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GEOLOGY

Evidence for Sveconorwegian (Grenvillian) Magmatic Activity in the Northwestern Baltic Shield

A. A. Arzamastsev[a], P. Montero[b], A. V. Travin[c], L. V. Arzamastseva[a], F. Bea[b], and Zh. A. Fedotov[a]

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The crustal structure in the Baltic Shield is determined by a system of geological blocks, which formed at different evolutionary stages of this largest stable Precambrian domain. Cratonization of the Archean Karelian, Kola, and Belomorian domains terminated after the Svecofennian orogeny 1.88–1.75 Ga ago [1]. Up to now, the principal structural elements of the shield formed by that time have remained practically unchanged over its entire area. The Paleozoic lithospheric plume-related processes that were responsible for the formation of the Kola alkaline province 0.38–0.36 Ga ago [2] did not provoke systemic transformations of the Precambrian basement. Thus, the geological history of the ancient Archean core of Fennoscandia included a long-term (>1.3 Ga) amagmatic period. However, structural reorganization related to the Sveconorwegian orogenesis took place in the southwestern areas of the shield considered as a continuation of the Grenvillian foldbelt of North America [3]. This stage, manifested 1.20–0.93 Ga ago as substantial deformations of the basement and formation of high-grade metamorphic belts, was accompanied by bimodal magmatism ranging from mantle-related basites to typically crustal late orogenic granitoids. Basites represented by

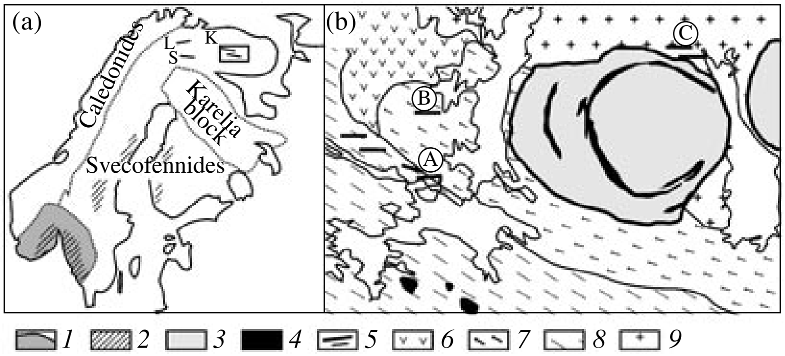

Fig. 1. Schematic distribution of the manifestation of Sveconorwegian basic magmatism in (a) the Baltic Shield and (b) the central Kola Peninsula. (*1*) Domain of Sveconorwegian orogenesis; (*2*) domain of basic volcanics and dolerite dikes; (*3*) Paleozoic alkali and (*4*) alkali–ultramafic magmatism; (*5*) dolerite dikes (out of scale): (L) Laanila, (S) Salla, (K) Kola region. Rocks of the Early Proterozoic and Late Archean basement: (*6*) mafic and ultramafic rocks of Proterozoic layered intrusions, (*7*) supracrustal and plutonic rocks of the Proterozoic Imandra–Varzuga riftogenic complex, (*8*) gneisses, amphibolites, and granodiorites of the Belomorian geoblock, (*9*) granodiorites and gneisses of the Kola geoblock. Detailed areas in Fig. 1b: (A) Voche–Lambina, (B) Mt. Devich'ya, (C) Chuda River.

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[a] *Geological Institute, Kola Scientific Center, Russian Academy of Sciences, ul. Fersmana 14, Apatity, 184200 Russia*
e-mail: arzamas@geoksc.apatity.ru
[b] *United Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences, pr. akademika Koptyuga 3, Novosibirsk, 630090 Russia*
[c] *Department of Mineralogy and Petrology, University of Granada, Fuentenueva s/n., 18002, Granada, Spain*

plutonic gabbroids, volcanics, and doleritic dikes played a specific role in the evolution of magmatism of that period [4–6]. Igneous rocks of the Sveconorwegian stage, localized largely in the southwestern Baltic Shield (Fig. 1a), are traced in central Sweden and western Finland [7]. The northernmost manifestations of basaltic magmatism are represented by the rare Salla and Laanila dikes (Finland) dated back to 1122 ± 5 (based on the U–Pb zircon and titanite methods [8]) and 985 Ma (based on the Sm–Nd method [9]), respectively.

When dating and correlating Proterozoic and Paleozoic subvolcanic rocks from the central Kola Peninsula, we revealed dike swarms that can be correlated with igneous rocks from southwestern Fennoscandia in terms of their age and isotopic–geochemical characteristics.

Geological position of igneous complexes. West of the Khibiny Massif, Upper Archean and Lower Proterozoic basement rocks host a swarm of several doleritic dikes (0.5 to 15 m thick) that constitute a band (20 × 40 km in size) mapped in the Voche–Lambina domain (Fig. 1b, area A) and southern spur of Mt. Devich'ya (area B). Dikes are usually near-vertical and are characterized by both the dominant near-latitudinal strike (80° ± 5°) and the occasional SE-oriented strike (120° ± 10°) corresponding to that of the Salla Dike. In the comprehensively studied Voche–Lambina domain [10], dikes traceable over 350 m are oriented parallel to a near-latitudinal system of tectonic fractures marked by foliation zones without significant lateral displacements and deformations of the basement. Near-latitudinal doleritic dikes observed in the northeastern framing of the Khibiny Massif (area C) probably belong to the same swarm.

Petrography and composition. All the examined dikes are characterized by an azonal structure, small thickness of the quenching zone, and typical dolerite composition. The ophitic texture of rocks is formed by plagioclase (An_{55-74}) laths and isometric clinopyroxene and orthopyroxene aggregates. Olivine, quartz, and biotite are subordinate. Trace minerals are represented by titanomagnetite, ilmenite, and apatite. No metamorphic alterations are observed.

The chemical composition of dikes (Table 1) suggests that their dolerites belong to the tholeiitic series. Variations in the contents of main major elements in various rocks from different swarm dikes are insignificant: the magnesian index, mg# = 100 MgO(MgO + FeO_{tot}), is as high as 61–65. All the dolerites are characterized by normal contents of either quartz (0–3 mol %) or olivine (0–3 mol %). The REE distribution demonstrates a low fractionation coefficient (La/Yb_N = 1.6–2.6) and lack of the europium anomaly (Eu/Eu* = 0.92–1.05). Similar petrochemical characteristics are typical of mafic rocks in the peripheral zone of the Salla Dike [8].

Table 1. Chemical composition of dolerites from the central Kola Peninsula (major elements are given in wt %, trace elements, in ppm)

Component	Sample A02-01	Sample IL 1250	Sample 98-1	Sample 1260	Sample UL1257
SiO_2	48.07	47.86	49.00	49.47	48.62
TiO_2	0.82	0.77	0.81	0.76	1.48
Al_2O_3	13.99	13.52	13.62	12.96	12.29
Fe_2O_3	3.55	3.79	3.67	2.25	2.74
FeO	6.44	8.02	6.86	7.81	7.94
MnO	0.19	0.18	0.18	0.18	0.20
MgO	10.06	10.10	9.96	10.88	11.10
CaO	11.01	10.86	10.08	10.80	11.00
Na_2O	1.53	1.48	1.32	1.14	1.40
K_2O	0.14	0.11	0.41	0.46	0.37
P_2O_5	0.07	0.06	0.05	0.01	0.05
CO_2	0.42	0.26	0.04	0.10	0.10
S_{tot}	0.05	0.03	0.08	0.11	0.01
H_2O^+	2.74	1.99	2.54	2.50	2.49
H_2O^-	0.57	0.57	1.00	0.27	0.13
Total	99.65	99.61	99.61	99.70	99.92
Rb	4.00	5.00	23.5	24.0	24.0
Sr	97.8	89.0	107	83.5	92.4
Ba	43.5	70.0	59.1	80.6	41.6
Sc	41.7	43.4	41.2	41.7	47.7
V	258	275	265	253	270
Cr	622	587	609	694	697
Co	51.9	57.0	51.9	56.1	58.8
Ni	180	195	194	216	227
Cu	78.5	100	97.0	87.4	111
Zn	67.9	81.0	74.5	65.8	81.3
Y	16.7	16.3	17.1	15.3	16.2
Nb	2.50	2.32	2.70	3.12	2.61
Ta	0.15	0.20	0.18	0.52	0.23
Zr	47.0	54.0	49.0	43.2	46.2
Hf	1.33	1.50	1.35	1.17	1.00
Pb	1.58	15.0	2.85	1.35	3.51
U	0.21	0.21	0.21	0.19	0.19
Th	0.81	0.74	0.78	0.86	0.76
La	4.14	4.39	3.99	5.69	4.00
Ce	8.94	9.97	8.78	9.66	9.39
Pr	1.32	1.36	1.28	1.28	1.36
Nd	6.00	6.66	5.93	6.03	6.30
Sm	1.79	1.82	1.81	1.74	1.96
Eu	0.68	0.66	0.68	0.63	0.67
Gd	2.19	2.57	2.24	2.13	2.58
Tb	0.40	0.41	0.42	0.37	0.44
Dy	2.71	2.69	2.68	2.50	2.94
Ho	0.59	0.58	0.59	0.55	0.63
Er	1.69	1.83	1.68	1.58	1.73
Tm	0.26	0.24	0.26	0.24	0.27
Yb	1.69	1.65	1.69	1.53	1.74
Lu	0.27	0.23	0.27	0.23	0.25

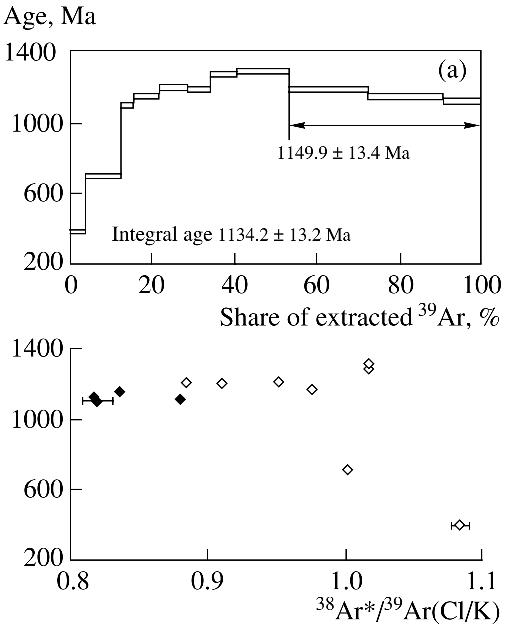

Fig. 2. ^{40}Ar/^{39}Ar isotope data on dolerite dikes. The age spectrum and ^{38}Ar*/^{39}Ar (Cl/K) plot demonstrate the age obtained for mineral fractions of phlogopite A02-01 (a) and IL 1250 (b). Solid rhombs in plots show points with low Cl/K values included into the age plateau.

Among diverse coeval subvolcanic rocks from the southeastern Baltic Shield, Mesoproterozoic dolerites of the Kola Peninsula can be correlated with basic volcanics and dikes of southern Sweden and Norway adjacent to the Protogine zone [6, 11]. The comparison shows that Kola dolerites are characterized by geochemical parameters (MgO 10.0–11.1 wt %; Ni 180–250 ppm; Cr 590–700 ppm) corresponding to the most primitive magmatism of the Sveconorwegian period. Close geochemical analogues of Kola dolerites are recorded among dikes of the Dal [6] and Tromöy [5] areas, where dolerites with the highest magnesian index represent initial members of the tholeiitic magmatic series. The negative niobium anomaly in the Kola and South Scandinavian basites is probably an initial characteristic of the source rather than a consequence of fractional crystallization (La/Nb > 1). The isotopic characteristics of Kola samples ($\varepsilon_{\mathrm{Nd}(t)}$ = +3.5, $\varepsilon_{\mathrm{Sr}(t)}$ = +15.5) and the cited geochemical data indicate the mantle melt source.

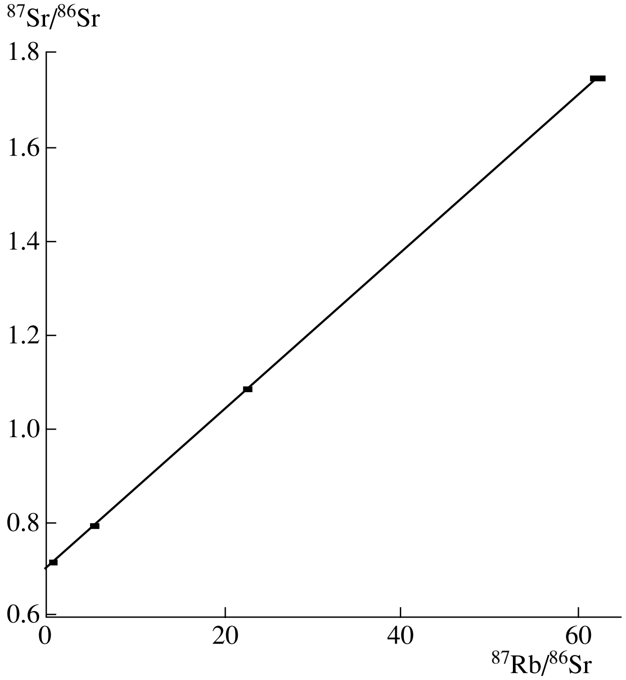

Fig. 3. Rb–Sr isochron diagram for dolerites (sample 98-1) from a dike of the Voche–Lambina area. Age 1176 ± 28 Ma, $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_0 = 0.7042 \pm 0.0061$, MSWD = 14.

Age of igneous rocks was determined by the ^{40}Ar/^{39}Ar method involving the stepwise heating of biotite from two samples taken from doleritic dikes in the Mt. Devich'ya area. The obtained age spectra are characterized by intricate patterns (Fig. 2): the stepwise increase in values that begins with an age of 409–386 Ma is followed first by relatively elevated values and then by a plateau with ages of 1150 ± 13 and 1161 ± 13 Ma in the high-temperature region of the spectrum. Steps constituting the plateau are characterized by minimal ^{38}Ar*/^{39}Ar (Cl/K) values (Fig. 2), indicating that the high-temperature argon source corresponds to phlogopite grain areas unaffected by subsequent alterations. The Paleozoic age of superimposed impacts is evident from the low-temperature regions of the spectra. The dolerite age was also determined by the

Table 2. Rb–Sr and Sm–Nd isotope data on rocks and minerals in dolerite from a dike of the Mt. Devich'ya area (sample A02-01)

Material	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Rock, bulk	23.7	105	0.6543	0.71692 ± 0.002
Biotite-1	340	16.0	61.7309	1.74578 ± 0.040
Biotite-2	209	26.8	22.5797	1.08382 ± 0.005
Pyroxene	27.4	14.4	5.5178	0.79517 ± 0.060
	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$
Rock, bulk	1.92	6.59	0.1757	0.512656 ± 0.00003

Rb–Sr method. The mineral isochron (Table 2) based on four data points corresponds to an age of 1176 ± 28 Ma (Fig. 3). The influence of Paleozoic magmatism (dikes are located 20 km away from the western contact of the Khibiny Massif) did not distort the Rb–Sr isotopic system, although it resulted in the overestimation of the mean square deviation.

The dates obtained by different methods are consistent with each other. They show that dikes of the Kola region formed during the extension phase at the initial stage of orogenesis and involved southern Fennoscandia [9]. The dominant near-latitudinal strike of the dikes suggests that they did not inherit Archean and Early Proterozoic structures of the basement during the Sveconorwegian orogeny. The analysis of space images revealed the spatial coincidence of dikes with morphologically well-manifested near-latitudinal faults. Their wide distribution in the Kola region was noted in [12]. It can be assumed that the influence of the Sveconorwegian orogeny in the northeastern part of the shield was locally manifested in metamorphic transformations of Precambrian basements rocks, in addition to tholeiitic magmatism. This is evident from ages registered in isotopic zircon systems based on the lower intercepts of U–Pb concordia for the Lukkulaisvaara, Tsipringa, Burakovka, and Pana layered basite intrusions [13]. Thus, the obtained data indicate that the Sveconorwegian orogeny provoked the structural reorganization of not only southwestern Fennoscandia but also a significant part of the Baltic Shield (including its northeastern part) and initiated the injection of mantle tholeiitic melts into the crust.

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