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GEOLOGY

The Vendian–Cambrian Boundary: Rb–Sr Isochron Age of the Final Event of Alkaline Ultrabasic Magmatism in the Northeastern Sayan Region

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The Vendian–Cambrian boundary is one of the most important geological milestones in the Earth's evolution. It is suggested that the short-living Pannotia supercontinent was breaking out at that time as a result of vigorous global tectonothremal activity. Magmatism of this age was spectacular at the periphery of the West African Craton, which played the role of thermal insulation cover in the Late Precambrian. The heat release as a consequence of magmatic activity induced the melting of the polar ice sheet, eustatic sea-level rise, and greenhouse and other effects favorable for the bloom of living organisms [1]. Study of Late Precambrian magmatic events at margins of other cratons are required to substantiate this hypothesis. In this work, we report the results of Rb–Sr isotopic dating of the late Vendian Zima alkaline ultrabasic igneous rock complex from the Sayan uplift of the Siberian Craton basement.

A geochronological investigation of the Zima Complex had been carried out since 1962 by researchers from several scientific institutions. Forty-four K–Ar datings of nephelinites and carbonatites yielded values ranging from 700 to 500 Ma (data from [2–4], recalculated with a new constant of ^{40}K decay). The ^{40}Ar–^{39}Ar ages of 666 ± 18 and 584 ± 6 Ma have been obtained for micas from kimberlite-like rocks [6]. The Rb–Sr age of 635 ± 18 Ma was reported for the whole-rock samples of nepheline-bearing rocks from the Bol'shetagnin and Belozimin intrusions [7].

However, the published geochronological material do not provide reliable dating of the Zima Complex emplacement, because K–Ar datings were performed for whole-rock samples and mineral fractions of cancrinite-bearing nepheline rocks and for amphiboles and micas from carbonatites [2–4]. The results obtained are obviously overestimated owing to a large quantity of excess Ar in cancrinite [8]. The presence of excess Ar in amphiboles and micas from carbonatites is also probable, because the ^{40}Ar/^{36}Ar ratio in these minerals (up to 1000 or more) is much higher than the atmospheric value of 295.5 [5, 9]. Rb–Sr dating [7] was performed for whole-rock samples that underwent recrystallization, and the scattering of data points does not fit the isochron model, as indicated by a high MSWD value [10]. The ^{40}Ar–^{39}Ar results [6] are the most reliable, but they have been obtained for kimberlite-like rocks having vague relationships with nephelinites and carbonatites typical of the Zima Complex.

We found a 1.5-m-thick nephelinite vein, which was not affected by secondary alterations commonly accompanying the intrusion of carbonatites, at the source of the Belaya Zima River, 3 km northwest of the Verkhnii Sayan carbonatite massif (Fig. 1). The nephelinite is greenish gray and has a sporadophyric texture. Nepheline, mica, clinopyroxene, and magnetite occur as phenocrysts. The poikilitic groundmass is composed of nepheline (80%) and clinopyroxene (20%).

The nepheline phenocrysts vary from 2 to 10 mm in size and are often replaced by cancrinite. According to microprobe results (Table 1, sample 6-89/1), the calcilite molecule content does not exceed 20–25%. Nepheline of the groundmass makes up poikilitic intergrowths with clinopyroxene and is not affected by secondary alterations. It is compositionally similar to nepheline phenocrysts (Table 1, Sample 6-89/2).

Mica (biotite) occurs only as phenocrysts, 2–5 mm in size. According to the Fe/(Fe + Mg) ratio, the biotite from nephelinite (Table 1, samples 6-89/3 and 6-89/4) is similar to the counterpart from nephelinitic intrusive rocks of the Verkhnii Sayan massif and differs by a lower Fe/(Fe + Mg) ratio from biotite of the Nizhnii Sayan massif (unpublished data of B.M. Vladimirov).

Clinopyroxene is deep green with a bluish tint and corresponds to aegirine–augite in chemical composition (Table 1, samples 6-89/5 and 6-89/6). Sporadic magnetite phenocrysts are commonly replaced by martite.

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Monomineral fractions of pyroxene, mica, and nepheline phenocrysts were picked up for the dating. Nepheline from the groundmass was also taken. The sample decomposition was performed with concentrated fluoric and nitric acids under pressure in Teflon bombs. Strontium was separated on chromatographic columns filled with Dowex 50 × 8 resin. The Sr and Rb concentrations and Sr isotopic composition were measured on a MI-1201 mass spectrometer with a PRM-2 attachment. The measurement technique is described in [11]. The results are presented in Table 2. The age and initial Sr isotope ratio were calculated by a linear regression method [10] using the ISOPLOT program [12], and by the pair method, which takes into account the probability function of measured age values for each pair of points [13]. The ^{87}Rb decay constant was accepted $1.42 \cdot 10^{-11}$ yr^{-1} [5].

The slope of regression line for all minerals yielded 547.0 ± 8.3 Ma (±2σ) and $(^{87}Sr/^{86}Sr)_0 = 0.70308 \pm 0.00019$, MSWD = 3.17. The points for mica and two nepheline fractions yielded 546.1 ± 2.2 Ma (±2σ) and $(^{87}Sr/^{86}Sr)_0 = 0.70359 \pm 0.00074$, MSWD = 0.93 (Fig. 2). Both age values are defined by the high Rb/Sr ratio in mica and are concordant within the error limits. The low initial Sr isotope ratios point to a slightly depleted mantle source.

The age distribution function based on the pair method [13] is close to the normal (Gaussian) distribution (Fig. 3). The measured age within the 95% confidence interval falls in a range from 544 to 550 Ma with the most probable value of 546.7 Ma. The standard deviation of age is 3.2 times higher than the theoretical value issuing from measurement uncertainties.

The low MSWD value for the linear regression [10] and almost normal distribution of ages in the pair method [13] allow us to accept the obtained Rb–Sr date of 546–547 Ma as the age of the nephelinite vein. All calculated age values coincide within error limits with the Vendian–Cambrian boundary at 544 Ma established by the U–Pb zircon method for pyroclastic breccia at the base of the Nemakit–Daldyn Stage (Manykaian Formation) [14]. Its stratotype is situated at the northeastern margin of the Siberian Craton, whereas the

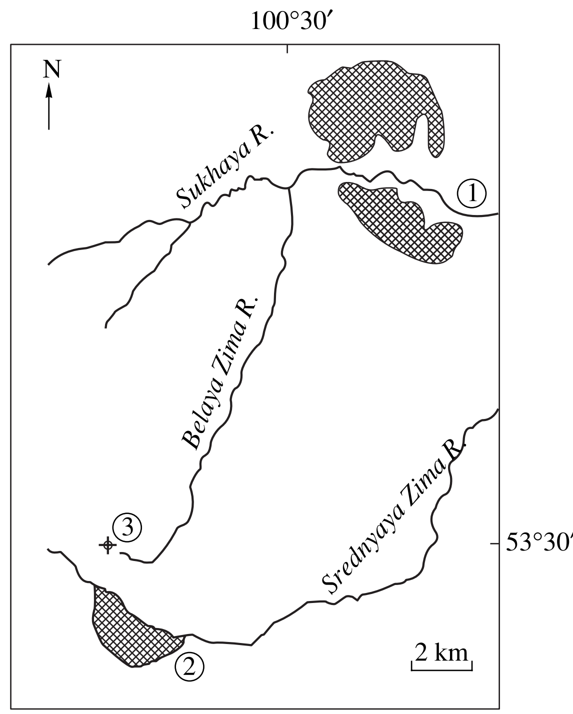

Fig. 1. Position of the dated nephelinite dike of the Zima alkaline ultrabasic complex. (1) Nizhnii Sayan massif, (2) Verkhnii Sayan massif, (3) nephelinite dike.

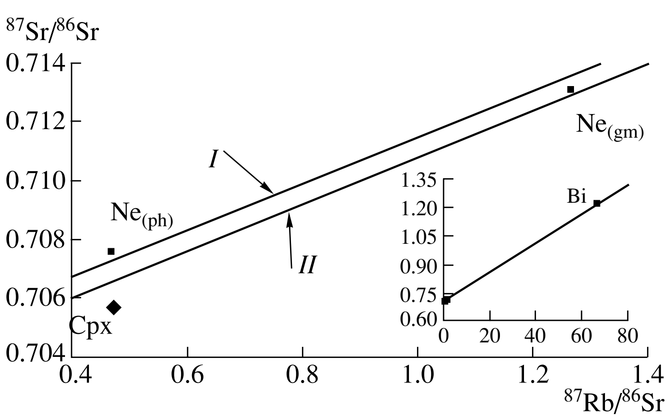

Fig. 2. Rb–Sr isochron diagram for nephelinite minerals. Calculations were carried out by the York method [10]. (Cpx) Clinopyroxene, ($Ne_{(gm)}$) nepheline from groundmass, ($Ne_{(ph)}$) nepheline phenocryst, (Bi) biotite. (*I*) Isochron without clinopyroxene: MSWD = 0.93, $t = 546.1 \pm 2.2$ Ma, $(^{87}Sr/^{86}Sr)_0 = 0.70359 \pm 0.00074$; (*II*) all points: MSWD = 3.17, $t = 547.0 \pm 8.3$ Ma, $(^{87}Sr/^{86}Sr)_0 = 0.70308 \pm 0.00019$.

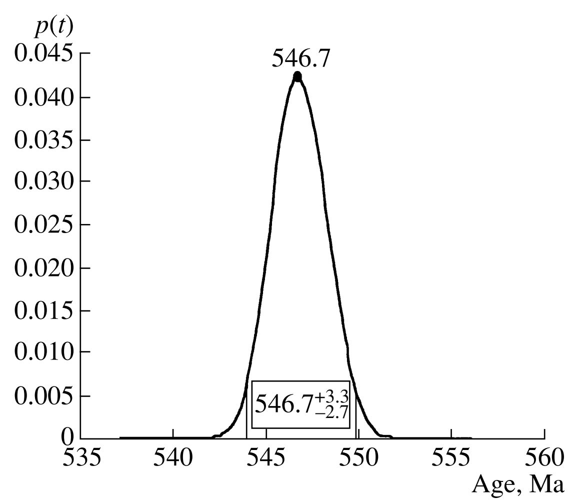

Fig. 3. Distribution density of mineral pair ages. Calculation was performed by the pair method [11]. The parameter $p(t)$ is given in relative units.

Table 1. The chemical composition of nephelinite and minerals therein, wt %

Component	6-89	6-89/1	6-89/2	6-89/3	6-89/4	6-89/5	6-89/6
SiO_2	47.14	45.27	44.35	36.65	37.87	50.20	50.70
TiO_2	0.86			3.07	3.84	0.47	0.41
Al_2O_3	17.65	32.80	32.78	13.10	12.65	1.55	1.46
Fe_2O_3	5.38	0.88	1.03			11.82	11.36
FeO	3.31			19.70	18.75	8.69	9.29
MnO	0.35			0.64	0.54	0.62	0.65
MgO	1.25			11.91	11.34	6.14	6.04
CaO	7.76	0.12	0.11	0.022		16.34	16.17
Na_2O	8.34	15.00	16.11	0.48	0.45	4.15	4.22
K_2O	3.43	5.88	5.99	9.34	9.73		
P_2O_5	0.53						
H_2O^-	0.20			3.88	3.91		
L.O.I.	2.53						
CO_2	1.32						
Total	100.0	99.95	100.37	99.07	99.13	99.98	100.30

Note: (6-89) nephelinite, wet chemical analysis, analyst G.V. Bondareva; (6-89/1) nepheline phenocryst; (6-89/2) nepheline from groundmass; (6-89/3, 6-89/4) biotite phenocrysts; (6-89/5) clinopyroxene phenocryst; (6-89/6) clinopyroxene from groundmass. The mineral compositions were determined with an MS-46 Cameca microprobe, analysts V.I. Lipskaya and V.G. Barankevich. BaO contents in samples 6-89/4 and 6-89/5 are 0.26 and 0.04 wt %, respectively.

Table 2. Results of mass-spectrometric measurements of Sr isotope ratios and Sr and Rb concentrations

Sample	Rb, $\mu g \cdot g^{-1}$	Sr, $\mu g \cdot g^{-1}$	$^{87}Rb/^{86}Sr$	$\pm\sigma$	$^{87}Sr/^{86}Sr$	$\pm\sigma$
Biotite	618.0	28.12	66.636	0.0045	1.22235	0.00097
Clinopyroxene	40.81	249.0	0.4730	0.0011	0.70569	0.00057
Nepheline from groundmass	172.0	392.6	1.2659	0.0015	0.71312	0.00050
Nepheline phenocryst	135.9	840.0	0.4671	0.0013	0.70762	0.00055

dated nephelinite vein of the Zima Complex occurs at the opposite, southwestern margin.

The dated events (547–544 Ma ago) indicate a release of abyssal magmatic heat at the Precambrian–Cambrian boundary on both the West African and Siberian continents, although the scale of magmatic activity in the latter region remains ambiguous. The nearly coeval (~551 Ma ago) flood basalt eruptions in the Volyn Province are similar in volume to the Deccan Traps. They are spatially related to an abortive Middle Baltic rift and the separation of Baltia from Amazonia [15 and references therein]. Further geochronological investigations must clarify how extensive magmatism was at the Vendian–Cambrian boundary at the Siberian and other continents.

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