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# GRANITES OF THE NORTHERN TIMAN – PROBABLE INDICATORS OF NEOPROTEROZOIC STAGES OF RODINIA BREAKUP

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**ABSTRACT.** The Northern Timan is an uplifted block of Late Precambrian basement of the Timan Ridge, where Neoproterozoic sedimentary-metamorphic rocks of the Barmin Group are cut by intrusive rocks of different composition and all unconformably overlain by Lower Silurian limestone. To determine the age of granites, U-Pb dating of zircons was carried out using secondary ion mass spectrometry (SIMS). Two episodes of Neoproterozoic granite magmatism were established. Granite rocks of the Bolshoy Kameshek (613 ± 6 Ma) and Cape Bolshoy Rumyanichny (614 ± 11 Ma) plutons are interpreted to be associated with the formation of Central Iapetus Magmatic Province and record the Ediacaran stage of Rodinia breakup. The granites of the Sopki Kamennyie pluton (723–727 Ma) formed in Cryogenian time and are assumed to represent an earlier episode of Rodinia breakup. Their ages correlate with the age of the Franklin LIP that existed in Northern Laurentia and is believed to have spread to South Siberia.

**KEYWORDS:** granites; Northern Timan; zircon; U-Pb isotopic age; Rodinia

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# ГРАНИТЫ СЕВЕРНОГО ТИМАНА – ВЕРОЯТНЫЕ ИНДИКАТОРЫ НЕОПРОТЕРОЗОЙСКИХ ЭТАПОВ РАСПАДА РОДИНИИ

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**АННОТАЦИЯ.** Северный Тиман представляет собой приподнятый блок позднедокембрийского фундамента Тиманской гряды, где неопротерозойские осадочно-метаморфические образования барминской серии прорываются интрузивными породами различного состава и перекрываются известняками нижнего силура. Для установления возраста гранитов проведено U-Pb датирование цирконов методом масс-спектрометрии вторичных ионов (SIMS), в результате чего в эволюции Северного Тимана установлено два эпизода гранитоидного магматизма. Граниты массивов Большой Камешек (613±6 млн лет) и мыса Большой Румяничный (614±11 млн лет) могли быть связаны с формированием Магматической Провинции Центрального Япетуса и фиксируют эдиакарский этап распада Родинии. Граниты массива Сопки Каменные (723–727 млн лет) образовались в криогении и коррелируются с более ранним эпизодом распада Родинии. Они одновозрастны с Франклинской крупной магматической провинцией, существовавшей в Северной Лаврентии и, как полагают, захватывающей Южную Сибирь.

**КЛЮЧЕВЫЕ СЛОВА:** граниты; Северный Тиман; циркон; U-Pb изотопный возраст; Родиния

**ФИНАНСИРОВАНИЕ:** Работа выполнена по теме госзадания ГР N АААА-А17-117121270035-0 ИГ Коми НЦ УрО РАН при частичной финансовой поддержке Комплексной программы УрО РАН (проект 18-5-5-46) и Национального научного фонда США (премии NSF по тектонике 0948673 и 16-24582 для Э. Миллер).

## 1. INTRODUCTION

In the Kanin-Timan region of the northwestern Russia (Fig. 1) , which includes the Kanin Peninsula and the Timan Ridge, intrusive gabbro-dolerites and dolerites, granites, syenites, olivine-kersutite gabbros and alkaline gabbroic rocks are exposed only in the northwestern part of Northern Timan [Ivensen, 1964; Mal'kov, 1972; Kostyukhin, Stepanenko, 1987]. These magmatic rocks are of undoubted scientific interest due to the fact that they are located on the Neoproterozoic passive margin of the Baltica paleocontinent and provide information on timing of plume- or rift-related magmatism in this region. Theoretically, their ages are directly related to timing of Rodinia breakup, a topic widely debated among geologists studying the Precambrian history of the Earth [e.g., Torsvik et al., 1996; Pisarevsky, Natapov, 2003; Li et al., 2008; Merdith et al., 2017; Bogdanova et al., 2009; Ernst et al., 2008; and references therein].

In the Northern Timan, the intrusive bodies consisting of gabbroic rocks, syenites and granites cut sedimentary and metamorphic rocks of the Neoproterozoic Barmin Group and are overlain unconformably by Silurian (Llandoverian) limestone (Fig. 1).

Initially, the age of pre-Silurian igneous rocks of the Northern Timan, including granites, was based on the single whole rock K-Ar isotopic date [Mal'kov, 1966; Akimova, 1980]. In the late 1990s, the ages of the Northern Timan granitoids were investigated using whole rock Rb-Sr isotopes, indicating intrusion of granitoids in early Vendian (Ediacaran) time. The Rb-Sr isochron ages of granites include the following: 597 ± 6 Ma (n = 8, $I_{Sr}$ = 0.7078 ± 0.0006, MSWD = 0.9) – Bolshoy Kameshek pluton; 591 ± 7 Ma (n = 4, $I_{Sr}$ = 0.7225 ± 0.0017, MSWD = 1.2) – Sopki Kamennyie pluton; and 587 ± 4 Ma (n = 6, $I_{Sr}$ = 0.72027 ± 0.00021, MSWD = 1.2) – Cape Bolshoy Rumyanichny pluton [Andreichev, 1998]. All calculation errors cited here and in the text below are 2σ.

The Pb-Pb ages of single zircons from granitoids penetrated by boreholes at 3–4.5 km depth in the basement of the Pechora Basin were published by [Gee et al., 1998]. These ages range from 567–551 Ma, which corresponds to the boundary of the Early – Late Vendian at ca. 570–555 Ma [Stratigraphic Code, 2006]. Since the Timan and Pechora Basin are parts of the Pechora plate, Timan granites are often correlated with the granites in the basement of the Pechora basin [Belyakova et al., 1997; Gee, Pease, 1999]. However, the zircon ages of the granites from the basement of the Pechora Basin led to doubts concerning the Rb-Sr ages reported from the Northern Timan granites, and additional dating of zircons from these granites was performed. The first Pb-Pb ages of single zircons from granites of the Bolshoy Kameshek pluton were obtained using stepwise Pb-evaporation in the Laboratory for Isotope Geology at Swedish Museum of Natural History (Stockholm). The weighted average age for four grains is 621 ± 3.5 Ma [Andreichev, Larionov, 2000]. The results yielded ages older than the Rb-Sr age, but the Pb-Pb method does not discriminate between concordance and discordance, and therefore more reliable U-Pb dating of zircons was needed. In addition, due to the low radiogenic $^{207}Pb$ content in relatively young (<1 Ga) zircons, the $^{206}Pb/^{238}U$ ages are potentially more reliable, while still allowing us to estimate the degree of concordance. For this reason, in order to correctly date the Northern Timan granites, it

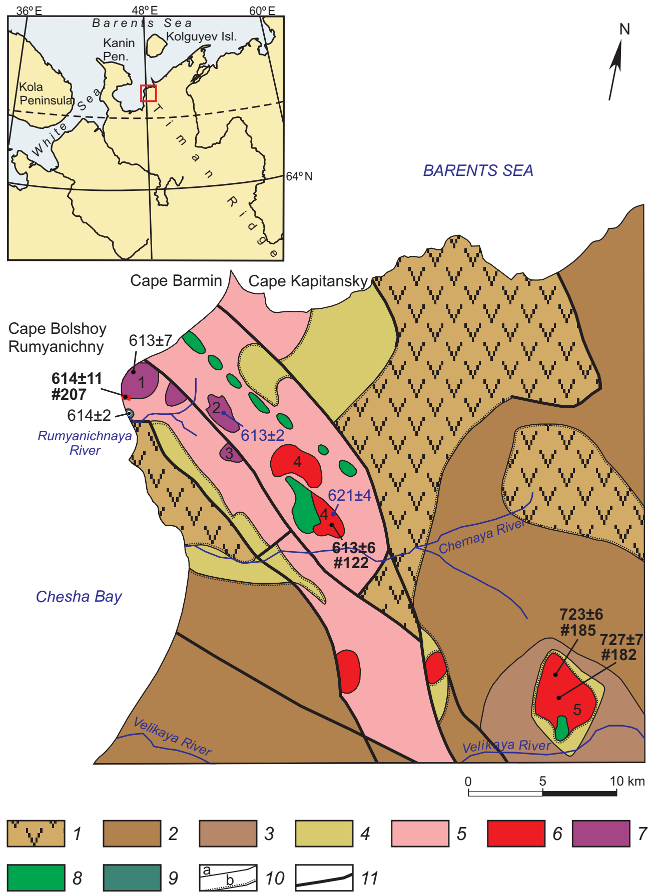


**Fig. 1.** Schematic geological structure of the Northern Timan [Olovyanishnikov, 2004].
*1* – Upper Devonian basalt; *2* – Middle Devonian sandstone, conglomerate; *3* – Lower Devonian siltstone, sandstone, clay; *4* – Lower Silurian limestone with siltstone and sandstone interlayers; *5* – shale, quartzite, quartzite like sandstone of the Neoproterozoic Barmin Group; *6* – granite; *7* – syenite; *8* – metagabbro-dolerite, dolerite; *9* – olivine-kersutite gabbro; *10* – geological boundaries: a – between units with conformable bedding, and boundaries of intrusive bodies, b – unconformity; *11* – principal faults. Numbers refer to plutons: 1 – Cape Bolshoy Rumyanychny, 2 – Krayny Kameshek, 3 – Malyi Kameshek, 4 – Bolshoy Kameshek, 5 – Sopki Kamennyie. Zircon ages (Ma) are shown next to the plutons: U-Pb (black), Pb-Pb (blue), new U-Pb ages (calculated in our study) with sample number (bold black).

**Рис. 1.** Схема геологического строения Северного Тимана, по [Olovyanishnikov, 2004].
*1* – верхнедевонские базальты; *2* – среднедевонские песчаники и конгломераты; *3* – нижнедевонские алевролиты, песчаники, глины; *4* – нижнесилурийские известняки с прослоями алевролитов и песчаников; *5* – сланцы, кварциты, кварцитопесчаники барминской серии; *6* – граниты; *7* – сиениты; *8* – метагаббро-долериты и долериты; *9* – оливин-керсутитовые габбро; *10* – геологические границы: согласные и границы интрузивных тел (a), несогласные (b); *11* – главные разломы. Цифрами обозначены массивы: 1 – мыса Большой Румяничный, 2 – Крайний Камешек, 3 – Малый Камешек, 4 – Большой Камешек, 5 – Сопки Каменные. Возраст цирконов (млн лет) подписан около массивов: U-Pb (черный), Pb-Pb (синий), новые U-Pb датировки (эта статья) с номерами образцов (черный жирный).

was necessary to carry out new U-Pb zircon dating using secondary ion mass spectrometry (SIMS).

## 2. GEOLOGICAL SETTING AND PETROGRAPHIC CHARACTERISTICS OF GRANITES

Granites compose the Bolshoy Kameshek and Sopki Kamennyie plutons and small intrusions in the area of Cape Bolshoy Rumyanichny syenite pluton.

The Bolshoy Kameshek pluton is a stockwork-shaped body exposed across an area of about 7.5 km$^2$. Massive, often gneissic, coarse-grained and porphyritic biotite granites compose the main part of this pluton. Gneissic fabrics strike 335-350° NNW and are sub-vertical. Gneissic foliation is best developed in the central part of the pluton, where it is defined by the planar orientation of fine aggregates of biotite. In the northern, eastern and southern parts, one can occasionally see the contacts of the granites with metamorphic country rock schists. The intrusive contacts of the granites with gabbro-dolerites are observed in the western part of the pluton, where fine-grained aplite-like granites form numerous vein-like, thin branching bodies that clearly intrude the more mafic igneous rocks.

The contacts of the granites with metasedimentary country rocks are sharp and clearly intrusive. At the contacts, aureoles schists are sericitized and silicified. In the marginal part of the pluton, we observed a chilled zone represented by fine-porphyry granite several tens of centimeters to several tens of meters thick. The contacts between the granites and the gabbro-dolerites are more complex and diverse. Gradual transitions are often observed between these rocks. Towards the contacts with granites, gabbro-dolerites are gradually replaced by biotite and feldspar rich rocks where these minerals are porphyroblastic in rocks with an overall composition of quartz syenite. Leucocratic granites composing the central parts of the pluton are gradually replaced by biotite and biotite-amphibole granosyenites toward to the contact with gabbro-dolerites, and along the contact itself, by quartz syenites. Dikes of granite-porphyry and granite-aplites (0.2-5.5 m thick) cut the granitoids and gabbro-dolerites. All magmatic rocks of the pluton are cut by narrow deformation zones striking 280-320° NW, within which granitoids and gabbro-dolerites were subjected to intensive cataclasis and mylonitization. At some locations along the deformation zones, granites are transformed into greisen composed of carbonate-fluorite-quartz-muscovite.

The main rock-forming minerals of the granites are microcline-perthite, quartz and plagioclase, with biotite present in minor quantities. Amphibole appears near the contacts with gabbro-dolerites. Accessory minerals include zircon, titanite, apatite, anatase, monazite, thorite and tourmaline. Secondary minerals are albite, sericite, chlorite, epidote, calcite, clinozoisite, pyrite, fluorite, molybdenite, galena, sphalerite, chalcopyrite, and leucoxene aggregate. In the zones of cataclasis and mylonitization, granites contain appreciable volumes of muscovite and chlorite.

The exposed area of the Sopki Kamennyie pluton is about 15 $km^2$. Granites form two flat hills separated by a narrow depression. The contact of granites with gabbro-dolerites is exposed and best observable in the southern part of the pluton. Granites in the contact zone are more melanocratic and are represented by rocks rich in biotite. Gabbro-dolerites in the contact aureole around granites (50–70 m wide) are subjected to feldspathization and biotitization.

The most widespread rock of the pluton is a massive pink porphyry granite that composes the northern and northeast parts of the pluton. In its southern part, medium to coarse grained, uniformly grained, often gneiss-like granites are present. Massive fine-grained aplite-like granites predominate in the western part. The vein-like granite-porphyry bodies consist of fine-grained leucocratic rocks with scattered phenocrysts of feldspar and quartz which cut granites in the southern part of the pluton. Granite porphyries are, in turn, intersected by veins of granite-aplites, represented by pink and white equigranular fine-grained rocks. The mineral composition of the rocks is similar to that of the granites of the Bolshoy Kameshek pluton.

Cataclasis and mylonitization are most pervasive in the northwestern and southern parts of the pluton, where granites almost everywhere have gneissic foliations striking 290–335° NW, dipping 60–90° NE. Gneissic fabrics are defined by the subparallel orientation of biotite. In NW trending (290–330°) zones of intense ductile to brittle deformation, the rocks are altered to greisen that resulted in the appearance of secondary fluorite.

In the southern part of the Cape Bolshoy Rumyanichny pluton, syenites and dolerites, as well as the enclosing metamorphic schists are intruded by 0.2–20 m thick veins of fine-grained biotite granites. The biotite granites consist of quartz, microcline, plagioclase, with a small amount of sodic amphibole. Accessory minerals are represented by apatite, zircon, and garnet. Secondary minerals are albite, calcite, muscovite, tourmaline, pyrite, and molybdenite.

## 3. ANALYTICAL METHODS

Major-element concentrations (reported as oxides in Table 1) were determined by the traditional wet chemical analysis following procedures described in [Unified., 1979] at the Institute of Geology of Komi Science Center, Ural Branch of RAS (Syktyvkar). Inductively coupled plasma mass spectrometry (ICP-MS) was conducted at the Institute of Geology and Geochemistry, Ural Branch of RAS (Yekaterinburg) and at VSEGEI (Saint Petersburg) to obtain trace elements content (Table 2), following procedures published in [Ronkin et al., 2005] and at https://vsegei.ru/ru/activity/labanalytics/lab/lab-operations/masspec.php.

U-Pb zircon dating using secondary ion mass spectrometry (SIMS) was performed on a SHRIMP-RG ion

**Table 1.** Main oxide contents in granites of the Northern Timan, wt. %

**Таблица 1.** Содержание петрогенных оксидов в гранитах Северного Тимана, мас. %

| Pluton | Sample | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bolshoy Kameshek | 105-2 | 77.04 | 0.07 | 12.00 | 0.51 | 0.75 | 0.01 | 0.24 | 0.67 | 3.48 | 4.54 | b.d. | 0.57 | 99.88 |
| | 108-1 | 73.61 | 0.32 | 12.97 | 1.18 | 1.47 | 0.02 | 0.45 | 0.64 | 2.98 | 5.20 | 0.04 | 0.97 | 99.85 |
| | 122 | 75.58 | 0.22 | 11.92 | 1.13 | 0.48 | 0.01 | 0.11 | 0.82 | 3.37 | 5.32 | 0.02 | 0.94 | 99.92 |
| | 125-2 | 76.64 | 0.11 | 11.31 | 1.22 | 1.38 | 0.04 | 0.06 | 0.46 | 4.11 | 4.09 | b.d. | 0.31 | 99.73 |
| | 128 | 69.19 | 0.35 | 15.70 | 0.58 | 1.56 | 0.03 | 0.55 | 0.80 | 3.95 | 6.39 | 0.03 | 0.79 | 99.92 |
| | 133 | 71.89 | 0.26 | 13.94 | 0.97 | 1.69 | 0.03 | 0.45 | 0.77 | 3.38 | 5.75 | 0.05 | 0.69 | 99.87 |
| | 134-1 | 72.34 | 0.30 | 13.45 | 0.57 | 2.09 | 0.03 | 0.47 | 0.81 | 3.51 | 5.28 | 0.06 | 0.87 | 99.78 |
| | 176 | 72.48 | 0.30 | 12.97 | 0.91 | 1.86 | 0.03 | 0.38 | 0.88 | 2.73 | 6.07 | 0.06 | 1.08 | 99.75 |
| Cape Bolshoy Rumyanichny | 199 | 74.19 | 0.08 | 13.91 | 0.50 | 0.35 | 0.03 | 0.44 | 1.37 | 4.44 | 2.26 | 0.14 | 1.56 | 99.27 |
| | 207-1 | 76.05 | 0.09 | 13.16 | 0.21 | 0.35 | 0.03 | 0.19 | 0.55 | 4.50 | 4.68 | 0.12 | 0.24 | 100.17 |
| | 207-2 | 75.06 | 0.10 | 13.46 | 0.20 | 0.68 | 0.04 | 0.15 | 0.40 | 4.63 | 4.80 | 0.12 | 0.21 | 99.85 |
| | 207-3 | 73.73 | 0.26 | 13.61 | 0.55 | 0.31 | 0.03 | 0.27 | 0.40 | 4.83 | 5.03 | 0.19 | 0.3 | 99.51 |
| | 214-1 | 72.87 | 0.14 | 14.08 | 1.09 | 0.16 | 0.04 | 0.25 | 0.37 | 5.89 | 4.27 | 0.20 | 0.17 | 99.53 |
| | 220-1 | 72.74 | 0.01 | 14.87 | 0.41 | 0.22 | 0.02 | 0.27 | 0.50 | 5.18 | 5.12 | 0.26 | 0.14 | 99.74 |
| Sopki Kamennyie | 182 | 76.76 | 0.11 | 11.89 | 1.12 | 0.32 | 0.01 | 0.17 | 0.13 | 3.30 | 5.30 | b.d. | 0.58 | 99.69 |
| | 184 | 77.96 | 0.11 | 11.41 | 1.21 | 0.11 | b.d. | 0.09 | 0.13 | 2.85 | 5.30 | b.d. | 0.77 | 99.94 |
| | 185 | 75.60 | 0.22 | 11.79 | 0.50 | 1.45 | 0.01 | 0.40 | 0.60 | 2.65 | 5.52 | 0.03 | 1.04 | 99.81 |
| | 186 | 75.52 | 0.23 | 11.96 | 0.62 | 1.31 | 0.01 | 0.35 | 0.59 | 2.82 | 5.36 | 0.03 | 0.73 | 99.53 |
| | 187 | 75.17 | 0.29 | 12.16 | 0.53 | 1.48 | 0.02 | 0.35 | 0.40 | 2.92 | 5.39 | 0.03 | 0.83 | 99.57 |
| | 188 | 75.28 | 0.17 | 11.90 | 0.50 | 1.24 | 0.04 | 0.02 | 0.82 | 2.65 | 6.13 | 0.03 | 0.70 | 99.48 |
| | 189-2 | 74.85 | 0.25 | 12.56 | 0.61 | 1.37 | 0.01 | 0.33 | 0.28 | 2.73 | 6.07 | 0.03 | 0.82 | 99.91 |
| | 190 | 75.30 | 0.26 | 12.12 | 1.24 | 0.55 | 0.01 | 0.35 | 0.25 | 2.60 | 5.95 | 0.02 | 0.89 | 99.54 |
| | 191 | 77.10 | 0.12 | 11.49 | 0.39 | 1.12 | 0.01 | 0.15 | 0.50 | 2.93 | 5.34 | 0.01 | 0.59 | 99.75 |

Note. b.d. – below the limit of detection.

Примечание. b.d. – содержание меньше предела обнаружения.

microprobe jointly operated by Stanford University and the U.S. Geological Survey, following procedures outlined by [Ireland, 1995] and [Coble et al., 2018]. Cathodoluminescence images of zircons were taken by a JEOL LV 5600 scanning electron microscope. Processing of the analytical data was performed using the SQUID-2 program [Ludwig, 2009]. When plotting U-Pb concordia diagrams, the program ISOPLOT/Ex was used [Ludwig, 2012].

## 4. MAJOR AND TRACE ELEMENT COMPOSITION OF ROCKS

Almost all the rocks studied (see Table 1) are characterized by relatively high to high alkalinity. For the rocks of the Bolshoy Kameshek pluton with $SiO_2$ content from 69.19–77.04 wt. %, the $Na_2O+K_2O$ sum varies from 8.02–10.34 wt. %, and an agpaitic index (molar proportion of (Na+K)/Al) is high and amounts to 0.81–0.99. According to the petrochemical classification (Fig. 2, a), these are subalkaline granites, subalkaline leucogranites, and alkaline granites. For the rocks from the Sopki Kamennyie pluton with $SiO_2$ varying from 74.85–77.96 wt. %, the $Na_2O+K_2O$ sum amounts to 8.15-8.80 wt. %, and the agpaitic index is high (from 0.87–0.94). According to the petrochemical classification (Fig. 2, a) these are subalkaline leucogranites. The rocks composing the veins in the Cape Bolshoy Rumyanichny pluton are granites, subalkaline granites, subalkaline

**Table 2.** Trace element contents in granites of the Northern Timan, ppm
**Таблица 2.** Содержание элементов-примесей в гранитах Северного Тимана, г/т

| Component | Bolshoy Kameshek | | | | | | Cape Bolshoy Rumyanichny | | | | Sopki Kamennyie | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 105/2* | 108/1 | 122 | 133* | 134/1 | 176 | 199* | 207/1* | 214/1* | 220/1 | 182* | 188* | 190 |
| V | 2.50 | 91.93 | 4.59 | 10.60 | 1.72 | 4.80 | 4.21 | 2.50 | 4.81 | 0.14 | 2.50 | 6.52 | 4.71 |
| Cr | 31.70 | 46.28 | 8.85 | 34.80 | 12.66 | 10.12 | 30.70 | 34.20 | 18.20 | 5.56 | 19.60 | 537.00 | 11.78 |
| Co | 1.35 | 18.44 | 0.92 | 2.66 | 0.73 | 1.05 | 5.74 | 0.51 | 1.18 | 0.08 | 0.89 | 3.50 | 0.86 |
| Ni | 16.40 | 41.96 | 4.94 | 17.30 | 7.12 | 5.27 | 12.90 | 14.50 | 5.99 | 2.18 | 9.18 | 261.00 | 6.31 |
| Cu | 46.00 | 39.47 | 2.35 | 15.00 | 3.50 | 4.04 | 31.40 | 19.50 | 19.90 | 1.07 | 40.30 | 41.80 | 12.92 |
| Zn | 61.50 | 23.09 | 12.14 | 41.50 | 6.38 | 9.32 | 47.70 | 32.00 | 34.50 | н.п.о. | 64.10 | 56.70 | 6.79 |
| Ga | 25.20 | 7.83 | 8.48 | 22.30 | 10.08 | 7.62 | 16.00 | 14.20 | 16.30 | 8.18 | 26.70 | 21.90 | 7.96 |
| Rb | 372.00 | 36.16 | 81.99 | 262.00 | 131.21 | 26.00 | 56.70 | 243.00 | 186.00 | 28.12 | 429.00 | 305.00 | 67.11 |
| Sr | 49.10 | 239.60 | 36.36 | 58.70 | 19.42 | 27.26 | 173.00 | 10.30 | 25.90 | 0.22 | 7.75 | 22.20 | 8.12 |
| Y | 98.10 | 10.39 | 24.15 | 52.10 | 24.52 | 9.90 | 9.18 | 8.39 | 12.90 | 0.40 | 93.00 | 67.40 | 12.07 |
| Zr | 118.00 | 50.95 | 100.85 | 243.00 | 124.14 | 113.53 | 35.00 | 42.30 | 29.10 | 3.50 | 147.00 | 143.00 | 100.64 |
| Nb | 89.00 | 21.81 | 27.77 | 50.80 | 34.88 | 28.61 | 6.71 | 12.10 | 15.60 | 1.77 | 57.90 | 29.80 | 19.91 |
| Mo | 0.89 | 0.92 | 0.92 | 1.48 | 0.69 | 0.72 | 1.33 | 1.12 | 2.75 | 0.23 | 0.95 | 13.60 | 0.46 |
| Sn | 6.68 | 1.83 | 4.27 | 3.96 | 7.95 | 3.17 | 8.77 | 6.13 | 1.78 | 1.19 | 10.50 | 8.71 | 5.98 |
| Cs | 3.36 | 3.42 | 5.38 | 5.56 | 5.02 | 4.75 | 1.98 | 10.10 | 1.24 | 0.69 | 6.20 | 2.77 | 4.22 |
| Ba | 129.00 | 487.21 | 494.31 | 527.00 | 229.15 | 694.33 | 325.00 | 31.80 | 20.70 | 6.29 | 50.10 | 179.00 | 342.56 |
| La | 81.60 | 35.25 | 122.23 | 83.40 | 110.84 | 47.13 | 4.62 | 3.14 | 12.40 | 2.29 | 75.60 | 101.00 | 42.19 |
| Ce | 156.00 | 60.52 | 218.98 | 154.00 | 201.92 | 76.47 | 10.90 | 5.36 | 19.40 | 3.33 | 145.00 | 195.00 | 80.37 |
| Pr | 15.80 | 7.67 | 25.16 | 16.10 | 22.32 | 12.18 | 1.23 | 0.57 | 1.95 | 0.26 | 18.80 | 20.50 | 11.60 |
| Nd | 53.70 | 29.56 | 85.28 | 55.00 | 72.97 | 45.14 | 5.74 | 1.96 | 6.41 | 0.80 | 66.20 | 72.50 | 45.54 |
| Sm | 10.20 | 5.77 | 14.55 | 9.75 | 12.74 | 8.38 | 1.52 | 0.58 | 1.72 | 0.21 | 15.00 | 14.00 | 9.25 |
| Eu | 0.17 | 1.81 | 0.91 | 0.93 | 0.56 | 0.78 | 0.36 | 0.06 | 0.29 | 0.05 | 0.21 | 0.42 | 0.59 |
| Gd | 10.70 | 5.90 | 12.72 | 8.73 | 12.01 | 7.93 | 1.28 | 0.58 | 1.66 | 0.23 | 14.50 | 11.60 | 9.26 |
| Tb | 2.01 | 0.76 | 1.75 | 1.50 | 1.77 | 1.10 | 0.27 | 0.16 | 0.35 | 0.04 | 2.62 | 2.03 | 1.28 |
| Dy | 13.20 | 4.75 | 11.48 | 8.89 | 12.24 | 7.20 | 1.74 | 1.23 | 2.31 | 0.29 | 16.10 | 11.30 | 8.18 |
| Ho | 2.67 | 0.95 | 2.35 | 1.87 | 2.62 | 1.47 | 0.34 | 0.28 | 0.45 | 0.06 | 3.22 | 2.26 | 1.69 |
| Er | 8.93 | 2.66 | 7.09 | 5.56 | 8.27 | 4.35 | 1.01 | 0.83 | 1.34 | 0.20 | 10.20 | 6.91 | 5.10 |
| Tm | 1.44 | 0.37 | 1.07 | 0.83 | 1.28 | 0.64 | 0.16 | 0.14 | 0.22 | 0.04 | 1.56 | 1.02 | 0.75 |
| Yb | 9.33 | 2.27 | 6.78 | 5.45 | 8.49 | 3.97 | 1.11 | 1.10 | 1.38 | 0.29 | 9.47 | 6.44 | 4.74 |
| Lu | 1.41 | 0.32 | 0.97 | 0.72 | 1.23 | 0.57 | 0.16 | 0.14 | 0.21 | 0.04 | 1.36 | 0.93 | 0.69 |
| Hf | 5.98 | 2.73 | 6.14 | 8.68 | 9.69 | 7.65 | 1.07 | 1.37 | 0.80 | 0.21 | 7.43 | 6.61 | 8.36 |
| Ta | 9.32 | 2.60 | 4.64 | 4.39 | 7.73 | 4.30 | 1.86 | 2.30 | 2.88 | 0.35 | 6.22 | 3.12 | 3.49 |
| Pb | 12.70 | 9.61 | 10.76 | 14.70 | 6.62 | 4.47 | 11.10 | 13.70 | 2.62 | 0.62 | 33.80 | 33.90 | 4.95 |
| Th | 79.20 | 2.81 | 15.83 | 25.70 | 29.98 | 11.43 | 0.82 | 2.19 | 1.81 | 0.69 | 47.20 | 33.90 | 10.66 |
| U | 22.00 | 0.67 | 2.60 | 5.23 | 4.40 | 0.96 | 8.11 | 3.54 | 1.57 | 0.21 | 4.16 | 3.33 | 1.65 |

Note. Analysis performed at VSEGEI, Saint-Petersburg, are marked with asterisk.
Примечание. Анализы, выполненные во ВСЕГЕИ, Санкт-Петербург, отмечены звездочками.

leucogranites, and alkaline leucogranites (Fig. 2, a) with the $SiO_2$ content ranging from 72.74–76.05 wt. % and the $Na_2O$+$K_2O$ sum from 9.18–10.16 wt. %, except one sample with $Na_2O$+$K_2O$=6.7 wt. %. Their agpaitic index is extremely high in all but one sample – 0.95–1.02. Considering the $Na_2O/K_2O$ ratios (0.45–1.00 and 0.43–0.62, respectively), granites from the Bolshoy Kameshek and Sopki Kamennyie plutons belong to potassium-sodium type granites, and the Cape Bolshoy Rumyanichny pluton (0.96–1.96) is of the sodium type.

The granitoids of the Bolshoy Kameshek and Sopki Kamennyie plutons are characterized by significant variations

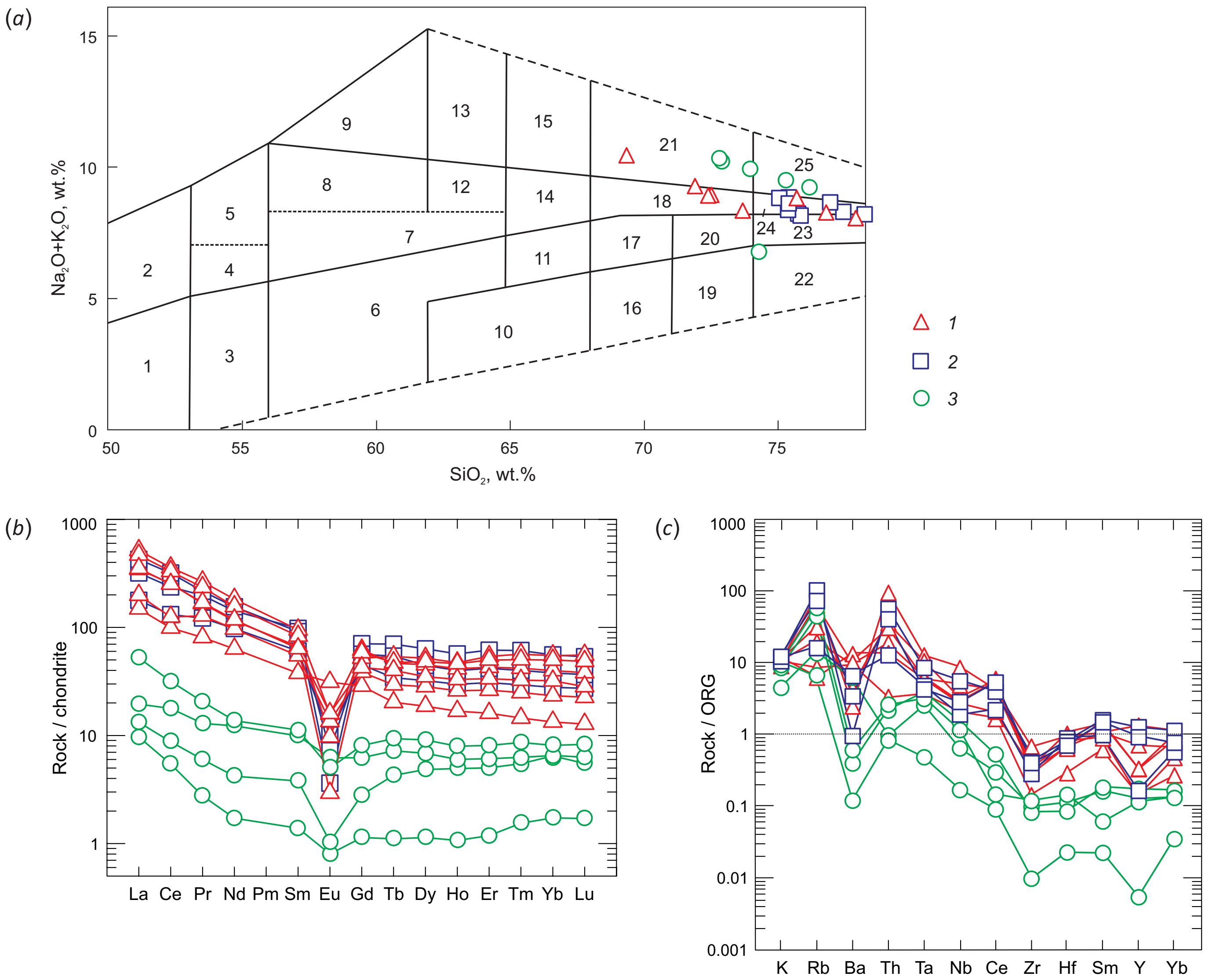


**Fig. 2.** Classification diagrams for granitoids of the Northern Timan. (*a*) – ($Na_2O$+$K_2O$)–$SiO_2$ [Popov, Bogatikov, 2001], (*b*) – chondrite-normalized REE chart, (*c*) – spider-diagram for trace elements normalized to ORG.

Numbers refer to plutons: *1* – Bolshoy Kameshek, *2* – Sopki Kamennyie, *3* – Cape Bolshoy Rumyanichny. Numbers refer to fields: 1 – gabbronorite, gabbro, gabbrodiorite; 2 – monzogabbro; 3 – diorite, 4 – monzodiorite; 5 – monzonite; 6 – quartz diorite; 7 – quartz monzodiorite; 8 – syenite; 9 – alkaline syenite; 10 – tonalite; 11 – granodiorite; 12 – quartz syenite; 13 – alkaline quartz syenite; 14 – granosyenite; 15 – alkaline granosyenite; 16 – trondhjemite; 17 – adamellite; 18 – subalkaline granite; 19 – plagiogranite; 20 – granite; 21 – alkaline granite; 22 – plagioclase leucogranite; 23 – leucogranite; 24 – alaskite; 25 – alkaline alaskite.

**Рис. 2.** Классификационная диаграмма ($Na_2O$+$K_2O$)–$SiO_2$, по [Popov, Bogatikov, 2001] (*a*), хондрит-нормализованные спектры РЗЭ (*b*), спайдер-диаграмма распределения элементов-примесей, нормированных на ORG (*c*) для гранитоидов Северного Тимана.

Массивы: *1* – Большой Камешек, *2* – Сопки Каменные, *3* – мыса Большой Румяничный. Поля на диаграмме (*a*): 1 – габбро-нориты, габбро, габбро-диориты; 2 – монцогаббро; 3 – диориты, 4 – монцодиориты; 5 – монцониты; 6 – кварцевые диориты; 7 – кварцевые монцодиориты; 8 – сиениты; 9 – щелочные сиениты; 10 – тоналиты; 11 – гранодиориты; 12 – кварцевые сиениты; 13 – щелочные кварцевые сиениты; 14 – граносиениты; 15 – щелочные граносиениты; 16 – трондьемиты; 17 – адамеллиты; 18 – субщелочные граниты; 19 – плагиограниты; 20 – граниты; 21 – щелочные граниты; 22 – плагиоклазовые лейкограниты; 23 – лейкограниты; 24 – аляскиты; 25 – щелочные аляскиты.

of trace elements (Table 2). Compared with the model composition of granites from the mid-oceanic ridges [Pearce et al., 1984], the granitoids are enriched in large ion lithophile elements (LILE) and virtually lack depletion in high field strength elements (HFSE) (Fig. 2, c). The main characteristics of these rocks are high contents of rare earth elements (total REE =159–511 ppm in granites of the Bolshoy Kameshek pluton, and 221–446 ppm in granites of the Sopki Kamennyie pluton), Nb (22–89 and 20–58 ppm, respectively), Y (up to 98 and 93 ppm, respectively), Th (up to 79 and 47 ppm, respectively), low concentrations of Sr and V, and moderate concentrations of Ba, Rb and Zr. Chondrite-normalized REE plots demonstrate (Fig. 2, b) the enrichment of LREE compare to HREE ($La_N/Yb_N$ – 6.27–12.94 and 6.38–11.25) and a noticeable Eu-minimum ($Eu_N/Eu_N^*$ – 0.05–0.94 and 0.04–0.19). Increased alkalinity, a very high agpaitic index, and high contents of REE, Nb, Y, and Th show that the granites of the Bolshoy Kameshek and Sopki Kamennyie plutons can be considered as A-type granites [Whalen et al., 1987].

The granitoid veins of the Cape Bolshoy Rumyanichny pluton significantly differ from the rocks of other plutons: they are more sodium-rich (see Table 1) and contain much less REE (8–50 ppm). Their REE distributions (Fig. 2, b) are characterized by weak enrichment by LREE compare to HREE, and LREE and HREE compare to MREE ($La_N/Yb_N$ – 2.05–6.45, $La_N/Sm_N$ – 1.96–6.98, $Gd_N/Yb_N$ – 0.44–1.00) with a small Eu minimum ($Eu_N/Eu_N^*$ – 0.31–0.77). The most alkaline rocks show very low concentrations of both LILE (Ba – 6–32, Sr – 0.2–26 ppm) and HFSE – Nb (2–16 ppm), Y (0.4–13 ppm), Zr (4–42 ppm), and Th (1–2 ppm) (Fig. 2, c). High alkalinity and the agpaitic index of the granites correspond to A-type granites, but all trace elements occur in very low concentrations in these rocks. Such a relationship sometimes occurs in fractionated leucogranites and could be caused by fractional crystallization of rock-forming and accessory minerals, e.g. [Zhang et al., 2019].

## 5. RESULTS OF U-Pb DATING OF ZIRCONS

The Bolshoy Kameshek pluton: Zircons from granite sample 122 (67.4881°N, 48.1324°E) are subhedral, bipyramidal-prismatic crystals with most pronounced pyramid (111) and prism (110) faces. They are light pinkish brown, semi-transparent or opaque with rough faces. Their size ranges from 150–400 μm, and elongation is 2.5-5. Zircons contain numerous small inclusions that are black in transmitted light. Cathodoluminescent images (Fig. 3) show that almost all the grains have well-defined central domains and rims with oscillatory or patched zoning, sometimes partially damaged zoning. Based on textural observations, these central domains are not interpreted to be detrital cores because they are not rounded and usually have crystallographic outlines and are covered with rims up to 100 μm wide with distinct fine-scale or coarse-scale oscillatory zoning.

Ten spots on zircons yielded individual $^{206}Pb/^{238}U$ ages of 594–631 Ma (Table 3). Isotopic data form a reproducible concordant age cluster with a weighted mean age of 613 ± 6 Ma (Fig. 4).

The Cape Bolshoy Rumyanichny pluton: Zircon crystals and crystal fragments from granite sample 207 (67.5744°N, 47.8315°E) vary in size from 50–250 μm. Cathodoluminescent images (Fig. 5) demonstrate the presence of several types of zircons with different luminescence character and internal structure: (1) small dark non-zonal portions of grains 6.1, 8.1, and a fragment of subhedral crystal 7.1; (2) subhedral dark grains 3.1 and 5.1 with low-contrast poorly distinguishable oscillatory zoning; (3) fragments of grains 4.1 and 9.1 with damaged zoning; (4) a fragment of grain 2.1 of a complex structure with patchy zoning, including relict core and rim relations; (5) grain 1.1 containing a core with damaged zoning and an unzoned rim.

The heterogeneity of zircons is also observed in the large scatter of isotopic ages (Table 3). The range of individual $^{206}Pb/^{238}U$ ages for 9 grains is 309 to 1146 Ma. We interpret

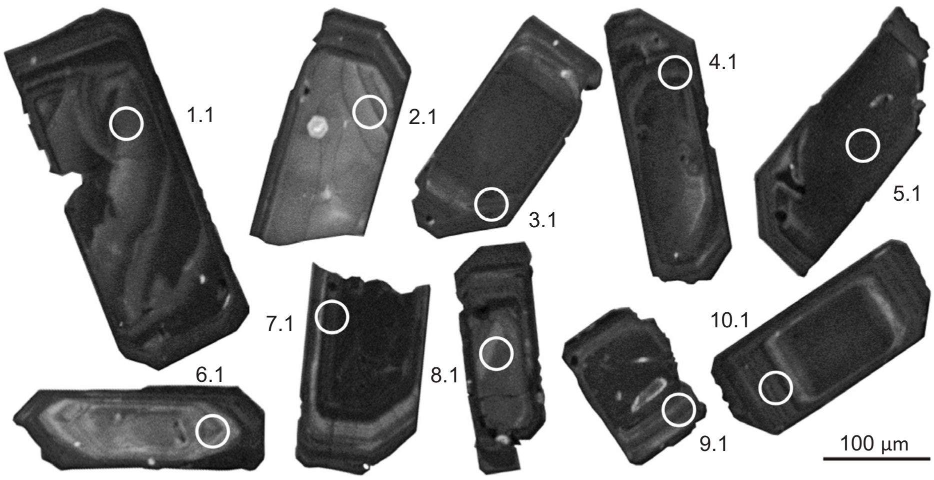


**Fig. 3.** Cathodoluminescent images of zircon grains from granite of the Bolshoy Kameshek pluton, sample 122. The figure shows grain numbers and analyzed spots.

**Рис. 3.** Катодолюминесцентное изображение цирконов из гранита массива Большой Камешек (обр. 122) с номерами датированных зерен и аналитических кратеров.

**Table 3.** Results of U–Pb dating of zircons from granites of the Northern Timan
**Таблица 3.** Результаты U–Pb изотопных исследований цирконов из гранитов Северного Тимана

| Grain, spot | $^{206}Pb_c$, % | Content, ppm | | | $^{232}Th/^{238}U$ | Corrected Ratios ±% (1σ) | | | CC | Age ± 1σ, Ma | | D, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $^{206}Pb^*$ | U | Th | | $^{206}Pb/^{238}U$ | $^{207}Pb/^{235}U$ | $^{207}Pb/^{206}Pb$ | | $^{206}Pb/^{238}U$ | $^{207}Pb/^{206}Pb$ | |
| Bolshoy Kameshek pluton, sample 122 | | | | | | | | | | | | |
| 5.1 | b.d. | 123 | 1482 | 1300 | 0.91 | 0.0964 ± 0.8 | 0.802 ± 1.0 | 0.0603 ± 0.5 | 0.8 | 594 ± 5 | 614 ± 11 | 3 |
| 8.1 | b.d. | 22 | 258 | 129 | 0.52 | 0.0982 ± 1.1 | 0.820 ± 1.7 | 0.0605 ± 1.3 | 0.6 | 604 ± 6 | 621 ± 27 | 3 |
| 3.1 | 0.08 | 56 | 649 | 368 | 0.59 | 0.1000 ± 1.0 | 0.827 ± 1.4 | 0.0600 ± 0.9 | 0.7 | 614 ± 6 | 603 ± 21 | −2 |
| 9.1 | 1.80 | 40 | 462 | 339 | 0.76 | 0.1009 ± 1.7 | 0.910 ± 12.5 | 0.0654 ± 12.4 | 0.1 | 620 ± 10 | 787 ± 261 | 27 |
| 4.1 | 0.24 | 129 | 1482 | 766 | 0.53 | 0.1010 ± 0.6 | 0.854 ± 1.6 | 0.0614 ± 1.5 | 0.3 | 620 ± 3 | 651 ± 32 | 5 |
| 7.1 | 0.51 | 61 | 707 | 352 | 0.51 | 0.1012 ± 2.7 | 0.844 ± 3.0 | 0.0605 ± 1.4 | 0.9 | 621 ± 16 | 622 ± 29 | 0 |
| 2.1 | 0.14 | 23 | 263 | 83 | 0.33 | 0.1021 ± 1.1 | 0.824 ± 1.9 | 0.0585 ± 1.6 | 0.6 | 627 ± 7 | 549 ± 34 | −12 |
| 10.1 | b.d. | 64 | 730 | 296 | 0.42 | 0.1024 ± 4.3 | 0.849 ± 4.4 | 0.0601 ± 0.7 | 1.0 | 628 ± 26 | 608 ± 16 | −3 |
| 1.1 | 0.12 | 39 | 445 | 157 | 0.36 | 0.1026 ± 3.3 | 0.830 ± 3.6 | 0.0586 ± 1.4 | 0.9 | 630 ± 20 | 553 ± 31 | −12 |
| 6.1 | 1.08 | 15 | 170 | 103 | 0.62 | 0.1029 ± 2.9 | 0.872 ± 5.9 | 0.0615 ± 5.1 | 0.5 | 631 ± 18 | 656 ± 109 | 4 |
| Cape Bolshoy Rumyanichny pluton, sample 207 | | | | | | | | | | | | |
| 7.1 | 3.70 | 95 | 2249 | 537 | 0.25 | 0.0490 ± 2.9 | 0.381 ± 7.5 | 0.0564 ± 6.9 | 0.4 | 309 ± 9 | 466 ± 154 | 51 |
| 4.1 | 15.07 | 4 | 58 | 112 | 2.01 | 0.0783 ± 2.7 | 0.897 ± 34.4 | 0.0832 ± 34.3 | 0.1 | 486 ± 13 | 1273 ± 669 | 162 |
| 8.1 | 9.62 | 52 | 742 | 3263 | 4.54 | 0.0817 ± 2.1 | 0.633 ± 14.7 | 0.0562 ± 14.6 | 0.1 | 506 ± 10 | 460 ± 323 | −9 |
| 6.1 | 6.66 | 300 | 3666 | 12691 | 3.58 | 0.0954 ± 4.5 | 0.798 ± 16.3 | 0.0607 ± 15.7 | 0.3 | 587 ± 25 | 627 ± 338 | 7 |
| 1.1 | 5.20 | 8 | 97 | 84 | 0.90 | 0.0990 ± 1.5 | 0.950 ± 15.0 | 0.0696 ± 14.9 | 0.1 | 608 ± 9 | 917 ± 307 | 51 |
| 9.1 | 11.72 | 20 | 237 | 531 | 2.31 | 0.1006 ± 1.5 | 1.022 ± 20.1 | 0.0737 ± 20.0 | 0.1 | 618 ± 9 | 1034 ± 404 | 67 |
| 2.1 | 0.09 | 31 | 353 | 116 | 0.34 | 0.1029 ± 23 | 0.849 ± 2.7 | 0.0598 ± 1.5 | 0.8 | 631 ± 14 | 596 ± 32 | −6 |
| 5.1 | 0.19 | 98 | 599 | 254 | 0.44 | 0.1897 ± 0.9 | 3.079 ± 1.0 | 0.1177 ± 0.6 | 0.8 | 1120 ± 9 | 1922 ± 10 | 72 |
| 3.1 | 0.08 | 13 | 78 | 28 | 0.37 | 0.1945 ± 2.4 | 2.069 ± 3.1 | 0.0771 ± 2.0 | 0.8 | 1146 ± 26 | 1125 ± 40 | −2 |
| Sopki Kamennyie pluton, sample 185 | | | | | | | | | | | | |
| 1.1 | 2.71 | 75 | 754 | 694 | 0.95 | 0.1150 ± 0.6 | 1.009 ± 1.8 | 0.0636 ± 1.7 | 0.3 | 702 ± 4 | 729 ± 32 | 4 |
| 9.1 | b.d. | 68 | 678 | 342 | 0.52 | 0.1168 ± 0.6 | 1.029 ± 0.9 | 0.0639 ± 0.7 | 0.6 | 712 ± 4 | 738 ± 15 | 4 |
| 4.1 | 0.13 | 68 | 670 | 322 | 0.50 | 0.1179 ± 0.6 | 1.044 ± 1.1 | 0.0642 ± 0.9 | 0.6 | 718 ± 4 | 748 ± 18 | 4 |
| 6.1 | b.d. | 153 | 1508 | 815 | 0.56 | 0.1184 ± 0.8 | 1.035 ± 0.9 | 0.0634 ± 0.5 | 0.8 | 721 ± 5 | 720 ± 11 | 0 |
| 8.1 | b.d. | 30 | 287 | 127 | 0.46 | 0.1210 ± 2.1 | 1.054 ± 2.3 | 0.0631 ± 1.1 | 0.9 | 737 ± 14 | 712 ± 23 | −3 |
| 7.1 | b.d. | 94 | 899 | 404 | 0.46 | 0.1216 ± 1.1 | 1.064 ± 1.3 | 0.0635 ± 0.6 | 0.9 | 740 ± 8 | 723 ± 13 | −2 |
| 10.1 | b.d. | 42 | 403 | 169 | 0.43 | 0.1223 ± 1.6 | 1.072 ± 1.9 | 0.0636 ± 0.9 | 0.9 | 744 ± 11 | 726 ± 19 | −2 |
| 5.1 | 0.39 | 41 | 394 | 194 | 0.51 | 0.1226 ± 2.7 | 1.067 ± 3.1 | 0.0631 ± 1.3 | 0.9 | 746 ± 19 | 712 ± 31 | −5 |
| 2.1 | b.d. | 23 | 218 | 103 | 0.49 | 0.1226 ± 1.4 | 1.057 ± 1.9 | 0.0625 ± 1.3 | 0.7 | 746 ± 10 | 690 ± 28 | −8 |
| 3.1 | b.d. | 55 | 517 | 143 | 0.29 | 0.1237 ± 1.7 | 1.085 ± 1.9 | 0.0636 ± 0.8 | 0.9 | 752 ± 12 | 728 ± 18 | −3 |
| Sopki Kamennyie pluton, sample 182 | | | | | | | | | | | | |
| 10.1 | 2.71 | 191 | 2122 | 1035 | 0.50 | 0.1050 ± 2.9 | 0.978 ± 7.2 | 0.0676 ± 6.6 | 0.4 | 644 ± 18 | 855 ± 37 | 33 |
| 9.1 | 12.58 | 249 | 2720 | 1957 | 0.74 | 0.1069 ± 8.1 | 0.890 ± 33.8 | 0.0604 ± 32.8 | 0.2 | 655 ± 51 | 617 ± 708 | −6 |
| 4.1 | 1.01 | 448 | 4747 | 3050 | 0.66 | 0.1100 ± 3.5 | 0.982 ± 3.8 | 0.0648 ± 1.6 | 0.9 | 673 ± 22 | 767 ± 34 | 14 |
| 2.1 | 0.17 | 127 | 1339 | 509 | 0.39 | 0.1107 ± 0.8 | 0.974 ± 1.1 | 0.0638 ± 0.8 | 0.7 | 677 ± 5 | 735 ± 16 | 9 |
| 3.1 | 0.33 | 159 | 1658 | 1015 | 0.63 | 0.1116 ± 1.6 | 0.981 ± 2.1 | 0.0637 ± 1.3 | 0.8 | 682 ± 11 | 733 ± 27 | 8 |
| 7.1 | 2.65 | 309 | 3159 | 1972 | 0.64 | 0.1139 ± 3.1 | 1.023 ± 4.2 | 0.0652 ± 2.8 | 0.7 | 695 ± 21 | 780 ± 60 | 12 |
| 11.1 | 0.10 | 44 | 440 | 190 | 0.45 | 0.1177 ± 1.2 | 1.032 ± 1.7 | 0.0636 ± 1.2 | 0.7 | 717 ± 8 | 727 ± 24 | 1 |
| 1.1 | 1.02 | 61 | 598 | 312 | 0.54 | 0.1180 ± 0.9 | 1.087 ± 2.2 | 0.0668 ± 2.0 | 0.4 | 719 ± 6 | 832 ± 41 | 16 |
| 6.1 | 0.23 | 424 | 4181 | 2534 | 0.63 | 0.1180 ± 1.6 | 1.038 ± 1.7 | 0.0638 ± 0.5 | 1.0 | 719 ± 11 | 734 ± 10 | 2 |
| 12.1 | b.d. | 129 | 1244 | 574 | 0.48 | 0.1204 ± 1.9 | 1.066 ± 2.0 | 0.0642 ± 0.6 | 1.0 | 733 ± 13 | 750 ± 12 | 2 |
| 8.1 | 0.48 | 458 | 4371 | 2543 | 0.60 | 0.1219 ± 1.9 | 1.078 ± 2.3 | 0.0642 ± 1.3 | 0.8 | 741 ± 13 | 750 ± 28 | 1 |
| 5.1 | 0.28 | 457 | 4337 | 2548 | 0.61 | 0.1228 ± 2.9 | 1.077 ± 3.0 | 0.0636 ± 0.5 | 1.0 | 747 ± 21 | 729 ± 10 | −2 |

Note. Error in the calibration standard is 0.15 % (samples 122, 185) and 0.28 % (samples 207, 182). $^{206}Pb_c$ and $^{206}Pb^*$ – common and radiogenic lead; b.d. – below the limit of determination (≤0.04). Corrected Ratios ($^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$, and $^{207}Pb/^{206}Pb$) and $^{206}Pb^*$ content are corrected for $^{204}Pb_c$. CC is the error correlation coefficient of radiogenic $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$. D is discordance: D = 100 × [age ($^{207}Pb/^{206}Pb$)/age ($^{206}Pb/^{238}U$) – 1].

Примечание. Ошибка в калибровке стандарта составляет 0.15 % (обр. 122, 185) и 0.28 % (обр. 207, 182). $^{206}Pb_c$ и $^{206}Pb^*$ – обыкновенный и радиогенный свинец, b.d. – ниже предела определения (≤0.04). Изотопные отношения и содержания $^{206}Pb$ скорректированы по измеренному $^{204}Pb$. D – дискордантность: D = 100 × [возраст ($^{207}Pb/^{206}Pb$) / возраст ($^{206}Pb/^{238}U$) – 1]. CC – коэффициент корреляции между ошибками определения изотопных отношений $^{206}Pb/^{238}U$ и $^{207}Pb/^{235}U$.

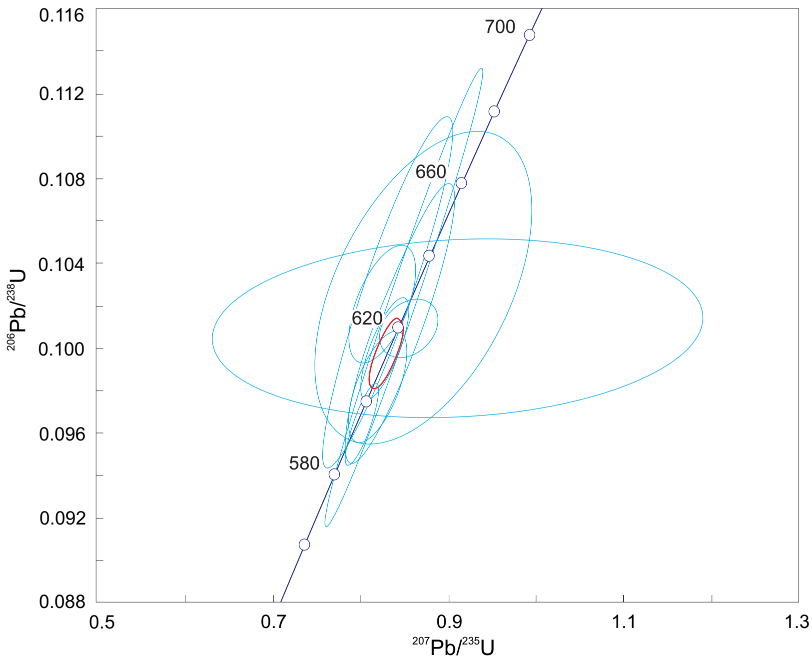


**Fig. 4.** Concordia diagram for zircons from granite of the Bolshoy Kameshek pluton, sample 122. In this and subsequent diagrams, the analysis values are the centers of the error ellipses (2σ).
The calculated concordant age of 613 ± 6 Ma (95 %, n = 10, MSWD = 0.3) is shown by the red ellipse.

**Рис. 4.** Диаграмма с конкордией для цирконов из гранита массива Большой Камешек (обр. 122). Здесь и далее координаты аналитических точек – центры эллипсов погрешностей (2σ).
Красным цветом выделен эллипс, соответствующий рассчитанному конкордантному возрасту 613±6 млн лет (95 %, n = 10, СКВО = 0.3).

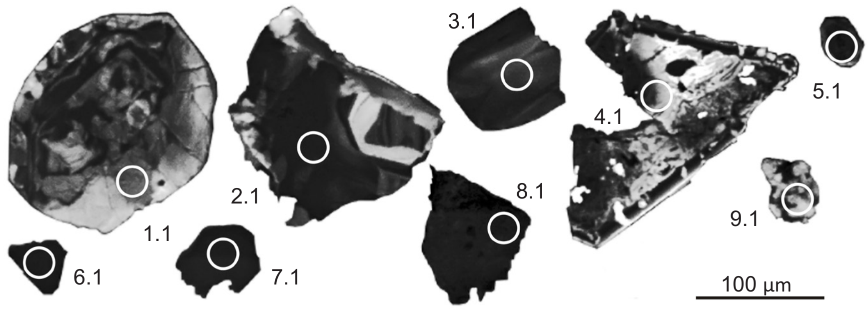


**Fig. 5.** Cathodoluminescent images of zircon grains from granite of the Cape Bolshoy Rumyanichny pluton, sample 207. The figure shows grain numbers and analyzed spots.

**Рис. 5.** Катодолюминесцентное изображение цирконов из гранита мыса Большой Румяничный (обр. 207) с номерами датированных зерен и аналитических кратеров.

the three younger zircon ages (309 Ma for grain 7.1, 486 Ma for grain 4.1, and 506 Ma for grain 8.1) to reflect Pb-loss, and these values were omitted from the age calculations. Zircons with ages older than 1000 Ma or discordant (1146 Ma for grain 3.1 and 1120 Ma for grain 5.1) are likely to be inherited and were excluded as well from the age cluster used to estimate the age of crystallization. Isotope ratios for the rest of the four grains analyzed in the wide rims of zircon grains 1.1 and 2.1 and in the central parts of small grains 6.1 and 9.1 (Fig. 5) yielded a weighted mean concordant age of 614 ± 11 Ma, similar to the age of granites of the Bolshoy Kameshek pluton and is assumed to represent the age of crystallization (Fig. 6).

The Sopki Kamennyie pluton: Zircons were analyzed from two samples (185 and 182) of granites at different times. Repeat analyses were carried out because the age of zircons obtained in the first analytical session yielded ages much older than the granites discussed above and other igneous rocks of the Northern Timan.

Initially, zircon grains from granite sample 185 (67.3973°N, 48.5346°E) from the northern part of the pluton were analyzed. Zircons are subhedral, bipyramidal-prismatic, with the

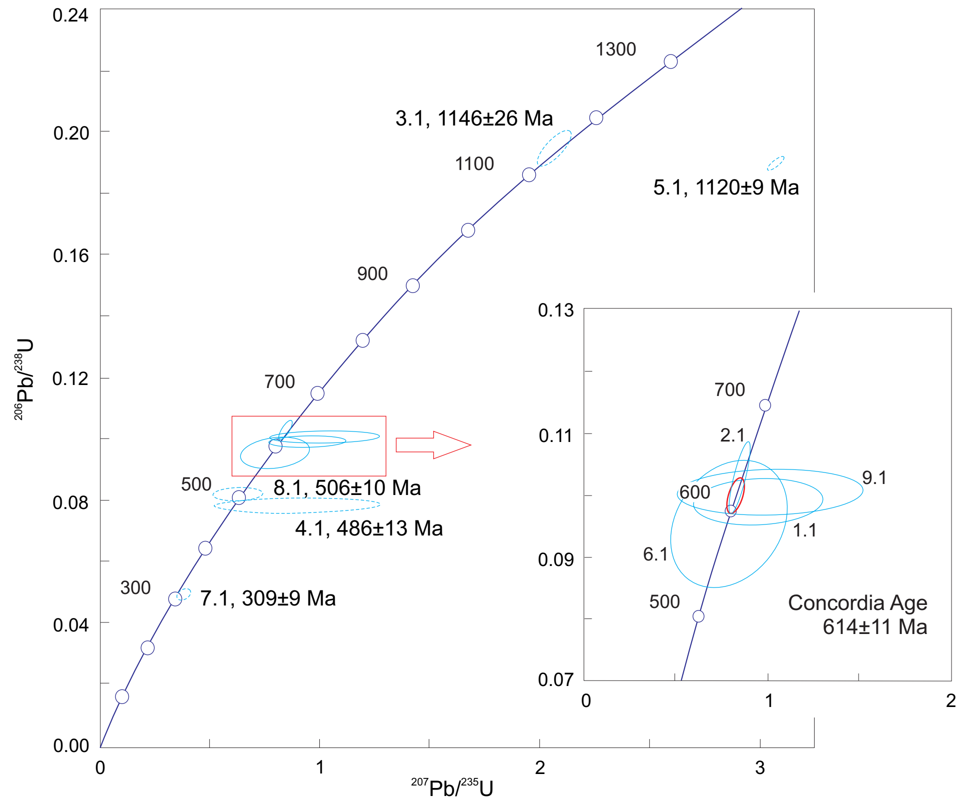


**Fig. 6.** Concordia diagram for zircons from granite of the Cape Bolshoy Rumyanichny pluton, sample 207.
The calculated concordant age of 614 ± 11 Ma (2σ, n = 4, MSWD = 0.17) is shown by the red ellipse in the insert. The error ellipses of analyses that were excluded from the mean age calculations are dashed. The $^{206}Pb/^{238}U$ ages are shown in the diagram.

**Рис. 6.** Диаграмма с конкордией для цирконов из гранита мыса Большой Румяничный (обр. 207).
На вставке красный эллипс соответствует рассчитанному конкордантному возрасту 614±11 млн лет (2σ, n = 4, СКВО = 0.17). Эллипсы погрешностей анализов, исключенных из расчета среднего возраста, показаны пунктиром. Возраст указан по отношению $^{206}Pb/^{238}U$.

most pronounced pyramid (111) and prism (110) slightly rough or smooth shiny faces. They are light brownish-pink and semitransparent. The length of the crystals is 100–200 μm, and elongation is 2–3. These zircons contain numerous small inclusions that are black in transmitted light. Cathodoluminescent images (Fig. 7) show coarse-scale oscillatory zoning in the dark peripheral parts of the grains. The central parts of analyzed grains 2.1, 5.1, 7.1, and 9.1 show coarse-scale oscillatory or patchy damaged zoning. They are not interpreted to be detrital cores because they usually have crystallographic outlines and zoning that is not truncated by rims. The central parts of the crystals with damaged zoning contain rather large black inclusions and damage areas (up to 30–50 μm).

Individual $^{206}Pb/^{238}U$ ages for 10 zircon grains range from 702 to 752 Ma (Table 3). Isotopic data for 9 grains form a reproducible concordant group with a weighted mean age of 723 ± 6 Ma (Fig. 8). Analytical data for point 1.1 (702 Ma) are excluded from the calculation. This grain seems young due to its alteration and/or Pb-loss, as suggested by the high Fe content (273 ppm). The main conclusion is that the granites of the Sopki Kamennyie pluton turned out to be almost 100 Ma older than other granites of the Northern Timan. This seemed a bit unusual, so we carried out further work, dating zircons from sample 182 collected in the central part of the pluton.

Zircons extracted from sample 182 (67.3867°N, 48.5366°E) are subhedral, bipyramidal-prismatic, with predominant pyramid (111) and prism (100), less often with pyramid (111) and prism (110) faces with slightly smooth edges, and rough or shiny faces. The zircons are dark pink to brownish orange, semitransparent or opaque, 50–150 μm long, and elongation is 1.5–3. Several grains are light pink, they are transparent or semitransparent. The zircons contain numerous small black, brown, and orange inclusions. In the cathodoluminescent images, they are dark with slight oscillatory zoning and look similar to the zircons from sample 185. Growth zones are wide, non-contrasting, few (2-3) or not visible at all (Fig. 9).

The zircons from sample 182 differ from the zircons of sample 185 by their higher content of uranium, thorium and lead (Table 3). Their U-Pb ages are more scattered and have larger errors. The individual $^{206}Pb/^{238}U$ ages range from 644 to 747 Ma, with two populations of ages being interpreted. Due to the high content of common lead and a large age determination error, analysis 9.1 was excluded from consideration (note: it is not plotted in Fig. 10). The weighted mean age of five grains from a younger group is

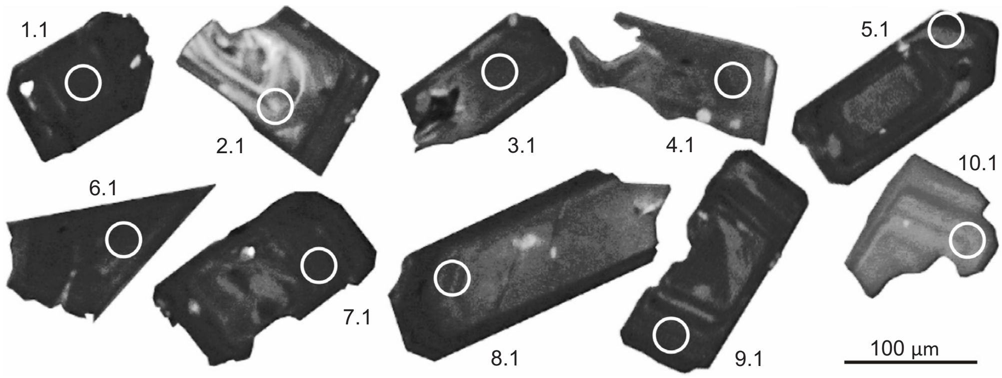


**Fig. 7.** Cathodoluminescent images of zircon grains from granite of the Sopki Kamennyie pluton, sample 185. The figure shows grain numbers and analyzed spots.

**Рис. 7.** Катодолюминесцентное изображение цирконов из гранита массива Сопки Каменные (обр. 185) с номерами датированных зерен и аналитических кратеров.

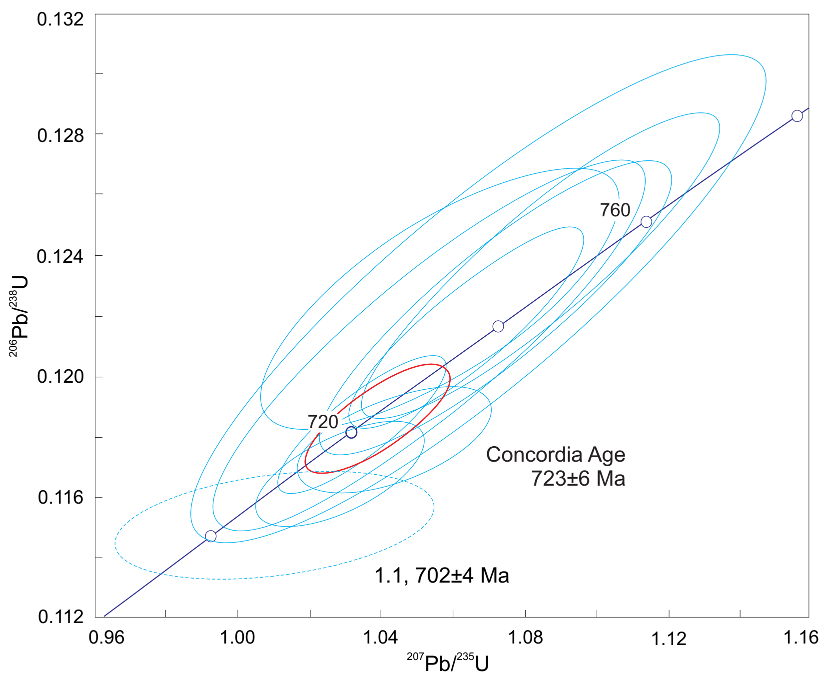


**Fig. 8.** Concordia diagram for zircons from granite of the Sopki Kamennyie pluton, sample 185.
The calculated concordant age of 723 ± 6 Ma (95 %, n = 9, MSWD = 0.19) is shown by the red ellipse. The error ellipse of analysis excluded from the calculation of mean age is dashed.

**Рис. 8.** Диаграмма с конкордией для цирконов из гранита массива Сопки Каменные (обр. 185).
Рассчитанный конкордантный возраст 723±6 млн лет (95 %, n = 9, СКВО = 0.19) обозначен красным эллипсом. Эллипс погрешности анализа, исключенного из расчета среднего возраста, показан пунктиром.

676 ± 9 Ma (2σ, MSWD = 1.1), and that of six grains from an older group is 723 ± 8 Ma (2σ, MSWD = 0.95). The mean concordant age for these six grains is 727 ± 7 Ma (Fig. 10). The latter age coincides with the age of the zircons from sample 185 and confirms the Cryogenian age of the granites from the Sopki Kamennyie pluton.

## 6. DISCUSSION

In summary, the U-Pb isotopic dating of zircons carried out for the granitoids of the Northern Timan suggests two episodes of magmatism. The zircon age of the granites of the Sopki Kamennyie pluton (723 ± 6 and 727 ± 7 Ma) indicates a Cryogenian age of intrusion. The intrusion of the granites of the Bolshoy Kameshek (613 ± 6 Ma) and Cape Bolshoy Rumyannichny (614 ± 11 Ma) plutons occurred in Ediacaran time. Other alkaline rocks and associated gabbros of the Northern Timan are Ediacaran as well. Thus, the U-Pb (SIMS) ages of zircons from syenites and gabbros of the Bolshoy Rumyanichny pluton are 613 ± 7 Ma and 617 ± 6 Ma, respectively. The age of zircons from olivine-kersutite gabbros exposed near the mouth of the Rumyanichnaya River is 614 ± 2 Ma [Larionov et al., 2004]. The

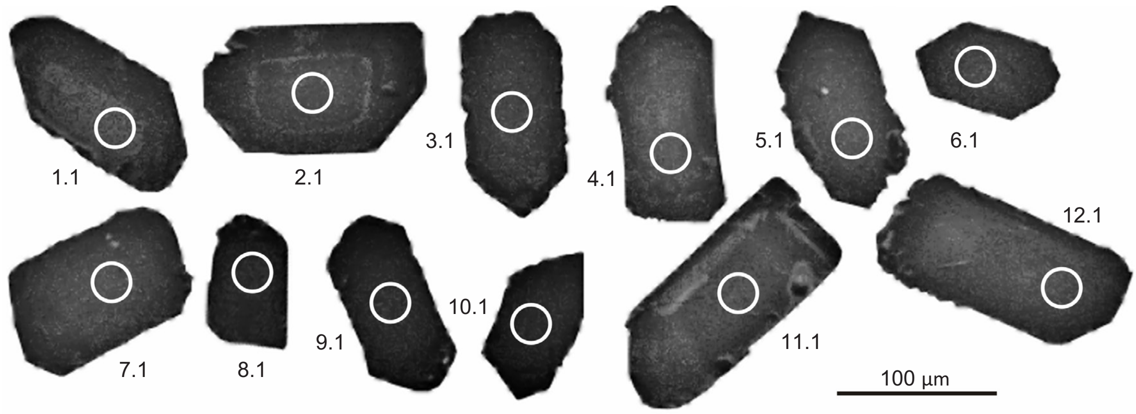


**Fig. 9.** Cathodoluminescent images of zircon grains from granite of the Sopki Kamennyie pluton, sample 182. The figure shows grain numbers and analyzed spots.

**Рис. 9.** Катодолюминесцентное изображение цирконов из гранита (обр. 182) с номерами датированных зерен и аналитических кратеров.

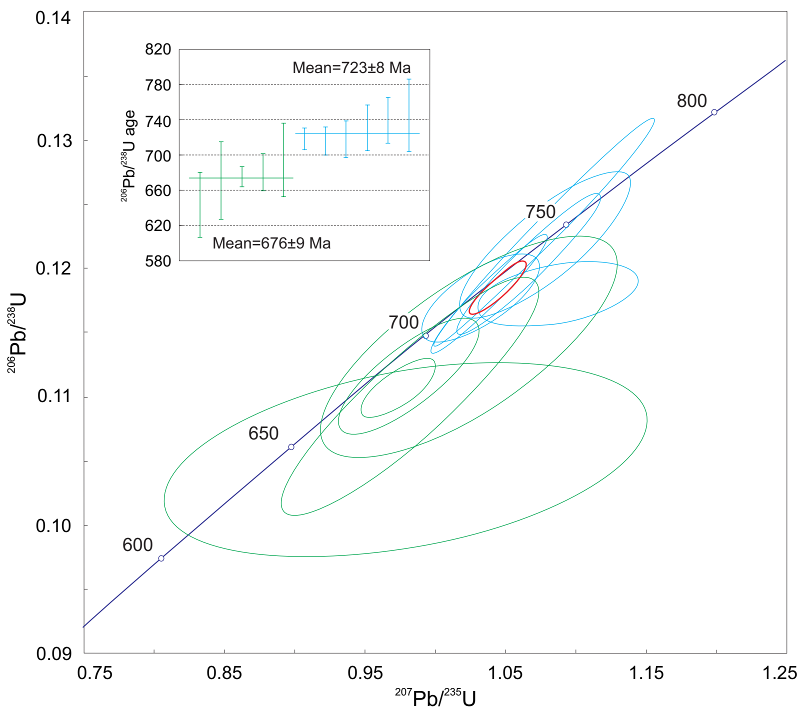


**Fig. 10.** Concordia diagram and weighted mean age of zircons from granite of the Sopki Kamennyie pluton, sample 182.
Error ellipses and bars are shown at 2σ. The calculated concordant age of 727 ± 7 Ma (2σ, n = 6, MSWD = 3.9) is shown by the red ellipse. Error ellipses and bars of analyses from the younger age group are shown in green.

**Рис. 10.** Диаграмма с конкордией и график средневзвешенного возраста для цирконов из гранита массива Сопки Каменные (обр. 182).
Эллипсы и отрезки погрешностей соответствуют 2σ. Рассчитанный конкордантный возраст 727±7 млн лет (2σ, n = 6, СКВО = 3.9) показан красным эллипсом. Эллипсы и отрезки погрешностей анализов для более молодой группы обозначены зеленым.

$^{207}$Pb / $^{206}$Pb age of single zircon grains from syenites of the Krayny Kameshek pluton is 613 ± 2 Ma [Andreichev, Larionov, 2000].

The intrusion of granites, gabbros and syenites in the Northern Timan in the Ediacaran period could have had an effect on the older Cryogenian granites composing the Sopki Kamennyie pluton. Heating, metamorphism and/or the presence of fluids could result in Pb-loss in zircons, which is evidenced by the group of zircons with younger ages from 644–695 Ma (Table 3) discovered in one of the two granite samples from the Sopki Kamennyie pluton.

The age of the igneous rocks of the Northern Timan correlates with the late Cryogenian and Ediacaran stages of the breakup of the early-Neoproterozoic Rodinia supercontinent [Li et al., 2008; Ernst et al., 2008; Bogdanova et al., 2009].

The first mantle-plume events occurred within Rodinia at about 830 Ma, and the four stages of its breakup occurred at 825–800, 780–755, 740–720, and 650–550 Ma [Bogdanova et al., 2009; Ernst et al., 2008; Li et al., 2008]. One of the largest plume-related magmatic provinces – the Franklin Large Igneous Province (LIP) covering an area of >3 Mkm$^2$ occurred 725-715 Ma ago (Fig. 11) in the northern Laurentia and probably in the southern Siberia [Ernst et al., 2016]. This magmatic province produced gabbro and dolerite sills and dikes as well as basalts in the northern Canada and the northwestern Greenland [Fahrig, 1987; Heaman et al., 1992; Denyszyn et al., 2009a, 2009b; Macdonald et al., 2010; Buchan et al., 2010; Buchan, Ernst, 2013] (Fig. 12).

Plume-related Franklin-age magmatic rocks are known only in a few regions in the world, including the Kalahary craton [Ernst, Buchan, 2001], the southern Siberia [Ariskin et al., 2013; Polyakov et al., 2013; Gladkochub et al., 2010; Ernst et al, 2008, 2016], and the Yenisey Ridge in the western part of the Siberian craton [Nozhkin et al., 2013; Likhanov, Reverdatto, 2019]. The age of the southern Siberia magmatic event, referred to as the Irkutsk LIP [Ernst et al., 2016], support the model showing the southern Siberia connected with the northern Laurentia in the Neoproterozoic [Pisarevsky et al., 2008].

It is believed that Baltica and Laurentia were connected in the Cryogenian, although paleomagnetic data for Baltica are not available for the 800–700 Ma interval [Merdith et al., 2017]. No matches of key magmatic events between these two continents was known, so there was little evidence to support a shared history of the Baltica and Laurentia cratons in this time interval. Our new data on the U-Pb ages of the A-type granites of the Sopki Kamennyie pluton (723 ± 6 and 727 ± 7 Ma) correlate with both the Franklin magmatic event and the ages of magmatic complexes in the southern

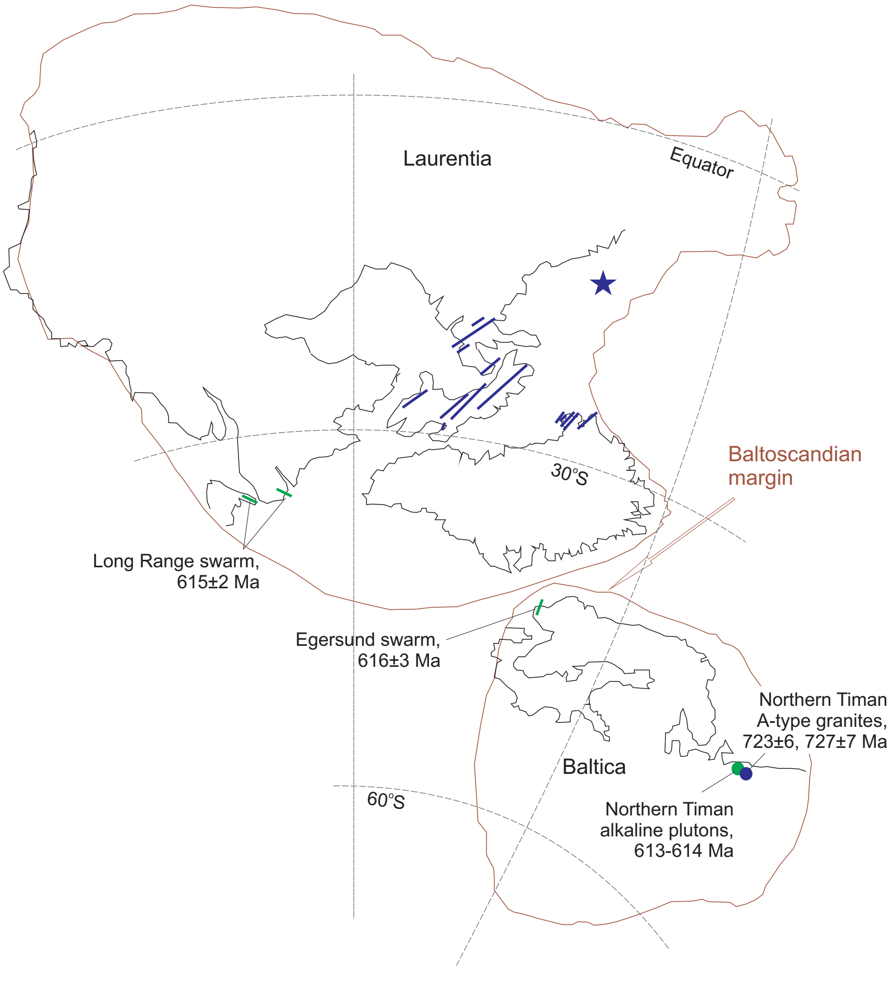


**Fig. 11.** Northern Laurentia and northern Baltica at ca. 650–600 Ma according to [Torsvik et al., 1996].
Late Cryogenian and Ediacaran magmatic dike swarms related to the Franklin LIP [Ernst, Buchan, 2001] and CIMP are shown in blue and green, respectively. Star – assumed centre of the Franklin LIP [Ernst, Buchan, 2001]. The figure is modified from [Bingen et al., 1998]. Circles – locations of granites in the Northern Timan.

**Рис. 11.** Северная Лаврентия и Северная Балтика в период около 650–600 млн по [Torsvik et al., 1996].
Рои магматических даек позднекриогенового и эдиакарского возраста, связанные с Франклинской крупной магматической провинцией [Ernst, Buchan, 2001] и CIMP, показаны синим и зеленым соответственно. Предполагаемый центр Франклинской крупной магматической провинции обозначен звездочкой [Ernst, Buchan, 2001]. Рисунок из [Bingen et al., 1998], с изменениями. Места выходов гранитов на Северном Тимане показаны кружками.

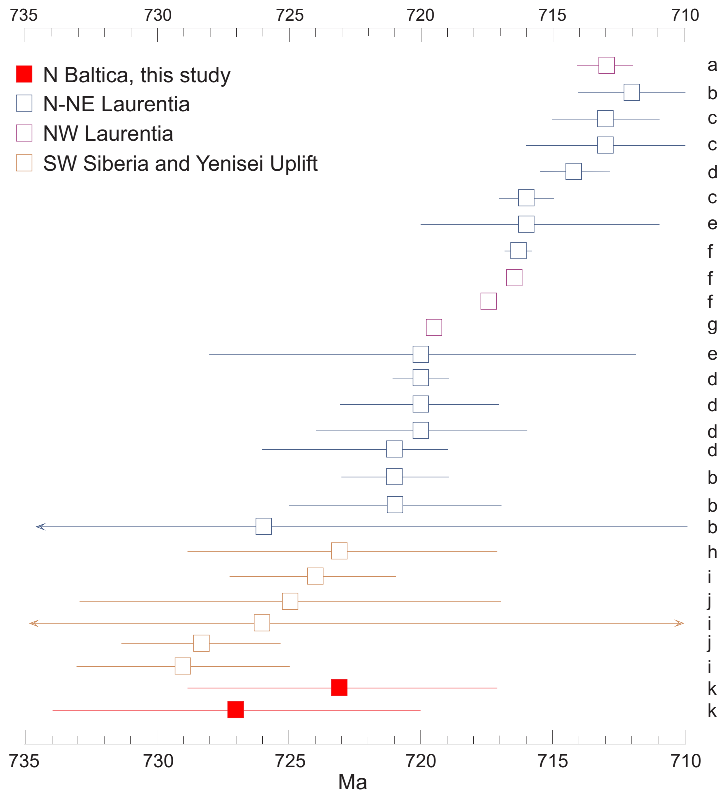


**Fig. 12.** U-Pb zircon and baddeleyite ages of magmatic rocks from the northern and north-eastern Laurentia related to the Franklin LIP, and those from similar igneous provinces of the north-western Laurentia and Siberia.
The figure is modified after [Cox et al., 2018]. Sources of U-Pb ages: a – [Cox et al., 2018], b – [Denyszyn et al., 2009b], c – [Denyszyn et al., 2009a], d – [Heaman et al., 1992] (recalculated in [Macdonald, Wordsworth, 2017]), e – [Pehrsson, Buchan, 1999], f – [Macdonald et al., 2010], g – [Cox et al., 2015], h – [Likhanov, Reverdatto, 2019], i – [Ernst et al., 2016], j – [Ariskin et al., 2013], k – this study.

**Рис. 12.** U-Pb возраст циркона и бадделеита из магматических пород Северной и Северо-Восточной Лаврентии, связанных с Франклинской крупной магматической провинцией, Северо-Западной Лаврентии и Сибири.
Рисунок из [Cox et al., 2018] с изменениями. Приведены U-Pb возрасты из: a – [Cox et al., 2018], b – [Denyszyn et al., 2009b], c – [Denyszyn et al., 2009a], d – [Heaman et al., 1992], с пересчетом [Macdonald, Wordsworth, 2017], e – [Pehrsson, Buchan, 1999], f – [Macdonald et al., 2010], g – [Cox et al., 2015], h – [Likhanov, Reverdatto, 2019], i – [Ernst et al., 2016], j – [Ariskin et al., 2013], k – данные из этой статьи.

Siberia and the Yenisei Ridge (Fig.12). We suggest that these Franklin-age A-type granites located in the northern Baltica are plume-related and give evidence of the late Cryogenian stage of Rodinia break-up.

The final rifting of the supercontinent occurred in the Ediacaran period [Torsvik et al., 1996], when the Iapetus Ocean was formed during the separation of Baltica, Laurentia, and Amazonia. The main geological evidence for the existence of this ocean are swarms of mafic dikes of the same composition and age, which intruded previously connected cratons that were subsequently separated by rifting. Correlative dike swarms (Fig. 11) are found in the Norwegian part of Baltica (Egersund dikes [Bingen et al., 1998]) and in Laurentia on the Labrador Peninsula (Long Range dikes [Kamo et al., 1989]). Their U-Pb baddeleyite ages are 616 ± 3 and 615 ± 2 Ma, respectively. It is believed that these dikes are associated with the formation of so-called Central Iapetus Magmatic Province – CIMP [Ernst, Bell, 2010; Youbi et al., 2011], which existed up to ~600 Ma. Paleomagnetic data confirm the beginning of rifting after ~615 Ma, showing that until this time, the above-mentioned dyke swarms were located in mid-latitudes and with magnetic poles that overlap [Merdith et al., 2017; Walderhaug et al., 2007]. In the late Ediacaran, low to medium latitudes are reconstructed for Baltica, and a counter-clockwise rotation by 90° is proposed [Lubnina et al., 2014; Meert, 2014], suggesting the opening of the Iapetus Ocean from about 600 Ma forward [Meert, 2014]. The interval of 620-600 Ma is the most likely time for the occurrence of magmatism associated with CIMP [Weber et al., 2019]. The igneous rocks of the Ediacaran age from the Bolshoy Kameshek and Cape Bolshoy Rumyanichny plutons might thus be related to this stage of rift-related magmatism. The position of the studied granite bodies within the Timan Ridge, which belonged to the Late Riphean passive margin of Baltica, together with the association of granites with syenites and alkaline gabbroic rocks, suggests an anorogenic nature and a possible connection with plume magmatism.

It is highly likely that the zircons from the granites of the Cape Bolshoy Rumyanichny pluton, which are dated to the

Mesoproterozoic (1146 Ma and 1120 Ma), were inherited from the basement or country rocks. Noteworthy is the fact that these ages correspond to the youngest ages of detrital zircons from the host Upper Riphean terrigenous rocks of the Barmin Group [Andreichev et al., 2014, 2017, 2018].

## 7. ACKNOWLEDGEMENTS

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## 8. REFERENCES

Akimova G.N., 1980. Geochronology of Precambrian of Timan. Soviet geology (12), 71–85 (in Russian) [Акимова Г.Н. Геохронология докембрия Тимана // Советская геология. 1980. № 12. С. 71–85].

Andreichev V.L., 1998. Isotopic Geochronology of Northern Timan Intrusive Magmatism. Publishing House of the Ural Branch of RAS, Ekaterinburg, 90 p. (in Russian) [Андреичев В.Л. Изотопная геохронология интрузивного магматизма Северного Тимана. Екатеринбург: УрО РАН, 1998. 90 с.].

Andreichev V.L., Larionov A.N., 2000. $^{207}Pb/^{206}Pb$ Dating of Zircon Single Crystals from Igneous Rocks of the Northern Timan. In: Isotope Dating of Geological Processes: New Methods and Results. Abstracts of the I Russian Conference on Isotopic Geochronology (Moscow, November 15–17, 2000). GEOS Publishing House, Moscow, p. 26–28 (in Russian) [Андреичев В.Л., Ларионов А.Н. $^{207}Pb/^{206}Pb$ датирование единичных кристаллов циркона из магматических пород Северного Тимана // Изотопное датирование геологических процессов: новые методы и результаты: Тезисы докладов I Российской конференции по изотопной геохронологии (15–17 ноября 2000 г. Москва). Москва: ГЕОС, 2000. С. 26–28].

Andreichev V.L., Soboleva A.A., Gehrels G., 2014. U-Pb Dating and Provenance of Detrital Zircons from the Upper Precambrian Deposits of North Timan. Stratigraphy and Geological Correlation 22 (2), 147–159. https://doi.org/10.1134/s0869593814020026.

Andreichev V.L., Soboleva A.A., Hourigan J.K., 2017. Results of U-Pb (LA-ICP-MS) Dating of Detrital Zircons from Terrigenous Sediments of the Upper Part of the Precambrian Basement of Northern Timan. Bulletin of Moscow Society of Naturalists. Geological Series 92 (1), 10–20 (in Russian) [Андреичев В.Л., Соболева А.А., Хоуриган Дж.К. Результаты U–Pb (LA-ICP-MS) датирования детритовых цирконов из терригенных отложений верхней части докембрийского фундамента Северного Тимана // Бюллетень МОИП. Отдел геологический. 2017. Т. 92. № 1. С. 10–20].

Andreichev V.L., Soboleva A.A., Khubanov V.B., Sobolev I.D., 2018. U-Pb (LA-ICP-MS) Age of Detrital Zircons from Meta-Sedimentary Rocks of the Upper Precambrian Section of Northern Timan. Bulletin of Moscow Society of Naturalists. Geological Series 93 (2), 14–26 (in Russian) [Андреичев В.Л., Соболева А.А., Хубанов В.Б., Соболев И.Д. U-Pb (LA-ICP-MS) возраст детритовых цирконов из метаосадочных пород основания верхнедокембрийского разреза Северного Тимана // Бюллетень МОИП. Отдел геологический. 2018. Т. 93. № 2. С. 14–26].

Ariskin A.A., Kostitsyn Y.A., Konnikov E.G., Danyushevsky L.V., Meffre S., Nikolaev G.S., McNeill A., Kislov E.V., Orsoev D.A., 2013. Geochronology of the Dovyren Intrusive Complex, Northwestern Baikal Area, Russia, in the Neoproterozoic. Geochemistry International 51 (11), 859–875. https://doi.org/10.1134/S0016702913110025.

Belyakova L.T., Bogatsky V.I., Danilevsky S.A., Dovzhikova E.G., Laskin V.M., 1997. Geodynamic Position of Granitoids of the Timan-Pechora Plate and its Influence on the Location of Hydrocarbon Deposits. In: Granitoid Volcano-Plutonic Associations: Petrology, Geodynamics, Metallogeny. Proceedings of the All-Russian Meeting (May 21–23, 1997, Syktyvkar). Geoprint Publishing House, Syktyvkar, p. 86–87 (in Russian) [Белякова Л.Т., Богацкий В.И., Данилевский С.А., Довжикова Е.Г., Ласкин В.М. Геодинамическая позиция гранитоидов Тимано-Печорской плиты и ее влияние на размещение залежей углеводородов // Гранитоидные вулкано-плутонические ассоциации: петрология, геодинамика, металлогения. Информационные материалы Всероссийского совещания (21–23 мая 1997 г., Сыктывкар). Сыктывкар: Геопринт, 1997. С. 86–87].

Bingen B., Demaiffe D., van Breemen O., 1998. The 616 Ma Old Egersund Basaltic Dike Swarm, SW Norway, and Late Neoproterozoic Opening of the Iapetus Ocean. Journal of Geology 106 (5), 565–574. https://doi.org/10.1086/516042.

Bogdanova S.V., Pisarevsky S.A., Li Z.X., 2009. Assembly and Breakup of Rodinia (Some Results of IGCP Project 440). Stratigraphy and Geological Correlation 17 (3), 259–274. https://doi.org/10.1134/S0869593809030022.

Buchan K.L., Ernst R.E., 2013. Diabase Dyke Swarms of Nunavut, Northwest Territories, and Yukon, Canada. Geological Survey of Canada, Open File 7464, 24 p. https://doi.org/10.4095/293149.

Buchan K.L., Ernst R.E., Bleeker W., Davies W., Villeneuve M., van Breemen O., Hamilton M., Söderlund U., 2010. Proterozoic Magmatic Events of the Slave Craton, Wopmay Orogen and Environs. Geological Survey of Canada, Open File 5985, 26 p.

Coble M.A., Vazquez J., Barth A.P., Wooden J., Burns D., Kylander-Clark A., Jackson S., Vennari C.E., 2018. Trace Element Characterization of MAD-559 Zircon Reference Material for Ion Microprobe Analysis. Geostandards and Geoanalytical Research 42 (4), 481–497. https://doi.org/10.1111/ggr.12238.

Cox G.M., Halverson G.P., Denyszyn S., Foden J., Macdonald F., 2018. Cryogenian Magmatism along the North-Western Margin of Laurentia: Plume or Rift? Precambrian Research 319, 144–157. https://doi.org/10.1016/j.precamres.2017.09.025.

Cox G.M., Strauss J.V., Halverson G.P., Schmitz M.D., McClelland W.C., Stevenson R.S., Macdonald F.A., 2015. Kikiktat

Volcanics of Arctic Alaska – Melting of Harzburgitic Mantle Associated with the Franklin Large Igneous Province. Lithosphere 7 (3), 275–295. https://doi.org/10.1130/L435.1.

Denyszyn S.W., Davis D.W., Halls H.C., 2009a. Paleomagnetism and U-Pb Geochronology of the Clarence Head Dykes, Arctic Canada: Orthogonal Emplacement of Mafic Dykes in a Large Igneous Province. Canadian Journal of Earth Sciences 46 (3), 155–167. https://doi.org/10.1139/E09-011.

Denyszyn S.W., Halls H.C., Davis D.W., Evans D.A.D., 2009b. Paleomagnetism and UPb Geochronology of Franklin Dykes in High Arctic Canada and Greenland: a Revised Age and Paleomagnetic Pole Constraining Block Rotationsin the Nares Strait Region. Canadian Journal of Earth Sciences 46 (9), 689–705. https://doi.org/10.1139/E09-042.

Ernst R.E., Bell K., 2010. Large Igneous Provinces (LIPs) and Carbonatites. Mineralogy and Petrology 98 (1–4), 55–76. https://doi.org/10.1007/s00710-009-0074-1.

Ernst R.E., Buchan K.L., 2001. Large Mafic Magmatic Events through Time and Links to Mantle Plume Heads. In: R.E. Ernst, K.L. Buchan (Eds), Mantle Plumes: Their Identification through Time. Geological Society of America Special Paper, Vol. 352, p. 483–575. https://doi.org/10.1130/0-8137-2352-3.483.

Ernst R.E., Hamilton M.A., Soderlund U., Hanes J.A., Gladkochub D.P., Okrugin A.V., Kolotilina T., Mekhonoshin A.S., Bleeker W., LeCheminant A.N., Buchan K.L., Chamberlain K.R., Didenko A.N., 2016. Long-Lived Connection between Southern Siberia and Northern Laurentia in the Proterozoic. Nature Geoscience 9 (6), 464–469. https://doi.org/10.1038/ngeo2700.

Ernst R.E., Wingate M.T.D., Buchan K.L., Li Z.X., 2008. Global Record of 1600–700 Ma Large Igneous Provinces (LIPs): Implications for the Reconstruction of the Proposed Nuna (Columbia) and Rodinia Supercontinents. Precambrian Research 160 (1–2), 159–178. https://doi.org/10.1016/j.precamres.2007.04.019.

Fahrig W.F., 1987. The Tectonic Setting of Continental Mafic Dike Swarms: Failed Arm and Early Passive Margin. In: H.C. Hall, W.F. Fahrig (Eds), Mafic Dyke Swarms. Geological Association of Canada Special Paper, Vol. 34, p. 331–348.

Gee D.G., Beliakova L., Pease V., Larionov A., Dovzhikova L., 1998 (erschienen 2000). New, Single Zircon (Pb-Evaporation) Ages from Vendian Intrusions in the Basement beneath the Pechora Basin, Northeastern Baltica. Polarforschung 68, 161–170.

Gee D.G., Pease V., 1999. Neoproterozoic and Palaeozoic Sutures in the Eurasian High Arctic. In: Timan-Pechora-Polar Urals Tectonic Evolution. Abstracts of Timpebar Workshop. Geoprint Publishing House, Syktyvkar, p. 21–22.

Gladkochub D.P., Pisarevsky S.A., Donskaya T.V., Ernst R.E., Wingate M.T., Söderlund U., Mazukabzov A.M., Sklyarov E.V., Hamilton M.A., Hanes J.A., 2010. Proterozoic Mafic Magmatism in Siberian Craton: An Overview and Implications for Paleocontinental Reconstruction. Precambrian Research 183 (3), 660–668. https://doi.org/10.1016/j.precamres.2010.02.023.

Heaman L.M., LeCheminant A.N., Rainbird R.H. 1992. Nature and Timing of Franklin Igneous Events, Canada: Implications for a Late Proterozoic Mantle Plume and the Break-Up of Laurentia. Earth and Planetary Science Letters 109 (1–2), 117–131. https://doi.org/10.1016/0012-821X(92)90078-A.

Ireland T.R., 1995. Ion Microprobe Mass-Spectrometry: Techniques and Applications in Cosmochemistry, and Geochronology. In: M. Hyman, M. Rowe (Eds), Advances in Analytical Geochemistry, Vol. 2. JAI Press, Bingley, UK, p. 1–118.

Ivensen Yu.P., 1964. Magmatism of Timan and Kanin Peninsula. Nauka Publishing House, Moscow, Leningrad, 126 p. (in Russian) [Ивенсен Ю.П. Магматизм Тимана и полуострова Канин. М.–Л.: Наука, 1964. 126 с.].

Kamo S.L., Gower C.F., Krogh T.E., 1989. Birthdate for the Iapetus Ocean? A Precise U-Pb Zircon and Baddeleyite Age for the Long Range Dikes, Southeast Labrador. Geology 17 (7), 602–605. https://doi.org/10.1130/0091-7613(1989)017<0602:BFTLOA>2.3.CO;2.

Kostyukhin M.N., Stepanenko V.I., 1987. Baikalian Magmatism in the Kanin-Timan Region. Nauka Publishing House, Leningrad, 232 p. (in Russian) [Костюхин М.Н., Степаненко В.И. Байкальский магматизм Канино-Тиманского региона. Л.: Наука, 1987. 232 с.].

Larionov A.N., Andreichev V.L., Gee D.G., 2004. The Vendian Alkaline Igneous Suite of Northern Timan: Ion Microprobe U–Pb Zircon Ages of Gabbros and Syenite. In: D.G. Gee, V. Pease (Eds), The Neoproterozoic Timanide Orogen of Eastern Baltica. Geological Society, London, Memoirs, Vol. 30, p. 69–74. https://doi.org/10.1144/gsl.mem.2004.030.01.07.

Li Z.X., Bogdanova S.V., Collins A.S., Davidson A., De Waele B., Ernst R.E., Fitzsimons I.C.W., Fuck R.A., Gladkochub D.P., Jacobs J., Karlstrom K.E., Lu S., Natapov L.M., Pease V., Pisarevsky S.A., Thrane K., Vernikovsky V., 2008. Assembly, Configuration, and Break-Up History of Rodinia: A synthesis. Precambrian Research 160 (1–2), 179–210. https://doi.org/10.1016/j.precamres.2007.04.021.

Likhanov I.I., Reverdatto V.V., 2019. The First U-Pb (SHRIMP II) Evidence of the Franklin Tectonic Event at the Western Margin of the Siberian Craton. Doklady Earth Sciences 486 (2), 605–608. https://doi.org/10.1134/S1028334X19060187.

Lubnina N.V., Pisarevsky S.A., Puchkov V.N., Kozlov V.I., Sergeeva N.D., 2014. New Paleomagnetic Data from Late Neoproterozoic Sedimentary Successions in Southern Urals, Russia: Implications for the Late Neoproterozoic Paleogeography of the Iapetan Realm. International Journal of Earth Sciences 103 (5), 1317–1334. https://doi.org/10.1007/s00531-014-1013-x.

Ludwig K.R., 2009. SQUID 2: A User's Manual. Rev. 12 April, 2009. Berkeley Geochronology Centre Special Publication, No. 5, 110 p.

Ludwig K.R., 2012. Isoplot 3.75, a Geochronological Toolkit for Excel. Berkeley Geochronology Center Special Publication, No. 5, 75 p.

Macdonald F.A., Strauss J.V., Cohen P.A., Johnston D.T., Schrag D.P., 2010. Calibrating the Cryogenian. Science 327 (5970), 1241–1243. https://doi.org/10.1126/science.1183325.

Macdonald F.A., Wordsworth R., 2017. Initiation of Snowball Earth with Volcanic Sulfuraerosol Emissions. Geophysical Research Letters 44 (4), 1938–1946. https://doi.org/10.1002/2016GL072335.

Mal'kov B.A., 1966. New Data on the Age of Pre-Silurian Intrusive Complexes of Timan and Kanin. Doklady AN SSSR 170 (3), 669–672 (in Russian) [Мальков Б.А. Новые данные о возрасте досилурийских интрузивных комплексов Тимана и Канина // Доклады АН СССР. 1966. Т. 170. № 3. С. 669–672].

Mal'kov B.A., 1972. Petrology of the Dyke Series of Alkaline Gabbroic Rocks of Northern Timan. Nauka Publishing House, Leningrad, 128 p. (in Russian) [Мальков Б.А. Петрология дайковой серии щелочных габброидов Северного Тимана. Л.: Наука, 1972. 128 с.].

Meert J.G., 2014. Ediacaran–Early Ordovician Paleomagnetism of Baltica: A Review. Gondwana Research 25 (1), 159–169. https://doi.org/10.1016/j.gr.2013.02.003.

Merdith A.S., Collins A.S., Williams S.E., Pisarevsky S., Foden J.D., Archibald D.B., Blades M.L., Alessio B.L., Armistead S., Plavsa D., Clark C., Müller R.D., 2017. A Full-Plate Global Reconstruction of the Neoproterozoic. Gondwana Research 50, 84–134. https://doi.org/10.1016/j.gr.2017.04.001.

Nozhkin A.D., Kachevskii L.K., Dmitrieva N.V., 2013. The Late Neoproterozoic Rift-Related Metarhyolite-Basalt Association of the Glushikha Trough (Yenisei Ridge): Petrogeochemical Composition, Age, and Formation Conditions. Russian Geology and Geophysics 54 (1), 44–54. https://doi.org/10.1016/j.rgg.2012.12.004.

Olovyanishnikov V.G., 2004. Geological Evolution of the Kanin Peninsula and Northern Timan. Geoprint Publishing House, Syktyvkar, 80 p. (in Russian) [Оловянишников В.Г. Геологическое развитие полуострова Канин и Северного Тимана. Сыктывкар: Геопринт, 2004. 80 с.].

Pearce J.A., Harris N.B.W., Tindle A.G., 1984. Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. Journal of Petrology 25 (4), 956–983. https://doi.org/10.1093/petrology/25.4.956.

Pehrsson S.J., Buchan K.L., 1999. Borden Dykes of Baffin Island, Northwest Territories: A Franklin U-Pb Baddeleyite Age and a Paleomagnetic Reinterpretation. Canadian Journal of Earth Sciences 36 (1), 65–73. https://doi.org/10.1139/e98-091.

Popov V.S., Bogatikov O.A. (Eds), 2001. Petrography and Petrology of Magmatic, Metamorphic and Metasomatic Rocks. Logos Publishing House, Moscow, 768 p. (in Russian) [Петрография и петрология магматических, метаморфических и метасоматических горных пород / Ред. В.С. Попов, О.А. Богатиков. М.: Логос, 2001. 768 с.].

Pisarevsky S.A., Natapov L.M., 2003. Siberia and Rodinia. Tectonophysics 375 (1–4), 221–245. https://doi.org/10.1016/j.tecto.2003.06.001.

Pisarevsky S.A., Natapov L.M., Donskaya T.V., Gladkochub D.P., Vernikovsky V.A., 2008. Proterozoic Siberia: a Promontory of Rodinia. Precambrian Research 160 (1–2), 66–76. https://doi.org/10.1016/j.precamres.2007.04.016.

Polyakov G.V.,Tolstykh N.D., Mekhonoshin A.S., Izokh A.E., Podlipskii M.Yu., Orsoev D.A., Kolotilina T.B., 2013. Ultramafic-Mafic Igneous Complexes of the Precambrian East Siberian Metallogenic Province (Southern Framing of the Siberian Craton): Age, Composition, Origin, and Ore Potential. Russian Geology and Geophysics 54 (11), 1319–1331. https://doi.org/10.1016/j.rgg.2013.10.008.

Ronkin Yu.L., Lepikhina O.P., Golik S.V., Zhuravlev D.Z., Popova O.Yu., 2005. Multielement Analysis of Geological Samples by Acid Decomposition and Termination on HR ICP-MS Element2. Information Digest of Scientific Works of the IGG UB RAS. Yearbook 2004, IGG UB RAS, Yekaterinburg, 423–433 (in Russian) [Ронкин Ю.Л., Лепихина О.П., Голик С.В., Журавлев Д.З., Попова О.Ю. Мультиэлементный анализ геологических образцов кислотным разложением и окончанием на HRICP-MS Element2. Информационный сборник научных трудов ИГГ УрО РАН. Ежегодник-2004. Екатеринбург: ИГГ УрО РАН, 2005. С. 423–433].

Stratigraphic Code of Russia. Third Edition, 2006. VSEGEI Publishing House, Saint Petersburg, 96 p. (in Russian) [Стратиграфический кодекс России. Издание третье. СПб.: Изд-во ВСЕГЕИ, 2006. 96 с.].

Torsvik T.H., Smethurst M.A., Meert J.G., Van der Voo R., McKerrow W.S., Brasie M.D., Sturt B.A., Walderhaug H.J., 1996. Continental Break–Up and Collision in the Neoproterozoic and Palaeozoic – A tale of Baltica and Laurentia. Earth-Science Reviews 40 (3–4), 229–258. https://doi.org/10.1016/0012-8252(96)00008-6.

Unified Methods for the Analysis of Silicate Rocks Using Complexonometry, 1979. All-Union Research Institute of Mineral Raw Materials, Moscow, 33 p. (in Russian) [Унифицированные методы анализа силикатных горных пород с применением комплексонометрии. М.: Всесоюзный научно-исследовательский институт минерального сырья, 1979. 33 с.].

Walderhaug H.J., Torsvik T.H., Halvorsen E., 2007. The Egersund dykes (SW Norway): A Robust Early Ediacaran (Vendian) Palaeomagnetic Pole from Baltica. Geophysical Journal International 168 (3), 935–948. https://doi.org/10.1111/j.1365-246X.2006.03265.x.

Weber B., Schmitt A. K., Cisneros de León A., González-Guzmán R., 2019. Coeval Early Ediacaran Breakup of Amazonia, Baltica, and Laurentia: Evidence from Micro-Baddeleyite Dating of Dykes from the Novillo Canyon, Mexico. Geophysical Research Letters 46 (4), 2003–2011. https://doi.org/10.1029/2018gl079976.

Whalen J.B., Currie K.L., Chappell B.W., 1987. A-Type Granites: Geochemical Characteristics, Discrimination and Petrogenesis. Contributions to Mineralogy and Petrology 95 (4), 407–419. https://doi.org/10.1007/bf00402202.

Youbi N., Ernst R., Söderlund U., Soulaimani A., Doblas M., Bertrand H., Marzoli A., El Hachimi H., Bensalah M. K., Hafid A., Ikenne M., Kouyaté D, El Bahat A., Mohamed B.A., Madeira J., Mata J., Martins L., Bellieni G., Vérati C., Mahmoudi A., 2011. The Central Iapetus Magmatic Province (CIMP) Large Igneous Province. Distribution, Nature, Origin, and Environmental Impact. AAPG Search and Discovery, Article #90137. Available from: http://www.searchanddiscovery.com/pdfz/abstracts/pdf/2011/european_region/abstracts/ndx_Youbi2.pdf.html?q=%252BtextStrip%253Acimp.

Zhang Li.X., Wang Q., Zhu D.C., Li S.M., Zhao Z.D., Zhang L.L., Chen Y., Liu S.A., Zheng Y.C., Wang R., Liao Z.-L., 2019. Generation of Leucogranites via Fractional Crystallization: A Case from the Late Triassic Luoza Batholith in the Lhasa Terrane, Southern Tibet. Gondwana Research 66, 63–76. https://doi.org/10.1016/j.gr.2018.08.008.

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