ISSN 0016-7029, Geochemistry International, 2007, Vol. 45, No. 12, pp. 1197–1209. © Pleiades Publishing, Ltd., 2007.
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Petrogeochemical Characteristics of the Kimberlites from the Middle Markha Region with Application to the Problem of the Geochemical Heterogeneity of Kimberlites

A. V. Lapin[a], **A. V. Tolstov**[b], **and V. B. Vasilenko**[c]

[a] *Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements,*
ul. Veresaeva 15, Moscow, 121357 Russia
e-mail: lapin@imgre.ru
[b] *Botuobinskaya Geological Prospecting Survey of the A/K ALROSA, ul. Lenina 44b, Mirnyi, Sakha Republic, 678170 Russia*
[c] *Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences,*
ul. Akademika Koptyuga 3, Novosibirsk, 630090 Russia

Received October 2, 2006

Abstract—A comparative geochemical investigation of kimberlites from the Middle Markha region and traditional diamond-bearing areas of Yakutia supported the division of kimberlites into two geochemical types. One of them includes kimberlites from the traditional diamond-bearing areas of Yakutia, and the other is represented by the kimberlites of the Middle Markha region and the rocks of the Zolotitsa field and V. Grib pipe of the Arkhangelsk province. The obtained representative parameters of the two kimberlite types indicate a sharp geochemical contrast between them, and the individual features of correlation relationships between the elements in the rocks of the two types suggest that these differences are related to fundamental genetic factors, which concern primarily the group of highly charged incompatible trace and radioactive elements. The presence of geochemically contrasting rocks within a rather uniform petrochemical association and the geochemically specialized occurrences of kimberlites and related rocks are consequences of repeated metasomatic transformations of mantle rocks under the influence of deep-derived fluids or volatiles released during the recycling of subducted crustal materials. The metasomatic processes resulted in the formation of a geochemically heterogeneous source and subsequent derivation of geochemically specialized types of deep magmas showing signatures of individual mantle sources.

DOI: 10.1134/S0016702907120026

INTRODUCTION

The progress of mineralogical and petrogeochemical investigations aimed at a more reliable identification of diamondiferous rocks has made evident that it is advisable to use the term kimberlite sensu stricto, restricting its application to the rocks containing diamond and diamond-associated minerals and showing specific petrogeochemical and mineralogical characteristics.

The recent revision of the structure of the family of kimberlites and convergent rock played an important role in the development of this approach. It allowed a comparison within a natural rock series of diamondiferous kimberlites or kimberlites sensu stricto with compositionally similar diamond-free or diamond-poor rocks of other associations and metallogenic types (kimpicrites and alpicrites). Indicator parameters were determined for each member of this series, and diagnostic diagrams were proposed for the assignment of rocks to a certain association and metallogenic type [1]. The end-members of the natural series are diamondiferous kimberlites, on the one hand, and picrite–alnoite rocks associating with rare-metal carbonatite complexes, on the other hand. A variety of diamond-free or diamond-poor alkali picrites, which do not have a distinct metallogenic specialization (kimpicrites), lie between these end-members.

In the systematics of kimberlites and rocks convergent with them, the rocks of the natural series considered form a specific population or subfamily, which can be considered as opposed to terms of petrogeochemical and isotopic parameters by another population or subfamily comprising olivine lamproites, orangeites, and madjgawanites. One of the results of the more strict systematization of the family of kimberlites and related rocks is that it provided a basis for the correct solution of the problem of the investigation of petrogeochemical heterogeneity and internal structure of each association type of igneous rocks, primarily the rocks of the kimberlite association.

PETROGEOCHEMICAL CHARACTERISTICS OF KIMBERLITES FROM THE MIDDLE MARKHA REGION

An important achievement of the past years is the detection of the geochemical heterogeneity of kimberlites, which was established for the first time during the investigation of the Arkhangelsk province. The geochemical parameters of kimberlites from this province appeared to be significantly different from those of diamondiferous rocks from the traditional diamond-bearing regions of Yakutia, which are considered as reference complexes of diamondiferous kimberlite associations [2]. Subsequently, after the discovery of diamond-bearing kimberlite pipes in the Middle Markha region (Nakyn field), the heterogeneity of kimberlites was established within the Yakutian diamondiferous province [1, 3–5]. Geochemically anomalous kimberlites were recently reported from the Slave province of Canada [6, 7].

It is clear that the investigation of the geochemical heterogeneity of kimberlites is of prime importance for the efficient metallogenic forecasting and assessment of the prospects of alkaline ultramafic igneous complexes, because it allows one to establish more precisely the parameters of potentially diamondiferous objects. On the other hand, the solution of this problem is undoubtedly of scientific interest, as providing necessary conditions for the creation of adequate petrologic models of igneous association originating at the greatest depths.

With this in mind, in order to scrutinize this problem, obtain reliable characteristics of contrasting geochemical types of rocks, and analyze the possible nature of the geochemical heterogeneity of kimberlites, we carried out a comparative petrogeochemical investigation of kimberlites from the Middle Markha region and the traditional diamond-bearing areas of Yakutia. Table 1 presents the analyses of individual samples for the kimberlites of the Nakyn field and average kimberlite compositions for several pipes from the traditional diamond-bearing regions of Yakutia, because of the great amount of data for the latter. However, the graphical interpretation of the results and construction of petrochemical and geochemical diagrams involved the analyses of individual samples for all of the complexes considered here.

The petrochemical diagrams previously proposed by us [1] were used for the interpretation of the results. In the petrochemical diagrams (Fig. 1), the rocks of the Middle Markha region fall unambiguously within the field of diamondiferous kimberlites, which was outlined using the compositions of kimberlites from the traditional diamond-bearing regions of Yakutia, which are considered as reference rocks for this association. The indicator geochemical parameters of the rocks of the Nakyn field are within the ranges of values characteristic of kimberlites from the traditional diamond-bearing regions of Yakutia.

The kimberlites of the Nakyn field are somewhat peculiar in that their points are mainly confined to the low-Ti part of the kimberlite field (Fig. 1c) and are slightly shifted toward elevated ($Al_2O_3 + Na_2O + K_2O$) values (Fig. 1b). However, these features are not sufficient to distinguish contrasting petrochemical groups of kimberlites; our data suggest that their compositions are rather uniform.

Fundamentally different conclusions can be drawn from a geochemical comparison of the Middle Markha kimberlites with the rocks from the traditional diamond-bearing regions of Yakutia. The geochemical parameters of these kimberlite groups are distinctly different, which allows us to distinguish two geochemical types of rocks. The main geochemical type corresponds to the petrotype of the kimberlites association and can be represented by the rocks of the traditional diamond-bearing regions of Yakutia: Malaya Botuobiya, Daldyn–Alakit, and Upper Muna. The rocks of this type show moderately high contents of highly charged trace and radioactive elements.

These rocks are in sharp contrast to the kimberlites of the Nakyn field, which show significantly lower contents of Nb, Ta, Ce, U, and Th. This geochemical type of kimberlites is distinguished by the negative anomaly of highly charged trace and radioactive elements, relatively low (compared with other occurrences of kimberlite rocks) concentrations of titanium, and low Ce/Y, Nb/Zr, and Th/U values. In addition to the kimberlites of the Nakyn field, similar characteristics were observed in the rocks of diamondiferous pipes from the Arkhangelsk province [1, 2, 7, 8].

The division of kimberlites into two geochemical types is clearly manifested in the covariation diagrams of highly charged lithophile elements: Zr–Nb (Fig. 2a), Ce–Y (Fig. 2b), and U–Th (Fig. 2c) and their indicator ratios: Zr/Nb–Ce/Y (Fig. 3a) and Ce/Y–Th/U (Fig. 3b). In all of these diagrams, the rocks of the Nakyn field are clearly distinguished from the kimberlites of the traditional diamond-bearing regions of Yakutia, falling near the rocks of the Zolotitsa field and the V. Grib pipe in the Verkhotina field of the Arkhangelsk diamondiferous province.

The analysis of geochemical differences between the two types of kimberlites suggests that they are related to fundamental genetic distinctions reflecting the specific character of mantle sources for these rocks. This is indicated by the Ce–Y (Fig. 4a) and Ce–P_2O_5 (Fig. 4b) relationships in the two groups of kimberlites. In the Ce–Y diagram (Fig. 4a), the rocks of each pipe from the traditional diamond-bearing regions of Yakutia occur mainly in their own characteristic field; all of these fields are confined to a common regression line. The rocks from the Botuobiya and Nyurbinskaya pipes of the Nakyn field also fall within individual fields, which overlap in part and form a common regression line. The slope of the line is significantly different from that of the above-described trend for the traditional dia-

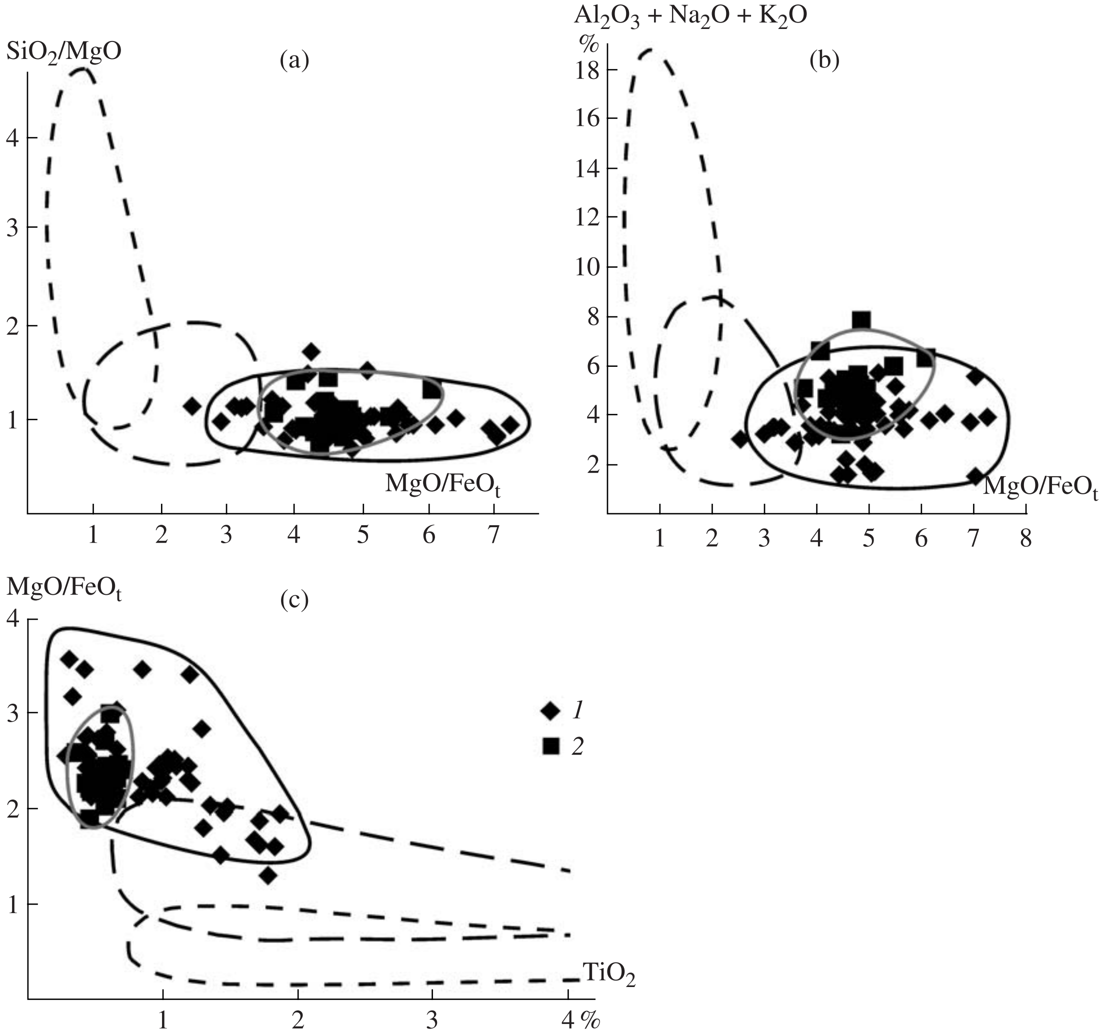

Fig. 1. Compositions of kimberlites from the traditional diamond-bearing areas and the Middle Markha region of Yakutia in the (a)SiO_2/MgO – MgO/FeO_t, (b) ($Al_2O_3 + Na_2O + K_2O$) – MgO/FeO_t, and (c) MgO/FeO_t – TiO_2 diagrams. Kimberlite pipes: (*1*) Mir, Internatsional'naya, Udachnaya, Aikhal, Yubileinaya, Komsomol'skaya, 23rd Party Congress, Taezhanaya, Dachnaya, (*2*) Botuobiya, and Nyurbinskaya. The solid line shows the field of diamondiferous kimberlites, the long-dashed line shows the field of kimpicrites, and the short-dashed line shows the field of alpicrites. The solid gray line encloses the field of kimberlites from the Middle Markha region.

mond-bearing regions of Yakutia and the Ce content is significantly lower. The Ce–Y diagram (Fig. 4a) illustrates considerable differences both in the concentration of Ce-group REE and in the composition of REE in the kimberlites of the two groups. This is supported by Fig. 5, which shows the distribution patterns of REE in the kimberlites. The less fractionated REE patterns of the rocks of the Nakyn field reflect a substantial decrease in the concentration of light lanthanides and a relatively high role of heavy lanthanides and yttrium in their composition, as compared with the kimberlites of the traditional diamond-bearing regions of Yakutia.

Similar relationships can be observed in the Ce–P_2O_5 diagram (Fig. 4b), where two correlation lines, one for the kimberlites of the traditional diamond-bearing regions of Yakutia and the other for the rocks of the Nakyn field, indicate that different modes of Ce-group REE occurrence dominate in the two kimberlite types: phosphates in the former case and silicates or oxides in the latter case.

Important relationships were observed in the Nb–Ti diagram (Fig. 6). The rocks of the Nakyn field cluster in the region of low Nb contents along a distinct regression line, which is restricted to low Ti contents. In contrast, the kimberlites of the traditional diamond-bearing regions of Yakutia plot at much higher Nb contents and show considerably variable Ti contents, from low to moderately high ones. In the general data set, the points of rocks from individual pipes are usually confined to rather narrow specific intervals of Ti contents, within which a direct correlation between Nb and Ti is often

Table 1. Major element compositions (wt %) and trace element contents (ppm) of the kimberlites of Yakutia

Component	Botuobiya													Nyurbinskaya		
	E-407	E-408	E-409	E-410	E-411	E-412	E-413	E-416	E-417	E-418	16/4/310	16/4/320	mean	G-880	G-881	G-882
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	30.22	28.25	30.33	27.31	29.68	31.96	32.82	31.73	33.17	32.66	27.62	30.90	30.55	25.47	50.53	30.40
TiO_2	0.63	0.61	0.59	0.54	0.62	0.63	0.54	0.56	0.53	0.67	0.52	0.54	0.58	0.41	0.31	0.46
Al_2O_3	3.39	3.12	3.38	3.23	3.18	3.72	3.48	3.79	3.85	4.92	2.81	2.18	3.42	4.27	2.71	3.97
Fe_2O_3	6.55	7.07	6.41	5.69	6.60	6.97	6.76	3.96	5.76	6.05	6.69	7.10	6.30	6.39	4.41	6.92
FeO	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
MnO	0.12	0.12	0.12	0.13	0.13	0.12	0.14	0.11	0.11	0.12	0.08	0.07	0.11	0.14	0.12	0.13
MgO	28.78	26.41	26.41	22.94	27.40	30.86	29.85	21.76	28.30	26.28	28.66	28.26	27.16	21.17	20.72	29.45
CaO	10.39	13.69	12.21	16.99	12.48	7.45	8.57	15.97	9.91	10.05	11.69	9.91	11.61	15.17	6.01	8.22
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.05	0.01	0.00	0.00	0.00
K_2O	1.14	1.32	1.72	1.69	1.34	1.10	1.36	2.38	1.92	2.76	1.51	0.70	1.58	0.62	0.26	0.17
P_2O_5	0.69	0.70	0.71	0.65	0.71	0.73	0.59	0.63	0.54	0.66	0.78	0.62	0.67	0.48	0.34	0.43
L.O.I.	18.41	18.96	18.36	20.93	18.18	16.73	16.11	19.42	16.30	16.23	19.04	19.46	16.56	25.55	14.10	19.18
Total	100.32	100.25	100.24	100.10	100.32	100.27	100.22	100.31	100.39	100.40	99.48	99.79	98.55	99.67	99.51	99.33
Be	4.50	4.93	7.58	8.27	5.86	3.65	4.91	4.90	7.55	5.08	4.53	5.36	5.59	3.13	4.05	1.83
Ti	3840	4255	4576	4491	4552	4149	3743	3613	4678	4063	3582	3687	4102	3131	2103	2698
V	77.17	73.30	87.07	84.29	82.80	71.98	66.16	70.59	82.50	70.62	63.34	61.55	74.28	57.45	46.01	50.51
Cr	1136	798	1018	1084	1077	983	805	695	917	765	698	813	899	560	380	403
Mn	881	400	649	605	612	500	803	321	496	381	620	594	572	849	567	639
Co	63.48	104.93	57.83	56.97	56.77	48.54	46.96	74.13	38.63	101.18	26.41	153.16	69.08	61.25	75.21	62.86
Ni	1156	1374	1195	1111	1271	1109	1140	1455	909	1308	1280	1825	1261	1087	1230	1301
Cu	14.75	40.68	14.95	11.55	17.71	16.70	16.37	10.44	16.93	38.40	19.92	27.85	20.52	15.77	30.13	15.35
Zn	77.57	50.88	75.33	50.61	68.78	53.31	46.42	53.16	58.04	49.25	179.78	214.98	81.51	53.92	21.87	26.71
Ga	7.26	7.57	7.48	7.28	7.67	7.01	6.36	6.83	9.16	7.18	6.47	5.89	7.18	7.56	6.28	7.43
Rb	28.39	51.57	38.28	32.76	24.59	24.67	39.22	41.15	59.90	49.95	44.01	21.61	38.01	6.57	6.09	11.49
Sr	1106	829	612	768	754	478	1313	694	947	789	331	579	767	552	251	142
Y	8.38	12.64	11.38	12.36	11.10	9.99	10.63	9.77	17.31	12.04	8.99	9.11	11.14	7.84	7.35	8.71
Zr	85.57	84.60	91.43	92.93	92.54	86.76	77.67	85.83	109	79.92	124	61.54	89.33	66.39	42.24	60.41
Nb	34.44	34.75	46.55	43.24	44.58	41.67	33.71	28.32	36.26	33.19	31.77	31.50	36.67	23.14	16.07	21.49

Table 1. (Contd.)

Component	Botuobiya													Nyurbinskaya		
	E-407	E-408	E-409	E-410	E-411	E-412	E-413	E-416	E-417	E-418	16/4/310	16/4/320	mean	G-880	G-881	G-882
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Mo	1.16	1.49	2.09	1.15	1.07	1.45	1.18	2.47	1.18	1.24	1.36	2.61	1.54	0.97	1.07	0.89
Cs	0.13	0.27	0.30	0.16	0.11	0.10	0.21	0.23	0.32	0.26	0.35	0.35	0.23	0.07	0.09	0.18
Ba	693	731	1100	847	605	583	844	516	792	692	404	366	681	176	110	41
La	14.91	19.93	24.63	17.27	17.81	15.12	16.95	14.40	15.47	18.95	13.45	17.28	17.18	15.56	20.93	13.23
Ce	27.51	36.02	54.95	38.87	30.71	32.81	38.09	29.30	34.71	34.71	28.05	35.40	35.10	30.47	39.12	27.14
Pr	3.49	4.79	6.94	5.24	4.23	4.33	5.08	3.88	4.67	4.56	3.68	4.65	4.63	3.88	4.72	3.44
Nd	14.00	20.52	26.99	22.77	17.66	18.10	22.27	15.38	19.82	19.18	15.85	19.47	19.33	16.11	19.10	13.98
Sm	2.82	4.20	4.99	4.72	3.88	3.99	4.52	3.24	4.23	4.25	3.35	3.92	4.01	3.17	3.50	2.79
Eu	0.68	1.43	1.29	1.47	0.94	0.99	1.40	0.92	1.31	1.38	0.99	1.05	1.15	0.93	0.97	0.81
Gd	2.25	3.54	3.79	3.71	3.19	3.16	3.53	2.70	4.06	3.24	2.49	3.17	3.23	2.46	2.66	2.16
Tb	0.32	0.46	0.50	0.48	0.47	0.43	0.44	0.38	0.57	0.48	0.38	0.40	0.44	0.31	0.32	0.33
Dy	1.74	2.33	2.43	2.50	2.26	2.19	2.25	1.98	3.25	2.33	1.85	1.97	2.26	1.63	1.46	1.67
Ho	0.29	0.42	0.41	0.41	0.37	0.36	0.35	0.33	0.59	0.40	0.31	0.34	0.38	0.29	0.23	0.31
Er	0.82	1.04	0.96	0.98	0.91	0.93	0.85	0.76	1.49	0.97	0.76	0.73	0.93	0.62	0.61	0.79
Tm	0.12	0.12	0.12	0.13	0.13	0.13	0.11	0.11	0.18	0.11	0.09	0.09	0.12	0.09	0.08	0.11
Yb	0.65	0.65	0.64	0.71	0.68	0.76	0.59	0.66	1.09	0.70	0.57	0.52	0.69	0.51	0.47	0.66
Lu	0.09	0.11	0.09	0.09	0.10	0.12	0.08	0.10	0.17	0.09	0.08	0.07	0.10	0.06	0.06	0.09
Hf	1.88	1.92	2.07	1.88	1.95	1.94	1.75	1.89	2.50	1.81	2.59	1.43	1.97	1.46	1.00	1.38
Ta	0.26	0.94	0.87	0.43	0.88	1.15	0.34	0.68	1.03	0.88	0.99	0.17	0.72	0.29	0.53	0.72
W	1.37	<.1	0.97	<.1	<.1	0.82	0.17	<.1	<.1	<.1	<.1	<.1	0.83	0.29	1.19	0.42
Pb	4.01	0.61	1.14	0.76	2.27	0.95	0.47	2.81	1.70	0.62	0.46	0.87	1.39	0.77	0.42	0.52
Th	1.21	0.88	2.43	1.08	1.17	1.20	1.09	0.97	1.16	0.89	0.99	0.97	1.17	0.92	0.62	0.98
U	0.61	0.42	0.51	0.50	0.51	0.62	0.56	0.55	0.68	0.41	0.51	0.42	0.52	0.40	0.30	0.54

Table 1. (Contd.)

Component	Nyurbinskaya								Mir	International	Yubileinaya	Aikhal	Udachnaya	Komsomol'skaya	23rd CPSU Congress	Dachnaya	Taezhnaya
	G-883	G-884	G-885	G-886	G-887	G-888	G-889	mean	mean (10)	mean (10)	mean (6)	mean (4)	mean (4)	mean (6)	mean (6/3)	mean (11/3)	mean (13/3)
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
SiO_2	29.74	36.02	14.72	19.67	36.35	24.85	30.26	29.80	31.39	33.40	32.62	25.05	25.13	32.46	23.60	42.14	33.47
TiO_2	0.43	0.39	0.41	0.42	0.53	0.42	0.46	0.42	1.06	0.40	1.01	0.62	0.98	1.69	0.66	0.70	1.06
Al_2O_3	3.64	3.41	3.66	3.82	4.43	3.66	3.94	3.75	2.57	2.52	1.10	2.21	2.15	2.71	2.56	5.43	3.12
Fe_2O_3	5.76	5.62	4.48	5.02	6.55	5.63	5.68	5.65	6.54	6.21	6.10	4.87	5.43	9.22	3.78	2.63	4.32
FeO	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.16	1.74	1.77
MnO	0.13	0.13	0.15	0.14	0.13	0.14	0.14	0.14	0.13	0.12	0.10	0.05	0.07	0.10	0.12	0.09	0.09
MgO	25.24	22.85	17.64	19.40	23.60	22.88	24.27	22.72	28.70	28.67	32.52	23.19	20.43	25.75	20.32	12.24	21.81
CaO	13.75	9.77	22.69	20.15	8.73	14.69	13.73	13.29	10.24	7.96	7.81	16.64	20.45	8.05	21.87	13.36	13.57
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.62	<0.003	0.14	0.06	0.03	0.21	0.16	0.11
K_2O	0.24	0.66	0.99	1.16	2.03	1.55	1.52	0.92	0.88	1.16	0.12	0.97	0.94	0.49	0.52	2.27	0.71
P_2O_5	0.42	0.38	0.40	0.40	0.38	0.42	0.43	0.41	0.45	0.44	0.24	0.42	0.32	0.22	0.51	0.24	0.75
L.O.I	19.92	20.06	34.18	29.63	16.86	25.15	18.93	22.36	17.85	18.32	–	–	–	–	24.09	19.11	19.57
Total	99.27	99.29	99.32	99.81	99.59	99.39	99.36	99.45	99.88	99.80	81.59	74.14	75.93	80.71	99.40	100.11	100.33
Be	2.84	2.10	2.88	2.51	2.58	2.70	2.05	2.67	2.90	2.97	1.17	2.33	1.56	1.42	2.43	2.86	1.38
Ti	2657	2510	2864	2858	2541	2581	2612	2655	6717	2819	6363	4097	6110	10987	3506	4090	6493
V	54.10	46.11	54.71	55.50	61.37	59.67	65.36	55.08	103	63.95	76.40	68.86	87.93	122	69.65	84.56	91.50
Cr	480	435	500	468	451	458	515	465	618	774	842	607	570	811	1475	788	1127
Mn	567	444	699	503	676	527	376	584	751	550	844	556	518	746	389	754	970
Co	64.17	52.73	69.01	71.65	70.37	68.35	69.27	66.49	74.42	68.16	90.21	75.00	65.75	92.04	47.31	48.05	57.65
Ni	1641	1189	1634	3013	1545	1506	1317	1546	1189	1355	1698	1258	1060	1295	762	685	814
Cu	40.60	13.35	28.99	17.03	20.47	47.11	12.16	24.10	27.88	32.86	23.18	26.61	27.41	59.91	17.14	33.88	30.24
Zn	42.61	34.40	41.01	55.67	52.65	45.20	53.19	42.72	161	40.22	45.69	32.19	77.58	77.36	172	307	52.46
Ga	8.21	7.34	8.04	7.62	7.39	7.16	7.45	7.45	7.56	6.65	5.02	6.42	5.90	6.77	5.70	6.97	4.48
Rb	10.46	17.81	14.28	11.39	13.42	17.14	12.40	12.11	30.12	23.66	8.64	27.82	31.66	31.50	10.43	32.78	17.28
Sr	286	551	140	445	117	245	407	314	1017	990	111	636	787	226	836	2898	467

Table 1. (Contd.)

Component	Nyurbinskaya								Mir	Inter-natsion-al'naya	Yubilei-naya	Aikhal	Udach-naya	Komso-mol'skaya	23rd CP-SU Con-gress	Dach-naya	Taezh-naya
	G-883	G-884	G-885	G-886	G-887	G-888	G-889	mean	mean (10)	mean (10)	mean (6)	mean (4)	mean (4)	mean (6)	mean (6/3)	mean (11/3)	mean (13/3)
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Y	7.66	7.57	9.11	6.68	7.50	6.44	5.65	7.45	12.14	11.43	5.11	11.24	8.41	7.54	13.26	17.73	12.39
Zr	63.41	66.81	70.66	65.01	60.32	60.92	76.61	63.28	152	143	78.73	133	95.02	110	153	210	106
Nb	20.44	19.24	22.21	21.77	18.47	19.44	20.46	20.27	148	122	129	138	136	121	129	125	109
Mo	1.56	0.96	1.26	1.26	1.18	0.94	1.14	1.12	2.60	4.60	1.98	2.18	2.33	2.97	0.93	1.40	1.71
Cs	0.20	0.26	0.37	0.35	0.28	0.22	0.19	0.22	0.26	0.10	0.13	0.26	0.80	0.55	0.23	0.34	0.24
Ba	142	181	126	154	166	228	131	145	783	701	106	1215	602	361	707	1437	488
La	18.08	13.31	11.95	12.52	70.84	12.53	11.23	20.02	68.59	80.23	50.96	80.58	59.79	42.03	105	128	73.17
Ce	28.57	29.08	27.53	25.70	36.62	26.16	24.15	29.45	136	153	97.44	152	110	72.66	185.76	242	141
Pr	3.59	3.61	3.48	3.23	10.26	3.26	3.04	4.25	14.92	16.43	10.16	16.04	11.55	7.65	19.78	26.13	14.98
Nd	15.02	14.90	14.46	12.46	31.23	13.13	12.59	16.30	52.07	55.64	33.57	54.97	38.96	26.39	67.34	89.62	51.45
Sm	3.04	2.97	2.89	2.35	2.66	2.53	2.39	2.83	7.51	7.59	4.44	7.57	5.33	3.77	8.97	12.65	7.35
Eu	0.84	0.83	0.86	0.65	0.77	0.76	0.61	0.80	1.91	1.87	1.06	2.05	1.33	1.04	2.14	3.28	1.62
Gd	2.42	2.24	2.43	1.87	2.23	1.95	1.87	2.23	4.74	4.63	2.62	4.45	3.15	2.38	5.45	7.70	4.61
Tb	0.29	0.30	0.34	0.28	0.31	0.25	0.25	0.30	0.59	0.56	0.31	0.56	0.40	0.32	0.65	0.90	0.56
Dy	1.61	1.58	1.84	1.39	1.58	1.38	1.22	1.54	2.81	2.57	1.34	2.55	1.87	1.53	2.90	4.06	2.65
Ho	0.26	0.27	0.33	0.23	0.29	0.27	0.20	0.27	0.45	0.41	0.20	0.41	0.31	0.27	0.46	0.65	0.43
Er	0.66	0.75	0.84	0.62	0.72	0.62	0.50	0.67	1.05	0.94	0.44	0.97	0.75	0.69	1.02	1.39	0.94
Tm	0.08	0.09	0.10	0.08	0.08	0.09	0.06	0.09	0.14	0.12	0.05	0.12	0.09	0.10	0.13	0.18	0.13
Yb	0.50	0.59	0.66	0.53	0.53	0.56	0.44	0.55	0.79	0.69	0.33	0.69	0.55	0.57	0.72	0.86	0.63
Lu	0.07	0.09	0.10	0.06	0.08	0.08	0.06	0.07	0.11	0.10	0.04	0.09	0.07	0.08	0.10	0.12	0.09
Hf	1.46	1.58	1.62	1.44	1.39	1.36	1.72	1.44	3.47	2.99	1.96	3.01	2.23	2.71	3.46	4.71	2.29
Ta	0.19	0.69	0.82	0.58	0.13	0.65	0.42	0.50	2.60	1.77	2.70	1.34	3.50	1.95	7.79	6.92	8.47
W	0.29	0.82	0.70	0.39	1.27	<.1	0.46	0.65	1.04	96.70	1.01	3.20	1.76	1.68	–	–	–
Pb	0.81	0.50	1.39	2.22	2.54	1.14	1.86	1.22	0.88	0.83	0.88	0.60	0.92	3.30	–	–	–
Th	0.97	0.89	1.03	0.99	0.87	0.89	0.92	0.91	7.60	7.44	6.13	7.70	6.77	4.12	14.96	19.51	11.92
U	0.56	0.52	0.61	0.51	0.58	0.65	0.52	0.52	2.76	2.94	1.98	2.87	2.42	1.72	1.54	3.01	1.99

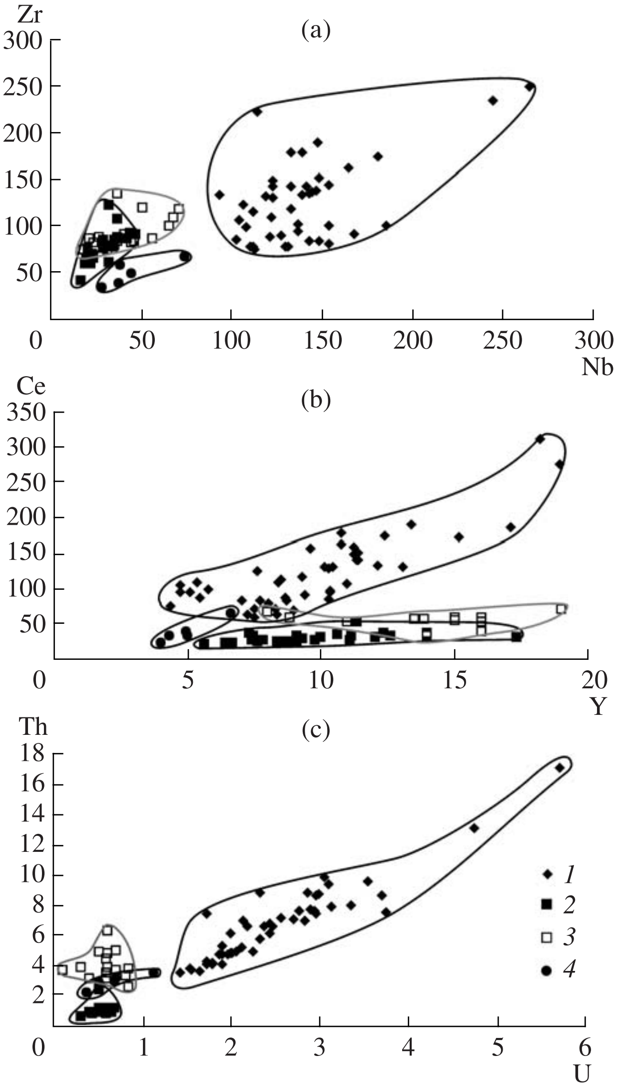

Fig. 2. Correlations between the contents of (a) Zr and Nb, (b) Ce and Yb, and (c) Th and U in the kimberlites of the Nakyn and Zolotitsa fields and traditional diamond-bearing regions of Yakutia. (*1*) Kimberlites from the traditional diamond-bearing regions of Yakutia (Mir, International, Udachnaya, Aikhal, Yubileinaya, Komsomol'skaya, 23rd Party Congress, Taezhnaya, and Dachnaya pipes); (*2*) kimberlites from the Nakyn field of Yakutia (Botuobiya and Nyurbinskaya pipes); (*3*) V. Grib pipe in the Verkhotina field of the Arkhangelsk province; and (*4*) kimberlites of the Zolotitsa field of the Arkhangelsk province (Lomonosovskaya, Pionerskaya, and Karpinskii pipes).

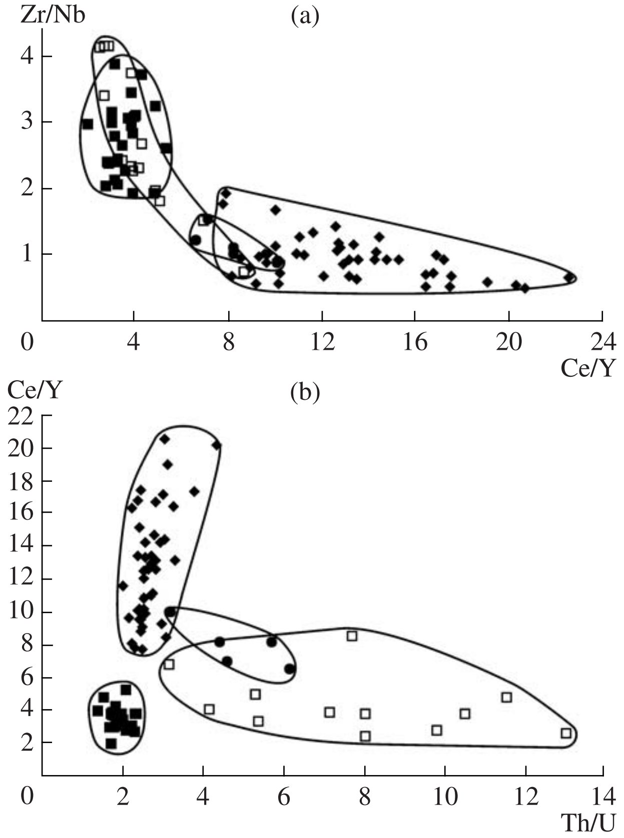

Fig. 3. Correlations between the element ratios (a) Zr/Nb–Ce/Y and (b) Ce/Y–Th/U in the kimberlites of various geochemical types. The symbols are the same as in Fig. 2.

observed. The slopes of these correlation lines are different from that of the Nakyn field kimberlites.

It is noteworthy that the character of correlation relationships between Nb and Ti in the kimberlites of this type varies depending on the level of Ti content. The regression line is steep at low Ti (International pipe), and a slight increase in Ti content is accompanied by a sharp increase in Nb. With increasing Ti content, the slope of the regression lines decreases, and at high Ti contents, a significant increase in Ti is accompanied by only a slight increase in Nb concentration. The regular change in the character of correlation relationships between Nb and Ti, which is manifested by a gradual decrease in the slope of regression lines with increasing Ti content, indicates common genetic features for the kimberlites of the traditional diamond-bearing regions of Yakutia. Such a character of the regression lines is probably related to the fact that Nb has a higher charge and a smaller effective ionic radius compared with Ti, which results in its preferential partitioning into Ti-bearing minerals during the early stages of their crystallization. The peculiar characteristics of the kimberlites of the Nakyn field, which do not follow the general trend of Nb and Ti relationships formed by the kimberlites of the traditional type, indicate that the two types of kimberlites are probably contrasting in terms of both geochemistry and genesis.

ON THE NATURE OF THE GEOCHEMICAL HETEROGENEITY OF KIMBERLITES

As follows from our analysis, the geochemical parameters of kimberlites are much more variable compared with their petrochemical characteristics and vary within broad limits. The systematic character of these variations allows us to distinguish contrasting

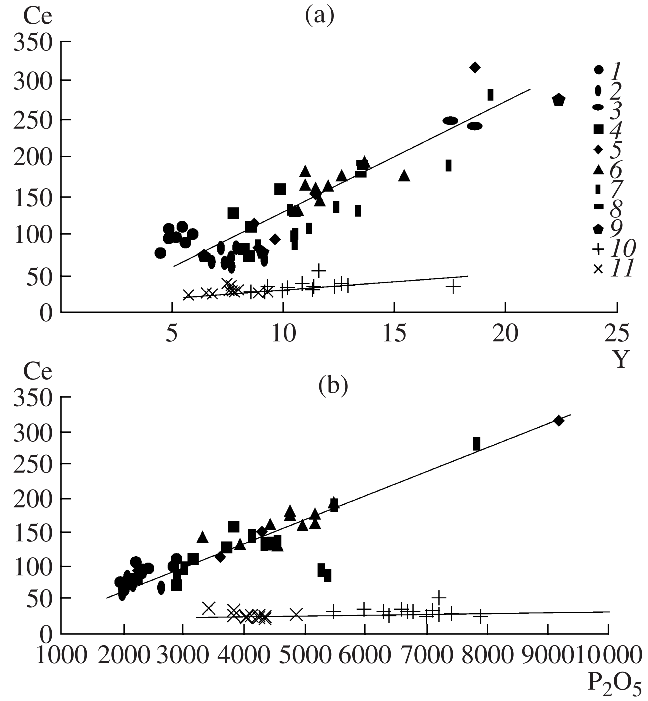

Fig. 4. Correlations between the contents of (a) Ce and Y and (b) Ce and P_2O_5 in the kimberlites of the Middle Markha region and traditional diamond-bearing regions of Yakutia. Kimberlite pipes: (*1*) Yubileinaya, (*2*) Komsomol'skaya, (*3*) Dachnaya, (*4*) Udachnaya, (*5*) Aikhal, (*6*) International, (*7*) Mir, (*8*) 23rd Party Congress, (*9*) Taezhnaya, (*10*) Botuobiya, and (*11*) Nyurbinskaya.

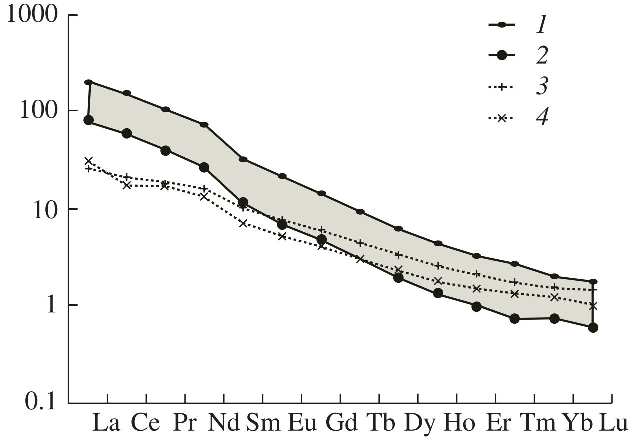

Fig. 5. Pyrolite-normalized (McDonough and Sun, 1995) distribution of rare earth elements in the kimberlites of the traditional diamond-bearing regions (Malaya Botuobiya and Daldyn–Alakit) and the Middle Markha region of Yakutia. The gray shading indicates the field of kimberlites from the traditional diamond-bearing regions; (*1*) and (*2*) extreme compositions of this field (*1*, kimberlites of the Dachnaya pipe and *2*, kimberlites of the Yubileinaya pipe); (*3*) and (*4*) kimberlites of the Middle Markha region (*3*, Botuobiya pipe and *4*, Nyurbinskaya pipe).

geochemical types of rocks. The existence of contrasting geochemical types of diamondiferous kimberlites indicates both geochemical and genetic heterogeneity of this association and metallogenic type of igneous rocks. The origin of kimberlite heterogeneity is not fully understood and deserves special consideration. It is evident that it is connected with some specific features of the sources of these rocks or different conditions of their generation.

The dramatic geochemical differences between the kimberlites with rather similar petrochemical properties allow us to conclude that the geochemical and petrochemical parameters of these rocks are decoupled and were probably controlled by different factors. The major element composition of rocks depends mainly on the composition of the magma-generating mantle source. Under the condition of incipient melting and fluidization, this material is extensively incorporated into the kimberlite. Thus, the petrochemistry of kimberlites is a function of the parameters that, similar to the diamond content of rocks, are controlled by the depth of generation. This is why the diamond content of kimberlites is always correlated with their petrochemical parameters and distribution of compatible elements [9–11].

On the other hand, the main factor controlling the geochemistry of rocks, including the distribution of incompatible HFS elements, is probably the metasomatic alteration of mantle rocks, which occur repeatedly under the influence of deep fluids or volatiles released during the recycling of subducted crustal materials. The processes of mantle metasomatism, which operate both long before the generation of kimberlites and immediately prior to their formation, could be responsible for the formation of geochemically heterogeneous source materials and subsequent generation of geochemically specialized types of deep-derived magmas showing signatures of individual mantle sources.

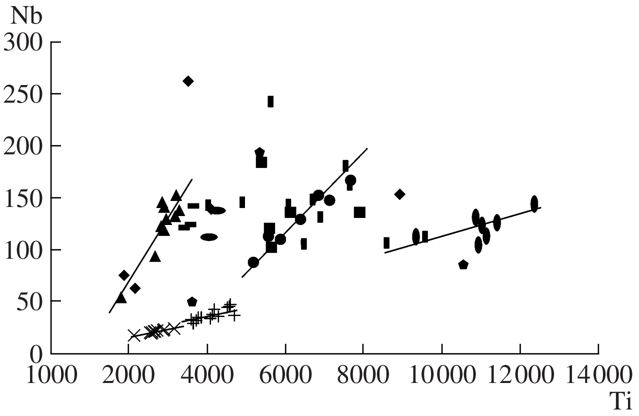

Fig. 6. Covariations of Nb and Ti contents in the kimberlites of the Middle Markha region and traditional diamond-bearing regions of Yakutia. The symbols are the same as in Fig. 4.

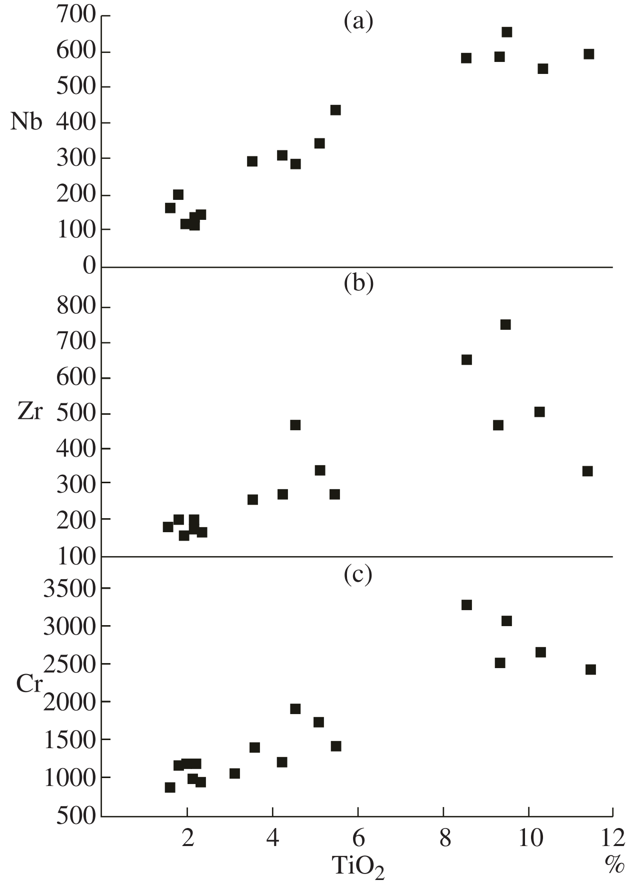

Fig. 7. Correlation between the concentrations of TiO_2 (wt %) and (a) Nb, (b) Zr, and (c) Cr in the kimberlites of Liberia.

An alternative mechanism that is often proposed for the formation of geochemical and isotopic heterogeneities in mantle rocks and their magmatic derivatives is the mixing of a primitive mantle source with a lithospheric reservoir of the EM-1 or EM-2 type. This suggestion was invoked, for example, to interpret the isotopic signatures of lamproites and orangeites, which are strongly different from those of group 1 kimberlites. Given the similarity of the isotopic characteristics of the enriched sources to those of the lower crust, one possible scenario is the subduction of crustal material, younger (Neoproterozoic) in the case of the EM-2 source or older (Late Archean–Paleoproterozoic) for the EM-1 source. It is believed that the subduction of the crust could supply volatile components (promoting melting) and incompatible elements.

Although the theoretical possibility of the occurrence of the subduction mechanism cannot be denied, there are a number of arguments for a more universal role of deep flows of thermal fluids (mantle jets) and metasomatism caused by these flows. The results of these phenomena are similar to those of subduction processes. There is direct evidence that in many cases the chemical heterogeneity of mantle material affecting the geochemical characteristics of kimberlites and related rocks is caused by mantle metasomatism, which is most commonly manifested in the development of the phlogopite–ilmenite assemblage. This assemblage occurs in kimberlites as inclusions of phlogopite–ilmenite and phlogopitized ultrabasic rocks, deformed phlogopite xenocrysts, and coarse-grained ilmenite clots and nodules.

It can be shown that the geochemical characteristics of kimberlites are directly related to the presence and amount of the minerals of metasomatic phlogopite–ilmenite assemblages. For instance, the rocks that are almost free of ilmenite (kimberlites of the Nakyn field of Yakutia and the Zolotitsa field of the Arkhangelsk province) have anomalously low contents of not only titanium but also niobium, zirconium, thorium, uranium, and cerium. In contrast, elevated contents of ilmenite in kimberlites and kimpicrites are usually accompanied by enrichment in niobium, zirconium, and some other elements. This is clearly illustrated by the kimpicrites of Liberia containing abundant ilmenite xenocrysts [12]. An increase in titanium content in these rocks is correlated with an increase in niobium, zirconium, and chromium, i.e., the elements that reside primarily in ilmenite (Fig. 7).

As was noted above, there were probably several deep metasomatic events, which might have different geochemical signatures and significantly different concentration levels and proportions of incompatible elements. The repeated occurrence of metasomatic processes deep in the mantle is supported by strongly variable model ages of the mantle sources of kimberlites, lamproites, and rocks convergent with them (Table 2). As follows from Table 2, each regional and association group of kimberlites and related rocks, as well as each geochemical type of kimberlite, corresponds to a certain interval of the model ages of the mantle source.

Such intervals were established for the kimberlites from the majority of pipes of the traditional diamond-bearing regions of Yakutia (~600–700 Ma). The kimberlites of the Udachnaya and Aikhal pipes (~700–900 Ma) are conspicuous within this group. The model age of the Nakyn field kimberlites is from 800 to 1240 Ma, and each pipe shows its individual model age (1180–1240 Ma for the Nyurbinskaya pipe and 832–979 Ma for the Botuobiya pipe). The model ages of kimberlites from the Zolotitsa field (~1200–1300 Ma) and V. Grib pipe (~880–1050 Ma) are close to these intervals. Noteworthy are markedly older model ages of the source rocks of the lamproite family, olivine lamproites of Kostamuksha and madjgawanites of India, which are usually higher than 2 Ga and occasionally up to 2.6–2.7 Ga.

The geochemical signature of metasomatic processes is probably affected by a number of factors, including the temporal and geochemical stage of Earth evolution, the character of phase transitions in the interiors, the depth of origin and source of juvenile emanations, etc. The existence of geochemically specialized metasomatic processes in the mantle is supported by

Table 2. Model Nd age of kimberlites, lamproites, and related rocks

Analysis no.	Sample no.	Rock	Pipe, region	Absolute age of rock	T(DM)	T(DM2)
1	038/284/154	kimberlite	Yubileinaya	360	601	703
2	508/1040	″	Aikhal	360	790	898
3	“Int”	″	International	360	588	668
4	G-751	″	International	360	632	732
5	V-585	″	Mir	360	617	704
6	V-585	″	Mir	360	637	732
7	502/865	″	Udachnaya	360	779	960
8	513/1050	″	Udachnaya	360	687	802
9	113/251	″	Komsomol’skaya	358	604	700
10	G-887	″	Nyurbinskaya	364	1242	1204
11	G-889	″	Nyurbinskaya	364	1180	1209
12	E-410	″	Botuobiya	364	832	779
13	E-412	″	Botuobiya	364	979	935
14	16/4/305	″	Botuobiya	364	911	868
15	P-1490/937-941	″	Pionerskaya	350	1346	1368
16	L-488/723-726	″	Lomonosovskaya	350	1209	1376
17	G-9Ts/981	″	V. Grib	350	878	1050
18	77/243-246	kimpicrite	Terskii Coast	350	1000	1253
19	M-52	madjgawanite	Madjgawan	1140	2510	2392
20	M-52a	″	Madjgawan	1140	1729	1947
21	17-E	olivine lamproite	Kostomuksha	1230	2183	2649
22	31	″	Kostomuksha	1230	2174	2673

Note: The Nd isotope compositions were analyzed at the center of isotope investigations of the All-Russia Geological Institute. The measured values were corrected for Nd fractionation by normalizing to $^{148}Nd/^{144}Nd = 0.241578$ and adjusting to $^{143}Nd/^{144}Nd = 0.511860$ in the La Jolla international isotope standard.

the compositions of the alkaline ultramafic rocks of the lamproite clan, olivine lamproites and madjgawanites. The geochemical peculiarity of these rocks includes the extremely high (for ultramafic rocks) concentrations of Ti, Zr, Ce, K, Rb, Ba, P, and F at elevated Zr/Nb, Ce/Y, and Ba/Sr values [13, 14]. The fact that the concentrations of most of these elements in the rocks of the lamproite clan are much higher than those of crustal rocks is difficult to explain in terms of the mixing and recycling of crustal materials. On the other hand, these data and the old model age of the source of lamproitic rocks suggest a contribution from ancient deep-seated metasomatism to the formation of a geochemically peculiar source material enriched in incompatible elements and radiogenic isotopes.

The existence of ancient mantle metasomatism with a geochemical signature similar to that of lamproitic rocks is directly supported by the metasomatic phenomena that were documented by Spetsius [15] in a garnet–orthopyroxene nodule from the kimberlites of the Udachnaya pipe. The nodule contains a secondary assemblage of metasomatic minerals (phlogopite + rutile + zircon), which developes between the garnet and orthopyroxene grains and often intersects the garnet. The modal composition of the inclusion is the following: *Opx* – 30.4%; *Gr* – 29.4%; *Fl* – 36.6%; *Ru* – 3.0%, and *Zr* – 0.6%. The U–Pb age of the zircon was estimated by Spetsius as 1.8 Ga. Judging from the composition of the metasomatic assemblage, this ancient metasomatic process had a K–Ti–Zr specialization similar to that of lamproite magmas.

Examples of geochemically specialized occurrences of kimberlites and related rocks were found in various provinces of the world. Among them are the rocks of the Koidu complex in Sierra Leone (Nb, Ce, Th, and U), the Aries pipe in Western Australia (Nb and Th), and the Alto Paranaiba province in Brazil (Zr, Ce, and U) [7, 12, 16, 17].

Based on these data and the results of the geochemical investigation of xenoliths of metasomatically altered ultrabasic rocks in kimberlites [18], it can be concluded that the metasomatic alteration of mantle rocks under the influence of deep fluids is always accompanied by enrichment in indicator trace elements, primarily incompatible highly charged trace and radioactive elements. This allows us to propose a more comprehensive interpretation of the origin of the peculiar geochemical type of kimberlites which is represented by the rocks of the Nakyn field of Yakutia and the Zolotitsa field and V. Grib pipe of the Arkhangelsk province. These rocks are characterized by a negative anomaly of highly charged trace and radioactive elements. The kimberlites of this type show very low titanium contents and are almost free of ilmenite. These observations cast doubt on the significant role of deep metasomatism in the formation of these rocks and their mantle source and allow us to prefer the variant of a lithosphere source metasomatized under the influence of fluids supplied from the subducted crust [19]. This example can probably be considered as a geochemical precedent reflecting the contribution of the processes of subduction and recycling of crustal material to the genesis of kimberlites.

CONCLUSIONS

The geochemical investigation of kimberlites from the Middle Markha region and their comparison with kimberlites from the traditional diamond-bearing areas of Yakutia supported the discrimination between two geochemical types of kimberlites. One of them is represented by the rocks of the traditional diamond-bearing regions of Yakutia, whose parameters correspond to the petrotype of the kimberlite association. In addition to the kimberlites of the Middle Markha region, the second type includes the rocks of the Zolotitsa field and V. Grib pipe of the Arkhangelsk province and the kimberlites of the Slave province of Canada. This type can be considered as geochemically anomalous. The obtained representative parameters of the two kimberlite types indicate a considerable geochemical contrast between these rocks, and the individual features of correlation relationships of elements in the two types of rocks suggest that their differences are related to essential genetic reasons.

Contrasting differences were established primarily for the group of incompatible highly charged trace and radioactive HFS elements, including Ce, Nb, Zr, U, and Th. The Ce/Y, Nb/Zr, and Th/U ratios can be used as geochemical indicators. The contrasting geochemical differences between petrochemically uniform kimberlites emphasize the heterogeneous nature of these rocks and their mantle source. In contrast to the major components and geochemically similar compatible trace elements (Cr, Ni, Co, V, etc.), whose contents are controlled by the composition of the mantle source and depend on the depth of kimberlite generation, the main factor controlling the distribution of incompatible HFS elements is probably the metasomatic alteration of mantle rocks under the influence of deep-derived fluids or volatiles released during the recycling of subducted crustal material. The processes of mantle metasomatism that occurred both long before the derivation of kimberlites and immediately prior to their generation could promote the appearance of geochemically heterogeneous materials and subsequent generation of geochemically specialized types of deep magmas showing the signatures of individual mantle sources.

The geochemical specialization of deep metasomatic processes probably depends on a number of factors, the detailed study of which will be a subject of future studies. The real existence of geochemically specialized metasomatic processes can be proved by some occurrence of kimberlites and convergent rocks, such as Koidu in Sierra Leone, Aries in Western Australia, Alto Paranaiba in Brazil, as well as the olivine lamproites of Western Australia and other alkaline ultramafic occurrences of lamproitic rocks. The metasomatic alteration of mantle rocks under the influence of fluids of deep-seated origin is always accompanied by a considerable increase in the concentrations of alkalis, titanium, and highly charged incompatible trace and radioactive elements. This can be considered as an additional argument for the suggestion that the rocks of the Middle Markha field, as well as other kimberlite occurrences with negative HFSE anomalies are generated in a lithospheric source region metasomatized by fluids released from the subducted crust.

REFERENCES

1. A. V. Lapin, A. V. Tolstov, and D. V. Lisitsin, *Kimberlites and Related Rocks* (IMGRE, Moscow, 2004) [in Russian].
2. *Arkhangelsk Diamondiferous Province: Geology, Petrography, and Mineralogy*, Ed. by O. A. Bogatikov (Mosk. Gos. Univ., Moscow, 2000) [in Russian].
3. N. P. Pokhilenko, N. V. Sobolev, and N. N. Zinchuk, “Essential Features of Anomalous Kimberlites from the Siberian Platform and Slave Craton with Application to the Problem of Forecasting and Prospecting,” i*n Proceedings of All-Russia Conference on the Diamond Potential of the Timan–Ural Region* (Syktyvkar, 2001) [in Russian].
4. O. A. Bogatikov, V. A. Kononova, Yu. Yu. Golubeva, et al., “Variations in Chemical and Isotopic Compositions of the Yakutian Kimberlites and Their Causes,” Geokhimiya, No. 9, 915–939 (2004) [Geochem. Int. **42**, 799–821 (2004)].
5. V. A. Kononova, Yu. Yu. Golubeva, O. A. Bogatikov, et al., “Geochemical Diversity of Yakutian Kimberlites: Origin and Diamond Potential (ICP-MS Data and Sr, Nd, and Pb Isotopy),” Petrologiya **13**, 493–509 (2005) [Petrology **13**, 205–228 (2005)].
6. N. P. Pokhilenko, McDonald J. A., A. M. Agashev, et al., “Kimberlites and Carbonatites of the Snap Lave/King Lake Dike System: Structural Setting, Petrogeochemistry and Petrology of a Unique Type of Association,” in *Long Abstracts of 8th International Kimberlite Conference, Victoria, Canada, 2003* (Victoria, 2003).
7. A. V. Lapin and A. V. Tolstov, “Problems of the Geochemical Heterogeneity of Kimberlites,” Prikl. Geokhim. **2** (7), 77–93 (2005).
8. V. A. Kononova, L. K. Levsky, V. A. Pervov, et al., “Pb–Sr–Nd Isotopic Systematics of Mantle Sources of Potassic Ultramafic and Mafic Rocks in the North of the

East European Platform," Petrologiya **10**, 493–509 (2002) [Petrology **10**, 433–447 (2002)].

9. V. A. Milashev, *Petrochemistry of the Yakutian Kimberlites and Factors of Their Diamond Potential* (Nedra, Leningrad, 1965) [in Russian].
10. N. N. Sardsadskikh and V. A. Blagul'kina, "Petrographic and Petrogenetic Differences of Kimberlites from the Rocks Showing a Similarity in Some Characteristics," Zap. Vseross. Mineral. O-va **98**, 415–421 (1969).
11. V. B. Vasilenko, N. N. Zinchuk, V. O. Krasavchikov, et al., "Diamond Potential Estimation Based on Kimberlite Major Element Chemistry," J. Geochem. Explor. **76**, 93–112 (2002).
12. W. R. Taylor, L. A. Tompkins, and S. E. Haggerty, "Comparative Geochemistry of West African Kimberlites," Geochim. Cosmochim. Acta **58**, 4017–4037 (1994).
13. A. L. Jaques, J. D. Lewis and B. D. Smith, *The Kimberlites and Lamproites of Western Australia*, Geol. Surv. W. Aust. Dep. Mines Bull. **132** (1986) (Mir, Moscow, 1989).
14. A. V. Lapin and A. D. Khar'kiv, "Majgawanites as a Special Petrochemical Type of Diamondiferous Igneous Rocks," Geokhimiya, No. 11, 1–10 (2003) [Geochem. Int. **41**, 1081–1089 (2003)].
15. Z. V. Spetsius, "Metasomatism and Partial Melting in Xenoliths from the Kimberlite Pipes of Yakutia in the Context of Diamond Genesis," in *Proceedings of 4th International Seminar on Sources of Deep-Seated Magmatism and Their Relations with Plume Processes, Irkutsk–Ulan Ude, Russia, 2004* (Irkutsk–Ulan Ude, 2004), pp. 107–143 [in Russian].
16. A. L. N. Araujo, R. W. Carlson, J. C. Gaspar, and L. A. Bizzi, "Petrology of Kamafugites and Kimberlites from the Alto Paranaiba Alkaline Province, Minas Gerais, Brazil," Contrib. Mineral. Petrol. **142**, 163–177 (2001).
17. D. Edwards, N. M. S. Rock, W. R. Tailor, et al., "Mineralogy and Petrology of the Aries Diamondiferous Kimberlite Pipe, Central Kimberley Block, Western Australia," J. Petrol. **33**, 1157–1191 (1992).
18. A. V. Lapin and A. D. Khar'kiv, "Geochemical Features of Ilmenite–Phlogopite Ultramafic Xenoliths in Kimberlites and the Role of Fluids in Mantle Differentiation," Dokl. Akad. Nauk **255**, 1269–1271 (1980).
19. Yu. Yu. Golubeva, V. A. Pervov, and V. A. Kononova, "Low-Ti Diamondiferous Kimberlites—A New Petrogeochemical Type," in *Proceedings of Scientific and Applied Conference on 50th Anniversary of the Discovery of the First Diamondiferous Pipe Zarnitsa, VSEGEI, Russia, 2004* (VSEGEI, St. Petersburg, 2004), pp. 96–99 [in Russian].