Pt-bearing Fedorovo-Pansky Layered Complex (Kola Peninsula): Sm-Nd geochronology and Nd-Sr characteristics

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Abstract. Results of isotope-geochronological Sm-Nd studies of the Paleoproterozoic platiniferous Fedorovo-Pansky layered intrusive are presented. Implementation of a complex of isotope-geochemical methods (Sm-Nd, U-Pb, Rb-Sr) allowed a more reliable and precise study of the age, formation patterns, and conditions of ore substance localization in the major units of the complex, i.e., the Fedorova Tundra and Kievey deposits. Geological, mineralogical, and isotope-geochemical data combined facilitate the identification of three ore-magmatic systems within the Fedorovo-Pansky ore area: 1) early troctolite-gabbronorite (2526–2507 Ma); 2) major ore-bearing norite-gabbronorite-anorthosite (2502–2470 Ma); 3) anorthosite (2447 Ma). The main industrial PGE mineralization of the Fedorovo-Pansky ore area is related to the norite-gabbronorite-anorthosite ore-magmatic system with the age of 2500–2470 Ma. Analysis of Sm-Nd model ages for the Fedorova Tundra (2.9 – 3.4 Ma) and West-Pana (2.8 – 3.1 Ma) blocks of the complex indicated that the age range for the Fedorova Tundra intrusive chamber is inclined to more ancient ages, which is confirmed by geological observations of individual intrusive chambers of the complex blocks.

1. Introduction
Focused studies of the Fedorovo-Pansky layered complex (FPLC) began by the turn of the 1980s and 90s, when it got a positive evaluation of prospects for discovering an industrial mineralization of complex raw materials (PGE, Au, Ag, Cu+Ni+Co) [1, 2]. An objective to determine age of the complex main phases was being accomplished alongside active geological-petrological studies. The first data on the age were obtained for gabbronorites of the Lower Horizon of the West-Pana block of the intrusion – 2501 ± 1.4 Ma, 2491 ± 1.5 Ma [3], 2496 ± 10 Ma [4], 2487 ± 51 Ma [5]; for gabbropegmatites – 2470 ± 9 Ma [4,5] and magnetite gabbros – 2498 ± 5 Ma [4].

A further intensive geochronological study of the Fedorovo-Pansky layered complex was led by the RAS academian F.P. Mitrofanov in the 2000s and carried out mainly by the staff of the Laboratory of Geochronology and Isotope Geochemistry at GI KSC RAS. U-Pb (zircon, baddeleyite) and Sm-Nd isotope-geochronological characteristics of rock complexes of the Fedorova Tundra, West-Pana, and East-Pana blocks of the intrusive were obtained. Age constraints of the Fedorovo-Pansky layered complex formation within 2526 Ma – 2440 Ma [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [22] were defined and scientifically substantiated. The following development of the Sm-Nd dating method and a new approach using sulfide minerals as geochronometers [23-25] allowed defining the formation age of low-sulfide mineralization within the Kievey and Fedorova Tundra deposits [26]. The system approach using isotope-geochemical and mineral-petrological methods allowed a more reliable and precise study of the age, formation patterns, and conditions of ore substance localization in the major units of the complex.
2. Results and discussion
In the framework of Sm-Nd studies, rocks, rock-forming and ore minerals of the intrusive were studied in its Fedorova Tundra and West-Pana blocks. Rocks of the Lower and Upper Layered Horizons within the West-Pana block of the intrusive were researched since major ore areas of the complex are related to these horizons. From the Lower Layered Horizon (LLH), ore gabbronorites SN-3, H-08-01, FPM-1, MP-1; norite SN-6, and mineralized gabbro H-08-02/1 were sampled for Sm-Nd dating; gabbronorites H-08-04 and SN-1 and anorthosites H-08-05 (Fig. 1) were sampled from the Upper Layered Horizon (ULH).

Samples were taken in the Fedorova Tundra block from all major areas of the complex (stratigraphically from bottom to top), i.e. taxite, norite, gabbronorites, and gabbro areas (Fig. 1). From the taxite area, harzburgites (F-1), taxite gabbronorites (F-2 and FT-2), and plagiopyroxenites (F-3) were sampled; from the norite area – pyroxenite (FT-1); from the gabbronite area – olivine gabbronorite (FT-3) and gabbro (F-4); from gabbro – gabbro (BGF-616).

Contents and Sm, Nd, Rb, Sr isotope compositions were defined using standard methods at the Core Facility Centre FRC KSC RAS (Apatity) [27].

![Figure 1. A generalized column for (a) West-Pana and (b) Fedorova Tundra blocks with Sm-Nd results](image-url)

2.1. West-Pana block, Kievey deposit
Rock-forming minerals (clino- and orthopyroxenes, plagioclase) and the whole rock were analyzed in the gabbronorite SN-1 sampled from an olivine horizon of the West-Pana block (Fig. 1). The Sm-Nd age of 2495 ± 24 Ma was obtained for these gabbronorites, the neodymium isotope composition corresponds to the εNd(T) value of -2.4. The approximate age of 2498 ± 39 Ma was obtained for the gabbronorites SN-3 from the gabbronorite area of the intrusive (Figs. 1, 2). Yet, the neodymium isotope composition for these gabbronorites is less radiogenic, εNd(T) = -0.3, which can be related to isotope heterogeneity of differentiates.
Figure 2. Mineral Sm-Nd isochrones for rocks of the West-Pana block (Kievey deposit).

A sample of the ore-hosting norite SN-6 containing Cu-Ni and Pt-Pd mineralization was taken from a lower endocontact of the West-Pana block (lower ore area). Monofractions of ortho- and clinopyroxenes, plagioclase were used for studies. Sm-Nd isochron of the isolated minerals and the whole rock correspond to the age of 2484 ± 46 Ma (Fig. 2) with isotope characteristics of enriched mantle source – εNd(T) = -0.2.

Clino- and orthopyroxene, plagioclase, and a mixture of pyroxenes were isolated from the LLH ore gabbronite sample H-08-01. In the Sm-Nd diagram, these minerals and the whole rock (WR) form an isochronous dependency corresponding to the age of 2472 ± 33 Ma, where εNd(T) = -2.9. The Sm-Nd isotope age of the mineralized gabbro H-08-02 is 2470 ± 39 Ma (Fig. 2). The obtained Sm-Nd ages are similar to the U-Pb ages of LLH gabbropegmatites, for which the age of 2470 ± 9 Ma was obtained [8]. Yet, a parallel U-Pb analysis of zircons was carried out for the same samples; the age obtained for the sample H-08-01 is 2505±5 Ma, and 2496 ± 8 Ma for the sample H-08-02 [28]. Such difference in the ages obtained using two separate methods can be explained by different temperatures of the closure of isotope systems in zircons and rock-forming minerals [29], [30], [31], as well as by duration of rock cooling processes.

Clino- and orthopyroxene, plagioclase, and a mixture of pyroxenes were isolated from the ULH gabbronites sample H-08-04. A Sm-Nd mineral isochron of these minerals and the whole rock combined gives the age of 2485 ± 24 Ma, where εNd(T) = -0.4±0.5 (Fig. 2). The age is interpreted as the age of crystallization of the Upper Layered Horizon gabbronites. Particularly noteworthy is the anorthosite...
sample H-08-05. These are anorthosites the industrial Pt-Pd mineralization of the Upper Layered Horizon is related to. Rock-forming migmatic minerals, i.e., plagioclase and clinopyroxene, were isolated from the sample H-08-05 for Sm-Nd studies. In conjunction with the whole rock, they form a Sm-Nd mineral isochron with the age of 2442 ± 74 Ma (Fig. 2). After the earlier obtained data, the U-Pb age (in baddeleyite) of these anorthosites is 2447±12 Ma [8]. Yet, recent analyses based on studies of a drill sample of boreholes from the Main Anorthosite Layer (MAL) and the U-Pb study of zircons using the SHRIMP-II allowed determining a more ancient age of the ULH anorthosites, i.e., 2509.4 ±6.2 Ma [32]. Nowadays, the age of the Upper Layered Horizon anorthosites (or the Main Anorthosite Layer) remains contentious and requires further study.

Clear monofractions of pyrrhotine, pentlandite, and a mixture of chalcopyrite with pentlandite, as well as rock-forming plagioclases and pyroxenes, of the LLH gabbronorite sample from the Kievey deposit (sample MP-1) were studied. The Sm-Nd isochron constructed for these minerals and the whole rock corresponds to the age of 2482 ± 61 Ma (Fig. 2). The εNd(T) parameter has a small negative value of -1.3 typical of Paleoproterozoic intrusions of the Baltic Shield. It indicates a mantle source with anomalous characteristics. Monofractions of rock-forming plagioclase and pyroxenes from ore gabbronorite (sample FPM-1) of the same stratiform deposit, as well as of ore pyrrhotine, chalcopyrite, and a mixture of pentlandite with pyrite, showed the Sm-Nd isochron age of 2482 ± 29 Ma (Fig. 2). The εNd(T) value of -1.6 also indicates an anomalous mantle source of magmas, which formed the intrusive.

2.2. Fedorova Tundra
The Sm-Nd age of plagioclase, olivine, pyroxenes, and the whole rocks was obtained for harzburgite (F-1) from a lens-shaped body among gabbronorites of the taxite area. The age is 2494 ± 24 Ma, where εNd(T)= -1.0. Within an error, the obtained age is similar to the age of ore norite (F-2) containing the main industrial sulfide (Cu, Ni) and PGE (Pt, Pd, Rh) mineralization. Cumulus plagioclase and intercumulus orthopyroxene and clinopyroxenes were sampled from this ore norite for Sm-Nd dating. The Sm-Nd isotope age of this norite is 2481 ± 24 Ma (Fig. 3), and it indicates the formation time of ore differentiates of the Fedorova Tundra intrusive chamber of the layered complex. The rock has isotope characteristics of anomalous enriched mantle, i.e., εNd(T)= -2.4. The obtained age is interpreted as the age of ore mineralization formation within the Fedorova Tundra block of the intrusion.

Clino- and orthopyroxene, plagioclase, and the whole rock were studied in the orthopyroxenite sample (F-3). The obtained age of 2523 ± 41 Ma (Fig. 3) indicates the formation time of rocks of the most ancient oreless intrusive and is similar to the U-Pb age of zircon from the same sample – 2526 ± 6 Ma [11], [15]. The εNd(T) value of -1.7 is typical of an anomalous upper mantle source [21], [22]. The obtained age is the most ancient for the whole Paleoproterozoic Cu-Ni-PGE ore-magmatic system of the north-eastern Baltic Shield.

A gabbro sample (F-4) was taken from a drill sample of the gabbronorite area of the Fedorova Tundra chamber of the intrusive. In the Sm-Nd diagram, cumulus plagioclase and orthopyroxene and intercumulus clinopyroxene, as well as the whole rock, give an isochronous dependency with the age of 2516 ± 23 Ma (Fig. 3). The 143Sm/144Nd ratios for the studied rock vary from 0.08 to 0.22, which ensured obtaining a relatively small value of age determination error for the Sm-Nd method. The obtained age is similar to the U-Pb age of zircon, i.e. 2516 ± 7 Ma [11], [15]. The isotope composition of neodymium with εNd = -1.4 corresponds to an anomalous mantle source.

Orthopyroxene, plagioclase, clinopyroxene, and a mixture of clino- and orthopyroxene were isolated from the orthopyroxene sample FT-1. In the Sm-Nd diagram, these minerals and the whole rock (WR) form an isochronous dependency showing the age of 2481 ± 32 Ma, where εNd(T) = -0.7 (Fig. 3). This age is interpreted as the age of orthopyroxenite intrusion of the Fedorova Tundra block. The εNd(T) parameter of -0.7 indicates an enriched mantle source of magmas with anomalous geochemical characteristics.
Figure 3. Mineral Sm-Nd isochrones for rocks of the Fedorova Tundra deposit

Pyroxenes (ortho- and clinopyroxene), plagioclase, and a mixture of sulfide minerals were also isolated from the gabbronorite sample FT-2. In conjunction with the whole rock, they form a Sm-Nd isochron with the age of 2491 ± 28 Ma, where εNd(T) = +1.0 (Fig. 3). The obtained age corresponds to the earlier determined U-Pb age of zircons, which is 2491 ± 5 Ma [16]. This age indicates the time of crystallization of the Fedorova Tundra mineralized gabbronorites. The positive εNd(T) value atypical of rocks of layered intrusions can indicate a geochemically heterogeneous source of magmas, which formed the intrusive, or additional intruding injections of magmas with different isotope characteristics.

Orthopyroxene, plagioclase, and olivine were isolated from the olivine gabbronorites sample FT-3 for studies. The Sm-Nd mineral isochron for these minerals and the whole rock shows the age of 2497 ± 32 Ma, where εNd(T) = -0.6 (Fig. 3). The obtained age indicates the formation time of the Fedorova Tundra gabbronorites. Compared to the U-Pb age of zircons [16], which is 2507±11 Ma, a value of the Sm-Nd age...
is relatively younger, which can be related to different temperatures of the closure of isotope systems in zircons and rock-forming minerals. Yet, taking into account the age determination error in the Sm-Nd systematics, the obtained values are similar. The εNd(T) parameter of -0.6, as well as for the block orthopyroxenites, indicates a mantle source of magmas with anomalous geochemical characteristics. The approximate age was obtained for the ore gabbro BGF-616, within which two generations of plagioclase, pyrite, chalcopyrite, and a mixture of pyrrhotine with pyrite were studied. In conjunction with the whole rock, they give the isochron age of 2493 ± 54 Ma (Fig. 3), which indicates the time of formation of gabbroids with sulfide mineralization.

Analysis of Sm-Nd model ages for the Fedorova Tundra and West-Pana blocks indicated that the age range of the Fedorova Tundra intrusive chamber is inclined to more ancient ages. If the West-Pana block values of model ages vary within 2.8 – 3.1 Ga, then rocks of the Fedorova Tundra block have Sm-Nd model ages in the range of 2.9 – 3.4 Ga. It supports the hypothesis proposed earlier based on geological and isotope studies [8], [11], [14], [18] that blocks of the complex formed from individual ore-magmatic chambers.

In general, the obtained Sm-Nd and U-Pb geochronological data are well intercorrelated, supplement each other, and allow getting reliable results during the dating of the composite layered complex. Such approach using separate and different isotope systems was successfully implemented not only during the study of the Fedorova-Pana complex, but also for other industrial objects of the Kola region [21], [22].

2.3. Nd-Sr characteristics and sources of substance of layered complexes within the north-eastern Baltic Shield

The implementation of the data on different U-Pb, Sm-Nd, Rb-Sr, and He/He isotope systems for Paleoproterozoic layered intrusions of the Kola region shows evidence that they formed from an anomalous (enriched) mantle reservoir, which was a source of long-lived plume Paleoproterozoic magmatism in the region [14], [19], [20] [21], [22], [37], [38], [39], [40]. On the other hand, some layered intrusions of the Karelia-Kola region (Burakovo-Aganozero complex, Monchepluton, drusite massifs of the South Kovdor area) differ by significant dispersion of εNd(T) values. They particularly vary from +1.5 to −6 for the Monchepluton [41], from +2.8 to −2.9 for the Burakovo-Aganozero complex [42]. Such dispersion of εNd(T) values was also determined for the Monchetundra massif, i.e., +2 to −3.5 [41], [43]. A model of combined different sources, depleted and enriched, is used to explain these variations, and a possible contamination by melts of crustal rocks is considered to be an additional factor for the lowest negative values.

In addition to the Sm-Nd dating, an analysis of strontium isotope compositions was carried out for the Fedorovo-Pansky complex to construct a diagram within the coordinates εNd(T) - I86Sr (Fig. 4, Table 1). These Rb-Sr isotope data correspond to earlier obtained results for rocks of the West-Pana block of the intrusive [44]. Initial 87Sr/86Sr ratios for the analyzed rocks are within the range of 0.7026-0.7036, which, in conjunction with Sm-Nd isotope-geochemical data, indicates an anomalous mantle source with characteristics similar to the EM-1 [45], [46].
Figure 4. Plot for $\varepsilon$Nd(T) vs I$_{Sr}$ for layered intrusions (2.53–2.39 Ga) in the Fennoscandian Shield. Isotope data from [14], [43], [47], [48], [49].

Table 1. Rb-Sr data for rocks of the Fedorovo-Pansky complex.

| Rock                                      | Concentrations, ppm | Isotopic Ratios | \(^{87}\text{Sr}/^{86}\text{Sr}\) | ISr          |
|-------------------------------------------|---------------------|-----------------|---------------------------------|--------------|
| Ore-bearing norite West-Pana block (SN-6) | 0.55 17.97          | 0.0075          | 0.70315±20                     | 0.70288      |
| Ore-bearing gabbro-norite West-Pana block (SN-1) | 1.02 19.33          | 0.0153          | 0.70311±21                     | 0.70256      |
| Ore-bearing norite Fedorova Tundra (F-2)   | 0.95 19.27          | 0.0103          | 0.70394±17                     | 0.70357      |
| Gabbro Fedorova Tundra (F-4)               | 1.53 33.24          | 0.0053          | 0.70303±15                     | 0.70284      |
| orthopiroxenite Fedorova Tundra (F-3)      | 1.47 45.17          | 0.0035          | 0.70291±13                     | 0.70278      |

The combined geological, mineralogical, and isotope-geochronological data allow defining at least three ore-magmatic systems within the Fedorovo-Pansky ore area: 1) troctolite-gabbro-norite (2526–2507 Ma) with sulfide-intermetallic and arsenide mineral association of minerals of platinum metals (MPM); 2) norite-gabbro-norite-anorthosite (2502–2470 Ma) with a prevalent sulfide-bismuth-telluride mineral association of MPM; 3) anorthosite (2447 Ma) with low-temperature bismuth-telluride-sulfide mineral association of MPM.

The first ore-magmatic system includes occurrences of ridges of the Fedorova Tundra massif; the second one – the Fedorova Tundra, Kievey, and North Kamennik deposits and; the third one – occurrences in the South Ridge of the West-Pana massif. Therefore, the conducted studies indicate that the main industrial PGE mineralization of the Fedorovo-Pansky ore area is related to the norite-gabbro-norite-anorthosite ore-magmatic system with the age of 2502–2470 Ma [33], [36].

Therefore, the obtained geochemical data allowed defining some special features of formation of the Fedorovo-Pansky layered complex. It was found that the Fedorova Tundra block formed earlier than other structure blocks of the intrusive, which is supported by geochronological [11, 14] and geological
observations [16]. More ancient Sm-Nd model ages of rocks of this block [14], presence of taxite gabbronorites of the marginal area and diorite xenoliths (enclosing rocks), which are absent in other blocks of the intrusive [16], also indicate an early formation of the Fedorova Tundra intrusive chamber.

Complex isotope studies [8], [10], [11], [14], [16] allowed finding reliable age constraints of the platiniferous Fedorovo-Pansky massif formation:

(i) 2526 – 2516 Ma – nearly oreless pyroxenites and gabbro of the Fedorovo magmatic chamber;
(ii) 2502 – 2485 Ma – gabbronorites and gabbro of the ore-magmatic chambers of the West-Pana block, earlier disseminated PGE mineralization and relatively enriched Cu-Ni sulfide mineralization in marginal parts of the intrusive (Fedorova Tundra deposit);
(iii) ca. 2470 Ma – LLH pegmatoid gabbronorthosites with enriched PGE mineralization;
(iv) ca. 2440-2450 Ma – late anorthosite injections and lens-shaped bodies of enriched Pt-Pd ore occurrences of the Upper Layered Horizon.

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