

Sm–Nd and U–Pb Age of Metabasic Dikes in the Granulite–Gneiss Domain of the Aldan Shield As Evidence of Paleoproterozoic Thermotectogenesis Duration

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The integral process of autonomous deformation, magmatism, and metamorphism superimposed on seemingly consolidated older rock complexes was called *thermotectogenesis* by Pavlovskii [1]. The most vigorous tectonothermal events that affected the Archean tectonic units of the Earth's crust occurred in the Paleoproterozoic 2.76–1.65 Ga ago as a manifestation of mantle plumes [2]. As elsewhere, the Paleoproterozoic thermotectogenesis was widespread in the Aldan Shield and resulted in the formation of its zonal structure, including the central granulite–gneiss domain and granite–greenstone framework; the emplacement of autonomous anorthosite massifs [3] and complementary granitoids; and the injection of mafic dikes, which are regarded as indicators of mantle plumes [2]. These processes were accompanied by rearrangement of isotopic systems, so that the dating of rocks encounters problems [5–7]. This work is aimed at estimation of the duration of the aforementioned processes on the basis of geological and isotopic data on mafic dikes in the Sunnagin enderbite dome that occupies the northern sector of the multidomal granulite–gneiss domain of the Aldan Shield (Fig. 1).

The geology of the Sunnagin dome, the largest one (380 × 300 km) among similar structures of the Aldan Shield, was described in detail in [8]. Its core is composed of low-K enderbite (<2 wt % K₂O) with numerous dark metabasic inclusions (pyroxene–plagioclase crystalline schists), which are considered to be frag-

ments of the basic protocrust (infrastructural complex). Enderbites of the first generation are compared with the Archean plagiogranites that occur in the western Aldan Shield in the core of the Central Aldan dome (Grekov rapids in the Aldan River) with the U–Pb zircon age of 3570 ± 60 Ma (classic method) and 3335 ± 3 Ma (SHRIMP method) at the upper intercept of concordia with discordia and 1860 ± 50 and 1935 ± 9 Ma, respectively, at the lower intercept [7]. The Paleoproterozoic ages obviously mark the disturbance of isotopic systems in regenerated zircon grains induced by an extensive thermal event. This contention is supported by the U–Pb zircon age of low-K enderbite from the Sunnagin dome (1977 ± 36 and 1985 ± 2 Ma) and of medium- and high-K enderbites of the second generation (>2 wt % K₂O) dated at 2044 ± 6 Ma [6] (Fig. 1). The younger granitoids universally replace the infrastructural complex that is retained only in shadow relicts. The geologically discordant ages of zircons in enderbites of the first and second generations should be regarded as a reflection of isotopic system disturbance related to different thermotectonic pulses (see below).

The limbs of the dome are composed of migmatized supracrustal gneiss series that consists of high-Al gneisses and crystalline schists with sporadic interlayers of quartzite, marble, and calciphyre.

In addition to metabasic rocks of the infrastructural complex, the melanocratic sills and dikes occur in the core and at the limbs of the Sunnagin dome. These minor intrusions regarded as main indicators of plume events [2] were chosen as the objects of our study. The sills and dikes are composed of fine- and medium-grained, massive and coarse-banded pyroxene–plagioclase and amphibole–pyroxene–plagioclase crystalline schists with occasional garnet and biotite [8, 9]. These rocks are subdivided into three morphogenetic types (A, B, and C) of different ages.

The sampling and processing were carried out using the standard techniques [5, 6]. The geochemical and isotopic studies were performed at the Vinogradov

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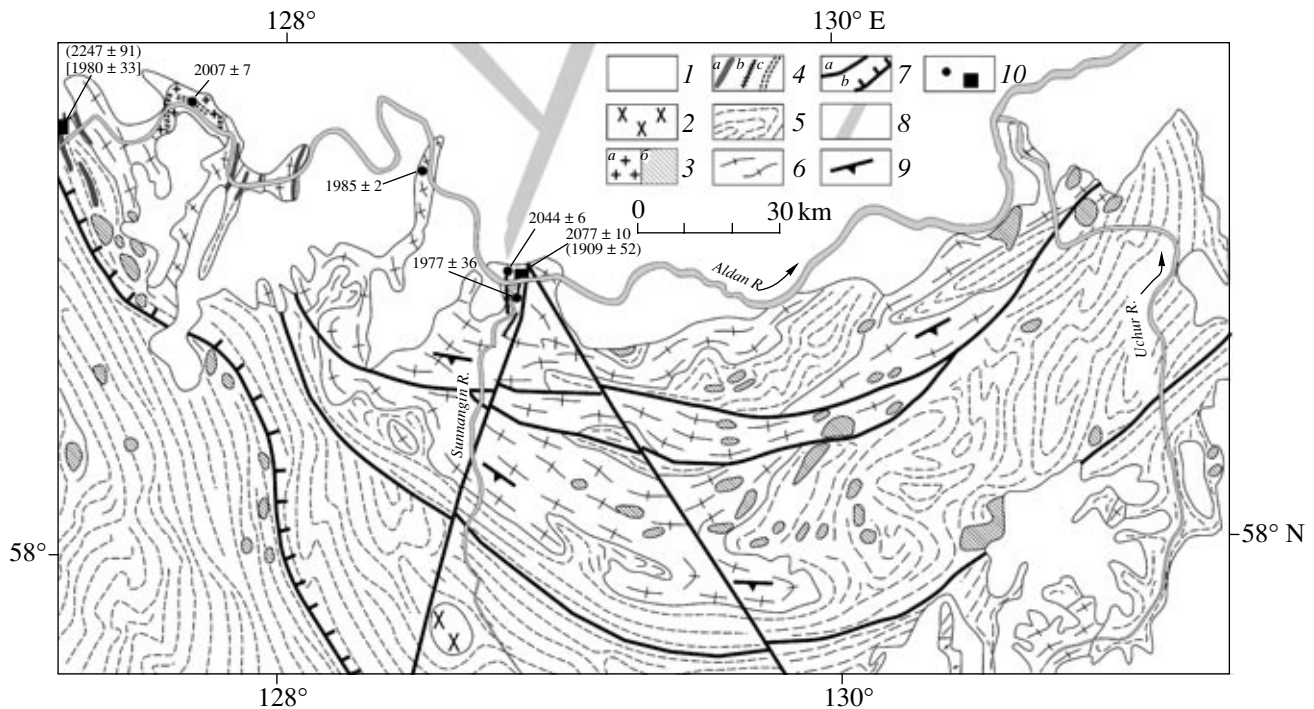


Fig. 1. Geological sketch map of the southern Sunnagin enderbite dome. (1) Platform cover, unspecified; (2) Mesozoic syenite; (3) Paleoproterozoic granitoids: (a) hypersthene granodiorite of the Emelleli massif and (b) alaskite; (4) mafic dike types: (a) A, (b) B, and (c) C; (5, 6) Archean rocks: (5) gneiss series, unspecified (supracrustal complex), (6) unspecified association of enderbites and basic rocks of the infracrustal complex and enderbites of normal alkalinity; (7) faults: (a) concentric faults of the dome, (b) Timpton Thrust Fault; (8) axes of positive magnetic anomalies; (9) orientation of gneissic banding in enderbites; (10) samples and their isotopic ages: (a) enderbite and granodiorite, (b) metabasic rocks. Datings are based on the U–Pb zircon method (without parentheses), Sm–Nd method (in parentheses), and Rb–Sr method (in brackets). See text for additional explanation.

Institute of Geochemistry, Siberian Division, Russian Academy of Sciences (RAS), and at the Geological Institute, Kola Scientific Center, RAS, respectively. Analytical results are presented in Tables 1–3.

Metabasic rocks of type A make up thick (up to 400 m) and extended (up to a few kilometers) sill-shaped bodies and dikes commonly lying conformably with migmatized rocks of the Archean supracrustal gneiss series and granitoids. To determine the composition and age of these metabasic rocks, a 340-m thick sill-shaped body exposed on the western limb of the Sunnagin dome (Fig. 1) has been sampled. The sampling was carried out with a spacing of 20–60 m.

In terms of facies conditions, the metabasic sill-shaped bodies and dikes of type A correspond to granulite metamorphism [9] that promoted a relative retention of the Sm–Nd isotopic system. Therefore, we can judge about the age of this high-temperature (700–800°C) event.

As is evident from Table 2 and Fig. 2a, the Sm–Nd isochron age of type-A metabasic rocks (6 whole-rock samples) is 2247 ± 91 Ma ($\epsilon_{Nd} = +1.8 \pm 0.3$). The average model Nd age ($T_{DM} = 2.35$ Ga) is close to the Sm–Nd age of dike emplacement and testifies to a short crustal prehistory of the rocks. The Rb–Sr isochron age of the same samples determined previously at $1980 \pm$

33 Ma [9] most likely indicates the age of closure of the Rb–Sr isotopic system at 500–400°C at the final stage of thermotectogenesis.

Thus, the synmetamorphic metabasic dikes of type A, which were previously suggested to be Archean, are actually Paleoproterozoic.

Metabasic rocks of type B make up deformed dikes similar to the Precambrian Ameralik and Melene granulite- and amphibolite-facies dikes in southwestern Greenland [11]. The type B dikes are controlled by N–S- and NW-trending radial faults of the Sunnagin dome that extend for 500 and 200 km, respectively. These faults are hidden beneath the platform cover but are traceable in the anomalous magnetic field [8] (Fig. 1). The metabasic rocks of diverse configurations are exposed at the southern margin of the longitudinal swarm, on the left bank of the Aldan River and along the channel of its right tributary (Sunnagin River). The dikes are hosted here in enderbites of elevated alkalinity. The dike fragments, as long as 2 m and more, reveal distinct contacts with enderbites of the second generation. In addition, melanocratic boudins or extended bent ribbons up to a few meters wide and a few tens of meters long are hosted in the enderbite. Sample G-5/3 (small rock fragments, 10 kg in total weight) was taken from the central sector of a dike 1.3 m thick on the left

Table 1. Major oxide (wt %) and trace element (ppm) compositions of mafic dikes (types A, B, and C)

Component	A	B	C	Element	A	B	C	Ratio	A	B	C
SiO ₂	50.60	45.93	45.26	Ba	380	317	129	Ba/La	16.60	15.85	12.28
TiO ₂	0.70	2.02	0.80	Sr	396	249	346	Rb/La	1.88	1.30	2.00
Al ₂ O ₃	14.55	8.65	13.15	Rb	43	26	21	Rb/Sr	0.11	0.10	0.06
FeO	8.70		3.80	Zr	98	142	73	(La/Yb) _N	8.12	10.30	4.60
Fe ₂ O ₃		17.43	9.40	La	22.86	20	10.50	(La/Sm) _N	1.86	2.06	2.09
MnO	0.18	0.20	0.20	Ce	49.60	43	22.30	(Ce/Yb) _N	6.65	8.42	3.71
MgO	10.45	13.79	12.84	Nd	34.30	26	12.10	Eu/Eu*	0.60	0.89	0.77
CaO	10.25	8.54	10.80	Sm	6.66	6.00	3.10				
Na ₂ O	3.00	1.59	1.99	Eu	1.20	1.70	0.68				
K ₂ O	1.25	1.08	0.90	Gd	5.10	5.60	2.10				
P ₂ O ₅	0.20	0.20	0.1	Er	2.20	2.00	1.78				
Total	99.88	99.43	99.49	Yb	1.90	1.30	1.53				

Note: (A) average of 8 samples, (B) one sample, (C) average of 6 samples.

Table 2. Sm–Nd isotopic data on metabasic rocks from type A dikes (nos.1–6) and type B dikes (nos. 7–10)

Ord. no.	Sample	Content, ppm		Isotope ratio		Model Nd age, t_{DM} , Ma
		Sm	Nd	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	
1	2/1	6.503	36.686	0.107160	0.511402 ± 16	2329
2	2/2	4.201	21.585	0.117650	0.511555 ± 14	2374
3	2/4	7.792	37.920	0.124218	0.511647 ± 9	2386
4	2/5	5.861	31.164	0.113687	0.511513 ± 10	2306
5	2/6	5.607	23.901	0.141806	0.511921 ± 10	2348
6	2/8	3.663	18.026	0.122845	0.511634 ± 9	2354
7	5/3 Amp	61.329	270.377	0.137120	0.511660 ± 20	
8	5/3 Px	7.204	30.416	0.143176	0.511741 ± 12	
9	5/3 Pl	4.994	30.205	0.099943	0.511195 ± 15	
10	G-5/3	5.5	23.8	0.14021	0.511699 ± 13	2296

Note: (Amp) amphibole, (Px) pyroxene, (Pl) plagioclase, (G-5/3) whole-rock sample.

Table 3. U–Pb isotopic data on zircons from the type B metabasic dike (sample G-5/3)

Ord. no.	Charge, mg	Content, ppm		Pb isotopic composition			Isotope ratios and age, Ma			Rho
		Pb	U	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{207}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{208}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	
1	0.50	53.0	135.0	3825	7.5527	8.5862	6.46752	0.363763	2084	0.91
2	0.30	35.6	88.0	962	7.0036	6.7297	6.38045	0.358582	2085	0.92
3	0.50	29.4	68.4	843	6.2841	5.1653	6.28613	0.352578	2089	0.85

bank of the Aldan River, opposite to the mouth of the Sunnagin River (Table 1, Fig. 1).

The U–Pb age has been determined for three zircon grain varieties (Table 3). The first variety is pale yellow long-prismatic crystals of the hyacinth-zircon type with

rounded apices and distinct faces, 0.225 ± 0.05 mm in size (elongation coefficient 4.5). The grains are transparent and have a glassy luster. The second variety comprises dark yellow crystals of the same morphology and 0.275 ± 0.1 mm in size (elongation coefficient 2.8). The third variety is dark yellow, transparent short-pris-

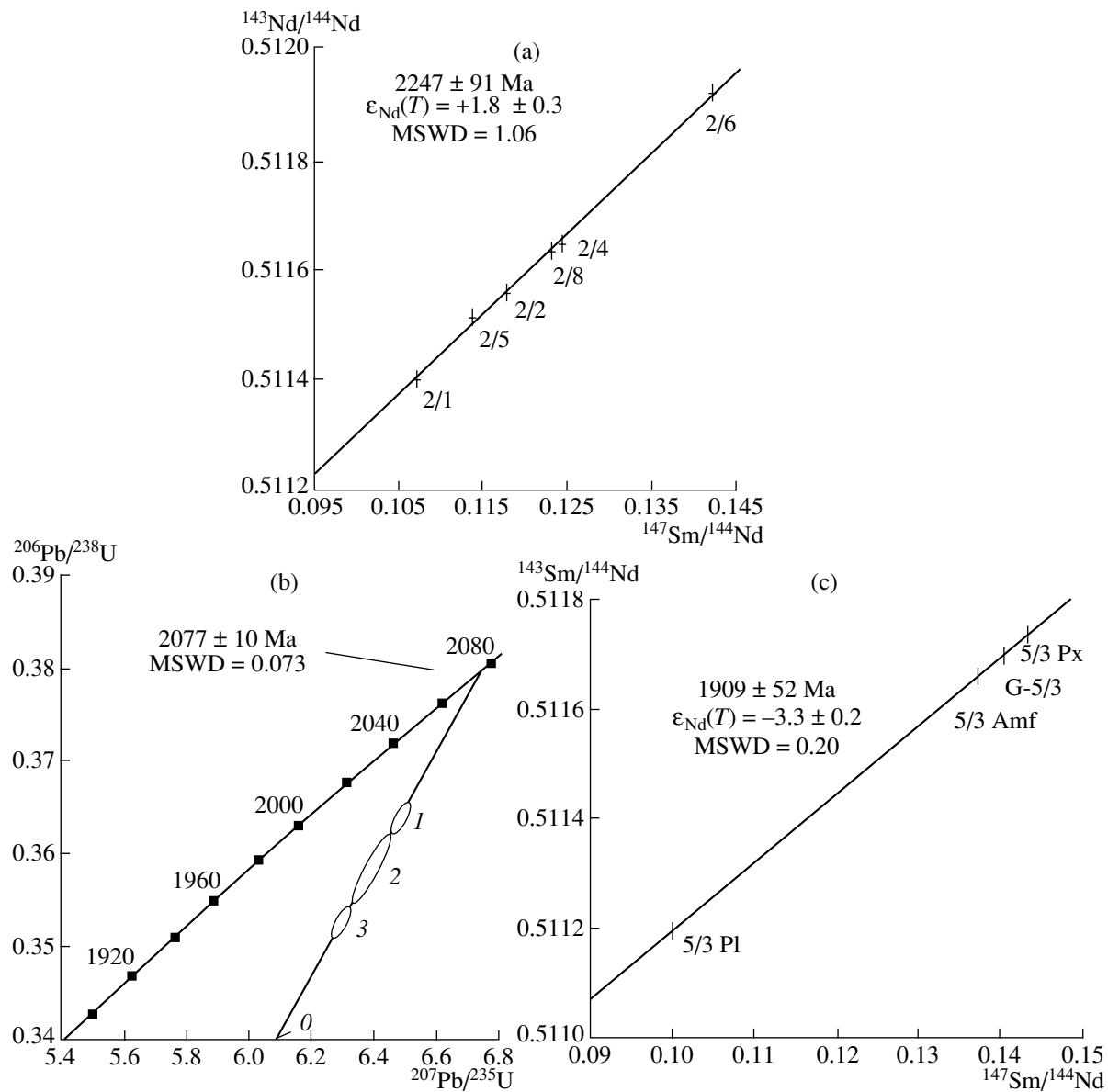


Fig. 2. (a, c) Sm–Nd isochrons for metabasic rocks of types A and B, respectively. (b) U–Pb diagram with concordia for zircons from type B metabasic rocks.

matic crystals 0.15 ± 0.0075 mm in size with a glassy luster (elongation coefficient 2.0). The surfaces of all grains are corroded, and a distinct fine zoning is observed in the immersion liquid.

The Sm–Nd isochron age of metabasic rocks was determined for coexisting minerals (amphibole, pyroxene, plagioclase) and a whole-rock sample (Table 2).

As follows from theory [10], if a U–Pb zircon age of 2077 ± 10 Ma (Fig. 2b) corresponds to the Paleoproterozoic time of magma generation and emplacement of type B dikes, which were previously considered Archean [8], then the Sm–Nd isochron age of 1909 ± 52 Ma and $\epsilon_{\text{Nd}} = -3.30 \pm 0.20$ (Fig. 2) marks the time of metamorphism and deformation of these dikes. At $T =$

2100 Ma, the model Nd age of its protolith (T_{DM}) is 2996 Ma (ϵ_{Nd} is -3.12 ± 0.25).

The type C dikes occur in the Emelleli dome-shaped massif 17 km in diameter, which is composed of high-temperature ($710\text{--}840^\circ\text{C}$) hypersthene granodiorite with U–Pb zircon age of 2007 ± 7 Ma [5]. The dikes 20–50 m thick fill synkinematic fractures, which, as magmatic banding, are conformable to the massif morphology (Fig. 1).

The chemical compositions of type C metabasic dikes are presented in Table 1.

The close spatial and structural association of these dikes with Paleoproterozoic granodiorite allows us to suggest that they have similar ages.

As indicated by the compositional features (Table 1), the recognized morphogenetic types of dikes different in age are most likely related to the activity of the mantle plume [2, 12, 13]. All dikes are enriched in lithophile elements (primarily K, Rb, Sr, and Ba) and LREE (see the La/Yb, La/Sm, and Ce/Yb ratios in Table 1). They are also enriched in Mg or Fe in different places. The Ba/La, Rb/La, and Rb/Sr ratios are higher than the PM values (9.27, 1.0, and 0.03, respectively). At the same time, the high TiO₂ content (>2 wt %) typical of plume basalts [12] is established only for type B metabasic rocks with negative ϵ_{Nd} (enriched mantle) and a Neoproterozoic age of the protolith. The type A dikes contain less TiO₂ and are characterized by positive ϵ_{Nd} (depleted mantle) and a Paleoproterozoic age of the protolith. These discrepancies may be caused either by different depths of magma generation and the degree of partial melting reflected in REE patterns (Table 1) or by the composition of the Archean subcontinental mantle affected by metasomatism in the process of Paleoproterozoic thermotectogenesis [14].

Thus, the Paleoproterozoic mafic dikes in the granulite–gneiss domain of the Aldan Shield are indicators of a mantle plume. Its ascent bore a pulsatory character and was accompanied by a high heat flow and considerable stress in the upper portion (as much as 800 MPa [13]). These conditions provided repeated regional granulite-facies metamorphism of Archean infra- and supracrustal complexes initially metamorphosed under conditions of amphibolite facies, their remobilization, and rearrangement of isotopic systems. The thermal pulses are recorded in the closure of the Rb–Sr and Sm–Nd systems in dikes of types A and B and the U–Pb system of regenerated zircon grains in Archean granitoids (approximately 1950–2050 Ma). The thermal pulses could have predated, accompanied, and terminated the stages of magmatic activity. While the plume was ascending, the Archean metasomatically altered lithospheric mantle was involved in partial melting with formation of magma sources for synmetamorphic mafic dikes of the first two stages of thermotectogenesis dated at 2247 ± 91 and 2077 ± 10 Ma. The dikes were injected into concentric and radial fractures and faults that cut enderbite domes. At the third stage (2007 ± 7 Ma), the partial melting of the lithospheric mantle and lower crust resulted in the formation of a quartz-dioritic melt and emplacement of the Emelleli granodiorite [5] and related mafic dikes.

Thus, the Paleoproterozoic thermotectogenesis in the Aldan Shield developed discretely during ~250 Ma. Three magmatic and metamorphic pulses, dated at

approximately 2.25, 2.08, and 2.0 Ga fill an interval between the major superplume eras in the Earth's history that occurred around 2.4 and 1.8 Ga [2]. The long-term Paleoproterozoic thermotectogenesis focused on the multidomal granulite–gneiss domain of the Aldan Shield was probably related to the origination and development of the Precambrian continental crust in the course of its multistage and irreversible tectonic evolution in the near-equatorial belt of mantle plumes of the early Earth [15].

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