

GEOCHEMISTRY

## Sm–Nd Isotopic System in Garnet Megacrysts from the Udachnaya Kimberlite Pipe (Yakutia) and Petrogenesis of Kimberlites

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The discrete xenocryst association is a significant component of kimberlites. Most kimberlite bodies comprise one or several minerals of the following association: olivine ± garnet ± clinopyroxene ± orthopyroxene ± ilmenite ± phlogopite ± zircon [1]. Ilmenite in this association is characterized by the  $\text{Cr}_2\text{O}_3$  and  $\text{Al}_2\text{O}_3$  admixture, while garnet is characterized by a high amount of  $\text{TiO}_2$  admixture, depending both on the medium composition and the formation temperature [2]. The xenocryst association is usually subdivided into megacrysts (>1 cm) and macrocrysts (<1 cm). The low-Cr megacryst association is supposed to be the product of crystallization of the OIB-type asthenospheric magma at high  $PT$  values in lower horizons of the lithospheric mantle. Such conclusions are based on calculations of fractional crystallization [3, 4] (with respect to the REE composition of xenocrysts) and isotope data [5–7]. The parental (protokimberlitic) magma may evolve to kimberlitic magma as the result of interaction with the lithospheric mantle basement and assimilation of rocks enriched in incompatible elements. Therefore, the study of the geochemical–isotopic composition of megacrysts provides a unique possibility of assessing the composition of the protokimberlitic magma and obtaining new information about processes in lower parts of the lithospheric mantle, as well as about kimberlite petrogenesis.

Three megacrysts of dark orange garnet from the Udachnaya kimberlite pipe have been studied in this work. They occur as isometric grains (~3–4 cm across) with a fused surface. In terms of the composition of petrogenic elements, these megacrysts belong to high-Ti (1–1.3 wt %  $\text{TiO}_2$ ) and low-Cr (1.4–1.7 wt %  $\text{Cr}_2\text{O}_3$ ) garnets. The results of microprobe analyses indicate the absence of significant and systematic zoning in garnets from the center to edge over a distance of 1 cm (Table 1).

The chemical composition of these megacrysts differs greatly from the composition of discrete macrocrysts of subcalcic pyropes from the Udachnaya and Mir pipes studied in [8]. Most of them belong to dunite–harzburgite paragenesis (diamond association), according to the classification in [9]. Megacrysts from the Udachnaya and South African pipes exhibit rather a homogeneous composition, with  $\text{Cr}_2\text{O}_3$  content usually not exceeding 2 wt %. Subcalcic pyropes vary in CaO and  $\text{Cr}_2\text{O}_3$  contents (Fig. 1).  $\text{TiO}_2$  is virtually absent.

Garnet samples for isotopic analysis were sawed and blocks  $5 \times 5 \times 5$  mm in size were cut out of their central parts to avoid contamination by the kimberlite melt, which may show up in marginal parts. After dissolution of the sample following a standard procedure and chemical extraction of Sm and Nd [10], the samples were analyzed with a Finnigan MAT 262 mass spectrometer in the University of Hokkaido (Japan). The measured  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios were normalized to

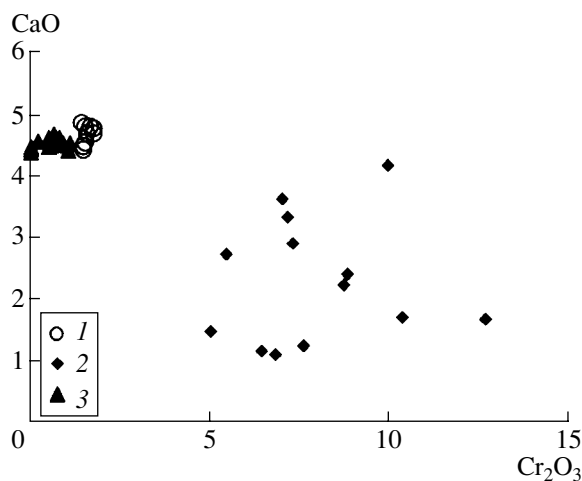


Fig. 1. Variations in the CaO and  $\text{Cr}_2\text{O}_3$  contents in garnets from kimberlites in Yakutia and South Africa. (1) Megacrysts from the Udachnaya Pipe (this work), (2) subcalcic garnets [8], (3) megacrysts from South Africa [7].

**Table 1.** Chemical composition of garnet megacrysts from the Udachnaya kimberlite pipe

Sample	SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Cr <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	NiO	CaO	Na <sub>2</sub> O	Total
Uv1Gm center	42.15	1.12	19.80	1.52	10.36	0.30	19.05	0.03	4.52	0.12	98.97
	42.09	1.22	19.85	1.56	10.28	0.35	18.94	0.02	4.66	0.09	99.05
	42.21	1.16	19.91	1.50	10.23	0.35	19.13	0.00	4.78	0.11	99.38
Uv9/99 center	42.38	1.02	20.16	1.46	9.92	0.33	19.74	0.02	4.45	0.14	99.60
	42.72	1.12	19.64	1.41	10.03	0.26	18.89		4.83	0.19	99.09
	42.50	1.12	20.00	1.48	9.95	0.35	19.18		4.40	0.12	99.09
Uv18/99 center	41.97	1.13	19.89	1.78	10.36	0.25	20.03	0.02	4.66	0.15	100.24
	42.26	1.15	20.01	1.76	9.91	0.33	19.76	0.03	4.77	0.08	100.04
	42.03	1.13	19.78	1.66	10.13	0.33	19.89		4.77	0.14	99.87

**Table 2.** Isotopic composition of the Sm–Nd system in garnet megacrysts from the Udachnaya kimberlite pipe

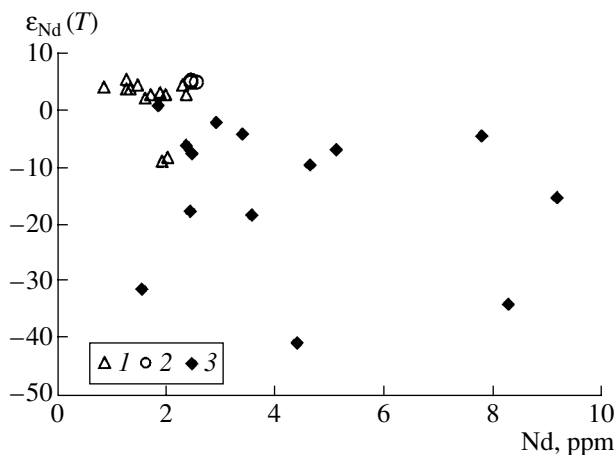
Sample	Sm	Nd	<sup>147</sup> Sm/ <sup>144</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd	<sup>143</sup> Nd/ <sup>144</sup> Nd(T)	ε <sub>Nd</sub> (T)
Uv18/99Gm	1.303	2.497	0.31569	0.513175 ± 14	0.512416	4.89
Uv1/99Gm	1.380	2.476	0.33717	0.513244 ± 12	0.512434	5.23
Uv9/99Gm	1.178	2.600	0.27394	0.513081 ± 13	0.512423	5.02
Kimberlite			0.0815	0.51258	0.512384	4.26

the value  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ . The La Jolla international isotopic standard yielded  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511847$  ( $\pm 8$ ) during the experimental period. The results are given in Table 2.

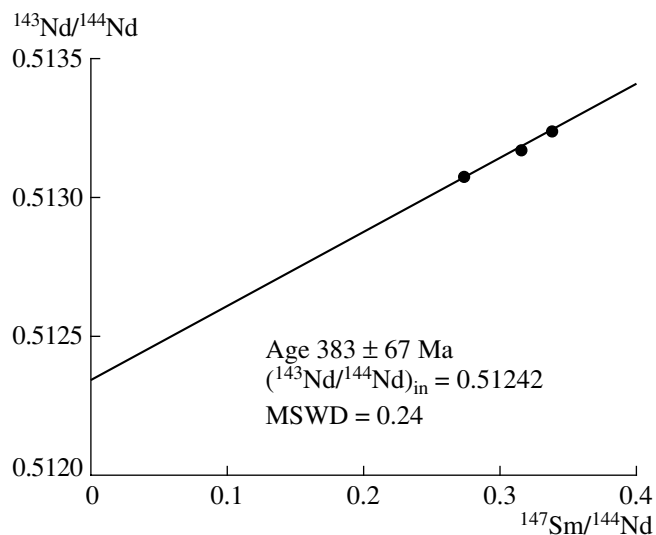
All the garnet samples are characterized by similar Sm and Nd contents (1.18–1.38 and 2.48–2.6, respectively). Present-day  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios show significant difference between samples. However, they are generally similar to ratios for the MORB or depleted mantle (DM) model and considerably higher than for the host kimberlites. Ratios of Nd isotopes (adjusted for the tim-

ing of the Udachnaya–Vostochnaya Pipe kimberlites (367 Ma) [11]) in garnet megacrysts are similar and only slightly higher than in kimberlites (Table 2). The  $\epsilon_{\text{Nd}}(T)$  value in the megacrysts is only 0.7–1 u. higher. In terms of the composition of the Sm–Nd isotopic system, high-Ti megacrysts considerably differ from xenocrysts of subcalcic garnets that are characterized by considerable variations of the Nd isotopic composition and Sm and Nd contents [8]. The  $\epsilon_{\text{Nd}}(T)$  value for subcalcic garnets varies from +1 to –40, and the Nd content varies from 0.5 to 12 ppm (Fig. 2). In terms of the composition of major elements, the subcalcic garnets belong to dunite–harzburgite paragenesis [9] (i. e., highly depleted variety). However, subcalcic garnets are often enriched in LREEs (Nd is a member of this group) as compared to garnets crystallized from the asthenospheric magma (megacrysts).

Isochronous dating based on the composition of the Sm–Nd system of three garnet megacrysts yielded  $383 \pm 67$  Ma (Fig. 3). Despite a great error due to similarity of Sm–Nd ratios in garnets, it is important that the date obtained is close to the age of enclosing kimberlites. The evolution line of the Sm–Nd isotopic systems (Fig. 4) shows that megacrysts and the kimberlite source substrate could be in the isotopic equilibrium within the time interval of 0–100 Ma prior to kimberlite intrusion. The subsequent evolution was characterized by closure of the Sm–Nd system in garnets (this is reflected in the growth of Nd isotope ratios relative to the kimberlite source substrate), the capture of megacrysts by the kimberlite magma, and their exhumation. The Sm–Nd garnet and pyroxene datings for kimberlites of South Africa [3, 6] are also similar or older by



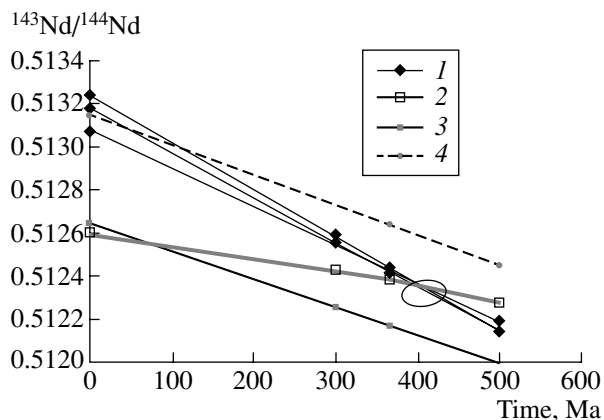
**Fig. 2.** Nd isotope content and composition in discrete garnet xenocrysts from kimberlites in Yakutia and South Africa. (1) Megacrysts from South Africa, (2) megacrysts from the Udachnaya Pipe, (3) subcalcic garnets [8].



**Fig. 3.** Isochronous age calculated by the isotopic composition of the  $^{143}\text{Nd}/^{144}\text{Nd}$  system for three garnet megacrysts from the Udachnaya Pipe kimberlites.

0–40 Ma than the age of enclosing kimberlites. Similar results were obtained based on isochrons of the Lu–Hf isotopic system of garnet and ilmenite megacrysts from South Africa [7]. The protokimberlitic melts are likely to be derived from the lower mantle, as evidenced by the composition of Lu–Hf and Sm–Nd isotopic systems in South African megacrysts and kimberlites. Compositions of these systems differ from the global linear mantle–crust trend and probably are inherited from an unknown geochemical reservoir located in the lower mantle [7].

The obtained data in combination with the geochemical nature of kimberlites [10, 12] suggest the following conclusions concerning the petrogenesis of kimberlites. Based on isotopic-geochemical data, these rocks evolved in two stages in the lower parts of the continental lithosphere. At the first stage, the asthenospheric magma of the low degree of partial melting intruded 470–370 Ma ago, i.e., not earlier than 100 Ma prior to kimberlite intrusion. Unfortunately, it is impossible to assess the event more exactly at this stage of investigation, but the age well correlates with the timing of the major stage of enrichment of the kimberlite source in incompatible elements. Based on the insufficiently mature Nd isotopic composition, this stage retained the depleted nature and should precede the formation of kimberlites [10]. Intrusion of asthenospheric melts produced an enriched (in incompatible elements) reservoir, which was compositionally heterogeneous at the scale of several kilometers. The evolution involved metasomatism of the peridotite substrate, fractional crystallization of megacrysts, their removal from the system, and formation of residual magma enriched in volatile and incompatible elements. Geochemical manifestations of these processes were revealed by the



**Fig. 4.** Evolution lines for Sm–Nd isotope systems of (1) garnet megacrysts from the Udachnaya Pipe, (2) kimberlite of this pipe, and models of (3) primitive (PM) and (4) depleted (DM) mantle. Calculations are based on compositions of PM ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ ,  $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ ) and DM ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$ ,  $^{147}\text{Sm}/^{144}\text{Nd} = 0.2138$ ). The  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio in the kimberlite source was taken as 0.12.

study of different materials from kimberlites of the Udachnaya Pipe. Metasomatic enrichment in incompatible elements is evident in the composition of subcalcic garnets [8] and peridotite xenoliths. Concentration of these elements in the peridotite xenoliths was a multistage process [13]. An appreciable reworking of depleted peridotites from the lower parts of the lithospheric mantle during interaction with asthenospheric melts transformed Cr-pyroxene harzburgite–dunites into clinopyroxene-rich lherzolites [14]. Melt inclusions enriched in volatiles, as well as carbonate and chloride phases, are observed in olivine from unaltered kimberlites of the Udachnaya Pipe [15].

At the second stage, intrusion of the asthenospheric magma or a mere warming-up of the enriched reservoir to the temperature slightly exceeding that of solidus of carbonized peridotite initiated the melting of kimberlites. An ascending mantle flux (possibly, a lower mantle plume) served as a source of heat (fluid, melt). It is likely that areas of the heterogeneous source enriched in residual magma generated kimberlites characteristic of the Aikhal and Internatsional'naya pipes, while the areas of megacryst concentration generated the rocks of the Zarnitsa and Komsomol'skaya pipes. This conclusion is consistent with the geochemical–mineralogical features of these pipes, since the Aikhal and Internatsional'naya pipes are enriched in volatiles and REE. However, relative to the Zarnitsa and Sytykanskaya pipes, the Aikhal and Internatsional'naya pipes are depleted in megacrysts of all types (ilmenite megacrysts are virtually absent). With respect to the geochemistry and content of megacrysts, the Udachnaya Pipe occupies the intermediate position between the kimberlite types mentioned above.

## ACKNOWLEDGMENTS

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## REFERENCES

1. R. H. Mitchell, *Kimberlites* (New York, Premium Press, 1986).
2. D. H. Green and N. V. Sobolev, *Contrib. Mineral. Petrol.*, No. 50, 217 (1975)
3. R. A. Jones, in *Mantle Xenoliths* (Chichester, Wiley, 1987), pp. 711–724.
4. W. L. Griffin, R. O. Moore, K. J. Ryan, et al., *Geol. Geofiz.* **38**, 398 (1997).
5. W. L. Griffin, N. J. Pearson, E. Belousova, et al., *Geochim. Cosmochim. Acta*, No. 64, 133 (2000).
6. G. R. Davis, A. J. Springs, and P. J. Nixon, *J. Petrol.*, No. 42, 159 (2001).
7. G. M. Nowell, D. G. Pearson, D. R. Bell, et al., *J. Petrol.*, No. 45, 1583 (2004).
8. D. E. Jacob, E. Jagoutz, and N. V. Sobolev, *Neues Jahrb. Mineral. Abh.*, No. 172, 357 (1998).
9. N. V. Sobolev, Y. G. Lavrent'ev, N. P. Pokhilenko, et al., *Contrib. Mineral. Petrol.*, No. 40, 39 (1973).
10. A. M. Agashev, Yu. Orihashi, N. P. Pokhilenko, et al., *Geol. Geofiz.* **41** (1), 90 (2000).
11. P. D. Kinny, B. J. Griffin, L. M. Heamen, et al., *Geol. Geofiz.* **38** (1), 91 (1997).
12. A. M. Agashev, N. P. Pokhilenko, et al., in *Extended Abstract Volume of the 2nd International Superplume Workshop* (Tokyo, 2002), pp. 244–248.
13. F. R. Boyd, N. P. Pokhilenko, D. G. Pearson, et al., *Contrib. Mineral. Petrol.*, No. 28, 228 (1997).
14. N. P. Pokhilenko, N. V. Sobolev, S. S. Kuligin, and N. Shimizu, in *Proceedings of the 7th International Kimberlite Conference* (Cape Town, 1999), Vol. 2, pp. 689–698.
15. M. B. Kamenetsky, A. V. Sobolev, V. S. Kamenetsky, et al., *Geology* **32**, 845 (2004).