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Petrology of highly aluminous xenoliths from kimberlites of Yakutia

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Abstract

Highly aluminous xenoliths include kyanite-, corundum- and coesite-bearing eclogites, grospydites and alkremites. These xenoliths are present in different kimberlites of Yakutia but have most often been found in Udachnaya and other pipes of the central Daldyn–Alakitsky region. Kimberlites of this field also contain eclogite-like xenoliths with kyanite and corundum that originate in the lower crust or the lower crust–upper mantle transition zone. Petrographic study shows that two rock groups of different structure and chemistry can be distinguished among kyanite eclogites: fine- to medium-grained with mosaic structure and coarse-grained with cataclastic structure. Eclogites with mosaic structure are characterized by the occurrences of symplectite intergrowths of garnet with kyanite, clinopyroxene and coesite; only in this group do grospydites occur. In cataclastic eclogites, coarse-grained coesite occurs, corresponding in size to other rock-forming minerals. Highly aluminous xenoliths differ from bimineralic eclogites in their high content of Al_2O_3 and total alkali content. Coesite-bearing varieties are characterized by low MgO content and higher Na/K and Fe^{2+}/Fe^{3+} ratios, as well as high contents of Na_2O. Geochemical peculiarities of kyanite eclogites and other rocks are exhibited by a sloping chondrite-normalized distribution of rare earth elements (REE) in garnets and low Y/Zr ratio, in contrast to bimineralic rocks. Coesite is found in more than 20 kyanite eclogites and grospydites from Udachnaya. Grospydites with coesite from Zagadochnaya pipe are described. Three varieties of coesite in these rocks are distinguished: (a) subhedral grains with size of 1.0–3.0 mm; (b) inclusions in the rock-forming minerals; (c) sub-graphic intergrowths with garnet. The presence and preservation of coesite in eclogites indicate both high pressure of formation (more than 30 kbar) and set a number of constraints on the timing of xenolith cooling during entrainment and transport to the surface. Different ways of formation of the highly aluminous eclogites are discussed. Petrographic observations and geochemistry suggest that some highly aluminous rocks have formed as a result of crystallization of anorthosite rocks in abyssal conditions. $\delta^{18}O$-estimations and other petrologic evidence point out the possible origin of some of these xenoliths as the result of subduction of oceanic crust. Diamondiferous samples have been found in all varieties except alkremites. Usually these eclogites contain cubic or coated diamonds. However, two sample corundum-bearing eclogites with diamonds from the Udachnaya pipe contain octahedra that show evidence of resorption.

Keywords: Xenolith; Eclogite; Lithosphere; Diamond; Kyanite; Coesite; Siberia

1. Introduction

Highly aluminous xenoliths include kyanite-, corundum- and coesite-bearing eclogites, grospydites and alkremites. These xenoliths are present in many

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different Yakutian kimberlites but are most common in Udachnaya and other pipes of the central Daldyn–Alakitsky region (Bobrievich et al., 1959; Ponomarenko et al., 1976; Spetsius and Serenko, 1990). Granulites or eclogite-like xenoliths with kyanite and corundum belonging to the lower crust or transitional lower crust–upper mantle zone are also present in kimberlites of this field. All varieties of these highly aluminous xenoliths except alkremites and eclogite-like rocks include diamondiferous examples. Evidence discussed below indicates that these xenoliths represent a specific group of mantle rocks that could not be formed by the differentiation of primitive mantle but represent the remnants of subducted crust. The presence of coesite reflects a number of constraints bearing on conditions of the xenoliths origin and kimberlite formation.

The Siberian craton occupies about 4×10^9 km^2, mostly buried beneath Riphean–Phanerozoic sedimentary cover 1–8 km thick, averaging about 4 km. The main structural blocks and tectonic zones are shown in Fig. 1. According to the terrane concept, the craton's structure results from the collision and amalgamation (accretion) of heterochronous microcontinents, which were transformed into terranes or tectonic blocks of varying genesis (Rosen et al., 2002). Their bounding shear zones show traces of tectonic compression and overthrust in zones of collision. The accretion of terranes seemed to have occurred in several stages, and generally larger units,

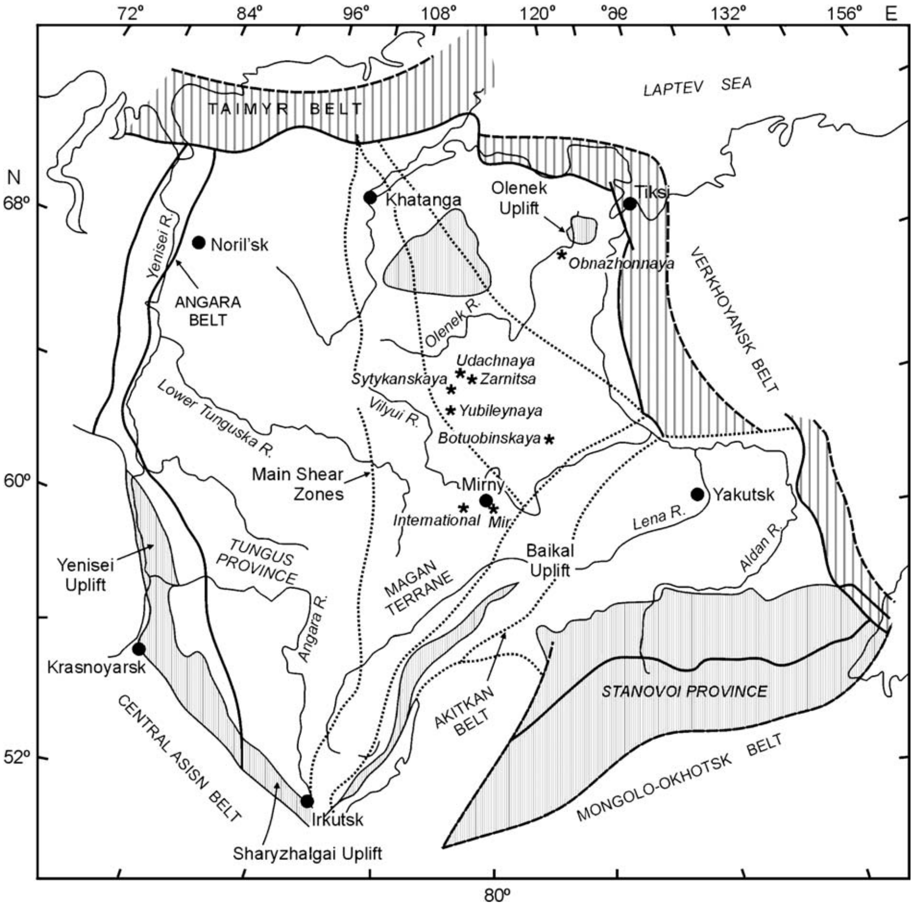

Fig. 1. Sketch map of the basement of the Siberian Craton (after Rosen et al., 2002 with addition), showing main structural elements and localities of xenoliths from kimberlite pipes (star ornament) mentioned in the text.

superterranes or tectonic provinces had appeared before they consolidated as the craton. Fig. 1 shows the main structural domains of the craton as well as the location of the main well-known pipes referred to in this paper. Kimberlite diatremes occur from the Vilui River in the south to the lower reaches of the Olenek and Kotui Rivers in the north, over an area of more than 1100 km in longitude and 800 km in latitude. Situated in the northeastern part of the Siberian craton, the Yakutian kimberlite province occupies mostly the territory of the Anabar superterraine, including the Magan and Daldyn granulite–gneiss terranes and the Markha granite–greenstone terrane. A more detailed description is given in Rosen et al. (2002).

2. Samples and analytical techniques

More than 200 samples of mantle xenoliths from the kimberlite pipes situated in different parts of the Yakutian kimberlite province were studied. Modal analyses have been performed for the major part of xenoliths. For most samples major rock chemistry was determined. Major-element analyses were performed for the rock-forming and minor minerals. Trace element compositions were obtained for some minerals. All the samples were classified into different varieties of eclogites according to their petrographic and chemical features.

Major element compositions of silicate and oxide minerals in the xenoliths were determined with a Superprobe JXA-8800R electron microprobe at the ALROSA (Mirny, Russia) and partly using a CAMECA SX-50 electron microprobe at the Institute of Geology (Yakutsk). Part of the rock-forming garnets and clinopyroxenes and also different secondary phases of eclogites were investigated by ESM with EDS at the University of Western Australia (Perth). Analytical conditions included an accelerating voltage of 15 keV, a beam current of 20 nA, beam size of 5 μm, and 20 s counting time for all elements. All analyses underwent a full ZAF correction.

The trace elements (TRE) have been measured in rock-forming and some secondary minerals of eclogites by laser ablation ICP-MS (LAM) at the RSES, Australian National University, Canberra, using NIST 610 glass as external standard and Ca as internal standard; pit diameters were 40–50 mm.

3. Results

Highly aluminous xenoliths are predominantly presented by eclogites typically containing kyanite (up to 30%) as an additional phase to the high-Ca garnets and high-jadeite clinopyroxenes (up to 11% Na_2O). Wide variations of garnet (20–80%) and clinopyroxene (20–60%) are typical of these rocks. Coesite and corundum are common, with rare rutile, sulfides, and ilmenite. The petrographic peculiarities of kyanite eclogites showed two rock groups of different texture which coincide with differences in chemical composition: fine- to medium-grained with mosaic structure and coarse-grained rocks with cataclastic or more seldom granoblastic structure. Eclogites with mosaic structure are characterized by medium-grained (0.5–2.5 mm size) constitution, banding, and occurrences of symplectic intergrowths of garnet with kyanite, clinopyroxene and coesite. In a number of samples, there is later development of kyanite. Grospydites were found only in this group. Coarse-grained kyanite eclogites are characterized by (1–4 mm size) constitution, strong garnet kelyphitization and euhedral kyanite, which are often replaced by mullite and corundum. In this group of kyanite eclogites, coarse-grained coesite with the same size as the other rock-forming minerals occurs.

Highly aluminous xenoliths differ from bimineralic eclogites in their high content of Al_2O_3 and total alkali content (Table 1). Coesite-bearing varieties are characterized by low MgO content and higher Na/K and Fe^{2+}/Fe^{3+} ratios, as well as high contents of Na_2O. Geochemical peculiarities of kyanite eclogites and other rocks exhibit themselves in a sloping chondrite-normalized distribution of rare earth element in garnets, in contrast to bimineralic rocks, as well as in low Y/Zr ratio. Preliminary data for the trace elements that were taken by dissolution on garnet separated from alkremites and analysed by quadrupole ICP-MS at Durham University suggest an extremely high $^{176}Lu/^{177}Hf$ ratio (>20) at least for one sample from the Udachnaya pipe (Nowell et al., 2003).

Table 1
Average major compositions of highly aluminous xenoliths from kimberlites of Yakutia (analyses recalculated on 100% dry weight basis)

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	#
1	46.36	0.34	24.08	1.32	4.19	0.08	7.13	13.85	1.89	0.72	0.04	8
2	44.34	0.37	17.27	3.6	5.73	0.17	14.64	11.77	1.14	0.91	0.06	33
3	44.99	0.28	25.16	2.96	3.97	0.11	8.09	11.36	1.61	1.4	0.07	43
4	46.31	0.3	25.22	2.68	4.53	0.1	6.42	11.22	2.23	0.93	0.07	10
5	30.02	0.16	32.86	5.49	2.84	0.22	25.02	2.88	0.07	0.4	0.04	12
6	44.85	–	28.18	1.71	2.84	–	7.72	12.45	1.57	0.68	–	11

Analyses: 1, eclogite-like xenoliths from the Udachnaya pipe; 2, bimineralic magnesian (group A) eclogites from the Udachnaya pipe; 3, kyanite eclogites from the Udachnaya pipe; 4, coesite eclogites from the Udachnaya pipe; 5, alkremites from the Udachnaya pipe; 6, grospydites from the Zagadochnaya pipe (after Sobolev, 1977). # = number of analyzed samples.

3.1. Mineralogy of highly aluminous xenoliths

The mineralogy of the eclogite-like rocks with kyanite is not so variable as eclogites. The main minerals are garnet, clinopyroxene, and plagioclase with addition of secondary formed clinopyroxene and kyanite in intergrowths. Representative compositions of all minerals are given in Table 2. In these xenoliths the modal kyanite content varies considerably (1% to 15%). Kyanite occurs as spectacular intergrowths with clinopyroxene. This texture consists of fine subhedral laths (0.1 × 1.2 mm) of both minerals (Fig. 2). These intergrowths are usually associated with garnet or situated between garnet and plagioclase and sometimes they have a star-like appearance. Similar textures have been described by Fadili and Demaiffe (1999) in xenoliths from the Mbuji Mayi kimberlites. Rare samples of these rocks with dispersed corundum grains (0.2–1.5 mm in size) are present among xenoliths of the Udachnaya pipe. It should be pointed out that samples exist that are transitional from the kyanite-bearing eclogite-like rocks with single plagioclase grains to the kyanite eclogites (Spetsius and Serenko, 1990).

Table 2
Compositions of minerals in kyanite-bearing eclogite-like xenolith from the Udachnaya (sample U-2295)

	Gt (1)	Pl (2)	Cpx (3)	Ky (4)	Cpx (5)	Gt (6)
SiO_2	41.35	52.31	50.29	36.51	52.6	41.39
TiO_2	0.1	0.03	0.56	0.05	0.1	0.03
Al_2O_3	22.75	29.82	10.26	61.31	5.13	22.75
Cr_2O_3	0.14	0.05	0.34	0.22	0.41	0.3
FeO	12.19	0.03	2.25	0.39	2.26	12.13
MnO	0.14	0.02	0.03	0.07	0.13	0.14
MgO	14.05	0.14	12.26	0.16	14.61	11.71
CaO	9.1	12.75	22.25	0.05	22.6	10.75
Na_2O	0.08	4.69	1.66	0.04	1.84	0.32
K_2O	0.01	0.23	0.02	0.01	0.03	0.02
Total	99.91	99.84	99.92	98.81	99.71	99.54

Numbers in parenthesis correspond to the points of analyses on Fig. 2.

3.2. Eclogite xenoliths

Clinopyroxene in kyanite eclogites is omphacite characterized by high Mg# and high-Al content (Table 3). There is a clear correlation of jadeite content in omphacites of bimineral and kyanite eclogites with their CaO content; this relationship holds for eclogite clinopyroxenes from all the pipes (Spetsius and Serenko, 1990). The comparison of eclogite clinopyroxenes from pipes Mir, Obnazhonnaya and Udachnaya shows that the clinopyroxenes of the last have a more variable composition due to the absence of eclogites of high-Al composition in the first two pipes. Omphacites in eclogites from pipe Udachnaya are enriched in lithophile trace elements, perhaps resulting from the action of metasomatic fluids (Spetsius, 1995).

Garnet from highly aluminous xenoliths has a wide variation in Fe, Mg and Ca content (Table 4). Garnets of these xenoliths differ by higher Ca# from the garnets from bimineral eclogites and usually they have high Mg#. They contain over 40 mol% of pyrope, 10–20 mol% of almandine and variable number (20–60 mol%) of grossular components. Garnets relatively high in Cr_2O_3 (containing up to 1.0 wt.%) are found in some kyanite eclogites. A wide range of content of Ca, Mg, Fe, Cr and Ti is typical of garnets from xenoliths of the eclogite suite from individual pipes (Spetsius and Serenko, 1990). The

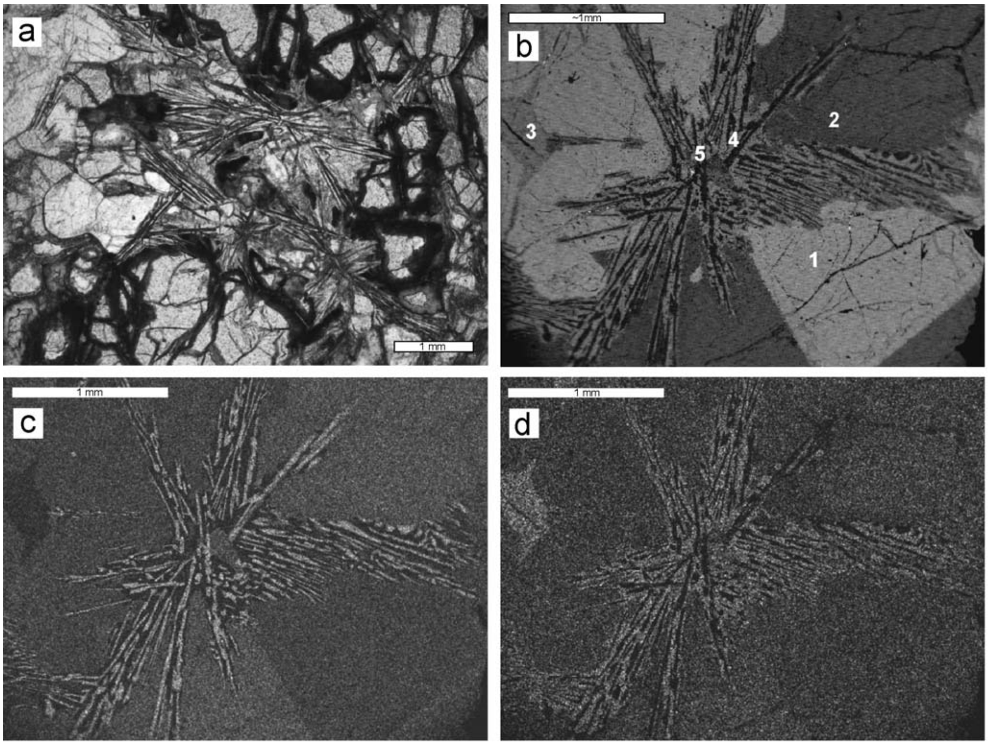

Fig. 2. Kyanite-bearing eclogite-like xenoliths from the kimberlites of Yakutia. (a) Plane-polarized light (intergrowths of Cpx and Ky between grains of Gt and Plag are obvious, sample Zr-18 from Zarnitsa pipe); (b–d) scanning electron microscope images of eclogite-like xenoliths from the kimberlite pipe Udachnaya: (a) backscattered image of Ky-Cpx intergrowth (sample U-2295); (c,d) images in Al K_{α} and Ca K_{α}. Points of microprobe analyses of minerals are shown (see data in Table 2).

garnets from kyanite eclogites of Udachnaya vary widely in Ca/(Ca + Mg) from 22% to 76%. The most calcic samples (>50% Ca#) are thus grospydites. There are smaller variations in Ca# of eclogite garnets from the Mir pipe where kyanite eclogites and grospydites are absent. It should be pointed that garnets from kyanite eclogites with coesite have wide variations in Ca/(Ca + Mg) (Fig. 3) and in some cases have occupied the field of C-group eclogites and B-group as well.

Kyanite differs by its euhedral and “fresh” outlook from the other rock-forming minerals, except in rare cases, when it is replaced by corundum and mullite. Two types of kyanite are recognisable: (1) crystals of tabular shape, of macroscopic blue colour, sometimes with a greenish tint (chrome containing); (2) needle-shaped colourless kyanite, typical for eclogite-like rocks sometimes occurring in kyanite eclogites where it is the latest. In some samples, there are symplectite intergrowths of kyanite with garnet.

Coesite is found in more than 20 samples of kyanite eclogites and grospydites from the Udachnaya pipe where it was first discovered in mantle xenoliths (Ponomarenko et al., 1977). The abundance of coesite ranges from trace quantities (single grains and inclusions) to approximately 10% by volume. Grospydites with coesite also occur in the Zagadochnaya pipe. Three morphological varieties of coesite are recognized: (a) subhedral coesite grains with a size of 1.0–3.0 mm (Fig. 4a–c); (b) coesite inclusions in the rock-forming eclogite minerals; (c) subgraphic intergrowths with garnet (Fig. 4d). The presence and preservation of coesite in eclogites indicate high pressure of formation (more than 30 kbar) and set a number of limitations on the timing of cooling of xenoliths during their capture and transportation to surface by kimberlitic magma.

Table 3
Representative compositions of omphacites from highly aluminous xenoliths from the Udachnaya pipe

Sample	U-9	U-154	U-157	U-947	U-163	U-188	U-2290	U-2310	Ud-45	Ud-155
Analyses	1	2	3	4	5	6	7	8	9	10
SiO_2	55.3	54.62	54.78	56.21	54.99	55.67	56.46	54.49	55.87	59.58
TiO_2	0.23	0.16	0.17	0.3	0.24	0.24	0.22	0.28	0.22	0.25
Al_2O_3	14.83	13.42	12.27	16.52	14.47	16.12	16.88	1652	9.05	18.16
Cr_2O_3	0.05	0	0.13	0.06	0.02	0.04	0.05	0.03	0.07	0.04
FeO	2.82	1.74	1.99	1.98	2.57	3.07	1.77	1.95	2.56	1.04
MnO	< 0.03	< 0.03	0.03	< 0.03	< 0.03	< 0.03	0.01	0	0.03	< 0.03
MgO	7.05	8.4	9.64	5.8	7.1	5.67	6.56	6.04	10.96	4.44
CaO	13.12	15.62	16.44	10,06	13.38	9.9	9,98	12.88	15.99	9.21
Na_2O	4.02	4.89	5.07	8.88	5.98	8.39	8.04	6.48	0.2	6.66
K_2O	0.07	0.02	0.04	0.22	0.02	0.03	0.03	0.04	5.19	0.12
Total	97.52	98.87	100.56	100.03	98.79	99.14	100	98.7	100.14	99.49

Analyses: 1 and 2, kyanite eclogites; 3, grospydite; 4, kyanite eclogite with sanidine; 5–7, coesite eclogites; 8, coesite-bearing grospydite; 9–10, diamondiferous eclogites (9, corundum-bearing eclogite, 10, kyanite eclogite with corundum).

Corundum is present in the form of small needles 0.01–0.2 mm long. Usually corundum replaces kyanite (Fig. 5a) and more rarely forms separate lamellar crystals up to 2 mm in kyanite eclogites. It has a dark-blue color and can be designated as sapphire. In some eclogites, the corundum is ruby-red in color and forms elongated crystals up to 1–3 mm. Such corundum is present in a diamondiferous sample that contains more than 90% of garnet in the rock (Fig. 5b). It is more likely that corundum has a secondary origin in this case also. In their compositions these samples are close to the xenoliths described as corganites by Mazzone and Haggerty (1989).

3.3. Diamonds

Diamondiferous samples have been found in all varieties of these xenoliths except alkremites. Usually kyanite eclogites from the Udachnaya pipe contain cubic or coated diamonds, which are small in size

Table 4
Representative compositions of garnets of highly aluminous xenoliths from the Udachnaya pipe

Sample	U-9	U-154	U-157	U-947	U-163	U-2290	U-2310	Ud-114	Ud-155	U-306	U-294
Analyses	1	2	3	4	5	6	7	8	9	10	11
SiO_2	39.32	39.65	40.3	40.21	39.26	39.68	38.99	38.93	40.56	47.72	42.92
TiO_2	0.14	0.13	0.09	0.01	0.2	0.07	0.31	0.19	0.32	0.02	0.05
Al_2O_3	22.48	22.42	22.6	22.65	22.34	22.74	21.98	22.72	22.92	24.08	22.45
Cr_2O_3	0.01	< 0.03	0.17	0.06	0.01	< 0.03	0.01	0.01	0.06	0.1	0.5
FeO	16.39	8.43	8.86	12.35	12.2	15.58	8.41	7.04	10.77	5.96	5.52
MnO		0.04	0.14	0	0.17	0.26	0.02	0.04	0.11	0.34	0.1
MgO	9.36	6.35	6.9	8.28	5.37	8.87	3.61	10.83	8.97	24.55	14.55
CaO	11.86	22.6	21.19	16.56	20.42	12.01	25.67	19.67	17.35	1.42	14.12
Na_2O	< 0.03	< 0.03	0.05	0.11	< 0.03	0.19	< 0.03	0.24	0.03	n.d	n.d
Total	99.77	99.62	100.31	100.24	99.97	99.41	99.01	99.67	101.09	100.19	100.29

Analyses: 1 and 2, kyanite eclogites; 3, grospydite; 4, kyanite eclogite with sanidine; 5–7, coesite eclogites; 8, corundum-bearing diamondiferous garnetite; 9, kyanite eclogite with corundum; 10 and 11, alkremites (after Ponomarenko and Leskova, 1980). n.d. = not detected element.

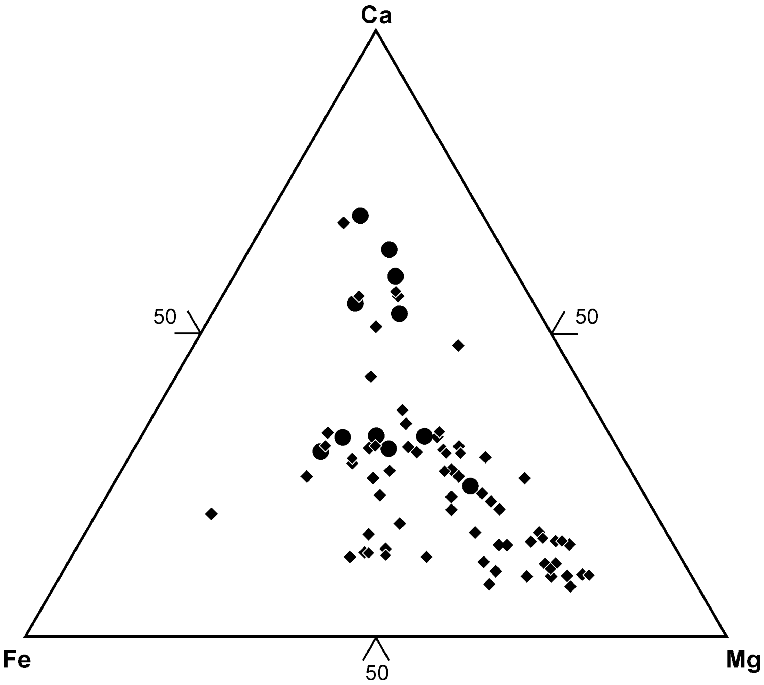

Fig. 3. Garnets compositions of eclogite xenoliths from the Udachnaya pipe (filled circles—coesite eclogites).

(about 1 mm) in most cases (Spetsius, 1995). There exists some evidence for their secondary metasomatic origin due to introduction of fluids enriched in H_2O and other volatile components (Spetsius, 1999). However, a new discovery of two samples of corundum-bearing eclogites with diamonds from the Udachnaya pipe is not consistent with this origin; the xenoliths contain large diamonds (size 4–5 mm) that are present as planar octahedral crystals and show smooth faces (Fig. 5c,d). The diamond crystals are colorless. A black, small mineral inclusion is seen in the center of one of the crystals and is probably sulfide. In addition, the diamonds show obvious features of dissolution and resorption in one sample (Fig. 3c). Most probably its unresorbed parts were inside the xenolith while the resorbed faces projected from it. The surface textures of the diamond crystals imply that the present resorbed surfaces seen on diamonds most probably resulted from their dissolution in the kimberlite melt, since the parts of the diamonds that resided inside the xenolith remained unresorbed. The petrography, mineral composition and geochemistry of these two samples of corundum-bearing eclogites show close affinities with garnetites from this pipe. Thin section study clearly showed secondary formation of corundum in these samples and so a secondary late origin of diamonds cannot be excluded as well.

3.4. Trace element distribution in eclogite minerals from the Udachnaya pipe

Trace element data for mantle xenoliths has important implications in many aspects: (a) the estimation of distribution in minerals and correct definition of partitioning of trace elements between minerals of mantle rocks in relationship with the PT conditions of their formation, (b) the deciphering of the complex history and evolution of mantle eclogites, which is a subject of much discussion (Ireland et al., 1994; Snyder et al., 1997), (c) the elucidation of possible distinctions in the behavior of trace elements in different mantle processes.

A suite of about 20 xenoliths from the Udachnaya kimberlite pipe have been studied for the trace element composition of their minerals. Only six of the samples were simple bimineral or kyanite eclo-

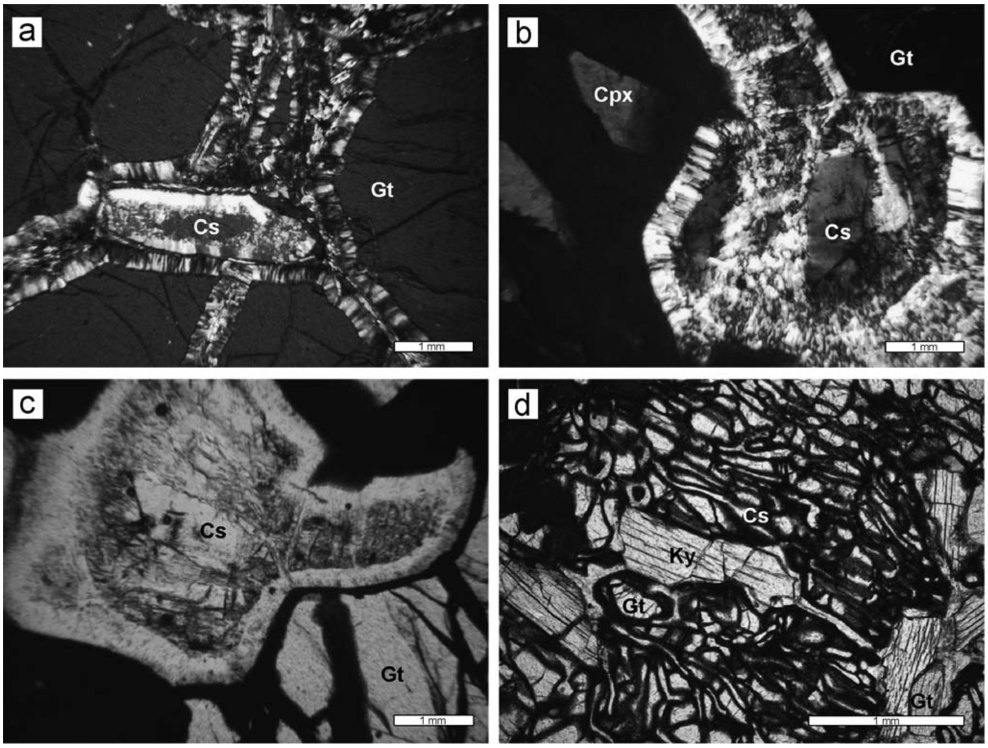

Fig. 4. Coesite-bearing eclogite xenoliths from the Udachnaya kimberlite pipe. (a,b) Crossed polarizers and (c,d) plane-polarized light. Legend for these and next photomicrographs is as follows: Gt = garnet, Cpx = clinopyroxene, Cs = coesite, Ky = kyanite, Cd = corundum. (a) View of coesite relict with pronounced palisade texture of surrounding secondary quartz between grains of garnet (sample U-2290). (b,c) Relicts of coesite surrounded by rims of palisade quartz with addition of fine grained quartz (sample U-256). (d) Intergrowth of coesite with garnet (sample U-168).

gites without diamonds. Diamondiferous xenoliths include not only bimineral eclogites, but one sample of garnet clinopyroxenite and two xenoliths of garnetites (with content of clinopyroxene less than 1%). Abundance of trace elements has been studied in coexisting garnets and clinopyroxenes in nearly all samples, and in secondary clinopyroxenes in some xenoliths. The special checking of core and rim parts of garnet grains shows that they are homogeneous in major and trace element composition. A little zonation of garnet is found only in two samples where rims are slightly enriched in Nd, Sm, Eu, Dy and Ho. It is necessary to stress that during the analysis of primary garnet and clinopyroxene in intensively metasomatized and partially melted xenoliths only the fresh relicts of these minerals were chosen.

Salient features of the results of LAM analyses can be summarized as follows:

- Chondrite-normalized REE pattern of garnets usually shows a convex shapes and varies from slightly to strongly enriched in LREE (Fig. 6), whereas clinopyroxenes have characteristically high LREE abundance and show broad variations in MREE (Fig. 7).
- On the basis of the REE distribution three different types of garnets are distinguished in the studied eclogite xenoliths: (1) a “normal” group having upwardly convex pattern with initial steep progressive increase in LREE followed by a slower rate of increase in HREE, (2) a “HREE depleted” group in which the HREE showed no marked increase from Dy to Yb, and (3) an “Eu-anomalous group” in which there is a small positive Eu anomaly and a generally flat HREE pattern (Spetsius et al., 1998).
- The trace element content of most of the group 1 garnets are similar, excluding garnetite sample

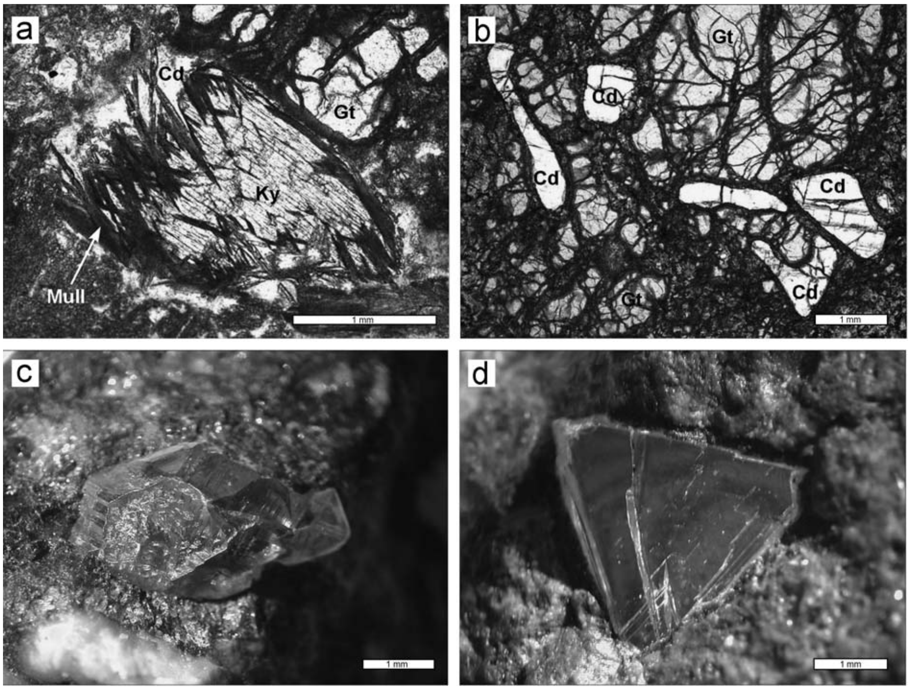

Fig. 5. Diamondiferous corundum-bearing eclogite xenoliths from the Udachnaya kimberlite pipe. (a,b) Plane-polarized light and (c,d) microphotographs. (a) Needles of secondary corundum (sapphire variety) in association with mullite replacing kyanite (sample U-820). (b) Corundum of ruby variety in diamondiferous garnetite (sample Ud-114). (c) Intergrowth of two octahedral diamonds in corundum-bearing eclogite. Resorption texture on the bigger crystal is obvious (sample Ud-155). (d) Plane-faced octahedron in corundum-bearing garnetite (sample Ud-114).

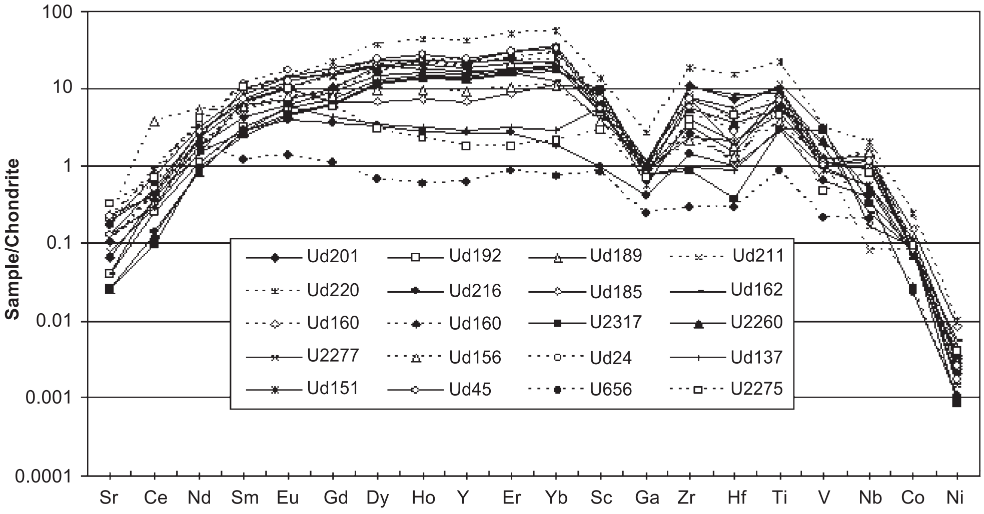

Fig. 6. Chondrite-normalized REE diagram for garnets of eclogites from the Udachnaya kimberlite pipe (Spetsius et al., 1998; unpublished data, ICP-MS, National University of Australia). Data normalized against chondrite values of McDonough and Sun (1995).

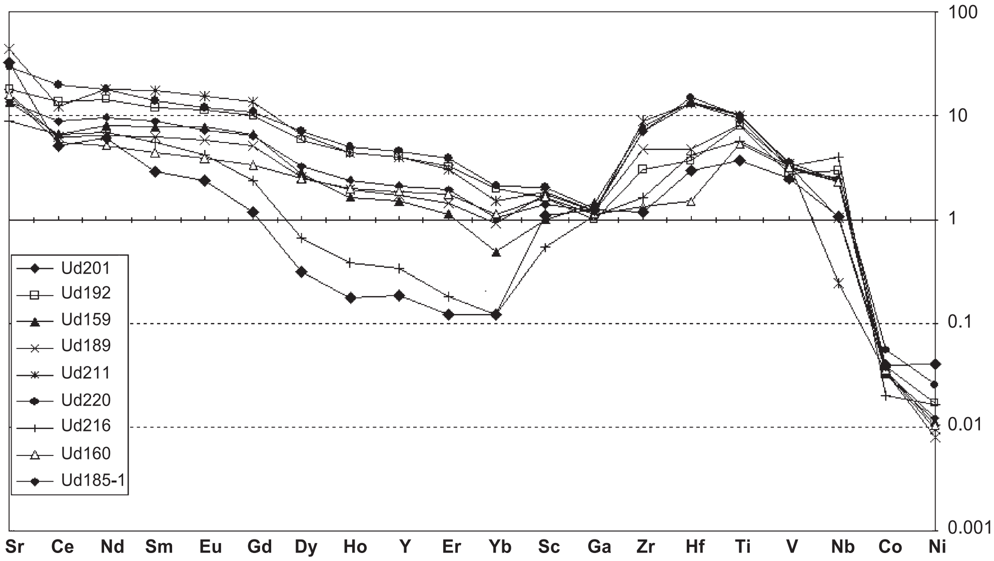

Fig. 7. Chondrite-normalized REE diagram for clinopyroxenes of eclogites from the Udachnaya kimberlite pipe (Spetsius et al., 1998; unpublished data, ICP-MS, National University of Australia). Data normalized against chondrite values of McDonough and Sun (1995).

(Ud-220) where this mineral is very rich in Sc, Ga, Yt, Nb, Zr, Ce, Gd, Dy, Ho, Er, Yb, Lu and Hf (Fig. 6).

- Wide variations in REE and also in Sr are observed for clinopyroxenes (Fig. 7); the most suitable explanation for this enrichment is partial melting connected with metasomatism. Clinopyroxene Ud-2260 has especially high Y, Sm, Dy, Ho, Er and Yb.
- The highly aluminous xenoliths have slightly positive Eu-anomalies and low HFSE abundances that give some evidence for crustal protoliths, in accordance with the findings of Jacob and Foley (1999).
- Primary clinopyroxenes of most samples are enriched in LREE suggesting widespread cryptic metasomatism in many eclogite xenoliths from Udachnaya, this confirms the results of petrographic observation (Spetsius, 1995).

It should be pointed out that the substitution of Sr, Ba and such incompatible elements as V, Zr, Ni, and others into garnet and clinopyroxene is not controlled essentially by T and P or bulk composition of minerals (Spetsius et al., 1998). These observations indicate that part of the trace elements has independent behavior and support the suggestion (Ireland et al., 1994) that enrichment or depletion of eclogite xenolith rock-forming minerals from Udachnaya pipe in some trace elements is due to complicated metasomatic and partial melting events. The REE abundance in coexisting garnets and clinopyroxenes and Cpx/Gt partition coefficients for some trace elements in eclogite xenoliths from Udachnaya (Spetsius et al., 1998) are similar to those found by O'Reilly and Griffin (1995) for eclogites from South Africa, but these occurrences differ in Sr, Zr and Ni suggesting some distinct differences in the evolution of the mantle eclogites of the Siberian and South African cratons.

4. Discussion

Highly aluminous xenoliths are common amongst the eclogite xenolith suite from many pipes of the Yakutian province, especially in kimberlites of the Daldyn–Alakitsky region. By their petro- and geochemistry these rocks belong to the group C eclogites of Coleman et al. (1965). Aside from the presence of coesite or corundum, there are no apparent differences in texture of xenoliths and major chemistry of garnets and clinopyroxenes. In addition, most xenoliths of this suite contain kyanite. Coesite is present in silica oversaturated- and corundum in silica undersaturated bulk-composition rocks. The presence of coesite implies that the eclogites from kimberlites must have been subducted to a depth of greater than 100 km, at pressures in excess of 3 GPa (Spetsius and Serenko, 1990 and references therein). Highly aluminous xenoliths including kyanite-, corundum- and coesite-bearing eclogites, grospydites and alkremites constitute a minor portion of the mantle-derived xenoliths and are predominantly of the eclogite suite. The mineralogy of these rocks and isotopic compositions of minerals suggest that they could represent subducted oceanic lithosphere (Ireland et al., 1994).

It should be pointed out that only rare estimations for oxygen isotope composition of garnet from these rocks have been made but values of the $\delta^{18}O$ are in the range 4.5–7.0‰ (Spetsius and Taylor, 2003). These data are in accordance with the oxygen isotope estimation for garnets of coesite eclogites from Roberts Victor (Schulze et al., 2000) and provide strong evidence for their possible origin as the products of oceanic crust subduction.

It is possible to use well-documented representatives of mantle (xenoliths and diamonds) to estimate the distribution of subducted crustal remnants in the upper mantle underlying the Siberian platform. The populations of mantle xenoliths from the main well-investigated kimberlite pipes of the Yakutian province are well known, and there are published data and estimations of the distribution of light C isotope diamonds in populations from different kimberlite pipes (e.g., Bulanova et al., 2002; Galimov, 1991). The carbon isotopic ratios of diamonds from the Yakutian kimberlites have shown that many diamonds have $\delta^{13}C$ distinct from the typical mantle values (e.g., Bulanova et al., 1999; Galimov, 1991). The reasonable explanation for the high $\delta^{13}C$ is a contribution from subducted oceanic crust. These results show that in many pipes kyanite eclogites or isotopically light diamonds are present, or both. This is confirmed first of all for the kimberlites of central Daldyn–Alakitsky region. The presence and preservation of coesite in eclogites and diamonds (Sobolev et al., 1998) give strong proof of the involvement of subducted oceanic crust in the formation of the sub-continental lithospheric mantle (SCLM).

The study of xenoliths in kimberlite from pipes of the Yakutian province indicates an obvious difference in their distribution in separate pipes and fields (Spetsius, 1995). Comparison of eclogite suite xenoliths on the profile from the south to the north of the province shows that there is a lateral mantle heterogeneity over a distance of about 1000 km. It is expressed by the presence of a suite of the highly aluminous rocks in kimberlite pipes of the Daldyn–Alakitsky field in the central part of the province. Such xenoliths were found in Udachnaya, Zagadochnaya, Zarnitsa and other pipes. It should be noted that these mantle xenoliths are found and coupled with some crustal granulite xenoliths such as eclogite-like rocks sometimes containing kyanite.

Eclogitic mantle xenoliths occur in all kimberlite provinces worldwide and various origins have been postulated for them. Two contrasting petrogeneses are in favour: either mantle eclogites represent (1) high-pressure magmatic cumulates which occur as magma chambers or dykes within the Upper Mantle (Dawson and Carswell, 1990; Smyth et al., 1989; Snyder et al., 1993) or (2) recycled and metamorphosed Archaean oceanic crust (Ireland et al., 1994; Jacob et al., 1994; Jacob and Foley, 1999; Barth et al., 2001, 2002). There exists mineralogical and isotopic evidence that mantle eclogites may have multiple origins and both types may occur even within one kimberlite pipe (e.g., Taylor and Neal, 1989; Snyder et al., 1997). The petrology of these rocks has been properly characterised but the origin of eclogite xenoliths is still a matter of debate. At the same time it should be pointed out that eclogites and especially xenoliths with such rare and unique minerals as coesite and corundum may provide valuable information about asthenosphere–lithosphere interaction and the conditions of the SCLM formation and diamond origin.

It is possible that some eclogites are the products of subducted oceanic crust. This is confirmed for the coesite-bearing and diamondiferous eclogites from kimberlites of Yakutia, as well as from other kimberlite provinces (e.g., Jacob et al., 1994; Barth et al., 2002; Spetsius and Taylor, 2003). According to the distribution of different types of eclogites, and the presence of isotopically light as well as cubic crystals of diamonds in kimberlites of the Yakutian province, it is possible to estimate the amount of crustal sources added to the mantle under Siberian platform. In the central part of the Siberian platform the remnants of subducted crust could be about 5–10% of the total upper mantle. If we assume that all isotopic light diamonds were crystallized in remnants of subducted crust we could use this for the estimation of the contribution of subducted oceanic crust in the formation of the cratonic roots under the Siberian platform. According to these data about 10% of the diamond population from kimberlites of Yakutia originated in subducted rocks.

There exist two possible ways for highly aluminous eclogites to form: (i) as a result of transformation of initial rocks of gabbro-anorthosite composition through the intermediate stage of eclogite-like rocks during the process of subduction or delamination; (ii) as a result of fractional crystallization of ultramafic melts under mantle conditions. The first alternative is suggested by petrographic, petrochemical and isotopic investigations that show a genetic relationship of all the series of these rocks (Spetsius and Serenko, 1990). The second alternative is proved by the presence of subsolidus changes in eclogites and by continuous sets of highly aluminous xenoliths from kyanite eclogites up to alkremites and by linear differentiation trends of their compositions (Exley et al., 1983; Spetsius, 1995). The possibility of forming some eclogites via subduction and subsequent metamorphism of oceanic crust, as is proved by simplified isotopic composition of diamonds in different eclogites, is not excluded. Such diversity of origin and also the subsequent evolution of eclogites during the process of partial melting and mantle metasomatism have been considered in a number of papers (Spetsius and Serenko, 1990; Snyder et al., 1993, 1997; Ireland et al., 1994; Pearson et al., 1995; Spetsius and Taylor, 2002 and references therein), and, in turn, determine the specific nature of these rocks in separate pipes.

Based on highly enriched Sr isotope composition ($^{87}Sr/^{86}Sr>0.8$), a crustal origin was proposed for alkremites and it was suggested that these rocks could represent the restites from subducted, melted pelitic sediments (Mazzone and Haggerty, 1989). Preliminary data on trace element content in garnet and high Lu/Hf ratio do not support this model (Nowell et al., 2003). It is more likely that these rocks were formed as a result of fractionation by melting of lithosphere as suggested first by Ponomarenko et al. (1977). In my opinion, at least some alkremites are formed as a result of fractional crystallization of ultramafic melts enriched in Al and Mg and probably these unique rocks could represent a residual melt after separation firstly of some kyanite eclogites.

5. Conclusions

Highly aluminous mantle xenoliths found in kimberlite, including kyanite and coesite eclogites and alkremites, comprise a specific rock group. The wide abundance of these types of xenoliths in the central region of the Yakutian Kimberlite province suggests a lateral petrographic heterogeneity of the SCLM under Siberian craton. The confinement of cubic diamonds to highly aluminous rocks is also matched by the lateral heterogeneity in the morphology of the diamond populations from the south to the north of the province. Two possible ways of formation of highly aluminous rocks could be proposed.

The correlation between the oxygen isotopes of eclogite minerals and carbon isotopes of diamonds gives strong support for subduction of oceanic crust having a role in the formation of the mantle root beneath the Yakutian Kimberlite Province within the Siberian platform, especially its central part. The presence of Ky- and Cs-bearing eclogites in kimberlite as well as light isotopic diamonds and cubic crystals in the diamond populations could be used for the estimation of the intensity of the subduction process at the time of the SCLM formation beneath any given kimberlite pipe or field.

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