

GRANITES OF THE NORTHERN TIMAN – PROBABLE INDICATORS OF NEOPROTEROZOIC STAGES OF RODINIA BREAKUP**V.L. Andreichev¹, A.A. Soboleva¹, O.V. Udoratina¹, Yu.L. Ronkin², M.A. Coble³, E.L. Miller³**¹ N.P. Yushkin Institute of Geology of Komi Science Center, Ural Branch of RAS, Syktyvkar, Russia² A.N. Zavaritsky Institute of Geology and Geochemistry, Ural Branch of RAS, Yekaterinburg, Russia³ Stanford University, Stanford, California, USA

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 разновозрастны 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 [Iverson, 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 (Llandoveryan) 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, $I_{Sr} = 0.7078 \pm 0.0006$, MSWD = 0.9) – Bolshoy Kameshek pluton; 591 ± 7 Ma (n = 4,

$I_{Sr} = 0.7225 \pm 0.0017$, MSWD = 1.2) – Sopki Kamennyie pluton; and 587 ± 4 Ma (n = 6, $I_{Sr} = 0.72027 \pm 0.00021$, MSWD = 1.2) – Cape Bolshoy Rummyanichny 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 ²⁰⁷Pb content in relatively young (<1 Ga) zircons, the ²⁰⁶Pb / ²³⁸U 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

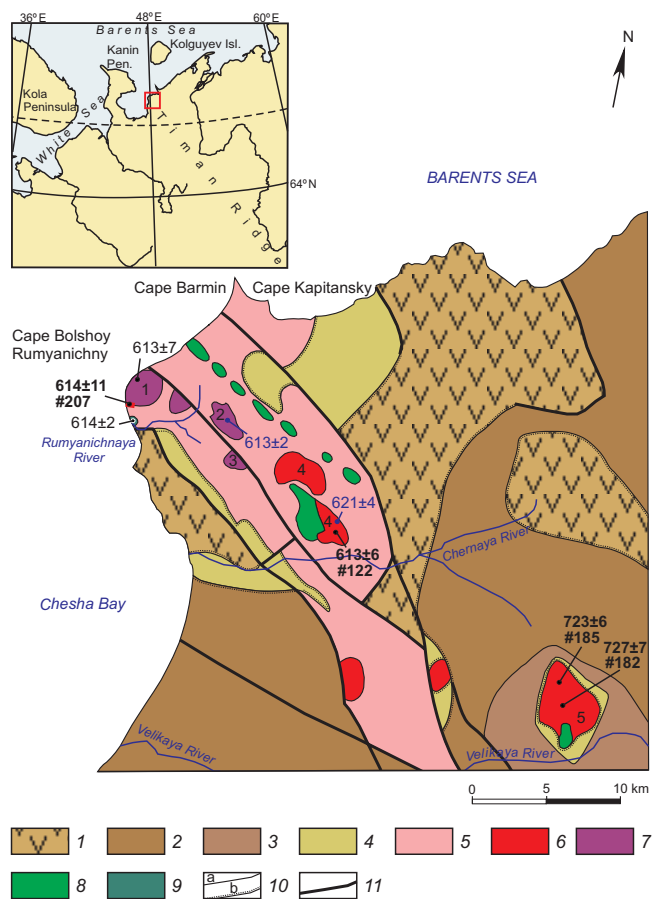


Fig. 1. Schematic geological structure of the Northern Timan [Olovyanishnikov, 2004].

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 – within units with conformable bedding, and boundaries of intrusive bodies, b – unconformity; 11 – principal faults. Numbers refer to plutons: 1 – Cape Bolshoy Rummyanichny, 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, кварцито-песчаники барминской серии; 6 – граниты; 7 – сиениты; 8 – метагаббро-долериты и долериты; 9 – оливин-керсутитовые габбро; 10 – геологические границы: согласные и границы интрузивных тел (а), несогласные (b); 11 – главные разломы. Цифрами обозначены массивы: 1 – мыса Большой Румянничный, 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 Rummyanichny syenite pluton.

The Bolshoy Kameshek pluton is a stockwork-shaped body exposed across an area of about 7.5 km². 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, chalcopryrite, and leucoxene aggregate. In the zones of cataclasis and mylonitization, granites contain appreciable volumes of muscovite and chlorite.

The exposed area of the Sopki Kamennyye pluton is about 15 km². 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 north-east 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 Rummyanichny 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 ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O 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 Rummyanichny	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 Kamennyye	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 SiO₂ content from 69.19–77.04 wt. %, the Na₂O+K₂O 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 SiO₂ varying from 74.85–77.96 wt. %, the Na₂O+K₂O 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 Rummyanichny 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 Rummyanichny				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 SiO₂ content ranging from 72.74–76.05 wt. % and the Na₂O+K₂O sum from 9.18–10.16 wt. %, except one sample with Na₂O+K₂O=6.7 wt. %. Their agpaite index is extremely high in all but one sample – 0.95–1.02. Considering the Na₂O/K₂O 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

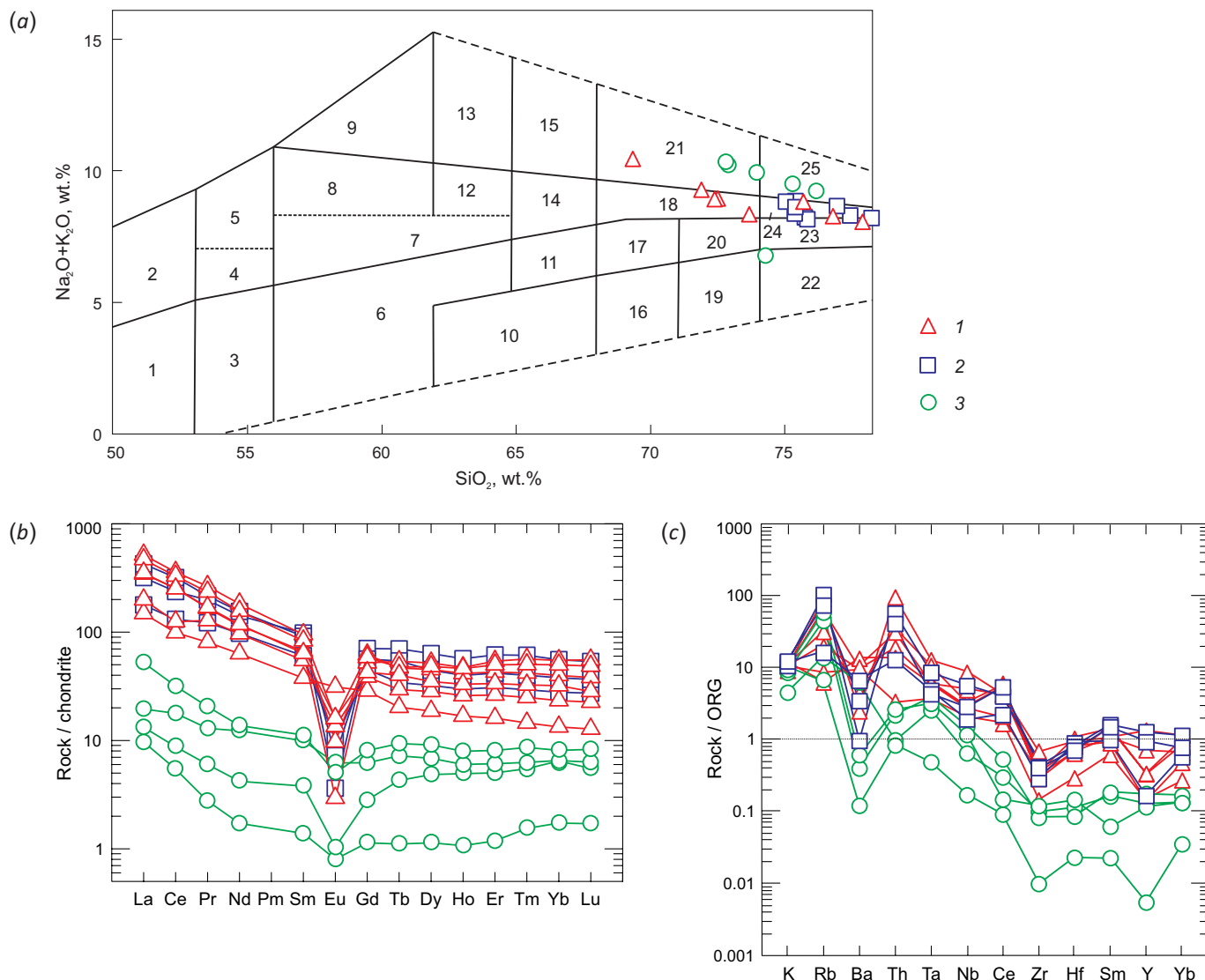


Fig. 2. Classification diagrams for granitoids of the Northern Timan. (a) – (Na₂O+K₂O)–SiO₂ [Popov, Bogatikov, 2001], (b) – chondrite-normalized REE chart, (c) – spider-diagram for trace elements normalized to ORG.

Numbers refer to plutons: 1 – Bolshoy Kameshek, 2 – Sopki Kamennyie, 3 – Cape Bolshoy Rumyanichny. Numbers refer to fields: 1 – gabbro-norite, 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 (Na₂O+K₂O)–SiO₂, по [Popov, Bogatikov, 2001] (a), хондрит-нормализованные спектры РЗЭ (b), спайдер-диаграмма распределения элементов-примесей, нормированных на ОРГ (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 – монзогаббро; 3 – диориты, 4 – монцодиориты; 5 – монзониты; 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 – трондjemиты; 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 Rummyanichny 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, bi-pyramidal-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 $^{206}\text{Pb}/^{238}\text{U}$ 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 Rummyanichny 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 $^{206}\text{Pb}/^{238}\text{U}$ ages for 9 grains is 309 to 1146 Ma. We interpret

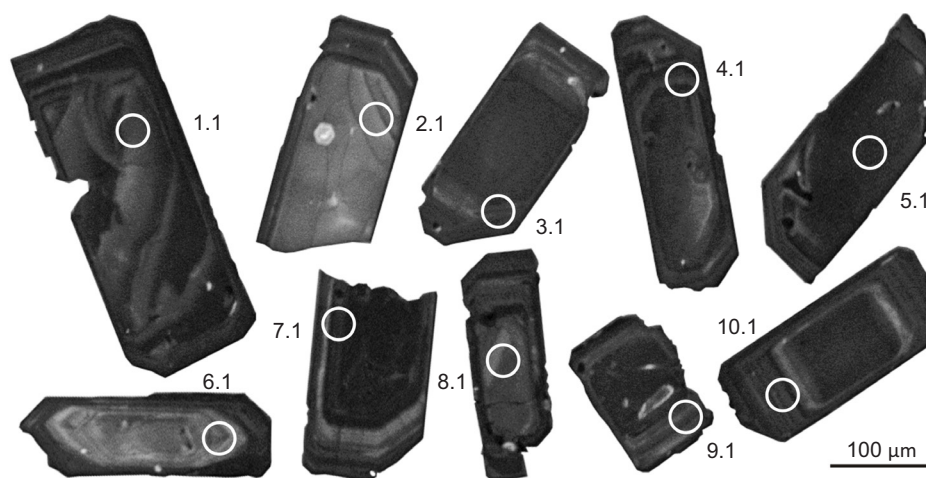


Fig. 3. Cathodoluminescent images of zircon grains from granite of the Bolshoy Kameshek pluton, sample 122. The figure shows grain numbers and analyzed spots.

Рис. 3. Катодолуминесцентное 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 ± 2.3	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). ²⁰⁶Pb_c and ²⁰⁶Pb* – common and radiogenic lead; b.d. – below the limit of determination (≤0.04). Corrected Ratios (²⁰⁶Pb/²³⁸U, ²⁰⁷Pb/²³⁵U, and ²⁰⁷Pb/²⁰⁶Pb) and ²⁰⁶Pb* content are corrected for ²⁰⁴Pb_c. CC is the error correlation coefficient of radiogenic ²⁰⁶Pb/²³⁸U versus ²⁰⁷Pb/²³⁵U. D is discordance: D = 100 × [age (²⁰⁷Pb/²⁰⁶Pb)/age (²⁰⁶Pb/²³⁸U) – 1].

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

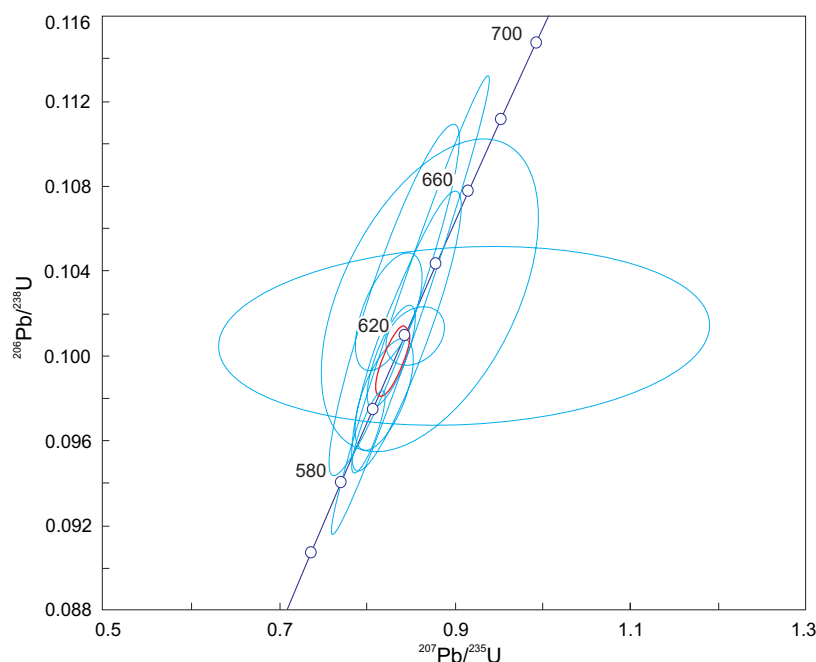


Fig. 4. Concordia diagram for zircons from granite of the Bolshoy Kameshek pluton, sample 122. In this and subsequent diagrams, the analysis values are the centers of the error ellipses (2σ).

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).

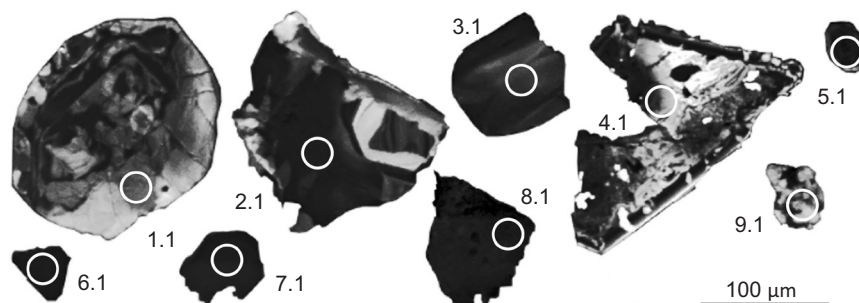


Fig. 5. Cathodoluminescent images of zircon grains from granite of the Cape Bolshoy Rumyanichny pluton, sample 207. The figure shows grain numbers and analyzed spots.

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

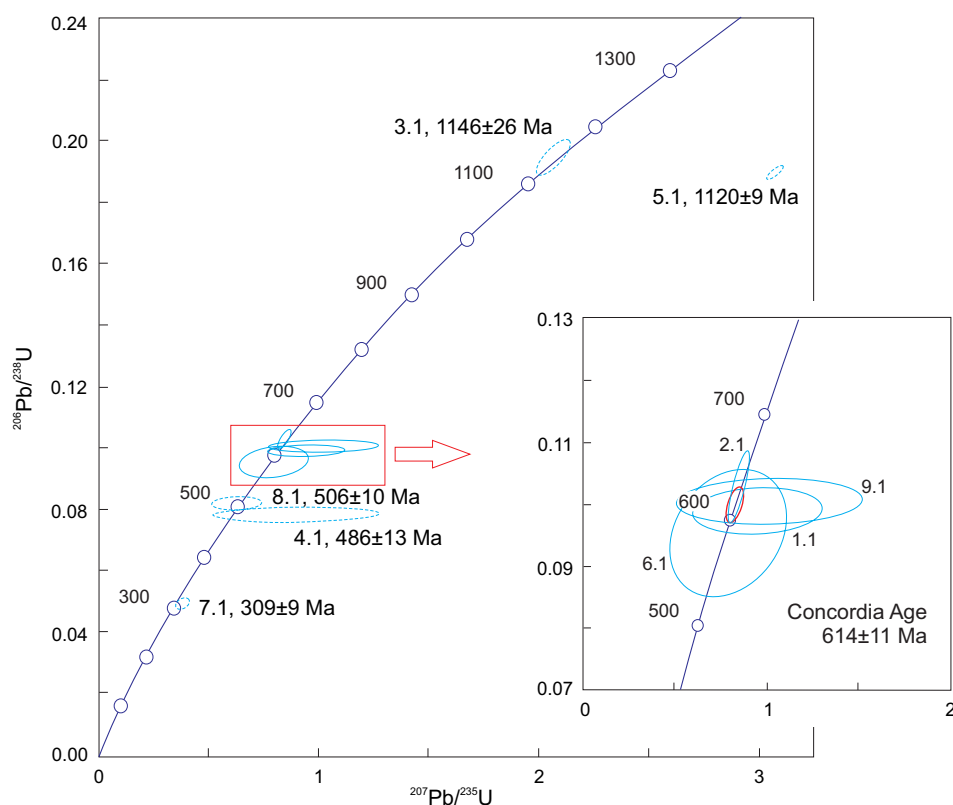


Fig. 6. Concordia diagram for zircons from granite of the Cape Bolshoy Rummyanichny pluton, sample 207. The calculated concordant age of 614 ± 11 Ma (2σ , $n = 4$, $\text{MSWD} = 0.17$) is shown by the red ellipse in the insert. The error ellipses of analyses that were excluded from the mean age calculations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

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

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 $^{206}\text{Pb}/^{238}\text{U}$ 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 $^{206}\text{Pb}/^{238}\text{U}$ 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

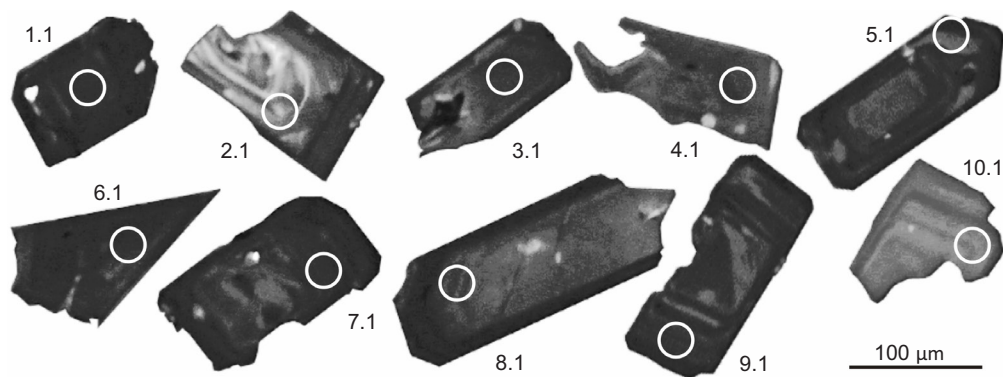


Fig. 7. Cathodoluminescent images of zircon grains from granite of the Sopki Kamennyie pluton, sample 185. The figure shows grain numbers and analyzed spots.

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

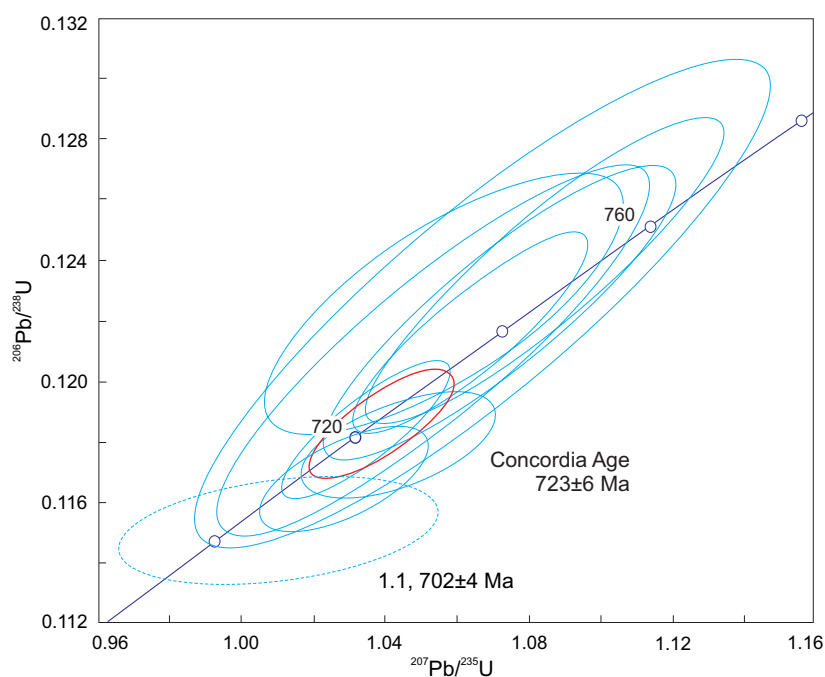


Fig. 8. Concordia diagram for zircons from granite of the Sopki Kamennyie pluton, sample 185.

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).

Расчитанный 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 Rummyannichny (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 Rummyannichny pluton are 613 ± 7 Ma and 617 ± 6 Ma, respectively. The age of zircons from olivine-kerutite gabbros exposed near the mouth of the Rummyannichnaya River is 614 ± 2 Ma [Larionov et al., 2004]. The

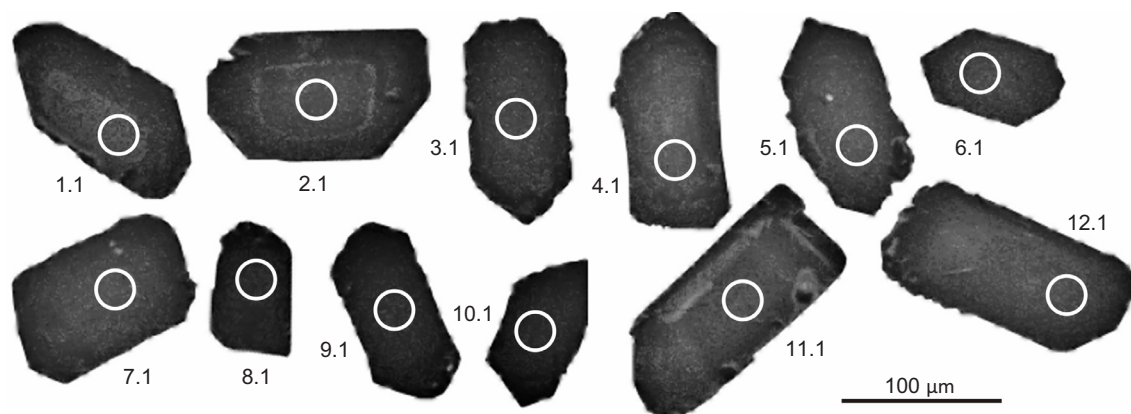


Fig. 9. Cathodoluminescent images of zircon grains from granite of the Sopki Kamennyie pluton, sample 182. The figure shows grain numbers and analyzed spots.

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

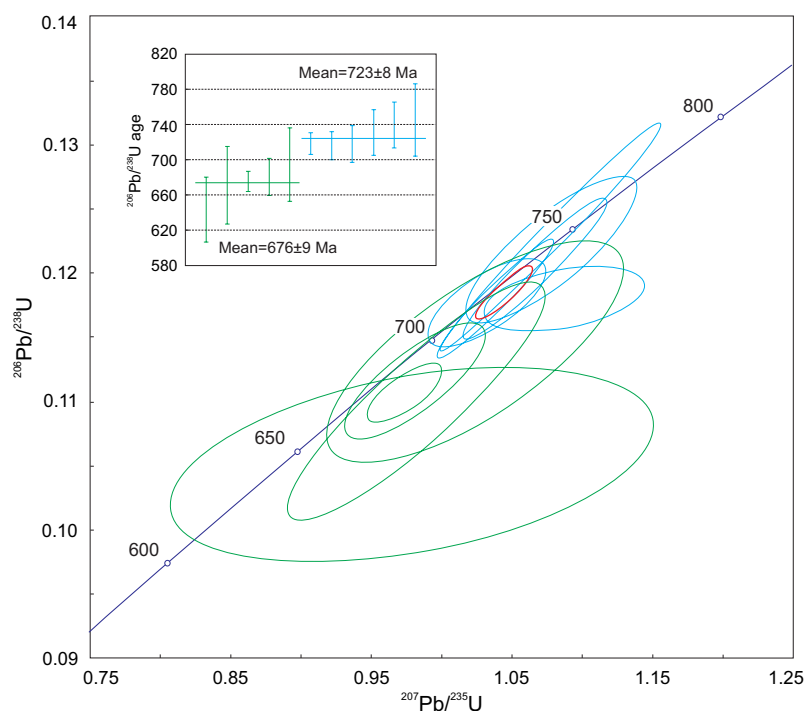


Fig. 10. Concordia diagram and weighted mean age of zircons from granite of the Sopki Kamennyie pluton, sample 182. Error ellipses and bars are shown at 2σ . The calculated concordant age of 727 ± 7 Ma (2σ , $n = 6$, $MSWD = 3.9$) is shown by the red ellipse. Error ellipses and bars of analyses from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

$^{207}\text{Pb} / ^{206}\text{Pb}$ age of single zircon grains from syenites of the Krayny Kameshek pluton is 613 ± 2 Ma [Andreichev, Lariov, 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 Mkm² 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

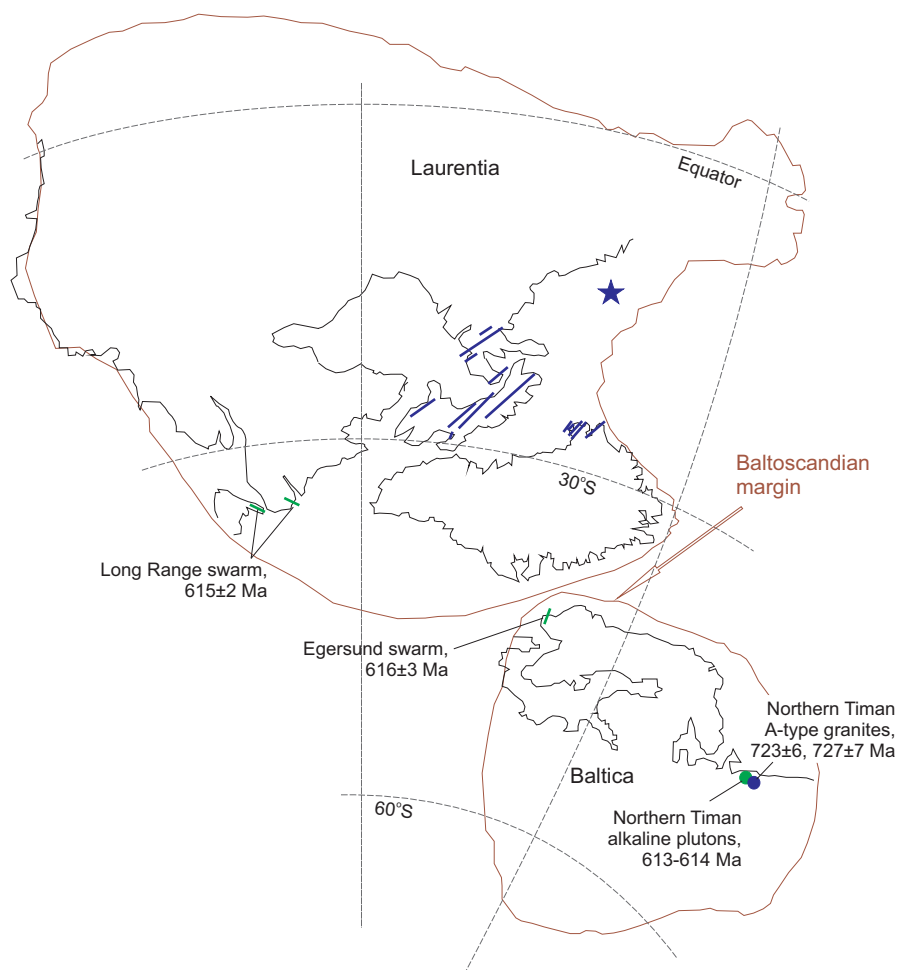


Fig. 11. Northern Laurentia and northern Baltica at ca. 650–600 Ma according to [Torsvik et al., 1996]. Late Cryogenian and Ediacaran magmatic dike swarms related to the Franklin LIP [Ernst, Buchan, 2001] and CIMP are shown in blue and green, respectively. Star – assumed centre of the Franklin LIP [Ernst, 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 СИМР, 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.

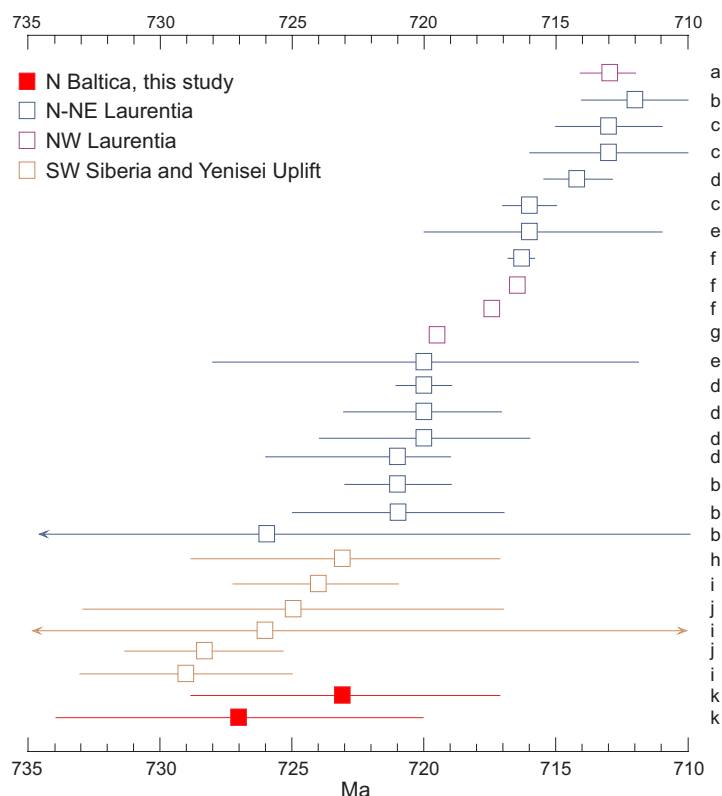


Fig. 12. U-Pb zircon and baddeleyite ages of magmatic rocks from the northern and north-eastern Laurentia related to the Franklin LIP, and those from similar igneous provinces of the north-western Laurentia and Siberia.

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 бадделейита 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], e – 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 Rummyanichny 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 Rummyanichny 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].

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