

# **Compositional heterogeneity of the continental mantle: Evidence from ultramafic xenoliths in cenozoic basalts from Northern Eurasia**

*A. F. Grachev*

Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

**Abstract.** A representative collection of spinel lherzolite xenoliths in Cenozoic basalts from the Baikal Rift (Khamar-Daban Range, Vitim Plateau, and Udokan Plateau), Tien Shan, Bohemian Massif, Pannonian Basin, Catalonia, central and southeastern Spain, Canary Islands, and Lanzarote Island was studied to compare the chemical and isotopic-geochemical composition of the mantle beneath these territories. Comparison of the He signatures, considered together with data on the whole-rock compositions and REE patterns of the samples, reveals variable degrees of lherzolite mantle depletion due to both its original composition and variations in the degree of its partial melting. Another real process is mixing of two reservoirs caused by mantle convection, for example, mixing of a plume component plus subducted lithosphere material. Chemical geodynamics offers various variants of mixing based on studying the isotopic composition not only of the He–Ar and Nd–Sr systems but also of the Pb, Hf, and Os, although realistic implications for chemical geodynamics can be obtained only from the former two systems.

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This is the e-book version of the article, published in the Russian Journal of Earth Sciences (doi:10.2205/2015ES000546). It is generated from the original source file using LaTeX's **epub.cls** class.

# Introduction

Ultramafic xenoliths in alkaline basalts are the only source of information on the chemical composition and physical properties of the deep interiors of the Earth. Studies conducted over the past five decades have proved that spinel lherzolite strongly dominates among rocks found as mantle xenoliths in lavas. Based on various lines of petrological and geochemical evidence, most researchers are currently prone to regard spinel lherzolite xenoliths as fragments of mantle material entrained in magmas and brought to the surface during volcanic eruptions [*Ringwood*, 1975; and many others].

One of the principally important issues actively discussed in the literature is the compositional heterogeneity of the upper mantle, which is remarkably differently interpreted by various researchers, first, in view of the lack of criteria for identifying this heterogeneity and, second, because the factual material is not always reliable enough. The possible heterogeneity of the upper mantle was first pointed out by Harris [*Harris et al.*, 1967]. Later, based on more representative material, Hutchinson with colleagues [*Hutchinson et al.*, 1975] arrived at the conclusion that the mantle underlying

the Massif Central is laterally heterogeneous. However, according to an alternative viewpoint, which was expressed, for example, in [*Basaltic...*, 1981], study of spinel lherzolite nodules provides very little information testifying to any significant compositional transformations in the upper mantle. The differences in the interpretations likely stem from the methods applied in studying the compositional heterogeneity of the Earth's mantle. First, there are no representative data on variations in the composition of nodules within single volcanic centers, and second, it is so far uncertain as to how much the compositional parameters of a mantle rock can vary within a single xenolith, which can be as large as 80–100 cm along their long axes.

Our study was focused on studying variations in the chemical and isotopic-geochemical composition of mantle xenoliths in Cenozoic alkaline basalts from various geodynamic settings in Northern Eurasia at various scale (the samples were collected at the Baikal Rift, northern Tien Shan, Pannonian Basin, Bohemian Massif, Catalonia, central and southeastern Spain, and Canary Islands).

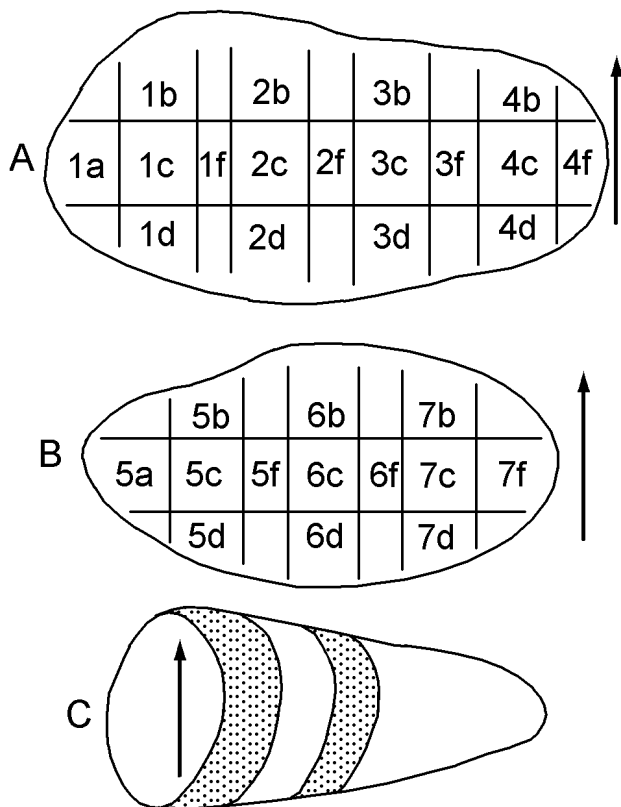
# **Chemical and Isotopic Heterogeneity of the Mantle Within Single Xenolith Samples**

## **Preparation Procedures of Samples for Their Analysis**

Our study was conducted using a sample of spinel lherzolite (sample CH-1) from Neogene basalt from the Bohemian Massif (from the Smrci area). No a priori considerations were assumed to select a sample for this study, and the only requirement was the absence of any traces of atmosphere-induced alterations, such as oxidation, secondary minerals, extensive fracturing, etc.

Our spinel lherzolite sample was a three-axial ellipsoid in shape, 34 by 15 by 9 cm along its principal axes. The sample was saw-cut perpendicular to its long axis into three parallel platelets 2.5 cm thick. One of the platelets was crushed and pulverized to analyze for major and trace elements and conduct some other detailed geochemical studies. The other two platelets were further saw-cut into seven 2-cm cubes (Figure 1). Oriented polished thin sections parallel to each faces of the cubes were then manufactured to examine the petrography and petrotexture of the rocks and to analyze its phases on a microprobe.

# CH-1



**Figure 1.** Layout of the studied fragments of sample CH-1: A and B are platelets (sections) CH-1/1-4 and CH-1/5-7, respectively; and C shows the general view of the sample. The vertical arrow coincides with marker arrows on the oriented thin sections.

## Variations in the Concentrations of Major and Trace Elements in Sample CH-1

The compositions of all rock-forming minerals were proved to vary from the central portion of the sample to its peripheries. Away from sample center, the olivine becomes systematically depleted in  $\text{MgO}$ , the clinopyroxene simultaneously enriches in  $\text{Na}_2\text{O}$ ,  $\text{SiO}_2$ , and  $\text{Cr}_2\text{O}_3$ , whereas the orthopyroxene shows practically no systematic variations in its composition. The character of these variations was elucidated using factor analysis. The olivine shows a negative correlation between the Mg, Si and  $\text{Fe}^*$  concentrations from the central part of the sample to its peripheries; the clinopyroxene displays negative correlations of Si, Ca, and Mg concentrations with its Ti and Cr contents; and the orthopyroxene exhibits analogous correlations of Mg with Cr and of Ca with Al and Si [Grachev *et al.*, 1987].

Similar tendencies are also seen in the behavior of trace elements: the Rb and Cs concentrations systematically vary from the central part of the sample to its peripheries. At the same time, the concentrations of Fe-group elements (Co and Cr) show significant variations not only from the central part of the sample to its peripheries but also within the sample. The maximum

Cr and Co concentrations are almost twice as high as their minimum values (Table 1).

Comparative analysis of variations in the concentrations of major and trace elements within the sample with analogous variations in xenoliths from other areas located far away from one another display overlaps in the ranges of their concentrations (Table 2).

These data demonstrate that the conclusion about

**Table 1.** Variations in the Concentrations (ppm) of Trace Elements Within Sample CH-1

Element	1	2	3	4	5	6	7
Li	3.1	2.8	3.4	3.1	2.9	1.9	2.5
Rb	5.0	8.4	7.8	10	10	12	17
Cs	1.6	0.88	2.9	2.8	2.1	3.2	5.1
Cr	1800	1500	1100	3000	1800	900	900
Mn	790	740	690	700	660	790	710
Co	78	30	35	25	115	40	35
Ni	2000	2000	2000	1800	1900	2400	2200
Cu	25	73	25	63	90	30	20
Zn	56	91	51	74	100	73	79

Note: numerals 1 through 7 correspond to the numbers of cubes in Figure 1.

**Table 2.** Average Concentrations (ppm) of Trace Elements and Their Limits in Sample CH-1 Compared to Those in Other Spinel Lherzolite Xenoliths From the Bohemian Massif and Pannonian Basin

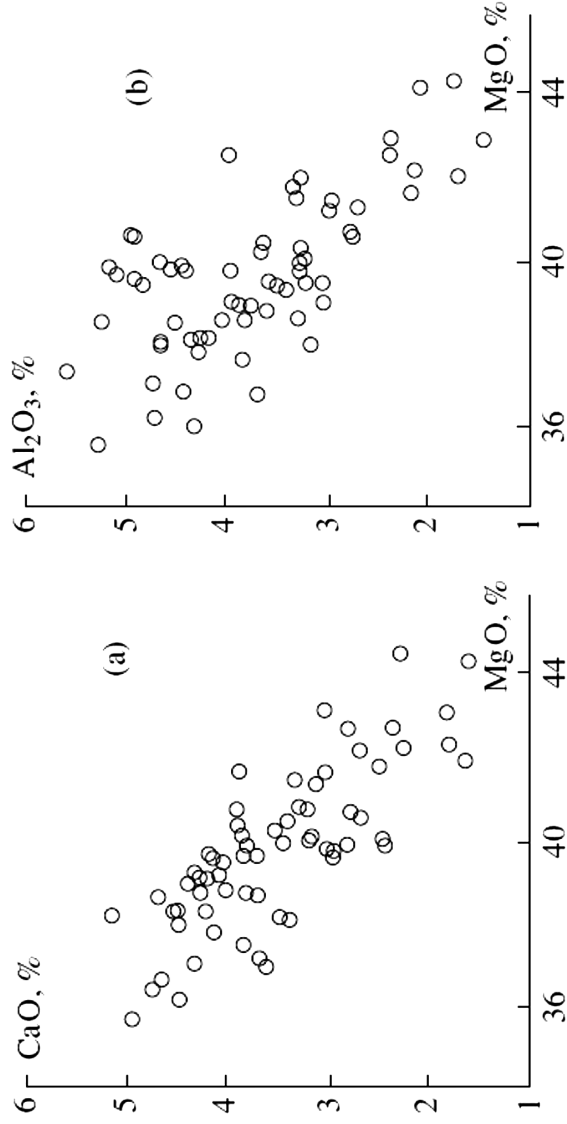
Element	1A		1B		2		3			
	A	max	min	A	A	max	min	A	max	min
Li	2.8	3.8	1.9	1.9	2.0	2.8	1.7	1.76	2.6	0.97
Rb	10.0	17	5.0	3.6	5.4	11.0	2.7	4.84	10.0	1.60
Cs	2.65	5.1	0.88	2.5	4.0	5.6	2.5	5.9	25.0	1.90
Cr	1571	3000	900	1900	1900	2800	900	2294	3200	1500
Mn	727	790	660	950	814	950	730	806	1000	710
Co	51.1	115	25	110	111	120	110	106	120	78
Ni	2042	2400	1800	2200	2337	2600	2200	2161	2500	1000
Cu	46.5	90	20	16	10.6	16	5	12.9	65	5
Zn	74.8	100	51	53	62	95	49	62.2	98	48

Note: 1A and 1B are sample CH-1; 1A is an average of the concentrations in seven cubes, 1B is the concentration in the platelet utilized for whole-rock analysis, 2 is the average concentrations (of eight xenoliths) for the Bohemian Massif, 3 is an average of analyses of eighteen xenoliths for the Pannonian Basin (author's data).

mantle heterogeneity based on data on single samples (their single thin sections or whole-rock analyses) can hardly be viewed as fully reliable. This puts forth the question about the limits of the ranges of concentrations of major and trace elements outside which it is reasonable to conclude that the mantle beneath certain Earth's territories is indeed heterogeneous.

### **Variations in the Chemical Composition of Spinel Lherzolite Xenoliths Within a Single Volcanic Center: An Example of Tumbusun-Dulga Volcano**

To elucidate how much the composition of mantle xenoliths varies within a single sampling site, we have collected a representative number of xenolith samples from the basalt neck of Tumbusun-Dulga volcano in the Khamar-Daban Range in the southeastern portion of the Baikal Rift. The 69 examined samples of spinel lherzolite xenoliths display significant variations in composition, from strongly depleted rock varieties with  $> 40$  wt % MgO and low CaO and  $\text{Al}_2\text{O}_3$  concentrations to rocks of composition close to that of the primitive mantle (Figure 2). Containing approximately 37 wt % MgO, the primitive mantle is also rich in CaO and  $\text{Al}_2\text{O}_3$  [Grachev, 1989]. These data testify that the

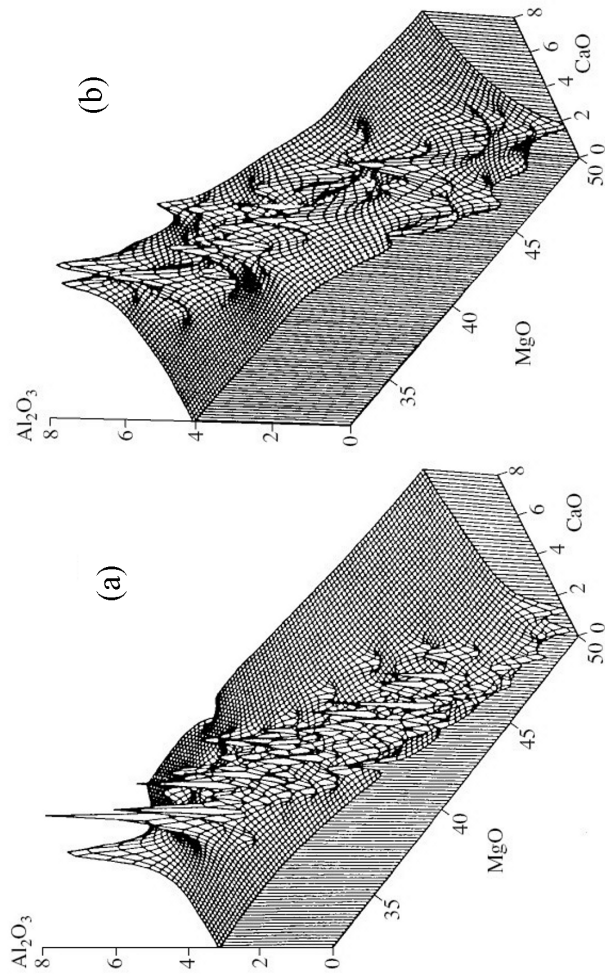


**Figure 2.** (a) MgO–CaO and (b) MgO–Al<sub>2</sub>O<sub>3</sub> diagrams for the composition of xenoliths from Tumbusun-Dulga volcano.

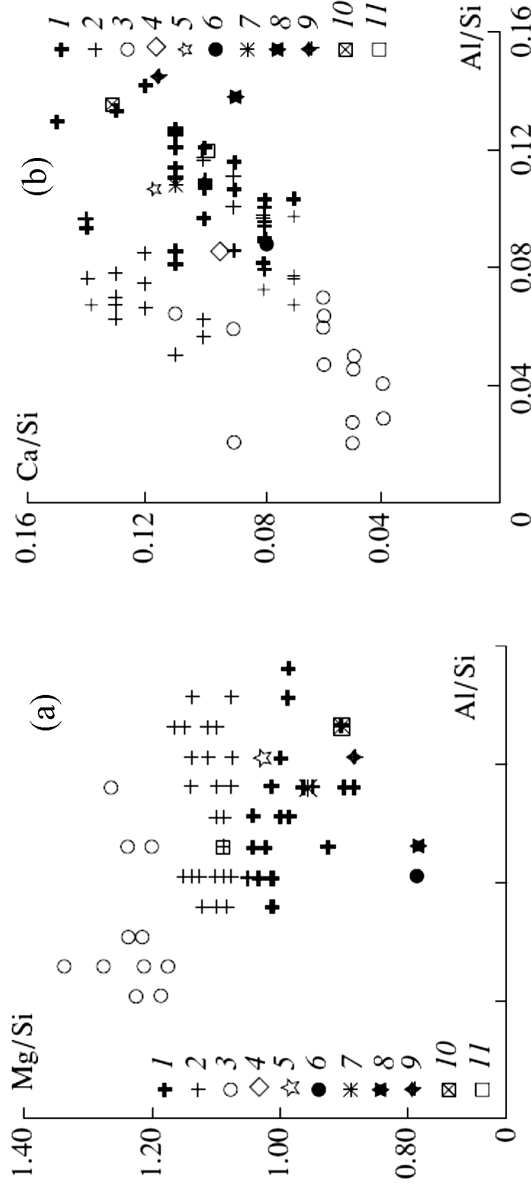
mantle underlying the Khamar-Daban Range is remarkably heterogeneous in composition.

Moreover, the variations in the mantle composition beneath this part of the Khamar-Daban Range are comparable with the compositional variability typical of the whole continental mantle shown in Figure 3. The degree of fractionation of mantle material is clearly seen in the Mg/Si–Al/Si and Ca/Si–Al/Si diagrams below (Figure 4a and Figure 4b), which also display for comparison the compositions of carbonaceous chondrite, pyrolite, and primitive mantle.

Most of the composition data points of the xenoliths cluster along the line of geochemical fractionation [Jagoutz *et al.*, 1979], thus reflecting variations in the depletion of the mantle beneath Tumbusun-Dulga volcano. At the same time, approximately 10% of all of the studied xenolith compositions lies near or coincides with the compositions of pyrolite and the primitive mantle (Figure 4a). Based on the Ca/Si ratio of mantle rocks, Morgan [1986] has classified them into three groups: weakly depleted ( $> 0.09$ ), moderately depleted ( $0.09\text{--}0.06$ ), and strongly depleted ( $< 0.06$ ). All of these groups were detected among xenoliths from Tumbusun-Dulga volcano, as can be seen in Figure 4b, which shows the compositional dis-



**Figure 3.**  $\text{Al}_2\text{O}_3$ – $\text{MgO}$ – $\text{CaO}$  (wt %) diagrams for ultramafic xenoliths of (a) the continental mantle as a whole and (b) from Tumbusun-Dulga volcano.



**Figure 4.** (a) Mg/Si-Al/Si and (b) Ca/Si-Al/Si diagrams for the compositions of ultramafic xenoliths from Tumbusun-Dulga volcano: 1-4 – mantle beneath Tumbusun-Dulga volcano; 1-4 – mantle beneath Tumbusun-Dulga volcano; 2 – weakly depleted, 3 – strongly depleted, 4 – average mantle composition beneath Tumbusun-Dulga volcano, 5 – pyroxite [Ringwood, 1975], 6 – C1 chondrite [Jagoutz *et al.*, 1979], 7 – primitive mantle [Hart, Zindler, 1986], 8 – same [Anderson, 1983], 9 – same [Palme and Nickel, 1985], 10 – same [Grachev, 1989], 11 – same [Kogarko *et al.*, 1987].

creteness of the xenoliths pronounced in their Al/Si ratio.

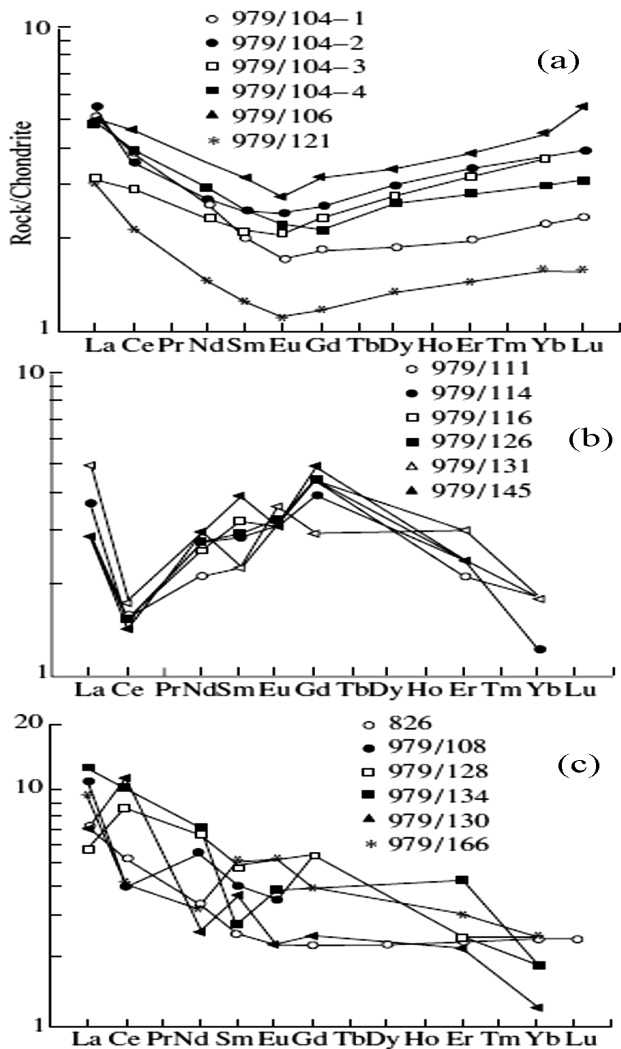
## **Variations in REE Concentrations in Mantle Xenoliths From Tumbusun-Dulga Volcano**

According to their REE concentrations, the rocks composing the xenoliths can be subdivided into three groups (Figure 5a, Figure 5b, and Figure 5c).

The first group comprises samples whose REE patterns are close to chondritic ones (Figure 5a), the second group is made up of samples with negative Ce anomalies (Figure 5b), and the third group includes samples with pronounced enrichment in LREE (Figure 5c).

The first group of xenoliths (Figure 5a) corresponds to the least depleted source and has REE concentrations two to five times higher than the chondritic ones. The second group (Figure 5b) of rocks with negative Ce anomalies consists of xenoliths of mildly depleted mantle material. As follows from data on alnoite xenoliths from Malaita Island, Solomon Islands [*Neal and Taylor, 1989*], the reason for the Ce anomaly was remelting of the crustal material in subduction zones.

Finally, the third group of xenoliths (Figure 5c), which



**Figure 5.** Chondrite-normalized REE patterns of xenoliths from Tumbusun-Dulga volcano (see text for explanations).

are obviously enriched in LREE, corresponds to mantle residues.

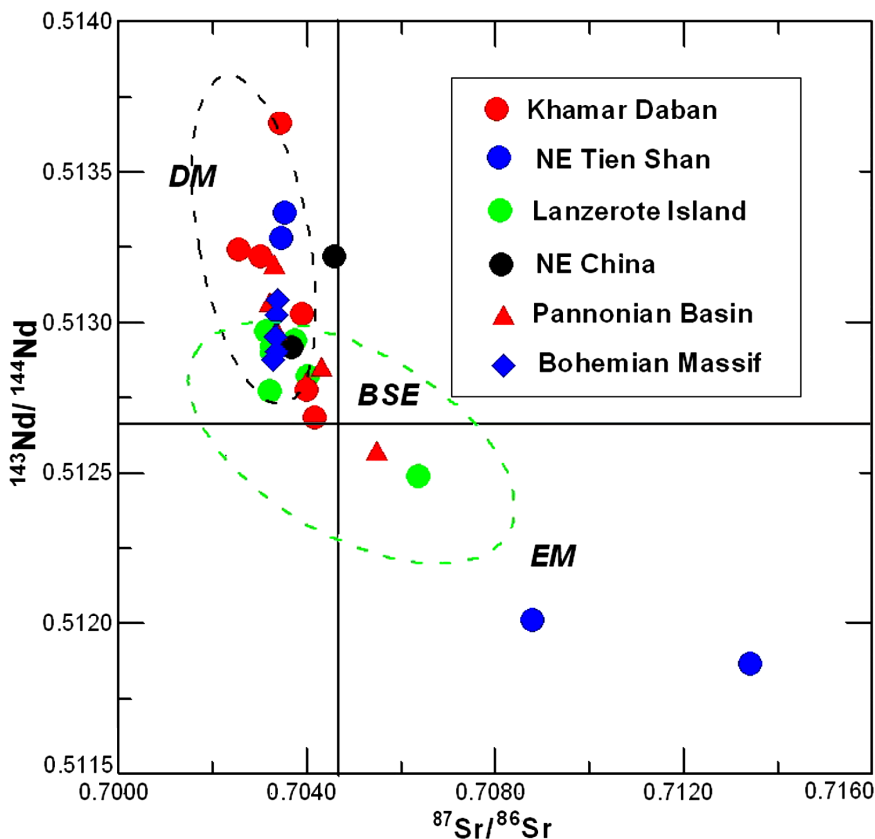
Comparison with known REE patterns of mantle rocks from elsewhere (Mongolia, southeastern Australia, San Carlos in the United States, and Dreiser Weiher in Germany), where single samples of ultramafic xenoliths in basalt were studied [*Agafonov and Erkushev*, 1984; *Frey and Prinz*, 1978; and several others] indicates that samples from a single locality may cover the whole range of variations in the REE concentrations relative to chondrite, except only for Alpine-type hyperbasites.

At the same time, data on REE distribution in mantle xenoliths from Tumbusun-Dulga volcano are in reasonably good agreement with data on the whole-rock composition of xenoliths from elsewhere and thus provides further support for the hypothesis that the regional mantle is indeed strongly chemically heterogeneous. One of the reasons for this heterogeneity is variations in the degree of melting, as follows from the evident correlations between the MgO and CaO concentrations with  $\text{Al}_2\text{O}_3$  (Figure 3).

## **Sm–Nd and He–Ar Isotopic Systematics of Mantle Xenoliths from Tumbusun-Dulga Volcano**

This section presents the results of studying the Nd, Sr, He, and Ar isotopic ratios of mantle rocks from beneath Tumbusun-Dulga volcano.

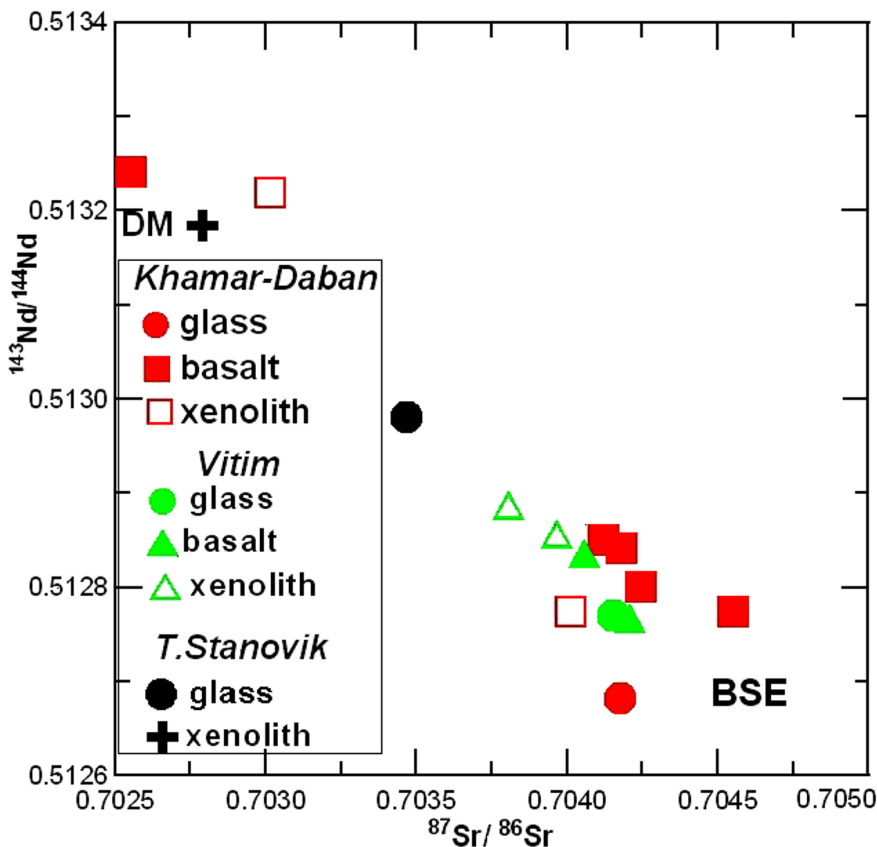
In modern chemical geodynamics, the following three major types of mantle material are distinguished: primitive mantle (PM), depleted mantle (DM or MORB), and enriched mantle (EM) [*Zindler and Hart, 1986*], with differences between them seen in the concentrations of major elements (Mg, Al, and Ca), REE, and Sm–Nd and He–Ar isotopic systems. The depletion of the mantle was related to its partial melting or metasomatism, and its enrichment was caused by subducted oceanic lithosphere (high  $^{87}\text{Sr}/^{86}\text{Sr} > 0.7050$ ). As follows from Figure 6, xenoliths from Tumbusun-Dulga volcano occur as a swarm of data points (as these data points also do in the diagrams in Figures 3, 4, and 5) extending from the primitive to depleted mantle fields. Note that this swarm of data points overlaps the field of the composition of the mantle beneath Europe. Data obtained on the Nd–Sr isotopic system of glasses from zones of partial melting in sample 979/152 from basalt of Tumbusun-Dulga volcano shed light on the reasons



**Figure 6.**  $^{143}\text{Nd}/^{144}\text{Nd}$ – $^{87}\text{Sr}/^{86}\text{Sr}$  diagram for xenoliths from Tumbusun-Dulga volcano in comparison with analogous data on xenoliths from elsewhere (our data). The black dashed line contours the compositional field of xenoliths from Western and Central Europe [Downes, 2001], and the green dashed line outlines the field of xenoliths from East Asia [Xu *et al.*, 2004]. BSE is the uniform chondritic reservoir.

for this chemical and isotopic heterogeneity. The xenolith represented by this sample, glasses in it, and its host basalt were proved to have closely similar isotopic signatures (Figure 7).

The Sr and Nd isotopic ratios of glass in xenoliths in basalts from the Khamar-Daban Range and Vitim Plateau are closely similar and plot in the vicinity of BSE, whereas the data points of the xenoliths themselves lie on the mixing line of the BSE and MORB mantle sources. The isotopic composition of glass from the partial melting zone for the Tok Stanovoi Range lies within the field of xenoliths from the Khamar-Daban and Vitim, and the xenolith itself has isotopic ratios typical of MORB. The composition of glass in the xenolith from the Khamar-Daban Range corresponds to picrite basalt, and the U–Pb isochron for the glass yields an age of  $22.7 \pm 4.2$  Ma, which is much older than the age of the host basalt, which was dated at 17–18 Ma. These data show that the mantle that is heterogeneous in chemical and isotopic composition beneath the Baikal Rift Zone (as follows from data on spinel ilmenite xenoliths in the basalts) includes material whose isotopic-geochemical parameters correspond to the primitive mantle. Studies of partial melting zones in mantle xenoliths from Tumbusun-Dulga vol-



**Figure 7.**  $^{143}\text{Nd}/^{144}\text{Nd}$ – $^{87}\text{Sr}/^{86}\text{Sr}$  diagram for the composition of xenoliths, partial melting zones in them, and their host basalts.

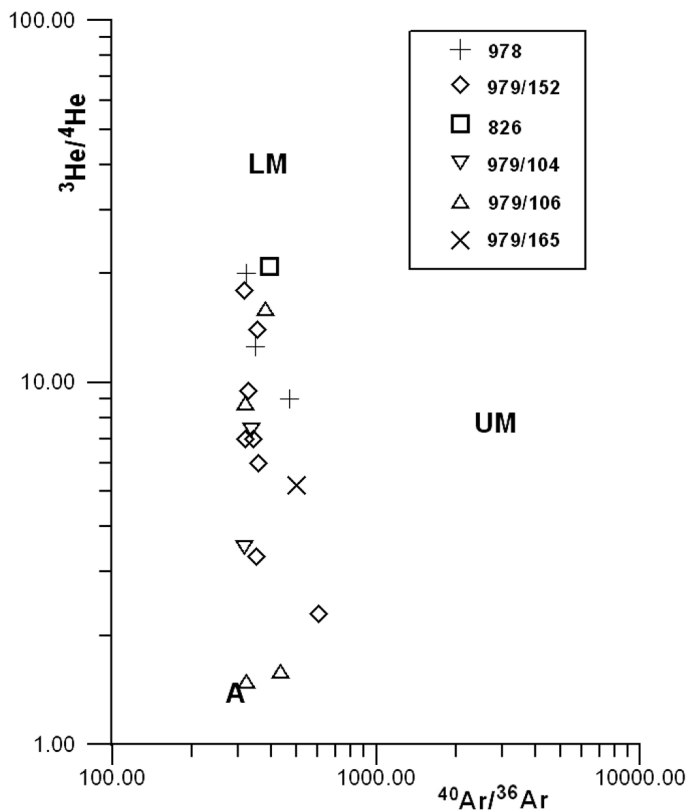
cano show that the partial melting of primitive mantle material may yield parental melts containing  $> 14$  wt % MgO.

## **Variations in the He Isotopic Composition of Xenoliths From the Khamar-Daban Range**

Figure 8 shows our data on the He isotopic system and the broad variations in the  $^3\text{He}/^4\text{He}$  ratio from values typical of the atmosphere to those of hotspots and/or primitive mantle.

Values typical of the atmosphere were determined in three of the 22 examined samples. The highest values were detected in samples 826 and 978, and the  $^3\text{He}/^4\text{He}$  ratios of the olivine are two to three times higher than those of the whole-rock samples. Analogous relations were also found in sample 979/152 (Figure 8).

It is interesting to analyze the variations within sample 979/152 of spinel lherzolite, whose He isotopic composition was determined (in the whole-rock sample and in olivine of various populations, including experiment on its leaching) [Grachev, 1998]. The  $^3\text{He}/^4\text{He}$  ratio varies from  $2.3$  to  $18 \times 10^6$ . The lowest value was yielded by the whole-rock sample, and the highest one



**Figure 8.**  $^3\text{He}/^4\text{He}$ – $^{40}\text{Ar}/^{36}\text{Ar}$  diagram for mantle xenoliths from Tumbusun-Dulga volcano: A – atmosphere, LM – lower mantle, and UM – upper mantle.

by olivine after its leaching with HCl. What is important, olivine porphyroclasts and neoblasts differ in He isotopic composition, which is more that twice as low in the porphyroclasts as in the neoblasts.

The occurrence of a number of olivine populations in mantle xenoliths is explained by the long-lasting deformation history of the latter as a result of solid-plastic flows in the mantle before the xenoliths were brought to the surface [*Mercier and Nicolas, 1975*]. Extensive studies indicate that these deformations occur in the presence of fluid and are associated with metasomatism and partial melting. These processes enriched the partial melting zones in U and modified their He isotopic ratios. Such changes were detected in sample 979/152, whose partial melting zones contain up to  $1500 \times 10^{-9}$  g/g U, i.e., roughly 1000 times more than this concentration in the olivine and 100 times more than its concentration in the xenolith [*Grachev and Komarov, 1994*]. In this process, the  $^3\text{He}$  concentrations remained unmodified, and the  $^4\text{He}$  concentrations increased and thus decreased the  $^3\text{He}/^4\text{He}$  ratio. Since practically all mantle xenoliths show traces of mantle metasomatism, the He isotopic ratio of the whole-rock samples are always lower than those of their olivine.

The latest data on the He isotopic composition of

mantle xenoliths in basalts from the Pannonian Basin, Bohemian Massif, Vitim Plateau, northern Tien Shan, and Lanzarote Island [*Grachev*, 2012a, 2012b, 2013; *Grachev et al.*, 2014] demonstrate that the variations in the  $^3\text{He}/^4\text{He}$  ratio can be controlled by several factors, first of all, by the U concentration, the effect of cosmic irradiation, and the occurrence of partial melting zones. To accurately compare data on He isotopic composition, these data must be obtained by the crushing techniques, which makes it possible to extract  $^3\text{He}$  from gas-liquid inclusions in olivine. The variations in the  $^3\text{He}/^4\text{He}$  ratio in the olivine porphyroclasts and neoblasts may reach the same orders of magnitude.

## **Heterogeneity of the Chemical and Isotopic Composition of the Mantle Beneath North Eurasia**

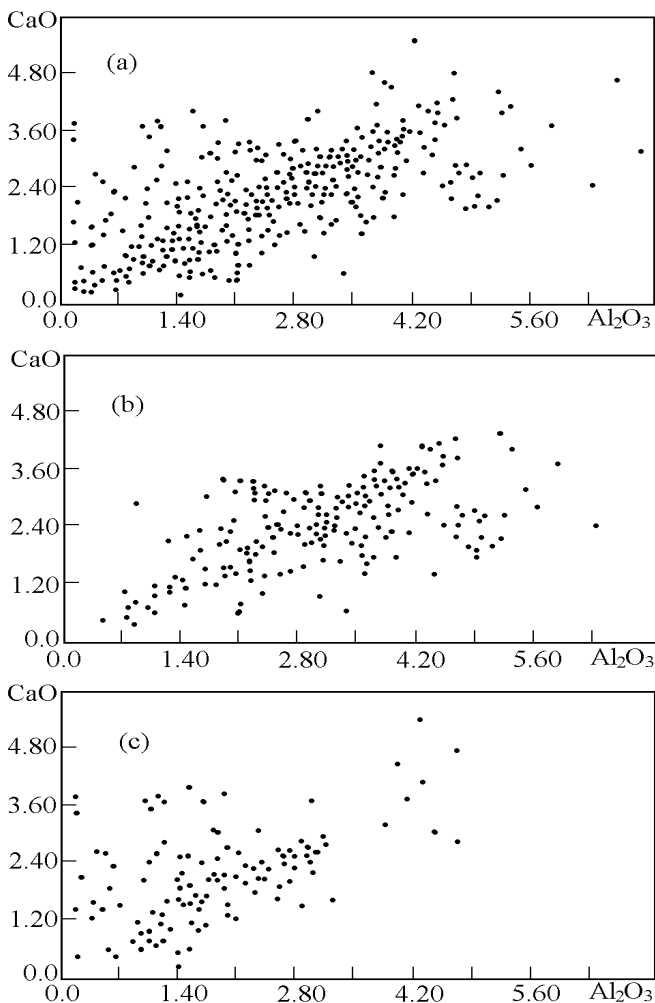
This study was conducted based on our database (more than 300 analyses) on the composition of xenoliths. For comparison, we also used data from [*Maaloe and Aoki*, 1977] on xenoliths in basalts from Europe.

Our earlier factor analysis of the chemical composition of mantle xenoliths [*Grachev*, 1989] has revealed

that the type of the mantle material (degree of its depletion relative to the chondrite reservoir) is determined by the CaO, Al<sub>2</sub>O<sub>3</sub>, and MgO concentrations. Undepleted mantle is characterized by high CaO, Al<sub>2</sub>O<sub>3</sub> (> 3 wt %), and MgO (35–37 wt %).

Figure 9 shows variations in the mantle composition beneath Europe and Asia in comparison with the composition of the whole continental mantle. As can be readily seen from the comparison of the variations in the composition of xenoliths in Figure 9 with data on xenoliths from Tumbusun-Dulga volcano in Figure 3, all of the xenoliths display analogous compositional trends and relations. This led us to conclude that the continental mantle at its spinel depth facies is well enough homogenized. The comparison of the He signatures, considered together with data on the whole-rock composition and REE patterns, of mantle xenoliths at various scales highlights similar degrees of lherzolite mantle depletion due to various degrees of partial melting of the primitive original composition.

There is another real process related to mantle convection: the mixing of various reservoirs, for example, a plume component plus subducted lithosphere. Chemical geodynamics offers a diversity of mixing scenarios based on data on the isotopic composition not only in



**Figure 9.** CaO– $\text{Al}_2\text{O}_3$  diagram for the composition of mantle xenoliths in Cenozoic basalts in Europe and Asia in comparison with data on the whole continental mantle. A – all continental mantle, b – Asia, c – Europe.

the He–Ar and Nd–Sr systems but also of Pb, Hf, and Os, but only the former two systems have implications for mantle geodynamics.

Table 3 presents our data on the Sm–Nd isotopic ratios of mantle xenoliths in basalts in various areas in northern Eurasia. These data were plotted in a diagram of these ratios (Figure 10), which obviously shows that all of the samples from various areas in Northern Eurasia plot within the region typical of the lherzolite mantle beneath Europe.

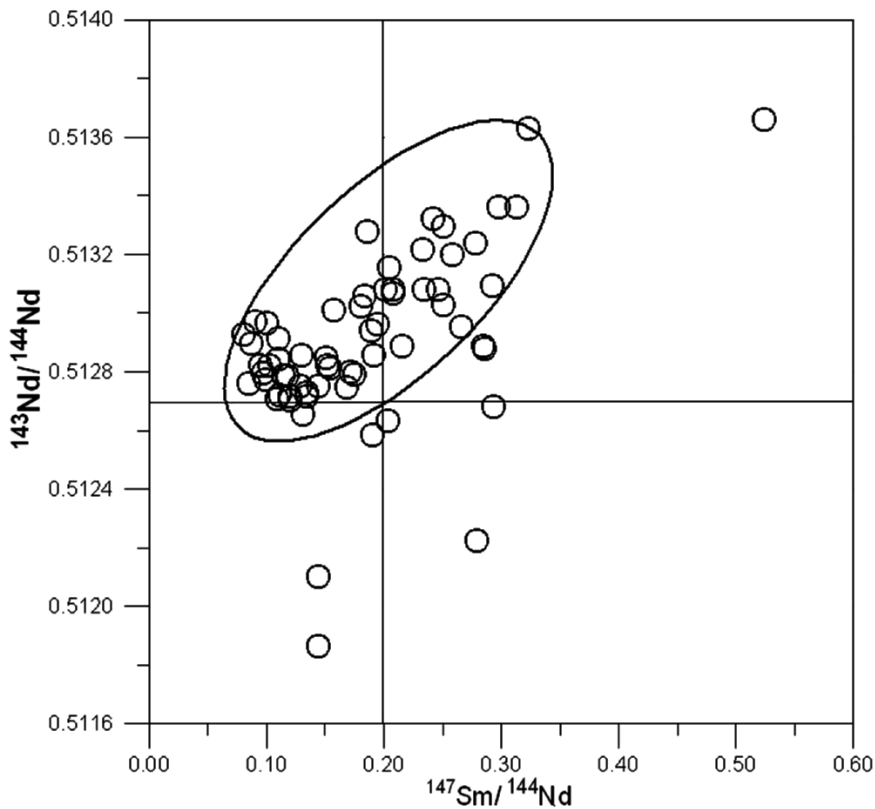
It follows that, similar to the variations in the chemical composition, the heterogeneity of Sm–Nd isotopic composition of the upper mantle beneath northern Eurasia is constrained within fairly narrow limits.

Currently available estimates for the Sm–Nd and Os dates for the continental mantle beneath Asia correspond to approximately 2 Ga. The oldest age was determined for the mantle beneath the Tien Shan: the Sm–Nd isochron of three minerals (olivine, diopside, and enstatite) corresponded to an age of  $2894 \pm 180$  Ma [Grachev *et al.*, 2014].

**Table 3.** Sm and Nd Isotopic Ratios of Mantle Xenoliths From Various Areas in Northern Eurasia

no.	Sample	Area	Concentration, ppm		Isotopic ratios	
			Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$
1	RC-88-1X cpx	Catalonia	4.749	26.246	0.109374	$0.512707 \pm 23$
2	RC-88-1/11a cpx		4.640	16.691	0.168044	$0.512749 \pm 12$
3	RC-88-1X bt		0.352	2.078	0.102443	$0.512823 \pm 21$
4	RC-88-1X bt		0.046	0.351	0.08450	$0.512762 \pm 42$
5	RC-88-1X cpx		5.58	30.52	0.11058	$0.512722 \pm 5$
6	RC-88-10 cpx		9.851	41.45	0.14366	$0.512751 \pm 3$
7	RC-88-11 hrnb		6.93	27.25	0.15371	$0.512811 \pm 6$
8	RC-88-11 cpx		5.72	20.19	0.17129	$0.512798 \pm 6$
9	RC-88-3x wr		5.69	22.84	0.15099	$0.512847 \pm 5$
10	RC-88-4x wr		0.615	3.147	0.14366	$0.512751 \pm 3$
11	RC-88-7x wr		7.744	36.24	0.12915	$0.512752 \pm 5$
12	RC-88-x wr		6.03	23.45	0.15210	$0.512824 \pm 6$
13	S-1 cpx	North China	0.447	1.451	0.18627	$0.513278 \pm 208$
14	S-1/1 ol		0.011	0.050	0.130797	$0.512656 \pm 42$
15	S-1/1 cpx		1.825	5.316	0.207576	$0.513080 \pm 15$
16	S-1/1 opx		0.033	0.097	0.208094	$0.513067 \pm 20$
17	S-3/2 cpx		3.188	17.486	0.110215	$0.512842 \pm 19$
18	S-3/2 cpx		3.29	18.14	0.10963	$0.512915 \pm 13$
19	S-3/2 opx		0.071	0.367	0.117275	$0.512788 \pm 41$
20	S-3-1a opx		0.019	0.036	0.323477	$0.513629 \pm 47$
21	S-3-1a cpx		1.723	4.236	0.245882	$0.513083 \pm 21$
22	780/1 opx	Baikal Rift	0.025	0.054	0.28605	$0.512880 \pm 5$
23	780/1 di		1.432	3.587	0.24121	$0.513323 \pm 11$
24	826 wr		2.454	14.98	0.09900	$0.512775 \pm 21$
25	978 wr		1.544	4.006	0.23296	$0.513219 \pm 7$
26	979/104 cpx		2.137	4.651	0.27777	$0.513241 \pm 10$
27	979/106 cpx		1.445	3.483	0.250080	$0.513028 \pm 51$
28	979/106 wr		0.500	1.490	0.20140	$0.513083 \pm 21$
29	979/152 cpx		0.477	1.528	0.18856	$0.512939 \pm 10$
30	979/163 opx		0.026	0.050	0.312538	$0.513360 \pm 28$

31	979/163 cpx		1.514	3.648	0.250955	0.513295 $\pm$ 17
32	979/167 opx		0.035	0.103	0.203582	0.512632 $\pm$ 62
33	979/167 cpx		1.803	4.658	0.234039	0.513080 $\pm$ 19
34	1065 cpx		0.927	2.597	0.21579	0.512887 $\pm$ 10
35	1069 cpx		7.11	22.42	0.19156	0.512857 $\pm$ 6
36	TS-90-1 opx	N. Tien	0.964	1.113	0.52345	0.513660 $\pm$ 53
37	TS-90-5 cpx	Shan	1.140	2.316	0.29762	0.5133625 $\pm$ 41
38	TS-90-5 opx		0.033	0.027	0.14442	0.511865 $\pm$ 115
39	CNT89-1 ol	Central	0.013	0.065	0.11970	0.512705 $\pm$ 120
40	CNT89-1 opx	Spain	0.013	0.040	0.19411	0.512962 $\pm$ 120
41	CNT89-1 cpx		1.407	4.162	0.20427	0.513155 $\pm$ 14
42	CNT89-2 ol		0.016	0.072	0.13414	0.512731 $\pm$ 73
43	CNT89-2 cpx		2.798	6.548	0.25829	0.513199 $\pm$ 8
44	CNT89-2 opx		0.041	0.084	0.29388	0.512682 $\pm$ 38
45	CNT89-3 ol		0.073	0.092	0.47933	0.512567 $\pm$ 51
46	CNT89-3 cpx		11.28	14.67	0.46458	0.512530 $\pm$ 9
47	CNT89-3 opx		0.298	0.208	0.88311	0.512416 $\pm$ 91
48	CNT-89/3 PL		1.047	2.266	0.27931	0.512227 $\pm$ 28
49	LP89-2/3 cpx		1.915	6.322	0.18309	0.513061 $\pm$ 13
50	LP89-2/3 opx	S.-E.	0.045	0.095	0.28459	0.512888 $\pm$ 164
51	LP89-2/3 ol	Spain	0.008	0.044	0.11388	0.512787 $\pm$ 88
52	32883 cpx		2.140	4.867	0.26546	0.512954 $\pm$ 11
53	32887 cpx		2.131	7.130	0.18060	0.513022 $\pm$ 55
54	32888 cpx		2.129	7.362	0.17475	0.512790 $\pm$ 10
55	L88-1 wr	Lanza-	0.060	0.190	0.19022	0.512587 $\pm$ 16
56	L88-3 wr	rote I.	0.720	1.491	0.29177	0.513095 $\pm$ 21
57	Tam-1 di		2.161	16.37	0.08007	0.512928 $\pm$ 27
58	Tam-2 di		3.747	22.66	0.10028	0.512968 $\pm$ 16
59	Tam-3 di		0.814	5.662	0.08717	0.512897 $\pm$ 21
60	Tim-1 di		2.024	13.54	0.09065	0.512969 $\pm$ 12
61	Tim-3 opx-I		0.014	0.058	0.143672	0.512100 $\pm$ 35
62	Tim-3 opx-II		0.028	0.129	0.129453	0.512858 $\pm$ 29
63	Tim-3 cpx		0.579	2.293	0.119727	0.512716 $\pm$ 17
64	GC-1 wr		0.008	0.054	0.09420	0.512820 $\pm$ 120
65	V-107 opx	Pann.	0.014	0.064	0.134099	0.512716 $\pm$ 35
66	V-107 cpx1	Basin	0.881	5.511	0.096613	0.512795 $\pm$ 9
67	V-107 cpx2		1.810	6.956	0.15727	0.513011 $\pm$ 11



**Figure 10.** Sm–Nd diagram for the composition of mantle xenoliths in northern Eurasia. The heavy line contours the composition of the continental mantle beneath Europe (according to [Downes, 2001]).

## Helium in Mantle Xenoliths From Northern Eurasia

The discovery of primary (planetary)  $^3\text{He}$  on Earth in 1969 [*Mamyrin et al.*, 1969] has stimulated studies of the He isotopic composition of, first and foremost, mantle rocks. The pioneering publication by I. N. Tolstikhin et al., which presented data on the He isotopic composition of samples from Kamchatka, Stanovoi Highland, Spitsbergen, and Antarctica, was followed by papers presenting data mostly on ultramafic xenoliths and basalts from oceanic islands. A few studies were centered on the He isotopic composition of ultramafic xenoliths and their host basalts within the continental lithosphere, but before our research, no such data have been obtained at all in Asia. The very first data on the He isotopic composition of mantle xenoliths in northern Eurasia were published in [*Drubetskoi and Grachev*, 1987]. It has been proved that mantle xenoliths (spinel lherzolites) in the Baikal Rift Zone (BRZ) usually hosted in the neck facies of basalts have various  $^3\text{He}/^4\text{He}$  ratios. Two mantle reservoirs were then distinguished: one of them has a  $^3\text{He}/^4\text{He}$  ratio much higher than the atmospheric one  $R_0 = 1.39 \times 10^{-6}$  and higher than the ratios typical of the MORB reservoir

( $R/R_0 = 8 \times 10^{-6}$ ) and pertains to the southwestern flank of BRZ (Khamar-Daban Range), and the other one has a  $^3\text{He}/^4\text{He}$  ratio close to the atmospheric one and is spatially restricted to the northeastern flank, the Tchara Rift (Udokan Range). These data and those on the chemical composition and He isotopic composition of basalts hosting the mantle xenoliths lead to the conclusion that the mantle underlying BRZ is characterized by at least two mantle reservoirs. It is important that all of the experiments were carried out by the melting technique. Later [*Staudacher and Allegre, 1991*] also applied this technique to study the He isotopic composition of xenoliths from the Vitim Plateau and Taryat Depression in Mongolia and demonstrated that the  $R/R_0$  ratio exceeds that typical of MORB ( $R/R_0 = 8 \times 10^{-6}$ ). The effect of cosmogenic He is so far uncertain.

The disadvantage shared by all papers published before ours was that, first, the studies of the He isotopic system were not coupled with detailed petrological and geochemical studies of the xenoliths themselves, and second, no variations in the He isotopic composition were simultaneously studied in the xenolith samples and within the sampling sites. Our data demonstrate that even within a single xenolith sample, olivine porphyro-

clasts and neoblasts have different He isotopic ratios: the  $R/R_0$  ratios of the porphyroclasts are two to three times higher than in the neoblasts because of magma hydraulic fracturing induced by in-situ melting of xenoliths before their entrainment by melt. He diffusion within individual mineral grains in xenoliths is still inadequately poorly understood with regard for the usually old model ages ( $> 2$  Ga) of the xenoliths.

Another important aspect of our studies is possible correlations between He, Sr, and Nd isotopic ratios. It was proved that the He isotopic ratios are not correlated with those of Sr and Nd and that these systems evolve independently.

While the technique most commonly applied in studying He isotopic composition involves crushing grains of olivine and other minerals to extract He from gas-liquid inclusions hosted in these minerals, which makes the values thus obtained independent of any metasomatic alterations that always variably affect all xenoliths, the Sr and Nd isotopic systems can, conversely, be significantly modified by these alterations. This has been demonstrated by studies of the so-called red mantle xenolith suite, in which metasomatism is pronounced most obviously (at the Udokan Range, Lanzerote Island, and Syria).

This publication summarizes the results of our long-term (for more than two decades) studies of the He isotopic composition of mantle xenoliths and their host Cenozoic basalts in an extensive area from the Iberian Peninsula in the west to China in the east. Over this time, data on the He and Ar isotopic compositions of 127 mantle xenoliths and 190 alkaline basalts were obtained. The He and Ar isotopic composition of basalts has never before been analyzed in samples from either Europe or continental Asia.

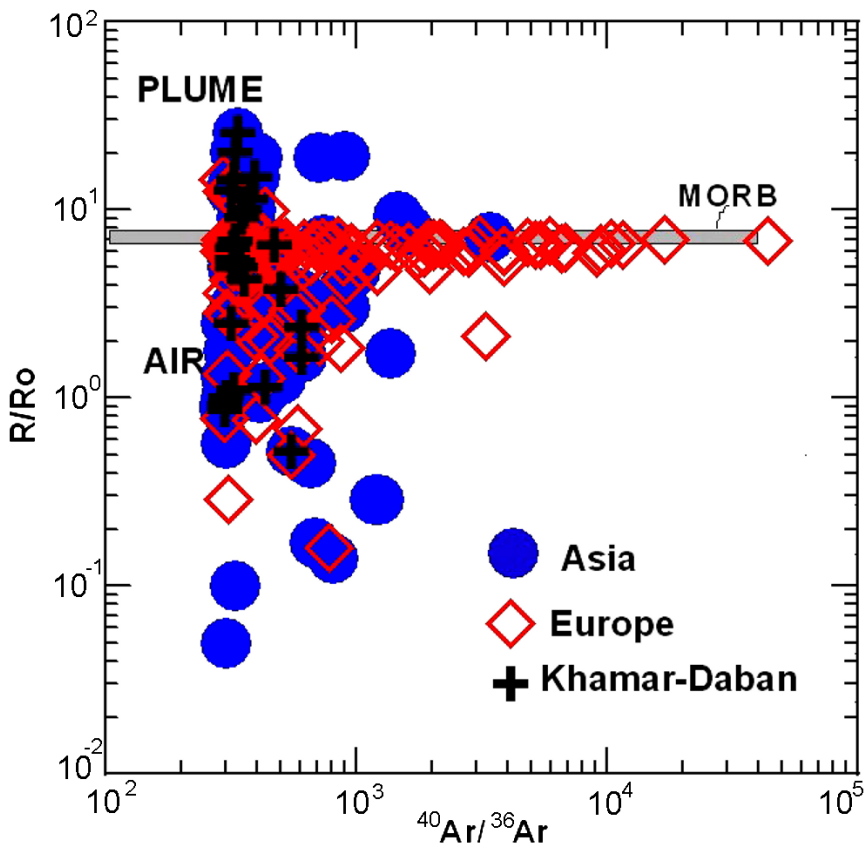
The isotopic studies were initially conducted at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, and the Geological Institute of the Kola Research Center, Russian Academy of Sciences, using techniques of melting, crushing and stepwise annealing at temperatures up to 1700°C of powdered rock samples of and monomineralic fractions. Crushing makes it possible to extract He from gas – liquid inclusions in minerals, melting extracts He from the crystal structures of minerals, and stepwise annealing at temperature higher than approximately 600°C makes it possible to get rid of radiogenic He.

The great majority of the examined mantle xenolith samples are spinel lherzolites. Their He isotopic composition was studied simultaneously with the de-

tailed isotopic-geochemical study of the rocks and their monomineralic separates. The results obtained on the He isotopic composition of mantle xenoliths are presented in Figure 11, which clearly demonstrates broad variations in the  $R/R_0$  ratios from values lower than atmospheric to those typical of mantle plumes. The  $R/R_0$  ratio of xenoliths from the sublithospheric mantle of Europe never exceeds values typical of MORB (except only for xenoliths in basalts from Ciudad Real in central Spain), whereas the values for the continental mantle beneath Asia define a swarm of data points (Figures 2–11) that is orthogonal to the field of data point for the mantle beneath Europe, and some analyses yield  $R/R_0$  ratios higher than in MORB. This pertains to such areas as the northern Tien Shan, Khamar-Daban, and Vitim Plateau in the Baikal Rift and to Shavaryn-Tsaram volcano in Mongolia, whose basalts show a complex of isotopic-geochemical features relating them to mantle plumes. However, high  $R/R_0$  ratios can also result from the effect of cosmogenic  $^3\text{He}$ . It is known that the productivity of spallogenic He is merely insignificantly dependent on the composition of the host minerals. In this context, it is uncertain (and calls for further studying) as to why various or the same minerals contain different concentrations of the

cosmogenic component.

Our data on the variations in the  $^3\text{He}/^4\text{He}$  ratio from the core to marginal portions of three xenolith samples



**Figure 11.** He–Ar isotopic ratios in mantle xenoliths in Cenozoic basalts in northern Eurasia.

indicate that this ratios increases by factors of two to three, i.e., the samples obviously contain cosmogenic  $^3\text{He}$ . The effect of cosmogenic He can be eliminated in the following two manners: (i) by obtaining a sample from an unexposed portion of the vertical section of rocks, from a depth of 3–4 m (this was done in the Tien Shan, where overlying rocks were removed by blasting operations in 1991) or (ii) by introducing a correction for  $3\text{Hecos}$ , which can be determined if the  $^3\text{He}/^4\text{He}$  ratios are known for two minerals [*Grachev et al.*, 2014]. To introduce such a correction, we have determine the  $^3\text{He}/^4\text{He}$  ratios of three minerals from single samples from all of the aforementioned areas; the correction for cosmogenic He did not exceed 20%. Nevertheless, a final conclusion concerning the effect of cosmogenic He can be obtained after studying the Ne isotopic composition: the very first data on the  $^{20}\text{Ne}/^{22}\text{Ne}$  ratios of xenoliths in basalts from the Vitim Plateau had ratios ( $> 11$ ) higher than the atmospheric ones [*Staudacher and Allegre*, 1991].

In any event, differences in variations in the He (and Ar) isotopic composition in the sublithospheric mantle beneath Asia and Europe are quite obvious. This conclusion follows from data on the whole-rock composition, geochemistry of trace elements and REE, and

the Sr and Nd isotopic composition of xenoliths.

## **Partial Melting of the Lherzolite Mantle**

Volcanic eruptions bring spinel lherzolites the surface from depths of 35–70 km, which correspond to the anomalous mantle (a zone of low velocities in it) [*Grachev*, 1987]. Because of this, mantle xenoliths usually show traces of partial melting, which has been evaluated in most publications on theoretical and experimental petrology at 1–3% [*Dobretsov et al.*, 1980; and others].

However, data on xenoliths from the Rein Graben has demonstrated that the degree of partial melting may reach 5–10% [*Maaloe and Printzlau*, 1979]. Examination of a reference collection of spinel lherzolite xenoliths in basalts from the Baikal Rift (> 70 samples) has also shown that partial melting zones make up 10–12% of several samples [*Grachev and Malevskii*, 1988]. In this situation, the amount of melt can be evaluated with the naked eye without studying thin sections. The glass broadly varies in composition from picrite to nepheline-normative basalt. This fact is of principal importance, because the host basalt of the xenoliths has an almost unvarying composition [*Grachev*,

1987]. Also, it is important to mention that not all of the xenoliths show traces of partial melting, and this testifies that the xenoliths did not partially melt as a consequence of their decompression, when entrained to the surface.

The U–Pb isotopic dating of glass in a sample of spinel lherzolite xenolith from basalt from Tumbusun-Dulga volcano in the Khamar-Daban Range, Baikal Rift, yielded an age of  $22.6 \pm 4.2$  Ma, whereas the host basalt is no older than 17–18 Ma. The former value corresponds to the age of the anomalous mantle beneath the Khamar-Daban Range.

Study of the tracks of U distribution in olivine from xenoliths in melting zones shows that the U concentration in these domains is higher than  $2000 \times 10^{-9}$  g/g [Grachev and Komarov, 1994]. Closely similar values were also obtained on xenoliths from elsewhere, e.g. Pannonian Basin and others [Grachev, 2013].

## Discussion and Conclusions

The continental mantle at a depth corresponding to the spinel facies has a long-lasting evolutionary history and is fairly good homogenized. The comparison of the He signatures, considered together with data on

the whole-rock composition and the REE patterns of mantle xenoliths, provides grounds to conclude that the lherzolite mantle is variably depleted, with these variations predetermined by both the original heterogeneity of the mantle and variations in the degree of its partial melting. Note that our earlier factor analysis of the chemical composition of xenoliths in large continental lithospheric blocks [Grachev, 1989] led us to identify two differentiation trends of the mantle. One of these trends corresponds to the undepleted mantle that is rich in CaO and  $\text{Al}_2\text{O}_3$  ( $> 3$  wt %) and contains 35–37 wt % MgO (as is typical of Eastern Asia, for example, Tumbusun-Dulga volcano). The other trend corresponds to the differentiation of the strongly depleted mantle, which is poor in CaO and  $\text{Al}_2\text{O}_3$  ( $< 2$  wt %), and contains 42–45 wt % MgO, as is typical of the portion of the continental mantle that has been produced at the sacrifice of the subducted lithosphere (for example, the Pannonian Basin and southwestern United States).

Another process able to mix materials from various reservoirs is mantle convection, which can mix, for example, a plume component and subducted lithosphere.

Studying the isotopic composition not only of the He–Ar and Nd–Sr systems but also Pb, Hf, and Os

makes it possible to suggest various mixing scenarios within the scope of chemical geodynamics, but only the former two systems have realistic implications for mantle geodynamics.

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