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Sergey Malyshev (✉ s.malyshev@spbu.ru)

Saint Petersburg University

Alexey Ivanov

Siberian Branch of the Russian Academy of Sciences

Andrey Khudoley

Saint Petersburg University

Vadim Kamenetsky

University of Tasmania

Maya Kamenetsky

University of Tasmania

Alexander Marfin

Siberian Branch of the Russian Academy of Sciences

Olga Lebedeva

Karpinsky Russian Geological Research Institute

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Global implication of Mesoproterozoic (1.4 Ga) magmatism within Sette-Daban Range (Southeast Siberia)

Sergey Malyshev^{1,*}, Alexey Ivanov², Andrey Khudoley¹, Alexander Marfin², Vadim Kamenetsky^{3,4}, Maya Kamenetsky^{3,4}, and Olga Lebedeva⁵

¹Institute of Earth Sciences, Saint Petersburg University, University Emb. 7-9, Saint Petersburg 199034, Russia

²Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, Lermontova St. 128, 664033 Irkutsk, Russia

³School of Natural Sciences and Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania 7001, Australia

⁴Institute of Experimental Mineralogy, Russian Academy of Sciences, Institutskaya str., Chernogolovka, 142432, Russia

⁵A.P. Karpinsky Russian Geological Research Institute, Sredniy pr., 74, 199106 St. Petersburg, Russia

*s.malyshev@spbu.ru

ABSTRACT

Mesoproterozoic period included several global tectonic events like break-up of Nuna and formation of Rodinia. However, although Siberia is a significant piece of both supercontinents, Mesoproterozoic time is marked by quiescence of magmatic and tectonic activity in it. We report here a mafic dyke (named Gornostakh dyke) in the southeastern Siberian Craton dated at 1419 ± 32 Ma by LA-ICPMS U-Pb geochronology of apatite. Paleogeographic reconstructions suggest that Siberia was connected to Laurentia and Baltica and their reconfiguration interrupts a prolonged tectonic quiescence in the Siberian Craton from ca. 1.88 Ga reflecting a transition from Nuna to Rodinia configuration. The 1419 Ma Gornostakh dyke and coeval deformation observed in the structure of the region may be a direct consequence of this transition. The dyke has tholeiitic compositions with high MgO and alkaline content, low-Ti, and arc-like trace element pattern. Due to the absence of subduction tectonics in the study area, geochemical data could be attributed to a significant contribution from metasomatically enriched subcontinental lithospheric mantle previously modified by subduction processes. Such mafic magmatism on the margin of the Siberian Craton could be related to a hypothetical large igneous province, which initiated the continental break-up.

Introduction

Mesoproterozoic is included in the time period which is called the Boring Billion (1.70–0.75 Ga)^{1,2}, which was marked by an absence of glacial deposits and Sr anomaly in the seawater record, lack of massive sulfide volcanic-hosted deposits and iron formations, lack of orogenic gold³. The paucity of new passive continental margins and abundance of unusual dry magmas such as A-type granites and anorthosites in Mesoproterozoic are interpreted in terms of single-lid tectonic hypothesis⁴. According to the paleomagnetic reconstructions in Mesoproterozoic, all of the continents were assembled into the supercontinent Nuna (Columbia) which were reassembled to Rodinia at the end of Mesoproterozoic e.g.^{5–7}, and reference within. Mafic dyke swarms act as a significant fingerprint for supercontinental reconstructions and their presence indicates tectonic markers of intracratonic crustal extension associated with deep-Earth dynamic processes such as mantle plumes, subduction (back-arc extension), and rifting during supercontinent break-up.^{8–10}.

Outcrops of Paleoproterozoic or early Mesoproterozoic crust in Siberia are restricted to isolated exposures of basement inliers and surrounding areas or lower Mesoproterozoic sediment cover of foreland Verkhoyansk fold-and-thrust belt (FTB). The largest dyke swarms are located within the basement inlier in Anabar uplift and Olenek uplift and their surrounding areas, and Sette-Daban range of Verkhoyansk FTB (with ages ~ 1500 Ma and 1000–950 Ma, respectively^{11,12}). The period of 1400–1300 Ma is marked by a few mafic intrusions across the Siberian craton: 1382 ± 2 Ma Chieress dyke cut the Mesoproterozoic sediment cover of the eastern slope of Anabar uplift¹³, 1385 ± 30 Ma mafic dykes cuts the Mesoproterozoic sediments on the Udzhia uplift¹⁴, Listvyanka and Goloustnaya dykes exposes in the south margin of the Siberian craton — 1350 ± 6 Ma¹⁵ and 1338 ± 3 Ma¹⁶, respectively.

Another poorly dated north-trending dolerite dyke at south Verkhoyansk FTB was explored. This dyke cuts the lower Mesoproterozoic sediments (Riphean according to the Russian stratigraphic nomenclature). The age of this dyke was estimated as ca. 1.34 Ga using Sm-Nd isochron¹⁷. We report here a new U-Pb age on apatite (1420 Ma), Nd-isotopes, and major and trace element geochemistry for this dolerite dyke to constrain mantle source and a possible link of this magmatic event with continental reconstruction in Mesoproterozoic.

Regional geology and sample description

The eastern part of the Siberian craton is separated from the Verkhoyansk FTB by a set of thrusts. The southernmost part of the Verkhoyansk FTB is widely known as the South Verkhoyansk segment^{18,19}. The study area is located in the western part of this segment, within the Sette-Daban Range (Figure 1).

Within the Sette-Daban area, the basement is totally covered by Mesoproterozoic to Carboniferous sedimentary succession. Meso- and Neoproterozoic rocks are exposed in the hanging walls of major thrusts which specifies the predominant structural style as imbricate thrust sheets. From the south to the north several thrusts pinch out, forming the wide Gornostakh Anticline with a gentle (10°–15° dip angle) west limb and a much steeper (40°–50° dip angle) east limb (Figure 1).

The Meso- and Neoproterozoic succession contains several kilometer-scale distinctive siliciclastic-carbonate cycles that are generally separated from each other by unconformities or erosional surfaces and are divided into the following six widely recognized units: the Uchur, Aimchan, Kerpyl, Lakhandu, Uy and Yudoma Groups²⁰. A detailed description of the sedimentary succession of the Sette-Daban region has been presented in several papers, but the important thing for this study is that only Uchur Group is estimated as early Mesoproterozoic in age, whereas others have middle Mesoproterozoic to Ediacarian ages²¹, and reference therein. The outcrops of the lower Mesoproterozoic succession (Uchur Group) are limited to isolated exposures within the Verkhoyansk FTB and represented by two locations: in the core of the Gornostakh Anticline and in the hanging wall of the northern branch of the Kyllakh Thrust (Ebeke-Khayata Range). Approximately 3-km thick Uchur Group consists of clastic and carbonate rocks formed in variable depositional environments²². These rocks are overlain by a middle Mesoproterozoic - Neoproterozoic succession with an angle unconformity and consists of several unconformity-bounded, kilometer-scale, clastic-carbonate cycles deposited in shallow-marine environments with total thickness on the east limb of the Gornostakh Anticline at 5 km.

Two major mafic magmatic events are recognized in the Sette-Daban: 1000–950 Ma Sette-Daban event, and 370–360 Ma Yakutsk-Vilyui LIP which are associated with rift-extensional tectonics in the area^{12,19,23,24}. Other mafic intrusions (mainly sills) with the age of 440–450 Ma are widespread on the eastern limb of the Gornostakh Anticline cutting Mesoproterozoic to Cambrian rocks and they are termed the Suordakh magmatic event^{25,26}. The analyzed in this study Gornostakh dyke according to the geological maps crosscuts only the sediments of the Uchur Group in the core of the Gornostakh Anticline (Figure 2). A preliminarily Sm-Nd isochron age of the Gornostakh dyke with the relatively large analytical error is 1339 ± 59 Ma¹⁷. If correct, this age suggests another mafic magmatic event in the area and the lack of exposure of the lower Mesoproterozoic sedimentary rocks in the Sette-Daban allows considering the Gornostakh dyke as a unique intrusion for assessing the nature of the early Mesoproterozoic magmatism in the region.

The field sampling site was targeted using 1:200 000 geological maps of the USSR, sheet P-53-XXIV^{27,28}. The dolerite sample was collected from the western slope of the Svetly Creek valley, approximately 7 km from its confluence with the Belaya River (Figure 2). Dyke has no bedrock exposure but does have concentrations of large boulders of dolerite forming a North-trending line, which is shown on maps as a dyke. Due to the lack of exposed contacts, the widths of the dyke are unknown, but estimated roughly as 15–20 meters. All rocks are relatively fresh, and weathering forms a thin pale brown crust which is developed along with fractures (Figure 3).

The sample is dolerite with intergranular ophitic to sub-ophitic texture, comprising 50–55% plagioclase, 40–45% clinopyroxene, up to 0.5% quartz and 4–5% opaque minerals (ilmenite) and trace apatite (Figure 4). The sample is moderately altered, particularly uraltic alteration of pyroxene and variable moderate sericitization of plagioclase. Most of clinopyroxene grains have been affected by alteration (80% of the grain volume) and are present in the form of relics broken by cracks or pseudomorphisms, completely overgrown by chlorite and amphibole. Amphibole grows from near grain boundaries to pervasive alteration of the entire grain into a mixture of colorless actinolite-tremolite and greenish-brown xenomorphic grains of hornblende. Plagioclase (andesine №35–37) preserves original polysynthetic twinning and the entire volume of grains is permeated with a thin aggregate of saussurite and thin needles of actinolite-tremolite. Opaque minerals appear as subhedral to

ehedral grains of ilmenite variable in size (0.1–2 mm) in groundmass and also as extremely fine-grained masses within altered pyroxene and along grain boundaries. Accessory apatite grains form thin prisms and needles up to 0.5 mm in size.

U-Pb geochronology and Nd isotopic methodologies

Apatite grains were employed for U-Pb dating, which was performed at the University of Tasmania (Hobart, Australia) by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) using an Agilent 7900 quadrupole mass-spectrometer connected to a 193 nm Coherent Ar-F excimer laser and Resonetics S155 ablation cell^{29,30}. Details of the procedure are provided in the Supplementary File along with the full analytical dataset.

The isotopic study was done at the Institute of Geology and Geochronology of the Precambrian, Russian Academy of Sciences. Accuracy at 2σ level of $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratio measurements was 0.5% and 0.005%, correspondently. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were reported relative to the value of 0.511860 for the La Jolla standard. During the period of this study, the weighted average of nine La Jolla Nd-standard runs yielded 0.511852 ± 8 (2σ , $n=10$) for the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio after normalization of the $^{146}\text{Nd}/^{144}\text{Nd}$ ratio to 0.7219.

Results

LA-ICP-MS U-Pb geochronology

A typical apatite grains were used for the U-Pb dating. The apatite grain was large enough to employ 30 μm diameter laser ablation spots to grain regions free of mineral and melt inclusions. On the Tera-Wasserburg diagram, the analyzed apatite grains are discordant, but form a pronounced regression line that intercepts in the lower part with the concordia at 1419 ± 32 Ma (Figure 5). The trace element composition of apatite can be used to clarify the initial composition of magma, which has been shown in numerous studies^{31,32} and reference therein. The multi-elemental spectra in the studied apatite indicate the closeness of the trace element composition of the grains. A characteristic feature of those apatite grains is the presence of pronounced Sr and Eu negative anomalies, which are typical for apatite from mafic igneous rocks.

Geochemistry

Major and trace element data for the studied sample N595 are presented together with those for the 1340 Ma Listvyanka dykes Irkutsk Promontory and the 1000 Ma Sette-Daban sills and dykes^{15,24}.

The sample of Gornostakh dolerite display relatively high MgO (9.83 wt%) and Al_2O_3 (15.4 wt%), moderate SiO_2 (45.6 wt%), FeO_t (11.1 wt%) and CaO (7.86 wt%), and low-Ti content (1.25 wt%) (Table 1). The sample has moderate total alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 3.9$ wt%) and $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio of 2.27. The sampled dyke is classified as alkaline basalt on the TAS diagram (Figure 6A,^{33,34}) and belongs to the boundary between tholeiitic and calc-alkaline series on the AFM diagram (Figure 6B,³³). The chondrite-normalized rare earth element pattern (Figure 6C) shows moderate enrichment of light REE (LREE) with $\text{La}_N/\text{Yb}_N=3.28$ where LREE profile is flat with $\text{La}_N/\text{Sm}_N=1.24$ slightly higher than the average values of N-MORB and lower than average values of E-MORB, whereas the heavy REE (HREE) profiles shows gentle slope with $\text{Tb}_N/\text{Yb}_N=2.52$. The primitive mantle-normalised trace element patterns (Figure 6D) show depletion of high field strength elements (HFSE) with prominent negative Nb-Ta and slightly negative Zr-Hf and Ti anomalies and enrichment in Pb, Rb and Ba.

The Gornostakh dyke sample was analyzed for Nd isotope. The corresponding initial $\epsilon\text{Nd}_{1420\text{Ma}}$ value shows a slightly negative value (-0.1), which is much lower than the inferred for the depleted mantle, suggesting involvement of an enriched reservoir (crustal component or enriched subcontinent lithospheric mantle).

Discussion

The Gornostakh dyke is coeval or close in age within analytical uncertainty with numerous mafic events across many continents³⁵, and reference within; such as the ca. 1435 Electra Lake gabbro pluton³⁶ and the ca. 1426 Michael gabbro intrusions³⁷, the ca. 1386–1380 Ma Hart River dykes³⁸ in North America, the ca. 1384–1380 Ma Zig Zag Dal Formation and Victoria fjord dykes in Greenland³⁹, the ca. 1384–1386 Ma Chieress and Udzha dyke in north Siberia^{13,14}, the ca. 1385 Ma Mashak volcanics in east Baltica⁴⁰, the ca. 1390 Ma Biberkine dykes in west Australia⁴¹ and the ca. 1400 Ma alkaline mafic sills in the South Africa⁴². No other mafic magmatism within an uncertainty of 1420 ± 30 Ma age for the Gornostakh dyke is currently known in the Sette-Daban or elsewhere in Siberia and the temporally closest magmatic events within the Siberia are the ca. 1350 Ma Listvyanka and Goloustnaya dykes^{15,43} in south Siberia and the 1490–1500 Ma Kuonamka LIP in north Siberia¹¹.

Tectonic setting of the Siberia at 1420 Ma

Precambrian mafic magmatism, typically as dykes, commonly is interpreted as continental rifting and as a consequence possible break-up of the supercontinent or advocated as plume-related or both. Typically, episodes of mafic magmatism in the continental record related to extensional tectonics, but there are some examples of dykes interpreted as the development of active margin tectonics (e.g. 1.3–1.2 Ga dykes in Southwest Fennoscandian Shield,⁴⁴ and 1.39 Ga in West Australia⁴¹). These mafic intrusions may represent extension as a reflection of convergent and collisional tectonics and characterize by high alkalinity (presumably potassic) and island-arc trace element signatures, e.g.⁴⁵, while continental rift-related mafic intrusions possess OIB or E-MORB trace element characteristics. At the same time, arc-like trace element profile are typical for low-Ti basalts from Phanerozoic large igneous provinces (LIP), which commonly related to plume-lithosphere interaction (e.g.⁴⁶) or to deep water and fluid recycling due to ongoing subduction⁴⁷ — in both cases those LIPs are either a reason to the continental break-up or not regardless their geodynamic causes. Thus, dyke swarms could be associated with plate-margin related processes or deep mantle geodynamics and not entirely with a continental break-up².

The Mesoproterozoic are considered as a period of relative tectonic quiescence in southeastern Siberia, characterized by the formation of extensive intra-cratonic basins with subsequent changing to a passive margin setting in the Neoproterozoic along the eastern margin of the craton. Paleogeographic reconstructions at ca. 1400 Ma suggest that the Laurentia, Baltica, and Siberia (Figure 7) composed the Nuna supercontinent core⁵. Nuna's lifespan is a highly debated topic in literature and there are at least two contrasting points of view. Roberts² overviewed this issue and based on several pieces of evidence, such as passive margin low abundance⁴⁸ and continental growth rate suggested that Nuna break-up had started at ca. 1.3 Ga and then fragments of Nuna reamalgamated to produce Rodinia at ca. 1.1–0.9 Ga. Others based on paleomagnetic and geological studies have argued that the interior of the supercontinent was affected by extension between 1.6 and 1.3 Ga, and finally, break-up took place around 1.3 Ga^{5,49–51}. In any case, most of the authors pointed the similarity between Nuna and Rodinia configuration and have suggested a lack of large-scale movement during the supercontinental fragmentation and assembly⁵.

Towards to Siberia margin there are recognized a few dykes in the age interval 1.42 to 1.35 Ga including studied Gornostakh dyke and on the adjacent to Siberia – Laurentia and Baltica (Figure 7). Since, according to paleogeographical reconstructions Siberia was connected to Laurentia by the south margin and to Baltica by the southeastern margin, the active margin tectonic setting for mafic magmatism is considered unlikely. Whereas the arc-like chemical composition of the Gornostakh dyke suggests an occurrence of some kind of flood basalt provinces on the southeastern Siberian craton at ca. 1.4 Ga and is associated with 1.39 Ga Mashak LIP in the southeast of Baltica⁴⁰. At the same time, such LIP activity could be initiated by extensional tectonic with the following continental break-up. Geological evidence for that scenario is in the structural unconformity between Uchur and Aimchan groups, which suggests a deformation event on Sette-Daban before the Aumchan Group has begun sedimentation^{20,52}. This line of evidence fits with a model of rotation of Baltica around Siberia/Laurentia described by Yakubchuk⁵³ which could be the reason for local deformations as a reflection on continental break-up. To test this hypothesis and determine the timing of the break-up and reassembling Nuna to Rodinia further geochemical, isotopic and paleomagnetic data across the spatial range of dykes within Columbia remains to be investigated.

Mantle sources

Evaluation of mobility of major and trace elements during alteration or metamorphism can be assessed using Zr, Nb, and Y, e.g.^{54,55}. Despite moderate growth of secondary minerals in dolerite of the dyke, the Zr/TiO and Nb/Y ratios (68 and 0.19) corresponds to subalkaline basalts according to classification by⁵⁵ indicating that immobile trace elements (Nb, Y, Zr, Ta, Th, REE) have been unaffected by post-magmatic processes and reflect the primary composition of magma. The Gornostakh dyke displays arc-like geochemical characteristics, including depletion of HFSE, enrichment of LILE, and unradiogenic initial Nd isotopes, which may have been conferred either by crustal contamination or derived from the metasomatically enriched source, or both⁵⁶. Significant crustal contamination appears unlikely which is supported by primitive mantle-like trace element ratios of Nb/Ta (17.0) and Zr/Sm (23.7) ratios (primitive mantle: Nb/Ta=17.39, and Zr/Sm=25.23;⁵⁷). This is supported further by La/Sm (1.9) and Sm/Nd (0.31) ratios, and relatively high Mg (61.3), while crustal material is characterized by high La/Sm and low Sm/Nd relative to rocks sourced from the asthenospheric mantle. Nonetheless the dyke displays arc-like trace element signatures such as the depletion of HFSE and enrichment of LILE, and low Ti. However, subduction also appears unlikely according to paleotectonic reconstructions, which displays intra-plate tectonic setting of the region and absence of active margins around the Siberia. These characteristics may also be attributed to Earth deep volatile cycling (e.g.⁴⁷) or partial melting of SCLM (sub-continental lithospheric mantle) enriched by ancient recycled components due to subduction processes⁵⁶ or low continental crust delamination⁵⁸. Based on the above geochemical and paleotectonic evidence, we prefer an interpretation where the predominant source of the dyke is an enriched SCLM previously modified by subduction processes.

The flat HREE profile of the Gornostakh dyke ($Tb/Yb_n=1.81$, $La/Sm_n=1.24$) indicates that partial melting likely occurred on the border of the spinel and garnet stability fields (~ 90 km) with a low degree of partial melting suggesting that there has not occurred lithosphere extension or delamination beneath and near the eastern margin of the Siberian craton before 1420 Ma. The younger in age the Sahara mafic sills at ca 1000 Ma²⁴ were emplaced through the same SCLM because they were sampled in areas where they outcrop close to each other. Whereas those intrusions have similar primitive mantle-normalized (arc-like) profiles they have significantly higher $\epsilon Nd(t)$ values of +4.4 to +6.8 than Gornostakh dyke and shallower spinel-bearing melting source, suggesting that their source involved a higher proportion of depleted mantle with less contribution from the enriched component due to crustal extension. The enriched LREE, LILE and isotopic compositions of both the Gornostakh and Sahara intrusions could have been produced through interaction between asthenospheric mantle and metasomatically enriched regions within the SCLM that formed during ancient subduction events.

Conclusions

A unique mafic dyke ca. 1419 Ma, here named the Gornostakh dyke, has been identified in the southeastern margin of Siberian Craton using in situ LA-ICPMS U-Pb dating of apatite. Current models for the Siberian Craton infer a magmatic and tectonically quiescent period between ca. 1.88 Ga and 1.3 Ga but indirect evidence from the other margins of the craton supports beginning intraplate magmatic activity which could be related to the transition from Nuna to Rodinia configuration. Obtained U-Pb age of the Gornostakh dyke constrains the sedimentation age of the Uchur Group and early Mesoproterozoic deformation tectonics in Sette-Daban Range. Paleogeographic reconstructions suggest that this could be a result of rotation and relative motion between Baltica and Siberia-Laurentia.

Preliminary geochemical analysis indicates that the dyke has tholeiitic compositions with arc-like trace elements profile with a significant contribution from metasomatically enriched subcontinental lithosphere previously modified by subduction processes. Altogether with paleotectonic reconstructions which indicate a lack of active margin tectonics in the area, the geochemical data of dyke composition indicates that the low-Ti Gornostakh dyke is the remnant of the large igneous province. Such magmatic activity make coincide with crust extension and continental break-up.

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Author contributions statement

S.M and A.I conceptualization, funding acquisition and original draft preparation, A.K. geology background, sample providing and original draft preparation, V.K and M.K. conducted the U-Pb dating, A.M. analysed the results, O.L. petrography description. All authors reviewed the manuscript.

The corresponding author is responsible for submitting a [competing interests statement](#) on behalf of all authors of the paper. This statement must be included in the submitted article file.

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Table 1. Major, trace element and isotope data for the sample N595. Notes: (a) Major element concentrations were determined by XRF using an ARL 9800 spectrometer, with trace and rare earth element (REE) compositions determined by inductively coupled plasma–mass spectrometry (ICP-MS) using an ELAN 6100 DRC ICP-MS. Measured concentrations were significantly above detection limits, with analytical uncertainties of <3% for major elements and 4–10% for trace elements and REE. The international standards OU-6 and SBC-1 were used in this study. (b) $Mg = 100 \times MgO/40.31/(FeO/71.85 + MgO/40.31)$ (c) Crystallisation age $t = 1420$ Ma.

XRF	N595 (wt %)	ICP-MS	N595 (ppm)	ID-TIMS	N595
SiO ₂	45.6	Rb	24	¹⁴⁷ Sm/ ¹⁴⁴ Nd	0.1709
TiO ₂	1.25	Sr	230	¹⁴³ Nd/ ¹⁴⁴ Nd	0.512391
Al ₂ O ₃	15.4	Y	18	εNd(0)	-4.8
Fe ₂ O ₃	2.82	Zr	85	εNd(t)	-0.1
FeO	8.54	Nb	3.4	T(Nd) _{DM} (Ma)	2697.6
MnO	0.15	Ba	500		
MgO	9.83	La	6.9		
CaO	7.86	Ce	17.17		
Na ₂ O	2.7	Pr	2.63		
K ₂ O	1.19	Nd	11.59		
P ₂ O ₅	0.11	Sm	3.59		
LOI	4.28	Eu	1.09		
Total	99.7	Gd	3.58		
		Tb	0.6		
FeO(total)	11.07	Dy	3.59		
Mg#	61.3	Ho	0.72		
		Er	1.79		
		Tm	0.3		
		Yb	1.51		
		Lu	0.22		
		Hf	1.82		
		Ta	0.2		
		Pb	2.9		
		Th	0.82		
		U	0.33

Figure 1. Simplified geological and sample location map of the central part of Sette-Daban Range (Southern Verkhoyansk FTD) and surrounding areas (after^{19,27} simplified and modified).

Figure 2. Geological setting of the central part and eastern limb of the Gornostakh Anticline (Belaya River area) and location of sampled dolerite dyke in this study (geology after^{27,28} modified and simplified). 450 Ma sills (Suordakh event) from^{25,26}.

Figure 3. (A) A view of the sample location, looking NNW. (B) Dolerite sample N595.

Figure 4. Photomicrograph of sample N595 (Gornostakh dyke). (A) Transmitted polarized light. (B) Cross-polarized light. Pl=plagioclase, Cpx=clinopyroxene, Amf=amphibole, Chl = chorite, Ilm=ilmenite.

Figure 5. Tera-Wasserburg concordia diagram for the dated apatite grains (on left). Weighted mean age is presented with 1σ error. In discussion we used 2σ error. Chondrite normalized rare earth elements spectra for analyzed apatite grains (on right). Grey field denotes to a typical range of apatite REE compositions from mafic host rocks³². Raw data presented in supplementary file.

Figure 6. (A) Total alkali-silica (TAS) plot after³⁴ with alkaline-sub-alkaline boundary after³³. Grey field denotes ca. 1000 Ma Sette-Daban sills and dykes from²⁴ and purple field the ca. 1340 Ma from Listvyanka dykes from¹⁵. (B) AFM plot after³³. (C) Chondrite and (D) primitive mantle normalised multi-element plots for Gornostakh (N595), Sette-Daban sills and Listvyanka dykes. OIB=ocean island basalt after⁵⁷ NMORB=mid ocean ridge basalt and EMORB=enriched MORB after⁵⁹.

Figure 7. Tectonic assemblage map of core of Nuna to time of initial early Mesoproterozoic breakup events (ca. 1400) after^{5,7} with magmatic events ca 1400–1350 Ma. Ages of magmatic events from: Lv¹⁵, Gl⁴³, Ch¹³, Ud¹⁴, M⁴⁰, BD⁶⁰, MZ and VL³⁹, HR¹³.

Figures

Figure 1

Simplified geological and sample location map of the central part of Sette-Daban Range (Southern Verkhoyansk FTD) and surrounding areas (after 19, 27 simplified and modified). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Geological setting of the central part and eastern limb of the Gornostakh Anticline (Belaya River area) and location of sampled dolerite dyke in this study (geology after 27, 28 modified and simplified). 450 Ma sills (Suordakh event) from 25, 26 Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors. .

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Figure 7

Tectonic assemblage map of core of Nuna to time of initial early Mesoproterozoic breakup events (ca. 1400) after 5, 7 with magmatic events ca 1400–1350 Ma. Ages of magmatic events from: Lv15, GI43, Ch13, Ud14, M40, BD60, MZ and VL39, HR13. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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