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Megacrysts from the Grib kimberlite pipe (Arkhangelsk Province, Russia)☆

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Abstract

The megacryst suite of the Grib kimberlite pipe (Arkhangelsk province, Russia) comprises garnet, clinopyroxene, magnesian ilmenite, phlogopite and garnet-clinopyroxene intergrowths. Crystalline inclusions, mainly of clinopyroxene and picroilmenite, occur in garnet megacrysts. Ilmenite is characterized by a wide range in the contents of MgO (10.6–15.5 wt.%) and Cr_2O_3 (0.7–8.3 wt.%). Megacryst garnets show wide variations in Cr_2O_3 (1.3–9.6 wt.%) and CaO (3.6–11.0 wt.%) but relatively constant MgO (15.4–22.3 wt.%) and FeO (5.2–9.9 wt.%). The pyroxenes also show wide variations in such oxides as Cr_2O_3, Al_2O_3 and Na_2O (0.56–2.95; 0.86–3.25; 1.3–3.0 wt.%, respectively). The high magnesium and chromium content of all these minerals puts them together in one paragenetic group. This conclusion was confirmed by studies of the crystalline inclusions in megacrysts, which demonstrate similar variations in composition. Low concentration of hematite in ilmenite suggests reducing conditions during crystallization. $P–T$ estimates based on the clinopyroxene geothermobarometer (Contrib. Mineral. Petrol. 139 (2000) 541) show wide variations (624–1208 °C and 28.8–68.0 kbars), corresponding to a 40–45 mW/m^2 conductive geotherm. The majority of Gar-Cpx intergrowths differ from the corresponding monomineralic megacrysts in having higher Mg contents and relatively low TiO_2. The minerals from the megacryst association, as a rule, differ from the minerals of mantle xenoliths, but garnets in ilmenite-bearing peridotite xenoliths are compositionally similar to garnet megacrysts. The common features of trace element composition of megacryst minerals and kimberlite (they are poor in Zr group elements) suggest a genetic relationship. The origin of the megacrysts is proposed to be genetically connected with kimberlite magma-chamber evolution on the one hand and with associated mantle metasomatism on the other. We suggest that, depending on the primary melt composition, different paragenetic associations of macro/megacrysts can be crystallized in kimberlites. They include: (1) Fe–Ti (Mir, Udachnaya pipes); (2) high-Mg, Cr (Zagadochna, Kusova pipes); (3) high-Mg, Cr, Ti (Grib pipe).

Keywords: Kimberlite; Megacrysts; High-chromium association; Genesis

1. Introduction

The Grib kimberlite pipe is located in the Kepino-Pachuga field of the Arkhangelsk kimberlite province

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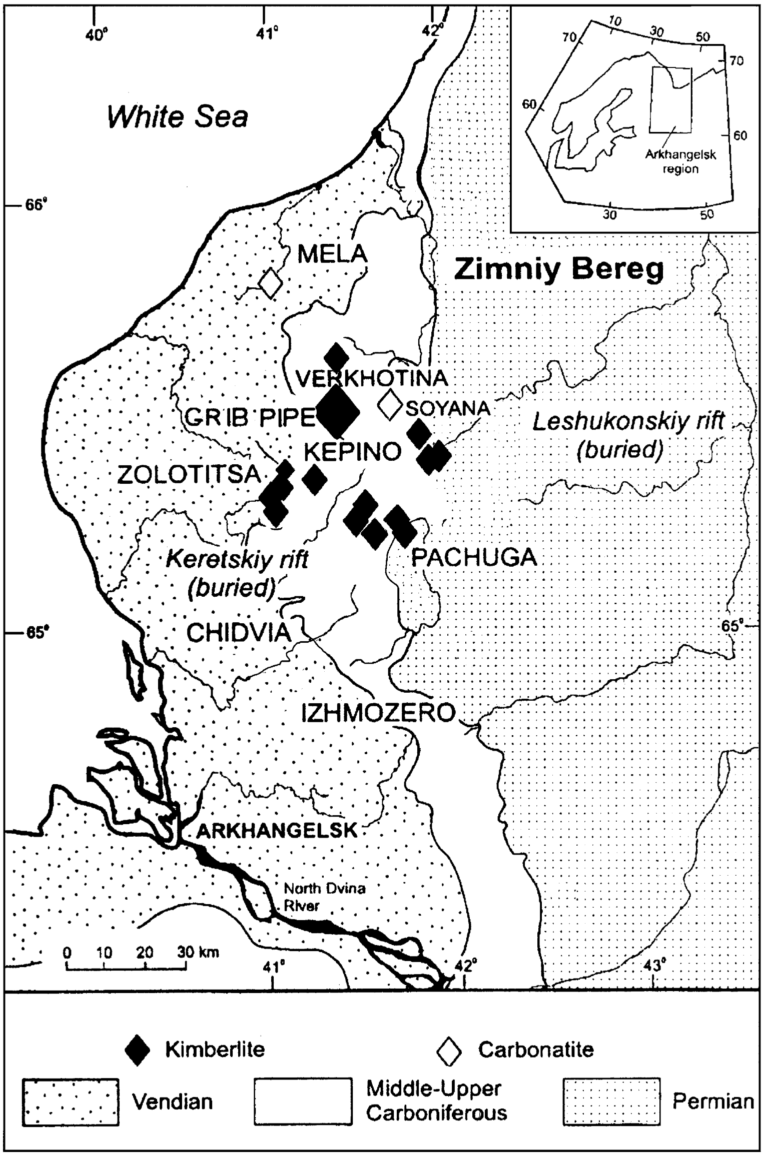

Fig. 1. Simplified geological sketch map of the Arkhangelsk Alkaline Igneous Province (Makhotkin et al., 2000).

(Fig. 1). The pipe, discovered in 1996, differs from certain other Arkhangelsk province kimberlites discovered earlier (e.g. Lomonosovo, Pionerskaya) in that the latter deposits contain abundant chrome spinel and lack typical megacryst phases like garnet and magnesian ilmenite. In contrast, the kimberlites from the high-grade Grib pipe contain abundant magnesian ilmenite, garnet, clinopyroxene, phlogopite and garnet-clinopyroxene intergrowths, whereas chrome spinel is a minor phase. Many of these phases occur as grains that are over 1 cm across and belong to the megacryst association.

Crystalline inclusions, mainly of clinopyroxene and picroilmenite occur in garnet megacrysts from the Grib kimberlite. Mineral compositions were analyzed by electron microprobe "JEOL" JXA-50A at Moscow State University, and JCXA-733 at the Institute of Geochemistry, Irkutsk. Trace

Table 2
Mineral analyses of megacryst garnets and ilmenite inclusions from Grib pipe

	1 gr1-1 Gar	2 gr1-1-1 Ilm	3 gr1-1-2 Ilm	4 gr1-6 Gar	5 gr1-6-1 Ilm	6 gr1-6-2 Ilm	7 gr1-8 Gar	8 gr1-8-1 Ilm	9 gr1-8-2 Ilm	10 gr1-8-3 Ilm	11 gr1-9 Gar	12 gr1-9-1 Ilm	13 gr1-9-2 Ilm
SiO_2	40.91	0.35	0.29	41.19	0.14	0.09	42.07	0.18	0.32	0.39	42.14	0.14	0.07
TiO_2	0.91	54.61	56.13	1.13	54.85	54.22	1.12	56.23	55.1	53.9	0.76	55.64	56.25
Al_2O_3	19.32	0.61	1.15	18.92	0.93	0.68	17.92	0.57	0.82	0.99	20.19	0.65	0.91
Cr_2O_3	2.89	2.81	3.2	3.26	3.46	4.37	3.93	3.01	3.65	3.63	2.76	2.03	2.41
Fe_2O_3		2.75	0		0	1.13		0	0	2.27		0.64	0
FeO	9.49	25.6	27.36	9.31	28.65	27.51	9.37	27.69	28.43	25.56	9.7	27.2	27.8
MnO	0.33	0.25	0.19	0.14	0.15	0.28	0.5	0.25	0.27	0.28	0.31	0.48	0.22
MgO	19.89	13.21	11.78	20.01	11.55	11.82	19.14	12	11.18	12.87	18.54	12.83	11.83
CaO	4.6	0.1	0.16	4.8	0.08	0	5.38	0.06	0.06	0.12	4.79	0	0
Total	98.34	100.29	100.26	98.76	99.81	99.99	99.43	99.99	99.83	99.78	99.19	99.61	99.49
mg#	78.9			79.3			78.4				77.3		

elements were analyzed by Laser-Ablation Inductively Coupled Plasma Mass Spectrometry (LAM-ICPMS; Hewlett Packard 7500) at GEMOC, Macquarie University, Australia. Methods and operating conditions have been described by Norman et al. (1996). Representative compositional data for megacryst-suite and related minerals are listed in Tables 1, 4, 6, 8 and 9. The compositions of ilmenite and clinopyroxene intergrowths with garnet are listed in Tables 2 and 5, respectively. Tables 1, 4–6 and 8 are presented as supplementary digital data sets on line.

2. Megacryst occurrence and compositions

2.1. Magnesian ilmenite

Mg-rich ilmenite is a dominant mineral in the kimberlite heavy fraction. It occurs as rounded,

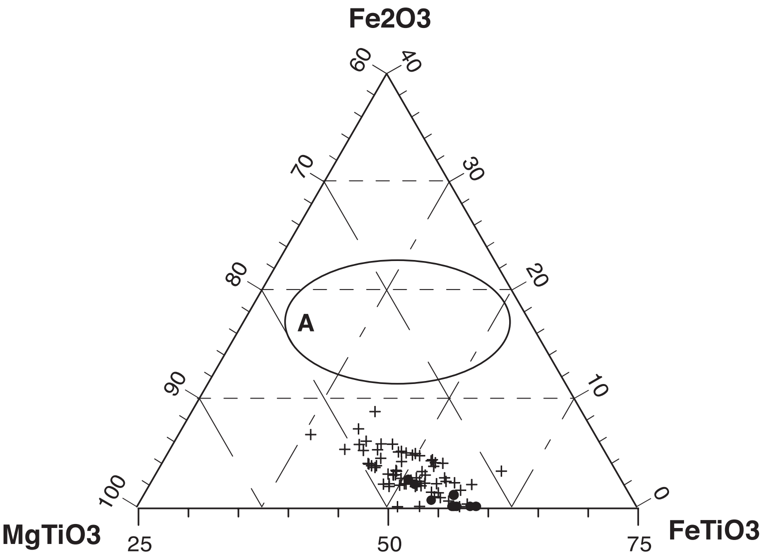

Fig. 2. Plot of magnesian ilmenite compositions: plus-megacrysts from the Grib pipe, black circle-inclusions in garnets from the Grib pipe, oval **A**-field of compositions of picroilmenite from Yakutian province.

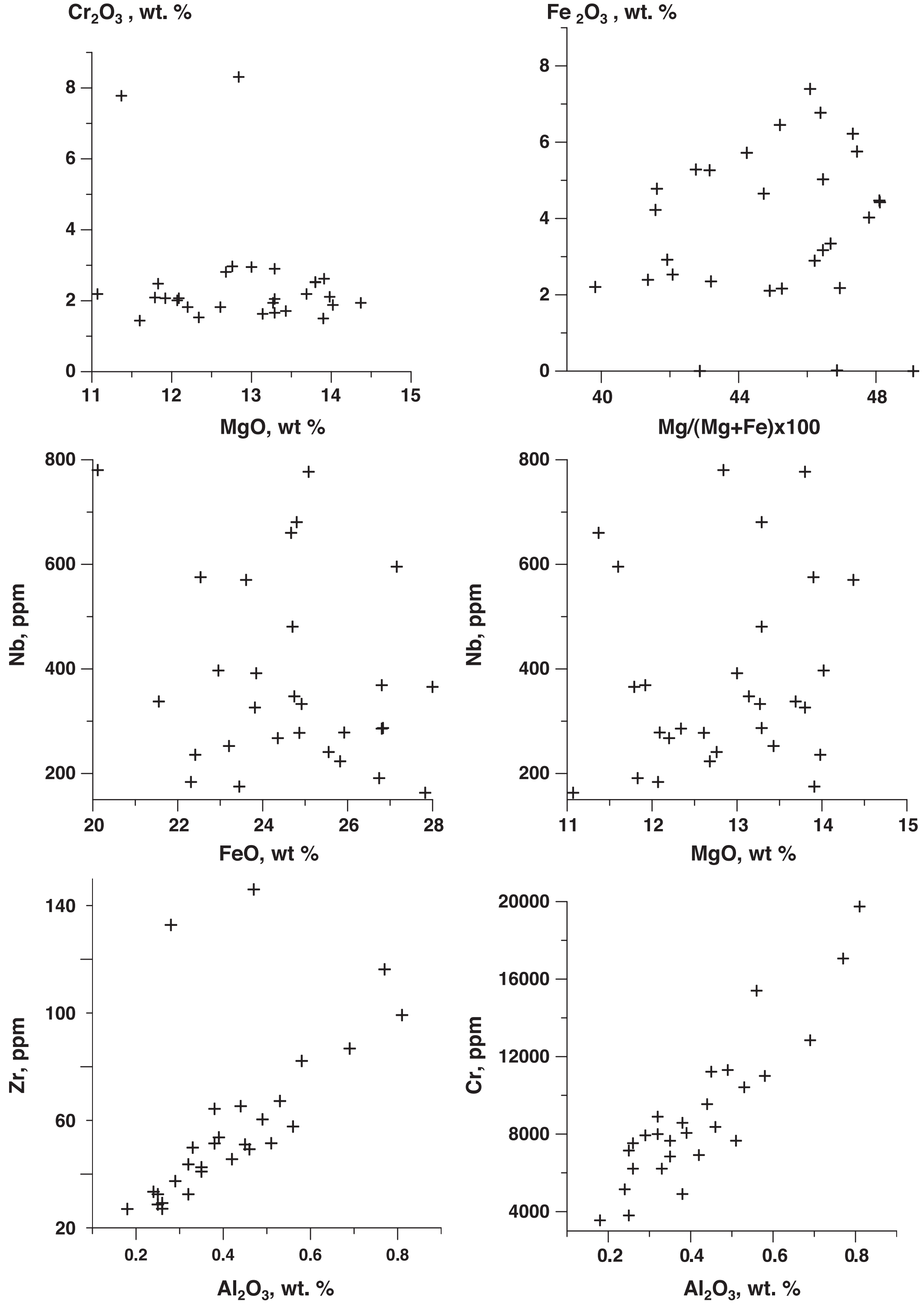

Fig. 3. Binary plots of correlation between major, minor oxides and rare elements in the ilmenites from the Grib pipe.

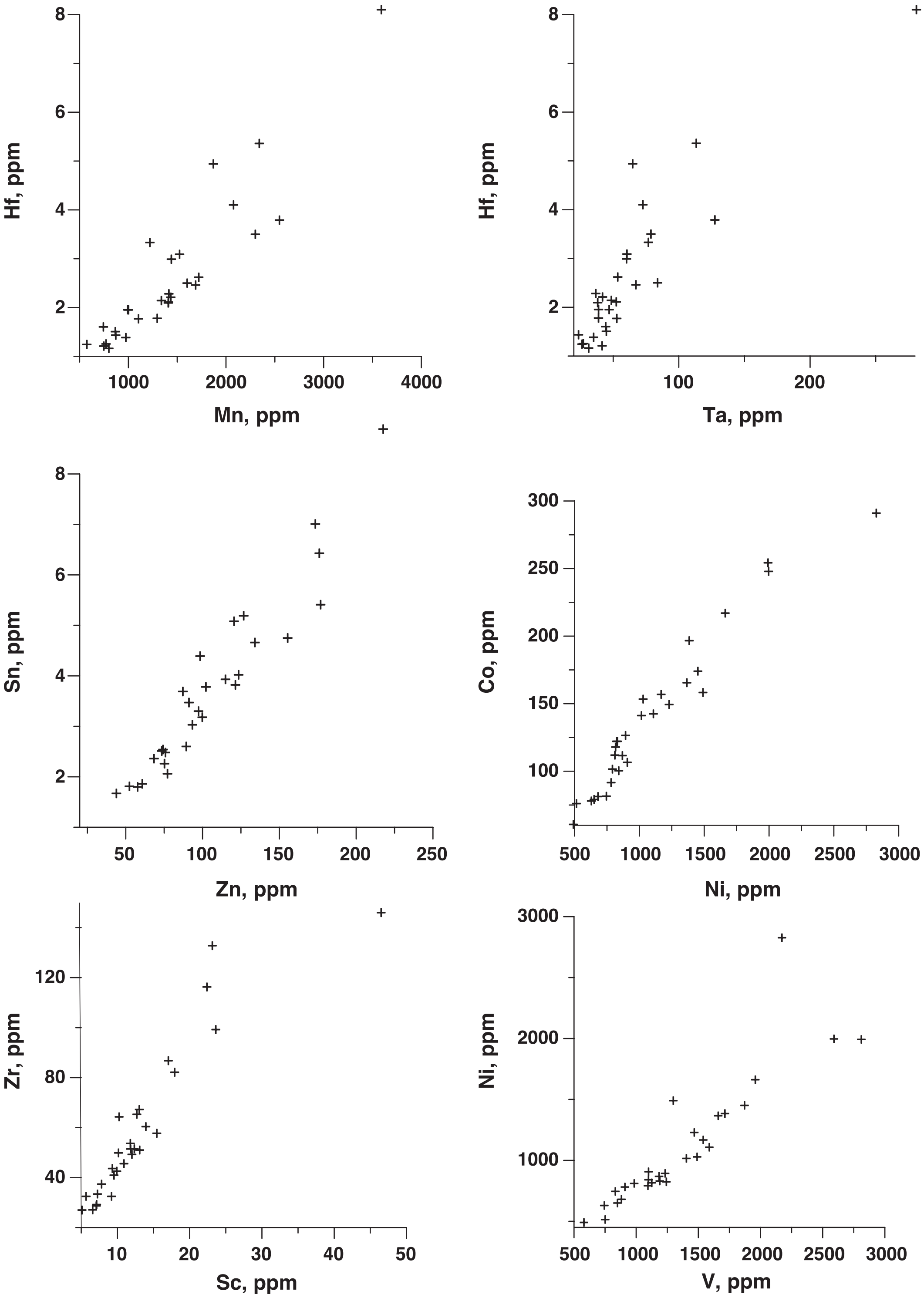

Fig. 3 (*continued*).

oval-flattened and fragmental-angular grains up to 15 mm across and as microcrystalline inclusions in garnet and phlogopite megacrysts. We have studied the composition of megacryst ilmenite grains varying in size from 5 to 15 mm and of ilmenite inclusions measuring 300×20 to 400×250 μm that occur in other phases. In addition to rounded and rounded-oval inclusions some of them are sliced and angular with resorbed margins. Tables 1 and 2 give representative picroilmenite compositions.

Mg-ilmenite megacrysts from Grib pipe are marked by wide variations in Fe and Mg concentrations, low iron oxidation state (Fig. 2) and high chromium contents. Average Cr_2O_3 and Fe_2O_3 contents are 2.4 and 3.6 wt.%, respectively. Megacryst ilmenite with such compositions has not been found in kimberlites of the Yakutian province. For example, in ilmenites from the Daldyn field (Kostrovitsky et al., 2003) the average Cr_2O_3 concentrations can reach as high as 1.5–1.8 wt.% (Osennya pipe), while minimum Fe_2O_3 contents are 10 wt.% (Leningradska pipe). The composition of ilmenite inclusions in garnet from Grib is similar to that of ilmenite macrocrysts, but is richer in Cr_2O_3 and poorer in Fe_2O_3 (Table 2). The composition of ilmenite inclusions from the same garnet can vary significantly (Table 2).

The megacryst ilmenites from the Grib kimberlite pipe are marked by a wide variation of trace element compositions and low Zr, Nb and Hf contents (Table 1). Most of the analyzed trace elements (V, Ga, Cu, Sn, Co,

Table 3
Variations, average content of trace elements (in ppm) in picroilmenite megacrysts from different locations. Data for South-African province from Griffin et al. (1997), for Yakutian province from Genshaft et al. (1983). Number of analyses is given in brackets. The numerator means variation range, the denominator means average content

	Grib pipe (29)	South-African Province (63)	Yakutian province (572)
Ni	(489-2023)/1108	(111-1350)/726	
Cu	(18-92)/51	(19-39)/20	
Zn	(43-176)/105	(75-130)/110	
Ga	(4-18)/9	(11-22)/12	
Zr	(27-132)/62	(415-1020)/592	
Nb	(163-1790)/415	(294-3220)/925	(577-1223)/916
Co	(60-291)/138		(175-207)/192
Sc	(5-46)/13		(18-31)/24
Hf	(1-5)/2		(8-26)/17
Ta	(23-281)/62	(47-695)/159	(65-211)/148

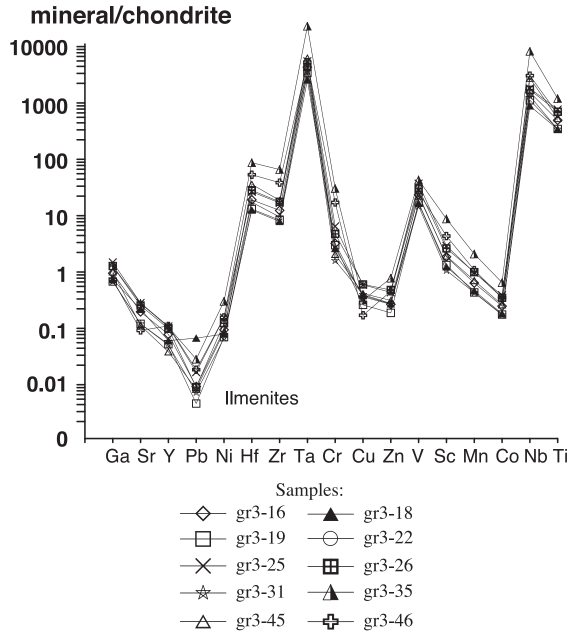

Fig. 4. Chondrite-normalized (McDonough and Sun, 1995) spidergram of trace elements in Grib ilmenites.

Y, Mn, Ni, Nb, Zr, Hf, Ta) are well correlated with one another (Figs. 3 and 4) and with minor oxides (Al_2O_3, Cr_2O_3, MnO). However, the correlation between major oxides and the minor oxides and trace elements is poor. Table 3 gives the trace element composition of picroilmenites from the Yakutian province and South African pipes for comparison. Chondrite-normalized spidergrams (Fig. 4) show groups of rare earth elements that behave similarly in ilmenite: (1) Ta, Nb (three to four orders higher than chondrite); (2) Hf, Zr, V (one to two orders higher than chondrite); (3) Ga, Cr, Sc, Mn (most similar to chondrite); (4) Cu, Zn, Co, Sr (two to eight times lower than chondrite); (5) Y, Ni, Pb (one to two orders lower than chondrite). The succession of groups reflects a real degree of element compatibility during the crystallization of magnesian ilmenite.

2.2. Garnet

Garnet occurs as individual megacrysts, which are typically rounded, in some cases with relics of crystallographic shape. Megacrysts are as a rule not over 10 mm in size. In addition, intergrowths of garnet and chrome-diopside are frequently found. Clinopyroxene and garnet commonly occur in equal proportions in

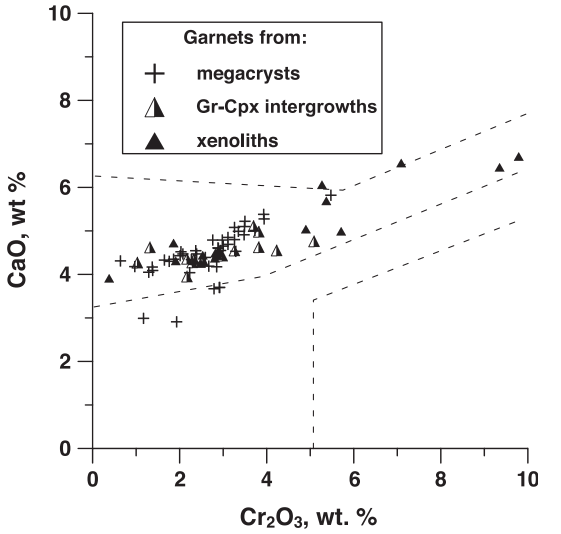

Fig. 5. Plot of Cr_2O_3 vs. CaO for the garnets from the Grib pipe. Fields shown for garnets are taken from Sobolev et al. (1974). Data for xenoliths are from Sablukova et al. (2003) and Malkovets et al. (2003).

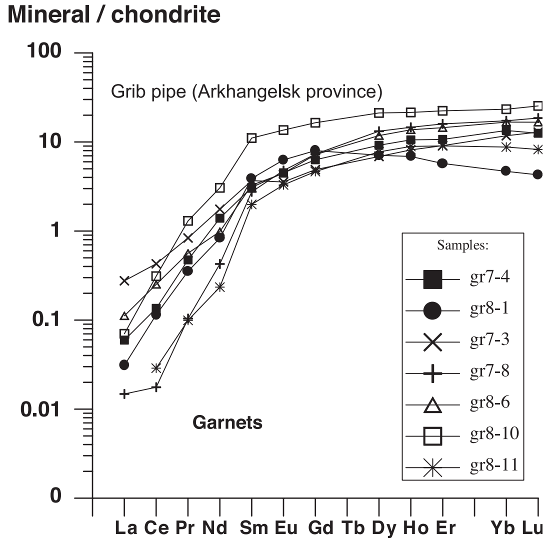

Fig. 7. Chondrite-normalized (McDonough and Sun, 1995) REE patterns for garnet megacrysts of the Grib pipe.

these intergrowths. These inclusions can occur both in the center and on the margins of megacrysts. In some cases, clinopyroxene is found on margins of the garnet megacrysts, forming separate grains with uneven borders or as a discontinuous rim. Intergrowths with a predominant clinopyroxene, and garnet as fine inclusions, are rare.

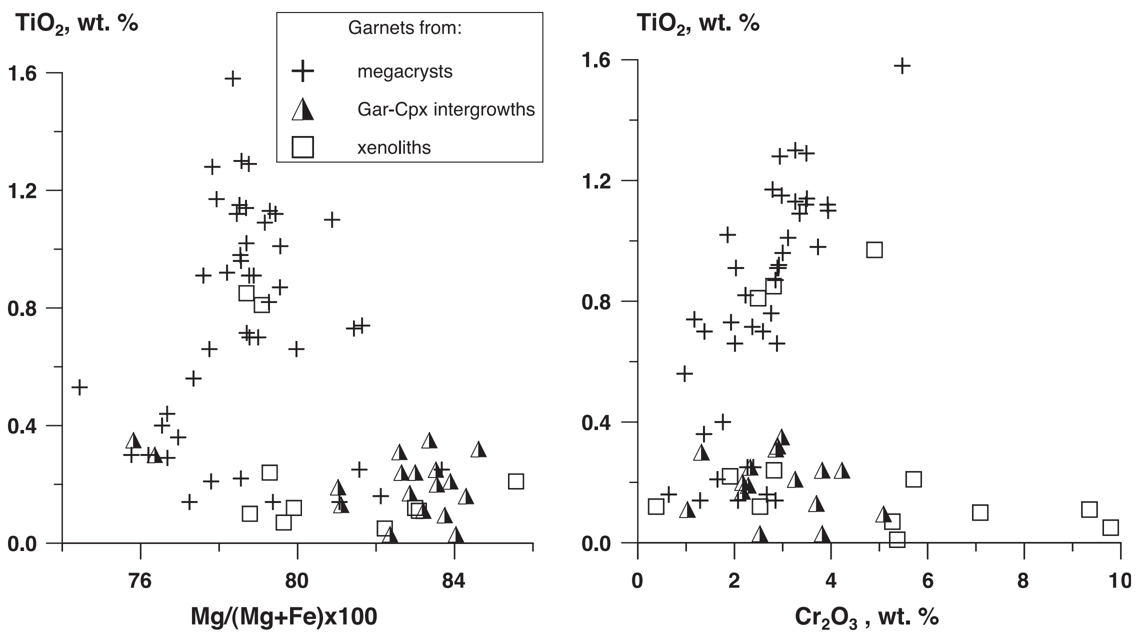

Fig. 6. Compositions of garnets from megacrysts, intergrowths and xenoliths from the Grib pipe. Data for xenoliths are from Sablukova et al. (2003). Mg/(Mg + Fe) is given as a molar ratio.

Table 7
The average content of Zr, Nb, Ta and Hf (in ppm) in garnet megacrysts and kimberlites from Grib pipe (data from Krotkov et al., 2001) and Yakutian province (data from Ilupin et al., 1978)

	Garnet megacrysts		Kimberlite	
	Grib pipe ($n=16$)	Yakutian province (not published data) ($n=14$)	Grib pipe (Krotkov et al., 2001) ($n=1$)	Yakutian province (Ilupin et al., 1978) ($n=18$)
Zr	28.1	79.4	59	133
Nb	0.12	0.67	38	121.9
Hf	0.47	2.3	1.1	2.7
Ta	<0.01		3.6	5.8

Garnets occurring as individual megacrysts (Table 4) and in Gar-Cpx intergrowths (Table 5) have high TiO_2 contents, and as such belong to groups 1, 2 and 9 of Dawson (1980). The majority of studied grains represent high-titanium pyropes of megacryst groups 1 and 2, but those from Grib are richer in Cr_2O_3. Based only on their CaO and Cr_2O_3 contents (Fig. 5) the megacrysts and Gar-Cpx intergrowths belong to the lherzolite paragenesis of Sobolev (1977). Despite wide variations in Cr_2O_3 (1.3–9.6 wt.%) and CaO (3.6–11.0 wt.%), the megacryst garnets are characterized by relatively constant MgO (15.4–22.3 wt.%) and FeO (5.2–9.9 wt.%). Variations in garnet composition are mainly due to variations in the uvarovite/pyrope ratio. Garnet and chrome-diopside in intergrowths demonstrate wide

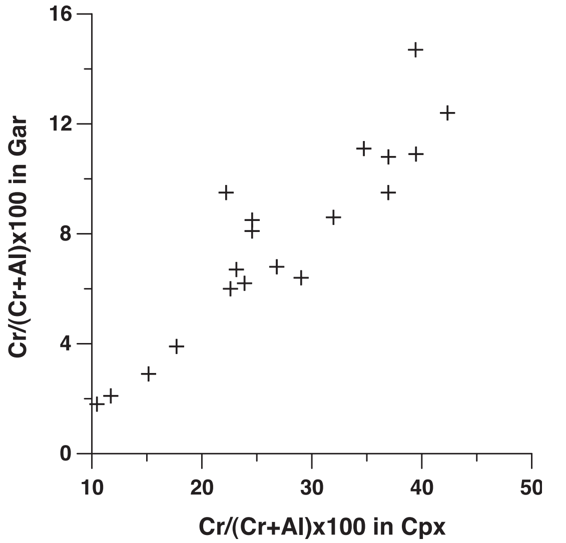

Fig. 9. High correlation of compositions of garnet and clinopyroxene from intergrowths of the Grib pipe.

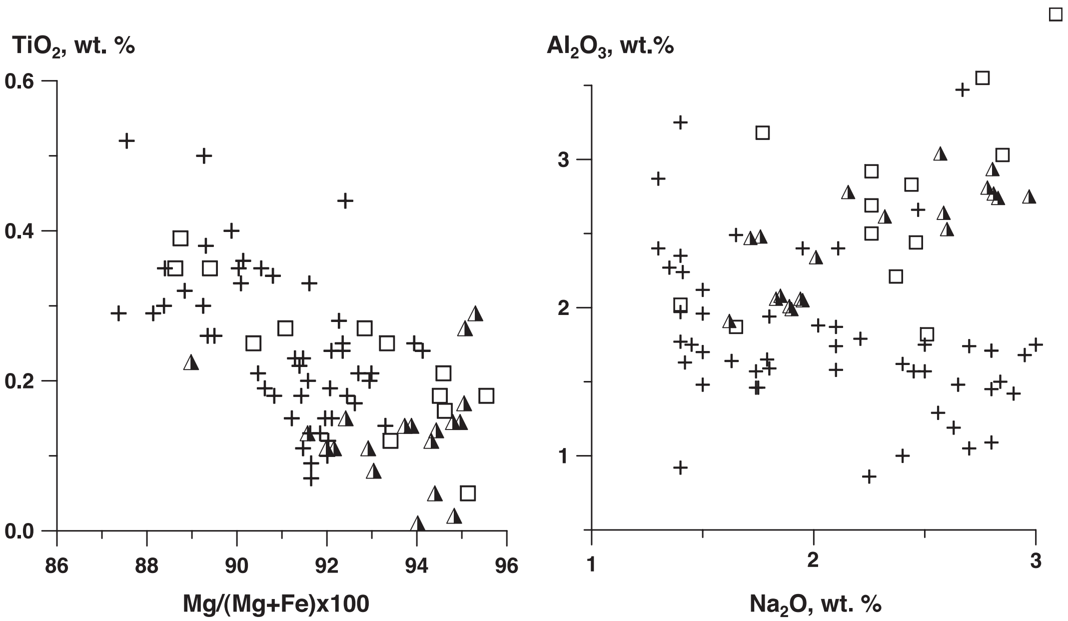

Fig. 8. Compositions of clinopyroxenes from megacrysts, intergrowths and xenoliths from the Grib pipe, with symbols as for Fig. 6. Data for xenoliths are from Sablukova et al. (2003) and Malkovets et al. (2003). Mg/(Mg + Fe) is given as a molar ratio.

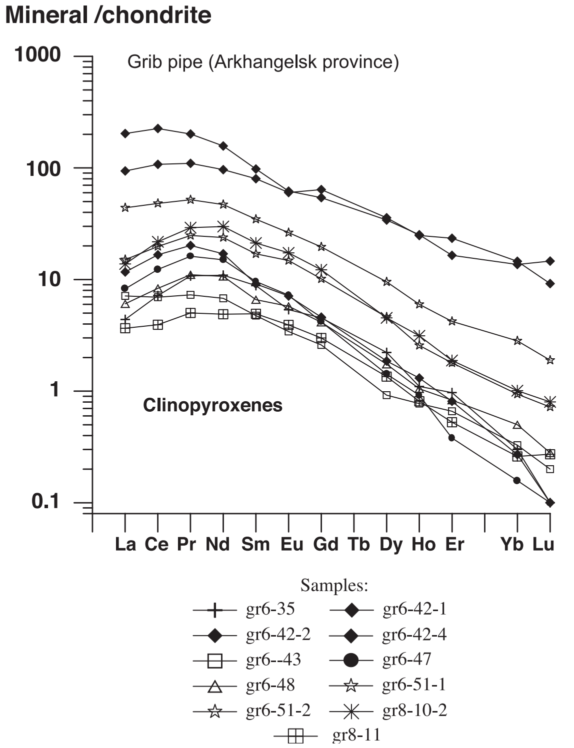

Fig. 10. Chondrite-normalized (McDonough and Sun, 1995) REE patterns for clinopyroxene megacrysts from the Grib pipe.

variations in composition. Compared to megacrysts, garnets from the Gar-Cpx intergrowths are characterized by relatively low TiO_2 contents and higher MgO (Fig. 6). Most of the investigated garnet megacrysts are homogenous, but a few show a weak zoning with a slight increase of Cr_2O_3 and decrease in TiO_2 towards their rims.

Among the garnets analyzed for trace element compositions (Table 6) only two grains (Gr 7-4 and Gr 8-1) could be reliably referred to as megacrysts. The distribution patterns of rare earth elements in garnets are similar for megacrysts and intergrowths (Fig. 7). The only difference is Zr and Hf enrichment in the megacryst garnets, correlated with relatively high titanium content. As in the ilmenite, the garnet megacrysts are depleted in the rare elements of the HFSE group (Zr, Nb, Hf, Ta). Table 7 gives average contents of those elements for garnet megacrysts and hosting kimberlite from the Grib pipe and the Yakutian province.

2.3. Clinopyroxene

Clinopyroxenes occur as discrete megacrysts which are rounded, elongated in some cases with a subidiomorphic crystallographic shape, and over 10 mm in size. By the classification of Dawson (1980) the pyroxenes of megacrysts and intergrowths with garnet from the Grib pipe are chrome-diopside and ureyitic diopside. Megacryst pyroxenes (Table 8) are marked by wide variations in the contents of Cr_2O_3, Al_2O_3 and Na_2O (0.56–2.95; 0.86–3.25; 1.3–3.0 wt.%, respectively) and in Mg/(Mg + Fe) and Ca/(Ca + Mg) ratios, which range from 87.4–94.3 and 43.1–50.7, respectively.

Pyroxenes from Gar-Cpx intergrowths, like the garnets, differ from the megacrysts by relatively low TiO_2 and slightly increased Mg/(Mg + Fe) (Fig. 8). Garnet and clinopyroxene from intergrowths show a clear correlation in terms of Cr/(Cr + Al) ratio (Fig. 9). Rare pyroxene megacrysts are inhomogeneous in composition. Margins of grains are relatively rich in Cr_2O_3

Table 9
Representative compositions of phlogopite megacrysts from Grib pipe

	Gr10-15	Gr10-15-3	Gr10-16	Gr10-16-3	Gr10-14	Gr10-1	Gr10-4	Gr10-8	Gr10-6	Gr9-20	Gr9-26
SiO_2	41.98	40.75	41.88	40.54	42.70	42.02	41.51	42.67	41.54	40.14	40.93
TiO_2	0.60	0.57	0.59	1.18	0.75	0.65	0.64	0.72	0.58	1.01	0.51
Al_2O_3	11.50	10.83	11.37	11.60	11.48	12.01	11.59	11.96	11.41	10.76	10.87
Cr_2O_3	0.31	0.40	0.64	0.62	0.72	0.84	0.67	0.68	0.69	0.55	0.56
FeO	3.70	4.86	3.58	4.22	3.58	3.57	3.78	3.63	4.42	3.59	3.31
MnO	0.05	0.00	0.09	0.06	0.15	0.00	0.03	0.10	0.07	0.06	0.05
MgO	25.00	27.60	25.71	24.64	24.61	24.88	24.97	25.27	26.15	23.77	25.59
K_2O	11.43	8.72	11.14	10.68	11.58	11.37	11.73	11.75	10.38	11.17	10.53
Total	94.57	93.73	95.00	93.54	95.57	95.34	94.92	96.78	95.24	91.04	92.35
mg#	92.33	91.01	92.74	91.23	92.46	92.55	92.16	92.54	91.38	92.19	93.22

and Al_2O_3 and poor in MgO. The REE contents of the clinopyroxenes are high and widely variable (Fig. 10).

2.4. Phlogopite

Phlogopite is found as large lamellar crystals with rounded margins and range in length from 2 to 15 mm. Their compositions (Table 9) are characterized by high MgO (23–30.2, average 25.4 wt.%), moderate TiO_2 (0.32–1.18, average 0.67 wt.%) and moderate Cr_2O_3 (0.22–0.85, average 0.6 wt.%) contents, values that are typical of the primary phlogopite from mantle peridotite xenoliths (Dawson and Smith, 1975).

3. Discussion

The high-chromium megacryst association (garnet, clinopyroxene, orthopyroxene, olivine) was for the first time described from kimberlites of the North-American province (Eggler et al., 1979). However, this association does not include picroilmenite. Kimberlites from the Grib pipe contain abundant megacrysts of picroilmenite, garnet, clinopyroxene and phlogopite. High MgO and TiO_2 and moderate to high Cr_2O_3 contents are common to all megacryst phases from Grib. The genetic similarity of the minerals and a common paragenesis are confirmed by studies of co-existing phases found as crystalline inclusions in the megacrysts. Magnesian ilmenite macrocrysts and crystalline ilmenite inclusions in garnet megacrysts are characterized by high chromium contents and similar MgO concentrations. This is the strongest argument to include picroilmenite in the same paragenetic association as garnet and chrome-diopside. A relatively high TiO_2 content is one of the essential features used to distinguish phases as megacrysts, irrespective of whether they belong to the low-chromium or high-chromium megacryst association.

Pressure–temperature (P–T) parameters of crystallization were calculated for clinopyroxene megacrysts, Gar-Cpx intergrowths and ultramafic xenoliths (data of Sablukova et al., 2003) using the clinopyroxene geothermobarometer of Nimis and Taylor (2000). The results show wide and similar P–T variations common to all parageneses (Fig. 11). Crystallization temperatures range from 624 to 1208 °C for clinopyroxene megacrysts, 730 to 1077 °C for intergrowths, and 733–

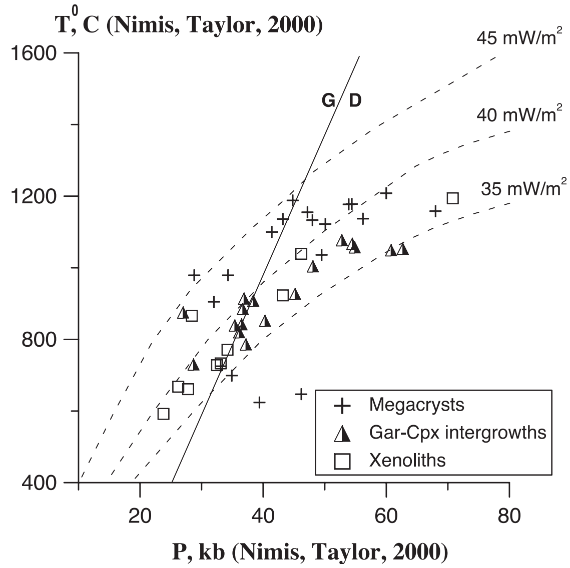

Fig. 11. Equilibrium P–T estimates for the Grib megacrysts, intergrowths and xenoliths according to Nimis and Taylor (2000). Data for xenoliths are from Sablukova et al. (2003) and Malkovets et al. (2003).

1194 °C for xenoliths. Pressure estimates range from 28.8–68 kbars for clinopyroxene megacrysts, 27–62.7 kbars for intergrowths and 28.4–70.8 kbars for xenoliths. Intergrowths and xenoliths give P–T estimates that correspond to a 35–40 mW/m^2 conductive geotherm, whereas estimates for megacrysts correspond to a slightly higher geotherm (40–45 mW/m^2).

It should be noted that the majority of studied minerals from Gar-Cpx intergrowths have higher MgO and lower TiO_2 than the corresponding monomineralic megacrysts (Figs. 6 and 8). During a decrease of temperature the recrystallization of Gar-Cpx intergrowths will lead to an increase in the MgO and Cr_2O_3 contents of clinopyroxenes and a decrease of TiO_2 abundance in garnets. Despite the large size of the garnet and clinopyroxene grains in the intergrowths, the latter cannot be referred to the megacryst association. The garnet and clinopyroxene from intergrowths are similar in composition to those from ultramafic xenoliths (lherzolites and pyroxenites) from the Grib pipe (Sablukova et al. 2003; Malkovets et al., 2003). On the other hand, individual megacrysts of garnet and clinopyroxene from the Grib pipe generally differ in their composition from minerals in xenoliths (Figs. 6 and 8). Only two garnets from ilmenite-bearing ultramafic xenoliths demonstrate a compositional affinity with garnet megacrysts. The clinopyroxene megacrysts differ from xenolith clinopyroxenes in their low Al_2O_3 content, and the two clinopyroxene populations form two distinct trends in the Na_2O vs. Al_2O_3 plot (see Fig. 8).

REE distribution in garnets and clinopyroxenes (Figs. 7 and 10) corresponds to the model of their joint crystallization and is typical of megacryst association minerals. A wide range in the composition of rare earth elements is common to all phases, in particular clinopyroxene.

The minerals of the megacryst association are similar to the association of minerals from the micaceous kimberlite pipes in Yakutia (e.g. Zagadochna, Kusova and Bukovinska). On Ca/(Ca + Mg) vs. Cr/(Cr + Al) and Ca/(Ca + Mg) vs. Mg/(Mg + Fe) plots, the chrome-diopsides from Grib pipe and those from the Yakutian mica-bearing kimberlites form a common cluster dissimilar to clinopyroxenes occurring in ultramafic xenoliths from the Udachnaya pipe (Fig. 12). According to Kostrovitsky and De Bruin (1998), the macrocryst mineral association and the host micaceous kimberlite are genetically connected. On the other hand, we believe that metasomatic processes played a significant role in the formation of the megacryst mineral association. The upper mantle metasomatism may have been spatially and temporally related to the formation of a kimberlitic source that is represented by the mineral compositions of the Grib megacryst assemblage. The formation of the megacrysts could have been related to the kimberlites as evidenced by low HFSE in both kimberlites and megacrysts and/or to mantle metasomatism as evidenced by similar mineral compositions of megacrysts and metasomatized ilmenite-bearing mantle xenoliths. We suggest that Grib megacrysts crystallized from a kimberlitic melt at a protomagmatic stage.

In conclusion we would like to note that Group-1 type kimberlites have elevated bulk FeO and TiO_2 contents (for example pipes Mir, Udachnaya and Yubileynaya, Yakutian province) and their heavy mineral fraction contains picroilmenite and orange-red garnet megacrysts, which belong to the low-chromium association. High-MgO kimberlites are less abundant and their heavy fraction is lacking in low-Cr megacrysts, but rich in high-Mg garnet and chrome spinels (for example Aikhal, Nachalnaya and Svetlaya pipes from Alakit field, Yakutian province). Micaceous high-Mg kimberlites are even less abundant (a few pipes from Bukovinska and Zagadochna clusters, Daldyn field, Yakutian province), and they do not contain low-Cr megacrysts. However, the high-Cr, high-Mg macrocryst mineral association (garnet, chrome-diopside, phlogopite) is widespread in these kimberlites (Kostrovitsky and De Bruin, 1998). The low-Cr and high-Cr associations of megacrysts have been described from the kimberlites of the North-American Province (Eggler et al., 1979). Their host kimberlites do not contain mantle xenoliths, which could be the source of the corresponding minerals. This is consistent with the assumption that the origin of megacrysts can be associated with the protocrystallization of different paragenetic mineral associations depending on the primary kimberlite melt composition.

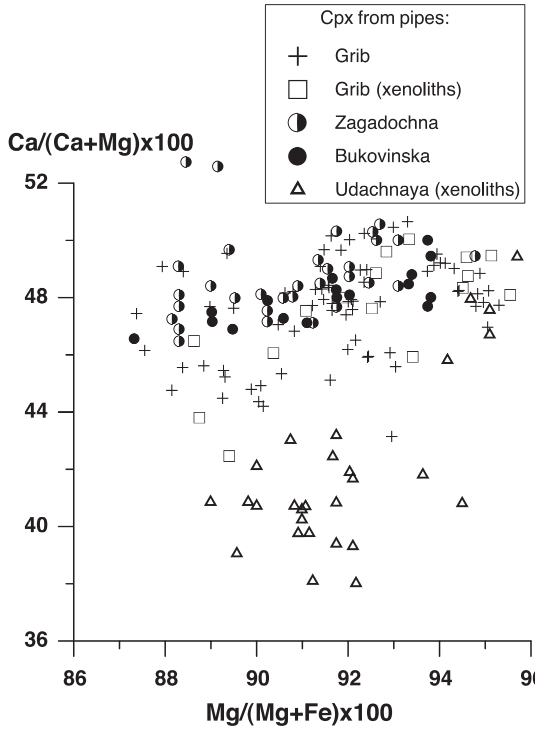

Fig. 12. Plot of Ca/(Ca + Mg) × 100 vs. Mg/(Mg + Fe) × 100 for clinopyroxenes from different locations (see legend). Data for xenoliths from Grib pipe are from Sablukova et al. (2003) and Malkovets et al. (2003), for xenoliths from Udachnaya pipe from Sobolev (1977) and for macrocrysts from Zagadochna and Bukovinska by the authors (unpublished).

4. Conclusions

The kimberlite from the Grib pipe contains a high-chromium megacryst association, marked by the occurrence of magnesian high-Cr picroilmenite. Low concentrations of the hematite molecule in ilmenite indicate reducing conditions during the crystallization of this assemblage. *P–T* estimates for clinopyroxene megacrysts based on the clinopyroxene geothermobarometer (Nimis and Taylor, 2000) show wide variations (624–1208 °C and 28.8–68 kbars), which correspond to a 40–45 mW/m^2 conductive geotherm. *P–T* estimates for garnet-clinopyroxene intergrowths and possibly related xenoliths show a similar wide range but correspond to a lower conductive geotherm (35–40 mW/m^2). The concentration of rare elements in megacrysts varies over a wide range, and strong correlations are found between most elements. A depletion in the HFSE group is common to megacrysts and the host kimberlite. The origin of megacrysts therefore is thought to be genetically connected with the evolution of the kimberlite magmatic chamber, and with associated mantle metasomatism.

We propose that, depending on the primary melt composition, chemically different paragenetic associations of megacrysts can be crystallized in kimberlites. They include: (1) low-Cr megacrysts in high Fe–Ti kimberlites (Mir, Udachnaya pipes), (2) high-Mg phlogopite + garnet + chrome-diopside associations in high-Mg, Cr kimberlites (Zagadochna, Kusova pipes) and (3) high-Cr megacrysts in high-Mg, Cr, Ti kimberlites (Grib pipe). Compositional differences in terms of megacryst major elements are mainly due to the heterogeneous lithosphere sources of the melts. The trace element composition of megacrysts, in particular for the incompatible elements, indicates close affinity with an asthenospheric source.

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References

Dawson, J.B., 1980. Kimberlites and Their Xenoliths. Springer-Verlag, Berlin.

Dawson, J.B., Smith, J.V., 1975. Chemistry and origin of phlogopite megacrysts in kimberlite. Nature 253, 336–338.

Eggler, D.H., McCallum, M.E., Smith, C.B., 1979. Megacryst assemblages in kimberlites from northern Colorado and southern Wyoming: petrology, geothermometry, barometry and areal distribution. In: Boyd, F.R., Meyer, H.O.A. (Eds.), The Mantle Sample: Inclusions in Kimberlites and Other Volcanics. Am. Geophys. Union, Washington, DC, pp. 213–226.

Genshaft, Yu.S., Ilupin, I.P., Kuligin, V.M., Vitozhents, G.Ch., 1983. Typomorphism of ilmenites from deep magmatic rocks. Composition and Properties of Deep Rocks of Earth Crust and Upper Mantle of Platform. Nauka, Moscow, pp. 95–190. in Russian.

Griffin, W.L., Moore, R.O., Ryan, C.G., Gurney, J.J., Win, T.T., 1997. Geochemistry of magnesian ilmenite megacrysts from Southern African kimberlites. Russian Geology and Geophysics 38, 398–419.

Kostrovitsky, S.I., De Bruin, D., 1998. Ultramafic association of minerals (garnet-ureyite diopside-chromspinelid) in micaceous kimberlites of Yakutian province. Ext. Abs. 7th Int. Kimb. Conf. Geological Survey of South Africa, Cape Town, pp. 463–465.

Kostrovitsky, S.I., Alymova, N.V., Ivanov, A.S., Serov, V.P., 2003. Structure of the Daldyn field (Yakutian Province) based on the study of picroilmenite composition. Ext. Abs. 8th Int. Kimb. Conf., vol. 207. DIAVIK (Diamond Mines Inc.), Victoria. CD-ROM.

Krotkov, V.V., Kudryavtseva, G.P., Bogatikov, O.A., Valuev, E.P., Verzhak, V.V., Garanin, V.K., 2001. New Technologies of Diamond Deposits Exploration GEOS, Moscow. 310 pp.

Makhotkin, I.L., Gibson, S.A., Thompson, R.N., Zhuravlev, D.Z., Zherdev, P.U., 2000. Late Devonian diamondiferous kimberlite and alkaline picrite (proto-kimberlite?) magmatism in the Arkhangelsk region, NW Russia. Journal of Petrology 41, 201–227.

Malkovets, V., Taylor, L., Griffin, W., O'Reilly, S., Pearson, N., Pokhilenko, N., Verichev, E., Litasov, K., 2003. Cratonic conditions beneath Arkhangelsk, Russia: garnet peridotites from the Grib kimberlite. Ext. Abs. 8th. Kimb. Conf., Victoria, vol. 220. Springer-Verlag, Berlin. CD-ROM.

McDonough, W.F., Sun, S.S., 1995. The composition of the Earth. Chemical Geology 120, 223–253.

Nimis, P., Taylor, W.R., 2000. Single clinopyroxene thermobrometry for garnet peridotites: Part 1. Calibration and testing of

a Cr-in Cpx barometer and an enstatite-in-Cpx thermometer. Contributions to Mineralogy and Petrology 139, 541–554.
Norman, M.D., Pearson, N.J., Sharma, A., Griffin, W.L., 1996. Quantitative analysis of trace elements in geological materials by laser ablation ICPMS: instrumental operating conditions and calibration values of NIST glasses. Geostandards Newsletter 20, 247–261.
Sablukova, L.I., Sablukov, S.M., Verichev, E.M., Golovin, N.N., 2003. Petrography and mineral chemistry of mantle xenoliths from the Grib pipe, Zimny Bereg area, Russia. Plumes and Problems of Deep Sources of Alkaline Magmatism. Proceedings of Intern. Seminar. Institute of Geochemistry, SB RAS, Habarovsk, pp. 65–95.
Sobolev, N.V., 1977. Deep-seated Inclusions in Kimberlites and the Problem of the Composition of the Upper Mantle. American Geophys. Union, Washington, DC.