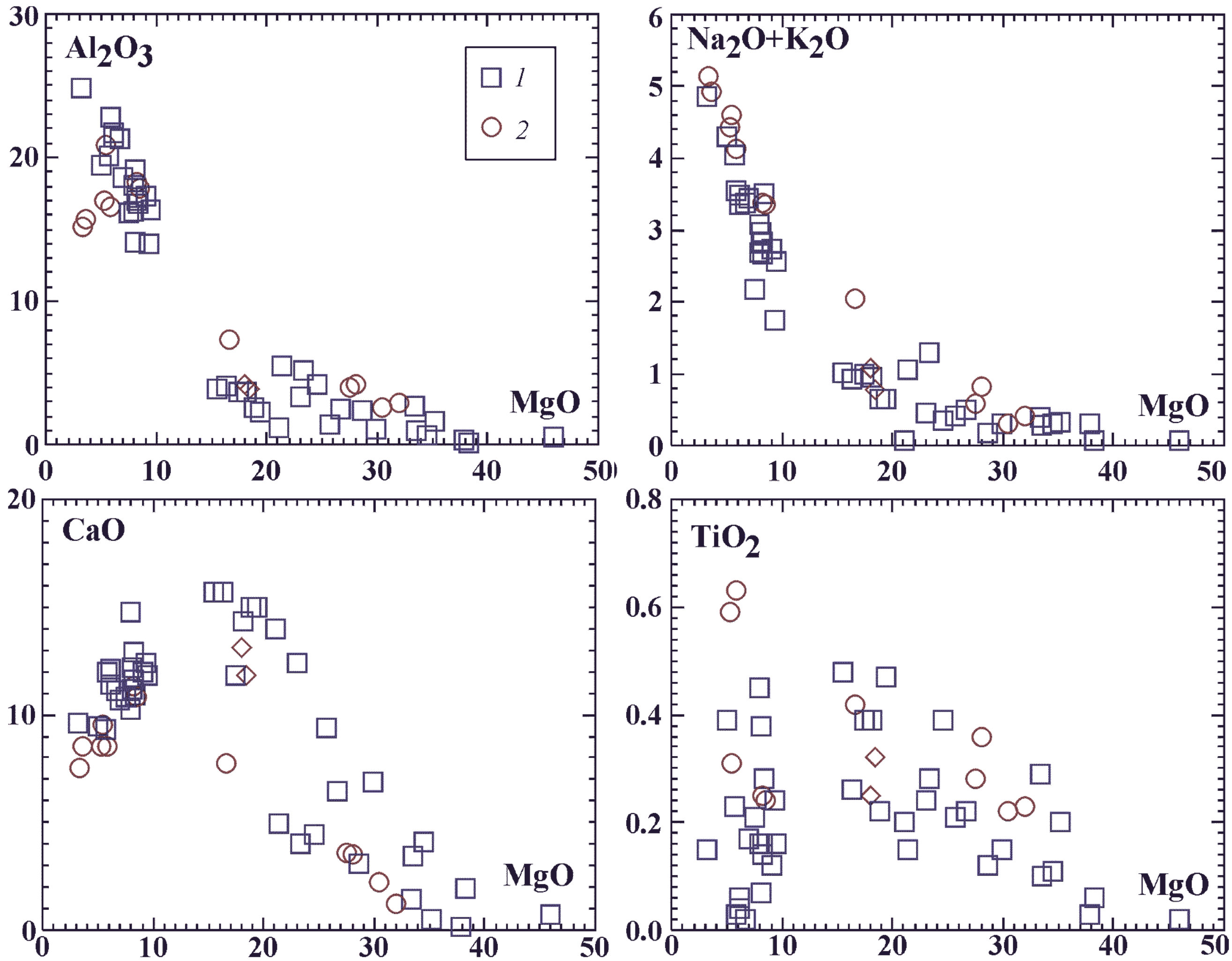

Figure 17. Percentages of oxides as a function of MgO in the rocks of the Burakovka Pluton. 1 – Aganozero Body, 2 – Shalozero–Burakovka Body.

the marker horizons and the structure of the southeastern segment of the Shalozero–Burakovka Body (Hole 67).

Origin of the marker horizons. As has been mentioned above, the specific feature of the pyroxenite, gabbronorite, pigeonite gabbronorite, and magnetite gabbronorite zones in both bodies is the occurrence of thin-bedded ultrabasic-rock marker horizons. The emplacement of these rock units among the cumulates of much lower temperatures suggests the injections of fresh magma portions into the solidifying magma chamber. This new magma had a higher density and spread over the chamber floor displacing the old, more evolved magma upward. As a result, the new magma was immediately involved in crystallization and later – in convection, as it lost its density, the composition of magma in the intrusive chamber was equalized, and the crystallization trend returned almost to its original state.

The fact that fresh magma was periodically injected into the solidifying magma chambers is proved by the findings of cumulate plagioclase crystals with a reversed zoning, the fact emphasized above. This kind of zoning could hardly be produced during magma crystallization in a stagnant zone, but was quite feasible where the settling crystals were stirred up by a fresh, hotter magma.

Above, we called the attention of the reader to the unusually great thickness of the ultramafic zone in the Aganozero body (as high as six kilometers). It is absolutely impossible to envision a magma that might have produced such a great thickness of olivine–chromite cumulates in the case of the single-act filling of an intrusive chamber. The presence of a poorly expressed rhythmic layering in this zone can be interpreted as the indication that its formation might have been associated with the multiple additions of fresh ultramafic melt into the crystallizing magma chamber. Inasmuch as the newly formed cumulates are almost indistinguishable from the pre-existing cumulates here, in contrast to the gabbroid portion of the intrusion, they built up the ultramafic rock sequence producing an impression of the single-act formation of the zone. In this case the old evolved magma, enriched in the products of the magma crystallizing differentiation, must have been displaced continuously upward to

Table 14. Sm-Nd and Rb-Sr isotope data for the Burakovka Pluton)

Sample	Mineral rock	[Sm] ppm	[Nd] ppm	[Rb] ppm	[Sr] pmm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd\pm2\sigma$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr\pm2\sigma$	$\varepsilon_{Nd}(T)$	$I_{sr}(T)$
						Aganozero Body					
20/1000	rock	0.046	0.190	0.395	3.11	0.14799	0.511726±28	0.36736	0.711970±24	−2.52	
273/5.4	rock	0.635	1.778	0.601	31.08	0.21662	0.512776±15	0.05587	0.707961±17	−3.58	0.705991
68/361	rock	0.448	1.610	1.362	84.58	0.61871	0.512068±19	0.04656	0.704898±21	−2.35	0.703257
68/80	rock	0.768	3.549	4.449	438.30	0.13128	0.511459±15	0.02936	0.704829±22	−2.49	0.703794
68/80	rock	0.795	3.603	21.61	421.40	0.13313	0.511513±16	0.14834	0.704844±28	−2.01	
68/80	Pl*	0.154	1.362	1.986	455.39	0.06857	0.510468±12	0.01261	0.704466±19		
68/80	Pl	0.568	4.366	6.276	833.70	0.07860	0.510626±28	0.02177	0.704710±12		
68/80	Opx	0.427	1.208	7.770	7.86	0.21391	0.512739±21	2.86265	0.719190±27		
						Shalozero–Burakovka Body					
31/383	rock	2.134	10.034	21.46	361.86	0.12899	0.511468±14	0.17158	0.709752±18	−1.59	0.703703
31/383	Pl	0.118	1.124	14.84	401.95	0.06350	0.510368±27	0.10683	0.707357±17		
46/78	rock	1.546	6.855	14.96	449.98	0.13679	0.511526±14	0.09615	0.707825±16	−2.91	0.704435
46/78	Pl*	0.081	0.858	10.41	508.78	0.05701	0.510240±21	0.05917	0.705683±21		
46/78	Pl	0.201	1.771	30.10	397.20	0.06867	0.510420±22	0.21912	0.705419±23		
46/78	Cpx	4.504	17.49	4.010	66.15	0.15558	0.511812±8	0.17535	0.708628±29		
174/83.7	rock	0.979	4.136	7.792	73.62	0.11559	0.511266±15	0.30633	0.712664±20	−1.23	0.701864

* – plagioclases treated by concentrated HNO_3.

form the upper, basic portion of the body, as the supply of fresh magma declined in connection with the attenuation of magma generation in the mantle.

So far, we cannot offer an unambiguous *interpretation of the rocks crossed by Hole 67.* There are three possible versions: (1) the lower megarhythm consists of the rocks of the Marginal Border Group, (2) the megarhythms are characteristic of the entire Shalozero intrusive body, but are not expressed as obviously in the other parts of the body, and (3) this structure is characteristic only of this segment of the body.

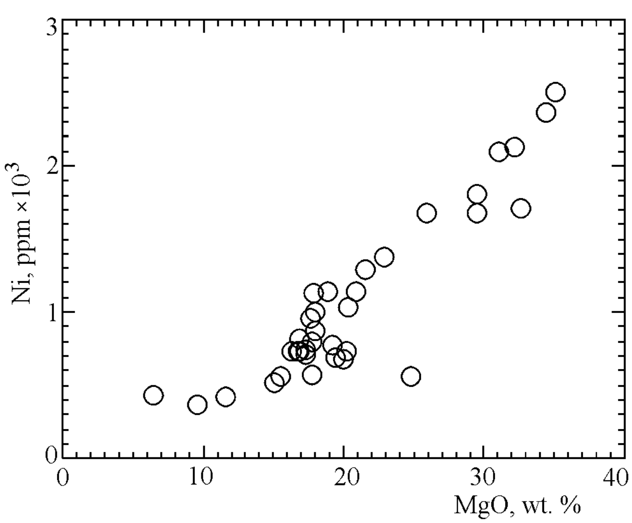

Figure 18. Variation of Ni content (ppm) as a function of MgO (wt.%) in the rocks from the central part of the Aganozero Body (Hole 68).

Version (1) does not agree with the higher-temperature rocks of the lower megarhythm where cumulate olivine is much more magnesian than that in the rocks of the Marginal Border Group (see above). Version (2) is also improbable, because the composition of the dark-colored silicates from the ultramafic rocks of the lower megarhythm is similar to that of the ultramafic rocks from the Ultrabasic Zone, and that from the upper megarhythm is more ferrous, similar to the composition of minerals from the peridotite marker horizon. Apparently, the more suitable version is (3) which suggests that this macrorhythmic pattern is a specific feature of the SE segment of the Shalozero body.

The presence of the two megarhythms that produced this rock sequence can be related to the intrusion of the new large portion of fresh magma into the partially solidified intrusive chamber (Figure 25), which might have resulted in the formation of the second (upper) peridotite layer with a thickness of >200 m. The potential analogs of the Upper megarhythm peridotite in the other parts of the Shalozero body are the peridotite layers in the Pyroxenite Zone, ranging between a few meters and 25–30 m in thickness and violating the general crystallization trend (Holes 174, 335, 338, and 341). Apparently, the macrorhythm was associated with the origin of a new magma channel in the SE part of the pluton.

This macrorhythmic pattern is not a unique feature of layered intrusions. One of the examples is the Zlatogorsky layered intrusion in Northern Kazakhstan, where there are two macrorhythms with thick dunite layers at the base, which are replaced, via the zones of rhythmic ultrabasic and basic cumulate interbedding, by norite and gabbronorite layers in the top [*Sharkov,* 1980].

Similarities and differences in the cumulate stratigraphy and composition of the Aganozero and Shalozero-Burakovka

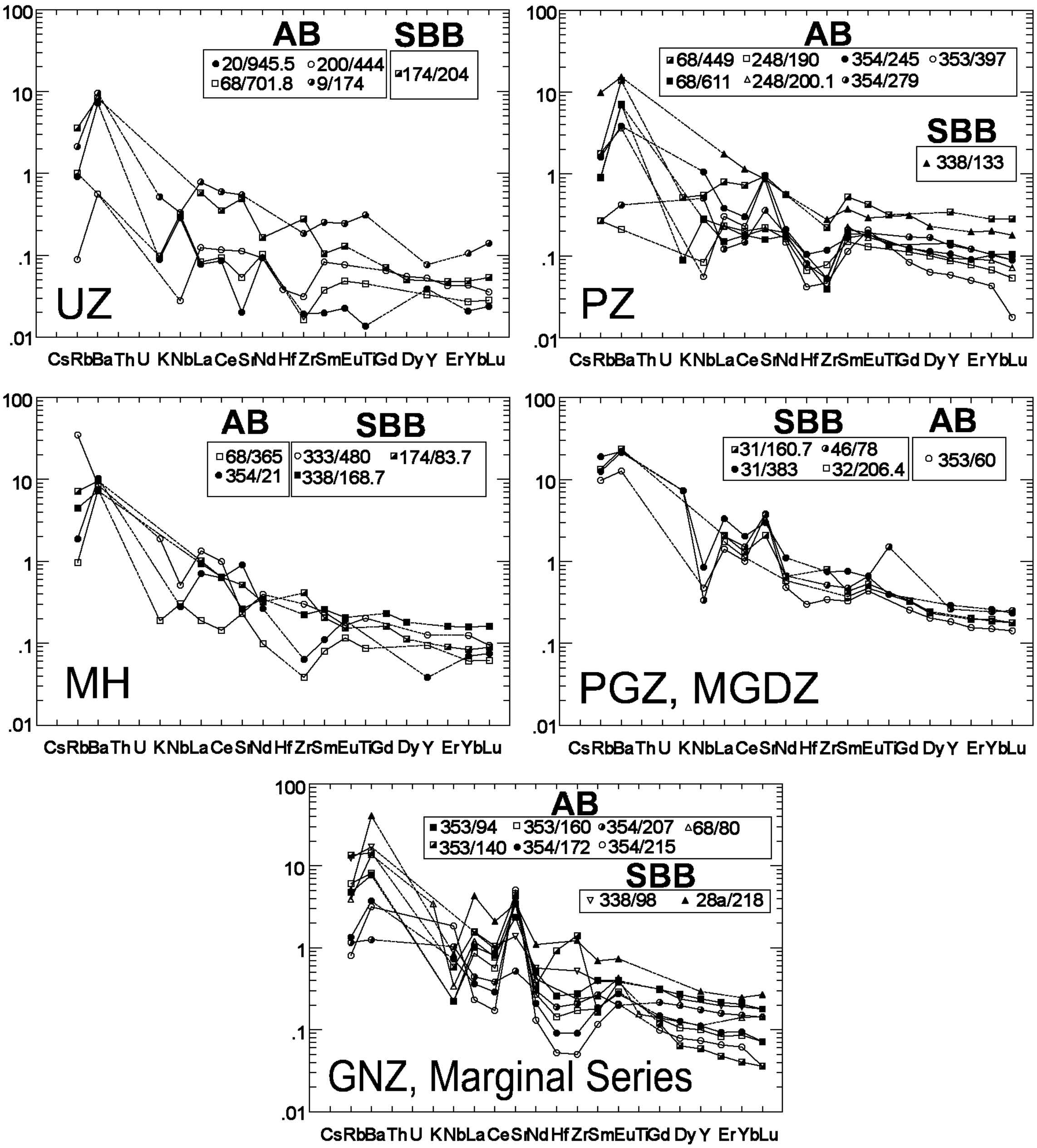

Figure 19. MORB-normalized distribution of trace and rare-earth elements in the rocks of the layered series in the rocks of the Burakovka Pluton.

rocks. The results of our study revealed the following specific features in the structure and composition of these two intrusive bodies. Both bodies are characterized by the high degree of layering, and their sections reflect the same main sequence of cumulate parageneses, this providing a basis for distinguishing similar zones in them. However, the more detailed study of the structure and composition of each zone revealed substantial differences between them. One example is that the Ultrabasic zone of the Shalozero–Burakovka Body contains only poikilitic peridotite, whose intercumulate phases are dominated by plagioclase with ubiquitous phlogopite. Conversely, the upper peridotite subzone of the ultrabasic zone in the Aganozero body includes dunite layers, with almost wholly absent plagioclase and scarce phlogopite.

Differences are even more substantial in the pyroxenite zones. In the Shalozero–Burakovka Body this zone is as thick as 80 m and consists mainly of websterite, orthopyroxenite, and their olivine varieties. In addition, its middle portion includes a peridotite layer interpreted as a marker horizon for the Shalozero Body. The Pyroxenite zone in the Aganozero Body is ca. 200 m thick and is dominated by clinopyroxenite with a noncumulus texture. The main

Table 15. Pb-Pb isotope data for the Burakovka Pluton*

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb ppm	U ppm	μ
			Aganozero Body			
68/80 Pl	14.552	15.142	34.391	2.502	0.008	0.192
68/80 Pl**	22.401	16.200	43.528			21.2
68/80	18.113	15.523	36.900	1.962	0.154	4.86
174/84	18.187	15.646	39.039	1.509	0.163	6.886
253/5.4	18.741	15.669	38.770	3.371	0.040	0.762
68/361	16.959	15.470	37.495	0.508	0.188	2.256
20/1000	18.550	15.700	38.677	1.221	0.007	0.344
			Shalozero–Burakovka Body			
31/383 Pl	14.586	15.148	34.403	6.185	0.034	0.314
31/383 Pl**	22.161	16.331	41.595			14.8
31/383	18.717	15.729	38.786	4.518	0.558	7.92
46/78 Pl	14.603	15.158	34.433	4.034	0.013	0.177
46/78 Pl**	22.682	16.424	42.678			18.8
46/78	17.852	15.636	38.577	3.439	0.347	6.37

Note: * – not corrected for the radiogenic Pb; ** – after leaching.

mineral composing up to 90% of the rock volume is inverted pigeonite–augite whose grains are seen to intensively corrode the single grains of cumulate augite and orthopyroxene. In the lower part of the zone, a clinopyroxene aggregate replaces the peridotite minerals with merely single relict areas remaining intact. All rocks of the Pyroxenite zone in the Aganozero Body contain numerous small inclusions mainly of a quartz-carbonate material.

The Gabbronorite zone of the Shalozero–Burakovka Body also has a reduced thickness and does not include a banded subzone represented by interlayered rocks of different compositions and accounting for up to half of the thickness of the Gabbronorite zone. We failed to correlate the structures of the overlying zones. In the Aganozero body, the Pigeonite gabbronorite zone is very thin, and the rocks of the Magnetite gabbrodiorite zone are absent. Moreover, in contrast to the Aganozero body, the pyroxene in the SBB is dominated by orthopyroxene, and there are intersticial quartz and orthoclase grains (2–3 vol.%) over the whole sequence of the Pyroxenite and overlying zones.

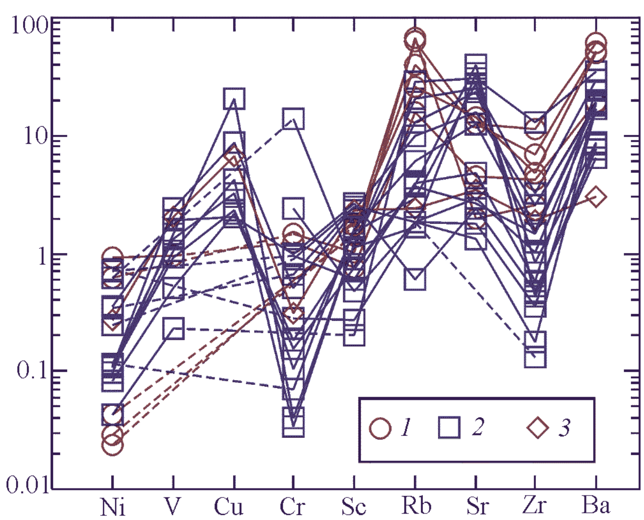

Figure 20. Distribution of trace and rare earth elements in the rocks of the Shalozero (1) and Aganozero (2) bodies and in the rocks of the marginal series in the Shalozero–Burakovka Body (3) normalized to the primitive mantle after *Hoffmann* [1988].

The comparison of the compositions of cumulate silicate minerals revealed their substantial similarity in the similar portions of the Aganozero and Shalozero-Burakovka bodies, this reflecting a similarity between the physicochemical conditions of magma crystallization during the emplacement of these intrusions.

To sum up, our analysis of the structure and composition of the Aganozero and Shalozero bodies shows that with the general sequence of cumulate mineral assemblages, common for both bodies, they show a number of significant differences. Our data suggest that the Aganozero and Shalozero–Burakovka intrusive bodies were derived from similar parental magmas, which, nevertheless, were slightly different in composition.

Age relations between the Aganozero and Shalozero-Burakovka intrusions. These two intrusive bodies are separated by a large fault, and there are two different views as to their age relations: (1) both bodies were intruded at the same time, and differences in their structure were caused by the tectonic activity that occurred during the emplacement of the pluton [*Tevelev and Grokhovskaya,* 1999]; (2) the two bodies of the Burakovka Pluton have different ages, the SBB being younger than the AB [*Berkovskii et al.,* 2000]. However, as a result of our study we found that the Aganozero Body was intruded 50 million years later than the Shalozero–Burakovka intrusion (see above).

To sum up, our study proved the Early Paleoproterozoic Burakovka Pluton to consist of two independent intrusive bodies, AB and SBB, which were emplaced with an interval

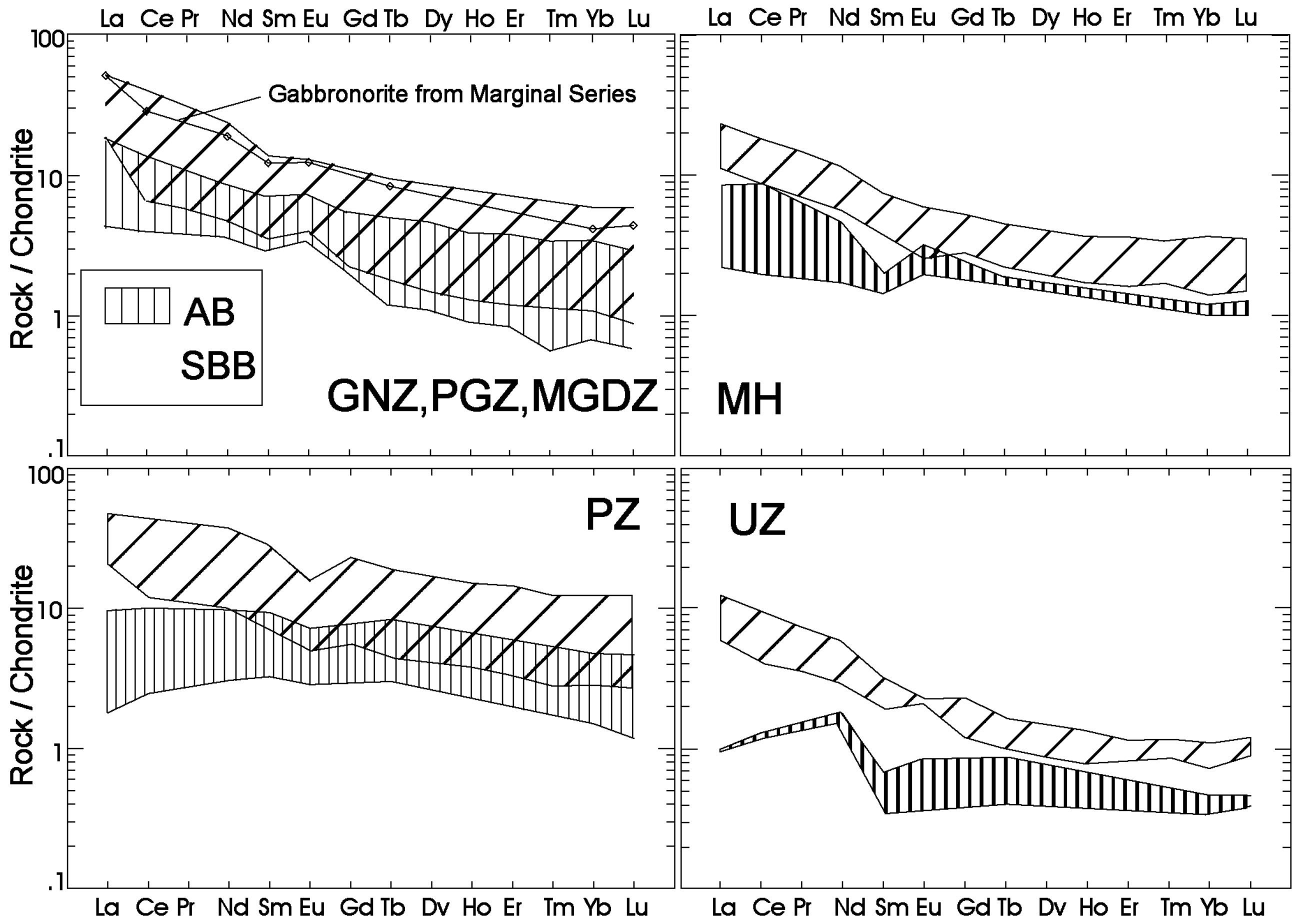

Figure 21. Chondrite C1 [*Sun,* 1982] normalized REE distribution in the rocks of the Burakovka Pluton.

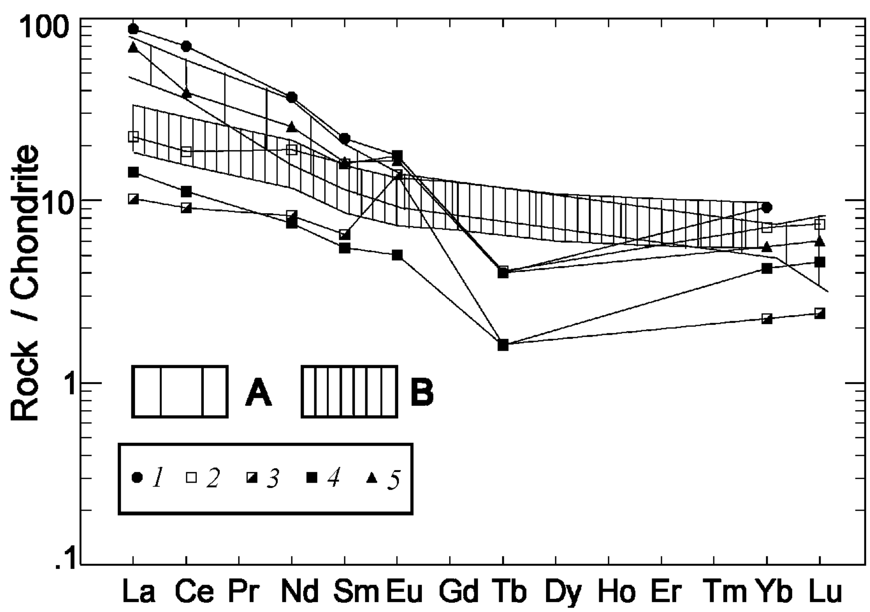

Figure 22. Comparison of chondrite-normalized REE abundance in rocks of silicic high-Mg (boninite-like) series: 1–3 – composition of chilled zones in some layered intrusions (after [*Hatton and Sharpe,* 1989]): 1 – Sudbury, 2 – Skaergaard, 3 – Kiglapait; 4 – average composition of Papua–New Guinea boninites [*Hickey and Frey,* 1982]; 5 – gabbronorite from the chilled zone of the Shalozero–Burakovka Body (see Table 13). Shaded areas: A – micropyroxenite from the chilled zone of the Bushveld intrusion (after [*Hatton and Sharpe,* 1989]) and B – high-Mg komatiite basalt (picrite) from the Vetrennyi Belt, Southern Karelia, Russia (after [*Pukhtel et al.,* 1993]).

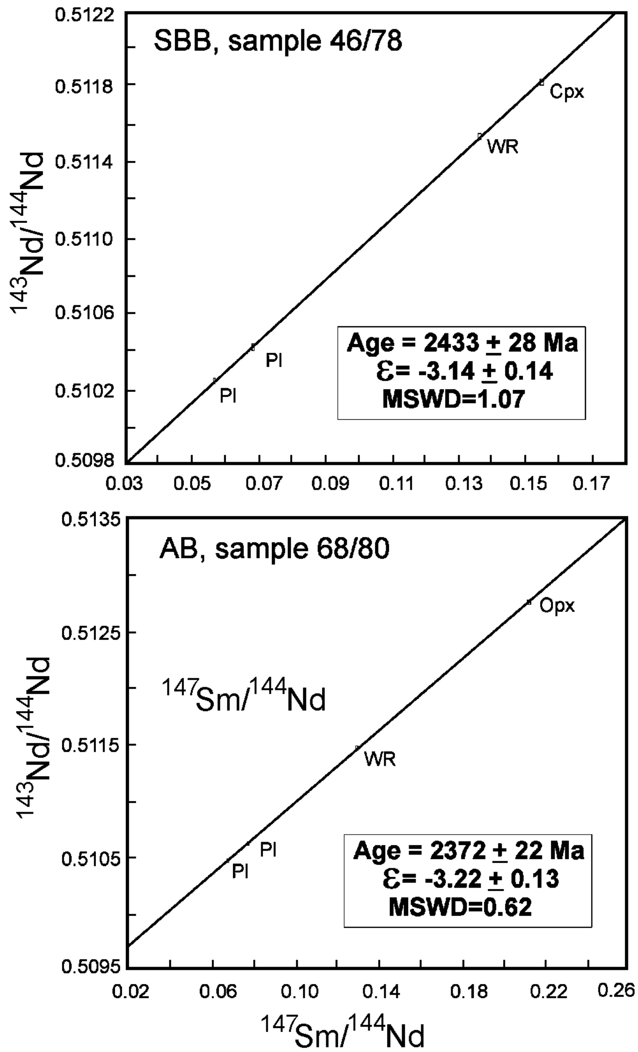

Figure 23. Sm–Nd mineral isochrons for the Aganozero and Shalozero bodies.

of ca. 50 million years, the pluton itself being a long-lived magmatic center. The intrusions were derived from similar-type but slightly different parental magmas of a silicic high-Mg series with similar isotopic and geochemical characteristics, this being responsible for the absence of principal differences in the physico-chemical trends of their crystallization. Both bodies were emplaced in the course of the regular replenishment of the solidifying intrusions by new portions of fresh magma from a mantle magma-formation source and also from intermediate crustal magma chambers rising through the crust by the mechanism of zone melting (see above).

This situation does not seem to be unique for the Baltic Shield. According to recent evidence [*Sharkov et al.,* 2001; *Smolkin et al.,* 2001], the Monchegorsk Complex in the Kola Peninsula, ranking second in size in the region concerned, also consists of two intrusive bodies: the Monchegorsk Ni-bearing pluton of ultrabasic and basic rocks and the Monche-Chuna-Volchie-Tundra gabbroid massif, which were emplaced with a period of 30–50 million years between them [*Sharkov et al.,* 2001; *Smolkin et al.,* 2001].

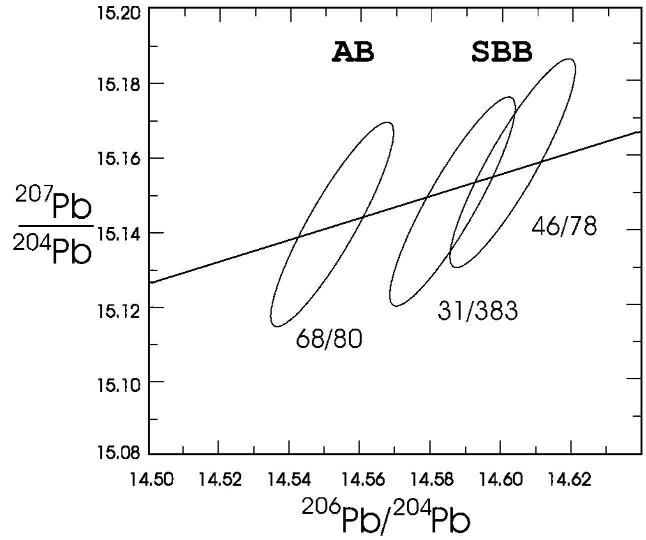

Figure 24. Pb–Pb isotope ratios in leached plagioclases from the rocks of the Aganozero and Shalozero bodies.

Burakovka Pluton as an Example of the Early Proterozoic Layered Intrusions of the Eastern Baltic Shield

The eastern part of the Baltic Shield is one of the largest regions in the world with many Early Proterozoic layered intrusions of basic and ultrabasic rocks: more than 12 very large massifs were found there (Figure 26). All of them had been derived from magmas of the siliceous high-Mg series (SHMS) and have a similar structure and a close composition, although many of them differ in structural details and cumulate stratigraphy [*Alapieti et al.,* 1990; *Sharkov and Smolkin,* 1998]. These intrusions are usually located at the peripheries of Paleoproterozoic sedimentary-volcanic structures, often plunging under their bases. Since the lower portions of these structures are usually composed of siliceous high-Mg volcanics, these intrusive massifs seem to have been

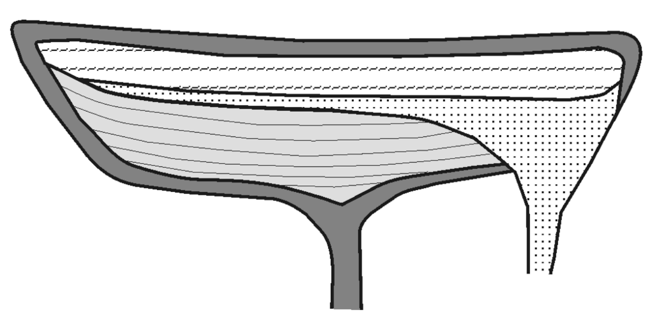

Figure 25. Suggested mechanism of macrorhythm formation in the Shalozero–Burakovka Body, Hole 67.

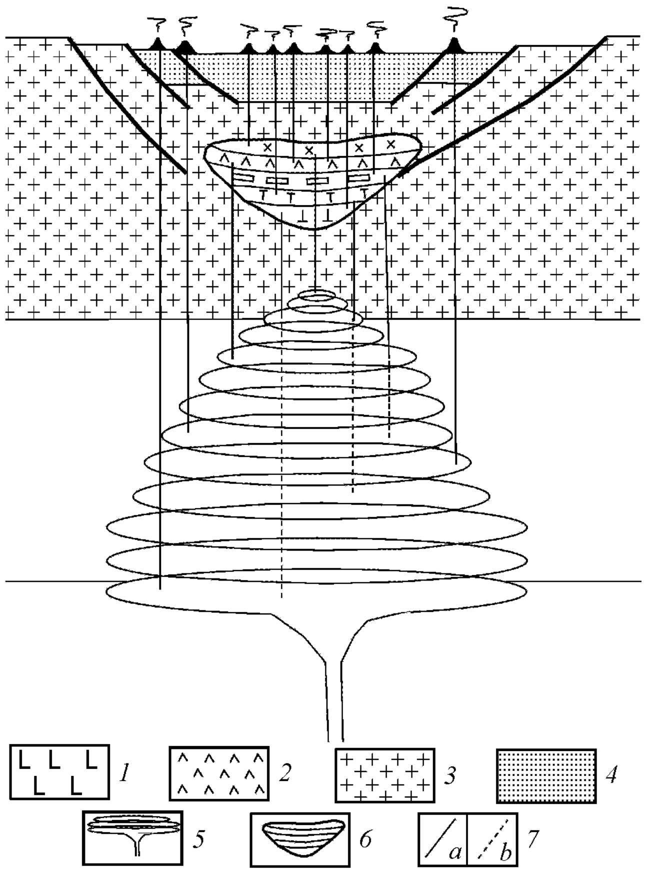

Figure 26. Schematic diagram illustrating the process of buoyant source magma rise in the Earth's crust, After *Sharkov et al.* [1997]: 1 – upper mantle; 2 – lower crust ("basalt" layer); 3–4 – upper crust: 3 – "granitic" layer, 4 – "sedimentary" layer; 5 – trend of magma source rise; 6 – large layered intrusion (upward): ultrabasic rocks, norite and gabbronorite, anorthosite, gabbronorite, and diorite; 7 – paths of magma migration from the source: a – maintained, b – reworked during subsequent processes.

intermediate magma sources for these structures. In some rare cases, for example, in the Burakovka Pluton, volcanic rocks occur outside of the intrusive massifs, apparently because their complementary volcanics were eroded.

With a very similar assemblage of cumulates, almost identical for most of the intrusive bodies, the latter differ in the development of their particular rocks. Usually, the massifs are dominated by basic cumulates, such as gabbronorite or gabbronorite-anorthosite, although there are some exceptions. For instance, it has been shown above that in the Aganozero Body ultrabasics dominate over basic rocks, the olivine–spinel cumulates having an unprecedented thickness of 6 km. This thickness is not higher than 2 km in the SBB, being a few hundred meters in most of the similar massifs. The same is true of the other cumulates; some bodies are dominated by pyroxene (usually orthopyroxene) cumulates, others, by plagioclase-pyroxene cumulates, still others, by plagioclase cumulates, and so on. Commonly found are various violations of the cumulate stratigraphy, associated with the repeated injections of new portions of fresh magma into the crystallizing intrusive chambers [*Sharkov and Smolkin,* 1998].

Apparently, differences in the composition of the layered intrusions were associated with the particular functioning mechanisms of individual magma systems, which were controlled by the flow rate of magma ascending from its source and intermediate chambers, by particular geomechanic conditions in the surrounding region, and also by the composition of the Archean crust in a given area, different under the granite–greenstone regions and under the granulite belts.

A good illustration for this is the Burakovka Pluton. The differences between its Aganozero and Shalozero bodies, revealed in this study, seem to have stemmed from the different contributions of the components which, as follows from [*Amelin and Semenov,* 1996], participated in the generation of this pluton's magma. This is in good agreement with our data on the long life of the Burakovka magma source. Differences in the rock compositions of the bodies can be explained by the crustal contamination of magma during its generation, by the different lithologies of these rocks, by differences in the source depths of the parental magma derived from the same mantle superplume, as has been demonstrated by *Abaouchami and Hofmann* [1998] using the Pb isotope ratios of the Hawaiian magmas. It appears that all of these factors were valid in our case.

Layered Intrusions as Members of the Large Baltic Igneous Rock Province of a Siliceous High-Mg Series (SHMS)

As has been shown above, during the Early Proterozoic, roughly 2.5 to 2.3 billion years ago, the eastern part of the Baltic Shield was a large igneous rock province of a siliceous high-Mg series, similar in its geological position to Phanerozoic trap basalt regions, but greatly different from them by the composition of its magmas, typical of subduction environments [*Sharkov et al.,* 1997, 2000].

The distinctive features of the rocks of this series are the high contents of SiO_2, MgO, and Cr, the medium contents of Ni, Co, Cu, and V, and the low contents of Ti, alkalies, and Nb. The predominant rock is basalt, the associated basaltic andesites and andesites being often characterized by an elevated Mg content. As far as the recent igneous rocks are concerned, these features are characteristic only of island-arc rocks, especially of the boninite series. These rocks resemble boninites and modern island-arc tholeiites in terms of their contents of major, trace, and rare-earth elements with their typical Nb and Ti minima and also in terms of their high Al_2O_3/TiO_2 ratios. Appreciable differences between them were found only in the isotopic characteristics of the SHMS rocks: the $\varepsilon_{Nd}(T)$ value varies from -1.0 in the ultramafics to -3.1 in the gabbroids. A similar pattern was found in the other similar layered intrusions: in Bushveld in South Africa [*Schiffries and Rye,* 1989] and in Stillwater in North America [*Lambert et al.,* 1994].

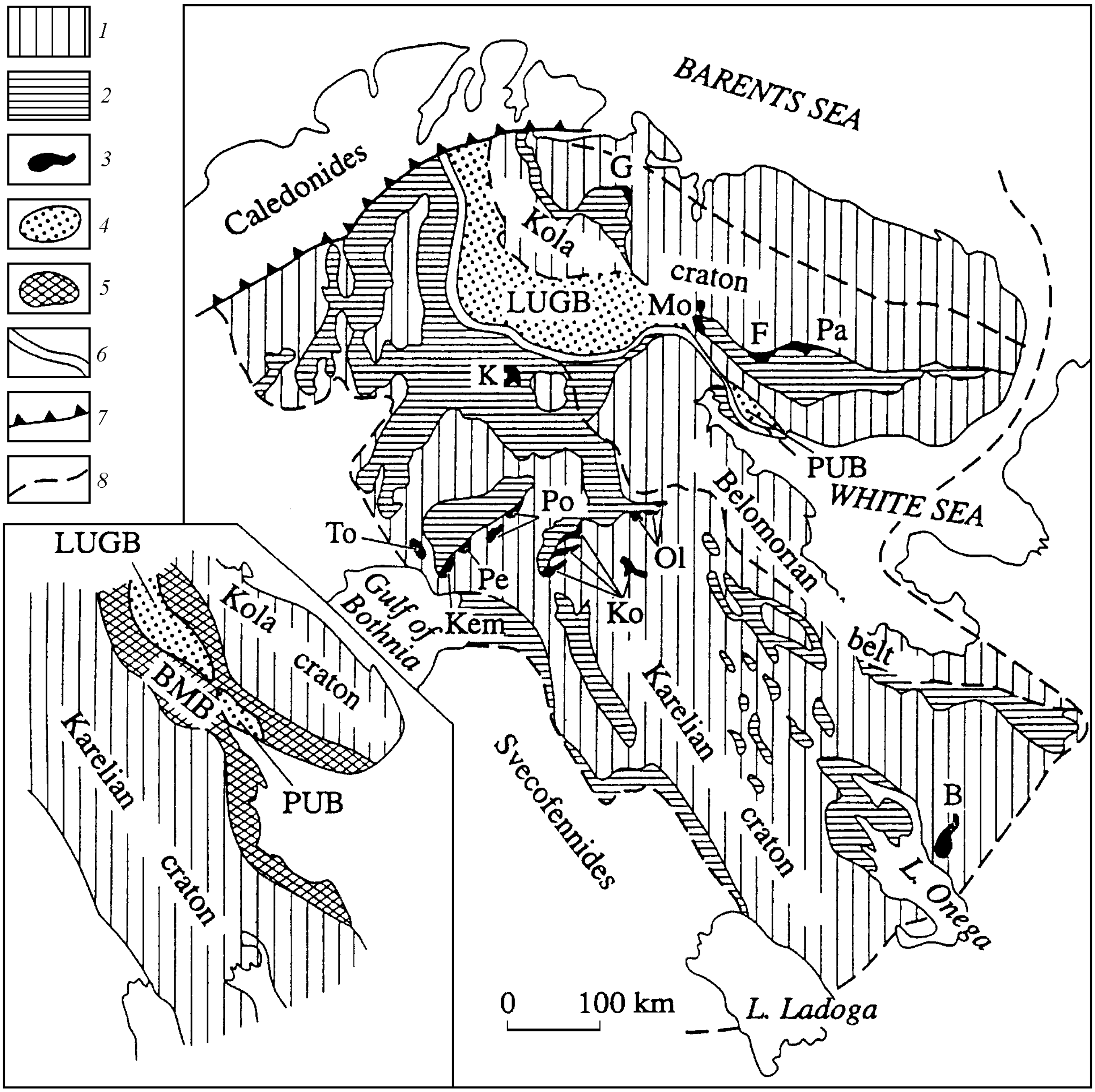

Figure 27. The Early Paleoproterozoic large Baltic igneous province of the silicic high-Mg rock series, after *Sharkov et al.* [1997]: 1 – location of the Baltic igneous province; 2 – Paleoproterozoic sedimentary-volcanogenic complexes with the SHMS rocks at the base; 3 – largest layered intrusions: (B) Burakovka, (Kem) Kemi, (K) Koitilainen, (O) Olanga Group, (Pe) Penikat, (To) Totnio, (G) Mt. Generalskaya, (Ko) Koilismaa, (Mo) Monchegorsk Complex, (Pa) Pana, (Po) Portimo, (F) Fedorova Tundra; 4 – LUGB – Lapland–Umba granulite belt [(Pub) Por'egubsko–Umba block]; 5 – BMB (Belomorian Mobile Belt); 6 – Main Lapland Suture; 7 – main thrusts; 8 – main faults.

The unusual geologic position of the origin of these magmas and the specific features of their geochemistry and isotopy suggest a principally different origin of the SHMS magma, as compared to the similar Phanerozoic magmas. We believe that the origin of the magmas discussed was associated with the extensive contamination of the parental high-T mantle magma with the Archean crustal material as it rose toward the Earth's surface. The leading mechanism seems to have been the "floating" of the high-T magma through the crustal rock sequence by melting the top by way

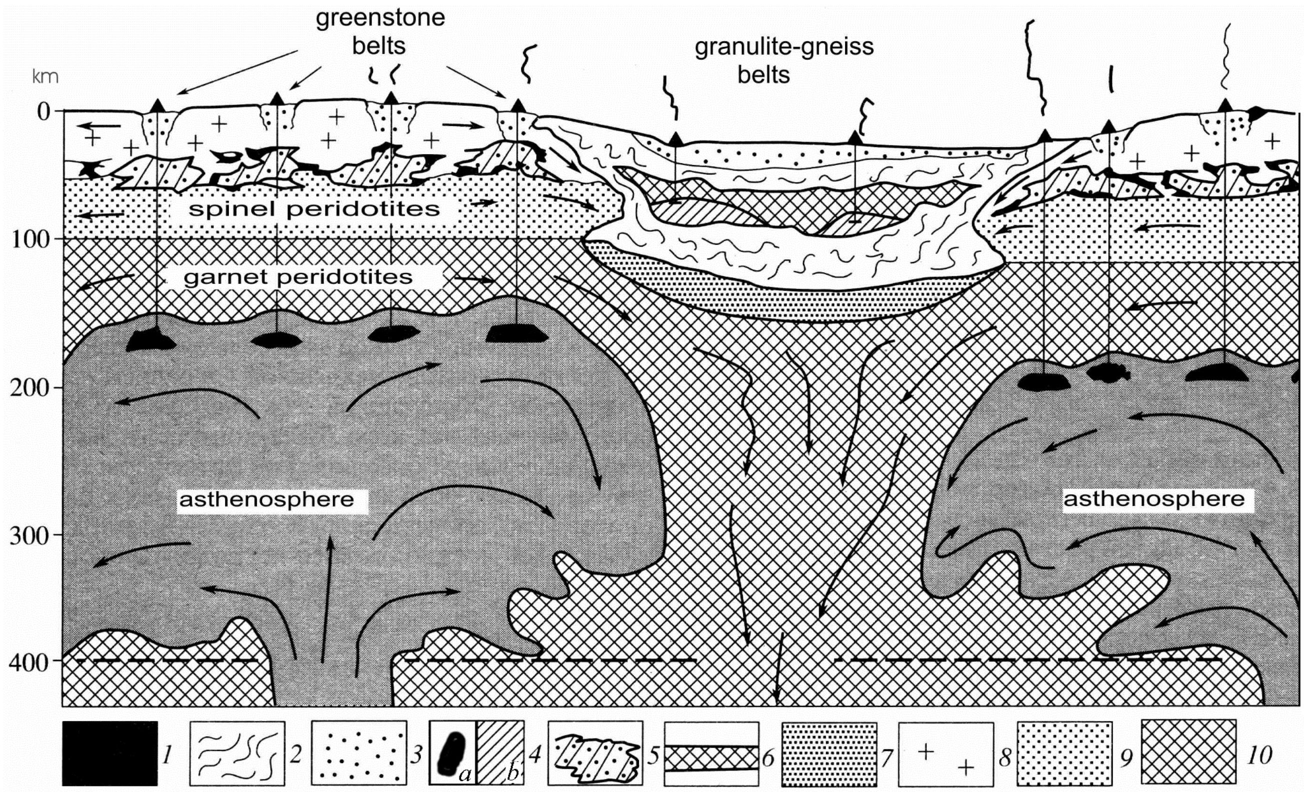

Figure 28. Schematic Early Paleoproterozoic intraplate tectonics of the Baltic Shield: 1 – spreading heads of superplumes; 2 – regions of sagging movements where excess crustal material accumulated and granulite belts were formed; 3 – sedimentary basins; 4 – magma-generation zones: in the mantle (a) and in granulite belts (b); 5 – underplating beneath rifts; 6 – newly formed lower crust in granulite belts; 7 – garnetized spinel peridotite under granulite belts; 8 – ancient continental crust; 9 – ancient lithospheric spinel peridotite; 10 – ancient garnet peridotite

of zone refinement [*Sharkov et al.,* 1997]. The layered intrusions seem to have acted as intermediate collectors where these melts accumulated (Figure 26).

In this connection it seems reasonable to discuss the character of tectonic processes that were operating in the Baltic Shield during the Early Paleoproterozoic. As one can see in Figure 27, the major tectonic elements that existed in the region at that time were the Kola and Karelian rigid cratons with the Laplandia-Umba granulate belt (LUGB) between them. The latter was a region of subsidence with a large sedimentary basin forming on its surface. Mobile belts were developing along the contacts between the granulite belt and the cratons being the zones of low-angle tectonic flow; the Belomorian mobile belt representing the best preserved zone. Fragments of a similar belt were found in the Tersky–Lotta Belt extending along the northeastern periphery of the Laplandia–Umba granulite belt. These major tectonic elements produce a regional structural and metamorphic zoning which is characterized by a slow growth in the intensity of deformation and metamorphism toward the granulite belt [*Sharkov et al.,* 2000].

In the Kola and Karelian cratons, igneous activity manifested itself in the formation of large layered intrusions, gabbronorite dike swarms, and volcanic sedimentary belts restricted to the linear graben-shaped structures. Here, the SHMS volcanics are represented by a great variety of rocks ranging from low-Ti picrite and basalt to andesite, dacite, and rhyolite, the dominating rocks being basalts. These volcanogenic-sedimentary belts had been continental rifts that developed mainly in subaerial environments.

The intermediate mobile belts of the Belomorian type were distinguished by a dispersed intrusive magmatism which resulted in the emplacement of numerous small synkinematic intrusions of basic and ultrabasic rocks of the same types found in the layered intrusions, except that here individual intrusions are composed of one rock variety, namely, peridotite, gabbronorite, or anorthosite (e. g., Belomorian drusitic complex). Highly subordinate are enderbite–charnockite massifs. The granulite belt does not contain any SHMS rocks, the main igneous rock types being crustal enderbite and charnockite.

To sum up, in contrast to the Phanerozoic foldbelts, the distinctive feature of the Early Paleoproterozoic tectonomagmatic activity in the Baltic Shield was the coexistence of three main types of structural domains:

(1) large regions of rising and extension, accompanied by intensive mantle magmatism and active erosion (Kola and Karelian cratons); magmatism was of within-plate type;

there is no evidence of any processes that operated at active plate boundaries;

(2) a region of compression and subsidence between them marked by abundant crustal enderbite–charnockite magmatism (Laplandia–Umba granulite belt), where excess of crustal (including sedimentary) material accumulated at the expense of erosion and denudation in adjacent areas;

(3) peculiar belts of the low-angle tectonic flowage of crustal material from regions of extension toward granulite belt, such as the Belomorian belt, which originated in the extension environment and had a mixed character of magmatism.

Of these structural provinces, only type (1) is the closest to the Phanerozoic type, because it resembles the regions of continental rifting and trap basalt emplacement, the origin of which is believed to be associated with mantle plumes. Our analysis of the geologic processes that occurred in the Baltic Shield during Early Paleoproterozoic time enables us to describe the geological situation of that time in terms of plate tectonics. In accordance with our model (Figure 28), the dominant mechanism of tectonic activity in the Early Precambrian, and also in the Phanerozoic, was the ascent of superplumes with the formation of large extension zones (cratons) above their spreading heads. However, in contrast to the Phanerozoic, the spreading process developed at depths of 150–200 km [*Girnis and Ryabchikov,* 1988] and, hence, was not accompanied by the breaking of the sialic crust, the formation of the oceanic lithosphere, or the origin of compensation-type structures, such as subduction zones. Instead of this activity, there arose extension and subsidence zones, typical of the Early Precambrian and complementary to the extension zones: moderate-pressure granulite belts surrounded by the intermediate zones of tectonic flow, similar to the Belomorian Belt [*Sharkov et al.,* 2000]. Apparently, this situation resembled the pattern that arose in the experiments of *H. Ramberg* [1981] in his simulation of the vertical rise of diapirs through a more viscous matrix, where the material of the latter flowed into the intermediate space between them.

Of interest is the point of the initial size of the Early Paleoproterozoic province of boninite-like magmatism, the Baltic province, discussed above, being its part. Similar rocks are traceable in the basement of the Russian Platform, in Scotland, Greenland, in the Canadian Shield (Matatchewan and Herst dike swarms and volcanic rocks at the base of the Huron basalt plateau) and in the Wyoming Craton [*Heaman,* 1997]. According to Heaman's paleomagnetic and stratigraphic reconstructions, these cratons were initially parts of the Laurentia–Baltia supercontinent and separated in the Late Proterozoic. The initial size of this igneous province was supposed to be 2500 km long and at least 1500 km wide, the size comparable with the largest Phanerozoic trap provinces.

As mentioned above, this type of igneous activity developed widely in the east of the Baltic Shield throughout the Early Paleoproterozoic, this suggesting the long existence (ca. 200 million years) of a superplume [*Sharkov et al.,* 1997]. A distinctive feature of geologic processes at that time was the localization of the centers of tectono-magmatic activity in the same geologic structures (Pechenga, Imandra–Varzuga, Vetrennyi Belt, etc.) with closely spaced periods (spaced 10–50 million years apart) of volcanic and intrusive activities (see Figure 27). Our evidence on the long-lasting activity of the Burakovka igneous center are in good agreement with this statement. Although there are some geochemical and isotopic differences between the individual bodies, the physico-chemical trends of their crystallization did not have any principal differences, as would be expected. Differences in the lithology can be explained either by differences in the degree of crustal rock contamination in the course of magma generation, or by differences between the depths of the parental magma in the same superplume.

Judging by geochemical data and the mineral composition of the highest-temperature cumulates including high-Mg olivines and pyroxenes, as well as chromites, the primary mantle magma was produced by the melting of a highly depleted ultramafic material. According to the isotopic and geochemical data available, as the newly produced magma ascended toward the Earth's surface, it assimilated the material of the ancient lower crust, getting enriched in Si, Al, and Ca, this explaining the predominance of basic rocks in the intrusions. The above evidence suggests that the composition of the early Paleoproterozoic mantle plumes was drastically different from that of the Phanerozoic plumes depleted in ultrabasic material. The primary melts were very hot (ca. 1600°C [*Girnis and Ryabchikov,* 1988]), this promoting the assimilation of crustal material, the process uncharacteristic of the Phanerozoic intraplate magmatism.

The emergence of local plumes responsible for the origin of long-lived magmatic centers, marked by large layered intrusions, was obviously associated with local rises on the superplume surface, where the mantle material was melted at the expense of decompression, and where the magmas of the siliceous high-Mg series were produced.

Conclusions

1. The Burakovka layered pluton of mafic and ultramafic rocks is one of the largest layered massifs in the Baltic igneous province of siliceous high-Mg rocks. It consists of two independent bodies (Aganozero and Shalozero–Burakovka), each having its own internal structure, which contact each other in their tops.

2. The two bodies of the pluton have a similar rock sequence consisting of five differentiated zones: ultramafics, pyroxenite, gabbronorite, pigeonite gabbronorite, and magnetite gabbronorite (the latter was found only in the Shalozero–Burakovka Body). However, with this general structural similarity, these bodies differ markedly in the character of their cumulate stratigraphies and, to a lesser extent, in their rock compositions.

3. A distinctive feature of the pluton is the presence of markers: single interlayers of high-temperature ultrabasic cumulates in the sequence of lower-temperature formations. Their origin is believed to be associated with the replenishment of fresh magma portions into the crystallizing magma chambers. The same mechanism explains the macrorhyth-

mical pattern recorded in the SE segment of the Shalozero-Burakovka body.

4. As follows from the geochemical, mineralogic, and isotopic-chronological data, the two bodies were produced by the compositionally siliceous high-Mg magmas, except that the Aganozero Body was intruded 50 million years later than the Shalozero–Burakovka Body, the Sm–Nd isochron age of the former being 2372±22 Ma ($\varepsilon_{\rm Nd} = -3.22 \pm 0.13$) and that of the latter, 2433±28 Ma ($\varepsilon_{\rm Nd} = -3.14 \pm 0.14$).

5. The Burakovka Pluton seems to have been a long-lived igneous center which evolved above a local mantle plume. The origin of the latter is believed to have been associated with the activity of a superplume which provided for the existence of the Baltic igneous province for ca. 200 million years.

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