Main Features of Yakutites from the Ebelyakh Placer

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Abstract. Yakutites (polycrystalline diamonds with lonsdaleite admixture) from the Ebelyakh placer (Yakutia, Russia) have been studied by optical microscopy, Raman spectroscopy, and neutron diffraction in order to reveal their difference from tagamite-hosted diamonds of the Popigai impact crater. The yakutite aggregates are 2.0 mm to 13.0 mm in size and have a shapeless morphology or sometimes preserve hexagonal contours of primary graphite. Raman spectra are characterized by a broadened line in the region of cubic 3C diamond, which is interpreted as the sum of spectra from cubic 3C diamond and three peaks related to Lonsdaleite: 1338 (E1g), 1280 (A1g) and 1224 (E2g). On the surface of yakutites revealed the presence of a silicate glass film. The main elements are iron, silicon from the surrounding silicate matter. Neutron stress diffractometry showed the content of diamond and Lonsdaleite in the sample of yakutite by 50%, two cases of preferential orientation of two phases were recorded: (110) diamond // (110) Lonsdaleite; (111) diamond // (001) Lonsdaleite. Both yakutites and tagamite-hosted diamonds are of impact origin and share similarity in the phase composition consisting of more abundant diamond and subordinate amounts of lonsdaleite. Differences between them depend on the place of their formation. Yakutites were formed in the epicenter of the explosion and were thrown out of the crater at a distance of more than 550 km in radial directions, and from the vertical ejection - they got back to the crater. In tagamites, impact diamonds were formed simultaneously with the rock melting due to the shock wave that came from the epicenter. The presence of a silicate glass film on the surface of yakutites indicates that they were hardened after ejection from the crater. Yakutites represent distinct mineral fraction outside the crater. They are found as placers along with common diamonds and other detritus. Within the crater they are genetically related to suevites – tuffaceous component of the impactites and enter the crater placers due to the physical weathering of suevites. Tagamite diamonds practically do not occur in the crater placers, because tagamite is a very hard rock and in the absence of chemical weathering these diamonds can't be released. Thus, diamonds from tagamites and yakutites, having a common impact nature, differ in some properties determined by the place of formation and post-impact history.

1. Introduction

Yakutites (polycrystalline diamonds with lonsdaleite admixture) are found in the vast territory of the North-East of the Siberian platform – in the East and South from the Popigai impact crater. The farthest dispersed findings of yakutites occur 550 km away from the crater or even more (the Kelimyar River
basin, the Olenek Uplift) [1, 2, 3]. The content of yakutites in placers can be up to 1 carat/m³. The study of yakutites and their subsequent comparison with impact diamonds from tagamite provides important material for understanding the impact diamond formation in the Popigai Crater and opens up new technological opportunities for the impact diamonds use. In this work we present the results of the study of yakutites from the Ebelyakh placer.

2. Materials
Yakutites have a shapeless morphology or sometimes preserve hexagonal contours of primary graphite (figure 1) [4]. The yakutite aggregates are 2–13 mm in size and weight of 0.1 to 4.0 carats.

![Figure 1. The surface morphology of yakutite – hexagonal contours of primary graphite.](image)

Yakutites from the Ebelyakh placer were divided into four main morphological types: massive-granular, tabular, parallel-columnar and tangled-fibrous (figure 2, A–F) [5]. In fact, these morphological types of polycrystalline diamonds are distinguishable only in appearance, and reflect the original morphology of graphite segregations in Archean gneisses. In a detailed study of surface micromorphology by electron microscopy, a number of common features were observed. One of them is the presence of interstitial voids of submicron size, between the boundaries of the grain subindividuals. As a rule, numerous voids are oriented in one direction. Subindividsusually have a lamellar appearance in tabular and fibrous appearance in parallel-columnar yakutites. The fibrous microfibrillar structure of tangled-fibrous samples is clearly traced on fresh chips and in natural voids by electron microscopy. Diamond microfibers and microplates are characteristic for all morphological types [5].

The color of Yakutites is brown with shades of red, rarely dark gray to black. We need to consider that on the surface of the grains can develop crust clay sedimentological products changing their real color. Photoluminescence of yakutites is weak in brick-red or orange tones, or absent. Due to morphological features (unlike conventional diamonds) and very weak luminescence, their diagnostic and extraction from alluvial material are very difficult, so in many cases they are simply missed.

3. Methods
A comprehensive study of the Yakutites from the Ebelyakh placer was carried out by Scanning Electron Microscopy, Raman Spectroscopy, and Neutron Diffraction.

Raman spectra were obtained by excitation of 325 nm (He-Cd laser) on confocal micro-Raman spectrometer LABRAM with OXFORD cryostat at 80 K (resolution 0.1 nm), measurements were made at 5–6 points for each.

Study of texture, determination of structural orientations of the diamond and lonsdaleite was performed on the diffractometer KOWARI, the Bragg Institute of ANSTO (Australian Nuclear Science & Technology Organisation) (Sydney, Australia, analysts Piazolo S., V. Luzin).
The film composition of several samples was studied on a scanning electron microscope with EMF chemical analysis system MIRA3LMU.

Figure 2. Morphology of yakutites from The Ebelaykh placer: massive - A, B; table - C, D; parallel-columnar - E; tangled-fibrous - F.

4. Results and Discussion
A typical Raman spectrum is shown in figure 3. There is a main line of 1332 cm\(^{-1}\), which is characteristic for the cubic 3C diamond. The line is considerably wide: its width at the level of half-height (FWHM) is 25 cm\(^{-1}\). FWHM is about 1–2 cm\(^{-1}\) for monocrystalline diamond from kimberlite.
This indicates strong deformations in the structure of studied yakutites. The values FWHM of some samples are up to 70 or even 90 cm\(^{-1}\). For two samples, the maximum of the main line is shifted to 1330 cm\(^{-1}\) and further to 1325 cm\(^{-1}\). The observed spectrum is interpreted as the sum of the spectrum from 3C cubic diamond and three peaks related to lonsdaleite: 1338 (E\(_{1g}\)), 1280 (A\(_{1g}\)) and 1224 (E\(_{2g}\)) [6, 7]. The shift of the line to the low-energy side, the broadening and weakening of the peak are typical for the cases of carbon sp\(^3\) structure, where the disordering is caused by nanosized structural units. Low-energy band 335–340 cm\(^{-1}\) binds to additional carbon (?) phases. A broad band in the region 2200–2450 cm\(^{-1}\) is interpreted as range of the second order for diamond and lonsdaleite.

![Raman Spectrum](image)

**Figure 3.** Typical Raman spectrum of yakutites

Neutron diffraction showed the content of diamond and lonsdale by 50\% in the sample of yakutite. Two cases of preferential orientation of diamond and lonsdaleite were recorded this method: (110)\(_{\text{diamond}}\) // (110)\(_{\text{lonsdaleite}}\); (111)\(_{\text{diamond}}\) // (001)\(_{\text{lonsdaleite}}\) (figure 4).

The composition of the silicate glass films, which are present on the surface of yakutites is studied by scanning electron microscopy (figure 5). It should be noted that the composition were studied from the natural surface of the samples. The sum of elements is very different due to the fact that the sample fragments are inclined differently with respect to the detector. Therefore, the obtained data give only a general idea of films composition. The main elements of film are iron, silicon from the surrounding silicate matter.

The obtained data show that yakutites consist of cubic (diamond) and hexagonal (lonsdaleite) phase of carbon with subordinate amounts of the second. It is the main criterion for their similarities with impact diamonds [6, 8-12]. The internal structure is similar: both are polycrystalline aggregates with nanosized grains [8, 9, etc.]. Yakutites and impact diamonds are paramorphs on graphite of target rocks of the Archean gneisses. Evidence of similarity of yakutites and impact of diamonds determine their genetic relationship and the relationship of yakutites with the Popigai astrobleme [13].
Difficulties of yakutites and impact of diamonds are determined by their formation place within the Popigai crater. Yakutites were formed in the epicenter of the explosion upon impact of the cosmic body and was immediately thrown out of the crater along with the melted material of the target species and their fragments. With the similarity of the phase composition of yakutites and impact diamonds, there are differences. Among the tagamite-hosted diamonds there are two varieties – light with a sharp predominance of the cubic phase and dark, where along with the cubic there is a hexagonal phase and graphite. Graphite is marked by Raman spectroscopy in yakutites, but x-ray studies do not detect it, apparently because of the extremely low content. In our opinion, it is due to the fact that yakutites were formed in the explosion epicenter at the maximum dynamic parameters, resulting in virtually all of the graphite moved to the high-pressure phase, whereas tagamite-hosted diamonds were formed at lower settings and are quite a lot of graphite. The nature of the phase composition of yakutites rejects the hypothesis that at the time of impact, lonsdaleite is formed, which, as annealing, passes into a cubic phase [1]. Yakutites not annealed, on the contrary, they have been hardened, but they combine cubic and hexagonal phase, which indicates the simultaneity of their formation.
5. Conclusions

Yakutites, as well as tagamite-hosted diamonds have an impact nature and are paramorphs on graphite of rocks of the target – Archean gneisses, were formed by martensitic way as a result of shock metamorphism at the time of the Popigay impact event. This is determined by the genetic relationship of yakutites and impact diamonds from tagamites. However, there are differences between them, which are determined by the place of their formation. Yakutites were formed in the epicenter of the explosion and were thrown out of the crater at a distance of more than 500 km in radial directions, and from the vertical ejection returned to the crater. In tagamites, impact diamonds were formed simultaneously with the melting of the rock due to the shock wave that came from the epicenter.

Results of the study make a significant contribution to the understanding of the nature of impact diamond formation and show ways for their further research.

Acknowledgment(s)

The work was supported by grants 18-45-140011r_a, 16-05-00873a, 17-17-01154a of the Russian Foundation for Basic Researchers and was carried out as a part of state assignments of DPMGI SB RAS, IGM SB RAS.

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