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PROPERTIES OF DIAMONDS IN XENOLITHS FROM KIMBERLITES OF YAKUTIA: IMPLICATION TO THEIR ORIGIN AND EXPLORATION

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Introduction

More than 400 diamondiferous xenoliths have been discovered in the kimberlite pipes of Yakutia. Diamond-bearing specimens are encountered among ultramafic xenoliths predominantly dunite-harzburgites and in all types of eclogitic rocks: bimineralic, kyanite and corundum eclogites and also in garnet-websterites (Spetsius, 1995). At that moment such samples have been found in 10 pipes of the Yakutian kimberlite province.
The diamonds in xenoliths are found mainly as separate crystals but in some xenoliths the amount of diamonds may be as high as 1000 (Ponomarenko et al., 1980). The distribution of crystals in the specimens is irregular and does not coincide with the specimen surfaces. The sizes of the crystals vary from fraction of millimeter to 10 millimeters. Mineral inclusions are rare in the xenolith diamonds. The main purpose of this investigation was to determine some physical properties of diamonds first of all variations of contents and aggregation state of nitrogen in crystals of different paragenesis.

Samples and Analytical techniques

Major element compositions of garnets and clinopyroxenes in the xenoliths were determined with a Superprobe JXA-8800R electron microprobe at the "ALROSA" open joint-stock Company (Mirny, Yakutia). Natural minerals and synthetic were used as standards. Analytical conditions included an accelerating voltage of 15 keV, a beam current of 20 nA, beam size of 5 µm, and 20 seconds counting time for all elements. All analyses underwent a full ZAF correction.
The trace elements have been measured by laser Ablation ICP-MS (LAM) at the Macquarie University, with NIST 610 glass as external standard and Ca as internal standard; pit diameters were 40 –50 mm.
It was studied the morphology and content of visible inclusions of 1200 crystals different in size from the new parcel of 30 diamondiferous eclogite xenoliths from the Udachnaya pipe. 630 diamonds from this new set of diamondiferous eclogites and 95 crystals from garnet pyroxenite from the Udachnaya pipe and about 200 crystals from peridotite and eclogite xenoliths of the Mir and Nyurbinskaya pipes were analyzed by micro-Fourier transform infrared (FTIR) spectroscopy to determine both nitrogen content (N_{FTIR}) and nitrogen aggregation state. IR spectra were obtained over the range of 370-4200 cm^{-1} with the use of Vertex 70 FTIR spectrometer and Hyperion 2000 microscope. The spectra resolution was 2 cm^{-1}; the number of scans - 256. Errors in nitrogen content (N_{FTIR}) and nitrogen aggregation state are estimated to be better than 20% and 5% respectively.

Results

Investigations of 30 xenoliths with diamonds from the Udachnaya pipe allowed to confirm mineralogy of these unique rocks and received new results on properties of diamonds. First off all we should point that total weight of xenoliths has constituted 1.178740 kg and total weight of recovered diamonds – 49.95 ct that allowed to estimate the diamond grade of xenoliths as 42 376 ct/t.
Most of samples are rounded coarse-grained rocks with rather wide variations of garnet and clinopyroxene content (Fig. 1). Intensive partial melting is characteristic feature for most of the specimens. To some extent this is a specific sign of diamondiferous eclogites as was shown by Spetsius and Taylor (2002).
The amount of diamonds in separate samples varies from 1 to 260 crystals with the predominating of small crystals (<1.0 mm). Octahedron crystals strongly predominate among diamonds of this parcel. In proposed topic will be summarized data on diamondiferous xenoliths predominantly from the Udachnaya, partly Nyurbinskaya and other pipes of Yakutia. These results comprise in the whole about 300 samples and include data on major and trace element chemistry of xenolith minerals with attention to the morphology and distribution of diamonds in separate xenoliths.

A)

B)

Fig.1. Examples of diamondiferous xenoliths from the Udachnaya pipe. A) - sample UE-02 with the step-faced octahedron crystal and B) - sample UE-28 containing octahedron with 2 inclusions of sulfides. Size of diamond is 4 and 5 mm respectively.

Garnets from eclogitic xenoliths have a wide variation in Fe-, Mg- and Ca-content (Fig. 2). They contain over 40 mol. % of pyrope, 10-20 mol. % of almandine and variable (20-40 mol. %) of grossular components. Garnets are relatively low in Cr_2O_3 (containing < 0.2 wt. %). 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 Taylor, 2008). It should be pointed that garnets from the most of studied samples belong to B-group eclogites and only garnets from two corundum eclogites have occupied the field of C-group eclogites, according (Taylor and Neal, 1989). Garnets of three eclogites with corundum differ by higher Ca# (up to 17.2 wt. % CaO content) from the garnets of bimineral eclogites and they have high Mg#. There are relatively low TiO_2 (< 0.6 wt. %) and high Na_2O contents (0.08-0.2 wt. %) in all eclogitic garnets (Fig. 2).

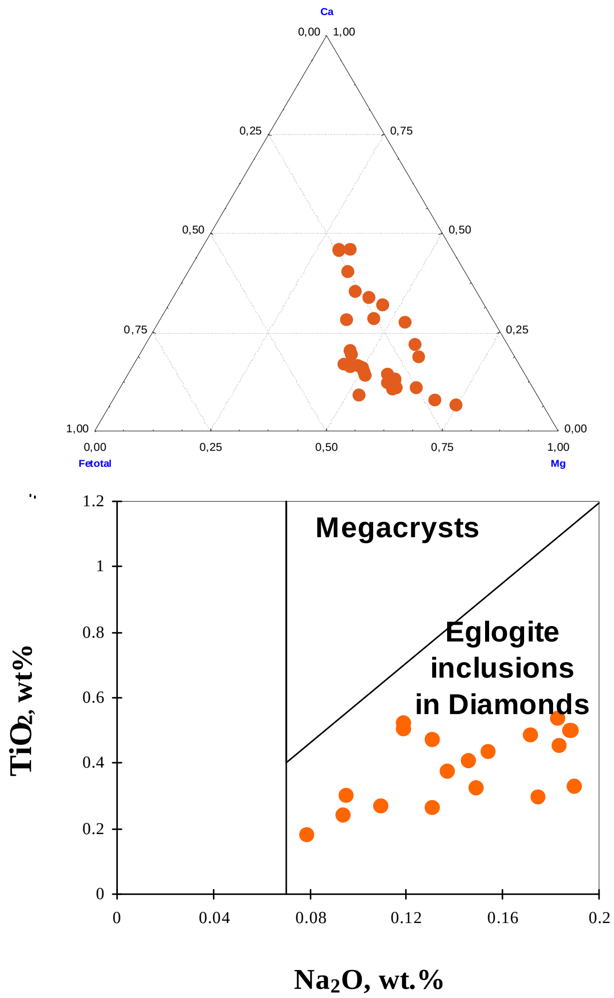

Fig.2. Garnets compositions of diamondiferous eclogite xenoliths from the Udachnaya pipe.

Clinopyroxene in eclogites is characterized by high Mg#, high-Al content and is typical omphacite (Fig. 3). Clear correlation of jadeite content in omphacites of eclogites exists with their Al_2O_3 and CaO-content, and therewith this relationship is maintained in eclogite clinopyroxenes from all the pipes (Spetsius, 2004). Most omphacites have low Fe (< 6 wt. % FeO) and Ti (< 0.5 wt. % TiO_2) contents but clinopyroxenes of eclogite UG-34 differ by high titanium content (0.63 wt. % TiO_2).

The rare earths elements (REE) and other trace elements have been obtained for the garnets and clinopyroxene of all samples. About 80% of analyses on trace elements garnets and some clinopyroxenes from investigated samples show positive or rarer negative Eu-anomalies that confirm of possible formation of eclogitic xenoliths trough the recycling of the crust (Spetsius et al., 2009).

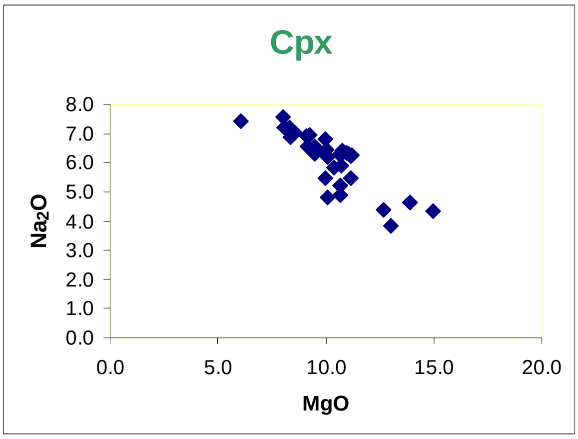

Fig. 3. Clinopyroxenes compositions of diamondiferous eclogite xenoliths from the Udachnaya pipe.

Special attention will be given to variation of physical properties of diamonds that were measured for 1200 crystals recovered from the new parcel of 30 diamondiferous xenoliths from the Udachnaya pipe. These properties include total content of nitrogen, co-variations in B1 and B2 defects and hydrogen. It should be pointed that there exist a rather strong correlation between morphology and some physical properties of diamonds. Diamonds from xenoliths have wide variations in total nitrogen: eclogitic 15 – 1500, pyroxenitic 170 – 1250 and peridotitic 240 – 650 ppm that are correlated with the morphology of crystals. Diamonds from individual xenoliths are similar by the luminescence spectra, absorption in visible area, IR range, external and internal morphology except rare cases of the presence crystals of two generations. The diamonds from xenoliths are correlated with the diamonds from kimberlites by their morphology and physical properties as well.

The main part of investigated crystal from xenoliths of the Udachnaya pipe contains the concentrations of the nitrogen from 300 to 700 ppm (at the average 536 ppm) (Fig. 4). In the whole only two diamonds were discovered with the concentration of the nitrogen less than 25 ppm (nitrogen-free). It should be stressed that for diamonds from kimberlites of the Udachnaya pipe is characteristic of the lowered content nitrogen admixture (< 300 ppm, Fig. 5). Among studied crystals sharply dominate the individuals with the percent content of nitrogen admixture in B-form 25-65 % (Fig. 4), and averaged for diamond samples of this parcel - 43 %. The absorption factors of B2-centre within the range of 1357-1385 cm^{-1} is basically < 25 cm^{-1}, but at the average 7, 6 cm^{-1}. The positions of the bands of these platelets in IK-spectrum correlate with the content of the general nitrogen in diamond. It is noted also straight line dependency of the intensity of the bands B2-centres from the concentration of B1-centres that is coincident with the stated earlier suggestion about joint formation of these optical defects. The absorption factors narrow line on 3107 cm^{-1} seldom exceed 7 cm^{-1} (at the average 1,5 cm^{-1}), but sometimes there are meet the individuals with the more than 10 cm^{-1} that allows to expect comparatively low contents of hydrogen admixture. This circumstance testifies to crystallization of diamonds in the enough poor ambiences on hydrogen.

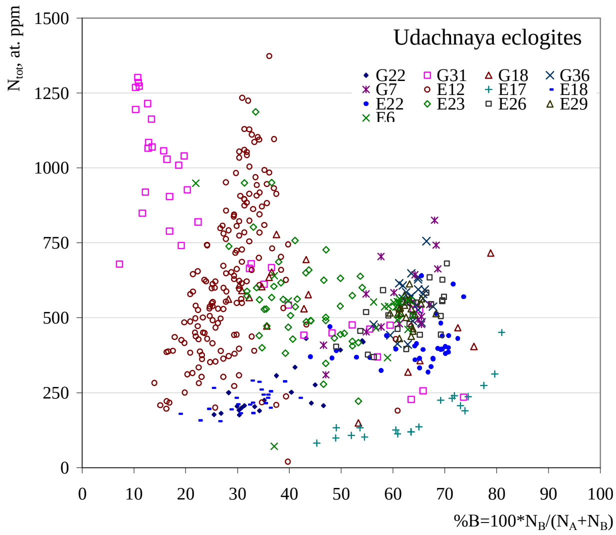

Fig. 4. Distribution of diamonds from xenoliths of the Udachnaya pipe by content of total nitrogen and proportion of aggregation.

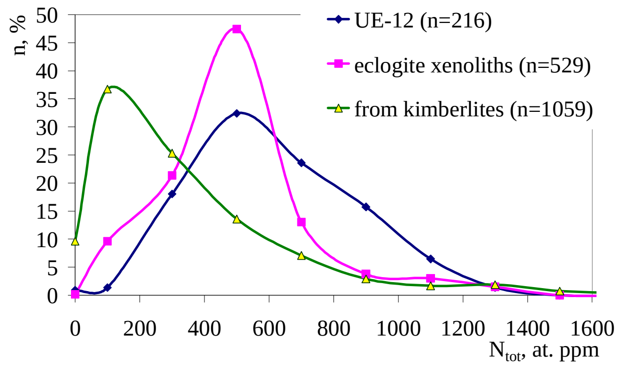

Fig. 5. Distribution of diamonds by content of total nitrogen from xenoliths and from the concentrate of the Udachnaya pipe.

Special remarks will be given to the evidence for the presence of two generations of diamonds in one given xenolith and possible metasomatic origin of diamonds in some xenoliths. Usually diamonds from individual xenoliths are similar by the content of total nitrogen and nitrogen admixture in B-form. Crystals with a strong difference in proportion of nitrogen aggregation were established only in one sample from the parcel of 30 xenoliths (Table 1).

Table-1 Content of total nitrogen and its aggregation in diamonds from eclogite UG-31

Sample 1st gen.	N FTIR (ppm)	N_B (%)	Sample 2nd gen.	N FTIR (ppm)	N_B (%)
147	522	58.1	145	1382	8.4
148	685	41.0	146	681	17.7
151	485	44.3	149	935	14.0
168	488	53.0	150	857	16.2
165	557	61.4	156	1111	14.0
154	682	36.7	157	1418	11.1
155	464	47.2	158	1177	12.7
162	615	36.3	159	1223	10.0
163	478	54.2	160	1359	8.8

Diamonds with high proportion of aggregation (>35%) are presented by fine stepped octahedron crystals that have sometimes slightly rose color and size > 1mm (Fig. 5a). Most of such crystals are containing tine inclusions of sulfides. It should be pointed that these crystals could be combine in the first generation of diamonds in this xenolith that probably were grown close with the time of formation of primary rockforming minerals garnet and clinopyroxene.
The diamonds with low aggregation state of the proportion of aggregation (<18%) are presented by plane octahedron crystals that are colorless and have smaller size <1mm (Fig. 5a). In most cases it is obvious that these crystals are distributed along the boundary of rockforming minerals or in veins filled by secondary phases of partial meting products that are wide spread in eclogite xenoliths from the Udachnaya pipe (Spetsius and Taylor, 2002). It should be pointed that these crystals could be combining in the second generation of diamonds in this xenolith that probably were grown close with the time of kimberlite formation and are connected with the metasomatic fluids.

Discussion

Careful examination of more than 500 diamonds from about 100 xenoliths from the Udachnaya pipe shows that 30% of diamonds (size > 1 mm) contain some visible inclusions. In most cases these are a little tiny opaque grain. Microprobe data suggest that overwhelming majority of them are sulfides. Silicate inclusions of garnet, clinopyroxene and very seldom rutile or others are rare. The diamonds in some specimens have sulfide rims around them. A number of facts show that in the process of diamonds growth the sulfide melt was present together with the silicate melt. The mechanism of diamonds growth should be discussed in a complex sulfide-silicate system enriched in fluids.

a)

b)

Fig. 5. Diamonds of first (a) and second (b) generation in eclogite xenolith, sample UG-31. Size of diamonds is 2.0 and 0.5 mm, respectively.

Thereby, in the course of optical-spectroscopic studies it is installed that diamonds from eclogites of the Udachnaya pipe are in the main middle- and high-nitrogen and contain the concentrations of the nitrogen from 300 to 700 ppm. Such contents of the nitrogen are typical for the diamonds of high grade pipes of the central part of Yakutian kimberlite province. It is installed the fact of the existence as minimum of two generations of diamonds in one given xenoliths that have crystals which are differ not only by their size and morphology but also by the content and aggregation state of nitrogen. These results confirm the possibility of the existence of two stages of diamonds formation that probably are different in composition of diamonds forming fluid and in time of their formation as was proposed by (Spetsius, 1999; Spetsius and Taylor, 2008; Spetsius et al., 2009; Thomassot et al., 2008).

As a result called on studies is installed that diamonds from xenoliths of the Udachnaya pipe have different composition on contents of the structured nitrogen. Given difference exists for diamonds from one xenolith so and for crystals from different eclogite samples. It is installed that in the eclogite xenolith G-31 are present two groups of diamonds, belonging to different temporary stages of diamond formation. The group of diamonds with high degree of the aggregations (more than 30%) possible refers to more early generation. The given crystals have a zonal distribution of luminescence centers, this is indicative that these diamonds are formed as minimum in two stages of formation. The second diamonds generation has followed rather later after the first and has touched partly already existing for that moment crystals. This stage corresponds to the crystals with high contents of nitrogen admixture in A-form (more than 800 at ppm), under low degree of the aggregations of the nitrogen (B% - less 30%). Most probable that diamonds of second generation may have grown as a result of the metasomatic fluid penetrations close in time with the kimberlite eruption.

Besides, it was established an obvious difference in nitrogen content in aggregation state between diamonds from different pipes and between crystals from eclogite and peridotite xenoliths (Fig. 6). These features of nitrogen in diamonds of eclogitic and peridotitic paragenesis should be checked on more samples but such a tendency is fixed.

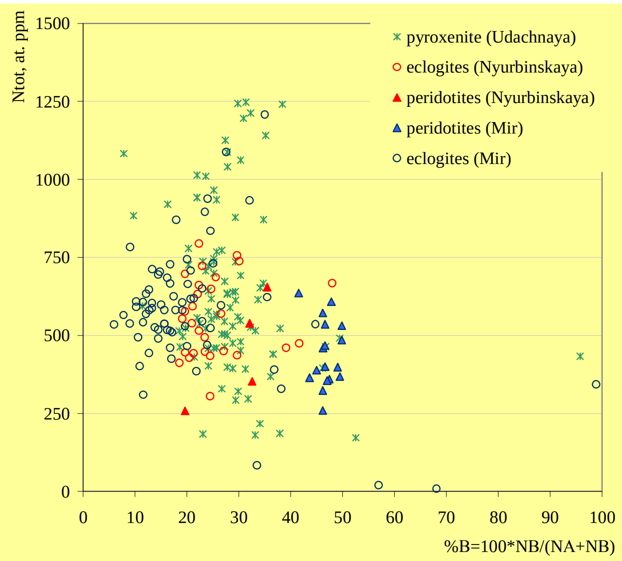

Fig. 6 Distribution of diamonds from xenoliths of different pipes of Yakutian province by the content of total nitrogen and proportion of aggregation.

We should stress that it was established an obvious difference in total nitrogen and its aggregation in eclogitic diamonds from

Conclusion

A detailed study of morphology and physical properties of diamonds in diamondiferous xenoliths from the Udachnaya, Mir and Nyurbinskaya pipes and previous results show several extreme features:
a) exceptionally high diamonds grade in individual samples, b) a possible predominance of diamonds with eclogitic paragenesis in some pipes, c) evidence for the metasomatic diamond growth, d) presence of two generations of diamonds in some xenoliths that are differ in the morphology of crystals, both nitrogen content (N_{FTIR}) and nitrogen aggregation state, e) the specificity of distribution of nitrogen content (N_{FTIR}) and nitrogen aggregation state in eclogite and peridotite xenoliths.

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