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Early Proterozoic Central-Type Volcano in the Pechenga Structure and Its Relation to the Ore-Bearing Gabbro–Wehrlite Complex of the Kola Peninsula

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Abstract—The Zapolyarnyi volcanic center is confined to the boundary between the oldest volcanic formations (I and II) of the Pechenga complex. Its structure and rock association are significantly different from those of numerous eruptive centers of areal basaltic volcanism in the Pechenga structure. It is an oval-shaped body, 700 × 300 m in size, composed of volcanic eruptive lava breccia. The clastic material of the breccia includes angular and partially molten fragments of granites, pegmatoid granites, epidosites, quartz, and feldspars embedded in basaltic lava. The basalts are titanium-rich and iron-rich varieties enriched in large-ion lithophile elements (Rb, Ba, and Sr); they are similar in composition, including Rb–Sr and Sm–Nd isotopic characteristics, to the ferropicrites of the youngest volcanic formation (IV) and their differentiation products. The basalts of the volcanic center show $\varepsilon_{Nd}(T)$ values from –3.13 to –1.17. In general, these rocks definitely represent the vent facies of an Early Proterozoic central-type volcano. The age of the basalt of the volcanic center is 1918 ± 3 Ma (U–Pb method on zircon) and is similar to the previously determined age of volcanics of volcanic formation IV (1990 ± 40 Ma, Sm–Nd method). The rocks of this formation participated 2000–1900 Ma ago in the formation of the volcanoplutonic ore-bearing ferropicrite–gabbro–wehrlite association of the Pechenga structure. The age of the ore-bearing Pilguyarvi gabbro–wehrlite intrusion was constrained between 1987 ± 5 Ma (U–Pb method on zircon) and 1980 ± 10 Ma (U–Pb method on baddeleyite). In addition, the first data were obtained for the age of comagmatic olivine norites of the Nyasyucka dike complex in the northeastern flank of the Pechenga structure (1941 ± 3 Ma, U–Pb method on baddeleyite) and the peridotites of the Allarechka ore field in the southern framing of the Pechenga structure (1918 ± 29 Ma, U–Pb method on zircon), which were previously considered Archean. Taking into account the geological and geochemical characteristics of the rocks of the Zapolyarnyi paleovolcano and the identical age of the Ludikovian intrusions, it can be concluded that the basalts of the paleovolcano were formed during late stages of the evolution of Early Proterozoic basic–ultrabasic magmatism, which was characterized by extensive explosive activity and strong magmatic differentiation responsible for the generation of the ore-bearing intrusions of the ferropicrite–gabbro–wehrlite association.

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INTRODUCTION

Paleovolcanological and petrogeochemical studies performed by the researchers of the Geological Institute, Kola Research Center, Russian Academy of Sciences during 1997–2000 in the Pechenga structure were accompanied by extensive geological, geophysical, mapping, mining, and drilling operations, as well as isotope geochemical and geochronological investigations. This work resulted in the compilation of the first paleovolcanological maps for the northern and southern Pechenga zones at a scale of 1 : 50000 (Skuf'in and Nikolaeva, 1980) and the analysis of associations of volcanic rocks of the Pechenga structure as a fragment of the large Pechenga–Varzuga greenstone belt (Predovskii et al., 1987; *Magmatism, Sedimentogenesis…*, 1995; Skuf'in, 1998).

This paper presents the results of an investigation of well-preserved Early Proterozoic rocks of the Ludikovian forming a relict central-type paleovolcano in the Pechenga structure (Skuf'in and Bayanova, 2003). The paleovolcano differs in structure and rock association from numerous previously mapped local eruptive centers of areal volcanism (Skuf'in, 1998). The goals of this study included the field examination of structures and textures of the rocks of the eruptive center; comprehensive investigations of the petrography, mineralogy, and geochemistry of the volcanics; and U–Pb zircon dating of the volcanics of this ancient volcano related to the basaltoid volcanism and gabbro–wehrlite magmatism of the Ludikovian.

REGIONAL GEOLOGY

The Pechenga zone is located in the Pechenga–Varzuga greenstone belt and is a well-studied Early Precambrian complex (Zagorodnyi et al., 1964; Predovskii et al., 1974; Skuf'in, 1993; Melezhik et al., 1994a, 1994b; Smolkin, 1997; etc.). It is an asymmetrical synclinorium with an area of more than 2000 km^2, the northern part of which (northern Pechenga zone) is a fragment of a volcanotectonic paleodepression filled with volcanosedimentary rocks of the Pechenga complex, about 11 km thick (Skuf'in, 1993). The southwestern part of the paleodepression is cut by the southern Pechenga zone, a sublinear suture depression. The thickness of the sequence of supracrustal rocks in the southern Pechenga zone is up to 5 km (Fig. 1). The time of formation of the rocks of the Pechenga zone was estimated mainly by the bulk-rock Rb–Sr method between 2500 and 1905 Ma (Balashov, 1996). The sedimentary and volcanogenic rocks of the complex rest with an angular unconformity on the eroded Late Archean basement gneisses and are divided into four megarhythms. Each megarhythm includes a sedimentary formation at the base and an upper volcanic formation. The section is represented by four superhorizons (from bottom to top): Sariolian (sedimentary formation I and volcanic formation I), lower Jatulian (sedimentary formation II and volcanic formation II), upper Jatulian (sedimentary formation III), and Ludikovian (volcanic formation III, sedimentary formation IV, and volcanic formation IV). The geochronology of the major portion of the Pechenga rock section is still poorly studied. The available age estimates for the volcanics of the northern and southern zones were obtained by the bulk-rock Rb–Sr method (Balashov, 1996) and are very approximate. More reliable data were obtained for the age of the beginning of Early Proterozoic magmatism, which was connected with the formation of layered basic–ultrabasic intrusions, including the intrusion of General'skaya Mountain at the base of the section of the Pechenga complex, Monche Pluton, and intrusions of the Fedorovo–Panskie tundra (2507–2493 Ma, U–Pb data for zircon and baddeleyite; Bayanova et al., 1999). Age estimates were also reported for the Ludikovian volcanism of the Pechenga zone, including the ferropicrites and basalts of volcanic formation IV and comagmatic gabbro–wehrlite intrusions (1980–1956 Ma, Sm–Nd, Re–Os, and Pb–Pb methods; Smolkin, 1992). The Shuoni-Yarvi and Kaskelyarvi plagiogranite–quartz-diorite massifs in the southern framing of the Pechenga structure were also dated by the U–Pb method on zircon (1940–1939 Ma; Vetrin et al., 1987; Skuf'in et al., 2000).

RESULTS

Titanium-rich ferrobasalts from sheet bodies and matrix of eruptive lava breccias forming a fragment of the neck of an Early Proterozoic central-type volcano in the northeastern part of the Pechenga structure are the subject of this paper.

The eruptive volcanic center was discovered in the northeastern outskirts of the town of Zapolyarnyi by the researchers of the Geological Institute, Kola Research Center, Russian Academy of Sciences as early as 1970s (Fedotov, 1971; Mirskaya, 1971). The relict paleovolcano is confined to the boundary between the oldest volcanic formations (I and II) of the Pechenga complex. It forms an oval-shaped body, 700 × 300 m in size, extending NNW, and built up of eruptive lava breccia. The rocks of sedimentary formation II separating the volcanics of volcanic formations I and II were not observed at the region where the eruptive center is located and were exposed by mine workings about 1000 m to the northwest. The lava breccias are separated from the enclosing trachybasalts of volcanic formation II by a distinct subvertical contact zone, where the rocks are schistose, corrugated, and cut by numerous quartz veins. The eruptive lava breccia is composed of angular and partially molten fragments of granites and pegmatoid granites, occasionally epidosites from the Archean basement of the Pechenga structure, as well as fragments of grayish white and blue opallike quartz embedded in a basaltic lava contaminated in places by the material of granitoid xenoliths (Fig. 2a). The distribution of clastic material is chaotic and irregular. There are coarse clastic eruptive breccias with fragments from a few centimeters to 1.5 m and fine clastic breccias with fragment sizes from microscopic to a few millimeters. The content of clasts in the rocks varies from a few percent to 70% by volume.

The matrix of the lava breccia is composed of massive sometimes amygdaloidal basalts of dark green color metamorphosed to epidote-amphibolite facies. The texture of the rocks is relict microphitic or ophitic. Amygdules account for 15 to 30 vol % and are composed of monomineralic plagioclase (albite) or hornblende. The average mineral composition of the basalt is (vol %) 45 *Hbl*, 2 *Bt*, 40 *Pl*, 8 *Spn*, and 5 *Ep*.[1] The eruptive lava breccias show a steeply dipping schistosity and development of secondary minerals along fractures: chlorite, biotite, quartz, and carbonate. Fragments of pink and light gray granite have a fine-, medium- or coarse-grained texture and a massive structure. The texture of the rocks was identified under a microscope as hypidiomorphic granular or pegmatitic. In addition, the rocks display a peculiar cement texture: feldspar grains in granite fragments are surrounded by rims of newly formed melt, which is represented by albitophyre with a felsitic, microprismatic, or spherulitic texture (Fig. 2d). The rims vary from 0.1 mm to a few millimeters in width. The albitophyre cement consists of elongated or short prismatic albite grains, which are turbid owing to the presence of dustlike decomposition products. In addition to albite, the cement contains quartz, biotite, chlorite, epidote, titanite, leucoxene, apatite, and zircon. Quartz fragments are from a few millimeters to tens of centimeters in size. Large fragments are rounded, partially molten angular, and, occasionally, angular. The fragments are built up of hetero-

[1] Mineral abbreviations: *Hbl*, hornblende; *Bt*, biotite; *Pl*, plagioclase; *Mc*, microcline; *Qtz*, quartz, *Spn*, titanite; and *Ep*, epidote.

granular aggregates of quartz grains showing undulating extinction. Parallel plates of green chlorite occur in the interstices between quartz grains. There are rare fragments of fine-grained massive epidosite, up to several centimeters across. The rock is composed of isometric grains of turbid epidote (50–55%) and quartz (35–40%). Plagioclase, calcite, actinolite, chlorite, biotite, and apatite occur in minor amounts. In addition, partially molten fragments of fine-grained amygdaloidal rocks of an andesite composition were found in the clastic material (Fig. 2b). The amygdules account for 35–40% of the rock by volume and are made up of an epidote–plagioclase aggregate with biotite scales and actinolite needles. The main constituent of the amygdaloidal rocks shows an intermediate–silicic composition, microphitic texture, and intermediate mineral composition (vol %): 40 *Hbl*, 3 *Bt*, 40 *Pl*, 8 *Spn*, 4 *Qtz*, and 5 *Ep*.

The central parts of the eruptive lava breccia body are most altered and dominated by porphyritic rhyodacites with small individual fragments of molten granites and corroded quartz and plagioclase grains. Basaltic rocks from the border zone of the body are better preserved, especially in its northern part, where exposures of fine- and very fine-grained basalts with fragments of medium- and coarse-grained granites were documented. Two steeply dipping sheetlike bodies of fine-grained basalt containing granite fragments in the hanging wall and footwall were found there. There is also a lenticular body of medium-grained gabbro-dolerite, up to 55 m thick, the central part of which is almost unaffected by contamination. The border zone of the gabbro-dolerite intrusion contains xenoliths of fine-grained basalt and hybrid rocks of the rhyodacite composition. The gabbro-dolerites show a relict gabbro-ophitic texture formed by tabular plagioclase grains among pyroxene replaced by hornblende (Fig. 2c) and have the following mineral composition (vol %): 34 *Hbl*, 8 *Bt*, 35 *Pl*, 10 *Spn*, 5*Qtz*, and 8 *Ep*. In addition to the crystals of relict altered plagioclase, turbid owing to the occurrence of small epidote grains, and biotite scales, biotite–quartz–plagioclase aggregates containing transparent laths of newly formed albite were observed in the interstices between plagioclase grains.

Thus, the rocks can be unambiguously interpreted as the vent facies of an Early Proterozoic central-type volcano, the main volcanic edifice of which has been completely eroded. This is suggested by the character of the outcrops of volcanic rocks; the steep dip of their schistosity, which is strongly different from the moderate- to low-angle SW dip of the schistosity of the country extrusive rocks; and the multiple successive intrusions of eruptive breccias, hybrid rocks of the rhyodacite composition, basalts, and gabbro-dolerites in this area. The abundant angular fragments of granitoids, amygdaloidal andesites, epidosites, quartz, and feldspar in the lava breccia and in the sheet bodies of basalt and gabbro-dolerite indicate the explosive character of eruptions, which were accompanied by shattering and entrapment of the rocks of the Archean granite basement and vent walls. During subsequent eruptions, the eruptive breccia was again shattered in places, and the resulting fractures were filled with secondary quartz, carbonate, and chlorite.

Since the body of vent eruptive lava breccias is located at the boundary between volcanic formations I and II, these rocks were assigned to volcanic formation II (Zagorodnyi et al., 1964; Fedotov, 1971; Mirskaya, 1971). The chemical composition of rocks from the Zapolyarnyi eruptive center is shown in Table 1. As can be seen from the table, the basalt cement of the lava breccia is chemically identical to the basalts and gabbro-dolerites of the sheet bodies. These rocks are represented by titanium-rich, high-iron, sodium–potassium varieties enriched in large ion lithophile elements (Rb, Ba, and Sr). Representative microprobe analyses of minerals from the gabbro-dolerite are given in Table 2. It is characteristic that both the turbid relict plagioclase of the gabbro-dolerite and the transparent newly formed plagioclase from the biotite–quartz–plagioclase aggregates have identical albite compositions, and the secondary plagioclase exhibits some excess of potassium at the expense of sodium (Table 2).

Table 3 shows the average chemical compositions of the rocks compared with the corresponding rocks of the Pechenga complex. Note that the moderately alkaline high-titanium iron-rich basalts of the volcanic center are chemically strongly different from the magnesian basalts of volcanic formation I and trachybasalts of volcanic formation II but are rather similar to the moderate-Ti ferrobasalts and ferropicrites of volcanic formation IV, as well as the subalkaline ferrobasalts and titanium-rich basalts of a differentiated rock unit from the section of volcanic formation IV, except for the elevated concentration of potassium in the basalts of the volcanic center, which is probably due to their contamination by the clastic granitoid material of the eruptive breccia. The REE distribution patterns of the basalts of the volcanic center are significantly different from the patterns of rocks from volcanic formations I and II but similar to the patterns of the ferrobasalts and ferropicrites of volcanic formation IV (Fig. 3). Note that the fragments of amygdaloidal andesite from the lava breccia (Table 3) are almost identical in composition, including REE distribution patterns, to the andesites of volcanic formation I but significantly different from the trachyandesite of volcanic formation II (Fig. 3, Table 3).

Thus, the petrochemical and geochemical investigation provided compelling evidence that the basalts of the Zapolyarnyi eruptive center are geochemically similar to titanium-rich ferrobasalts and, especially, ferropicrites of volcanic formation IV and products of their differentiation. Moreover, the Zapolyarnyi eruptive center is situated directly in the zone of the large Oreslompolo ore-controlling fault responsible for the formation of the eastern ore cluster of gabbro–wehrlite intrusions of the Pechenga ore field (Melezhik et al., 1994b), i.e., it is connected both geologically and

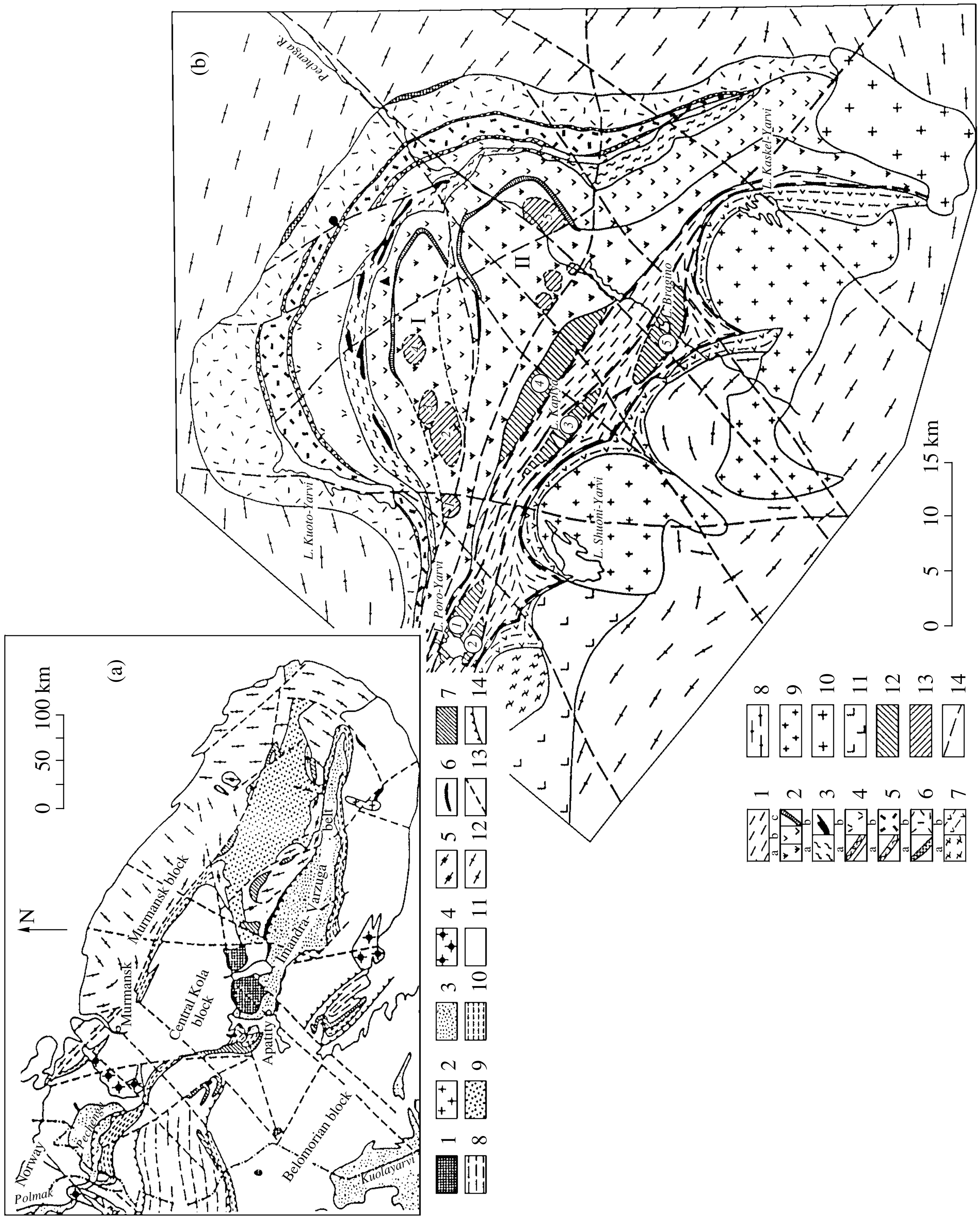
(a)
N
0 50 100 km
Norway
Polmak
Pechenga
Murmansk
Murmansk block
Central Kola block
Apatity
Imandra-Varzuga belt
Belomorian block
Kuolayarvi
(b)
Pechenga R.
L. Kuoto-Yarvi
L. Poro-Yarvi
L. Shuoni-Yarvi
L. Kaskel-Yarvi
I
II
0 5 10 15 km

Fig. 1. Geological sketch maps of (a) the Kola geoblock (modified after Smolkin, 1997) and (b) the Pechenga structure (Skuf'in, 1998).

(a) (1) Khibina and Lovozero plutons of Paleozoic age. Early Proterozoic: (2) granite and granodiorite; (3) supracrustal Karelide rocks; (4) charnockite; (5) peralkaline granite; (6) layered peridotite–gabbronorite intrusions; (7) gabbro-anorthosite; and (8) mafic and felsic granulites. Late Archean: (9) aluminous gneiss and schist; (10) amphibolite and other rocks of greenstone belts; and (11) granitic gneiss. Early Archean (?): (12) plagiogranite and tonalite. (13) Fault and (14) transpressional fault.

(b) (1) Volcanosedimentary rocks of the southern Pechenga complex (1700–1905 Ma); (2)–(6) volcanosedimentary rocks of the Pechenga complex (1905–2500 Ma): (2) volcanics of volcanic formation IV (Matert Formation) (1960–1990 Ma), including basalts and occasional ferropicrites of the (a) upper and (b) lower subformations and (c) volcanics of the layer of differentiated rocks including rhyolites and hypersilicic ferrorhyolites; (3) sedimentary formation IV (Zhdanov or Productive Formation): (a) tuff–sedimentary rocks and (b) rocks of ore-bearing gabbro–wehrlite association; (4) rocks of sedimentary formation III (Luchlompolo) and volcanic formation III (Zapolyarnyi) (2114 Ma): (a) sediments and (b) volcanics (basalts); (5) rocks of sedimentary formation II (Kuvernerinyoki) and volcanic formation II (Pirttiyarvi) (2214 Ma): (a) sediments and (b) volcanics (basalt, trachybasalt, and trachyandesite); (6) rocks of sedimentary formation I (Televi) and volcanic formation I (Mayarvi) (2324 Ma): (a) sediments and (b) volcanics (basalt, basaltic andesite, and andesite); (7) supracrustal rocks of uncertain stratigraphic positions: (a) gneissic schists and (b) schistose amphibolites; (8) gneiss–granite complex of the Archean basement; (9) plagiogranite and granodiorite of the Kaskelyarvi and Shuoni-Yarvi massifs (1940 Ma); (10) microcline granite of the Litsa–Araguba complex (1762 Ma); (11) gabbroid of the Kaskama–Shuort complex; (12) local volcanic centers in the southern Pechenga zone (numbers in circles): 1, Northern Poroyarvi; 2, Southern Poroyarvi; 3, Kaplya; 4, Poritash; 5, Bragino; (13) local volcanic centers in the northern Pechenga zone: 1, Shuoni-Yoki; 2, Kamaga-Yoki; 3, Forelnoozerski; 4, Sovayarvi; 5, Matert; and (14) dislocation. I, Northern trough and II, Southern trough. The filled circle shows the location of the Zapolyarnyi eruptive center, and the filled triangle indicates the Kola Superdeep Well.

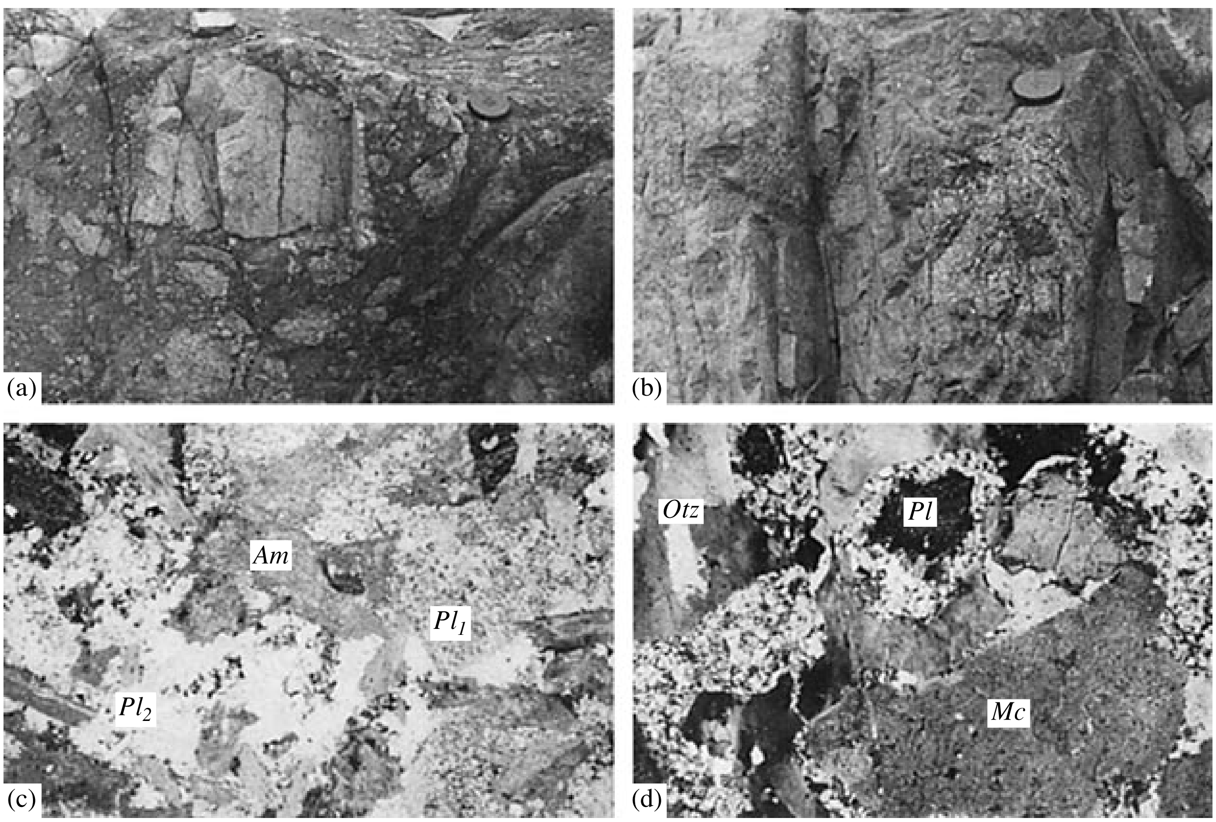

Fig. 2. Photos of outcrops and photomicrographs of the rocks of the Zapolyarnyi eruptive center. (a) Coarse clastic eruptive lava breccia with angular and partially molten fragments of medium-grained and pegmatiod granite in a basaltic cement. (b) Fragment of amygdaloidal andesite in the basaltic cement of eruptive breccia. (c) Gabbro-dolerite with turbid tabular plagioclase crystals of the first generation and transparent laths of albite of the second generation. The field of view is 8 mm across, without analyzer. (d) Fragment of pegmatoid granite; rims of newly formed albitophyre melt are clearly seen around plagioclase and microcline grains. The field of view is 5.5 mm across, with analyzer.

geochemically with the rocks of the ore-bearing ferropicrite–gabbro–wehrlite volcanoplutonic association. Hence, the estimation of the age of the Zapolyarnyi eruptive center is an important fundamental and practical problem.

Well crystallized gabbro-dolerites from the central part of a large lenticular body in the northern part of the paleovolcano were selected for the U–Pb dating of the basaltoids of the volcanic center. An 85-kg sample was collected from the gabbro-dolerite; 5 mg of zircons

Table 1. Chemical compositions of rocks from the Zapolyarnyi eruptive center

Component	02-10*	02-12	02-12B	02-17	02-12A	02-11A	02-11B
	1	2	3	4	5	6	7
SiO_2	50.13	51.09	50.43	47.78	57.49	76.55	69.43
TiO_2	2.61	2.15	2.41	2.55	0.77	0.03	0.17
Al_2O_3	12.92	12.67	12.24	12.46	12.77	12.74	16.61
Fe_2O_3	3.40	3.92	4.12	4.48	1.95	0.00	0.00
FeO	11.68	10.33	10.87	11.73	7.11	2.20	2.82
MnO	0.23	0.18	0.18	0.24	0.15	0.02	0.03
MgO	3.73	4.40	4.41	4.56	4.84	0.25	0.36
CaO	8.36	9.34	9.18	9.56	8.78	0.87	1.86
Na_2O	2.74	2.23	2.49	1.66	3.99	5.11	6.91
K_2O	1.57	1.06	1.40	1.03	0.61	1.41	0.66
H_2O^-	0.02	0.14	0.12	0.20	0.10	0.17	0.08
H_2O^+	2.01	2.23	1.92	2.90	1.55	0.24	0.64
P_2O_5	0.24	0.19	0.25	0.26	0.10	0.10	0.10
S_{tot}	0.05	0.01	0.04	0.21	0.01	0.01	0.01
CO_2	0.00	0.10	0.10	0.08	0.10	0.18	0.10
Total	99.72	99.96	100.07	99.70	100.32	99.88	99.78
Cu	160	160	400	660	120	88	70
Ni	55	130	100	96	81	35	36
Co	30	40	45	47	23	2.9	3
Cr	39	86	95	76	140	59	63
V	400	380	400	150	190	12	22
Rb	74	48	70	47	26	30	24
Ba	410	390	380	280	370	440	190
Sr	263	240	161	264	276	110	301
Nb	27	25	29	28	13	11	13
Zr	219	185	238	224	93	55	50
Y	36	29	37	37	14	6	6
La	22	n.d.	n.d.	n.d.	15	n.d.	n.d.
Ce	48	n.d.	n.d.	n.d.	29	n.d.	n.d.
Nd	30	n.d.	n.d.	n.d.	15	n.d.	n.d.
Sm	6.6	n.d.	n.d.	n.d.	2.9	n.d.	n.d.
Eu	1.9	n.d.	n.d.	n.d.	0.93	n.d.	n.d.
Tb	1.3	n.d.	n.d.	n.d.	0.50	n.d.	n.d.
Yb	4.2	n.d.	n.d.	n.d.	1.60	n.d.	n.d.
Lu	0.62	n.d.	n.d.	n.d.	0.21	n.d.	n.d.

Note: (1–4) Basalts of the eruptive center: (1) gabbro-dolerite, (2) and (3) basalt from the cement of lava breccia, and (4) fine-grained basalt from a sheet body; (5–7) rock fragments from eruptive breccia: (5) amygdaloidal andesite, (6) granite, and (7) granosyenite. The analyses were obtained at the chemical laboratory of the Geological Institute, Kola Research Center, Russian Academy of Sciences, analysts L.I. Konstantinova and G.G. Gulyuta. Oxides are in wt %, and elements are in ppm. n.d. denotes not determined.
* Sample number.

Table 2. Chemical compositions (wt %) of minerals from the gabbro-dolerite

Component	Amphibole		Plagioclase		Biotite	Titanite
	1	2	3	4	5	6
SiO_2	44.69	42.63	69.71	70.95	36.72	30.12
TiO_2	0.80	0.12	0.00	0.00	1.28	39.60
Al_2O_3	11.03	13.62	19.52	19.06	15.60	1.13
FeO	19.11	22.52	0.26	0.36	25.09	0.43
MnO	0.39	0.46	0.00	0.00	0.29	0.04
MgO	5.90	5.97	0.00	0.00	7.42	0.03
CaO	9.79	10.00	0.46	0.51	0.00	28.41
Na_2O	0.83	1.45	10.66	9.25	0.08	0.00
K_2O	0.74	0.40	0.06	0.26	8.67	0.01
Total	97.16	97.17	100.67	100.39	95.15	99.77

Note: The analyses were performed using an MS-46 electron microprobe at the Geological Institute, Kola Research Center, Russian Academy of Sciences, analyst E.E. Savchenko.

Table 3. Average chemical compositions (wt %) of rocks from the Zapolyarnyi eruptive center compared with the compositions of similar rocks from the Pechenga complex (analyses were recalculated to 100% on a volatile-free basis)

Component	1	2	3	4	5	6	7	8	9	10	11
	$n = 4$	$n = 1$	$n = 4$	$n = 12$	$n = 21$	$n = 24$	$n = 20$	$n = 39$	$n = 8$	$n = 3$	$n = 1$
SiO_2	74.36	58.24	51.60	51.42	59.88	52.51	59.67	49.83	48.62	49.30	44.30
TiO_2	0.09	0.83	2.43	1.09	1.07	1.94	1.42	1.85	2.04	2.27	4.91
Al_2O_3	14.56	12.90	13.16	14.18	12.96	13.96	15.47	14.05	8.82	13.07	13.08
Fe_2O_3	0.25	2.10	3.90	2.38	2.90	8.99	6.12	3.66	3.62	3.88	4.98
FeO	1.63	7.41	11.75	9.97	7.36	7.18	4.14	12.60	11.19	12.00	13.50
MnO	0.02	0.15	0.21	0.19	0.18	0.17	0.11	0.20	0.18	0.08	0.20
MgO	0.24	4.89	4.31	8.11	3.19	4.82	2.18	6.21	14.15	5.31	5.21
CaO	1.42	8.88	9.16	8.34	6.43	4.48	2.28	8.37	11.13	8.20	8.90
Na_2O	6.53	3.99	2.28	3.29	3.23	4.23	5.97	2.98	0.15	5.76	4.74
K_2O	0.90	0.61	1.20	1.03	1.80	1.72	2.64	0.25	0.10	0.13	0.18
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Note: (1–3) Rocks of the Zapolyarnyi eruptive center: (1) granite from fragments of eruptive breccia, (2) amygdaloidal andesite from fragments of eruptive breccia, and (3) basalt of sheet bodies and cement; (4) basalt and (5) andesite of volcanic formation I; (6) trachybasalt and (7) trachyandesite of volcanic formation II; (8) basalt of volcanic formation IV; (9) ferropicrite of volcanic formation IV; (10) ferrobasalt from the layer of differentiated rocks of volcanic formation IV; and (11) titanium-rich basalt from the same layer. The analyses were performed at the chemical laboratory of the Geological Institute, Kola Research Center, Russian Academy of Sciences, analysts Yu.N. Novikova, L.V. Malysheva, N.P. Kalugina, T.V. Ivonina, and E.A. Apanasevich. *n* is the number of analyses.

were separated from the sample using various magnets and bromoform; the zircons were further handpicked into four populations.

The first population is represented by transparent prismatic crystals with an adamantine luster and pink color, up to 125 μm in size; fractures parallel and normal to the grain axes and complex zoning patterns are visible in immersion oil (Fig. 4).

The second and third zircon populations include prismatic and short prismatic crystals with a purplish brown color, a zircon habit, and a vitreous luster; the crystals are fractured, zoned, and up to 175 μm in size.

Zircons of the fourth population are long prismatic grains, up to 200 μm in size, light brown in color, with slightly cavernous faces. These crystals show complex zoning patterns in immersion oil.

The U–Pb isotopic age of the four zircon types is 1918 ± 3 Ma (Fig. 4). The lower concordia intercept age is zero and reflects recent lead losses. The U–Pb system of the zircons is almost undisturbed. The chemical

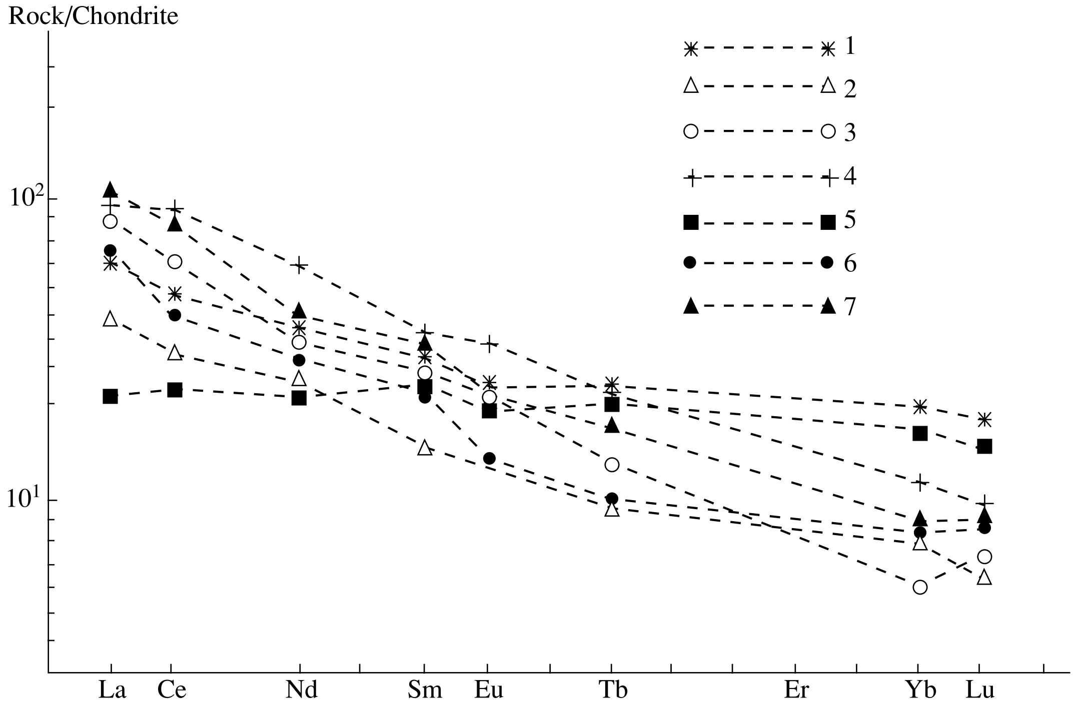

Fig. 3. Chondrite-normalized REE distribution patterns for the rocks of the Zapolyarnyi eruptive center and the volcanics of the Pechenga complex. (1) Basalt of the volcanic center; (2) andesite from a fragment in the eruptive breccia of the volcanic center; ferropicrites from the (3) lower and (4) upper parts of the section of volcanic formation IV; (5) ferrobasalt of volcanic formation IV; (6) basaltic andesite of volcanic formation I; and (7) trachybasalt of volcanic formation II.

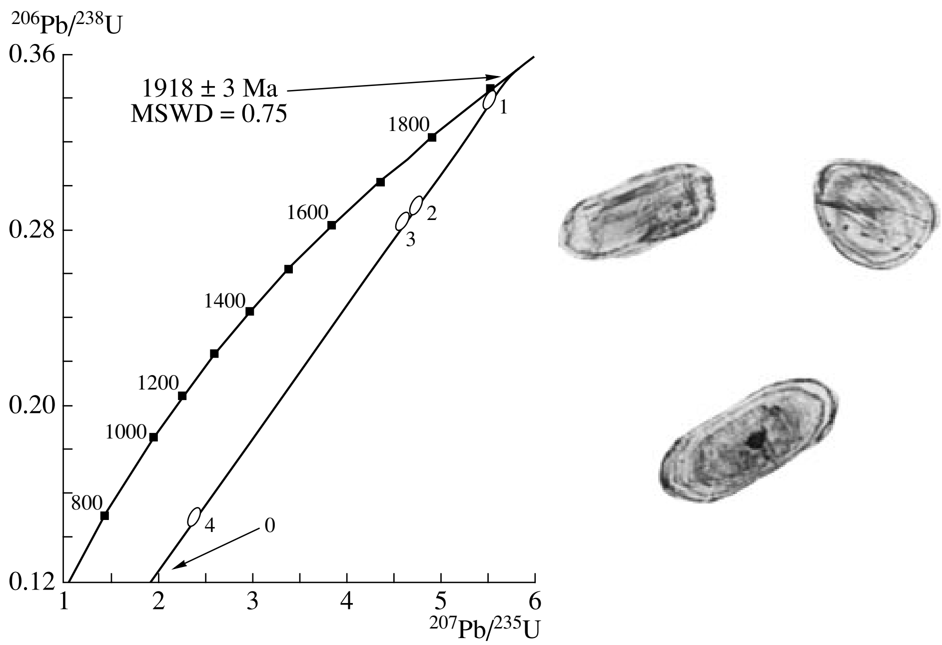

Fig. 4. U–Pb concordia diagram for zircons from the gabbro-dolerite of the eruptive center and morphological characteristics of zircon grains.

decomposition of zircon was performed using the procedures described by Krogh (1973); a mixed $^{208}Pb/^{235}U$ tracer and silica gel were employed. The coordinates of points and isochron parameters were calculated by the programs of Ludwig (1991, 1999) using universally accepted decay constants (Steiger and Jäger, 1977). All the reported errors correspond to the 2σ level (Table 4). The isotopic measurements were carried out on a Finnigan MAT-262(RPQ) seven-collector mass spectrometer operating in static mode.

Table 4. U–Pb isotopic data for zircon from the gabbro-dolerite

Sample no.	Weight, mg	Content, ppm		Lead isotope composition*			Isotope ratios and age, Ma**			*Rho****
		Pb	U	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	
1	1.60	44.5	118.1	9630	8.4213	6.0914	5.5117	0.3406	1916	0.89
2	0.50	171.4	532.2	9370	8.4030	6.0812	4.7192	0.2911	1920	0.96
3	0.55	245.1	829.2	3640	8.6265	11.1350	4.5901 (0.6%)	0.2838	1835	0.31
4	0.60	74.2	478.8	8230	8.7355	10.7350	2.4160	0.1489	1846	0.59

* All ratios were corrected for blank (0.08 ng Pb and 0.04 ng U) and mass discrimination (0.12 ± 0.04%).
** Correction for the admixture of common lead was carried using the model of Stacey and Kramers (1975).
*** Here and in Table 6, *Rho* is the correlation coefficient.

DISCUSSION

The available petrochemical, geochemical, and geological structural data suggest that the basalts of the Zapolyarnyi eruptive center are comagmatic with the rocks of volcanic formation IV (Matert Formation) of the Ludikovian. The volcanic rocks of this formation, up to 4.5 km thick, build up the central part of the Pechenga zone (Fig. 1) and overlie the carbonaceous sediments of sedimentary formation IV (productive), about 1 km thick. The volcanic formation is composed of basaltic lavas of two subformations, 2300 (mt_1, lower subformation) and 2100 m thick (mt_2, upper subformation). They are separated by a consistent layer of differentiated rocks, about 100 m thick (Skuf'in, 1998). In general, the section of volcanic formation IV is composed of 93% basalts (35% pillow lavas, 40% massive lavas, 11% tuffs and hyaloclastic breccias, and 7% gabbro-dolerite sills), 6% ferropicrites and picrobasalts (1% pillow lavas and 5% massive lavas), and 1% felsic lavas and tuffs. The basalts are iron-rich tholeiites with moderate titanium and low alkali contents (Table 3) and moderate concentrations of Ni, Co, Cr, Rb, Ba, Sr, and REE. The ferropicrites and picrobasalts show high concentrations of TiO_2 (>2 wt %) and total iron (>14 wt %). Their MgO content ranges from 13 to 17 wt %, and the total alkalis are 0.2–0.7 wt % (Skuf'in, 1998). Despite such low absolute contents of alkalis, these rocks are subalkaline picrites and, in addition to the high Fe and Ti, they are enriched in P, Zr, and Nb, i.e., typical elements of subalkaline magmas. The upper volcanic subformation is characterized by the occurrence of numerous local volcanotectonic caldera-type structures, from 1.5 to 5.0 km across (Fig. 1). These paleocalderas are typical structures of areal volcanism and were formed by sheet bodies of massive and basaltic pillow lavas and gabbro-dolerite sills.

The eruption of the volcanics of the upper subformation associated with dramatic changes in the structural pattern of the central part of the Pechenga volcanotectonic zone, which was caused by a local paroxysmal compression accompanying long-term rift-related extension (Skuf'in, 1998). This paroxysm was responsible for the unconformable deposition of the volcanics of the upper subformation on the underlying rocks, which is especially distinct in the eastern part of the structure; provided the formation of the Luotna Fault separating the northern (I) and southern (II) troughs (Fig. 1) in the central part of the structure; and activated movements along this fault, which promoted the separation of the northern and southern troughs with independent volcanic occurrences within each of them.

The period of local compression was terminated by significant horizontal movements of lithospheric blocks in the zone of the deep Poritash Fault, which separates the northern and southern Pechenga zones. This fault is a fragment of the Pechenga–Varzuga Fault, which controlled the time of generation and the morphology of the whole Pechenga–Varzuga belt. The Poritash Fault provided effective relaxation of stresses along the Pilguyarvi transpressional fault zone at the roof of sedimentary formation IV with subsequent intrusion in two large eruptive centers, Kauli (western) and Pilguyarvi (eastern), of subalkaline potassium-rich ferropicrite magma and primitive tholeiitic magma (Melezhik et al., 1994b). These portions of compositionally unusual magmas formed numerous basic and basic–ultrabasic massifs of the ore-bearing ferropicrite–gabbro–wehrlite volcanoplutonic association.

A typical example of the accumulation of numerous local eruptive centers of areal volcanism is the region of Mount Rayso-ayvi (west of the SG-3 Superdeep Well) made up of volcanic rocks of volcanic formation IV (Fig. 5). Volcanotectonic structures from a few hundreds of meters to 1 km across were mapped there. They are bordered by ring and arcuate faults and composed of cylindrical and sickle-shaped bodies of pillow and massive lavas, gabbro-dolerites, and eruptive breccias (Skuf'in, 1998). In addition, numerous dikes and complex intrusive bodies of eruptive breccias and lava breccias of basaltic and, occasionally, ferropicrite compositions were emplaced in the tectonically weakened zone at the contact of sedimentary formation IV and volcanic formation IV. The composition of the enclosing volcanic rocks at the base of the lower subformation (mt_1) differs from that of the typical titanium-rich ferrobasalts of volcanic formation IV in lower titanium and iron contents and higher CaO and alkalis (Table 5). The eruptive breccias and lava breccias forming numer-

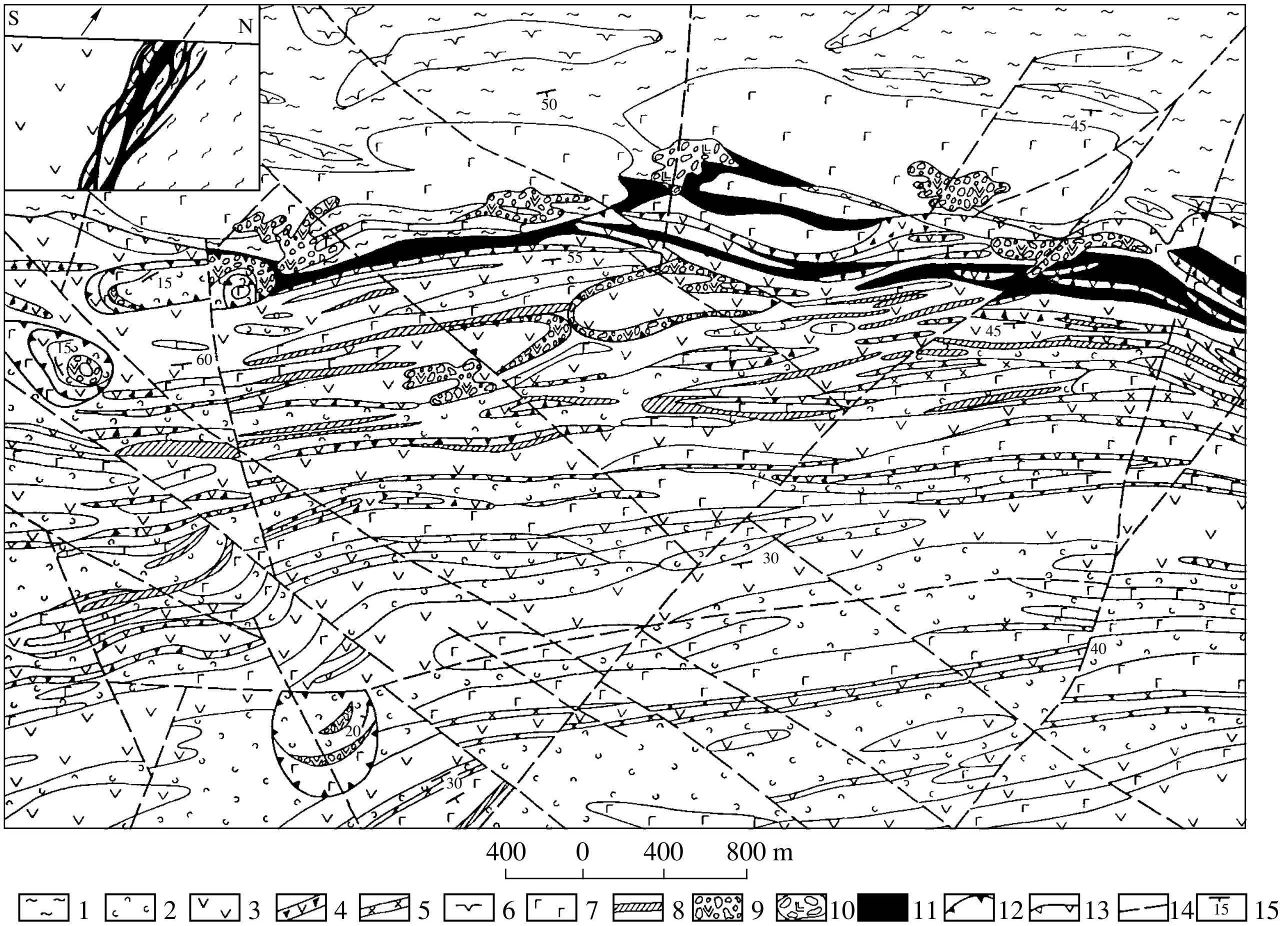

Fig. 5. Geological sketch map for the region of occurrence of the rocks of volcanic formation IV south of Mount Rayso-ayvi (area of the Eastern eruptive center) (Skuf'in, 1998). (1) Sediments of sedimentary formation IV; (2)–(11) volcanics of volcanic formation IV: (2) basaltic pillow lava, (3) massive basaltic lava, (4) basaltic tuff, (5) felsic tuff, (6) ultrabasic rocks of the gabbro–wehrlite association, (7) gabbroid of the gabbro–wehrlite association and gabbro-dolerite, (8) ferropicrite lava, (9) eruptive breccia of basaltic composition, (10) eruptive breccia of ferropicrite composition, and (11) eruptive lava breccia of basaltic composition; (12) ring faults of volcanotectonic structures; (13) Pilguyarvi transpressional fault along the boundary between sedimentary formation IV and volcanic formation IV; (14) fault; and (15) strike and dip elements. Inset in the upper left shows a simplified intrusion of eruptive lava breccias along the boundary between sedimentary formation IV and volcanic formation IV.

ous dikes and morphologically complex necks have diverse compositions. The matrix of the eruptive breccia is a fine clastic basaltic hyaloclastite. Basalts from the fragments and matrix of eruptive breccias are subdivided into two groups (Table 5): (1) tholeiitic basalts of normal silica contents and ordinary, occasionally elevated, alkali contents; and (2) alkali-poor ferrobasalts. The total iron content of the latter rocks may be as high as 18–20 wt % (sometimes, they are also enriched in TiO_2) at a strong alkali deficiency: less than 2 wt %, often about 0.5 wt %, and low silica content (often below 42 wt %). These extremely iron-rich low-alkali and low-silica basaltoids are depleted in large-ion lithophile elements (Rb, Sr, and Ba), enriched in siderophile elements (Ni, Cr, and Co), and could represent the most primitive mantle-derived varieties of basaltoids.

It is characteristic that in the SiO_2–(Na_2O + K_2O) diagram, the trends of undifferentiated primitive basalts converge at the point SiO_2 = 42 wt % and Na_2O + K_2O = 1.2 wt % (Perchuk and Frolova, 1979), which correspond to the contents of these components in the basalts from this site. Among the intrusive bodies of eruptive breccia, a body of vent-facies ferropicrite tuff agglomerates at the center of the site is of special interest (Fig. 5). This nearly isometric body of a complex shape, up to 400 m across, was traced to a depth of 1000 m, where it joins a lenticular gabbro–wehrlite body (Rayso-ayvi occurrence). The eruptive breccias are composed of angular and molten fragments of amygdaloidal vitrophyres of picritic compositions (Table 5) replaced by talc and chlorite. The cement matrix is a complex aggregate of secondary minerals: chlorite, talc, carbonate, and serpentine.

The period of local compression was also accompanied by the formation of a compositionally contrasting layer of differentiated volcanic rocks, about 100 m

Table 5. Chemical compositions of basalts and ferropicrites from the Rayso-ayvi area

Component	1	2	3	4	5	6	7	8	9	10
	C-28*	C-30	C-22	C-23	C-46	C-46A	C-74	C-75	2728-756.7	2728-1092.2
SiO_2	47.92	48.43	47.72	47.38	40.90	42.78	44.48	41.80	40.54	40.84
TiO_2	1.22	1.38	1.51	2.22	1.43	1.24	1.98	2.45	2.13	2.23
Al_2O_3	14.24	13.71	13.42	15.25	11.85	13.56	11.42	12.35	11.90	8.98
Fe_2O_3	5.06	2.95	2.21	4.37	6.57	5.26	4.90	5.07	2.61	4.25
FeO	7.74	9.45	10.56	10.07	12.16	12.17	12.89	14.08	12.60	13.32
MnO	0.22	0.20	0.22	0.18	0.17	0.12	0.21	0.29	0.26	0.22
MgO	7.15	7.03	9.01	5.75	7.45	6.48	4.45	5.37	16.30	15.98
CaO	9.56	9.19	6.61	4.45	9.91	9.00	12.95	10.60	8.36	4.72
Na_2O	3.00	3.48	2.42	2.02	0.38	0.30	0.45	1.55	0.20	0.18
K_2O	0.34	0.24	1.69	0.42	0.18	0.17	0.14	0.17	0.27	0.18
H_2O^-	0.39	0.34	0.46	0.82	0.72	0.38	0.12	0.37	0.30	0.35
H_2O^+	2.85	3.12	4.01	4.07	6.05	5.72	4.92	5.07	4.19	5.60
P_2O_5	0.15	0.10	0.11	0.21	0.10	0.07	0.12	0.19	0.20	0.20
CO_2	0.11	0.48	0.10	0.22	1.65	2.01	0.34	0.29	0.30	2.03
S_{tot}	0.11	0.10	0.15	2.02	0.25	0.90	1.00	0.10	0.10	0.83
Total	100.06	100.20	100.20	99.45	99.77	100.16	100.37	99.75	100.26	99.91
Rb	40	10	30	40	5	4	4	10	24	26
Sr	260	220	130	150	100	80	100	100	160	140
Ba	270	100	100	110	80	100	80	80	60	70
Ni	270	190	200	250	200	180	170	220	780	1000
Co	10	90	90	10	80	60	90	100	210	96
Cr	300	300	400	300	500	400	300	600	1100	1200

Note: (1) Pillow and (2) massive lava from the country basalt sheets of volcanic formation IV; (3–10) rocks of eruptive breccias: (3) fragments and (4) matrix of basaltic tuff agglomerate, (5) fragments and (6) matrix of basaltic lava breccia, (7) fragment of basaltic lava breccia, (8) matrix of basaltic lava breccia, and (9, 10) fragments from ferropicrite tuff agglomerate. The analyses were obtained at the chemical laboratory of the Geological Institute, Kola Research Center, Russian Academy of Sciences, analysts Yu.N. Novikova, L.V. Malysheva, T.V. Ivonina, and E.A. Apanasevich. Oxides are in wt %, and elements are in ppm.
* Sample number.

thick separating the lower (mt_1) and upper (mt_2) subformations. This layer is composed of lavas, tuffs, and paleoignimbrites of rhyolite and rhyodacite compositions, variolitic potassium-rich ferrobasalts and ferropicrites, iron-rich eucrites, and other exotic rocks.

In general, it can be concluded that the extensive compositionally uniform rift-related basaltic volcanism of the Ludikovian in the Pechenga structure was accompanied during certain stages by eruptions of strongly evolved melts of diverse compositions forming contrasting, occasionally bimodal volcanic associations with iron- and titanium-rich and felsic to hypersilicic rocks. They were formed under conditions of local compression accompanying large-scale explosive volcanic processes connected with the development of high-temperature and gas-saturated fluid systems.

A comparison of the morphology, structure, and compositions of rocks from the Zapolyarnyi eruptive center and various volcanic centers of areal volcanism of volcanic formation IV at the Rayso-ayvi area provides additional evidence that the Zapolyarnyi volcanic center is a fragment of an Early Proterozoic central-type volcano built up by lava breccia with abundant granitoid fragments indicating deep sources and explosive eruptions, whereas the eruptive centers of areal volcanism are local structures directly related to the eruption of basaltic or ferropicritic lavas from shallow transitional magma chambers.

It is important to compare the U–Pb zircon age of the volcanics of the Zapolyarnyi paleovolcano (1918 ± 3 Ma) with the age of rocks of Ludikovian volcanic formation IV, especially with the age of the intrusive gabbros and wehrlites that compose, together with the basalts and ferropicrites of this formation, the ore-bearing ferropicrite–gabbro–wehrlite volcanoplutonic association (Smolkin, 1992). It is well known that the major

Table 6. Results of U–Pb isotopic investigations of zircon, baddeleyite (*Bd*), and apatite (*Ap*) from the Ludikovian intrusive rocks of the Pechenga structure

Sample no.	Weight, mg	Content, ppm		Lead isotope composition[1]			Isotope ratios and age, Ma[2]			*Rho*
		Pb	U	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{207}Pb$	$^{206}Pb/^{208}Pb$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$	
Orthoclase gabbro of the Pilguyarvi intrusion (samples 444 and 448)										
444	0.35	51.9	131.8	1220	6.539	7.485	6.891	0.3511	2256	0.53
444, 2[3]	0.20	43.0	98.4	670	6.383	5.267	6.962	0.3680	2192	0.63
448[3]	0.35	20.2	47.9	440	5.782	5.609	6.918	0.3501	2268	0.65
448 (*Bd*)	0.90	74.1	211.2	5070	8.041	52.83	5.974	0.3559	1982	0.75
448 (*Bd*)	0.90	16.5	46.8	2230	7.824	35.32	5.941	0.3536	1983	0.65
Gabbro pegmatite of the Pilguyarvi intrusion (sample P-25)										
1 (*Ap*)[4]	5.20	3.7	4.1	114	4.2475	0.8431	6.055	0.3609	1983	0.95
2	0.45	102.7	265.5	1630	7.6808	7.9065	5.957	0.3541	1986	0.9
3	0.40	77.1	12.0	1670	7.7290	8.1346	5.5991	0.3341	1976	0.75
Olivine norites of the Nyasyucka dike complex (sample P-27)										
1 (*Bd*)[5]	0.85	129.0	328.4	466	6.7797	6.4842	5.5585	0.3385	1943	0.91
2 (*Bd*)[5]	0.70	135.4	370.9	638	7.1650	9.436	5.4410	0.3321	1939	0.91
3 (*Bd*)[5]	0.70	58.3	232.9	353	6.4052	5.3596	3.3823	0.2068	1936	0.82
4 (*Bd*)[5]	0.85	81.6	384.6	305	6.1690	4.3814	2.7496	0.1679	1938	0.46
Amphibole harzburgite of the Allarechka complex (sample P-30)										
1	0.30	11.8	23.6	1154	4.8863	2.7216	5.34534	0.329529	1921	0.60
2	0.20	59.7	182.2	1387	7.8341	2.2330	5.06711	0.311516	1926	0.78
3	0.35	21.0	53.0	808	7.1288	2.6806	4.82807	0.296217	1929	0.70

[1] All ratios were corrected for blank (0.08 ng Pb and 0.04 ng U) and mass discrimination (0.12 ± 0.04%).
[2] Correction for the admixture of common lead was determined using the model of Stacey and Kramers (1975).
[3] Corrected for the isotopic composition of the ore-bearing rock (metagabbro): $^{206}Pb/^{204}Pb = 21.39 \pm 0.02$, $^{207}Pb/^{204}Pb = 15.93 \pm 0.01$, and $^{208}Pb/^{204}Pb = 40.66 \pm 0.02$ (Pushkarev et al., 1985).
[4] Corrected for the isotopic composition of plagioclase: $^{206}Pb/^{204}Pb = 15.29$, $^{207}Pb/^{204}Pb = 15.16$, and $^{208}Pb/^{204}Pb = 34.97$.
[5] Corrected for the isotopic composition of plagioclase: $^{206}Pb/^{204}Pb = 15.316$, $^{207}Pb/^{204}Pb = 15.061$, and $^{208}Pb/^{204}Pb = 34.872$.

deposits of Cu–Ni sulfide ores of the Pechenga zone are confined to the Pechenga and Allarechka ore fields; the deposits are spatially and genetically connected with differentiated gabbro–wehrlite intrusions in the former field (Pechenga intrusive complex) and small peridotite (harzburgite) intrusions among amphibolites and amphibolized gabbro-dolerites in the latter field (Allarechka intrusive complex). The age relationships between the intrusions of these complexes have been the subject of long-standing debate (Smolkin, 1992; Melezhik et al., 1994b). In addition, small Cu–Ni ore occurrences are confined to large peridotite and olivine gabbro dikes of the Nyasyucka dike complex in the northeastern flank of the Pechenga structure.

Studies of 1990s focused on the geochemical and isotopic (Pb–Pb, Sm–Nd, and Rb–Sr) characteristics of the basalts and ferropicrites of volcanic formation IV, gabbro–wehrlites of the Pechenga complex, and the basic–ultrabasic dikes of the Nyasyucka complex cutting the granitic gneisses of the Archean basement. Based on these results, it was supposed that they are comagmatic and belong to a single ferropicrite–gabbro–wehrlite volcanoplutonic association (*Magmatism, Sedimentogenesis…*, 1995). The following Sm–Nd ages were determined using bulk-rock samples and major minerals: 1990 ± 40 Ma for the ferropicrites (Smolkin, 1992), 1970 ± 110 Ma for the gabbro–wehrlites of the ore-bearing Pilguyarvi intrusion of the Pechenga complex (Walker et al., 1994), and 1956 ± 20 Ma for the peridotite and olivine gabbro dikes of the Nyasyucka complex (Huhma et al., 1996). However, the accuracy of these age estimates was insufficient for reliable petrological reconstructions of the evolution of the Ludikovian magmatism and formation of ore-bearing intrusions, which were emplaced during several prolonged stages.

This problem can be approached by using high-precision methods, including the U–Pb dating of accessory zircon and baddeleyite. Samples for this investigation were taken from (1) the largest gabbro–wehrlite intrusion of the Pechenga intrusive complex, the Pilguyarvi massif, which is linked with the Pilguyarvi Cu–Ni sulfide deposit; (2) an olivine norite dike of the Nyasyucka intrusive complex occurring near the Kirikovan Quarry

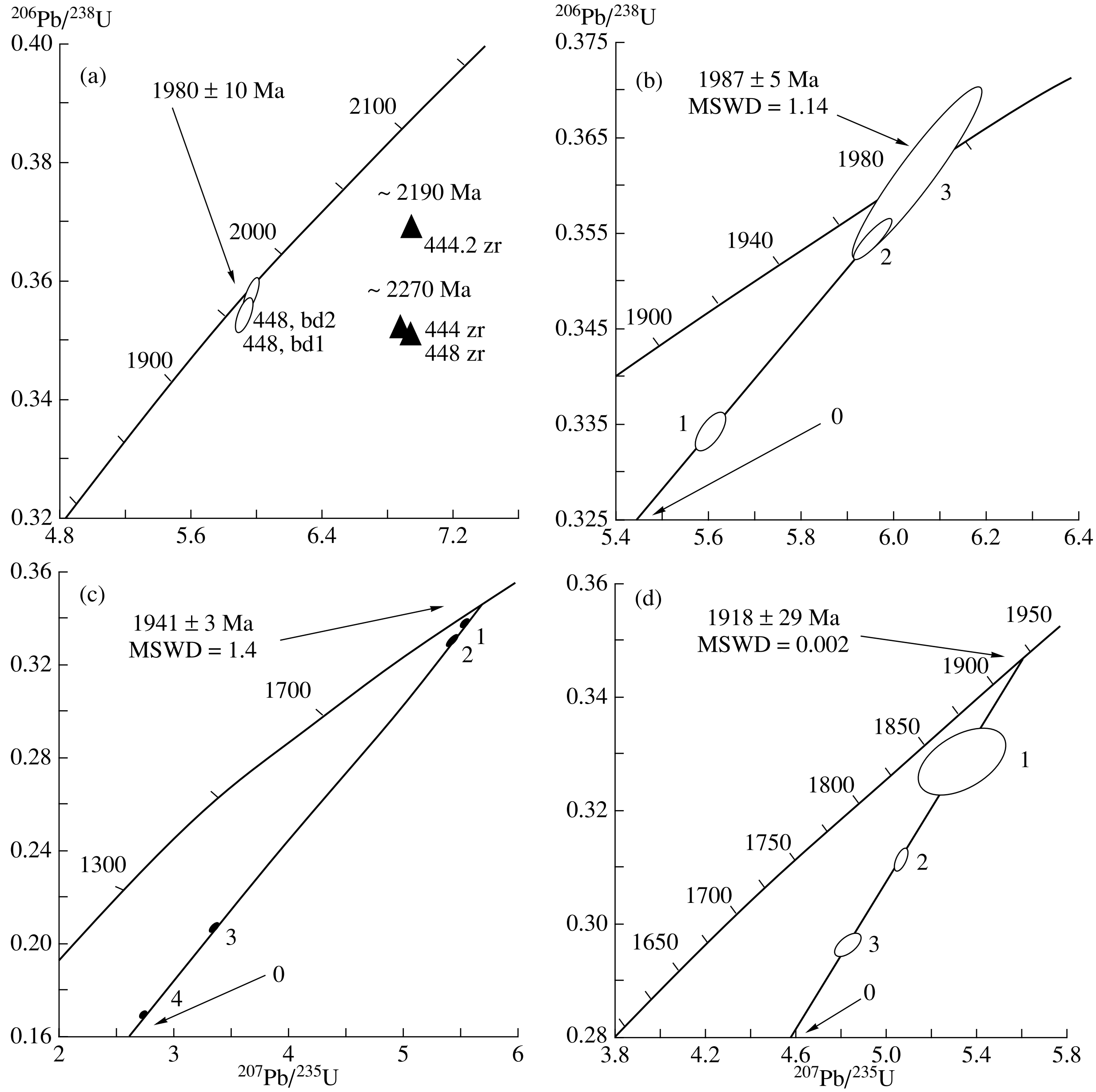

Fig. 6. U–Pb concordia diagrams for the accessory minerals from the Pechenga intrusive rocks of Ludikovian age. (a) Baddeleyite (*bd*) and zircon (*zr*) xenocrysts from the coarse-grained orthoclase gabbro of the roof zone of the Pilguyarvi intrusion (samples 444 and 448). (b) Zircon (1, 2) and apatite (3) from the gabbro pegmatite vein in the medium part of the section of the Pilguyarvi intrusion (sample P-25). (c) Four baddeleyite fractions from the border zone of an olivine norite dike belonging to the Nyasyucka dike swarm (sample P-27). (d) Zircon from the peridotite of the barren Akkim intrusion of the Allarechka intrusive complex (sample P-30).

south of the central peridotite dike; and (3) a barren peridotite intrusion from the Akkim area, southeast of the Allarechka Cu–Ni sulfide deposit.

The Pilguyarvi gabbro–wehrlite massif is composed of (from bottom to top) mineralized serpentinites and wehrlites; saussuritized banded and trachytoid gabbro separated from the wehrlites by a layer of clinopyroxenite with gabbro pegmatite pockets enriched in apatite (Smolkin, 1992); and coarse-grained subalkaline orthoclase gabbro. Subalkaline orthoclase gabbro from the roof zone of the massif and gabbro pegmatites from the clinopyroxenite layer were taken for U-Pb dating in the Central Quarry. The orthoclase gabbro contains tabular grains of brown baddeleyite (50–75 μm) and several varieties of corroded zoned zircon grains of various colors (50–175 μm). A concordant U–Pb age of 1980 ± 10 Ma was determined for baddeleyite from the orthoclase gabbro (Fig. 6a, Table 6). The two-point $^{207}Pb/^{206}Pb$ age of zircon varies from 2190 Ma (sample 444.2) to 2270 Ma (samples 444, 448). The zircons are

Table 7. Rb–Sr isotopic data for the basalts of the Zapolyarnyi volcanic center and the rocks of the Pechenga complex

Rock	Formation	Sample no.	^{87}Rb, ppm	^{86}Sr, ppm	$^{87}Rb/^{86}Sr$	Age, Ma	$(^{87}Sr/^{86}Sr)_0$
Basaltic andesite	Volcanic I	X-412.6	10.82	40.36	0.265	2320	0.7063
Subalkali basalt	Volcanic II	CK-73	5.91	20.00	0.292	2220	0.7024
Basalt	Volcanic III	41-80.6	0.335	16.05	0.0206	2115	0.7024
Basalt	Volcanic III	41-274.7	0.447	15.07	0.0293	2115	0.7041
Basalt	Volcanic III	41-39.0	0.513	9.41	0.0539	2115	0.7042
Basalt	Volcanic IV	87/27	0.612	9.66	0.0626	1980	0.7016
Ferropicrite	Volcanic IV	2988/88.0	0.344	3.01	0.1129	1980	0.7019
Basalt	Upper part of volcanic IV	91/1	6.123	13.18	0.4592	1970	0.7034
Basalt	Upper part of volcanic IV	91/2	6.573	16.59	0.3916	1970	0.7021
Basalt	Volcanic center	02/17	40.80	249.01	0.4874	1930	0.7084
Andesite (fragment)	Volcanic center	02/12A	32.50	274.71	0.35272	2320	0.7021

Note: Samples were analyzed using a MI-1201T mass spectrometer, analyst A.A. Delenitsin. The isotopic composition of Sr in all samples was normalized to 0.710235 for the NBS standard SRM-987. The uncertainties of Sr isotopic analysis were no higher than 0.04%. The blanks were 2.5 ng for Rb and 1.2 ng for Sr. The universally accepted value of the Rb decay constant (Steiger and Jäger, 1977) was used for calculations.

xenogenous and were evidently trapped by the melt from the underlying rocks of varying age, which is supported by the presence of small xenoliths of these rocks in the gabbro. Rounded unzoned or slightly zoned zircon grains were separated from the gabbro pegmatite sample. They show light brown (type 2) and brown (type 3) colors. In addition, we analyzed elongated prismatic crystals of apatite (type 1), some of which were observed as inclusions in plagioclase. The U–Pb age calculated for the two varieties of magmatic zircon and apatite is 1987 ± 5 Ma, MSWD = 1.14 (Fig. 6b, Table 6). The points of apatite fall within the errors on the concordia curve in the U–Pb diagram. The obtained results suggest that the Pilguyarvi massif, which is the largest massif of the Pechenga intrusive complex, was formed 1987–1980 Ma ago. This inference allows us to constrain the ages of other gabbro-wehrlite massifs of the Pechenga ore field.

Olivine norite dike of the Nyasyucka dike complex. A 35-kg sample of medium- and coarse-grained partially amphibolized norite varieties was taken from the border zone of the dike for U–Pb dating. Tabular grains of brown baddeleyite, up to 175 μm in size, and detrital zircon grains were extracted from the sample. Almost all the zircon grains are metamict. The U–Pb isotope data for four baddeleyite fractions gave an upper intercept age of 1941 ± 3 Ma (MSWD = 1.4), and the lower intercept reflects recent lead losses (Fig. 6c, Table 6).

Thin barren peridotite (harzburgite) bodies at the Akkim area. These bodies occur among the Late Archean amphibolites and amphibolized gabbro-dolerites and were penetrated by a series of exploration boreholes. Weakly altered peridotites were collected (44-kg sample) for U–Pb dating. Three varieties of corroded zircon grains showing brownish (type 1), yellow (type 2), and straw-yellow (type 3) shades were separated from the sample. The U–Pb isochron age of the three zircon populations is 1918 ± 29 Ma, and the lower concordia intercept reflects recent lead losses (Fig. 6d, Table 6). Consequently, the age of the Allarechka intrusions is Early Proterozoic rather than Late Archean, as was thought previously (Smolkin, 1992).

Our results lead us to the conclusion that the basalts of the Zapolyarnyi eruptive center are regular products of the evolution of the Ludikovian basic–ultrabasic magmatism. They are confined to the late stages of this magmatism, when sharply increasing explosive activity produced numerous local eruptive centers of areal volcanism, and the earliest central-type volcanoes, including Zapolyarnyi, were formed.

Taking into account the results of tomographic studies of the deep levels of the Pechenga region and adjoining part of the Barents Sea (Isanina et al., 2000; Kazanskii et al., 2002), the Pechenga structure and the entire Pechenga–Varzuga greenstone belt can be considered not simply as a long-lived rift structure, but rather as a zone affected by Proterozoic plumes ascending from the deep mantle (Mitrofanov and Bayanova, 1999; Kazanskii et al., 2002). The extensive magmatism of this region could be coeval with certain stages in the evolution of plume tectonic processes.

Rb–Sr isotopic and geochronological data were obtained for the volcanic and intrusive rocks of the Pechenga structure (Table 7). The procedures of Rb–Sr measurements were described by Bayanova (2004). In addition, a large number of Sm–Nd measurements have recently been reported for the rocks of Precambrian shields, including the Baltic shield. Considerable variations in $\varepsilon_{Nd}(T)$ values were established for the komatiites of the Archean greenstone belts of Karelia and the Kola Peninsula: from +1 in Palay-Lamba to +4 in Kos-

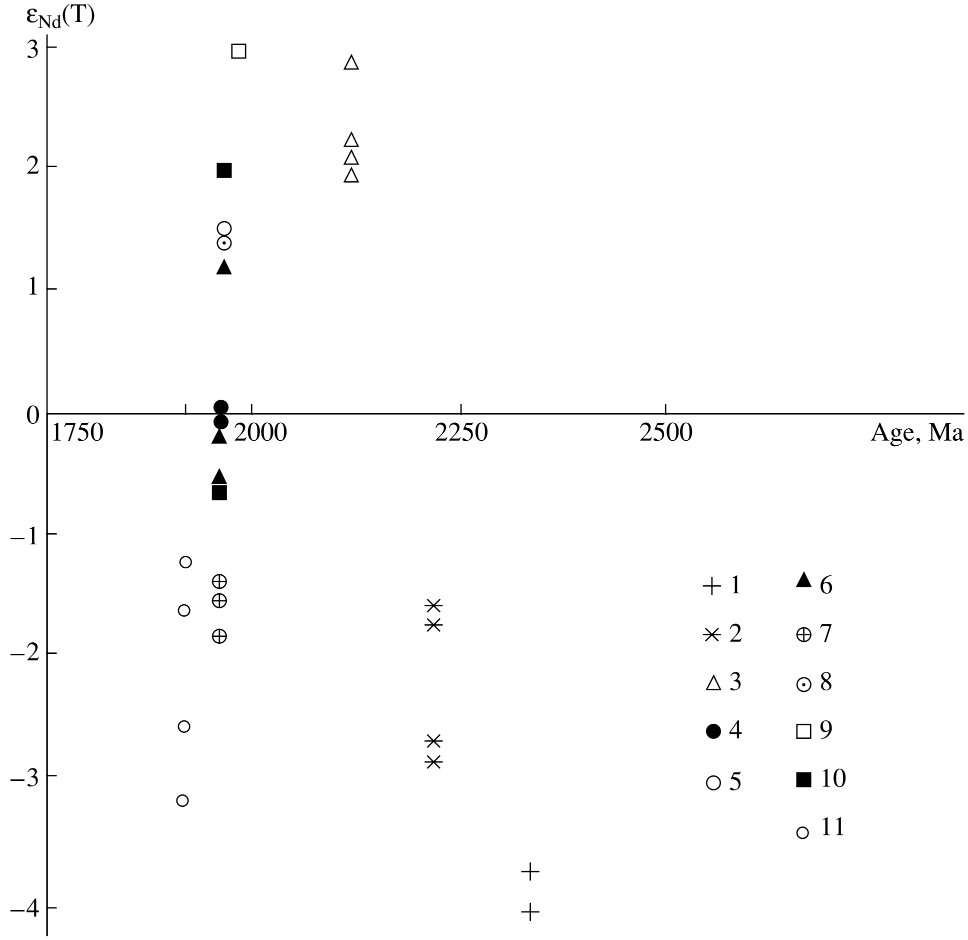

Fig. 7. Variations in $\varepsilon_{Nd}(T)$ for the volcanic and intrusive rocks of the Pechenga structure. (1) Basaltic andesite and andesite of volcanic formation I; (2) subalkaline volcanics of volcanic formation II; (3) basalt of volcanic formation III; (4)–(7) rocks of volcanic formation IV: (4) basalt, (5) titanium-rich basalt from the base of the layer of differentiated rocks, (6) ferropicrite, and (7) rhyolite; (8) intrusive rocks of the gabbro–wehrlite association (Hanski, 1992); (9) ophiolites of the early suite of the Jormua complex; (10) ophiolites of the late suite of the Jormua complex (Lahtinen and Huhma, 1997); and (11) basalt of the Zapolyarnyi volcanic center.

tomuksha (Vrevsky et al., 1995). Negative $\varepsilon_{Nd}(T)$ values from –1.2 to –2.3 were obtained for the layered peridotite–pyroxenite–gabbronorite intrusions with sulfide, chromite, PGE, and titanomagnetite mineralization, which were emplaced at the Archean–Proterozoic boundary (Bayanova, 1992). The layered intrusions were formed over a time span of 100 Ma, and there are two groups of intrusions: older Central Kola (Mt. Generalskaya, Monche Pluton, and Fedorovo–Panskie massifs; 2505–2490 Ma) and younger Finnish–Karelian (Kemi, Penikat, Koylismaa, Imandra lopolith, Burakovsky pluton, and Olanga plutons; 2445–2400 Ma). The picrobasalts of the Vetreny Belt are comagmatic with the younger group of intrusion and have an age of 2448 Ma at $\varepsilon_{Nd}(T)$ = –1.7 (Puchtel et al., 1991).

Two main types of mantle sources were proposed for the Jatulian and Ludikovian complexes of Karelia and the Kola Peninsula: (1) depleted mantle [Jatulian basalts of Karelia and komatiites of the Karasjok belt with an age of 2085 Ma and $\varepsilon_{Nd}(T)$ = +4.1 (Krill et al., 1985) and Jormua and Outokumpu ophiolites with an age of 1970 Ma and $\varepsilon_{Nd}(T)$ of +3.1 and +3.2 (Kontinen, 1987)]; and (2) metasomatized mantle (Smolkin, 1992) (gabbro–wehrlites of the Pechenga intrusive complex and comagmatic ferropicrite volcanics with an age of 1980–1956 Ma and $\varepsilon_{Nd}(T)$ of +1.4 and +1.5).

Our Sm-Nd isotopic investigations of the rocks of the Pechenga complex suggest more complex and diverse conditions of the formation of mantle-derived volcanics from the Pechenga structure (Table 8, Fig. 7). The procedures of Sm–Nd measurements were described in detail by Bayanova (2004). The basaltic andesites and andesites of volcanic formation I (T = 2324 Ma; $\varepsilon_{Nd}(T)$ of –3.39, –4.19, and –6.26) and subalkaline rocks of overlying volcanic formation II (T = 2214 Ma; $\varepsilon_{Nd}(T)$ of –1.56, –1.68, –2.69, and –2.83) have isotopic characteristics of the enriched mantle. The model age [$T_{Nd}(DM)$] of the andesites of volcanic

Table 8. Sm–Nd isotopic data for the basalts of the Zapolyarnyi volcanic center and the rocks of the Pechenga and southern Pechenga complexes

Sample no.	Rock	Formation	Content, ppm		Isotope ratio		T_{Nd}(DM), Ma	Age, Ma	ε_{Nd}(T)
			Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$			
Pechenga complex									
X-453.4	Andesite	VF I	4.81	25.72	0.113103	0.511148 ± 3	2878	2324	−4.19
X-412.6	Basaltic andesite		3.39	17.31	0.118437	0.511268 ± 10	2844	2320	−3.39
05/2	Basaltic andesite		3.46	17.24	0.121200	0.511219 ± 22	3017	2320	−6.26
K-74	Mugearite	VF II	11.46	52.61	0.131639	0.511546 ± 11	2789	2214	−2.83
K-53	Trachyandesite		10.43	45.82	0.137547	0.511697 ± 16	2697	2214	−1.56
K-54	Trachyandesite		11.51	52.75	0.131878	0.511557 ± 18	2773	2214	−2.69
X-267.0	Basalt		4.49	23.89	0.113727	0.511343 ± 5	2590	2214	−1.68
42-40.0	Basalt	VF III	3.34	12.66	0.159453	0.512232 ± 6	2266	2114	+2.18
41-274.5	Basalt		4.28	16.95	0.152453	0.512125 ± 10	2273	2114	+1.99
41-39.0	Basalt		3.50	13.68	0.154754	0.512165 ± 11	2258	2114	+2.15
41-120.5	Basalt		3.56	13.34	0.161203	0.512293 ± 11	2161	2114	+2.90
87/18	Ti-basalt	VF IV (lower part)	6.92	32.21	0.129767	0.511840 ± 12	2172	1980	+1.43
91/3	Basalt	VF IV (upper part)	2.85	11.54	0.149061	0.512013 ± 11	2422	1960	+0.04
91/2	Basalt		2.83	11.55	0.147853	0.511993 ± 9	2424	1960	−0.04
91/1	Basalt		2.73	11.03	0.149562	0.512013 ± 9	2442	1960	−0.09
87/75	Ferropicrite	VF IV	10.44	49.65	0.127087	0.511725 ± 10	2309	1980	−0.14
3077-350.0	Ferropicrite		5.70	22.95	0.150127	0.511993 ± 9	2470	1980	−0.48
3077-313.0	Ferropicrite		5.11	28.32	0.109073	0.511564 ± 7	2142	1980	+1.20
87/8	Rhyolite		14.94	77.16	0.117054	0.511513 ± 12	2404	1980	−1.83
87/3	Rhyolite		21.79	114.49	0.115026	0.511502 ± 12	2371	1980	−1.53
87/10	Rhyolite		13.41	69.85	0.116011	0.511523 ± 11	2362	1980	−1.37
1684/1	Peridotite	SF IV	3.81	18.67	0.123400	0.511746 ± 26	2177	1960	+1.4
Pet1/1.0	Gabbro		9.55	41.36	0.139600	0.511959 ± 10	2217	1960	+1.4
02/10	Gabbro-dolerite	Zapolyarnyi volcanic center	6.37	26.78	0.143859	0.511812 ± 23	2690	1920	−3.13
02/12	Basalt		4.94	21.17	0.140947	0.511804 ± 23	2595	1920	−2.56
02/12B	Basalt		6.52	27.46	0.143486	0.511887 ± 21	2505	1920	−1.57
02/17	Basalt		6.61	28.11	0.142031	0.511889 ± 14	2448	1920	−1.17
Southern Pechenga complex									
89-76	Picrite	Menel Formation	3.30	10.97	0.181832	0.512473 ± 10	2762	1865	+0.31
89-77	Picrite		3.44	13.04	0.159683	0.512473 ± 5	2317	1865	+0.62
89-78	Picrite		2.58	9.32	0.167526	0.512254 ± 11	2612	1865	−0.55
89-88	Picrite		2.24	7.63	0.177815	0.512430 ± 15	2618	1865	+0.43
89-95	Picrite		3.31	12.82	0.156087	0.512157 ± 6	2334	1865	+0.29
89-62	Mg-basalt		3.24	12.47	0.157121	0.512164 ± 5	2359	1865	+0.18
88-8	Andesite	Kaplya Formation	9.17	51.99	0.106597	0.511243 ± 9	2556	1855	−5.75
88-126	Andesite		8.11	46.34	0.105801	0.511217 ± 4	2574	1855	−6.07
88-130	Andesite		8.38	47.30	0.107161	0.511264 ± 5	2539	1855	−5.48
SYu-2	Basaltic andesite		7.13	39.16	0.110050	0.511393 ± 15	2418	1855	−2.63
C-1418403	Dacite	Intrusions of Mt. Poritash	2.22	10.14	0.132269	0.511542 ± 7	2820	1855	−4.55
C-1418701	Rhyolite		4.94	24.26	0.123059	0.511481 ± 8	2627	1855	−3.32
89-B134	Trachydacite	Subvolcanic intrusions	6.08	29.09	0.126281	0.511650 ± 5	2424	1855	−1.13
89-B145/8	Trachydacite		1.83	11.32	0.097842	0.511161 ± 6	2470	1855	−4.55
89-74	Trachydacite		2.15	13.55	0.096005	0.511158 ± 8	2435	1855	−2.92
89-184	Granite		1.08	6.73	0.096555	0.511103 ± 6	2519	1855	−5.06

Note: Sm and Nd isotopes were analyzed using a Finnigan MAT-262 seven-collector mass spectrometer operating in static mode. The precision of determinations was estimated by the repeated analyses of the Nd isotope standard La Jolla (0.511833 ± 6, $N = 11$) and was no higher than 0.0024 (2σ). The laboratory blank was 0.3 ng for Nd and 0.06 ng for Sm. The calculations were based on the Jacobsen and Wasserburg (1984) model. Samples 1684/1 and Pet/1.0 are after Hanski (1992). VF is volcanic formation, and SF is sedimentary formation.

formation I varies within 2844–3017 Ma, and the rocks of formation II yield T_{Nd}(DM) values within 2590–2789 Ma. On the other hand, the younger titanium-rich high-iron tholeiitic basalt of volcanic formation III show depleted mantle characteristics (T = 2114 Ma; ε_{Nd}(T) of +1.99, +2.15, +2.18, and +2.90), and their model age T_{Nd}(DM) is 2161–2273 Ma. The volcanics of youngest volcanic formation IV (1985–1956 Ma) show characteristics of anomalous metasomatized mantle, but their ε_{Nd}(T) values range from +1.43 for titanium-rich basalts at the base of the formation to +0.04, –0.04, and –0.09 for basalts from the upper parts of the formation. Similarly complex relationships were established for the ferropicrites. They also display significant ε_{Nd}(T) variations: +1.20, –0.14, and –0.48. Such a considerable scatters in ε_{Nd}(T) values for the basalts and ferropicrites of volcanic formation IV could be related to some specific features of the evolution of their mantle source.

The rhyolites from the layer of differentiated rocks produced by the fractionation of ferropicrite melt yielded ε_{Nd}(T) values of –1.37, –1.53, and –1.83. The T_{Nd}(DM) values of the basalts of volcanic formation IV vary within a narrow range of 2422–2442 Ma, and that of the ferropicrites and their rhyolitic derivatives is 2142–2470 Ma. A considerable scatter in ε_{Nd}(T) values is also characteristic of picrites from the younger Southern Pechenga complex (Table 8), where the picrites and Mg-basalts of the Menel volcanic formation (T = 1865 Ma) show anomalous mantle characteristics: ε_{Nd}(T) of +0.62, +0.43, +0.31, +0.29, +0.18, and –0.55. The T_{Nd}(DM) values of these rocks range from 2317 to 2762 Ma. On the other hand, the andesites of the Kaplya volcanic formation and the granitoid subvolcanic rocks of the southern zone show enriched mantle characteristics: T = 1855 Ma and ε_{Nd}(T) of –1.13, –2.63, –2.92, –3.32, –4.55, –4.55, –5.06, –5.48, –5.75, and –6.07; their T_{Nd}(DM) values lie within the range 2424–2820 Ma.

It is noteworthy that strong variations from negative to positive ε_{Nd}(T) values were observed in the ophiolites of the late suite of the Jormua complex, whereas the ophiolites of the early suite show consistent positive ε_{Nd}(T) values, typical of the depleted mantle (Lahtinen and Huhma, 1997).

The ε_{Nd}(T) values of the basalts of the Zapolyarnyi volcanic center (–1.17, –1.57, –2.56, and –3.13) are characteristic of anomalous or enriched mantle reservoirs and close to those of the ferropicrites of volcanic formation IV and their derivatives, especially rhyolites. The model ages T_{Nd}(DM) of the basalts of the volcanic center fall within the range 2448–2690 Ma.

CONCLUSIONS

(1) This paper reports the results of geological and petrogeochemical investigations of well-preserved Early Proterozoic (Ludikovian) rocks forming a relict fragment of a central-type volcano in the Pechenga zone. This paleovolcano differs in structure and rock association from numerous local eruptive centers of areal volcanism, which were previously mapped in this area. The Zapolyarnyi paleovolcano is confined to the boundary between volcanic formations I and II of the Pechenga complex and is an oval-shaped body composed of volcanic eruptive lava breccia. The clastic material of the breccia is represented by granites and pegmatoid granites of the Archean basement of the Pechenga zone embedded in a basaltic matrix. The moderate-titanium iron-rich basalts and gabbro-dolerites of the volcanic center are enriched in large ion lithophile elements (Rb, Ba, and Sr) and are chemically similar to the basalts and ferropicrites of volcanic formation IV. In general, these rocks are reliably interpreted as the vent facies of an Early Proterozoic central-type volcano, the volcanic edifice of which has been completely eroded.

(2) The U–Pb zircon age of the basalts of the Zapolyarnyi volcanic center is 1918 ± 3 Ma, which is similar to the previous age estimates for the basalts and ferropicrites of volcanic formation IV: 1990 ± 40 Ma by the Sm–Nd method and 1970 ± 45 Ma by the Re–Os method. The volcanics of this formation contributed 2000–1920 Ma ago to the formation of a single volcanoplutonic ferropicrite–gabbro–wehrlite ore-bearing association of the Ludikovian. The age of the ore-bearing Pilguyarvi gabbro–wehrlite intrusion was constrained as 1987 ± 5 Ma (U–Pb data for zircon) and 1980 ± 10 Ma (U–Pb data for baddeleyite), which allowed us to refine the ages of other gabbro–wehrlite massifs of the Pechenga ore field. New U–Pb ages were obtained for the comagmatic olivine norites of the Nyasyucka dike complex in the northeastern flank of the Pechenga structure (1941 ± 3 Ma for baddeleyite) and peridotites of the Allarechka ore field in the southern framing of the Pechenga structure (1918 ± 29 Ma). These estimates suggest that the rocks were emplaced during the final stage of the evolution of the late Ludikovian basic–ultrabasic magmatism. Taking into account that the titanium-rich ferrobasalts of the Zapolyarnyi eruptive center and the peridotites of the Allarechka ore field have identical isochron ages (1918 Ma), it can be concluded that the basalts of the eruptive center represent a regular component in the evolution of the Ludikovian basic–ultrabasic magmatism and are confined to its late stages, which showed a dramatic increase in explosive activity.

(3) The Rb–Sr and Sm–Nd isotopic investigations of the Pechenga volcanics indicate complex and variable conditions of their formation. The rocks of volcanic formation I (T = 2324 Ma; ε_{Nd}(T) of –3.39, –4.19, and –6,26; and T_{Nd}(DM) = 2844–3017 Ma) and volcanic formation II (T = 2214 Ma; ε_{Nd}(T) of –1.56, –1.68, –2.69, and –2.83; and T_{Nd}(DM) = 2590–2789 Ma) show characteristics typical of anomalous or enriched mantle reservoirs, whereas the younger titanium-rich high-Fe tholeiitic basalts of volcanic formation III have

depleted mantle values (T = 2114 Ma; ε_{Nd}(T) of +1.99, +2.15, +2.18, and +2.90; and T_{Nd}(DM) = 2161–2273 Ma). The basalts of volcanic formation IV (T = 1985–1956 Ma) show ε_{Nd}(T) from +1.43 (base of the formation) to +0.04, –0.04, and –0.09 (roof of the formation), and the ferropicrites of this formation show ε_{Nd}(T) values of +1.20, –0.14, and –0.48. The ε_{Nd}(T) values of the rhyolitic derivatives of ferropicrite melt are –1.37, –1.53, and –1.83. Such considerable variations in the ε_{Nd}(T) values of the rocks of volcanic formation IV could be related to specific features of the evolution of their mantle source. The model age [T_{Nd}(DM)] of the basalts of this formation is 2422–2442 Ma, and the ferropicrites and their rhyolitic derivatives show T_{Nd}(DM) values of 2142–2470 Ma. The ε_{Nd}(T) values of the basalts of the Zapolyarnyi volcanic center are –1.17, –1.57, –2.56, and –3.13, which correspond to an anomalous or enriched mantle reservoir and are similar to the ε_{Nd}(T) of the ferropicrites and their derivatives, especially rhyolites. The model age of the basalts of the volcanic center varies within the range 2448–2690 Ma.

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