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GEOLOGY

The Age of Metamorphism of Granulite Complexes of the Voronezh Crystalline Massif: The Monazite U–Pb Geochronology

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Over recent decades, studies on the reconstruction of the geodynamic evolution of the lithosphere of the East European Platform, including the Voronezh crystalline massif (VCM), have been carried out actively. The reliability of these reconstructions has some disadvantages due to insufficient geochronological knowledge of the Precambrian metamorphic regions, which is about 90% of the total volume of the continental crust within the VCM.

The Voronezh crystalline massif is a large rise (600 × 800 km) of the East European Platform basement, bounded by a system of grabenlike aulacogenes (Pachelmskii, Moskovskii, Gzhatskii, and Toropets-Vyazemskii) from the north and northeast, Dnepr–Donetsk aulacogene from the south, and the Orsha Depression from the south, and the Pricaspian depression from the east. The VCM together with the Ukrainian Shield (USh) forms one of Earth's three crust segments of the Precambrian basement of the East European Craton (Sarmatia) [1]. This VCM belongs to the northeast area of Sarmatia (Fig. 1). The VCM was separated from the Ukrainian Shield in the Phanerozoic by the Dnepr–Donetsk aulacogene. In the east the Lipetsk–Losevskii volcanogenic belt and the East Voronezh province separate the VCM and the Volga–Uralia crust segment.

The main peculiarities of the geological structure of the VCM are reflected in three main types of the structure: the Mesoarchean gneiss-migmatite and granulite areas, Neoarchean green belts, and the Paleoproterozoic mobile belts, connected with regional deep faults (Fig. 1).

Most of the VCM is occupied by areas of the Archean consolidation (Sumskaya, Rossoshanskaya, Kastornenskaya, Central, etc.). They are made of migmatized gneisses, gray gneisses of tonalite–trondhjemite–granodiorite composition (TTG), and granulites of the Oboyan complex (the former Oboyan series), which vary in the chemical composition. Extended Neoarchean greenstone belts (Belgorod-Mikhailovskii, Orel-Timskii) are composed of volcanogenic–sedimentary formations of the Mikhailovskaya series (Fig. 1). The Paleoproterozoic belts are represented by large synforms (Timskaya-Yastrebovskaya, Volotovskaya, Belgorodskaya, etc.), which is made of volcanogenic–sedimentary and ferruginous–siliceous formations of the Kursk and Oskol series, which coincide spatially with the Neoarchean greenstone belts (Fig. 1). The youngest rocks of the VCM are weakly dislocated Paleoproterozoic volcanogenic–sedimentary deposits of the Voronezh and Baygorovskaya suites and volcanites of the Glazunovskaya series, which are covered by ancient Precambrian complexes.

As in the Proterozoic the Ukrainian Shield and the Voronezh crystalline massif were parts of a unified segment of the Earth's crust, all extended structures of the VCM are traced also on the Ukrainian Shield [2]. The central part of Sarmatia is occupied by the Archean Symskaya-Pridneprovskaya granite-greenstone terrane, consisting of two blocks, i.e., the Middle Pridneprovskii within the Ukrainian Shield and the Sumskii within the Voronezh crystalline complex [3]. This area is bounded also by the Archean belts: the Sevsko-Kirovogradskii from the west and Oskol-Priazovskii from the east. To the west of the Sevsko-Kirovogradskii belt, the Paleoproterozoic Belotserkovskii-Odesskii belt is located, which separates the Volyn-Podolskii and Kirovogradskii blocks of the USh [3].

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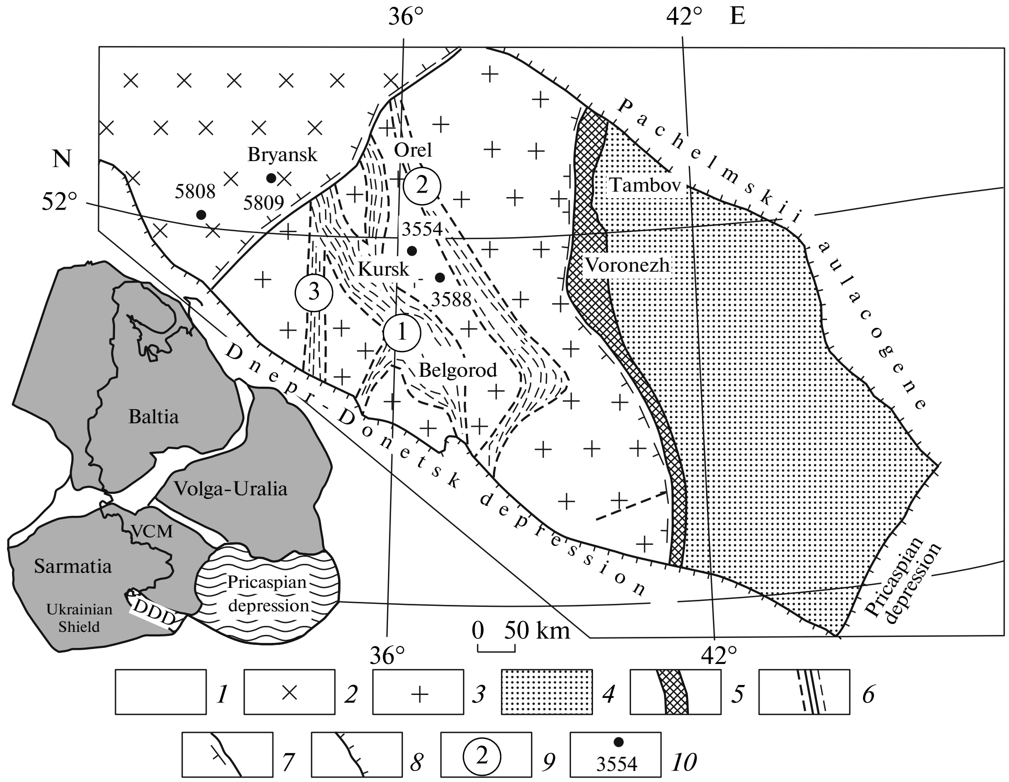

Fig. 1. The geological–structural scheme of the Voronezh crystalline massif (VCM), based on the Early Precambrian geological map of the VCM of 1 : 1 000 000 scale edited by N.M. Chernyshov, V.M. Nenakhov, et al., (1996). (*1*–*6*) Structural and compositional complex complexes: (*1*) platform complexes of the Riphean and the Phanerozoic; (*2*–*6*) pre-Riphean: the Bryansk (*2*) and Kursk (*3*) blocks, East Voronezh province (*4*), Lipetsk–Losevskii volcanogenic belt (*5*), riftogenic second-order structures (*6*); geological boundaries of blocks (*7*), the Voronezh crystalline massif (*8*), riftogenic second-order structures (*9*): (1) Belgorod-Mikhailovskaya, (2) Orel-Timskaya, (3) Krupetsk-Krivoi Rog; (*10*) location and numbers of wells where samples for isotopic age dating were collected.

The northern continuation of this belt is the Bryansk block of the VCM, composed of granulites and different granitoides. Granulites of the Kursk-Besedinskii block of the central part of the VCM are within the Oskol-Priazovskii belt.

Unfortunately, the recent geochronological studies of the Precambrian complexes of the VCM are still fragmentary. As a result, there are some difficulties in interpretation of the sequence of metamorphic events and definition of the metamorphic complexes of different ages. In order to fill a gap in our knowledge, geochronological U–Pb dating of monazite and Sm–Nd isotope-geochemical studies of metasedimentary rocks of granulite complexes of the central (Kursk-Besedinskii block) and the northwest (Bryansk block) parts of the VCM were carried out. The study results are given in this work.

Granulites of the Kursk-Besedinskii block of the VCM are represented by pyroxene–magnetite quartzites, metapelites, metabasites, and metaultrabasites. The main mineral paragenesises of metapelites are as follows: Qtz + Grt + Kfs + Pl + Crd + Sil + Spl + Bt + Mag (sometimes with Ilm and Py) and Qtz + Grt + Kfs + Sil + Opx + Spl + Crd + Bt + Py + Mag. Accessory minerals are magnetite, pyrite, zircon, apatite, monazite, and xenotime.

The Bryansk block is located in the northwest area of the VCM and occupies a fifth of the whole area (about 100 000 km^2). As the Precambrian complexes of the western part of the VCM are overlapped throughout the territory by sedimentary formations with a thickness of 320–640 m, the first data about the geological structure of the Bryansk block were obtained in the 1970s. By now only 13 wells have been drilled, which opened the Precambrian basement at a significant depth of 400 m.

Granulites of the Bryansk block are represented mainly by metasedimentary rocks (metapelites, marbles, calc-silicate rocks, ferruginous quartzites, and graphitic quartzites). The main paragenesises of minerals of metapelites are as follows: Pl + Grt + Opx + Kfs + Bt, Qtz + Pl + Sil + Bt + Crd + Kfs + Ilm, and Qtz + Pl + Kfs + Crd + Bt ± Sil ± Grt. The predominant accessory minerals are magnetite, apatite, zircon, and monazite.

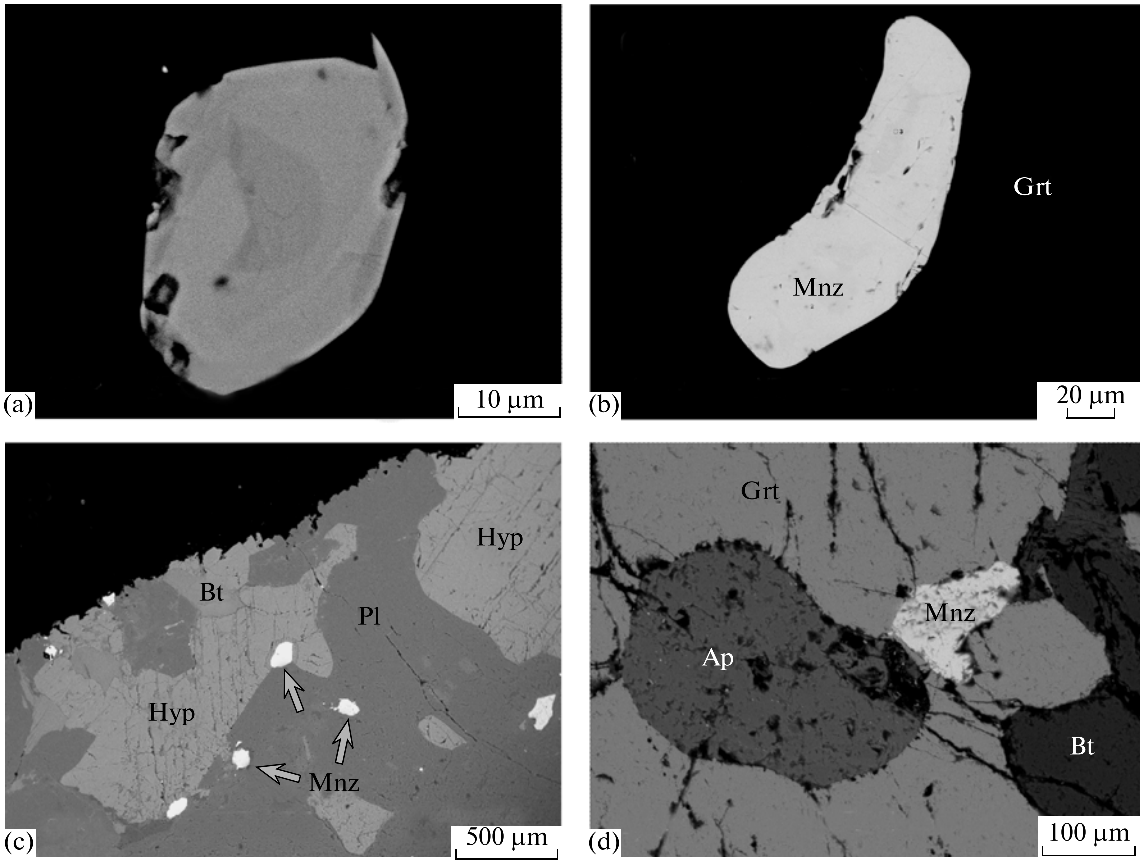

Fig. 2. Morphological types of monazites from metapelitic granulites of the Kursk–Besedinskii and Bryansk blocks. (a) A rounded grain of monazite in biotite, sample 5808/6; (b) an inclusion of an elongated grain of monazite in garnet, sample 3554/167; (c) paragenesis of monazite with rock-forming minerals, sample 5809/11; (d) inclusions of apatite and monazites in the rim of garnet, sample 3554/167.

In metapelites of the above-described blocks, monazite is a common accessory mineral, which is represented by rounded and extended grains with a size from 10–20 to 100 μm (Figs. 2a, 2b). It occurs predominantly as inclusions in different metamorphic minerals, such as garnet, plagioclase, spinel, and hyperstene (Figs. 2c, 2d). Large grains of monazite (more than 60 μm) often show a zonal structure; small grains (10–40 μm) are commonly homogenous. According to the chemical composition, monazites from granulites of the Bryansk block differ significantly from those from the Kursk–Besedinskii block. They are nonzonal; yttrium does not occur in monazites; and the LREE content is twice as much at a lower content of Ce_2O_3/La_2O_3. Moreover, monazites from metapelites of the Bryansk block are characterized by lower Pb and Nd contents (Table 1).

Heavy liquid separation of accessory monazites for U–Pb age dating was made according to the standard procedure. The chemical decomposition of monazite and extraction of Pb and U were made using the T. Crow method [4]. The total blank did not exceed 20 pg of Pb over the research period. Determination of the isotopic composition of Pb and U was made using the Finnigan MAT 261 mass spectrometer in the statistical or dynamic regime (using an electron multiplier). Experimental data were processed using PbDat and ISOPLOT programs [5, 6]. To calculate ages the typical U decay constants were used [7]. Correction for common Pb was applied according to model values [8]. All errors are given at the 2σ level.

Nd and Sm were separated using the method described in [9]. The isotopic compositions of Nd and Sm were analyzed using the Sector-54 multiple collector mass spectrometer with a triple line source (Ta–Re–Ta) in the multidynamic (for Nd) and statistical (for Sm) regimes with simultaneous registration of ion currents of different isotopes of a given element. Correction for isotopic fractioning by normalization to $^{146}Nd/^{144}Nd = 0.7219$ was according to the exponential law. The total blank was 0.01 ng of Sm and 0.03 ng of Nd. To calculate values of $\varepsilon_{Nd}(0)$ and model ages T_{Nd}(DM), the modern CNUR values [10] ($^{143}Nd/^{144}Nd = 0.512638$, $^{147}Sm/^{144}Nd = 0.1967$) and DM values ($^{143}Nd/^{144}Nd = 0.513151$, $^{147}Sm/^{144}Nd = 0.2136$) were used.

Table 1. Chemical composition of monazites from granulites of the Voronezh crystalline massif (VCM)

Component	σ	Kursk–Besedinskii block, sample 3554/167					Bryansk block, sample 5808/6			
P_2O_5	0.15	31.18	29.61	30.25	31.27	30.34	28.13	27.81	27.22	28.29
SiO_2	0.07	–	–	–	–	–	0.38	0.47	0.35	0.40
CaO	0.06	1.79	2.00	1.72	1.43	1.75	0.22	0.45	0.15	0.18
Y_2O_3	0.28	7.38	7.71	8.56	7.97	7.88	–	–	–	–
La_2O_3	0.31	6.77	6.14	5.93	6.10	5.53	20.69	20.32	20.64	20.03
Ce_2O_3	0.38	20.11	18.96	17.93	19.07	18.87	35.70	36.56	36.93	37.27
Pr_2O_3	0.32	1.99	2.57	2.52	2.27	2.33	3.86	2.60	3.14	1.96
Nd_2O_3	0.32	13.11	13.98	14.07	14.84	13.60	7.35	8.70	8.20	9.16
Sm_2O_3	0.29	2.87	2.54	4.13	4.00	3.54	–	0.34	–	–
Eu_2O_3	0.26	–	–	–	–	–	–	–	0.37	0.45
Gd_2O_3	0.28	3.89	4.51	4.22	4.49	4.52	–	–	–	
Dy_2O_3	0.38	1.56	2.34	2.24	1.82	2.47	–	–	–	–
Yb_2O_3	0.38	0.44	0.43	–	–	–	–			–
ThO_2	0.25	1.52	1.45	1.48	1.26	1.69	1.93	1.66	1.33	1.16
UO_2	0.23	5.01	5.30	4.50	2.91	4.35	0.55	0.47	0.27	0.45
PbO	0.25	1.82	1.33	1.85	2.89	2.17	–	0.50	0.18	–
Total		99.45	98.87	99.39	100.42	99.06	98.81	99.88	98.78	99.35
ΣLREE		28.87	27.67	26.38	27.44	26.73	60.25	59.48	60.71	59.26
Ce_2O_3/La_2O_3		2.97	3.08	3.02	3.13	3.41	1.73	1.80	1.79	1.86

Note: Samples were examined by scanning electron microscopy (SEM) (JEOL 6380LV) with an INCA 250 energy dispersive analyzer (the accelerating voltage is 20 kV, the absorption current on Cu is 1–2 nA, zonde diameter is 2 μm, focal length is 10 mm, spectrum acquisition time is 300 s) using REE synthetic standards.

Table 2. Pb–U isotope geochemistry results of monazites from granulites of the Kursk–Besedinskii block (sample 3554/167) and the Bryansk block (sample 5808/6) of the Voronezh crystalline massif (VCM)

Number of weight	Amount of grains	U/Pb*	Isotope ratios					*Rho*[b]	Age, Ma		
			$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb^a$	$^{208}Pb/^{206}Pb^a$	$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$		$^{207}Pb/^{235}U$	$^{206}Pb/^{238}U$	$^{207}Pb/^{206}Pb$
Sample 3554/167											
1	3	0.41	20360	0.1991 ± 1	3.9900 ± 2	15.079 ± 30	0.5492 ± 11	0.96	2820 ± 6	2822 ± 6	2819 ± 1
2	1	0.10	2343	0.1996 ± 4	19.747 ± 1	15.007 ± 127	0.5454 ± 44	0.96	2816 ± 24	2806 ± 23	2823 ± 4
3	4	0.68	988	0.1947 ± 1	2.2472 ± 2	12.982 ± 26	0.4835 ± 10	0.97	2678 ± 5	2543 ± 5	2783 ± 1
Sample 5808/6											
4	6	0.55	17805	0.1257 ± 1	4.5718 ± 2	6.4216 ± 128	0.3706 ± 7	0.98	2035 ± 4	2032 ± 4	2038 ± 1
5	7	0.57	15286	0.1257 ± 1	4.2996 ± 2	6.4286 ± 129	0.3709 ± 7	0.96	2036 ± 4	2034 ± 4	2039 ± 1

Note: (*) The weight of monazites was not determined; ([a]) isotope ratios, corrected on blank and common Pb; ([b]) the correlation coefficient of $^{207}Pb/^{235}U$–$^{206}Pb/^{238}U$ ratios. The error values (2σ) correspond to the last significant figures.

For the U–Pb geochemistry, microweights of monazite were used (1–7 grains, size fraction is –0.25...+0.10 mm), which were separated from metapelites of the Kursk–Besedinskii (sample 3554/167, Qtz + Grt + Kfs + Pl + Crd + Sil + Spl + Bt + Mag) and the Bryansk (sample 5808/6, Qtz + Pl + Sil + Bt + Crd + Kfs + Ilm) blocks. As is seen in Fig. 3, the points of isotopic composition of monazite from metapelites of the Kursk–Besedinskii block are approximated by the regression line. The upper intersection of the regression line with the concordia line corresponds to the age of 2822 ± 41 Ma (RMSD = 4.1) (Fig. 3, Table 2). Here, for both monazite microweights (nos. 1 and 2 in Table 2), we have a concordant age of 2819 ± 6 Ma (RMSD = 0.25) and the probability is 0.62 (Fig. 3, Table 2), which can be used as the most confident estimation of the crystallization age of this block. Two monazite microweights from metapelites of the Bryansk block (nos. 4 and 5 in Fig. 3 and Table 2) also show the concordant age of 2036 ± 4 Ma (RMSD = 1.09, probability is 0.30), which corresponds to the crystallization age of this block.

The results of Sm–Nd isotopic-geochemical study of metapelitic rocks of the Kursk-Besedinskii and Bryansk blocks are shown in Table 3. They are characterized by T_{Nd}(DM) = 3.4 Ga, which testifies to their formation from sources with an average Paleoarchean model age.

The concordant age of 2819 ± 6 Ma obtained for metapelites of the Kursk-Besedinskii block corresponds to the last high-temperature metamorphic event manifested within this block. As a result of this event, observed mineral paragenesises and reaction structures formed. Taking into account the fact that earlier published estimation of metapelites metamorphism age 3277 ± 33 Ma (U–Pb dating for zircons [12]), there are grounds to consider that the age of metamorphism of metapelites of this block published earlier should be considered as the age of detrital zircon that occurred in these rocks, but not as the metamorphism age. According to Sm–Nd isotope geochemistry results (T_{Nd}(DM) = 3.4 Ga, Table 3), the source area of metapelites described in this work could be rocks of the Paleoarchean continental crust. In addition, it should be noted that granulite rocks of the central part of the VCM are within the Oskol-Priazovskii terrane, where within the Priazovskii block tonalite gneisses and granitoides with an age of 3260–3360 Ma [12] occur and the manifestation of granulite metamorphism with an age of 2.8–2.9 billion years [13] was fixed.

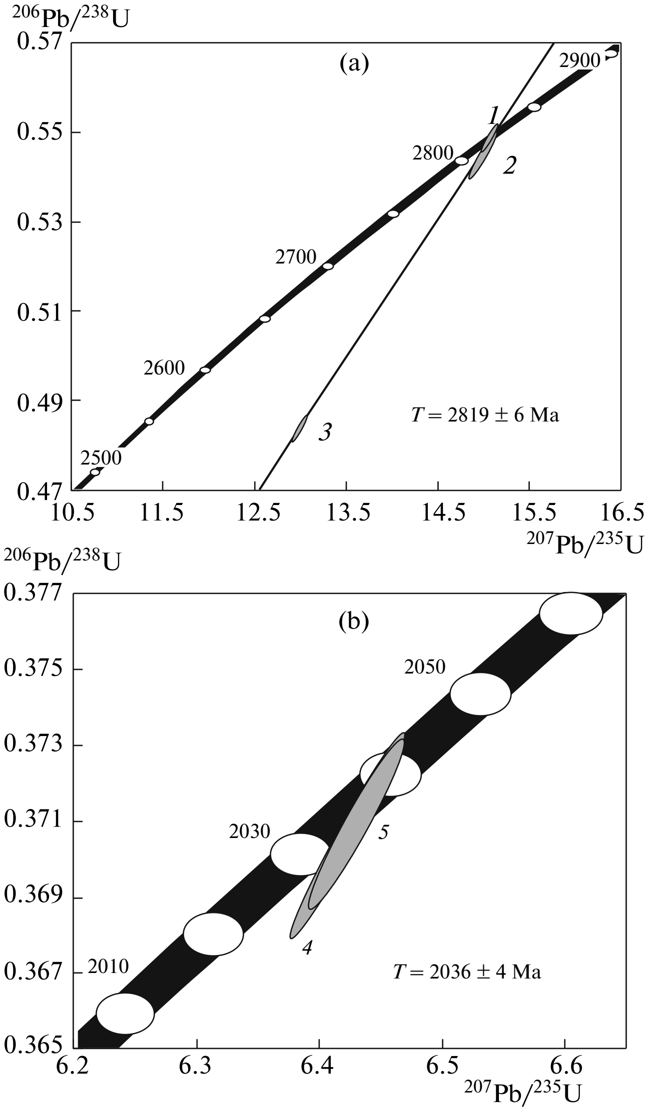

Fig. 3. U–Pb concordia diagrams for monazite from metapelitic granulites of the VCM: (a) Kursk–Besedinskii block (sample 3554/167); (b) Bryansk block (sample 5808/6). Numbers of points (*1–5*) correspond to numbers of microweights from Table 2.

Table 3. Sm–Nd isotope geochemistry results of granulites of the Voronezh crystalline massif (VCM)

Number of sample	Rock type	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(0)$	T_{Nd}(DM), Ma
		ppm					
99-179	Garnet–biotite gneiss	13.23	63.37	0.1186	0.510996	–5.9	3420
92-20	Ferruginous quartzite	23.61	8.94	0.1500	0.515560	–1.9	–
5818/14	Metapelitic gneiss	10.38	54.06	0.1160	0.510942	–4.0	3422

Granulites of the Bryansk block were considered as part of the Oboyan or Bryansk series of the Early Archean, which has not been confirmed by geochronological data obtained by E.B. Bibikova et al. [14]. It was found that the age of detrital zircon from metapelites of this block is 2.6 billion years, and the age of granulite metamorphism is 2.1–2.3 billion years [14]. This allows us to consider exposures of granulites of the Bryansk block as the northern continuation of the Belotserkovskii–Odesskii belt of the Ukrainian Shield [3], formed in Paleoproterozoic [15]. The U–Pb age data obtained testify that the age of the last stage of the granulite metamorphism within the Bryansk block is 2036 ± 4 Ma. Here, the Sm–Nd isotope geochemistry results [Table 3] show that formation of the protolith of granulite rocks of this block resulted from the reworking of the continental crust rocks with an average Sm–Nd model age of about 3.4 billion years. The facts described above allow us to consider the Bryansk block as a part of the Paleoproterozoic structure, resulted from the reworking of the Paleoproterozoic and Mesoarchean continental crust of the ancient core of Sarmatia.

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