

The Oldest Grey Gneisses and Tonalite-Trondhjemite Granodiorites in the Fennoscandian Shield: ID-TIMS and SHRIMP Data

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Abstract

Genesis of the oldest continental crust retains a marked trace in the Earth's evolution over its 4.5 Ga history. Despite ample isotope data on the role of the continental crust in the Earth's evolution, there has been much debate on the origin of grey gneisses and tonalite-trondhjemite-granodiorites (TTG). Precise U-Pb (ID-TIMS) and SHRIMP data on single zircon for paragneisses and TTG (3158.2 ± 8.2 Ma) have indicated the Central-Kola and Belomorian (White Sea) megablocks of the Fennoscandian Shield to be 3.16 Ga and 3.70 Ga, respectively. The newly obtained ages of zircon from these megablocks indicate the origin of the discrete continental crust to be 3.16 and 3.70 Ga. It is close to the Nordsim zircon data on the Siurua TTG (Finland), which are 3.45 and 3.73 Ga in the core. The new summarized data on the Earth's oldest rocks (basement and continental crust) indicate the younger age of the rocks in the Fennoscandian Shield as compared to those in Australia (Kronendonek *et al.*, 2019).

Keywords

Fennoscandian Shield, Geochronology, Hadean, ID-TIMS, SHRIMP, TTG, Grey Gneiss

1. Introduction

The oldest 35 pieces of the continental crust mostly composed of tonalit-

ic-trondjemitic-granodioritic (TTG) gneisses imprint the Earth's evolution during much of its ca. 4.5 Ga history [1]. The study of the Archean continental crust provides geological and geochemical insights to the early Earth due to asteroid and meteoritic impacts [2].

The Arctic region of the Fennoscandian Shield hosts large-scale strategic deposits, such as Neoproterozoic banded-iron formations (BIF) in the Olenegorsk ore area, Paleoproterozoic PGE-Cu-Ni and PGE-Cr-Ti deposits in the Monchegorsk, Fedorovo-Pana and Imandra ore areas, Cu-Ni deposits in Pechenga, as well as major Paleozoic apatite-nepheline and phosphorite deposits in the Khibiny, Lovozero, Kovdor, etc. Therefore, the study of their basement or continental crust is essential for understanding of processes that governed the deposits evolution.

The north-eastern part of the Fennoscandian Shield hosts the Murmansk, Central-Kola and Belomorian (White Sea) megablocks with the Archean continental crust (**Figure 1**). Previous Sm-Nd isotope data on rocks of the basement with continental crust (TTG and paragneisses) have yielded ages older than 3.0 Ga [3]. There has been very little evidence of Paleoproterozoic and Eoarchean rocks in the basement of the Belomorian megablock established on the basis of detrital zircons sampled from metasediments of the Lapland-Kola granulite belt [4].

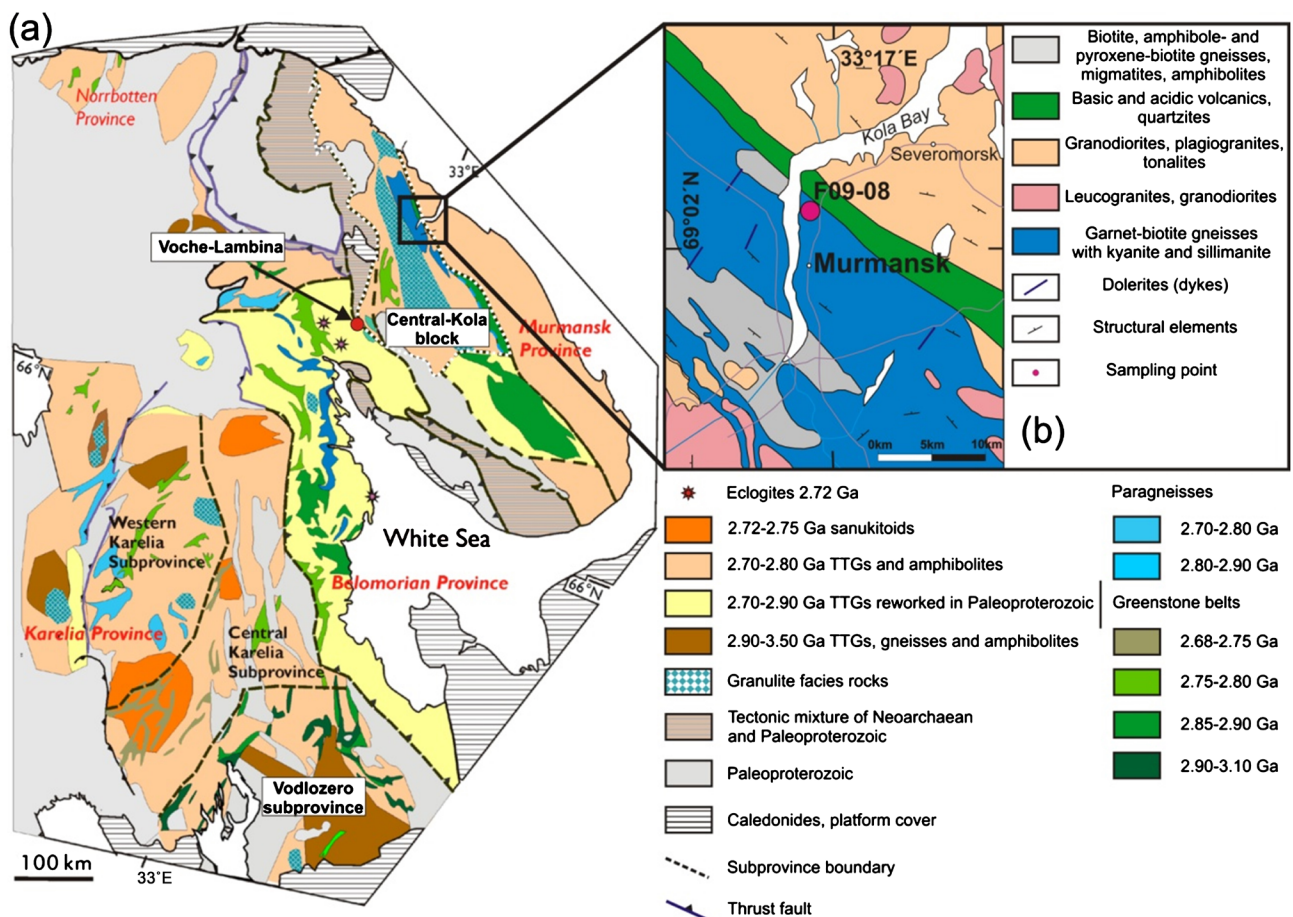


Figure 1. Generalized geological map of Archean rocks in Fennoscandia (a) after (Holttä *et al.* 2012); schematic map of the Murmansk area (b).

New U-Pb ID-TIMS and SHRIMP zircon ages of TTG in the Voche-Lambina area have been estimated at 2.9 - 2.82 Ga with Sm-Nd model ages of 3.0 Ga for the same rocks with positive ϵNd values of +0.6 to +3.2 [5]. There had been no chance to find a typical TTG complex with Paleoarchean zircon ages in the Central-Kola megablock for a long time. Only several SHRIMP zircon data had been available for the gneisses, which were not older than 3.6 Ga [6]. Precise zircon core ages of gneisses and TTG in the north-eastern Fennoscandian Shield (Siurua, Finland) estimated at Nordsim at 3.45 and 3.73 Ga [7] have revived the study of the oldest rocks in the Central-Kola megablock.

2. Brief Geological Description of the Archean Period in the Formation of the Fennoscandian Shield

According to Holta *et al.* [8], the Fennoscandian Shield hosts the Murmansk, Belomorian, Norbotten and Karelian provinces with TTG and amphibolites with the age range of 2.7 - 2.8 Ga, as well as paragneisses, greenstone belts and sanukitoids, with the age range of 2.72 - 2.75 Ga. The Karelian province comprises the West-Karelian and the Central-Karelian subprovinces. The Vodlozero province is composed of TTG gneisses and amphibolites of greenstone belts with the ages of 2.9 to 3.5 Ga.

The Belomorian province comprises TTG and amphibolites (2.7 - 2.9 Ga), which were modified in the Paleoproterozoic. Eclogites have been recently reported to occur there [9].

The province also hosts the Voche-Lambina geological site. SHRIMP analysis of zircons from TTG has yielded the age of 3158.2 ± 8.2 Ma [5] [10].

The studied rocks refer to grey gneisses of the Central-Kola megablock basement within the Murmansk province (Figure 2). They occur near the monument to the Defenders of the Soviet Arctic (Murmansk, Russia). These rocks are composed of garnet-biotite gneisses with kyanite and sillimanite. Besides, there are biotite-amphibole gneisses with migmatites and amphibolites. This subprovince accommodates mafic and felsic volcanics, quartzites, granodiorites, plagiogranites and tonalities [6] [11].

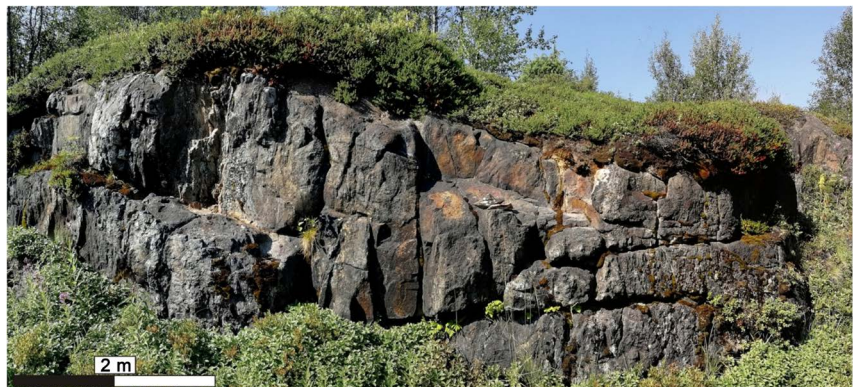


Figure 2. Outcropped staurolite-kyanite-sillimanite-garnet-biotite gneisses of the Central-Kola megablock.

3. Materials and Methods

Zircons have been separated from gneiss samples with the weight of about 30 kg. The U-Pb (ID-TIMS) dating of single grains has been carried out using the method described by Krogh [12] with an artificial ^{205}Pb spike; the results are shown in **Table 1**. Following this method, the samples have been dissolved in strong (48%) hydrofluoric acid at a temperature of 205°C - 210°C during 1 to 10 days. To dissolve the fluorides, the samples have been reacted with 3.1 N HCl at a temperature of 130°C for 8 to 10 hours. To determine the isotope composition of lead and to measure the concentrations of lead and uranium, the sample has been divided into two aliquots in 3.1 N HCl, and a mixed Pb + U tracer has been added. Pb and U have been separated on an AG 1 × 8, 200 - 400 mesh anion exchanger in Teflon columns. The laboratory blank for the whole analysis is 0.1 - 0.08 ng for Pb and 0.01 - 0.04 ng for U. All isotopic determinations for zircons have been made on a Finnigan MAT-262 mass spectrometer; the Pb isotopic composition has been analyzed on a secondary-ion multiplier in an ion-counting mode. The measurements of the Pb isotopic composition are accurate to 0.025% when calibrated against the NBS SRM-981 standards. The U and Pb concentrations have been measured in a single-filament mode with added H_3PO_4 and silica gel using the method described by Scharer and Gower [13] and Scharer *et al.* [14]. Pb and U concentrations have been measured within the temperature ranges of 1350 - 1450 and 1450°C - 1550°C, respectively. All the isotopic ratios are corrected for mass discrimination during the static processing of replicate analyses of the SRM-981 standard (0.12% + 0.04% per a.m.u.). The errors in the U-Pb ratios are calculated during the statistical treatment of replicate analyses of the IGF-87 standard and are assumed equal to 0.5%. If the actual analytical errors are higher, they are reported in the table of isotopic data. Isochrons and sample points have been calculated using the Squid and Isoplot programs [15] [16].

Age values have been calculated with conventional decay constants for U [17], all errors are reported at a 2-sigma level. Corrections for common Pb are made according to Stacey and Kramers [18]. Besides, corrections are made for the composition of Pb separated from syngenetic plagioclase or microcline if the admixture of common Pb is >10% of the overall Pb concentration and the

Table 1. Isotope U-Pb data on zircons from gneisses of the Central-Kola megablock (sample F-09-08).

Sample №	Weight mg	Concentrations, ppm		Isotope composition of Pb			Isotope composition and ages			Rho
		Pb	U	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{207}\text{Pb}$	$^{206}\text{Pb}/^{208}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{207}\text{Pb}/^{206}\text{Pb}$	
1	0.10	570.5	853.5	377.3	4.4960	4.6981	13.6639	0.520509	2746	0.90
2	0.40	73.4	122.4	1569.7	5.0300	7.3525	13.6052	0.517448	2752	0.96
3	0.20	105.6	62.5	39.4	2.0155	0.9683	13.1366	0.502440	2739	0.59
4	0.20	30.9	55.2	898.6	4.9505	6.5013	12.2840	0.472568	2729	0.95
5	0.20	139.6	170.5	1115.2	3.8733	3.3616	20.6889	0.604176	3174	0.97

$^{206}\text{Pb}/^{204}\text{Pb}$ ratios are <1000. **Table 1** provides the results.

The zircon fraction from the same gneisses has been analyzed using the SHRIMP method described by Williams *et al.* [19] at the A.P. Karpinsky Russian Geological Research Institute (VSEGEI); the results are given in **Table 2** and **Figure 6(b)**. All geochemical REE and trace element analyses of the whole rock have been made at the Institute of Geology and Mineralogy, Siberian Branch RAS, Novosibirsk, using the method described by Panteeva *et al.* [20].

4. Results

Petrography and Geochemistry of Gneisses in the Central-Kola Megablock

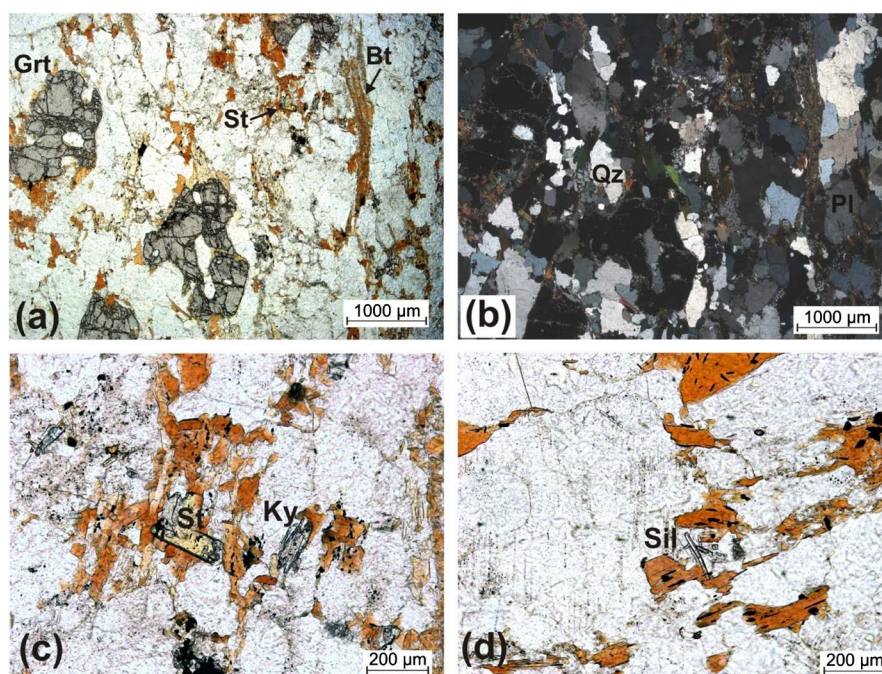
Petrographically, high-alumina gneisses include garnet-biotite, sillimanite-garnet-biotite, staurolite-kyanite-sillimanite-garnet-biotite gneisses [11]. These rocks are dark grey, fine-medium-grained and slightly schistose (**Figure 2**). Their texture is a combination of granoblastic, porphyroblastic and lepidoblastic varieties. The rocks consist of quartz, plagioclase, biotite, garnet, sillimanite, kyanite, staurolite and chlorite (**Figure 3**).

Plagioclase occurs as colorless isometric and usually not twinned grains. Some of them are slightly sericitized. Quartz appears in small irregular grains (0.2 - 0.6 mm) and also forms large lenses up to 3.5 mm in length (**Figure 3(b)**). Biotite is found in tabular or flaky 0.05 - 0.90 mm grains uniformly scattered throughout the rock. Biotite may also intergrow with garnet (**Figure 3(a)**). Garnet occurs as large porphyroblasts (2 - 3 mm) with irregular outlines and encloses quartz and biotite inclusions. Some of the garnet cracks are filled with fine-grained mica. Sillimanite forms colorless elongated prismatic grains with a length of up to 0.6 mm; fine-grained fibrolites are less common (**Figure 3(d)**). Kyanite grains include quartz, which has an elongated prismatic (0.3 - 1.1 mm) shape with irregular outlines. Staurolite is represented by sporadic elongated prismatic grains with a length of up to 0.5 mm (**Figure 3(c)**).

Table 2. Isotope SHRIMP data on zircon from Central-Kola megablock (Murmansk city area).

Spot	% $^{206}\text{Pb}_c$	ppm U	ppm Th	ppm $^{206}\text{Pb}^*$	$\frac{^{232}\text{Th}}{^{238}\text{U}}$	(1) $\frac{^{206}\text{Pb}}{^{238}\text{U}}$ Age	(1) $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$ Age	% Discor- dant	(1) $\frac{^{238}\text{U}}{^{206}\text{Pb}^*}$	±%	(1) $\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*}$	±%	(1) $\frac{^{207}\text{Pb}^*}{^{235}\text{U}}$	±%	(1) $\frac{^{206}\text{Pb}^*}{^{238}\text{U}}$	±%	err corr
F09-08_6.1	--	232	298	100.0	1.32	2622 ±27	2794 ±9	+8	1.99	1.2	0.1961	0.52	13.6	1.3	0.502	1.2	0.92
F09-08_7.1	0.05	141	91	66.3	0.67	2815 ±32	2803 ±14	-1	1.83	1.4	0.1971	0.85	14.9	1.7	0.548	1.4	0.86
F09-08_3.1	0.06	44	34	20.4	0.80	2763 ±43	2850 ±18	+4	1.87	1.9	0.2029	1.10	15.0	2.2	0.535	1.9	0.87
F09-08_2.1	--	126	100	60.0	0.82	2839 ±35	2886 ±13	+2	1.81	1.5	0.2075	0.78	15.8	1.7	0.553	1.5	0.89
F09-08_5.1	--	125	157	60.6	1.30	2878 ±33	2924 ±12	+2	1.78	1.4	0.2125	0.71	16.5	1.6	0.563	1.4	0.89
F09-08_4.1	--	135	119	69.8	0.91	3039 ±34	3006 ±10	-1	1.66	1.4	0.2235	0.60	18.6	1.5	0.602	1.4	0.92
F09-08_1.1	0.04	281	108	189.5	0.40	3740 ±39	3695 ±6	-2	1.27	1.4	0.3473	0.39	37.7	1.4	0.786	1.4	0.96

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively. Error in TEMORA Standard calibration—0.28%. (1) Common Pb corrected using measured ^{204}Pb .



Abbreviations: Grt—garnet; St—staurolite; Bt—biotite; Qz—quartz; Pl—plagioclase; Ky—kyanite; Sil—sillimanite.

Figure 3. Microphotographs of thin sections from grey gneisses in the Central-Kola megablock.

Isotope ID-TIMS and SHRIMP Data

Gneisses were sampled from the vast outcrops of the Central-Kola megablock to determine the age of a submeridional basite dyke, which cuts the complex of high-alumina paragneisses (**Figure 1(b)** and **Figure 2**).

According to the IUGS TAS plot, gneisses comply with the dacite field of tholeiitic series (**Table 3**; **Figure 4**). The gneiss samples are rich in LREEs and poor in HREEs (**Table 4**; **Figure 5**), which conforms to typical TTG patterns according to Moyen and Martin [21].

Four grains of single zircon crystals have yielded the age of 2753 ± 3 Ma in the U-Pb isochron (**Figure 6(a)**), which corresponds to the amphibolite facies metamorphism. The lower intersect of the Discordia-concordia line is at 443 ± 130 Ma. It reflects the Paleozoic magmatic activity in the north-eastern Fennoscandian Shield (**Figure 6(a)**) and circular alkaline Khibiny-Lovozero-Kovdor massifs, etc. One zircon point plots in the U-Pb isochron near the age of 3.17 Ga and implies the magmatic origin of the zircon (**Table 1**) from the oldest population. Hand-picked grains have magmatic oscillatory zoning and a diagnostic core with older ages.

All SHRIMP zircon ages for the high-alumina gneisses with different peaks and intervals of origin at 2794 - 2763 Ma are similar to the ID-TIMS data of amphibolite metamorphism (2753 ± 3 Ma). The data in the range of 2924 - 2886 Ma seem to reflect the low-granulite facies metamorphism. One point coinciding with the concordant age of 3695 ± 5 Ma represents the oldest age of the studied

gneisses (**Figure 6(b)** and **Figure 7(a)**). Coeval SIMS and LA-ICP-MS isotope measurements have been carried out for the Finnish part of the Fennoscandian Shield (**Figure 7(b)**). In result, the age of 3.45 Ga has been obtained for the rims and the age of 3.73 Ga has been obtained for the core parts of the zircon from

Table 3. Major elements (wt. %) of the high alumina gneisses of the Central Kola megablock.

Oxide	Sample	
	F-09-12 ^a	Grey gneisses ^b
	Oxide content, wt. %	
SiO ₂	66.19	67.67
TiO ₂	0.72	0.44
Al ₂ O ₃	16.49	14.87
FeO _T	5.82	3.58
MnO	0.06	0.07
MgO	0.44	1.86
CaO	1.69	3.35
Na ₂ O	3.06	4.18
K ₂ O	1.97	2.60
Total	96.44	98.62

^acomposition for high alumina gneisses of Central Kola megablock; ^baverage composition of Archaean grey gneisses according to [21].

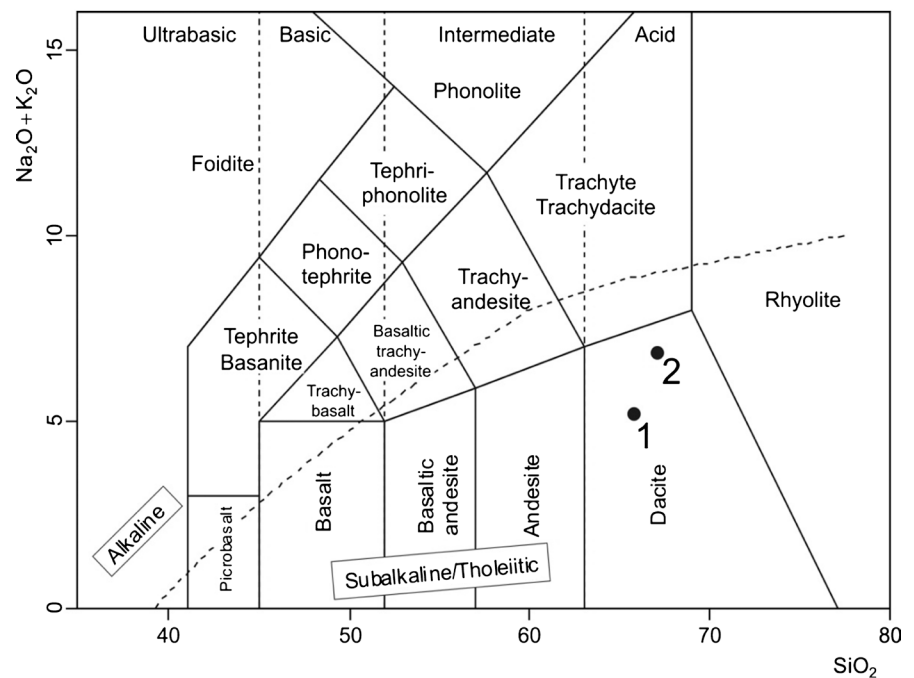
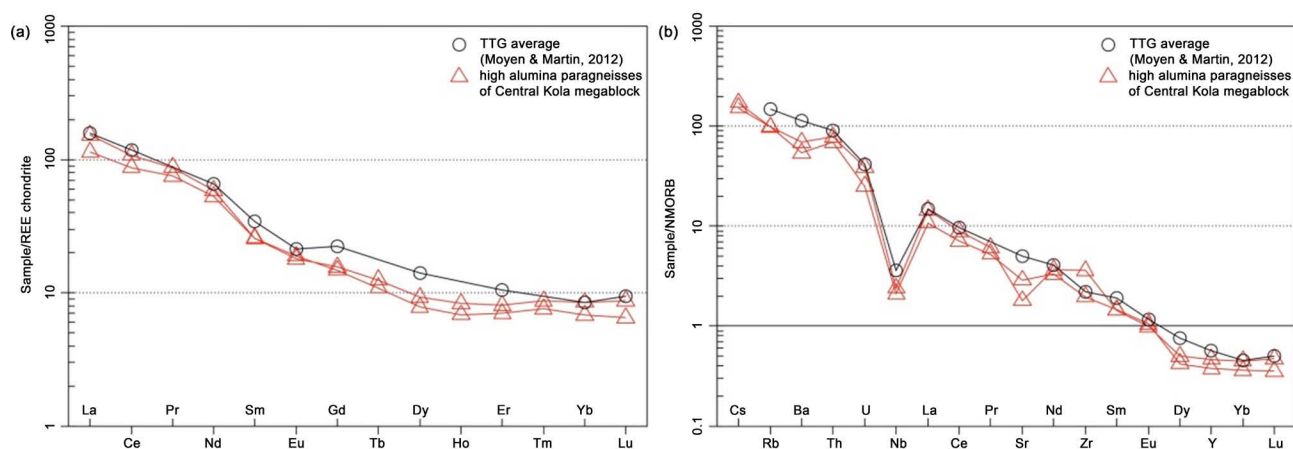


Figure 4. IUGS TAS plot for grey gneisses of the Central-Kola megablock (1) and average compositions (2) for Archaean grey gneisses after [21].

Table 4. Trace element composition for high alumina gneisses of the Central Kola megablock.

Element	Sample		
	F-09-12 ^a	H-09-1212 ^b	Grey gneisses ^c
	Element content, ppm		
Rb	55.51	54.86	83.98
Sr	260.00	162.52	455.56
Y	10.45	13.05	15.82
Zr	145.54	267.37	162.61
Nb	4.90	5.60	8.40
Cs	1.21	1.07	-
Ba	341.96	436.53	717.29
La	27.05	36.20	37.59
Ce	53.39	66.24	72.39
Pr	6.96	8.09	-
Nd	24.12	26.83	29.87
Sm	3.82	3.78	5.07
Eu	1.07	1.01	1.20
Gd	2.94	3.11	4.42
Tb	0.39	0.45	-
Dy	1.92	2.28	3.48
Ho	0.37	0.46	-
Er	1.12	1.28	1.68
Tm	0.19	0.21	-
Yb	1.09	1.37	1.37
Lu	0.16	0.21	0.23
Hf	3.77	6.55	4.73
Ta	0.38	0.42	0.90
Th	8.35	9.43	10.93
U	1.18	1.84	1.96

^{a,b} composition for high alumina gneisses of the Central Kola megablock; ^c average composition of Archaean grey gneisses according to [21].

**Figure 5.** Rock/chondrite [22] (a) and rock/N-MORB [23] normalized REE for grey gneisses of the Central Kola megablock (b).

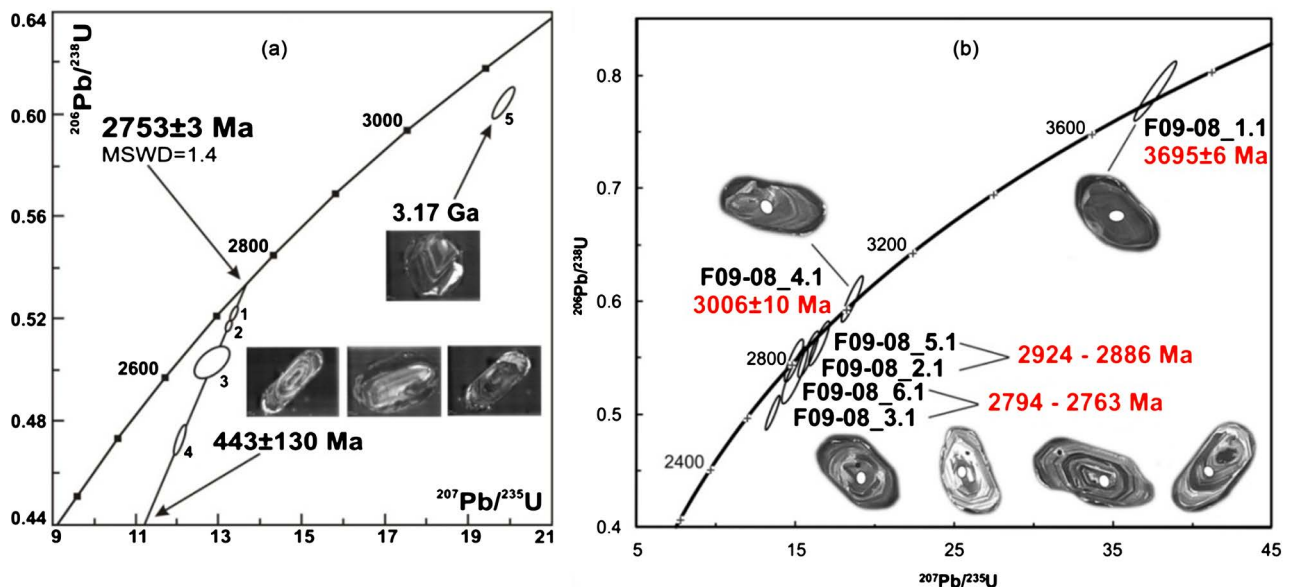


Figure 6. U-Pb (ID-TIMS) concordia plot for single zircons (a) and SHRIMP-II data for zircon grains from grey gneisses of the Central-Kola megablock (b), sample F09-08; isotope data are provided in Supplementary [Table 3](#) and [Table 4](#).

the Siurua TTG complex [7]. The U-Pb and Sm-Nd data [24] ([Figure 7\(b\)](#)) are found close to the U-Pb (ID-TIMS) and SHRIMP zircon data on the Central-Kola megablock.

5. Discussion

The new U-Pb (ID-TIMS) data on single zircons from paragneisses of the Central-Kola megablock show the age of 3.17 Ga. The cores of these zircons have the age of 3695 ± 5 Ma (SHRIMP-II) and ca. 100 Ma older ages as compared to paragneisses of the Central-Kola megablock, according to Myskova *et al.* [6] ([Figure 7\(a\)](#)). The age of the amphibolite facies metamorphism has been estimated at 2753 ± 3 Ma.

The Voche-Lambina geological site lies at the boundary between the Belomorian mobile block and the Central-Kola domain [5]. New Neoproterozoic U-Pb data on single zircons of the Voche-Lambina TTG have yielded the age of 3158.2 ± 8.2 Ma. The zircon has low U and Pb concentration and the low U/Th ratio of 0.2. REE plots for grey gneisses show high fractionation of La/Yb > 30 riched in LREE and poor in heavy Yb (<0.6 ppm). The precise (ID-TIMS) single zircon age of the amphibolite facies metamorphism has been estimated at 2704.3 ± 5.9 Ma. Model Sm-Nd WR data indicate the protolith ages of 3.4 to 3.2 Ga, positive ϵ_{Nd} of +1.29 to +3.3 and ISr of 0.702 [5].

Thus, the new data on single zircon grains from TTG and paragneisses of the Central-Kola megablock imply a long-term and discrete evolution of the continental crust in the Fennoscandian Shield (3.17 - 3.73 Ga). Noteworthy, the oldest part of the Hadean component is well-preserved in zircons that were subject to high-pressure metamorphism in Finland and granulite facies metamorphism [25] in Siberia (Aldan Shield, Russia). The latter has been dated using the ID-TIMS

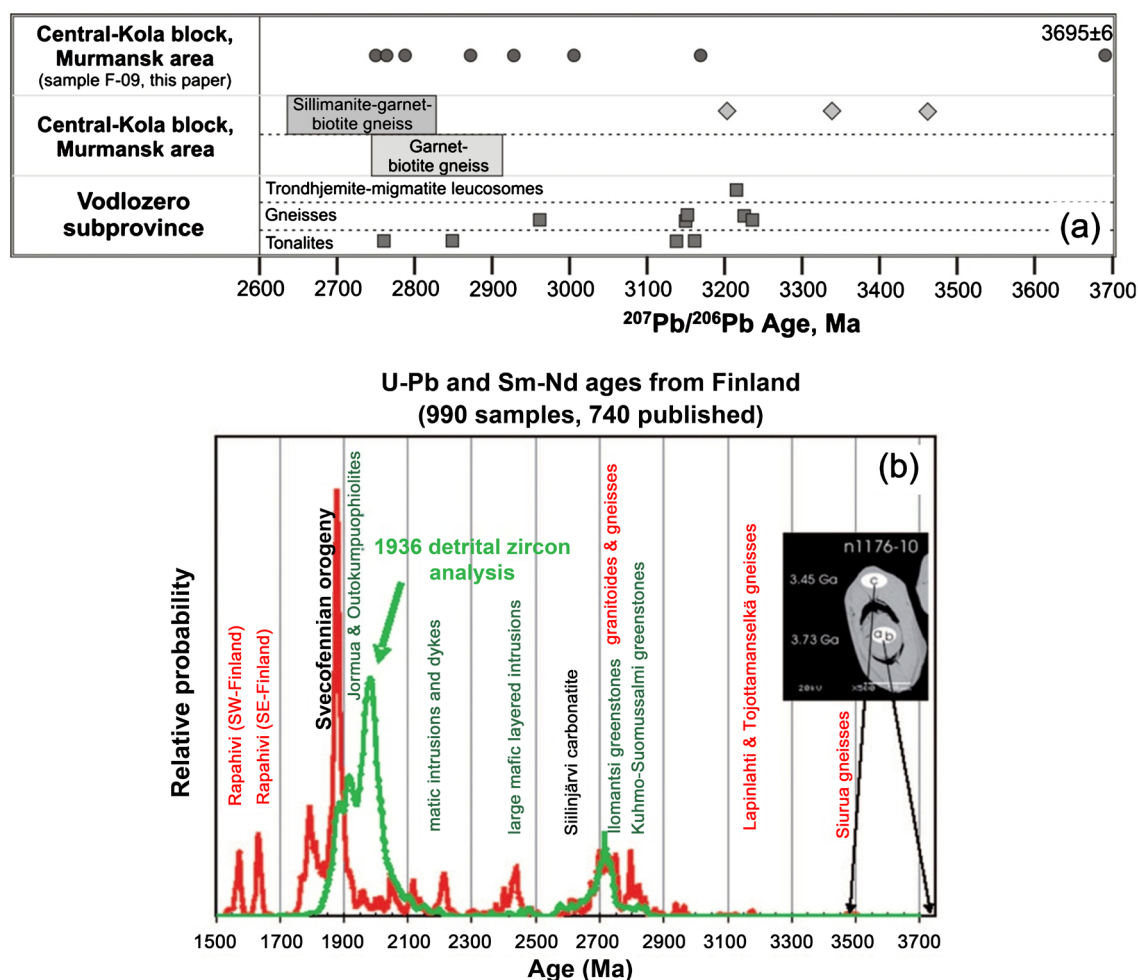


Figure 7. SHRIMP-II and ID-TIMS data (see Table 1) on zircon grains from Archean rocks of East Fennoscandia (a) and U-Pb and Sm-Nd ages of rocks from Finland (b). The red line indicates the primary rock based on results for 990 samples (data on 740 of them are published). The green line indicates the age distribution of detrital zircons in Paleoproterozoic metasediments based on 1936 U-Pb analyses made by SIMS (ca. 1000 published) and LA-MC-ICPMS (unpublished). Image of ca. 3.5 Ga zircon from the oldest rock in Siurua (Finland) with an older core of ca. 3.73 Ga [7].

method; the single zircon age has been estimated at 3.94 Ga.

6. Conclusion

For the first time, zircons from the Central-Kola megablock have been dated using the SHRIMP method. As a result, the oldest age of 3.7 Ga has been obtained. Taking into account the age of Siurua TTG, Finland (3.73 Ga), these results suggest the presence of older (Hadean) rocks with zircon ages of >4.0 Ga. It will also allow specifying the age of the continental crust, which provides the basement necessary for the formation of the regional deposits, such as the Neoproterozoic BIF in the Olenegorsk ore area, Paleoproterozoic PGE-Cu-Ni and PGE-Cr-Ti deposits (Monchegorsk, Fedorovo-Pana and Imandra ore areas) and Cu-Ni deposits (Pechenga, as well as large-scale Proterozoic apatite-nepheline and phosphorite deposits (Khibiny, Lovozero, Kovdor, etc.).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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