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Sources of the terrigenous material in the formation of metasedimentary rocks of the Archaean basement of the Paleoproterozoic Pechenga structure

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Abstract. The basement of the Paleoproterozoic Pechenga structure was cored by the Kola Superdeep Borehole SD-3 at the depths of 6842-12262 m. It consists of alternating strata of metavolcanic dacite, plagiorhytodacite rocks and high-alumina gneisses; the protoliths of these rocks corresponded mainly to graywackes. Resulting from the examination of zircons from metaterrigenous rocks of the 1st, 3rd, and 9th strata of the SD-3, the detrital, anatectic, metamorphogenic, and contact-metasomatic genetic types have been identified. Detrital zircons include several age groups. The most homogeneous, i.e., comparable to zircons from tonalite gneisses (bottoms of the SD-3 section) and from surrounding rocks, zircons have appeared to be those from gneisses of the deepest 9th stratum. The data on the age of these zircons, along with a poor rounding of the grains, signify formation of the host gneisses' protoliths owing to washing out and redeposition of material. Widening of alimentation areas, which supplied terrigenous material into sedimentation basins, took place during formation of alumina gneisses of the 3rd and especially 1st strata of the section.

Аннотация. Фундамент палеопротерозойской Печенгской структуры вскрыт Кольской сверхглубокой скважиной СГ-3 на глубинах 6842-12262 м и состоит из чередующихся толщ метаэффузивных пород дацит-плагиориодацитового состава и метаосадочных пород – высокоглиноземистых гнейсов, протолиты которых отвечали главным образом составам граувакк. В результате изучения цирконов из метатерригенных пород 1-й, 3-й и 9-й толщ СГ-3 выделены детритовые, анатектические, метаморфогенные и контактово-метасоматические генетические типы, при существенном преобладании цирконов первых двух типов. Среди детритовых цирконов обособлены несколько возрастных групп. К наиболее однородным, сопоставимым по возрасту и составу с цирконами из тоналитовых гнейсов основания разреза СГ-3 и аналогичных пород окружения скважины, относятся цирконы из гнейсов самой глубоко залегающей 9-й толщи. Данные по возрасту этих цирконов свидетельствуют об формировании протолитов вмещающих гнейсов за счет размыва и переотложения материала из местных источников. Расширение ареала областей сноса и увеличение числа источников, поставлявших терригенный материал в бассейны осадконакопления, происходило при образовании глиноземистых гнейсов 3-й и особенно 1-й толщ разреза, завершающей разрез архейских пород СГ-3.

Key words: Kola Superdeep borehole, Neoarchaean rocks, rare elements, zircons, U-Pb isotope age, sources of terrigenous material
Ключевые слова: Кольская сверхглубокая скважина, неоархейские породы, редкие элементы, цирконы, U-Pb изотопный возраст, источники терригенного материала

1. Introduction

The Kola Superdeep Borehole (SD-3) is drilled in the northern Paleoproterozoic Pechenga structure, which is part of the riftogenous Polmak-Pasvik-Pechenga-Imandra-Varsuga-Ust'-Ponoy belt. From the surface to the depth of 6842 m the borehole opens the Paleoproterozoic sedimentary-volcanogenic complex, and further to its extend at the depth of 12262 m – the Neoarchaean rocks of the basement of the Pechenga structure. Five rhythms stand out in the alternations of the Archaean rocks, the lower elements of which (2nd, 4th, 6th, 8th, 10th strata) are represented by dacite-plagiorhyodacite metavolcanic rocks (tonalite gneiss), constituting ~45 % of the section (*The Kola Superdeep Borehole*, 1998). The upper parts of the rhythms (1st, 3rd, 5th, 7th, 9th strata) consist of gneiss with the high-alumina minerals (HAM), constituting ~20 % of the rocks' volume. Jaspilite and amphibolites, the predominant part of which is of the Paleoproterozoic age, form about 30 % of the section, and ~5 % occurred by veins of granites. In order to solve the problem of the sources of terrigenous material in the formation of gneiss with HAM, the main and trace elements in them were determined as well as the morphological particularities and age of the zircon crystals. It was shown that the sources of material for gneiss with HAM were metavolcanics of the lower parts of the SD-3 section and surrounding rocks, gneiss of the Kola series situated to the north of the SD-3, and also rocks of basic composition. A widening of the area of scattering and an increase of the number of sources of the terrigenous material occurred from the 9th stratum, located in the lower part of the section, to the 1st stratum, completing the section of the Archaean Complex of the SD-3.

2. Analytical procedure

The chemical and rare-element composition of the gneiss was determined in the Norwegian Geological Service, Trondheim, and concentrations of REE in the 1st and 3rd strata in the scanning spectrometer MONOSPEC 1000 at the Institute of the Lithosphere RAS, Moscow. Monofractions of zircon were separated from gneiss with HAM of the 1st, 3rd and 9th strata at the GI KSC RAS for which the U-Pb isotope analysis was carried out on the ionic microprobe SHRIMP-II at TSII VSEGEI, St.-Petersburg (Table) according to the technique (*Williams*, 1998).

3. Petrology

Gneisses with HAM of all strata of the borehole are characterized by significant variations in the content of SiO_2 (52,2-72,2 %), associated by a negative correlation with other main components, the concentrations of which are also subject to significant variation (wt %): Al_2O_3 – 12,65-20,24; FeO – 2,96-10,23; MgO – 1,13-9,41; CaO – 0,98-3,36; Na_2O – 2,25-4,9; K_2O – 1,42-5,16. In the petrochemical diagrams (*Predovsky*, 1980; *Neelov*, 1980) the components of protoliths are reconstructed mainly as greywackes, with less presence of polymictic sandstones, aleuropelitic and pelitic argillites, all of which also partially overlap with a composition of tonalite gneisses of the SD-3 section, para- and orthogneisses of the Kola series. By comparison with standard types of magmatic rocks, various SiO_2 composition gneisses with HAM have a higher content of Al_2O_3 and contain more femic minerals and alsilite. This is due, probably, to the admixture of a clay component and detrital material of the basic structure in protolith of gneisses, which is confirmed, correspondingly, by the presence of a clearly positive correlation between Al_2O_3 and K_2O, and also a positive connection between relatively inert components in the conditions of weathering Al_2O_3 and TiO_2, Fe_2O_3, MgO. Gneisses of the 1st and 3rd strata have similar amounts of the main, rare and REE elements. Minima of Ba, Nb, P, Ti characteristic for the Archaean greywackes and the Postarchaean clay shists (PAAS) in gneisses are distinctly shown on a spidergram normalized to a primitive mantle of concentration of rare elements (Fig. 1A) with a close concentration of the majority of rare elements with the Archaean upper crust (*Taylor, McLennan*, 1985). Gneisses with HAM from the 1st and 3rd strata differ from PAAS formed as a result of substances consolidated continental crust by decreased concentrations of REE, K, Th, Ba, Zr, Nb, P and increased – Cr, Ni, which could have been caused both by differing composition of the sources of scattering, and the geodynamic conditions of the formation of the sedimentary rocks. They have a moderately fractionated spectrum REE with the relation $(La/Yb)_n = 11,3$ and 10,3, and the absence or weakly negative Eu-anomaly (Eu/Eu*, the average, correspondingly, 1,0 and 0,83). By the content and relation to REE, gneisses are close to the Late Archaean greywackes with La/Yb = 12,5 и Eu/Eu* = 0,88 and rocks of the Archaean upper crust (Fig. 1B). The content of mafic material in gneisses with HAM was determined by geochemical data using models of two-component mixing. Archaean rocks with a basic composition from the surroundings of the SD-3 represented at the current time by amphibolites (high Ti/Zr-, low La/Yb relations), and also tonalite gneiss and paragneiss of the Kola series (low Ti/Zr-, high La/Yb relations) are the most likely original components (the final components of the model). As shown in Fig. 2, the distribution of data points of gneisses with HAM on the mixing curve determines the quantity of femic material in the composition of gneisses within the limits 15-40 %.

4. Types and age of zircon

Four genetic types of crystals – detritic, anatectic, metamorphogenic, and contact-metasomatic, among which the first two types of zircons sharply predominate, were separated in the investigation of zircons. Data points of the studied zircons (Table) are given in the diagram in the coordinates "age (T), Ma – Th/U" (Fig. 3A) for comparison with the zircons from rocks produced by the main stages of magmatism and metamorphism of the northern part of the Baltic Shield. From this diagram, constructed only for the concordant age data of the zircons studied, it follows that the predominant part of the anatectic zircons are located in the field of amphibolite facies of metamorphism and migmatization with the age intervals of 2.7-2.77 Gyr. Several age groups can be distinguished among the detritic zircons. Zircons from gneisses of the 9th stratum are the most homogenous, comparable in age and composition with zircons from tonalitic gneisses of the basement of the SD-3 and analogous rocks surrounding the borehole. These zircons are often found in the form of sharp-edged crystals in the inner parts of anatectic crystals. This attests to the formation of protolithes containing gneisses due to weathering and movement of material from local sources, and short distances and replacement of materials. Part of the studied zircons changed during processes of the Neoarchaean metamorphism which determined the decrease in the age of the zircons and the lowering of the Th/U relation. Gneisses of the 9th stratum also experienced processes of the Proterozoic metasomatic events connected with the intrusion of rocks of basic and acid composition determined the formation of zircons aged 2.47-2.51 and 1.77 Gyr.

The increase in the area of scattering took place during the formation of high-alumina gneisses of the 3rd stratum and especially the 1st stratum. Detritic zircons of the 1st stratum are characterized by the well-roundedness of the crystals, and the wide spectrum of the age data – from 2.79 to >3.1 Gyr. They are located on the diagram in the field of composition of zircons from different types of rocks: the Neoarchaean tonalitic gneiss of SD-3 and surrounding rocks, ancient granitoids of the northern part of the Baltic Shield, and gneiss of the Kola series. According to the Th/U relation, the most ancient detritic zircons are located on the borders of the field of magmatic zircons from granitoids (*Kröner, Compston*, 1990) and xenogenous zircons from the gneiss of the Kola series. At the same time the similarity between the composition of zircons of the gneisses of the SD-3 1st stratum and the gneisses of the Kola series is well established by the content of common lead in them, concentrations of which in the studied zircons is 10-20 times lower than in zircons of the most ancient granitoids (Fig. 3B).

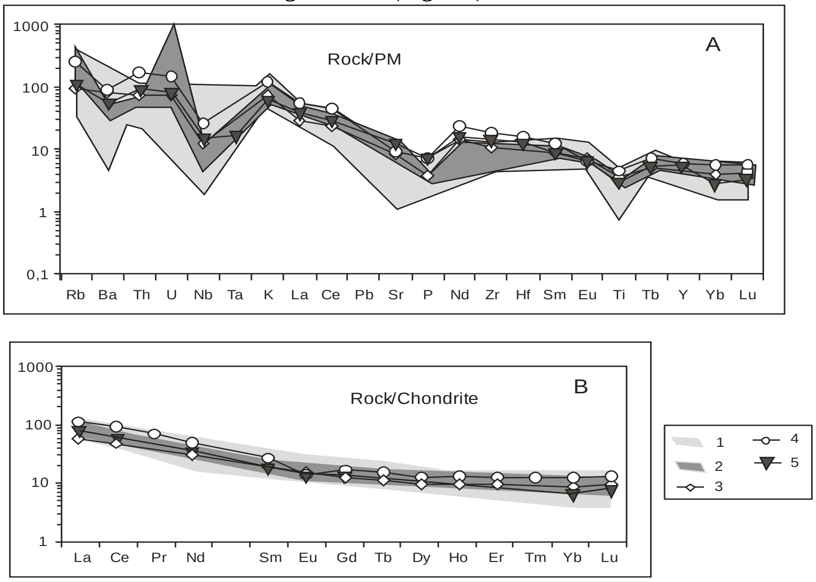

Fig. 1. Spidergram of rare (A) and REE (B) elements in high-alumina gneisses of the SD-3, normalized to the primitive mantle and chondrite. 1, 2 – respectively gneisses of the 1st and 3rd strata, 3 – argillite, 4 – PAAS, 5 – the Archaean greywackes (*Taylor, McLennan*, 1985)

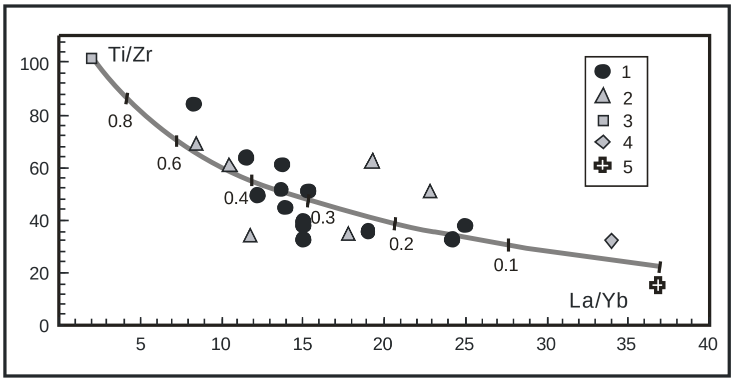

Fig. 2. Diagram in coordinates La/Yb – Ti/Zr. 1, 2 – gneisses of the 1st and 3rd strata, 3 – the Archaean amphibolites surrounding the SD-3 (*The Kola Superdeep Borehole*, 1998), 4 – paragneisses of the Kola Series (*The Kola Superdeep Borehole*, 1998), 5 – tonalite gneisses of the Svanik Complex (*Levchenkov et al.*, 1995)

5. Conclusion

This allows us to suggest that the sources of the scattering of felsic terrigenous material for the gneisses of the 1st stratum were mainly the Neoarchaean tonalite gneisses located below the portion of the borehole and its surroundings, and to a lesser degree the gneisses of the Kola series. Thus, the widening of the area of scattering and the increase in the number of sources of terrigenous material occurred from the 9th stratum, lying in the lowest part of the section, to the 1st stratum, ending the section of the Archaean Complex of the SD-3.

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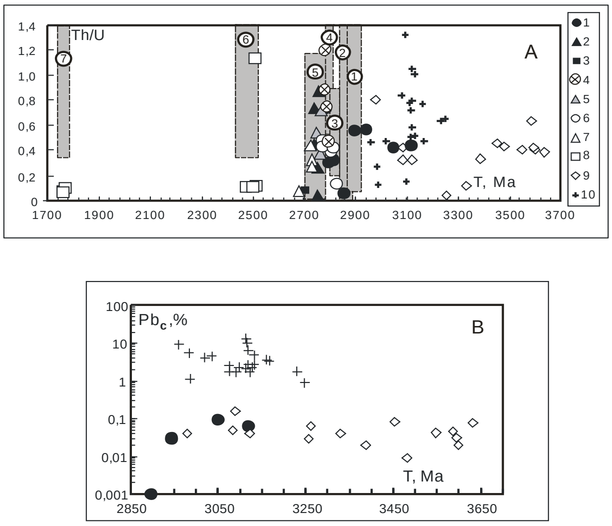

Fig. 3. Diagrams in coordinates "T, Ma – Th/U" (A) and "T, Ma – Pb_c" (B). Zircons of different genetic types: 1-3 – zircons from gneisses of the 1st stratum: 1 – detritic, 2 – anatectic, 3 – metamorphogenic; 4, 5 – zircons of gneisses of the 3rd stratum: 4 – detritic, 5 – anatectic; 6-8 – zircons from gneisses of the 9th stratum: 6 – detritic, 7 – anatectic, 8 – contact-metasomatic; 9 – zircons from orthogneisses of the Kola series (*Myskova et al.*, 2005), 10 – zircons from the most ancient granitoids of the northern part of the Baltic Shield (*Kröner, Compston*, 1990). Numbers in circles indicate the age and Th/U relation in zircons of: 1 – gneisses of the Kola series (*Myskova et al.*, 2005), 2 – metamorphic rock of granulite facies (*Avakyan*, 1992; *Balashov et al.*, 1992), 3 – tonalitic gneisses of the SD-3 and surrounding the borehole (*Chupin et al.*, 2009; *Levchenkov et al.*, 1995), 4 – granodiorites in the gneisses of the Kola series (*Levchenkov et al.*, 1995), 5 – rocks of amphibolite facies and migmatites from the section of the SD-3 and surrounding the borehole (*Chupin et al.*, 2009; *Bayanova et al.*, 2007), 6 – the Paleoproterozoic layered intrusions (*Balashov et al.*, 1992; *Bayanova*, 2004), 7 – the Proterozoic porphire-like granites (*Vetrin, Rodionov*, 2008)

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Table. U-Pb isotope data for zircons from gneiss with high-alumina minerals

Points	**$^{206}Pb_c$, %**	**U, ppm**	**Th, ppm**	**$^{232}Th/^{238}U$**	**$^{206}Pb^*$, ppm**	**T, Ma**				**D %**	**Isotopic relation**				**Rho**
						$^{206}Pb/^{238}U$		**$^{207}Pb/^{206}Pb$**			**$^{207}Pb^*/^{235}U$, ±%**		**$^{206}Pb^*/^{238}U$, ±%**		
	1th stratum														
1.1	–	63	28	0.465	29	2758	±30	2739	±19	-1	13.96	1.7	0.534	1.3	0.762
2.1	0.05	213	156	0.7554	99	2788	±24	2738	±13	-2	14.13	1.4	0.541	1.1	0.800
3.1	0.10	199	146	0.755	91	2748	±25	2785	±11	1	14.29	1.3	0.531	1.1	0.857
4.1	0.06	425	186	0.452	222	3059	±24	3118	±8	2	20.08	1.1	0.607	0.97	0.897
4.2	0.09	229	95	0.429	118	3018	±25	3049	±12	1	18.89	1.3	0.597	1	0.798
5.1	0.02	1187	75	0.065	568	2852	±21	2854	±4	0	15.61	0.96	0.556	0.92	0.961
5.2	–	441	141	0.330	204	2778	±22	2792	±7	0	14.54	1.1	0.538	0.99	0.921
6.1	0.08	244	212	0.897	111	2731	±23	2756	±10	1	13.94	1.2	0.527	1	0.862
7.1	0.03	1387	776	0.578	692	2951	±22	2943	±4	0	17.21	0.96	0.580	0.93	0.971
7.2	0.14	311	92	0.304	138	2674	±28	2829	±9	6	14.2	1.4	0.514	1.3	0.923
8.1	0.001	283	158	0.577	139	2922	±48	2895	±9	-1	16.5	2.1	0.574	2	0.962
9.1	0.08	802	66	0.084	342	2595	±50	2700	±10	4	12.66	2.4	0.496	2.4	0.970
10.1	0.02	264	69	0.27	159	3426	±64	3179	±12	-7	24.09	2.5	0.701	2.43	0.955
11.1	0,08	1478	65	0.045	690	2796	±53	2754	±11	-1	14.33	2.4	0.543	2.3	0.962
12.1	–	204	66	0.336	98	2873	±57	2813	±15	-2	15.36	2.6	0.562	2.5	0.939
13.1	0.30	171	58	0.350	70	2495	±55	2740	±18	10	12.37	2.9	0.473	2.6	0.921
14.1	0.04	243	64	0.274	116	2846	±57	2754	±14	-3	14.64	2.6	0.555	2.5	0.944
15.1	0.06	766	68	0.092	292	2365	±49	2699	±10	14	11.31	2.5	0.443	2.5	0.972
3rd stratum															
1.1	0.02	305	147	0.497	140	2761	±22	2796	±8	1	14.47	1.1	0.53	0.99	0.895
2.1	0.04	408	480	1.215	186	2747	±22	2781	±7	1	14.26	1.1	0.53	1.0	0.915
3.1	0.07	604	306	0.523	261	2626	±20	2700	±6	3	12.83	1	0.50	0.95	0.928
4.1	0.06	387	170	0.454	171	2677	±21	2751	±8	3	13.56	1.1	0.51	0.98	0.899
5.1	0.06	255	95	0.387	116	2743	±23	2762	±9	1	14.06	1.2	0.53	1	0.872
6.1	0.05	493	428	0.897	226	2752	±22	2775	±7	1	14.23	1.1	0.53	0.99	0.920
7.1	0.06	349	200	0.591	180	3031	±25	2874	±7	-5	17.05	1.1	0.60	1	0.913
8.1	0.05	285	212	0.765	134	2809	±23	2782	±9	-1	14.66	1.1	0.55	1	0.878
9.1	0.18	115	82	0.733	55	2845	±29	2768	±15	-3	14.77	1.5	0.55	1.2	0.807
10.1	0.06	533	287	0.557	244	2750	±21	2746	±7	0	13.97	1	0.53	0.96	0.921
11.1	0.03	843	261	0.320	342	2493	±19	2558	±6	3	11.07	1	0.47	0.94	0.931

9th stratum															
1.1	0.19	185	210	1.171	75	2484	±23	2509	±17	1	10.7	1.5	0.47	1.1	0.741
1.2	0.04	1367	147	0.111	548	2467	±19	2472	± 5	0	10.39	0.98	0.47	0.93	0.955
2.1	0.14	114	45	0.406	51	2683	±54	2802	±16	4	14.03	2.7	0.52	2.5	0.930
2.2	0.02	1993	230	0.119	825	2534	±19	2512	± 4	-1	10.98	0.95	0.48	0.92	0.969
3.1	0.04	271	114	0.434	127	2799	±23	2811	± 9	0	14.85	1.1	0.54	1	0.881
4.1	0.00	294	140	0.492	137	2793	±24	2771	± 8	-1	14.46	1.2	0.54	1	0.895
5.1	0.09	181	105	0.597	69	2363	±22	2503	±14	6	10.05	1.4	0.44	1.1	0.813
5.2	0.01	1324	146	0.113	542	2513	±19	2501	±5	0	10.8	0.97	0.48	0.93	0.957
6.1	0.04	1555	117	0.077	423	1774	±14	1758	±7	-1	4.70	1.0	0.32	0.92	0.924
7.1	0.03	3729	377	0.104	1030	1789	±14	1769	±4	-1	4.77	0.94	0.32	0.91	0.965
7.2	0.01	914	78	0.087	250	1779	±15	1760	±9	-1	4.72	1.1	0.32	0.96	0.891
8.1	0.01	3607	290	0.082	1600	2688	±20	2678	±3	0	13.04	0.92	0.52	0.91	0.984
9.1	0.25	201	66	0.34	90,4	2703	±58	2732	±18	1	13.56	2.8	0.52	2.6	0.923
9.2	0.17	154	67	0.45	70,5	2752	±57	2727	±20	-1	13.82	2.8	0.53	2.5	0.905
10.1	21.0	507	68	0.14	245	2874	±55	2827	±11	-2	15.5	2.5	0.56	2.4	0.964
11.1	0.17	252	68	0.28	113	2702	±57	2732	±17	1	13.56	2.8	0.52	2.6	0.931
11.2	0.08	405	72	0.18	157	2402	±51	2706	±20	13	11.57	2.8	0.45	2.5	0.899
12.1	0.26	161	68	0.44	72,6	2715	±56	2773	±21	2	13.98	2.8	0.52	2.5	0.895

Note: Pb_c and Pb* – respectively portions of common and radiogenic Pb; Rho – the correlation coefficient between $^{207}Pb^{*}/^{235}U$ and $^{206}Pb^{*}/^{238}U$; D – discordance.