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The Neoarchaean enderbite-granulite complex of the Central Kola block: Stages of evolution (Kola Peninsula)

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Abstract. The paper presents the results of geological-petrological and isotope-geochemical researches of rocks and minerals of the Neoarchaean enderbite-granulite complex (Central Kola block). The results obtained allowed the researchers to determine the sequence of endogenous processes, P-T conditions and duration of the enderbite-granulite complex evolution within 2.73-1.81 Ga. Three stages of metamorphism have been established in gneisses of the Kola Group: (I) – early granulitic (2.73-2.72 Ga); (II) – superimposed amphibolite facies (2.57-2.55 Ga); (III) – retrograde low-temperature amphibolite facies (2.54 Ga). Stages I and II were separated by emplacement of enderbites (2.66 Ga) and formation of cummingtonite-biotite orthogneisses after enderbites (2.64 Ga). Ultrametamorphism in gneisses of the Kola Group was accompanied by injections of anatectic veins of microcline-plagioclase granite with garnet and sillimanite (2.55 Ga). The tectonomagmatic activity in this region culminated by the injection of veined leucogranites (ca. 2.50 Ga) that crosscut gneisses of the Kola Group, enderbite and cummingtonite-biotite orthogneisses. Based on Sm-Nd and Rb-Sr methods, the influence of Paleoproterozoic processes on the granulite-enderbite complex with the alteration of isotopic systems is recorded at 2.50 and 1.81 Ga ago.

Аннотация. В статье изложены результаты геолого-петрологических и изотопно-геохимических исследований пород и минералов архейского эндербит-гранулитового комплекса (Центрально-Кольский блок). Полученные данные позволили установить последовательность эндогенных процессов, термодинамические условия и длительность развития эндербит-гранулитового комплекса в интервале 2.73-1.81 млрд лет. В гнейсах кольской серии определены три этапа метаморфизма: I – ранний гранулитовый (2.73-2.72 млрд лет); II – наложенный амфиболитовый (2.57-2.55 млрд лет); III – регрессивный низкотемпературный амфиболитовый (2.54 млрд лет). Ранний гранулитовый метаморфизм (I) и наложенный амфиболитовый (II) в гнейсах кольской серии разделены этапами эндербитообразования (2.66 млрд лет) и образованием куммингтонит-биотитовых ортогнейсов по эндербитам (2.64 млрд лет). Развитие ультраметаморфизма в гнейсах кольской серии характеризуется образованием жильных анатектит-гранитов микроклин-плагиоклазового состава с гранатом и силлиманитом (2.55 млрд лет). Завершение тектоно-магматической активности в данном районе фиксируется внедрением жильных лейкогранитов (около 2.50 млрд лет), секущих гнейсы кольской серии, эндербиты и куммингтонит-биотитовые ортогнейсы. Воздействие процессов палеопротерозоя на эндербит-гранулитовый комплекс с изменением изотопных Sm-Nd и Rb-Sr систем устанавливается в периоды около 2.50 и 1.81 млрд лет назад.

Key words: Central Kola block, enderbite-granulite complex, metamorphism, magmatism, P-T conditions, U-Pb, Sm-Nd, Rb-Sr isochrones data
Ключевые слова: Центрально-Кольский блок, эндербит-гранулитовый комплекс, метаморфизм, магматизм, P-T условия, U-Pb, Sm-Nd, Rb-Sr изохронные данные

1. Introduction

One of the most complicated and actual issues of modern geology is to reconstruct the conditions under which the Archaean lithosphere formed and evolved, for these considerably contributed to the today's geological structure and metallogeny of the continental crust. In this respect, the NE Baltic Shield composed of Archaean granite-greenstone and granulite-gneiss rock complexes is the very object to clear out the conditions under which the continental crust originated in the early stages of the Earth's evolution. The gneisses of the Kola Group intruded by the Archaean enderbites and oligoclase granites are related to the oldest granulite-gneiss units on the Kola Peninsula (*Polkanov*, 1935; *Kharitonov*, 1966; etc.). The granite-gneiss complexes have been long studied by geologists (*Tugarinov, Bibikova*, 1980; *Balashov et al.*, 1992; *Avakyan*, 1992; *Fonarev et al.*, 1993; etc.). Yet, their complicated scenario of emplacement and evolution brings up a lot of questions to be further discussed. This may help to gain an insight into the history and mechanisms of the Archaean crust formation, which underlie reliable scientific prediction and feasibility of exploration and prospecting works. The primary issues to be thereby addressed are as follows: age and nature of the protolith, stages of efficiency and mechanisms of spatiotemporal expansion of magmatic and metamorphic events. The key importance here is assumed by identifying sequence and duration of endogenous processes, reproducing the geological settings of igneous rock-forming events and metamorphic transformations on the basis of the best-preserved early mineral assemblages.

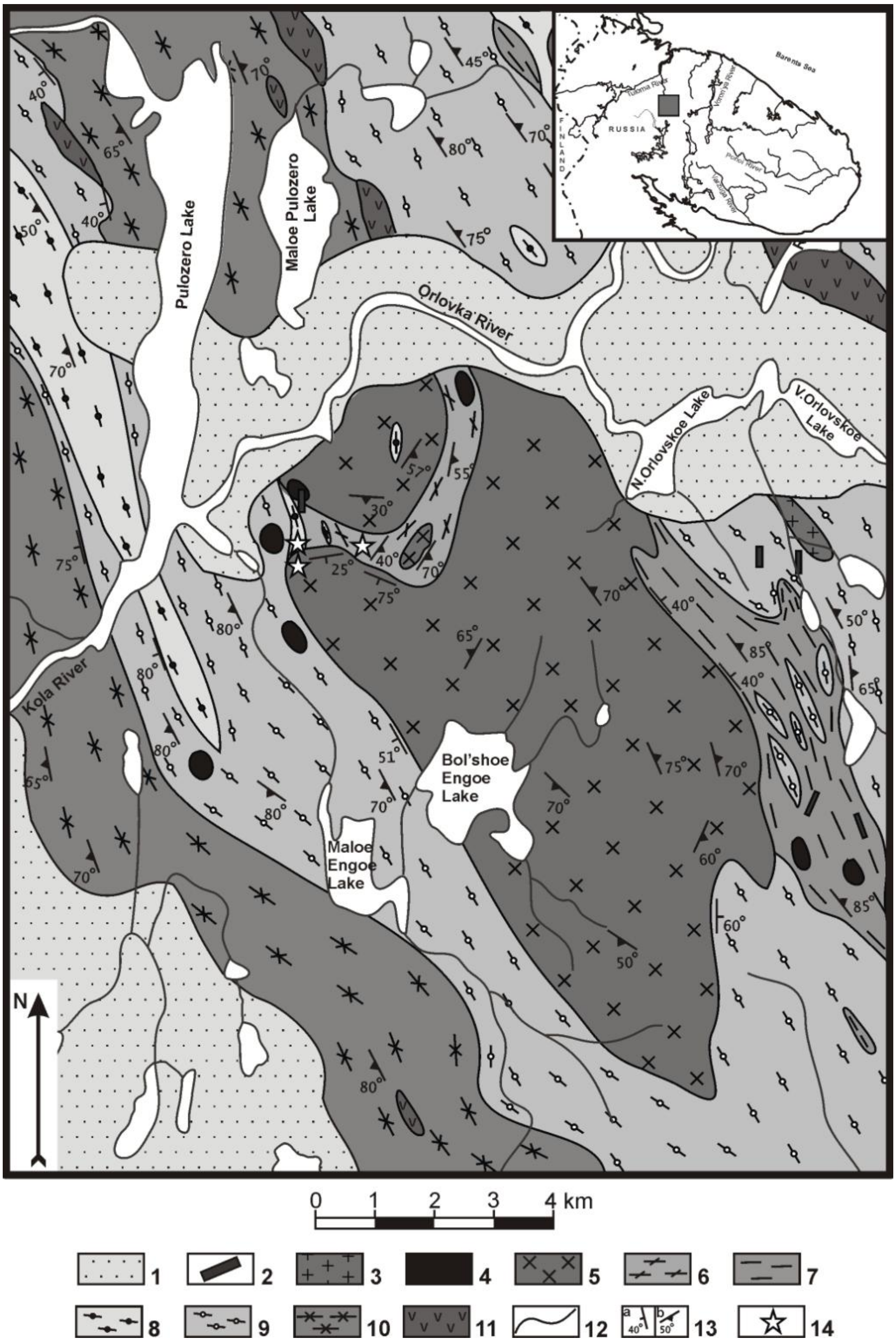

Fig. 1. Sketch map of the Pulozero-Polnek-Tundra region (Central Kola Block). The map was based on S.A. Dyukov materials (Funds of the Federal State Unitary Enterprise "Sevzapgeologia", 1957) and personal observations of L.S. Petrovskaya and M.N. Petrovsky.

Legend: 1 – quaternary sediments; 2 – pegmatoid veins; 3 – plagiomicrocline granites; 4 – metahabbro; 5 – enderbites varying in composition from quartz diorite to plagiogranite; 6 – the Kola Group high-calcium garnet-biotite and biotite gneisses; 7 – two-mica gneisses; 8 – the Kola Group medium-calcium garnet-sillimanite-biotite gneisses with interlayers of the Kola Group medium-calcium biotite and garnet-biotite gneisses; 9 – the Kola Group medium-calcium garnet-biotite gneisses with interlayers of the Kola Group medium-calcium garnet-sillimanite-biotite and biotite gneisses; 10 – pyroxene and amphibole-pyroxene gneiss-diorites, diorites, and locally granodiorites; 11 – amphibolites; 12 – geological boundaries; 13 – strike and dip: a) contacts, b) gneissosity; 14 – location of samples for isotopic dating

The paper is aimed at studying the age, duration and formational settings of the Archaean heterogenous enderbite-granulite complex of the Pulozero-Polnek-Tundra region located in the core of the Central Kola block. The region is composed of rocks varying in origin and composition that can be regarded as reference geological units for the purposes of reconstructing the history of the regional geological evolution. As opposed to the other similar regions, here, all the rock varieties contain Archaean mineral assemblages of different generations, and allow more reliable definition of the stages of metamorphic events. It should be noted that the rocks under discussion have not been strongly affected by the later Proterozoic imprints.

2. Analytical approaches of research

The analytical studies have been made at the laboratories of the Geological Institute, KSC RAS. The rocks were examined using an optical microscope, accompanied by detailed investigation of minerals using an electron scanning microscope (Leo 1450) with an energy-dispersive attachment by Roentec at an accelerating voltage of 20 kV, and a sample measuring current of 100-1000 nA. The compositions of the rock-forming minerals were determined using an X-ray microanalyzer (Cameca MS-46) at the accelerating voltage of 22 kV, and a sample measuring current of 30 nA (analyzed by A.V. Bazay, PhD and Ya.A. Pakhomovsky, PhD). The accessory minerals were extracted using a conventional procedure that involved magnetic separation, heavy liquids and handpicking of mineral grains (performed by L.I. Koval).

Zircon was dissolved in an acid and Pb and U concentrations were measured following the ID-TIMS method proposed by *T. Krogh* (1973). The U-Pb isochrones parameters and sample points were calculated by programs (*Ludwig*, 1991; 1999), errors are reported for a 2σ level. The conventional decay constants for U were used in calculations (*Steiger, Jäger*, 1977). All isotopic U-Pb determinations were made on Finnigan MAT 262 (RPQ) in an ion counting mode; the errors in external reproducibility were assumed equal to 0.5 % (*Bayanova*, 2004). During ID-TIMS were used $^{208}Pb/^{235}U$ spike with 0.08 ng of Pb and 0.04 ng of U blanks. Nevertheless the same samples were done with $^{205}Pb/^{235}U$ spike for single zircon grains with 1 pg for Pb and 10 pg of U blank according to *T. Bayanova et al.* (2007). Measurements of Sm and Nd isotope compositions and concentrations were performed using a multicollector mass-spectrometer Finnigan MAT 262 (RPQ) in a static mode using Re+Re and Ta+Re filaments. The measured reproducibility for eleven analyses of the Nd-isotope composition for the standard La Jolla = 0.511833±6 (2σ, N=11) was < 0.0024 % (2σ). The same reproducibility was obtained from 44 parallel analyses of the Japanese standard: JiNdi1=0.512078±5 (2σ, N=44). The isochron parameters were developed from programs of *K. Ludwig* (1999). The Sr isotope composition in all the measured samples was normalized to a value of 0.710235 recommended by NBS SRM-987. The adopted Rb decay constant (*Steiger, Jäger*, 1977) was used for age calculations. The isochron parameters were calculated according to K. Ludwig programs (*Ludwig*, 1999).

3. Brief geological description of the Pulozero-Polnek-Tundra region

The enderbite-granulite complex occurs in the central part of the Kola Peninsula which represents the northeastern margin of the Baltic Shield. The Neoarchaean enderbite-granulite complex of the Pulozero-Polnek-Tundra region includes rocks varying in origin and composition (Fig. 1). The metamorphic units are represented by parametamorphic and orthometamorphic rocks that sharply differ in mineral and chemical composition. The rocks of both types make up conformable extensive northwest-striking sheet-like and lens-like bodies. The supracrustal rock units are represented by aluminous medium-calcium and high-calcium gneisses of the Kola Group. The orthometamorphic rocks genetically include formations which are presented by mafic crystalline schists, amphibolites and orthogneisses. The intrusive rocks are enderbites, gabbros, plagiomicrocline granites, and veins of various composition. The large enderbites massif extends northwestwards and is introduced by the metamorphic complex rocks. Between granulites and enderbites there is a magmatic contact. The line of the contact cuts migmatitic banding in granulites off, with abundant xenoliths of garnet-biotite gneisses observed in the endocontact of enderbites. Cummingtonite-biotite orthogneisses are observed as separate parts (not larger than a few meters in size) of the enderbites body. The boundaries between enderbites and orthogneisses are vague with gradual transition. The synmetamorphic veined garnet-sillimanite-bearing microcline-plagioclase granites and garnet-bearing plagiogranites crosscut migmatitic banding of the medium-calcium gneisses. The youngest are leucogranite and alpite veins, which crosscut the Kola Group gneisses, enderbites, and cummingtonite-biotite orthogneisses.

4. Geological, petrological and isotope-geochemical investigations of the Neoarchaean enderbite-granulite complex

The supracrustal rock represented by aluminous medium-calcium and high-calcium gneisses, correspond to the rocks of intermediate and felsic composition in terms of silica content, with normal alkalinity and mainly potassium and potassium-sodium specialization. It is characteristic for TiO_2, FeO, MgO, Al_2O_3 that their content decreases simultaneously with the increase of the SiO_2 content which correlates well with the behaviour of minerals-concentrators of these elements: one can observe that the amount of garnet, biotite, magnetite and sulfides decreases from intermediate to felsic differences. In high-calcium gneisses, the CaO-content is twice as high and the Na_2O-content is 3-4 times as low as those in medium-calcium gneisses, with the silica contents being close. This is seen in the specific mineral composition of high-calcium gneisses: with the content of SiO_2 62.28-72.32 wt % – plagioclase is presented in the rocks as bytownite-anorthite.

Two stages of mineral formation have been established in the rocks of the Kola Group. These stages correspond to two stages of regional metamorphism which are shown in the metamorphic complex in the Pulozero-Polnek-Tundra region.

The first stage of the regional metamorphism in the Kola Group medium-calcium gneisses is recorded in the early subgranulitic mineral assemblage* Grt_{55-69} + Bt_{25-32} (reddish-brown) ± Sil + Pl_{23-29} ± Kfsp + Qtz. This assemblage is characterized by T = 700-800 °C and P = 5.5-7.3 kbar estimated using (*Perchuk*, 1981; *Ghent*, 1976). The presence of biotite in this assemblage may be explained by the specific composition of this mineral (elevated Mg content and enrichment in Ti up to 5 wt %), which is stable in a wide range of high temperatures. The U-Pb zircon age of subgranulite metamorphism is 2724±49 Ma (Fig. 2) (*Petrovskaya et al.*, 2007).

In high-calcium gneisses of the Kola Group, the granulite mineral assemblage is presented by: Opx ± Sil(?) + Grt_{59-69} + Bt_{32-45} (brown) + Pl_{69-99} ± Kfsp + Qtz, the P-T conditions of its formation correspond to the parameters determined for medium-calcium gneisses. The U-Pb age is dated for zircons of the granulite metamorphism occurrence at 2733±5.1 Ma (Fig. 3) and is close in time to the granulite metamorphism occurrence in the Kola Group medium-calcium gneisses.

The second stage of regional metamorphism in medium-calcium gneisses of the Kola Group is dated by the U-Pb zircon method at 2568±10 Ma (Fig. 2) and characterized by retrograde transformation under the conditions of amphibolite facies (*Petrovskaya et al.*, 2007). Cordierite-quartz simplektites replacing garnet are associated with cordierite that appears between garnet and sillimanite + quartz. The Fe mole fraction in garnet increases and while the Mg mole faction decreases. The superimposed amphibolite facies metamorphism is characterized by the formation of the late mineral assemblage: Grt_{75-80} + Bt_{38-42} (light-green) ± $Sil_{(fibrolite)}$ ± Crd_{13-17} + Pl_{22-24} + Qtz ± Kfsp. The formation conditions of the superimposed stage are estimated at T = 580-640 °C and P = 4.0-6.0 kbar (*Perchuk*, 1981; *Ghent*, 1976).

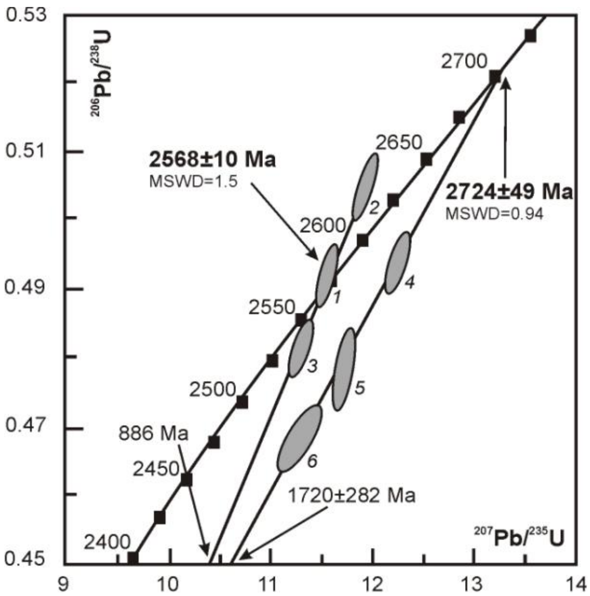

Fig. 2. U-Pb concordia diagram for zircons from the Kola Group medium-calcium gneisses

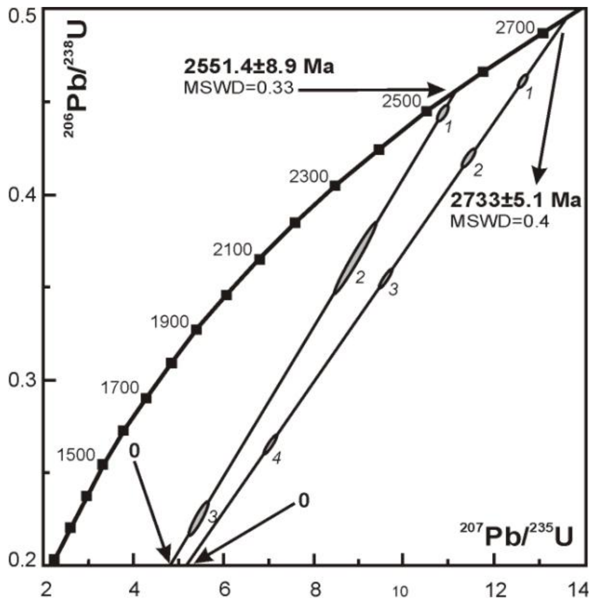

Fig. 3. U-Pb concordia diagram for single zircon grains from the Kola Group high-calcium gneisses

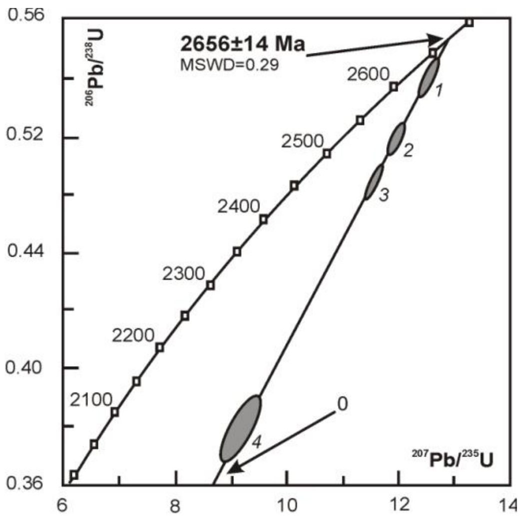

Fig. 4. U-Pb Concordia diagram for zircons from the enderbite

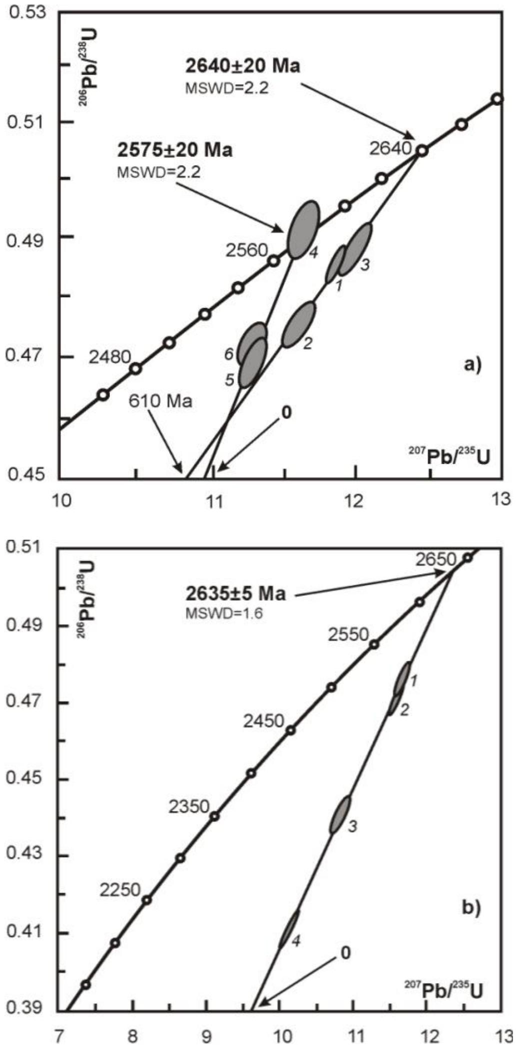

Fig. 5. U-Pb concordia diagram for zircons from the cummingtonite-biotite orthogneisses

The regional metamorphism in high-calcium gneisses of the Kola Group is characterized by the mineral assemblage: ±Ky + Grt$_{74-81}$ + Bt$_{35-38}$ (green) + Pl$_{63-92}$ + Qtz. The transformations occurred under the conditions of amphibolite facies are mainly expressed as retrograde transformation of the garnet and biotite compositions. The time period of the amphibolite metamorphism occurrence is dated by the U-Pb method for zircons at 2551.4±8.9 Ma (Fig. 3), which is close to the time period of the superimposed metamorphism occurrence in medium-calcium gneisses.

The large enderbite pluton was emplaced between two stages of regional metamorphism. The U-Pb zircon age of enderbite is 2656±14 Ma (Fig. 4). The U-Pb zircon age of cummingtonite-biotite orthogneisses is 2640-2635 Ma (Fig. 5a, b) and characterizes the time when enderbite was metamorphosed.

The P-T crystallization conditions of the igneous assemblage Opx$_{42-45}$ ± Cpx$_{30-35}$ + Bt$_{41-44}$ (reddish-brown) + Pl$_{27-33}$ + Qtz established in enderbite are estimated at T = 700-800 °C and $P_{(H2O)}$ = 2.0-4.0 kbar (*Dubrovsky*, 1987). Metamorphism of enderbite resulted in the hydration of pyroxenes, which were replaced with biotite and amphibole, and the formation of the mineral assemblage Cum$_{39-40}$ ± Hbl$_{40}$ + Bt$_{40-41}$ (brownish-green) + Pl$_{32-39}$ + Qtz. The presence of cummingtonite testifies to the P-T conditions of amphibolite facies of the andalusite-sillimanite type of metamorphism (*Krylova et al.*, 1991; *Zen et al.*, 2005).

The veined garnet- and sillimanite-bearing microcline plagioclase granites that cut gneisses of the Kola Group were formed at the ultrametamorphic stage of amphibolite-facies metamorphism and are characterized by the mineral assemblage: Bt$_{36}$ (brown) + Pl$_{22-25}$ + Kfs + Qtz ± (Grt$_{56-69}$ + Sil). The temperature of granite crystallization is estimated at 690 °C (*Dubrovsky*, 1987) and $P_{(H2O)}$ = 2.6 kbar. The U-Pb zircon age of this granite is 2550±5 Ma (Fig. 6). This age is close to the timing of superimposed amphibolite-facies metamorphism recorded in gneisses of

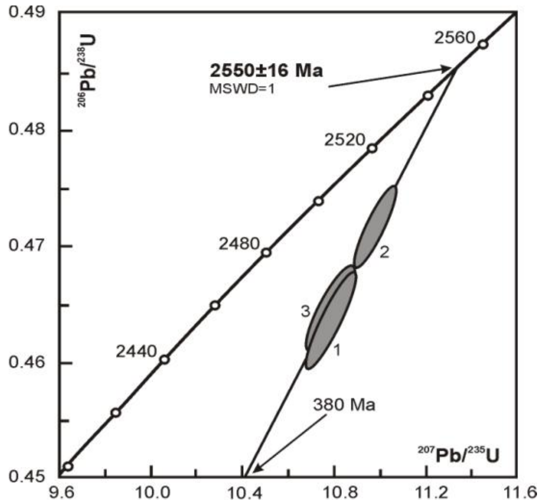

Fig. 6. U-Pb concordia diagram for zircons from the veined garnet-sillimanite-bearing microcline-plagioclase granite

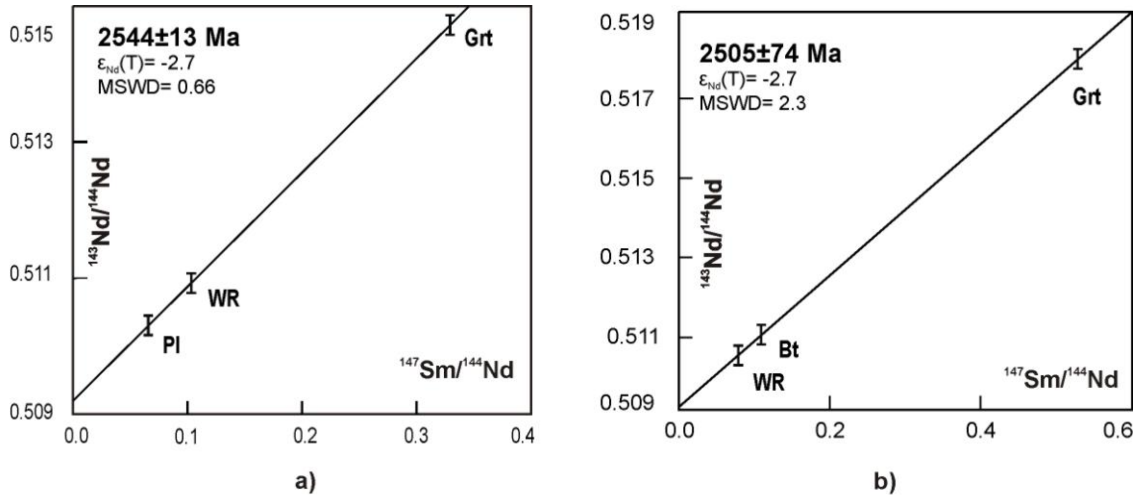

Fig. 7. Sm-Nd isochrones for rocks and minerals: a) – the Kola Group medium-calcium gneisses; b) – veined garnet-sillimanite-bearing microcline-plagioclase granite

the Kola Group (2568±10 Ma) and the late stage of amphibolite-facies metamorphism in cummingtonite-biotite orthogneisses (2575±20 Ma).

The retrograde stage of low-temperature amphibolite-facies metamorphism of gneisses from the Kola Group, which is based on variations in the marginal parts of the late garnet, is characterized by T = 500-600 °C and P = 2.2-5.3 kbar (*Perchuk*, 1981; *Ghent*, 1976). The Sm-Nd garnet-whole rock-plagioclase isochron age of this event is 2544±13 Ma (Fig. 7a).

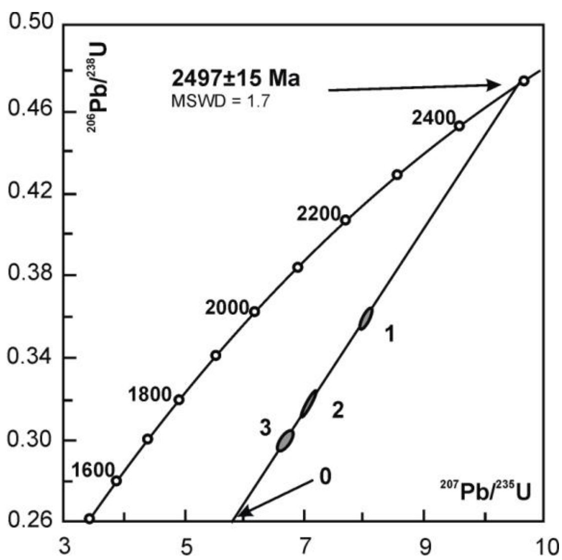

Fig. 8. U-Pb concordia diagram for zircons from the veined leucogranite-aplite

The leucogranitic-aplitic veins with a U-Pb zircon age of 2497±15 Ma (Fig. 8) that cut gneisses of the Kola Group, enderbites, and orthogneisses mark the upper age limit of folding and metamorphism in this district (*Petrovskaya et al.*, 2003). The mineral assemblages is Bt_{36} (brownish-green) + Kfs + Pl_{13} + Qtz. The crystallization temperature and water pressure are estimated at 690 °C and 3.6 kbar, respectively (*Dubrovsky*, 1987).

Isotope-geochemical Sm-Nd and Rb-Sr methods establish fluid-thermal imprints that affected the enderbite-granulite complex 2505-2485 Ma (Figs. 7b, 9c) and 1827-1811 Ma (Fig. 9a,b).

All the rocks of the enderbite-granulite complex have been dated by an isotope-geochemical Sm-Nd method. The studies have established that the protolith of the Kola Group gneisses are rocks which have a Mesoarchaean Sm-Nd model age within the interval of 2.96 to 2.85 Ga. The protolith of the intrusive complex also has Mesoarchaean Sm-Nd model age within the interval of 2.94-2.82 Ga.

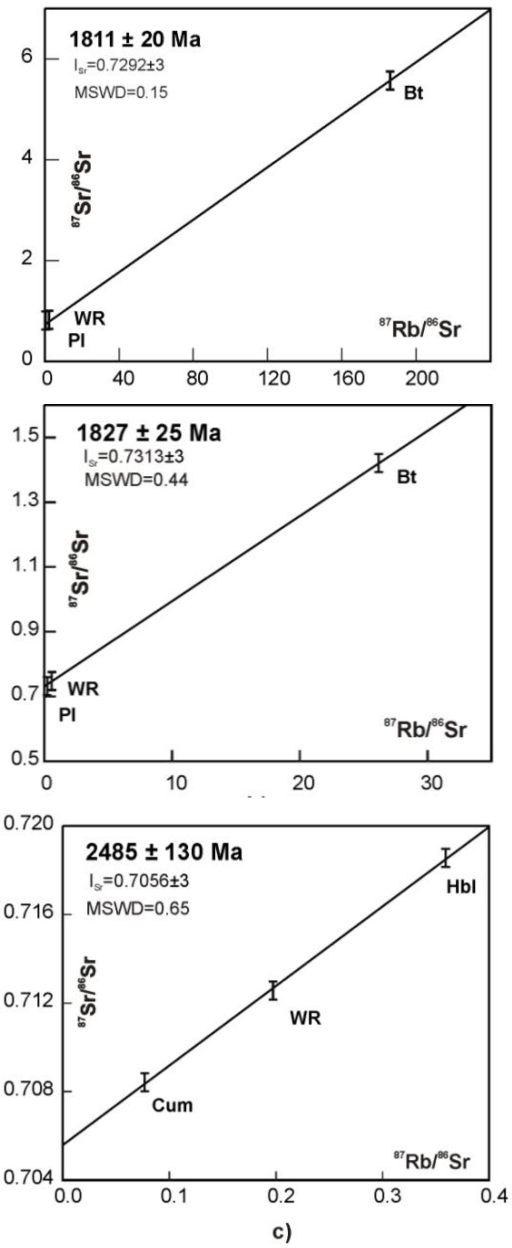

Fig. 9. Rb-Sr isochrones for rocks and minerals: a) – the Kola Group medium-calcium gneisses; b) – veined garnet-sillimanite-bearing microcline-plagioclase granite crosscutting the Kola Group gneisses; c) – cummingtonite-biotite orthogneisses

5. Conclusion

The Neoarchaean enderbite-granulite complex of the Pulozero-Polnek-Tundra region is a typical high-grade metamorphic granulite-gneiss unit. It is heterogenous in terms of its nature, and includes a supracrustal sequence and injected intrusive rocks that have different composition and are characterized by complicated mechanisms involved into the Central Kola block evolution. The endogenous Neoarchaean history of the enderbite-granulite complex is dated to fall within 2.73-1.81 Ga. Three stages of metamorphism have been documented in gneisses of the Kola Group: (I) – early granulitic (2.73-2.72 Ga); (II) – late superimposed amphibolite facies (2.57-2.55 Ga); and (III) – retrograde low-temperature amphibolite facies (2.54 Ga). Stages (I) and (II) in gneisses of the Kola Group were separated by emplacement of enderbite (2.66 Ga) and formation of cummingtonite-biotite orthogneisses after enderbite (2.64 Ga) under the conditions of amphibolite facies metamorphism of andalusite-sillimanite type. Ultrametamorphism in gneisses of the Kola Group was accompanied by injections of anatectic veins of microcline-plagioclase granite with garnet and sillimanite (2.55 Ga). The tectonomagmatic activity in the district under study was culminated by the injection of veined leucogranites (2.50 Ga) that crosscut gneisses of the Kola Group, enderbites, and cummingtonite-biotite orthogneisses. It is shown that the enderbite-granulite complex underwent retrograde metamorphism in the Neoarchaean that recorded a gradual drop of temperature and pressure with time. Isotope-geochemical methods establish Paleoproterozoic fluid-thermal imprints that affected the enderbite-granulite complex 2505-2460 and 1811-1827 Ma ago.

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***Abbreviations of minerals used in the present paper:** (Grt) garnet, (Crd) cordierite, Bt (biotite), (Sil) sillimanite, (Opx) orthopyroxene, (Cpx) clinopyroxene, (Cum) cummingtonite, (Hbl) hornblende, (Ky) kyanite, (Pl) plagioclase, Kfsp (potassium feldspar), and (Qtz) quartz. The subscripts denote the Fe mole fraction of Grt, Crd, Bt, Opx, Cpx, Cum, and Hbl and the content of the anorthite end member in plagioclase, mol %.

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