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Mineral inclusions in microdiamonds and macrodiamonds from kimberlites of Yakutia: a comparative study

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Abstract

Chemical compositions were determined on mineral inclusions recovered from 290 microdiamonds (< 1 mm) from 8 operating diamond mines in Yakutia. The sampled diamond mines include Mir, Udachnaya, Internatsionalnaya, Aykhal, Sytykanskaya, Yubileynaya, Komsomolskaya and Krasnopresnenskaya. The mineral inclusions include both ultramafic (peridotitic) suite (U-type) and eclogitic suite (E-type) examples. Olivines, chromites, Cr-pyropes, Cr-diopsides and enstatite were studied from U-type diamonds. Mg–Ca–Fe-garnets and omphacitic clinopyroxenes were studied from E-type microdiamonds. Abundances and compositions of these inclusions were compared with published and unpublished data on inclusions available from approximately 2000 macrodiamonds (>1 mm) from the same sources, and worldwide data for olivines and chromites. Although there are general similarities, notable exceptions were detected in about 10% of the inclusions from microdiamonds. For each of the pipes, anomalous compositions occur between the micro- and macrodiamond inclusions, but in different proportions, sometimes as high as 50% of the inclusions. Our study has demonstrated that mineral inclusions in microdiamonds are considerably more variable in their compositions and parageneses compared with inclusions in macrodiamonds.

Significant compositional anomalies in inclusions from microdiamonds include: (1) garnets containing pyroxene solid solution (majoritic component) both in U- and E-type microdiamonds from three pipes: Yubileynaya, Komsomolskaya and Krasnopresnenskaya. The moles of Si (pfu) in these garnets range from 3.07 to 3.13 and as high as 3.29, on the basis of 12 oxygens, along with a notable contents of Na_2O in two eclogitic garnets (0.43 and 0.93 wt.%) and uniquely high Cr_2O_3 and CaO contents in an ultramafic garnet of wehrlitic paragenesis; (2) coexisting wehrlitic garnets in a single microdiamond, one majoritic, the other normal, both with distinct +Eu anomalies, considered as signatures of crustal protoliths for the precursors to these garnets; (3) olivines with relatively low Fo (86–89) and high-NiO contents (0.46–0.64 wt.%), from Yubileynaya and Sytykanskaya microdiamonds; (4) chromites containing high-TiO_2 (up to 4.7 wt.%) and some extremely rich in MgO (Mg# 80). It is concluded that many of these compositional features observed may be related to a deeper origin for the microdiamond source region (>300 km), for at least a 10–30% portion of microdiamonds from each Yakutian pipe.

Keywords: Diamond; Inclusions; Siberian craton; Yakutia; Eclogite; Peridotite; Kimberlite

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1. Introduction

Kimberlites contain diamonds with a large range in size, varying from microdiamonds (< 1 mm) weighting on average about 1 mg (0.005 carats) up to large diamonds which may exceed several hundred carats. This gives a size range for diamonds in kimberlite spanning four to five orders of magnitude. The question logically follows: do the different sizes of diamonds vary in their mineral inclusions?

The diamond deposits of Yakutia (Russia) located in the northwestern region of the Siberian craton (Fig. 1) attracted the attention of scientists immediately after their discovery in mid the of 1950s (Sobolev, 1959, 1960, 1964; Sobolev and Burov,

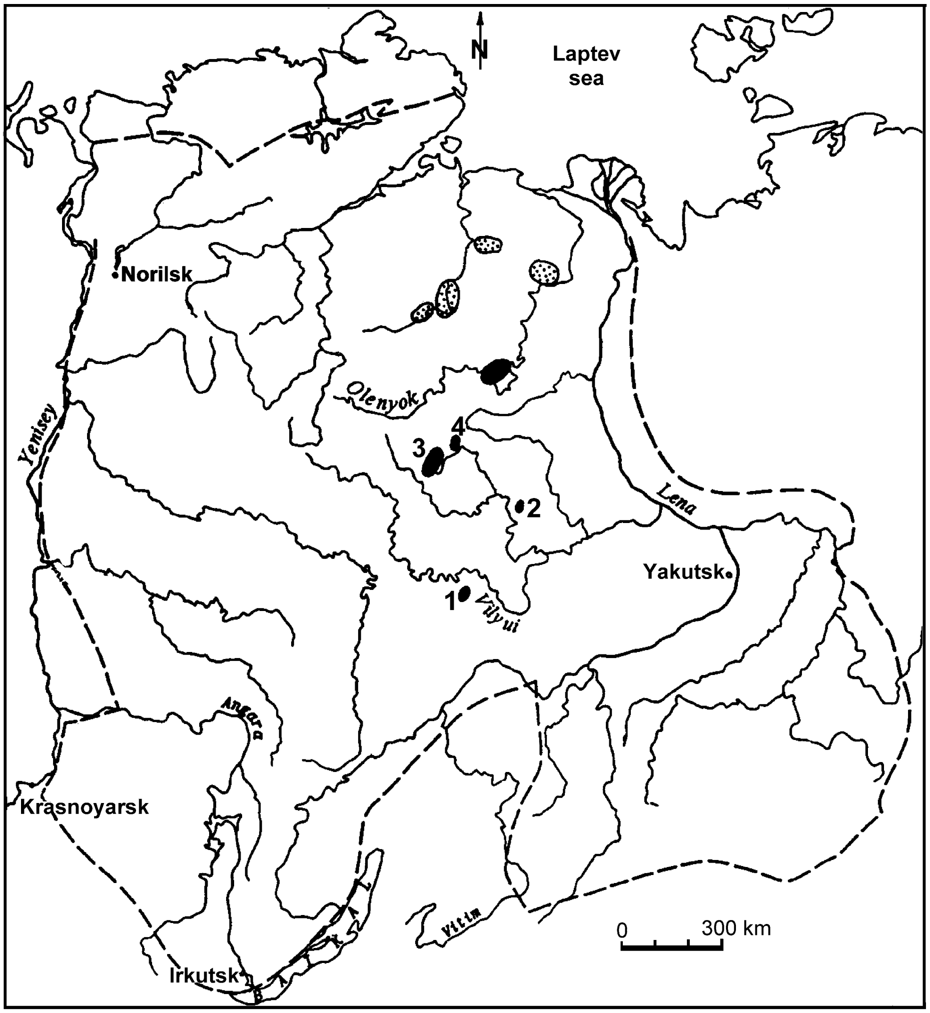

Fig. 1. Location of major kimberlite fields of the Siberian Platform of Paleozoic (solid symbols) and Mezozoic (dotted symbols) ages. Kimberlite fields with operating diamond mines: Mirny (1), Mir and Internatsionalnaya mines; Nakyn (2); Alakit (3), Aykhal, Sytykanskaya, Yubileynaya, Komsomolskaya and Krasnopresnenskaya mines; Daldyn (4), Udachnaya mine. All other fields include mostly barren and low grade kimberlite pipes. The boundaries of the Siberian craton are shown by dotted line. Modified after Sobolev et al. (1995).

1957). The most important diamond mines, Mir and Udachnaya, became the source of many samples of industrial-quality diamonds containing mineral inclusions that have been systematically studied and described, with the earliest results summarized by Sobolev (1974). Even in these early studies, both micro- and macrodiamonds were found within the same eclogite xenolith from the Mir pipe, thereby demonstrating a probable similarity in the conditions of formation for both sizes of diamonds, at least for this xenolith and some others (e.g., Anand et al., 2004).

Further exploration activities led to the discovery of a number of pipes within the fields 1–4 on the map in Fig. 1, and some of these kimberlites subsequently became operating mines. These include the Internationalnaya, Aykhal, Yubileynaya,

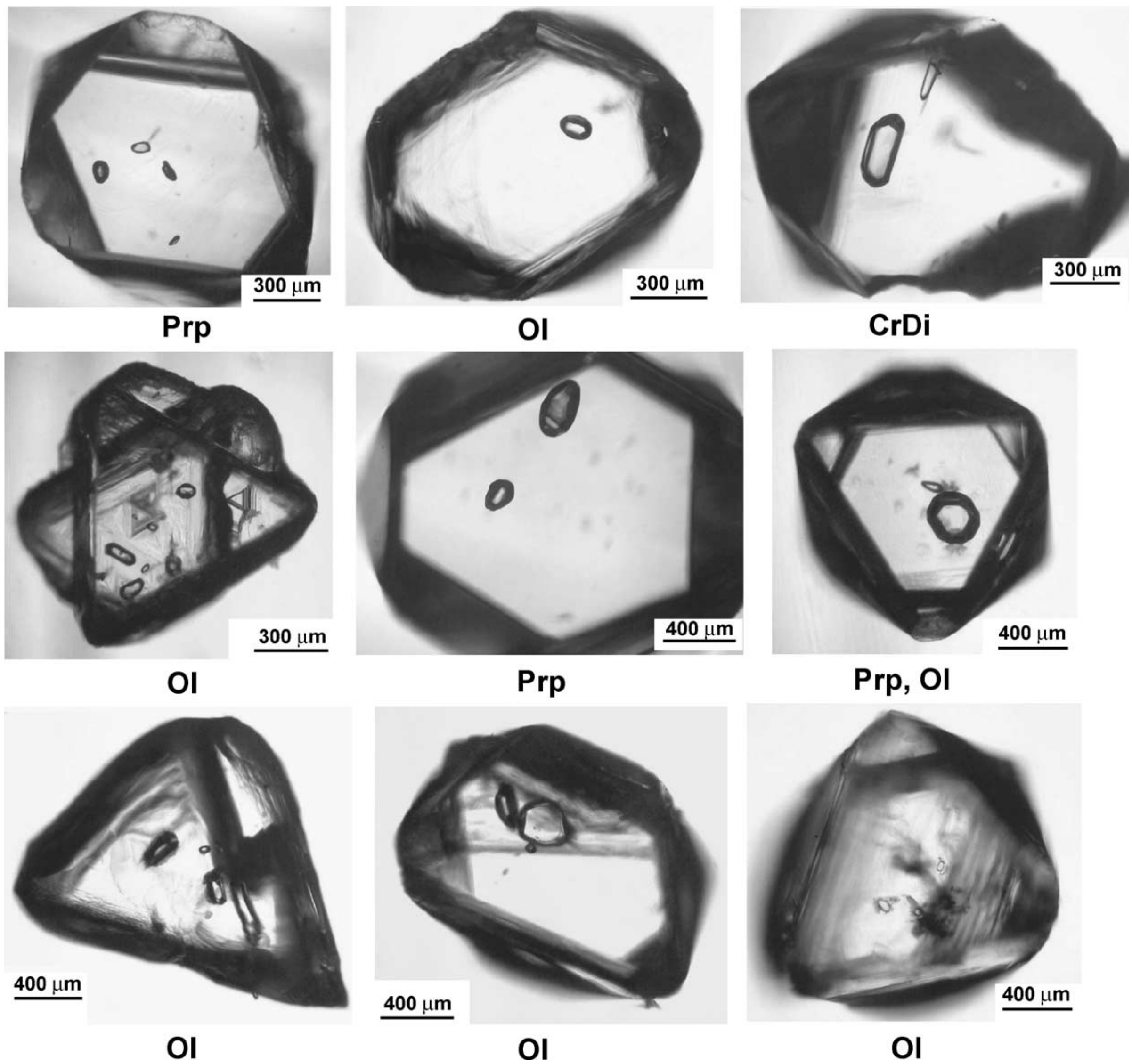

Fig. 2. Microdiamonds with mineral inclusions from Komsomolskaya mine. Symbols for mineral inclusions: pyrope (Prp), olivine (Ol), chromediopside (CrDi).

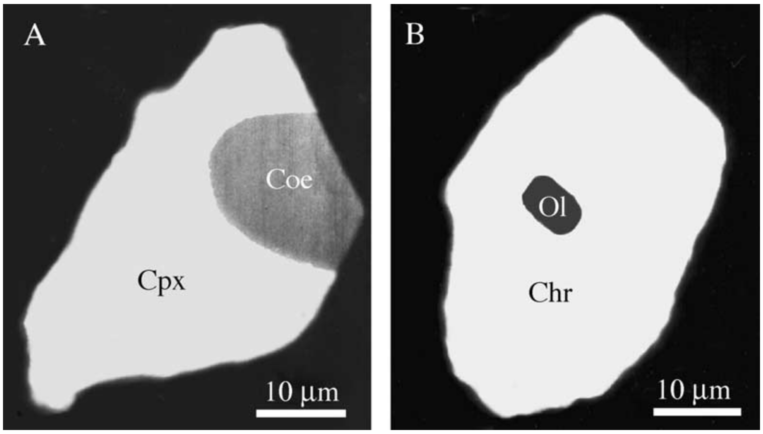

Fig. 3. Backscattered images of some polymineralic inclusions in microdiamonds from Udachnaya mine exposed at the polished surface of microdiamond crystals: omphacite (Cpx)–coesite (Coe)—A; olivine (Ol) inclusion in chromite (Chr)—B.

Sytykanskaya, Komsomolskaya and Krasnopresnenskaya pipes. As demonstrated by U–Pb zircon (Davis et al., 1980) and perovskite ages (Kinny et al., 1997), all listed pipes are Upper Devonian–Early Carboniferous.

Microdiamonds (< 1 mm) exhibit a wide range of physical characteristics that suggests the presence of different microdiamond populations at each location (McCandless et al., 1994; Bulanova, 1995; Pattison and Levinson, 1995; Trautman et al., 1997). In spite of the small dimensions of microdiamonds, their mineral inclusions are of comparable size (50–200 μm) to those from macrodiamonds (>1 mm) (Fig. 2). On occasions touching inclusion pairs were observed (Fig. 3) on the polished surface of a microdiamond sample. Recent investigations of mineral inclusions from a limited number of Yakutian microdiamonds have brought new results compared with inclusions from macrodiamonds of the same pipes. These include: (a) the most magnesian Group A garnet of eclogitic paragenesis from Mir diamonds, reported to date; (b) anomalously high NiO in low-Fo olivines; (c) the first report of ferropericlase from Udachnaya diamond inclusions; and (d) the first occurrence of Mg-spinel, containing no Cr_2O_3, also from Udachnayan diamonds (Zedgenizov et al., 1998, 2001; Sobolev et al., 2000; Logvinova et al., 2001). These results stimulated more extensive investigations microdiamonds from other Yakutian operating diamond mines, as presented in this study (Table 1).

Table 1
Mineral inclusions in microdiamonds from Yakutian kimberlites

N	Pipe	*n*	U-type					E-type				
			Ol	Chr	Prp	En	Cr-Di	Grt	Omph	Coe	Fe-per	Sp
1	Udachnaya	67	41	19	2	–	–	1	3	1	1	2
2	Yubileynaya	79	60	9	6*	–	–	1	1	–	–	–
3	Sytykanskaya	66	52	7	2	–	–	4	2	–	–	–
4	Aykhal	34	20	9	3	–	–	2	–	–	–	–
5	Mir	5	3	1	–	–	–	1	1	–	–	–
6	Internatsionalnaya	5	2	–	2	–	–	1	–	–	–	–
7	Komsomolskya	32	20	2	5	1	2	2*	–	–	–	–
8	Krasnopresnenskaya	2	–	–	1	–	–	1*	–	–	–	–
	Total	290	198	47	21	1	2	13	7	1	1	2

n = number of diamonds studied; * includes one majoritic garnet; Ol, olivine; Chr, chromite; Prp, pyrope; En, enstatite; Cr-Di, Cr-diopside; Grt, Mg-Fe garnet; Omph, omphacite; Coe, coesite; Fe-per, ferropericlase; Sp, Mg-spinel.

About 290 microdiamonds (<1 mm) from operating diamond mines in Yakutia were found to contain mineral inclusions (Table 1), which were subsequently analyzed for major- and minor-element compositions. Most of inclusions are similar in composition when compared with mineral inclusions studied from about 2000 macrodiamonds (>1 mm) from the same pipes. Recent studies of large macrodiamonds containing mineral inclusions has provided a means to visually estimate inclusions abundance and paragenesis. Such studies of inclusions exposed at the surface of some large rough diamonds (10–108 carats) from Yakutian mines have confirmed a general similarity of chemistry for all the mineral inclusions from diamonds over a wide range of sizes (Sobolev et al., 2001; Taylor et al., 2003). Macrodiamond inclusion data are mainly from publications of the senior author, as well as from unpublished data from this same research team. The aim of this contribution is to summarize all available results of mineral inclusions in Yakutian microdiamonds and compare them with inclusions from macrodiamonds.

2. Analytical methods

Micro-Raman spectroscopy was used for nondestructive inclusion identification. Mineral inclusions were liberated from diamonds both by crushing and burning as well as by polishing host diamonds exposing inclusions. As shown earlier by Taylor et al. (1996) in a comparative study of pyroxene inclusions liberated both by diamond burning versus simply crushing, the pyroxene from different fragments of the same diamond showed no differences in major- and trace-element contents—i.e., the burning process did not modify the mineral composition. During the present study, inclusion grains released by burning, as well as polished fragments of diamonds with exposed inclusions, were mounted on epoxy resin and polished for analysis.

X-ray diffraction, single-crystal analysis was performed on one of the garnet inclusions from microdiamond Yum-27, associated with pyrope-uvarovitic garnet and olivine. The crystal-structural study and refinement was performed with a Stoe STADI-4 diffractometer (graphite-monochromated MoKα radiation; scintillation counter) at room temperature. Unit-cell parameters were refined by centering 24 reflections in the 2θ range of 21–28°, and a total of 1554 diffraction intensities were collected up to $2\theta = 50°$, for the triclinic symmetry. The diffraction-intensity distribution revealed a cubic symmetry with observed systematic extinctions indicative of space group $Ia\bar{3}d$. The crystal structure was solved using SHELXS-86 (Sheldrick, 1986) and refined using SHELXL-93 (Sheldrick, 1993). Experimental details are given in Table 2 and confirmed that the Yum-27 inclusion has a garnet structure.

Major- and minor-element analyses were performed with a CAMEBAX electron microprobe at Novosibirsk and with CAMECA SX-50 electron microprobe at the University of Tennessee. The analyses were performed at 15 kV, with a 30-nA beam current and a 5–10-μm spot size. Counting times varied from 20 s for major elements to 100 s for minor-trace components. All analyses were fully corrected using the Cameca PAP software. It should be noted that a recent comparative study of analytical data on inclusions from large diamonds obtained with both instruments demonstrated a good agreement (2–3% of absolute amount) in the analyses from both Institutions (Sobolev et al., 2001; Taylor et al., 2003).

Trace-element analyses of the diamond inclusions were performed with the modified CAMECA IMS-3f ion microprobe at Washington University. Details of the experimental procedures are described

Table 2
X-ray diffraction single-crystal analysis for Yubileynaya inclusion Yum-27

Instrument	Stoe STADI-4 diffractometer
Crystal size (mm^3)	$0.04 \times 0.03 \times 0.02$ mm^3
2θ range (°)	8.48–49.72°
$h_{min,max}$, $k_{min,max}$, $l_{min,max}$	−13,13; 0,13; −13,13
Number of I_{hkl} measured	1554
Number of unique F^2_{hkl}	122
Crystal system	Cubic
Space group	$Ia\bar{3}d$
a (Å)	11.775(1) Å
V (Å^3)	1632.6(2) Å^3
Identified mineral	Garnet
a_{theor} (0.57 uvarovite + 0.43 pyrope)	11.78

by Zinner and Crozaz (1986a,b), Alexander (1994), Hsu (1995) and Fahey et al. (1987). Detection limits are variable, depending on the element and phase being analyzed, but may be as low as a few ppb in favorable cases.

3. Mineral inclusions

The mineral inclusions in our study are related to two main types of diamond parageneses: ultramafic (or peridotitic)—U/P-type and eclogitic (E-type), as classified by Sobolev (1974), Meyer (1987) and Gurney (1989) and unanimously accepted in the scientific literature.

3.1. U-type mineral inclusions

3.1.1. Olivine

Olivine is the most abundant mineral inclusion in Yakutian diamonds (Yefimova and Sobolev, 1977). Available olivine compositions from macro-

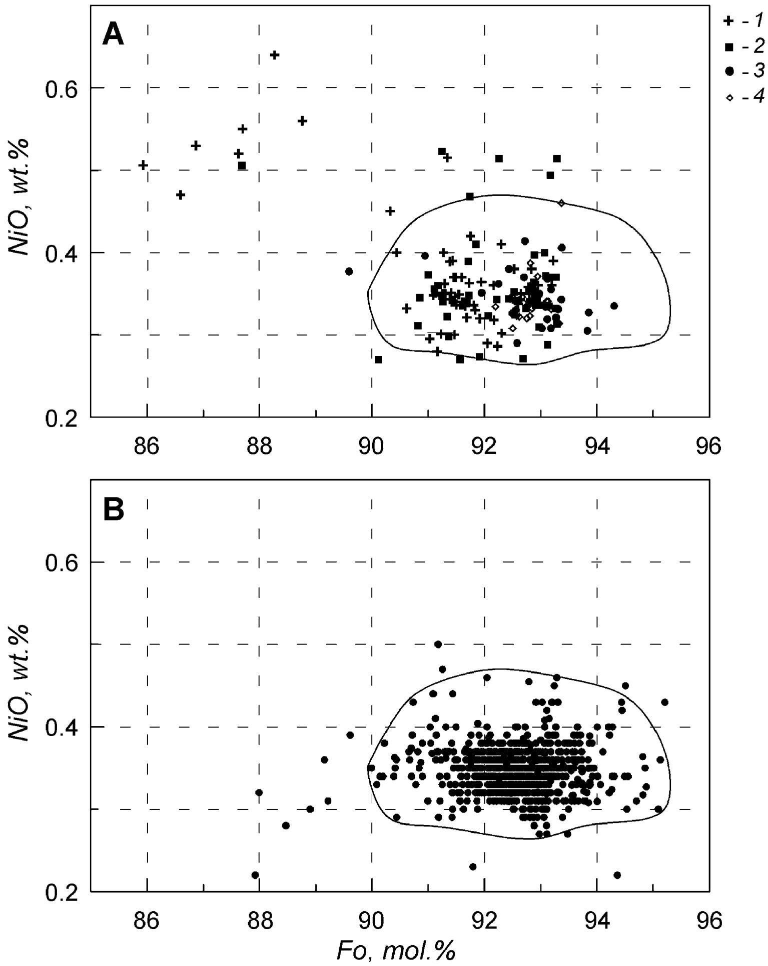

Fig. 4. NiO (wt.%) vs. Fo [100Mg/(Mg + Fe)] in olivine inclusions from microdiamonds of Yubileynaya (1), Sytykanskaya (2), Udachnaya (3) and Aykhal (4) mines (A). Plots of olivine inclusions from macrodiamonds worldwide (about 700 plots) are shown in (B) with a solid line surrounding about 98% of plots. Data sources for B: Daniels and Gurney (1989), Davies et al. (1999), Griffin et al. (1992), Gurney et al. (1979, 1985), Harris et al. (1991), Hervig et al. (1980), Jaques et al. (1998), Kopylova et al. (1997), McDade and Harris (1999), Meyer and Boyd (1972), Otter and Gurney (1989), Sobolev et al. (1993, 1997a,b, 2000), Stachel and Harris (1997), Stachel et al. (2000), Viljoen et al. (1999).

Table 3
Major-element compositions of selected olivine inclusions from microdiamonds

Sample	Yum-10	Yub-317	Yub-13	Yum-27	Yum-162	Yum-165	Yum-170	Yum-174	STI-303	STI-51	UVI-20	STI-52	STI-18	UDV-2	UD-8/01	UD-7	Mrm-2	Mrm-8
S_iO_2	40.5	40.3	40.7	41.3	41.1	41.2	41.4	41.2	40.7	41.6	41.1	41.9	41.1	40.7	40.9	41.4	41.6	41.7
Cr_2O_3	0.11	0.09	0.15	0.04	0.06	0.09	0.04	0.03	< 0.03	0.13	0.18	0.09	0.09	0.09	0.03	0.04	< 0.03	< 0.03
FeO	11.6	12.0	9.15	8.32	9.25	8.57	8.41	7.66	11.6	8.77	9.96	7.98	8.45	6.55	6.70	7.09	5.99	5.85
MnO	0.08	0.06	0.11	0.11	0.10	0.16	0.12	0.14	0.08	0.10	0.09	0.13	0.10	0.10	0.11	0.11	0.09	0.07
MgO	46.4	46.3	49.1	50.2	49.1	49.6	49.5	50.5	46.2	49.8	48.1	49.6	49.0	51.8	51.2	50.7	52.20	52.8
CaO	< 0.03	< 0.03	< 0.03	0.08	< 0.03	0.06	0.03	0.03	0.03	0.06	< 0.03	0.06	0.03	< 0.03	< 0.03	0.03	< 0.03	< 0.03
NiO	0.55	0.52	0.33	n.d.	0.40	0.28	0.35	0.36	0.51	0.37	0.38	0.39	0.36	0.41	0.33	0.41	0.35	0.35
Total	99.2	99.3	99.5	100.1	100.03	99.96	99.84	99.91	99.1	100.8	99.8	100.2	99.1	99.7	99.3	99.8	100.2	100.8
Ox	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Si	1.009	1.006	1.000	1.004	1.005	1.005	1.009	1.002	1.015	1.007	1.010	1.016	1.010	0.989	0.997	1.005	1.000	0.997
Cr	0.002	0.002	0.003	0.001	0.001	0.002	0.001	0.001	0.000	0.002	0.003	0.002	0.002	0.002	0.000	0.001	0.000	0.000
Fe	0.242	0.250	0.188	0.169	0.189	0.175	0.171	0.156	0.242	0.177	0.205	0.162	0.174	0.133	0.137	0.144	0.120	0.117
Mn	0.002	0.001	0.002	0.002	0.002	0.003	0.002	0.003	0.002	0.002	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.001
Mg	1.723	1.722	1.798	1.818	1.789	1.803	1.798	1.829	1.716	1.796	1.761	1.792	1.794	1.875	1.859	1.834	1.870	1.881
Ca	0.000	0.000	0.000	0.002	0.001	0.002	0.001	0.001	0.001	0.002	0.000	0.002	0.001	0.000	0.000	0.001	0.000	0.000
Ni	0.011	0.011	0.007	0.000	0.008	0.006	0.007	0.007	0.010	0.007	0.008	0.008	0.007	0.008	0.007	0.008	0.007	0.007
Total	2.989	2.992	2.998	2.997	2.994	2.995	2.990	2.998	2.985	2.993	2.988	2.984	2.989	3.009	3.002	2.995	2.999	3.002
Fo	87.7	87.3	90.5	91.5	90.4	91.2	91.3	92.2	87.7	91.0	89.6	91.7	91.2	93.4	93.2	92.7	94.0	94.1

Data source: Yum-10, Yub-317, Yub-13—from Sobolev et al. (2000); symbols Yum and Yub = Yubileynaya; STI = Sytykanskaya; UDV, UVI and UD = Udachnaya, and Mrm = Mir mines; n.d. = not determined.

diamonds worldwide are summarized by Meyer (1987), Sobolev et al. (2000), references to caption to Fig. 4 and new data in this paper. Information on NiO (wt.%) and Fo = 100 Mg/(Mg + Fe) show that the majority of compositions fall in the range of Fo 92–93 with NiO = 0.30–0.38 wt.% (Fig. 4). However, olivines from Yubileynaya microdiamonds demonstrate surprising exceptions with several samples having compositions in the range Fo − 86 to 89 and NiO = 0.46–0.64 wt.% (Table 3). These extreme compositions represent about 20% of all studied olivines from Yubileynaya microdiamonds (Sobolev et al., 2000). This discovery stimulated the additional study of a number of selected microdiamonds containing olivine inclusions from the Udachnaya (41 samples), Sytykanskaya (52 samples) and Aykhal (20 samples) mines (Table 1). All 41 olivine inclusions from Udachnaya microdiamonds average Fo 92.8, similar to 87 macrodiamond olivines from the same pipe. From averages of Yubileynaya olivines, significant differences are present between macro- (18 inclusions) and microdiamonds (61 inclusions) with Fo 92.8 and 91.7, respectively. A less pronounced but notable difference is also found for Sytykanskaya macro- (91) and microdiamond (52) olivines with Fo 92.7 and 92.2, respectively.

Five olivines from Sytykanskaya and two from Yubileynaya microdiamonds also plot outside of a 98% field for olivines from diamonds worldwide (Fig. 4). They also demonstrate unusual high-NiO contents, but their Fo contents fall within the range typical for olivine inclusions. These data do not correlate with a worldwide NiO-Fo positive correlation established by Simkin and Smith (1970). However, the occurrence of a positive correlation of low Fo and high NiO is pronounced and is probably related to unusual assemblages of Fe-enriched harzburgites with high-Opx contents (Kelemen et al., 1998; Sobolev et al., 2000).

3.1.2. Chromite

Chromite is a common inclusion in Yakutian diamonds (Yefimova and Sobolev, 1977) and also an important mineral in diamond exploration (Sobolev, 1971, 1974). The proportion of chromite-bearing diamonds from Yakutia is within 45–56% of the total of all inclusion-bearing diamonds. Forty-seven chromite samples from microdiamonds of the Udachnaya, Aykhal, Sytykanskaya, Mir, Komsomol-

Table 4
Selected compositions of chrome spinels from microdiamonds

Sample	AL-1	AL-4	AL-5	AL-10	AL-11	SYT-14	S-2/99	UD-PL/1	UD-PL/2	UD-4/01	UD-8	UV-608	Yum-16
TiO_2	0.31	0.11	0.14	1.41	0.21	4.15	1.73	0.20	0.18	0.51	0.22	0.06	0.14
Al_2O_3	6.13	7.00	6.26	6.64	7.47	9.63	5.57	5.28	5.47	4.93	16.2	7.09	6.36
Cr_2O_3	63.0	62.7	62.8	62.1	61.2	52.4	64.0	66.2	64.0	63.6	52.5	63.2	66.0
FeO	17.0	17.0	17.5	15.1	17.2	17.6	15.5	12.5	16.0	18.0	14.9	15.6	9.42
MnO	0.19	0.17	0.18	0.17	0.19	0.17	0.18	0.15	0.18	0.19	0.15	0.17	0.13
MgO	12.6	12.4	12.2	14.3	12.7	15.0	11.4	14.1	13.1	11.9	15.2	13.5	17.1
NiO	0.10	0.09	0.06	0.13	0.09	0.20	0.15	0.08	0.10	0.11	0.11	0.12	0.08
Total	99.3	99.5	99.1	99.9	99.1	99.2	98.5	98.5	99.0	99.2	99.3	99.7	99.2
Oxygen	4	4	4	4	4	4	4	4	4	4	4	4	4
Ti	0.008	0.003	0.004	0.035	0.005	0.100	0.044	0.005	0.004	0.013	0.005	0.001	0.003
Al	0.239	0.273	0.245	0.255	0.291	0.365	0.222	0.207	0.214	0.195	0.596	0.273	0.241
Cr	1.651	1.637	1.652	1.598	1.597	1.332	1.711	1.737	1.681	1.685	1.296	1.633	1.677
Fe	0.471	0.470	0.487	0.411	0.475	0.473	0.438	0.347	0.444	0.504	0.389	0.426	0.253
Mn	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.005	0.005	0.004	0.005	0.004
Mg	0.622	0.610	0.605	0.694	0.625	0.719	0.575	0.697	0.648	0.594	0.707	0.658	0.819
Ni	0.003	0.002	0.002	0.003	0.002	0.005	0.004	0.002	0.003	0.003	0.003	0.003	0.002
Total	2.999	3.000	3.000	3.001	3.000	2.999	2.999	2.999	2.999	2.999	3.000	2.999	2.999
Mg#	56.9	56.5	55.4	62.8	56.8	60.3	56.7	66.8	59.3	54.1	64.5	60.7	76.4
Cr/Cr + Al	87.3	85.7	87.1	86.3	84.6	78.5	88.5	89.4	88.7	89.6	68.5	85.7	87.4

Symbols: AL for Aykhal; SYT and S for Sytykanskaya; UD and UV for Udachnaya; Yum and Yub for Yubileynaya mines.

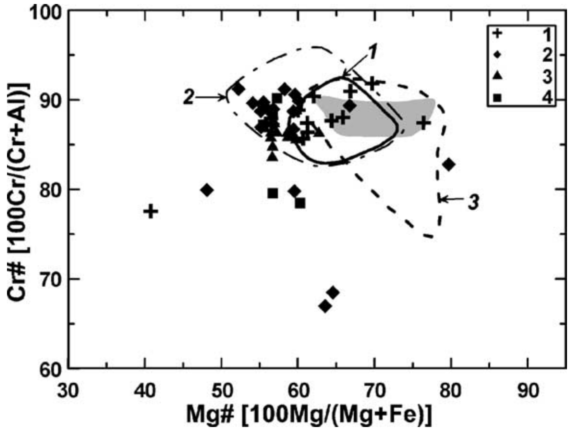

Fig. 5. Cr#—100Cr/(Cr + Al) vs. Mg#—100Mg/(Mg + Fe) in chromite inclusions from Yakutian (fields 1 and 2) and South African (field 3) macrodiamonds (Griffin et al., 1994; Sobolev et al., 1997b) and from microdiamonds of Yubileynaya (1), Udachnaya (2), Aykhal (3) and Sytykanskaya (4) pipes, Yakutia.

skaya and Yubileynaya pipes have been analyzed in this study (see Table 1), with the results of selected analyses presented in Table 4 and plotted in Figs. 5 and 6. The expanded compositional field of chromites from Yakutian diamonds (field 2 in Fig. 5) is based upon 700 data points and is considerably broader compared with that defined by Griffin et al. (1994). Only 10% of chromites from Yakutian macrodiamonds containing < 62 wt.% Cr_2O_3 and >0.7 wt.% TiO_2 and plot outside of this field (Sobolev, 1971, 1974; Sobolev et al., 1992, 1997a) .

Our first attempt to study chromite inclusions from microdiamonds has demonstrated extreme variations in their compositions. About 75% of all analyzed chromites plot within an expanded field of chromite compositions from Yakutian diamonds. This field includes analytical data for 34 chromite grains from an Udachnaya macrodiamond single crystal (Ud-34). This field is plotted as the shaded area in Fig. 5 (Sobolev and Yefimova, 1998). More than 25% of chromites from this study are significantly different compared to the major field. Compositions of some chromites are extremely Mg-rich with Mg# approaching 80. Some unusual chrome spinels include those containing high TiO_2.

In spite of their small size, some microdiamonds contain multiple inclusions of chromites. These features were found in nine diamonds samples from the available collection, and two chromite grains were analyzed from each of these samples. For the most contrasting compositions, data are presented in Table 4. In keeping with earlier studies of chromite inclusions in macrodiamonds (Sobolev and Yefimova, 1998), the majority of samples were found to contain chromite grains with distinct differences in compositions between individual inclusions within the same diamonds, but homogeneous within a single grain. Two trends of inhomogeneties are confirmed: (1) simultaneous differences in Al_2O_3 and Cr_2O_3 and MgO-FeO contents; (2) variations in only the MgO-FeO contents. It should be mentioned that the chemical "pristinity" (i.e., non–open-system behavior) of all these diamond inclusions is unknown.

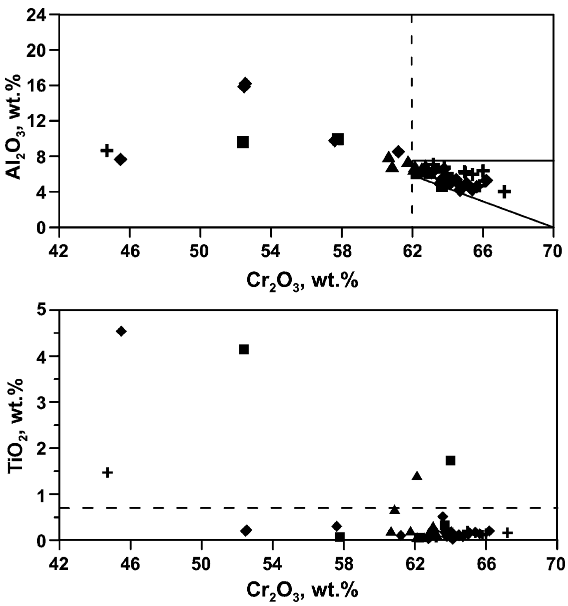

Fig. 6. Al_2O_3 vs. Cr_2O_3 and TiO_2 vs. Cr_2O_3 in chromite inclusions from macrodiamonds worldwide (solid field and dotted boundary) and from microdiamonds of Yakutian diamond mines (see Fig. 5 for symbols). Boundaries: 62 wt.% of Cr_2O_3 and 0.7 wt.% of TiO_2 for typical diamond inclusions and chromite related to diamonds from heavy concentrates of diamondiferous kimberlites are modified after Sobolev (1971) and Sobolev et al. (1975, 1992).

3.1.3. Cr-pyropic garnet

Cr-pyropes are rare as inclusions both in macro- and microdiamonds, compared with olivines and chromites. Only 19 microdiamonds from our available collection contained purple, lilac or dark-green inclusions characteristic of Cr-rich garnets, and confirmed by subsequent EMP analyses (Table 5). Along with a general similarity of Cr-rich garnets composition in both micro- and macrodiamonds, a unique Cr–Ca-rich majoritic garnet was discovered in single microdiamond from the Yubileynaya mine. It coexists with Cr–Ca rich non-majoritic garnet and olivine within the same diamond (Table 6, Fig. 7). Unfortunately, no details about relative position of these inclusions within a diamond crystals were available before burning of crystal. Positive identification of majoritic garnet was preliminary obtained by a single-crystal X-ray diffraction study (Table 2). The Si moles calculated from the microprobe analyses show 3.29 and 3.02 Si in the coexisting majoritic and non-majoritic garnets, respectively (Table 6). The coexisting olivine is Fo 91.5 (see Table 3 for analysis), which is consistent with the relatively low Mg# of the non-majoritic garnet. Furthermore, the Ca–Cr component of the majoritic garnet is unusually high (more than 50%). Fig. 8 shows the REE patterns of these garnets, in addition to another unusual majoritic garnet from Komsomolskaya. The complete trace-element contents of these garnets are given in Table 7. Both REE patterns from the majoritic and normal garnet inclusions from the Yubileynaya, Ym-27, diamonds are very similar and contain a notable anomaly. The presence of a distinct +Eu anomaly in both patterns is unique for Ca–Cr-rich garnets, having never been described previously. Such +Eu anomalies are indicative of the involvement of plagioclase feldspar sometime in the genesis of the garnet, and this is thought to be a signature of a low-T and low-P protolith for the rock from which the garnet was sampled by the diamond. This is evidence for the ancient subduction of oceanic crust beneath the Siberian craton.

Several more Cr-rich pyropes that were recovered from Yakutian microdiamonds are similar in composition to typical Cr-rich harzburgitic pyropes from macrodiamonds. Our extensive data base of Cr-rich pyropes included in Yakutia diamonds consists of about 650 samples, with an overwhelming majority of the samples coming from the Udachnaya and Mir mines, with lesser numbers from the Aykhal, Sytykanskaya and Yubileynaya pipes (Fig. 9).

3.1.4. Cr-diopside

Chrome diopside was recovered and studied from three Komsomolskaya microdiamonds. Two samples are enriched in Cr_2O_3 (6.5 and 6.8 wt.%) and contain up to 19 mol.% kosmochlor. One sample (100/23) is typical chrome diopside (e.g., Meyer, 1987), as shown in Table 8.

3.1.5. Enstatite

Enstatite was found in one microdiamond only from the Komsomolskaya mine (Table 8). This sample contained enstatite as an isolated grain. In general, this enstatite composition is different from typical enstatite inclusions in macrodiamonds (e.g. Sobolev, 1974; Meyer, 1987) in its lack of Al_2O_3 and very low contents of Cr_2O_3.

3.2. E-type mineral inclusions

3.2.1. Garnets

A small number of E-type garnets from microdiamonds fall outside the typical range of Mg–Ca–Fe contents (Fig. 9), containing up to 45% Ca (grossular) component along with high Mg# 67.8% and 30% Ca component (Aykhal sample) along with low Mg# 29.2 (Yubileynaya sample). Elevated (0.09–0.21 wt.%) Na_2O is typical of most of these garnets (Sobolev and Lavrent'ev, 1971). Their analyses are presented in Tables 5 and 6 and the REE pattern in Fig. 8. A series of Mg-rich garnets classified as indicative of Group A eclogites was detected for the first time in Mir diamonds (Logvinova et al., 2001). Two E-type majoritic garnets with the range of Si (pfu) from 3.05 to 3.13 and high Na_2O contents (up to 0.93 wt.%) were discovered in microdiamonds. The majorite garnets are similar to some garnet inclusions from Monastery mine in South Africa (Moore and Gurney, 1985). On a Na_2O (wt.%) versus Mg# diagram (Fig. 10), modified from Stachel (2001), both garnet compositions clearly plot within the field of majoritic garnets. High P–T experimental results on the origin of majoritic garnets (Gasparik,

Table 5

Selected compositions of garnets from Yakutian microdiamonds

Sample	Syt-1		Im-10	Im-21	Yub-212	Yub-322	Yum-150	AL-8	AL-9	Km-42/35 [10]	Km-64/23 [15]	Km-68/23 [10]	Km-69/23 [10]	Km-71/49 [12]	Im-3	STI-203/98	ST-203/00	AL-1	AL-2	Yum-31	Km-94/49 [8]
SiO_2	40.8	40.9	42.8	42.4	40.9	41.4	41.5	41.8	41.5	41.7 (2)	41.0 (4)	41.9 (3)	41.3 (3)	40.6 (3)	41.1	40.6	40.6	39.8	41.2	38.6	40.2 (3)
TiO_2	0.05	0.03	0.01	0.74	0.13	0.06	0.06	0.08	0.13	0.02 (1)	0.11 (0)	0.19 (1)	<0.02	0.02 (1)	0.78	0.23	0.6	0.03	0.24	0.05	0.55 (3)
Al_2O_3	12.4	13.0	19.5	20.5	13.2	15.6	16.6	17.9	16.5	17.6 (2)	15.4 (1)	17.5 (1)	18.2 (1)	15.7 (1)	21.2	22.0	21.0	21.6	22.1	21.1	22.6 (0)
Cr_2O_3	14.5	13.4	4.95	2.40	12.2	10.1	8.94	7.55	8.8	8.87 (20)	11.2 (0)	7.43 (7)	7.93 (8)	11.2 (1)	0.23	0.22	0.12	0.03	0.09	0.01	0.02 (1)
FeO	6.45	6.29	5.57	6.31	6.60	6.96	6.51	6.06	6.22	7.28 (7)	6.84 (5)	6.61 (8)	6.20 (5)	6.19 (6)	15.9	13.0	15.9	19.9	8.54	23.0	16.5 (1)
MnO	0.37	0.37	0.23	0.25	0.33	0.43	0.35	0.32	0.36	0.44 (1)	0.35 (1)	0.30 (1)	0.33 (1)	0.37 (2)	0.28	0.41	0.36	0.55	0.22	1.04	0.38 (1)
MgO	23.1	23.1	23.5	22.6	20.0	22.2	21.7	22.6	22.7	21.7 (1)	20.5 (2)	20.4 (1)	20.6 (2)	19.9 (1)	16.1	9.33	13.1	9.2	10.1	5.33	13.8 (1)
CaO	0.94	0.99	3.37	4.32	6.05	3.04	4.12	2.70	3.59	3.10 (3)	4.56 (2)	6.05 (2)	5.40 (4)	5.81 (4)	4.33	14.1	7.55	8.6	17.1	10.2	5.85 (3)
Na_2O	0.01	0.07	0.02	0.09	0.02	0.04	0.03	0.08	0.02	<0.02	<0.02	<0.02	0.03 (5)	0.03 (6)	0.18	0.20	0.21	0.03	0.09	0.01	0.17 (12)
Total	98.6	98.2	100.0	99.6	99.4	99.8	99.8	99.1	99.8	100.7	100.0	100.4	100.0	99.8	100.1	100.1	99.4	99.7	99.7	99.3	100.
Oxygen	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Si	3.023	3.032	3.031	3.013	3.031	3.011	3.008	3.016	3.000	2.992	2.998	3.019	2.980	2.975	3.017	3.024	3.030	3.024	3.038	3.016	2.969
Ti	0.003	0.002	0.001	0.040	0.007	0.003	0.003	0.004	0.007	0.001	0.006	0.010	–	0.001	0.043	0.013	0.034	0.002	0.013	0.003	0.030
Al	1.083	1.136	1.627	1.717	1.153	1.337	1.418	1.522	1.406	1.486	1.326	1.484	1.550	1.353	1.834	1.931	1.847	1.934	1.921	1.943	1.969
Cr	0.849	0.785	0.277	0.135	0.715	0.581	0.512	0.431	0.503	0.503	0.648	0.423	0.452	0.649	0.013	0.013	0.007	0.002	0.005	0.001	0.002
Fe	0.400	0.390	0.330	0.375	0.409	0.423	0.395	0.366	0.376	0.437	0.418	0.398	0.374	0.379	0.976	0.810	0.992	1.264	0.527	1.503	1.019
Mn	0.023	0.023	0.014	0.015	0.021	0.026	0.021	0.020	0.022	0.027	0.022	0.018	0.020	0.023	0.017	0.026	0.023	0.035	0.014	0.069	0.024
Mg	2.550	2.552	2.479	2.393	2.209	2.406	2.344	2.430	2.445	2.323	2.230	2.192	2.219	2.169	1.761	1.035	1.457	1.042	1.110	0.621	1.521
Ca	0.075	0.079	0.256	0.329	0.480	0.237	0.320	0.209	0.278	0.238	0.357	0.467	0.417	0.456	0.341	1.125	0.604	0.700	1.351	0.854	0.462
Na	0.001	0.010	0.003	0.012	0.003	0.006	0.004	0.011	0.003	0.002	0.002	0.001	0.004	0.004	0.026	0.029	0.030	0.004	0.013	0.002	0.024
Total	8.007	8.009	8.017	8.027	8.028	8.029	8.025	8.008	8.039	8.011	8.007	8.012	8.016	8.009	8.028	8.005	8.024	8.008	7.991	8.010	8.020
Mg#	86.5	86.7	88.3	86.5	84.4	85.0	85.6	86.9	86.7	77.4	74.3	71.6	74.0	85.1	64.3	56.1	59.5	45.2	67.8	29.2	50.7
Cr/Cr+Al	44.0	40.9	14.6	7.28	38.3	30.3	26.5	22.1	26.4	25.3	33.3	22.2	22.6	32.4	0.72	0.67	0.38	0.09	0.27	0.03	0.10

Symbols: Im=Internatsionalnaya; Syt, ST and STI=Sytykanskaya; AL=Aykhal; Km=Komsomolskaya; Yub and Yum=Yubileynaya mines.

Table 6
Chemical composition of majoritic and normal garnets included in microdiamonds from Yakutian kimberlites (Ym-27, Km-88/23, Kr-119/13) and Arkhangelsk kimberlite (Po-99)

Gt type	Yum-27		Km-88/23	Kr-119/13	Po-99
	Majorite	Normal	Majorite	Majorite	Majorite
# analysis	[8]	[10]	[5]	[17]	[17]
P_2O_5	0.05 (1)*	0.05 (1)	0.211 (6)	n.d.	n.d.
SiO_2	42.8 (2)	38.9 (1)	41.3 (1)	40.8 (2)	44.9 (2)
TiO_2	0.33 (1)	0.37 (1)	1.90 (2)	0.41 (1)	0.71 (2)
Al_2O_3	6.79 (3)	10.9 (1)	18.0 (1)	20.9 (1)	16.6 (1)
Cr_2O_3	10.2 (9)	13.4 (1)	0.05 (1)	0.07 (1)	1.23 (4)
FeO	5.67 (6)	9.11 (5)	16.0 (1)	14.1 (2)	8.65 (11)
MnO	0.28 (2)	0.31 (1)	0.29 (2)	0.31 (1)	0.21 (1)
MgO	12.2 (2)	12.9 (1)	8.82 (8)	9.41 (5)	23.5 (5)
CaO	20.8 (1)	12.8 (1)	12.2 (1)	12.9 (1)	3.77 (3)
Na_2O	0.04 (2)	< 0.02	0.93 (9)	0.43 (1)	0.25 (1)
Total	99.16	98.74	99.70	99.3	99.8
Oxygen	12	12	12	12	12
P	0.003	0.003	0.014	–	–
Si	3.293	3.022	3.131	3.068	3.200
Ti	0.019	0.022	0.108	0.023	0.038
Al	0.616	0.996	1.606	1.852	1.394
Cr	0.621	0.825	0.003	0.004	0.069
Fe	0.365	0.591	1.010	0.887	0.515
Mn	0.018	0.020	0.018	0.020	0.013
Mg	1.411	1.496	0.995	1.055	2.496
Ca	1.723	1.065	0.988	1.039	0.288
Na	0.005	0.000	0.136	0.063	0.035
Total	8.074	8.041	8.009	8.012	8.048
#Mg	79.3	71.6	49.6	54.3	82.9

*Numbers in ( ) are the one sigma variance in analyses for the least unit cited.

2002) clearly support the unusual deep origins for these garnets (i.e., >300 km).

3.2.2. Omphacite

A limited number of E-type clinopyroxene inclusions from microdiamonds were recovered, but demonstrate some interesting compositional features (Table 8). Sample Ud-2 represents an omphacite intergrowth with coesite, shown in Fig. 3, containing about 31% jadeite and high K_2O. The omphacite from a Yubileynaya microdiamond (Yum-20) is enriched in FeO. A single microdiamond from the Mir pipe (Logvinova et al., 2001) containing hundreds of minute mineral inclusions is characterized by the presence of clinopyroxene grains classified from Group-A eclogites, as classified by Taylor and Neal (1989). This is the first example of a Group-A pyroxene coexisting with high-Mg Group-A garnet from Mir diamonds, as shown in Fig. 11 (Sobolev et al., 1998).

4. Discussion

Mineral inclusions in 290 microdiamond from 8 Yakutian diamond mines have been characterized and form the basis for comparison with similar minerals from macrodiamonds from these same kimberlite pipes. Compositional data for inclusions of U- and E-type garnet and pyroxene, as well as olivine and chromite, from 98 of these microdiamonds were published earlier (Logvinova et al., 2001; Sobolev et al., 2000; Zedgenizov et al., 1998, 2001). About 70% of the microdiamond inclusions are represented by olivines and 16% Cr-spinels. Both U and E-type garnets represent only 11% of the collection, with the remaining samples represented by pyroxenes. At the present time, the inclusion data base from Yakutian macrodiamonds is almost an order of magnitude larger than that from microdiamonds. In spite of this limited and unequal sampling, some important compositional differences are readily apparent. These differences include the following specific features of inclusions from microdiamonds: (a) Cr–Ca-rich majoritic garnet from the Yubileynaya mine, coexisting in the same diamond with another Ca–Cr-rich non-majoritic garnet, but both with similar REE patterns, including +Eu anomalies; (b) majoritic eclogitic (E-type) garnets with a considerably wider range in compositions compared with inclusions in macrodiamonds (e.g., Meyer, 1987); (c) relatively high-NiO (0.45–0.64 wt.%) and low-Fo (<90) contents in olivines from the Yubileinaya (Sobolev et al., 2000) and Sytykanskaya mines; (d) Mg-spinels containing but traces of Cr (Zedgenizov et al., 1998), as well as high-magnesian (Mg# >75) and Ti-rich (>4 wt.% TiO_2) chromites; (e) ferropericlase inclusions in a microdiamond from the Udachnaya mine (Zedgenizov et al., 2001); (f) enstatite inclusion from Komsomolskaya microdiamond with extremely low Al_2O_3 and Cr_2O_3 contents.

A limited yet highly significant number (3) of majoritic garnets have been found both in U-type

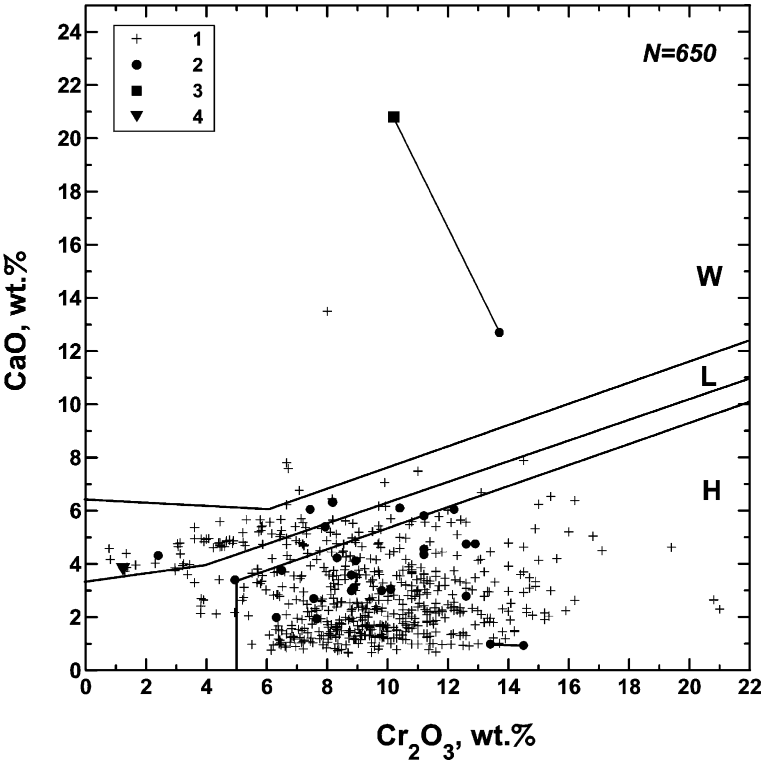

Fig. 7. CaO vs. Cr_2O_3 in Cr-bearing pyropes from macrodiamonds of major Yakutian diamond mines (1) and from microdiamonds of the same mines (2). Solid boundaries for garnet parageneses are from Sobolev (1971, 1974). H—harzburgitic, L—lherzolitic, W—wehrlitic parageneses. Majoritic garnet from microdiamond of Yubileynaya mine (3) associated with a "normal" garnet in the same diamond—two plots connected by solid line. The plot of majoritic garnet from Arkhangelsk microdiamond (4) is shown for comparison. Data source: Griffin et al. (1993), Kovalsky (1979), Sobolev (1974), Sobolev et al. (1997a, 2001), Zedgenizov et al. (1998) and authors database. *N*—number of analyses.

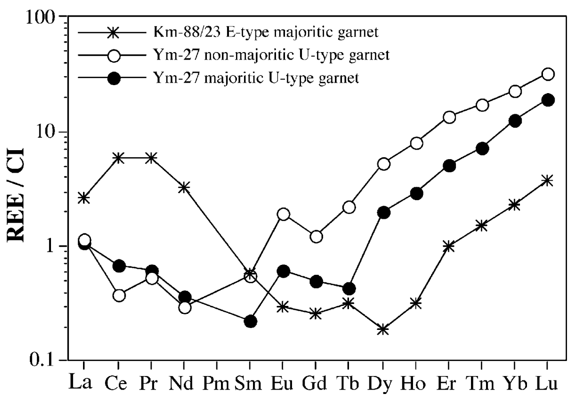

Fig. 8. Normalized REE patterns for two majoritic and one associated non-majoritic garnets (see Table 6 for major and Table 7 for REE and trace element analyses).

and E-type microdiamonds, but not in Yakutian macrodiamonds to date, in spite of there being at least 770 garnet inclusions from Yakutian macrodiamonds. Majoritic garnet of lherzolite-websterite paragenesis has also been documented from an Arkhangelsk microdiamond (Sobolev et al., 1997a,b). These observations, in an addition to other majoritic garnet inclusions by Stachel (2001), lead to the paradigm that *30–40% of kimberlitic pipes worldwide contain these unusual majoritic garnets as inclusions only in microdiamonds*. It should also be note that a significant number of majoritic garnets have been discovered from placer diamonds with unknown primary sources (e.g., Stachel, 2001; Gasparik, 2002).

The discovery of majoritic garnets in microdiamonds from three of the Yakutian diamond

Table 7
Trace-element concentrations of garnet inclusions determined by SIMS

	Km-88/23		Yum-27 non-majoritic		Yum-27 majoritic	
	Conc (ppm)	Conc/CI	Conc (ppm)	Conc/CI	Conc (ppm)	Conc/CI
K	7.2	0.013	2743	4.9	1124	2.0
Sc	149	26	213	37	225	39
V	323	5.7	627	11	474	8.4
Mn	2772	1.5	3190	1.6	2900	1.5
Rb	0.32	0.14	2.1	0.92	1.1	0.49
Sr	11	1.4	2.7	0.34	4.2	0.53
Y	0.95	0.61	15	9.6	4.9	3.2
Zr	0.42	0.11	5.7	1.5	26	6.5
Nb	0.68	2.7	12	49	4.3	18
Ba	0.12	0.053	41	18	4.0	1.7
La	0.62	2.7	0.27	1.2	0.26	1.1
Ce	3.6	6.0	0.23	0.39	0.42	0.70
Pr	0.53	6.0	0.048	0.54	0.054	0.61
Nd	1.5	3.3	0.13	0.30	0.17	0.37
Sm	0.084	0.57	0.083	0.56	0.034	0.23
Eu	0.017	0.30	0.11	1.9	0.035	0.62
Gd	0.052	0.26	0.24	1.2	0.099	0.51
Tb	0.012	0.32	0.080	2.2	0.016	0.43
Dy	0.046	0.19	1.3	5.3	0.50	2.0
Ho	0.018	0.32	0.45	8.0	0.17	3.0
Er	0.16	1.0	2.2	14	0.81	5.1
Tm	0.037	1.5	0.42	17	0.18	7.3
Yb	0.38	2.3	3.7	23	2.1	13
Lu	0.091	3.7	0.79	33	0.47	19

mines is of special interest and importance. Until recently, all majoritic garnets reported, dominantly eclogitic, were from but six kimberlitic pipes worldwide and two alluvial sources, as summarized by Stachel (2001) and Gasparik (2002). Our present study adds three additional pipes this still limited statistic. Along with recent discovery of a number of majoritic garnets in both U- and E-type diamonds from Snap Lake kimberlite, Canada (Pokhilenko et al., 2001, 2004), it is now possible to conclude that majoritic garnets represent virtually all known mineral parageneses of U-type diamonds (harzburgitic, lherzolitic, wehrlitic).

Wehrlitic garnet with significant majorite component is the rarest among all described majoritic garnets. In our study, we have presented the first discovery of such a wehrlitic majoritic garnet, as verified by X-ray diffraction data (see Table 2). This garnet coexists with a normal garnet in a single microdiamond from the Yubileynaya pipe (Tables 5 and 6; Fig. 8). Although normal garnets enriched both in Cr and Ca are very rare, only one additional sample has been described from Yakutian diamonds (Sobolev, 1974).

This Yubileynaya majoritic garnet associated in a single diamond with a normal garnet, as isolated grains, however, with uncertain relative positions, is most significant. They both are rich in Cr and Ca related to wehrlitic paragenesis. In spite of their differences in bulk compositions and majoritic component, they have very similar REE patterns, each displaying a distinct +Eu anomaly. In addition, the REE patterns (Fig. 8) do not have any HREE negative slope, characteristic of harzburgitic garnets (Taylor et al., 2003). We suggest that the majoritic garnet was encapsulated by the microdiamond at the depth >300 km, but that the microdiamond crystal continued to grow in a silicate environment of similar chemical composition. At considerably lower pressure, albeit still within the diamond stability field, a normal Cr–Ca garnet was encapsulated, in addition to an olivine grain.

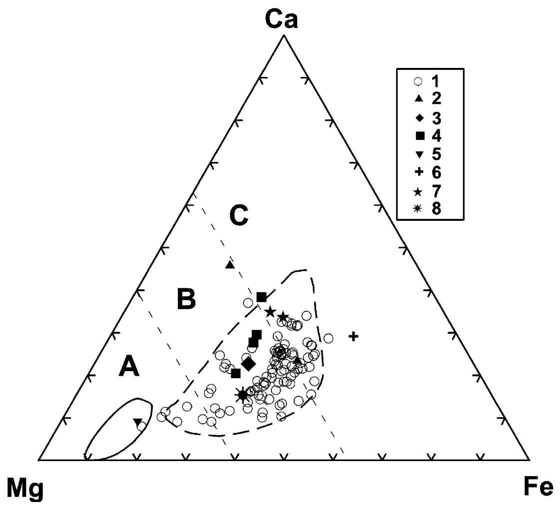

Fig. 9. Ternary diagram for garnets from E-type paragenesis in macrodiamonds from Mir and Udachnaya pipes (1), microdiamonds from Aykhal (2), Udachnaya (3), Sytykanskaya (4), Mir (5), Yubileynaya (6), Komsomolskaya, majoritic (7) and normal (8). Data source: this study, Sobolev et al. (1998) and Logvinova et al. (2001). Group boundaries are from Coleman et al. (1995).

Table 8
Selected compositions of pyroxenes from Yakutian microdiamonds

Sample	Kmsm-6 Cr-Di	Kmsm-7 Cr-Di	Kmsm-21 En	UD-2* Omph	STI-33 Omph	Yum-20 Omph
SiO_2	55.3	56.2	58.5	55.8	55.3	55.6
TiO_2	< 0.03	< 0.03	< 0.03	0.41	0.20	0.21
Al_2O_3	1.69	2.36	0.01	8.51	8.44	8.65
Cr_2O_3	6.50	6.80	0.08	0.04	0.04	0.03
FeO	1.90	1.96	4.62	3.52	3.88	7.26
MnO	0.09	0.09	0.13	0.10	0.05	0.07
MgO	14.9	14.2	36.5	11.4	11.4	8.99
CaO	15.3	14.6	0.27	14.5	16.1	14.5
Na_2O	3.20	3.91	0.1	4.46	4.02	4.56
K_2O	0.76	0.48	n.d.	0.58	0.12	0.66
Total	99.7	100.6	100.2	99.3	99.6	100.5
Oxygen	6	6	6	6	6	6
Si	2.009	2.016	1.996	1.998	1.982	2.001
Ti	0.000	0.000	0.000	0.011	0.005	0.006
Al	0.072	0.100	0.000	0.359	0.357	0.367
Cr	0.187	0.193	0.002	0.001	0.001	0.001
Fe	0.058	0.059	0.132	0.105	0.116	0.218
Mn	0.003	0.003	0.004	0.003	0.002	0.002
Mg	0.807	0.759	1.855	0.608	0.609	0.482
Ca	0.595	0.561	0.010	0.556	0.618	0.559
Na	0.225	0.272	0.007	0.310	0.279	0.318
K	0.035	0.022	—	0.026	0.005	0.030
Total	3.991	3.985	4.018	3.977	3.975	3.984
Mg#	93.3	92.8	93.4	85.2	84.0	68.8
Ca/Ca + Mg	42.5	42.5	0.53	47.8	50.4	53.7

Symbols: UD = Udachnaya; STI = Sytykanskaya; Yum = Yubileynaya; Kmsm = Komsomolskaya mines; n.d. = not determined.
* Associated (touching) with coesite (see Fig. 3).

A similar association of majoritic (Si, pfu = 3.17) and three normal E-type garnets were described in a diamond from DO-27 pipe, Canada (Davies et al., 1999). No information about the relative position of these garnet grains within the diamond was noted. This example supports our suggestion about a possibility of a single diamond growth within a considerably pressure range but in the environment of a similar chemical composition.

Our lack of knowledge of the relative garnet positions from the Yubileynaya diamond and the same lacking with the study of Davies et al. (1999), as discussed above, exemplifies the importance of *in-situ* examination of inclusions on polished surfaces of diamonds, as stressed by Taylor et al. (2000) and Taylor and Anand (in press). The findings that we have presented in this study for the inclusions in the Ym-27 diamond, although highly significant, would have been more valuable if the mineral observations had been made while still in the diamond. Then, the CL zoning, the N-aggregation from FTIR, and the chemistry of the diamond (e.g., $\delta^{13}C$, $\delta^{15}N$) could have been factored into the paragenesis of the inclusions and their adjoining host diamond.

5. Summary

We conclude that mineral inclusions in microdiamonds are considerably more variable in their compositions and parageneses compared with inclusions in macrodiamonds. The inhomogeneities between different grains of inclusions within the same microdiamond provide evidence for a complex growth history for at least some microdiamonds.

The percentage of mineral inclusions of unusual compositions in microdiamonds, particularly the olivines from Yubileynaya and Sytykanskaya; chromites from all Yakutian mines, and significantly majoritic garnets, leads us to conclude that many of these compositional features may be related to a deeper

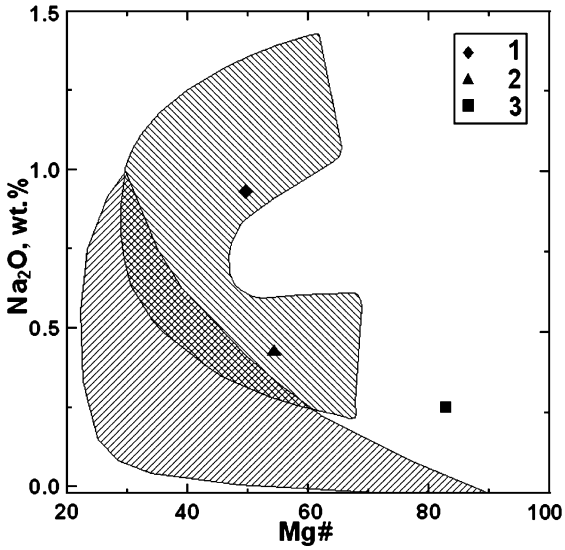

Fig. 10. Na_2O (wt.%) vs. molar pyrope content (Mg#) for "normal" (lower area) and majoritic (upper area) garnets. Note a very little overlap between high-Na normal and low-Na majoritic garnets. Modified from Stachel (2001). Komsomolskaya (1) and Krasnopresnenskaya (2) microdiamonds E-type majoritic garnets; Arkhangelsk microdiamond majoritic garnet (3); after Sobolev et al. (1997a).

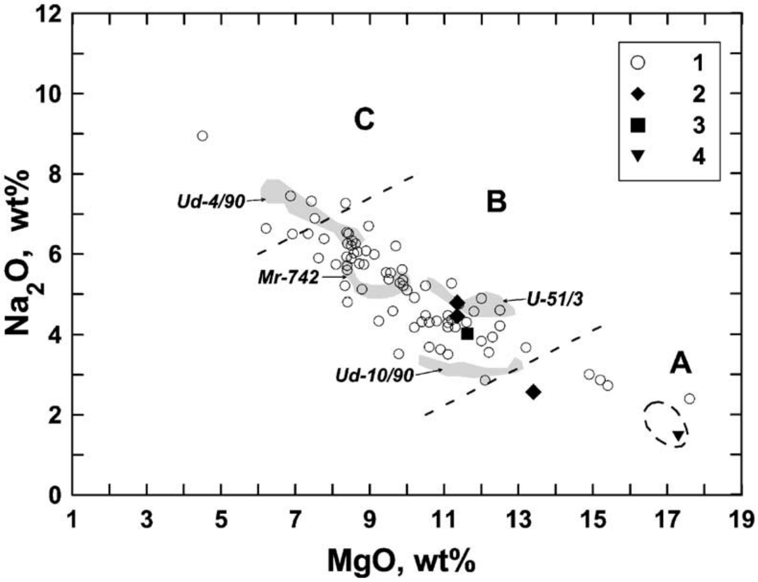

Fig. 11. Na_2O (wt.%) vs. MgO (wt.%) in clinopyroxenes from E-type macrodiamonds of Mir and Udachnaya pipes (1) and from microdiamond of the Mir pipe. For symbols, see Figs. 5 and 9. Group boundaries are from Taylor and Neal (1989). The hatching outlines the compositional domains of multiple pyroxene inclusions in individual macrodiamonds from Mir (Mr) and Udachnaya (Ud, U) pipe diamonds. Data source: Sobolev et al. (1998).

origin for the microdiamond source region (>300 km) for at least a 10–30% portion of microdiamonds from each Yakutian pipe.

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