

Isotopic Provinces and Evolution Stages of the Precambrian Crust at the Southwestern Margin of the Siberian Craton and Its Folded Framing

O. M. Turkina^a, A. D. Nozhkin^a, T. B. Bayanova^b, and N. V. Dmitrieva^a

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Highly metamorphosed rock associations of the Kan, Derba, and Arzybei blocks in the Central Asian Foldbelt (figure) are usually correlated with Early Precambrian basement complexes of the southwestern margin of the Siberian Craton. The tectonic blocks are often considered fragments of its crystalline basement. Recent precision datings revealed that the blocks include Paleoproterozoic–Early Paleozoic igneous rocks and granitoids [1–4]. In order to find isotopic signs of the Early Precambrian (primarily, Archean) crust in the folded framing of the Siberian Craton and to correlate rock complexes of Precambrian terranes with rock associations of the exposed craton basement, we carried out the first systematic investigation of the Nd isotopic composition of metamagmatic and metasedimentary rocks. The results obtained made it possible to identify isotopic provinces and major stages of crust-forming events at the Siberian Craton margin.

Identification of crustal isotopic provinces and crust-forming stages is based on determination of the Nd model age of rocks in line with the traditional method [5, 6]. We understand the *isotopic province* as a crustal block of granitoids and felsic orthomagmatic rocks, the model age range of which differs from that of adjacent structures [5]. Our approach is distinguished by the complex analysis of isotope parameters of both granitoids and terrigenous metasediments. Their isotopic compositions reflect parameters of the middle–lower and upper crusts, respectively, which served as felsic melt sources and provenances. We can divide the isotopic provinces into homogeneous and heteroge-

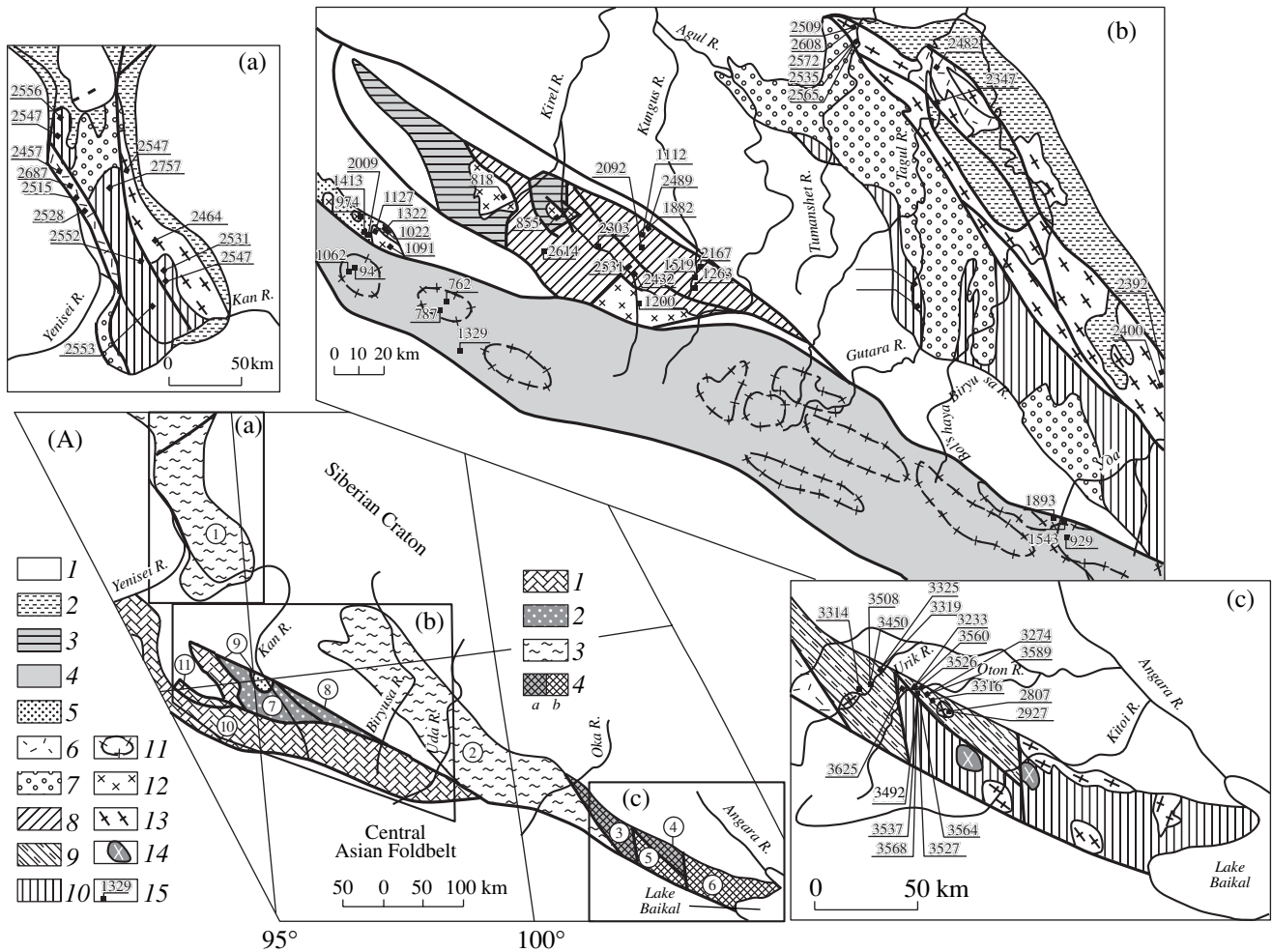
neous types. Homogeneous isotopic provinces have identical values of the model age of (meta)magmatic and (meta)sedimentary associations, whereas heterogeneous isotopic provinces are characterized by different values of the model age of the lower and upper crustal levels. Isotope data were analyzed with consideration of the possibility of rejuvenation of the model age of granitoids owing to the crust–mantle interaction in the course of their formation. We also took into account the possibility of age heterogeneity of crystalline complexes that served as sources of terrigenous material for sedimentary rocks.

Stages of crust-forming events can be identified based on the age of rocks of oceanic (ophiolite) complexes or the model age of felsic rocks with positive (close to the depleted mantle) ϵ_{Nd} values, because such rocks represent melting products of the juvenile crust [5, 6]. These constraints are best fulfilled by the Na-series granitoids (rocks of the tonalite–trondhjemite series) formed from basic or primarily crustal diorite–tonalite sources.

Our interpretations of results are based on the following suppositions: (i) Sm and Nd behave as immobile elements in the course of metamorphism; (ii) these elements are subject to insignificant fractionation during weathering, sedimentation, and intracrustal melting. In all rocks analyzed, the $^{147}\text{Sm}/^{144}\text{Nd}$ value (0.08–0.13) differs little from the average crustal value (0.12). Therefore, we can use values of the one-stage model age, $T(\text{DM})$ determined on the basis of the present-day values of isotope ratios for the depleted mantle (DM): $^{147}\text{Sm}/^{144}\text{Nd} = 0.21365$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.513151$. Calculation of $\epsilon_{Nd}(T)$ values was based on the present-day values for the chondrite uniform reservoir (CHUR): $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$. Sm and Nd concentrations and isotope ratios were mainly determined in the Geochronological Laboratory of the Geological Institute, Kola Scientific Center (Apatity) in accordance with the procedure described in [7].

^a Institute of Geology, Geophysics, and Mineralogy,
Siberian Division, Russian Academy of Sciences,
pr. akademika Koptyuga 3, Novosibirsk, 630090 Russia;
e-mail: turkina@uiggm.nsc.ru

^b Geological Institute, Kola Scientific Center, ul. Fersmana 14,
Apatity, Murmansk oblast, 184200 Russia



Crustal isotopic provinces at the southwestern margin of the Siberian Craton and its folded framing. (A) Provinces: (1) Meso-Neoproterozoic, (2) Paleoproterozoic, (3) Neoproterozoic, (4) Paleoproterozoic, (5) Neoproterozoic, (6) Paleoproterozoic, (7) Paleoproterozoic, (8) Paleoproterozoic, (9) Paleoproterozoic, (10) Paleoproterozoic, (11) Paleoproterozoic, (12) Paleoproterozoic, (13) Paleoproterozoic, (14) Paleoproterozoic, (15) Paleoproterozoic. (a) granite–greenstone, (b) granulite–gneiss. Blocks in the Siberian Craton basement (numbers in circles): (1) Angara–Kan, (2) Biryusa, (3) Erma, (4) Onot, (5) Kitoi, (6) Irkut; Precambrian blocks in the folded framing: (7–9) Kan ((7) Central, (8) Idar, and (9) Shumikha–Kirel terranes); (10) Derba; (11) Arzybei.

Legend for insets (a–c) showing geological sketches of the northwestern sector of eastern Sayan. (1) Phanerozoic complexes, (2–8) Precambrian stratificated complexes: (2–4) Neoproterozoic: (2) sedimentary, (3) metavolcanic, (4) metaterigenous–carbonate; (5) Mesoproterozoic metasedimentary–volcanic; (6–8) Paleoproterozoic: (6) metavolcanic–terrigenous, (7) metacarbonate–terrigenous, (8) metasedimentary–volcanic; (9, 10) Archean complexes: (9) granite–greenstone, (10) granulite–gneiss; (11–14) intrusive complexes: (11) Early Paleozoic (aureoles of veins and small massifs of the Derba Complex), (12) Meso–Neoproterozoic, (13) Paleoproterozoic, (14) Archean; (15) sampling points and Nd model age (Ma) based on the table and data reported in [1–4, 8, and 10].

Some analyses were carried out at the Institute of Precambrian Geology and Geochronology (St. Petersburg) and the Vernadsky Institute of Geochemistry and Analytical Chemistry (Moscow). In total, we examined the results of the isotopic analysis of approximately 80 samples presented in the figure, table, and our previous publications [1–4, 8, 9].

Based on values of the Nd model age, we can outline the Paleoproterozoic, Neoproterozoic, Paleoproterozoic, and Meso–Neoproterozoic crustal isotopic provinces (figure). Archean provinces correspond to uplifts of the Siberian Craton basement. The *Paleoproterozoic* province includes the Onot and Erma blocks in the northwestern

Sharyzhalgai Ridge composed of metasedimentary–volcanic rocks of greenstone belts and plagiogneisses and granitoids of the tonalite–trondhjemite–granodiorite (TTG) series. The model age is maximum (3.5–3.6 Ga) for TTG rocks of the Onot Block (table and [8, 9]). Based on the U–Pb dating of single zircon grains with magmatic zonation, plagiogneisses are 3386 ± 14 Ma old [8] and characterized by ϵ_{Nd} values close to 0 (from +1.2 to –0.4), suggesting the involvement of an older sialic material in their formation. Paleoproterozoic $T(DM)$ values (3.3–3.5 Ga) are also typical of TTG rocks from the Erma Block.

Sm–Nd isotope data on rocks from the southwestern margin of the Siberian Craton and its folded framing (Precambrian terranes)

Ord. no.	Sample no.	Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	T , Ma	$T(\text{DM})$, Ma	$\epsilon_{\text{Nd}}(T)$	Rock
		ppm							
1	49-03	2.40	15.0	0.096548	0.510446 ± 25	3400	3492	1.2	TTG gneiss
2	66-95	2.75	15.91	0.104269	0.510599 ± 27		3526		Tonalite
3	152-95	1.67	10.63	0.095080	0.510617 ± 18		3233		Trondhjemite
4	19-95	7.33	33.02	0.134151	0.511408 ± 20		3316		Metarhyolite
5	35-04	4.55	27.0	0.10180	0.510599 ± 15		3450		TTG gneiss
6	60-04	6.97	42.4	0.09930	0.510497 ± 19		3508		The same
7	67-04	5.11	34.9	0.08860	0.510402 ± 4		3325		Tonalite
8	69-04	3.03	23.5	0.07780	0.510170 ± 5		3319		Trondhjemite
9	23-04	13.3	96.1	0.08340	0.510297 ± 10		3314		Orthogneiss
10	98-73	7.99	44.17	0.1094	0.511395 ± 2		2553		Paragneiss
11	168-72	8.6	47.4	0.1097	0.511401 ± 6		2552		The same
12	1025	11.9	63.3	0.1140	0.511338 ± 5		2757		The same
13	314-79	24.6	134.8	0.11029	0.511415 ± 19	1750	2547	–4.5	Granite
14	187-82	8.35	47.51	0.106246	0.511411 ± 22	1880	2457	–2.1	Metadacite
15	288-78	9.27	51.95	0.107815	0.511275 ± 23		2687		Granite
16	242-78	6.82	33.96	0.1214	0.511612 ± 2	1880*	2528	–1.8	Paragneiss
17	283-78	6.95	38.6	0.1090	0.511416 ± 5	1880*	2515	–2.7	The same
18	289-81	8.18	40.83	0.121056	0.511636 ± 11	1880	2482	–1.3	Metarhyolite
19	253-81	2.71	18.27	0.089958	0.511232 ± 21	1860	2347	–1.9	Trondhjemite
20	124-93	3.46	19.63	0.10653	0.511363 ± 18	2300	2531	1.8	Orthogneiss
21	163-93	4.51	22.64	0.120473	0.511737 ± 16	2300*	2303	5.0	Paragneiss
22	210-96	6.0	33.38	0.108750	0.511342 ± 16	2300*	2614	0.7	The same
23	60-92	5.6	36.61	0.09245	0.512266 ± 22		1112		Trondhjemite
24	55-94	6.47	33.73	0.11595	0.511548 ± 20		2489		Paragneiss
25	44-94	6.54	33.54	0.11789	0.511965 ± 17		1882		The same
26	101-92	3.24	16.21	0.12087	0.511873 ± 14		2092		Orthogneiss
27	48-88	3.70	15.36	0.14563	0.512472 ± 10		1519		Paragneiss
28	63-88	5.94	35.57	0.10094	0.511542 ± 9		2167		The same
29	24-88	5.34	25.56	0.12262	0.512396 ± 7		1263		The same
30	83-94	2.09	13.1	0.09621	0.512521 ± 8	680	818	6.5	Trondhjemite
31	161-94	4.39	12.3	0.21541	0.513017 ± 8	680	–	5.8	Tonalite
32	25-92	1.96	8.99	0.131973	0.512442 ± 10		1322		Paragneiss
33	12-92	4.80	25.05	0.115900	0.511858 ± 12		2009		The same
34	230-90	1.91	9.65	0.119663	0.512521 ± 24		1022		The same
35	17-92	3.04	13.01	0.14135	0.512480 ± 20		1413		The same
36	101-91	1.12	7.26	0.09370	0.512552 ± 6	500	762	4.9	Granite
37	113-91	1.10	7.02	0.094932	0.512538 ± 18	500	787	4.6	The same
38	88-86	5.07	26.64	0.114984	0.511922 ± 20		1893		Paragneiss
39	71-86	4.93	23.49	0.126999	0.512272 ± 22		1543		The same
40	148-91	4.35	20.04	0.131257	0.512432 ± 19		1329		The same

Note: Blocks: (1–4) Onot, (5–9) Erma, (10–17) Angara–Kan, (18, 19) Biryusa, (20–31) Kan, (32–35) Arzybei, (36–40) Derba; terranes: (20–22) Central, (23–29) Idar, (30, 31) Shumikha–Kirel; (*) age of intercalating volcanic rocks. Sm and Nd concentrations and the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio were determined with an accuracy of $\pm 0.2\%$ (2σ). The accuracy of the determination of $^{143}\text{Nd}/^{144}\text{Nd}$ (2σ) is indicated in the table. The $^{143}\text{Nd}/^{144}\text{Nd}$ value during our work was 0.511833 ± 6 (2σ) for La Jolla ($N = 11$) and 0.512072 ± 2 (2σ) for Jindi ($N = 44$).

Thus, the Paleoproterozoic (3.4–3.6 Ga) stage of crust-forming events is marked by formation of the oldest igneous rocks in the Siberian Craton: plagiogneisses and tonalites and trondhjemites of TTG complexes. The subsequent evolution was related to recycling of the Paleoproterozoic crust. The overlying felsic metavolcanics of the Onot greenstone belt ($T(\text{DM}) = 3.3\text{--}3.6$ Ga) [8] and Paleoproterozoic (1.87–1.75 Ga) granitoids ($T(\text{DM}) = 2.8\text{--}2.9$ Ga, ϵ_{Nd} from -7.4 to -8.3) [9] are characterized by prograde decrease in the model age, reflecting the contribution of mantle material in the formation of felsic melts in the course of rifting and post-collisional extension [9, 10]. The Paleoproterozoic province also includes the Kitoi and Irkut granulite–gneiss blocks that represent the central and southeastern sectors of the Sharyzhalgai Uplift, respectively. Para- and orthogneisses rocks of these structures, which underwent early granulite metamorphism 2.6 Ga ago, have the $T(\text{DM})$ age of 3.1–3.4 Ga [11].

The *Neoproterozoic isotopic province* includes the Angara–Kan and Biryusa blocks (figure). The model age of para- and orthogneisses (metadacites) of the Kan and Khailama groups in the Angara–Kan and Biryusa blocks, respectively, varies from 2.6 to 2.8 Ga (table and [9]). This narrow age range serves as the timing of Neoproterozoic crust-forming events. Reconstruction of protoliths of metamagmatic rocks, which include metavolcanics of the differentiated basalt–andesite–rhyodacite association with the geochemical signature of island-arc volcanics (enrichment in LILE and depletion in HFSE), suggests the formation of the Neoproterozoic crust due to subduction magmatism. Rocks of the Paleoproterozoic (1.88 Ga) metavolcanic–sedimentary complex (Yenisei Group, Angara–Kan Block) formed at an active continental margin [12]. The $T(\text{DM})$ value in orthogneisses (ϵ_{Nd} from -1.2 to -2.0) and metaterrigenous rocks varies from 2.5 to 2.7 Ga (table).

The isotope parameters given above indicate that the formation of felsic metavolcanics and metapelites of the Yenisei Group and its age analogue in the Biryusa Block (Subluk Group) is related to the recycling and erosion of the Neoproterozoic crust. Data presented in the table and [9] suggest the following conclusions: the $T(\text{DM})$ value of Paleoproterozoic (1.84–1.75 Ga) granites of the Angara–Kan Block (ϵ_{Nd} from -2.8 to -4.5) varies from 2.5 to 2.6 Ga; this age range is virtually identical to the model age of host rocks (Kan Group), which could serve as the main source of felsic melts; in contrast, granitoids of the Biryusa Block are characterized by a lower model age ($T(\text{DM}) = 2.34\text{--}2.6$ Ga) relative to the host para- and orthogneisses of the Khailama Group (2.6–2.8 Ga); hence, both the Neoproterozoic crust and mafic material were involved in the formation of felsic melts. Thus, the Paleoproterozoic (1.88–1.75 Ga) history of the basement of the southwestern Siberian Craton was characterized by recycling of the older

(Archean) crust without any significant supply of juvenile material.

The Kan Block can be divided into the Central, Idar, and Shumikha–Kirel terranes (figure). The outlines of the Paleoproterozoic isotopic province fit the Central terrane of the Kan Block composed of the subduction-related metasedimentary–volcanic complex. The table shows that orthogneisses (metadacites) of this structure (~ 2.3 Ga [2]) are marked by positive values of ϵ_{Nd} (1.8–3.0) and $T(\text{DM})$ (2.4–2.5 Ga). Similar model age values (2.3–2.6 Ga) were also recorded for intercalations of metavolcanics with paragneisses, the protoliths of which could be island-arc graywackes. The isotope parameters of orthogneisses indicate the juvenile character of crust in the Central terrane. Therefore, we can identify the Paleoproterozoic (2.3–2.5 Ga) crust-forming stage marked by formation of the island-arc volcanic (basalt–andesite–dacite) complex.

The *Meso–Neoproterozoic isotopic province* comprises the Arzybei and Derba blocks and the Shumikha–Kirel terrane, which represents the northwestern segment of the Kan Block (figure). The island-arc complex of the Arzybei Block includes tholeiitic and cal-alkaline metavolcanics of the basalt–andesite–dacite association and intrusive tonalites and trondhjemites [3]. Intrusive tonalites and trondhjemites of the Arzybei Block (~ 1020 Ma) and postorogenic potassium granites (~ 560 Ma) have nearly DM parameters (ϵ_{Nd} from $+4.5$ to $+6.7$ and $T(\text{DM}) = 1.0\text{--}1.1$ Ga [3]). The Derba Block is composed of the Late Precambrian metaterrigenous–carbonate complex with the upsection grading of metaterrigenous rocks (graywackes and the less common pelites and quartzites) into the metacarbonate varieties. The early Caledonian orogenesis was responsible for the metamorphism of sedimentary rocks of this terrane and the formation of syncollisional quartz diorites (U–Pb age 498 Ma), tonalites, and microcline granites [4]. Depletion of garnet of the Derba Block in HREE ($\text{La}/\text{Yb}_m = 12\text{--}64$) indicates the formation of melts in equilibrium with granites at the middle and lower levels of the crust. Collisional granitoids of the Derba Block are characterized by an ϵ_{Nd} value ranging from $+1.4$ to $+4.9$ and the Nd model age of 0.8–1.1 Ga (table and [4]). These values suggest that the metasedimentary sequence is underlain by the Meso–Neoproterozoic crust, the timing of which is similar to that of rock complexes in the Arzybei Block. Isotope data on island-arc and collisional rocks (diorites, tonalites, and trondhjemites) of the Arzybei and Derba blocks with high positive values of ϵ_{Nd} (from $+6.7$ to $+2.9$) and the model age ($T(\text{DM}) = 0.9\text{--}1.1$ Ga) make it possible to identify the Mesoproterozoic crust-forming stage that produced the island-arc magmatic complexes. The validity of this stage is also supported by the U–Pb age of plagiogranites from ophiolites (1020 Ma) in the Dunzhugur island arc [13].

The REE distribution in metaterigenous rocks of the Arzybei and Derba blocks is similar to that in metasediments related to the erosion of island-arc magmatic rocks [4]. In contrast to granitoids, terrigenous metasediments are characterized by a wide range of Nd model ages varying from 1.0 to 2.0 Ga (table). The minimum value (1.0 Ga) suggests that the terrigenous constituent of sediments involved materials derived from the Meso–Neoproterozoic island-arc crust. In the metasediments, the model age shows a distinct positive correlation with the La/Sc and Th/Sc ratios. Isotope–geochemical data indicate that metagraywackes could be produced by the mixing of terrigenous material derived from the Meso–Neoproterozoic and Early Precambrian crust. The terrigenous component was related to the erosion of Meso–Neoproterozoic island-arc complexes similar to those in the Arzybei Block. Products of the Early Precambrian crust were enriched in La and Th due to the contribution of felsic magmatic rocks. Thus, vertical isotopic heterogeneity is typical of the continental crust in the Arzybei and Derba blocks.

The Neoproterozoic crust includes oceanic and island-arc metavolcanic (basalts and andesite–dacites) and plagiogranitoid complexes of the Shumikha–Kirel terrane [1]. Intrusive tonalites and trondhjemites of this structure (U–Pb zircon age 686 ± 32 Ma) are characterized by positive ϵ_{Nd} values (from +5.8 to +6.5) and $T(DM) = 0.8–0.85$ Ga (table and [1]). These values support the validity of the Neoproterozoic stage of crust formation. The Central Asian Foldbelt includes numerous Neoproterozoic oceanic and island-arc complexes with the age varying from 800 to 570 Ma [13, 14].

The age of the crust in the northern Idar terrane (Kan Block) remains a debatable issue because of the scarcity of felsic metavolcanic rocks and granitoids in this structure. The terrane is mainly composed of the lower metabasalt and the upper metasedimentary (metagraywacke) sequences [2]. Paragneisses (metagraywackes and metapelites) of the Idar terrane are similar to those in the Arzybei and Derba blocks in terms of the model age variation from 1.3 to 2.5 Ga (table), suggesting different ages of their provenances (Mesoproterozoic and older continental crusts). This interpretation is supported by the Mesoproterozoic model age (1.1 Ga) of vein trondhjemites and the Paleoproterozoic age (2.1 Ga) of orthogneisses (metadacites). The available data suggest that the Idar terrane can be a member of the Paleoproterozoic crustal isotopic province.

Thus, analysis of the isotope data allowed us to divide the southwestern margin of the Siberian Craton and its folded framing into four crustal isotopic provinces: (i) Paleoarchean province (3.1–3.6 Ga); (ii) Neoarchean province (2.6–2.8 Ga); (iii) Paleoproterozoic province (2.3–2.6 Ga); and (iv) Meso–Neoproterozoic province (0.8–1.1 Ga). In addition, we can outline several discrete stages of crust-forming events. The Paleoarchean (3.6–3.4 Ga) and Neoarchean (2.8–2.6 Ga) stages are identical to those previously revealed in crystalline

complexes of the Aldan and Anabar shields and the buried basement of the Siberian Craton [15]. The continental crust of Precambrian blocks in the folded framing of the Siberian Craton is genetically related to Proterozoic crust-forming events. This process was not accompanied by recycling of the Archean sialic material. Early Precambrian crystalline complexes of the Siberian Craton could only be a source of terrigenous material, resulting in the vertical isotopic heterogeneity of the Derba and Arzybei blocks. The juvenile Paleoproterozoic crust (2.3–2.5 Ga) represented by rocks of the Central terrane (Kan Block) in the modern structure is related to subduction magmatism. Crust-forming events are lacking in the interval of 1.2–1.6 Ga (Early and Middle Riphean). All Nd model ages of this range are confined to metasedimentary rocks. These values are related to the mixing of erosion products of island-arc complexes (≤ 1.1 Ga) and the Early Precambrian crust. Processes of the Meso–Neoproterozoic crust formation began after 1.1 Ga B.P. Our data and the available isotope–geochronological information [13, 14] testify to a discrete growth of the continental crust due to processes of subduction magmatism at the terminal Mesoproterozoic (1.1–0.9 Ga) and Neoproterozoic (0.8–0.57 Ga).

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