The Hypothesis of Impact Origin of Diamonds and Kimberlites

Alexey M. Lyukhin

Russian state geological prospecting university, Moscow, Russian Federation

INTRODUCTION

Despite a large volume of accumulated actual material the problem of origin of kimberlites and diamonds still remains unclear. It is reflected in the existence of a number of hypotheses differently and frequently alternatively ascribing the principal aspects of processes of natural kimberlite and diamond formation. Neither has been finally resolved the mechanism of formation of pipes themselves. None of the models offered to this time can adequately explain all features of their structure. The substantiation of a cause-and-consequence link, the conditions and mechanisms of formation of diamonds and all types of diamondiferous rocks is possible in the framework of an impact process – one of the most fundamental geological processes brought about in the Solar system.

KIMBERLITES, METEORITES, IMPACTITES AND DIAMONDS

Kimberlite is a hybrid ultra-basic rock. It is characterized by inequigranular structure caused by xenolithes and megacrystals of refractory minerals (olivine, pyroxene, phlogopite, garnet, picroilmenite) included in the fine-grained groundmass of low temperature minerals (serpentine, carbonate, chlorite). Here the impregnated minerals are represented not by crystals as in conventional magmatic rocks but by rounded "porphyric" grains. And in order to smelt these very refractory minerals, needless to say of the mantle's pressure, the temperatures of more than $2000^{0}C$ are required. The study of grains' surfaces of these minerals identified a surprising feature: their surface does not practically differ from the river pebble's surface. The so-called "shagreen surface" characteristic of the grains of olivine, garnet, ilmenite, apatite as well as the xenolithes of the "mantle" rocks and representing a typical corrosive microporous new formation is of most interest. Similar phenomena appear during the corrosion of turbine blades, surfaces of meteorites and tectites, i.e. in the processing of any body by hot gas jets [27]. Native Ag, Cu, Si, Zn, Sn, Al, Au, Fe, Pb, stistaite, tenite, moissanite, cogenite, armolcolite, ringwoodite are found in kimberlites among rare minerals [9]. Higher concentrations of platinum and iridium sometimes reaching commercial values for associated production are but not rarely traced in kimberlites (0,4 – 0,5 g/t) [28].

The hybrid nature of kimberlites is expressed by the presence of "related" inclusions in them represented by ultrabasic and eclogitic groups. Their concentration in kimberlites averages about 0,5 vol. % [24]. High-pressure minerals are found in peridotites, dunites and eclogites or in the form of phenocrysts buried in a fine-grained groundmass or in the form of grains and aggregates. The combination of mineral formation processes is characteristic of the inclusions of these rocks to what the zonal crystals of garnet, biotite, olivine testify [17], moreover the crystals of olivine in diamondiferous ultrabasic inclusions are ascribed both with direct and reverse zoning (in respect of Fe/Mg) [38]. The porphyric structures and the zoning of high-pressure minerals in kimberlites and related inclusions testify to the consolidation of rocks in the conditions of fast cooling [17]. Large garnets (1-2 cm) with Cr_2O_3 content 1-2 mass % and numerous lamels of clinopyroxene (products of dissociation of solid solution) have been registered in some xenoliths from the Yagersfontein pipe's kimberlites [42]. This testifies to the formation of garnet at the pressure of 10-13 GPa what corresponds to the depth of about 400 km. The autolithic kimberlite (in lamproites similar formations are called lapillic tuffs [71]), in which the ellipsoidal or rounded bodies of kimberlite (autoliths) are found in a matrix of fragmented kimberlite and which has a shape of pseudoconglomerate where kimberlite is cemented by kimberlite, is a widely spread variety of kimberlite. Many autoliths have cores around which the accretion of fine-grained kimberlite took place. The cores represent single crystals or small xenoliths of host rocks up to 10 cm in diameter. Likewise formations could have formed only in free space.

The presence in kimberlite of silicate drop-like and dumb-bell-shaped globules (spherules) with an ideally smooth and lustrous surface testifying to their formation in free space is a very interesting phenomenon (Fig. 1,2). Their sizes fluctuate from hundredth parts to 2-3 mm. The color – pale-green, green-to-black. The globules are X-rays-amorphous. Their chemical composition is characterized by a high content of CaO and Al_2O_3. The composition of gaseous inclusions in the globules is monotonous and rather exotic: N_2 – 57,7-96,9 v.%; hydrocarbons – 20-25 v.%; H_2 – 5 v.%; CO_2 – 10 v.% [18]. Such globules are known not only in kimberlites. Si carbides, Fe, fersilicide (FeSi), native Si, Fe, Al are found in spherical exsolutions from diamondiferous tuffs of the Northern Urals. A vanadium-bearing globule of silvery-white color is also traced. Its core contains intermetalide of $V_{63}Cu_{19}Mn_{16}Fe_2$ composition, the rim is composed of vanadium carbide. The refractoriness of vanadium compounds testify to unusually high temperatures (1900^{0}-$2800^{0}C$) that could be reached at the front of a shock wave. [32]. Similar formations in the form of globules (ore-bearing and silicate) from hundredth parts to several millimeters in size are observed in loose deposits of the known impact craters [26]. They represent the products of evaporation of a meteoroid's body and a target's substance in the impact process and are characteristic of impact structures.

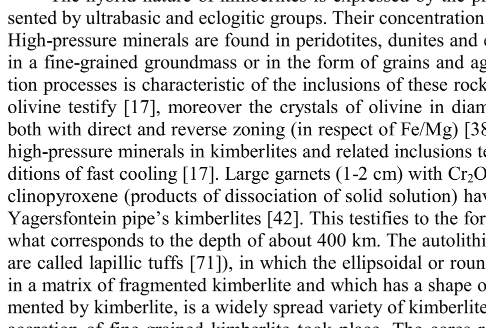

Fig. 1. Metallic spherules from the Ilnetskay astrobleme, Ukraine – the top line and kimberlites of the Udatchnaya pipe, Yakutiya – the bottom line; c,f – details of their surface. [61]

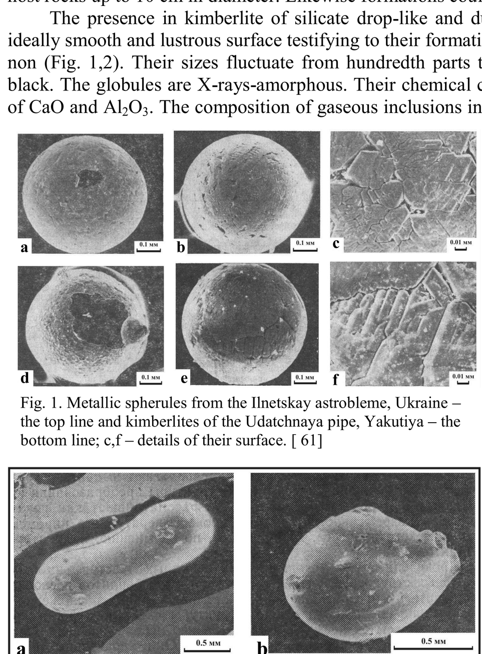

Fig. 2. Silicate spherules from the Ilnetskay astrobleme (a,b) and kimberlites of the Udatchnaya pipe (c,d). [61]

The kimberlite pipes on the surface occupy a small area – from several square meters to 1,5 square kilometers. Three heterogenous parts – crateral, diatremic and bottom are identified within the pipes. The crateral parts of the pipes represent funnels with relatively gently pitching contacts filled with disintegrated material of host rocks and kimberlites in a small amount. Their extent to depth reaches several hundreds of meters, the form is generally rounded and oval with rugged profiles. The diatremic parts of the pipes have a shape of cylinder contracted with depth. The pipes' walls are basically smooth with longitudinal gliding grooves, generally without signs of contact alterations of pipe-hosting rocks (Fig. 3). The diametric parts of the pipes generally represent several varieties (intrusion phases) of kimberlite breccias (e.g. the Dyutoitspen pipe (SAR) has 16 varieties).

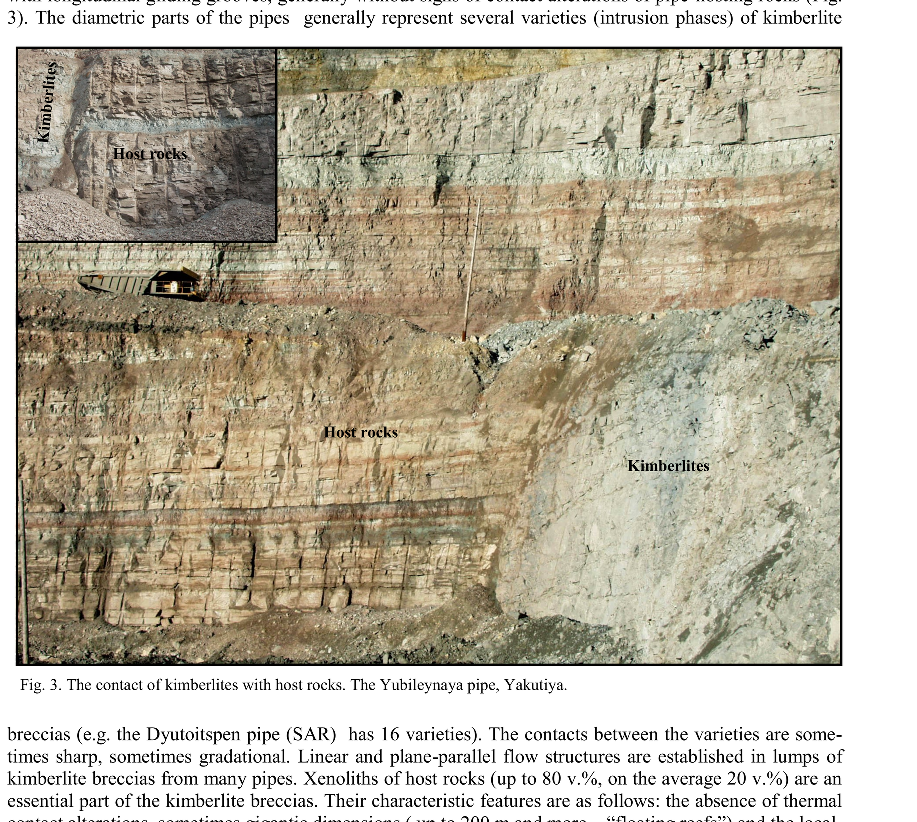

Fig. 3. The contact of kimberlites with host rocks. The Yubileynaya pipe, Yakutiya.

The contacts between the varieties are sometimes sharp, sometimes gradational. Linear and plane-parallel flow structures are established in lumps of kimberlite breccias from many pipes. Xenoliths of host rocks (up to 80 v.%, on the average 20 v.%) are an essential part of the kimberlite breccias. Their characteristic features are as follows: the absence of thermal contact alterations, sometimes gigantic dimensions (up to 200 m and more – "floating reefs") and the localization essentially below their initial occurrence. So the black schists of Dwyka are broken by a Kimberli pipe on the horizon of 15,5 m, and as part of kimberlitic breccia they are traced to a depth of 769 m from the recent surface (the Kimberli pipe changes into a dyke at a depth of 1073 m). It should be specially noted that non (!?) of the fragments of pipe-underlying rocks has been detected in the lamproite pipes of Australia [7]. At the transition from the diatremic parts of the pipes toward the bottom ones their shape sharply changes. In some cases it is changed for fanciful forms representing zones of crush, in other cases the diatremic pipes' parts are altered into dyke-shaped ones pinching out with depth. The "feeding" dykes are represented exclusively by massive kimberlite, moreover, no "intrusion phases" are fixed in them.

The contiguous groups of pipes and dykes are conventionally combined into kimberlite fields. The attempts to conceive continuity break dislocations in the crystalline basement to delineate the kimberlite fields were of no success. Moreover, many examples had showed the absence of causal and positional connection in the location of kimberlite bodies and continuity break dislocations identified in rocks of the crystalline basement of platforms according to geophysical data [22,23].

Diamond is an unusually disseminated mineral observed in the form of crystals and fissured fragments in some kimberlites. The diamond crystals contain inclusions that might open the curtain to understand its genesis. There exists a group of "central" inclusions that have no similarity with syngenetic inclusions in diamonds neither by composition, nor by form. Generally these are microinclusions without crystallographic cutting. Part of them refers to ore minerals (taenite, cogenite, carbonaceous iron, wüstite, monocrystalline graphite and sulfides), others are assumed to refer to a class of carbonates [2]. A wide distribution of graphite in the form of central inclusions is of special interest. A monocrystalline modification of this mineral is established. Graphite is encountered in the central zone of diamond from a CPSU 23-rd Congress pipe in association with cogenite and iron. The outer form of graphite inclusions and the discretion of fields of graphite and diamond thermodynamic stability testify to the fact that graphite is a protogenetic inclusion in diamond monocrystals. The monocrystalline graphite in interstitial and peripheral areas of diamond monocrystals is not established yet.

Some syngenetic inclusions of olivine discover the signs of melting what indicates the formation of diamond in an area of high pressure and temperature exceeding the values characteristic of a stable state of olivine that existed earlier. In a number of cases the chemical composition of minerals included in the diamond testify to its origin in the conditions other than those of the Earth. The concentration of chromium in olivines is higher than in those traced in a kimberlite proper. Chromic spinel is richer in chromium than a conventional chromite and resembles chromite present in meteorites [48]. Inclusions of coesite are very often encountered in diamonds. Single discoveries of magnesiowüstite and ferripericlase from Sloan and Koffifontein kimberlite pipes and also of moissanite in a diamond from Monastery kimberlites are known [50]. The inclusions of majoritic garnet that, according to the experimental data, can be formed at a pressure of 13-16 GPa (what corresponds to an interval of depths 480-650 km) have also been found in diamonds of the Monastery pipe [49]. The presence of eclogitic xenoliths [41] of crystalline aggregates in a monosulfide solid solution among the inclusions in diamonds [11] and in between-grains space, and the inclusions of native iron with an admixture of nickel [29] encountered in natural diamonds are of interest too. The inclusions of native metals – Fe, Cr, Ni, Cu, Ta and their alloys Fe-Ni and Fe-Cr, pyrite, wurtzite, chromspinellide, magnetite and tallium chloride were identified in a cryptocrystalline mass of polycrystalline diamond aggregate from the Udachnaya kimberlite pipe 1,3 carats in weight composed of a cryptocrystalline dark-gray groundmass that is close by structure to carbonado, and of separate crystals of diamonds up to 1,5 mm in size having an octahedron habit, by method of analytical translucent and scanning electronic microscopy. The inclusions of lonsdeilite identified in this sample pose special interest. As testified by the analysis of electronograms the lonsdeilite forms thin intercalations in a diamond matrix [30]. The inclusions of native metals and sulfides may be referred to a paragenesis of meteorites that was suggested by A. Shoji [57] to be identified separately among parageneses of inclusions in diamond monocrystals. It is interesting that the chemical composition of native iron from xenoliths of eclogites and diamonds does not differ. There is no difference in the composition of native iron from the diamonds of eclogitic and ultrabasic paragenesis either what, from the point of view of hypotheses on the abyssal origin, poses uncertainty in its paragenesis [2]. Melton and Giardini [45, 46] found nitrogen, water, hydrogen, carbon dioxide, argon, ethylene, ethyl alcohol, butane, oxygen in the composition of gaseous inclusions in diamonds of Africa, Arcansas and Brazil.

In the last years the attention of researchers is more attracted to the issues associated with a fluid regime in diamond crystallization. But a paradox lies in the fact that up to this time there are no reliable facts of detection of fluid inclusions in diamonds.

The study of inclusions in diamond shows their unusual composition expressed in the presence of two different polymorphous modifications of SiO_2 (coesite + quartz) and TiO_2 (rutile + anatase) in inclusions and a micro-layer of poorly ordered graphite at their boundary with the host diamond. A heterogeneous composition and the presence of unusual impurities are characteristic of the majority of inclusions. So a stable admixture of phosphorus in omphacite and that of titanium oxide in coesite are found. Apart from that one pays attention to non-constancy of the composition, and also to the presence of chlorine and possibly other volatile elements in K-Al-Si phases. A rather sharp change of pressure or temperature sustained by diamond in the post-growth period might be the most probable explanation for joint discovery of various polymorphous modifications of SiO_2, TiO_2 and carbon [2].

The analysis of the features of external and internal structure of octahedron crystals of natural diamond, the character of surfaces of contact with inclusions and host minerals in light of nowadays ideas about the mechanism of origin and growth of crystals indicates that diamond and syngenetic inclusions therein refer to the first-most crystallization phases. This gives rise to a single possible conclusion that the growth of octahedron diamond crystals takes place under the mechanism of layer-by-layer growth in free space, in the conditions of equal and full "nutrition". This could be realized only in the case if the diamond and paragenetic minerals were crystallized in a weighted state in gaseous or liquid medium [2]. However, the formation of diamonds in a liquid medium is poorly correlated with the results of geochemical study of minerals of diamond paragenesis [39, 56]. The essence of this contradiction consists in the impossibility of crystallization from silicate melts of minerals with such a high admixtures content (e.g. K,Rb, Sr, Pb and U in omphacite from diamonds).

Not only the inclusions but the morphology and inner defects of crystals of the diamond itself do testify to their rather composite history of growth and possibly give the key to resolve the problem of their origin. As a result of detailed consideration of these peculiarities Frank [37] outlined the following:

"1. The majority of diamonds, if they do not contain a considerable amount of nitrogen, to a certain extent sustained plastic deformations resulting in the series of dislocations in glide planes (111) identified due to double-refraction by an X-ray topographic method or by electronic microscope. It means that the diamonds were subjected to an impact of strong displacement stresses at a high temperature (probably more than $2000^{o}K$). Other crystals with inconsiderable double-refraction are also saturated with dislocations, but in this case the former are polygonized what indicates post-genetic high temperature deformations.
2. The majority of diamonds during the growth sustained numerous, often sharp changes in the chemical composition of a medium. Most easily identified evidences to this fact are the layers of growth with wide variations of nitrogen content.
3. In the process of diamond growth two stages of growth and one stage of solution are distinguished:
an early stage in the course of which the form of growth was rounded or tubercular-rounded, but poorly developed plane faces of octahedron were also present. In some diamonds this stage is not traced;
a stage of growth of diamonds of octahedron habit;
a stage of solution varying in intensity.
4. The nitrogen is generally present within very thin platelets, meanwhile there are sharp boundaries between the enriched platelets and the localities deprived thereof. It is assumed that the nitrogen must have entered the diamond during its growth at such a temperature at which the diffusion of nitrogen is insignificant and consequently the nitrogen diffused with the formation of platelets. The diffusion must have taken place either in isothermal conditions or in the conditions of considerable temperature increase after the growth; the turbulent growth of diamonds testifies in favor of the second explanation."

The model age of diamond crystals from different regions of the world obtained by a Sm-Nd method owing to subcalcium pyrope-prisoners is almost the same and estimated to be 3,1-3,4 billion years (Table 1). These data indicate that the process of global diamond formation was an one-act process not at all associated with the formation of kimberlites themselves.

Table 1

Radiological age of diamonds from kimberlites

Location of diamond crystals	Age of diamonds (bln. years)	Age of kimberlites (mln. years)	Reference
Pipe Kimberli (SAR)	3,4	90	55
Pipe Finsch (SAR)	3,2-3,3	90	55
Pipe Udachnaya (Yakoutia, RF)	3,1-3,4	360	54
Arcansas (USA)	3,1	100	47

Note: These data are likely to reflect the age of formation of diamonds with isotopic composition $\delta^{13}C$ from -2 to–10 $^{o}/_{oo}$.

The isotopic composition of diamonds from kimberlites has a wide range ($\delta^{13}C$ from +2,7 to –34,4 $^{o}/_{oo}$), however for the overwhelming majority of diamonds it varies within rather small limits ($\delta^{13}C$ from -1,9 to –9,7 $^{o}/_{oo}$). One should admit that the small range of $\delta^{13}C$ values is characteristic not only of diamonds from kimberlites but also of diamonds from the alluvial placers of Zaire, West Africa, Venezuela, Brazil, India, Kalimantan and the Urals as well as of diamonds from meteorites. Nevertheless, there are some exceptions. The diamonds from the Ebelyakh alluvial placer have $\delta^{13}C$ values from –11,5 to –22,2 $^{o}/_{oo}$, but for a gray diamond from the Mir pipe the $\delta^{13}C$ value makes –32,3 $^{o}/_{oo}$. The $\delta^{13}C$ for Brazilian carbonado (-28,0 $^{o}/_{oo}$) is close to the latter value. However the analysis of isotopic composition of carbon in bitumens contained in kimberlite pipes shows that it differs from that of diamonds, carbonates and graphites, its $\delta^{13}C$ making from –16,4 to –31,4 $^{o}/_{oo}$ [5].

From the information on isotopic geochemistry of diamonds of much interest are the local investigations into isotopic composition of carbon in separate zones of monocrystals growth. In single diamond monocrystals a regular and gradual increment (from the center toward periphery) of $\delta^{13}C$ content is marked [59]. The only possible mechanism of directed change of isotopic composition of carbon – is the formation of diamond monocrystals in one continuous process obeyed to the same objective laws of development.

On the whole, the study of isotopic composition of diamonds and sulfides syngenetic thereto testifies to their poligenosity, belonging to different rocks that have their own history of development [2].

Of special interest are the data on isotopic composition of helium in natural diamonds from kimberlites of South Africa, lamproites of Australia, as well as in alluvial diamonds of Russia, South-West and Central Africa, Brazil and North America yielded by M. Ozima with his collaborators [51-53]. The values of measured ratios of helium isotopes in diamonds fluctuate from typically radiogenic to those exceeding the planetary value (characteristic of primary helium of the Solar system) and being close to the composition of sun's wind $^{3}He/^{4}He \sim 4x10^{-4}$ and even higher [60] what testifies to the presence of a cosmogenic constituent in them [43].

Stone **meteorites** by composition are close to ultrabasic and basic Earth's rocks. Coaly and ordinary chondrites are composed of high temperature constituents represented by non-melted aggregates, chondras, xenoliths, crystals and their fragments enclosed in a fine-grained matrix (Fig. 4). Achondrites represent holocrystalline often brecciated rocks. The most spread mineral of meteorites is olivine, and zoning (both direct and reverse) is often characteristic of its crystals [8]. Chromite, spinel, perovskite, diopside, Ca-Al silicate glass, plessite, troilite, taenite, cogenite, pentlandite and others are most often encountered as secondary and accessory minerals. Montmorillonite, septechlorite, calcite, magnetite, gypsum are present in the matrix in considerable quantities. Carbon in meteorites is represented in the form of: composite organic compounds, hydrocarbons, amorphous and thinly dispersed carbon, graphite and its varieties – cliftonite. The characteristic feature of this graphite is its chemical purity. The studies of graphite from enstatitic chondrite by electronic micro-sounding revealed 100% of C [35]. As an associated mineral to meteorite diamonds it is traced in neogenic diamondiferous titanium placers of the Russian platform [15]. Impact effects are recorded in the majority of meteorites: from crushing and brecciation to strong darkening, recrystallization and melting [8]. This can be complemented by the discoveries in meteorites of high-pressure modifications of carbon – diamond, lonsdeilite, chaoite and other minerals of impact origin, such as moissanite, ringwoodite, majorite. The data of Rb-Sr, Sm-Nd and Pb-Pb methods to determine the age of differentiated meteorites indicate that they were crystallized 4,54 billion years ago. The lower Rb-Sr values (internal isochrone) for ages testify to an impact reworking of the substance of these meteorites not later than 1,5 billion years after its formation [8].

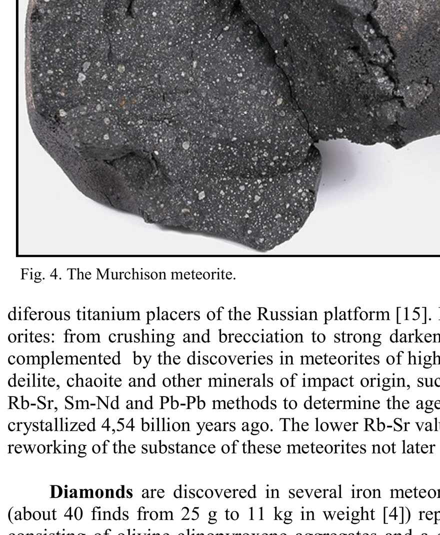
Fig. 4. The Murchison meteorite.

Diamonds are discovered in several iron meteorites and in the majority of ureilites. The ureilites (about 40 finds from 25 g to 11 kg in weight [4]) represent intensely impact-altered achondritic breccia consisting of olivine-clinopyroxene aggregates and a carbonaceous matrix. The olivine, most distributed mineral of ureilites, is uncommon and contains both calcium (0,26-0,42 % CaO) and chromium (0,6-0,9 % Cr_2O_3). The high calcium content testifies to a fast cooling process following high temperatures. The high chromium concentration indicates the conditions of formation under which the greater portion of this element was reduced to Cr^{2+}, and a special Fe-Mg zoning testifies to the further reduction process that the introduction of matrix material and the impact metamorphism were accompanied by. The ureilites matrix is unusually complicated. Apart from dominating polymorphous modifications of carbon, native iron and troilite, it contains chromite and many accessory minerals, and the ore minerals are represented in the shape of spherules. The history of ureilites had evidently covered several events: 1) the formation of a peridotite-like silicate association as a result of fractional crystallization or as a solid residue during partial melting; 2) mixing with a substance rich in carbon; 3) an impact effect simultaneous with the mixing process or further impact [8]. The diamonds in ureilites are represented by several varieties (I, III, V?, VII?, IX, X?, XI [15]), however the aggregates with polycrystalline texture are more distributed. The prevailing size of aggregates does not exceed 1 mm. Lonsdeilite as an admixture is rarely present. By the X-rays characteristic the diamonds of meteorites are similar to the Earth's natural and synthetic diamonds [3]. They also contain admixed nitrogen included in the composition of these and other centers of luminescence [19]. The micro-diamonds from ureilites have inclusions of plessite, troilite and chromite [3]. The carbon content in ureilites makes from 0,22 to 6,4 % [4], and the concentration of diamonds reaches and sometimes exceeds 1 % of the total mass of a meteorite what is by several orders higher than in kimberlites most highly rich in diamonds. The isotopic composition of carbon in the diamonds of ureilites ($\delta^{13}C$ -5,7 $^{o}/_{oo}$) is consistent with the isotopic composition of the initial carbonaceous matter ($\delta^{13}C$ from -0,7 to -11,1$^{o}/_{oo}$) [4,19] and similar to the isotopic composition of carbon in diamonds from kimberlites.

As a result of impacts by meteoroids the terrestrial surface forms craters filled with a poorly sorted and intensively mixed crushed and melted substance of terrestrial rocks, and, to a lesser degree, - with **impactites**. More than 200 impact structures up to 335 km have been discovered on earth of late. The fall of large meteoroids is the only known natural process under which an impact metamorphism characterized by instant occurrence, high peak pressure (from 10 to 1000 GPa) and residual temperature (exceeding $1500^{o}C$) may occur. During the impact metamorphism there appear high-pressure phases of a number of compounds (coesite, stishovite, diamond, moissanite, majorite, ringwoodite, chaoite and others), accompanied by the crushing of minerals, destruction of their crystalline lattices, recrystallization and melting of minerals and rocks. The speed of crystals growth during the explosion may reach 50 m/sec. [6]. By the conditions of formation the impactites are subdivided into five facies: a base facies, a bottom streams facies, an aerodynamic returned facies, an aerodynamic outburst facies and tectites [31]. The facies of bottom streams contains allogenic breccia of different dimensionality, melted rocks (tagamites) and mixed (suevites). They form a complex system of extended lenticular bodies, cleaved and pinched out in places. The suevites are lithified breccia comprising the fragments of polymineral impact glass of different size and rock fragments consolidated by the same thinly crushed material (Fig. 5). By a number of lithological and petrographic signs: the ratio and composition of vitroclasts, lithoclasts, grano- and crystalloclasts, as well as by their granulometry, aggregate state and the character of consolidation and so on, their more than 10 varieties are distinguished within astroblems. The accumulations of accreted lapilli representing rounded formations of a concentrically zonal structure 1-1,5 cm in diameter making up to 20-30 % of the rock volume are often traced in suevites. They consist of fragments of minerals of crystalline and sedimentary rocks (70-80 %) and glasses (10-15 %) of alevrolite and psammite dimensionality consolidated by the same material of pelite dimensionality [20]. The bedded bodies of tagamites sometimes change into sub-vertical bodies. The availability of intersecting injection bodies of tagamites is also a characteristic feature. The contacts between tagamites and suevites may be both sharp (though sinuous, uneven) and with gradual changes, sometimes small apophyses of ones into others are marked. In separate bodies there are peculiar eutaxites where the rocks of one variety are included in another. In some cases large blocks reaching tens and even first hundreds of meters across somewhat "float" in a mass of breccia of lesser dimensionality. The fragmental material contains rocks characterizing all known formations of different age in the surroundings of an impact crater. The complexity of contact relations, availability of reciprocal inclusions and cross sections, "hot" character of the contact interaction testifying to consolidation of these rocks in high temperature conditions are a common feature for the whole diversity of allogenic rocks. On the contrary, the rocks of aerodynamic facies and the tectites differ in deposition already after vitrification and essential cooling of the melt that take place in the process of transportation of the target's rock fragments and those of the melt along the ballistic tracks. It is testified to by "cold" contacts of melted and fragmented formations, the aerodynamic sculpture on the surface of glass-composed bombs and lapilli. The concentration of Ni, Co, Cr in impactites is 1,5-3 times as much and Ir – by an order higher than the background concentrations of crater-hosting rocks.

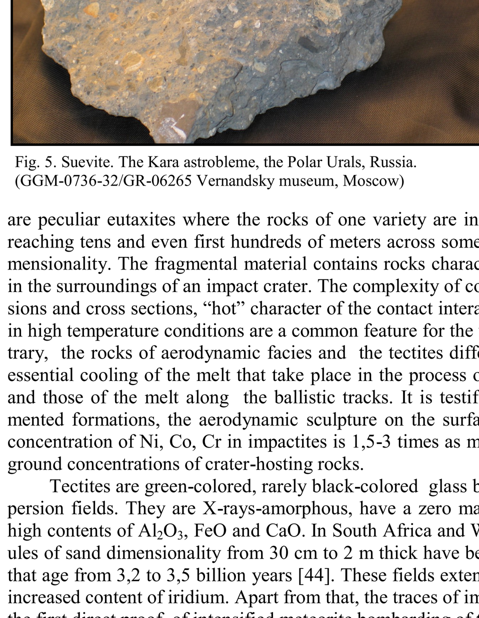
Fig. 5. Suevite. The Kara astrobleme, the Polar Urals, Russia. (GGM-0736-32/GR-06265 Vernandsky museum, Moscow)

Tectites are green-colored, rarely black-colored glass bodies, of various shape and sizes, forming dispersion fields. They are X-rays-amorphous, have a zero magnetization intensity and are characterized by high contents of Al_2O_3, FeO and CaO. In South Africa and Western Australia the deposits of silicate spherules of sand dimensionality from 30 cm to 2 m thick have been discovered in the Archean greenstone belts that age from 3,2 to 3,5 billion years [44]. These fields extending for almost 100 km are associated with an increased content of iridium. Apart from that, the traces of impact waves are seen in them. This discovery is the first direct proof of intensified meteorite bombarding of the Earth at that period of its history.

The diamonds in impactites from a number of astroblems appeared either owing to graphite, or because of a coal substance of high-degree carbonification [10]. The isotopic composition of carbon of after-graphite ($\delta^{13}C$ from –9,9 to –17,5 $^{o}/_{oo}$) and after-coal ($\delta^{13}C$ from –22,8 to –24,9 $^{o}/_{oo}$) diamonds is identical to the isotopic composition of the initial graphite ($\delta^{13}C$ from –12,0 to –17,3 $^{o}/_{oo}$) and the carbonic matter ($\delta^{13}C$ from –22,3 to –24,6 $^{o}/_{oo}$) [19]. The paramorphs of a diamond in case of graphite are mainly composed of microcrystallites of the cubic diamond phase 0,01-1 mcm (up to 10) in size, the hexagonal phase – lonsdeilitie, graphite is also present. However, purely cubic diamonds are widely distributed in the rocks of the Popigai crater too [36]. Four particular features are characteristic of them: 1. The absence of nest-like inclusions of lonsdeilite in aggregates; 2. The external signs of growth (octahedrons, cub-octahedrons) with strictly parallel orientation; 3. Ordered positions of nitrogen in the structure; 4. Contrary to other varieties of impact-generated diamonds, the cubic ones have regular crystallographic figures of natural etching. The diamonds brought about due to the carbonic matter are also composed of cubic and hexagonal phases but the latter is traced in them rather seldom. The inheritance is observed also in the chemical composition of after-coal aggregates to what testifies the discovery of such elements of initial carbonaceous substance as H, N, S, P. In this regard a certain analogy with the behavior of rare gasses in the carbonaceous matter of ureilites transformed into diamond is marked. There are two natural mechanisms of transformation of the carbonaceous substance into hyper-pressure phases: by diffusion and by way of solid-phase transformation. The paramorphs of diamond and lonsdeilite brought about as a result of the solid-phase transformation at the expense of primary crystals of graphite are not crystals. However, in special conditions (should the process continue) a diffusional growth of diamond crystals (octahedrons, cubes, cub-octahedrons) epitaxially intumescening (accreting) on the diamond-lonsdeilitic matrix also takes place [14]. The carbonado, widely distributed in placers that have no original sources of diamond, and also traced in kimberlites [1, 30, 40] are lately thought to be also associated with impact metamorphism [58]. The conventionality of division of diamonds into the varieties X (carbonado) and XI (yakutite) between which there are persistent transformations [25], as well as the similarity of carbonado's surface to the surface of meteorites [33] testify in favor of this idea.

THE PROCESS OF DIAMONDS AND KIMBERLITES FORMATION

The analysis of the above information makes it possible to assume that a great space catastrophe – the tenth planet of the Solar system – Faeton collided with a gigantic interstellar comet about 3,2-3,4 billion years. It is during this collision and the follow-up explosion that the formation of a major mass of diamonds currently found in meteorites and kimberlites is likely to have taken place. The major key moments of diamond genesis are as follows: the source of carbon, pulse P-T conditions to form diamond seeds, continuous feeding by carbonaceous matter at high temperature and pressure to ensure the growth for a certain time and an availability, upon the completion of growth, of certain conditions to preserve the crystals once formed. Except for the high temperature/pressure, the mantle hypothesis is not able to give an exactly answer to these questions. But in view of the suggested hypothesis all conditions are met (Fig. 6). Taking into account the composition of comets – H_2O, CO_2, CH_4, NH_3, C_3, C_2, CN, CH, OH, NH, NH_2 the source of carbon for the formation of coaly chondrites, ureilites and diamonds, the source of nitrogen in their crystalline lattice and the composition of gaseous inclusions are logically substantiated. The duration of a process of impact collision of even big meteoroids with the Earth makes from parts of seconds to several seconds. During this period only small crystals up to 1 mm in size can be formed. But the collision of a planet with a comet is quite another thing. The mass and density of a comets' core are inconsiderable, but the length of their tail reaches many millions of kilometers. When a planet and a comet collide, even keeping in mind their great speeds, the process of the shock collision, explosion and disintegration of the planet may last several hours, and during this time, in view of its scope, crystals much larger than that of Cullinan (3106 carats) could be grown. One can easily explain a great variety of morphological and crystallographic forms, sizes, color of diamond crystals as well as the composition and morphology of solid inclusions, the isotopic composition of helium and many other things resulting from such a process. The composition of gaseous inclusions in diamonds is not characteristic of the Earth's mantle what is acknowledged by the authors themselves of the mantle hypothesis of kimberlites origin. J. Dawson writes [9]: "Nitrogen is concentrated in the form of thinnest plates and in single centers inside a diamond, and it happens to be the only diamond location in the upper mantle known today. Should any though scarce data exist in respect of the sources of carbon and phosphorus, then the primary source of nitrogen and other rare gasses (e.g. ethylene, butane) in diamond remains a puzzle". The synthesis of composite organic compounds that are found in meteorites and have served as a source of organic life origin on the Earth is likely to have also taken place.

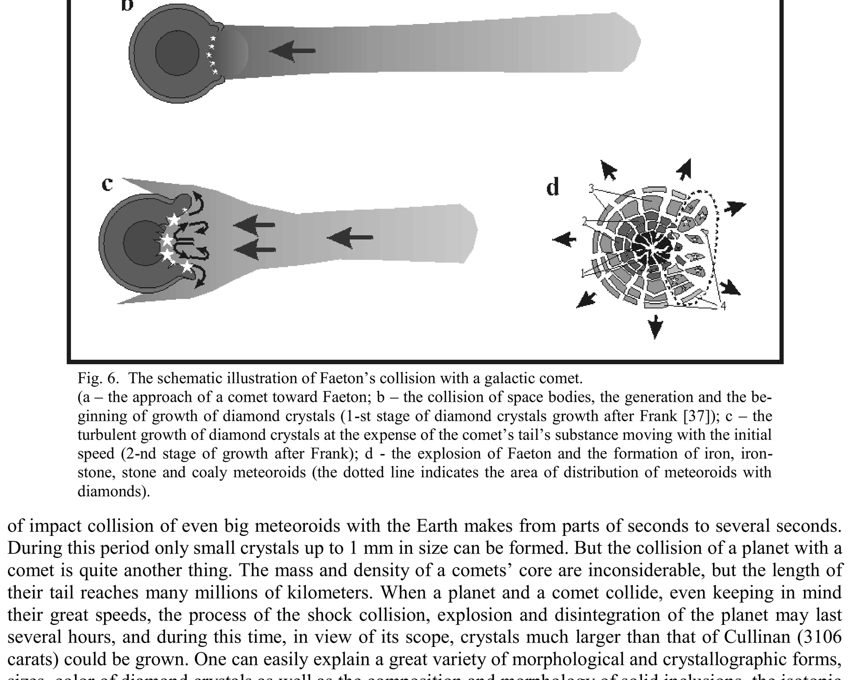

Fig. 6. The schematic illustration of Faeton's collision with a galactic comet.
(a – the approach of a comet toward Faeton; b – the collision of space bodies, the generation and the beginning of growth of diamond crystals (1-st stage of diamond crystals growth after Frank [37]); c – the turbulent growth of diamond crystals at the expense of the comet's tail's substance moving with the initial speed (2-nd stage of growth after Frank); d - the explosion of Faeton and the formation of iron, iron-stone, stone and coaly meteoroids (the dotted line indicates the area of distribution of meteoroids with diamonds).

As a result of collision Faeton exploded and disintegrated into stone (the substance of the mantle of ultrabasic composition) and iron (the substance of the core) fragments some of which (akin to ureilites) carried diamonds. It is these fragments that are a "**conserving**" and "**transporting**" medium for diamonds. As mentioned above, the absolute age of most diamonds is more than 3 billion years, and it is recognized by the majority of scholars in the whole world. It is hard to imagine the conditions to preserve diamond crystals in the mantle for billions of years but in the outer space they could have been preserved in the initial state for as long as possible. One part of the fragments - formed a belt of asteroids in the place of Faeton's orbit between Mars and Jupiter (Fig. 7). The other part ran into the field of gravitation of other planets (Mars, Jupiter and Saturn) and became their satellites. The third part - subjected the Solar system's large cosmic bodies to an intensive meteorite bombardment in the nearest time after the catastrophe. Finally, the fourth portion of the fragments keeps on moving within the Solar system at their orbits up to this time periodically making collisions with the Earth and other planets of the Solar system.

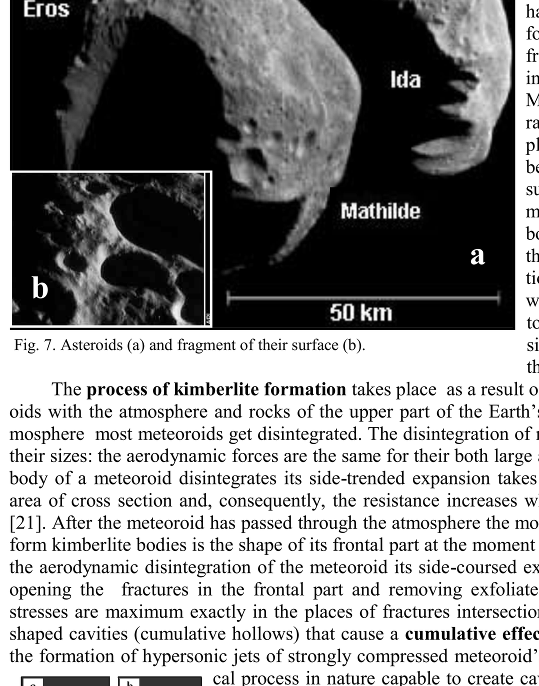

Fig. 7. Asteroids (a) and fragment of their surface (b).

The **process of kimberlite formation** takes place as a result of an impact interaction of stone meteoroids with the atmosphere and rocks of the upper part of the Earth's crust. Passing through the Earth's atmosphere most meteoroids get disintegrated. The disintegration of meteoroids does not actually depend on their sizes: the aerodynamic forces are the same for their both large and small representatives. As the major body of a meteoroid disintegrates its side-trended expansion takes place in which connection the overall area of cross section and, consequently, the resistance increases what causes a further growth of stresses [21]. After the meteoroid has passed through the atmosphere the most important and necessary condition to form kimberlite bodies is the shape of its frontal part at the moment of touching the Earth's surface. During the aerodynamic disintegration of the meteoroid its side-coursed expansion is brought about as a result of opening the fractures in the frontal part and removing exfoliated material sideways. At this time the stresses are maximum exactly in the places of fractures intersection what leads to the formation of cone-shaped cavities (cumulative hollows) that cause a **cumulative effect** at the moment of collision leading to the formation of hypersonic jets of strongly compressed meteoroid's substance. This is yet the only physical process in nature capable to create cavities of a pipe type in a solid medium (Fig. 8). The cone- or pyramid-shaped isometric hollows create pipes isometric in plan, the cone-like hollows of irregular shape create the same forms of pipes quaint in plan, the adjoined hollows form paired pipes, the linear and arch fractures opened at an acute angle - create linear and ring dykes and the like. Figuratively speaking, each pipe has its individual "face". Contrary to a cumulative charge, the rear meteoroid's part continuing to move on after the touch with the initial speed, since it is not yet subject to the processes taking place in the frontal part, plays the role of detonator here (and the source of a detonation wave); and the stone material of the hollow's walls is a shell. The formed high-speed jet (jets) breaks through terrestrial rocks forming a pipe-like cavity (Fig. 3). Subject to the shape and sizes of the hollow the cavity's depth could make from tens of meters to first kilometers. Reaching a certain depth, as the energy recedes, the jet's substance either fills a fracture in host rocks or pinches out. The cooled jet's material having filled the lower parts of pipes and dykes represents a **intrusive kimberlite** with melted monocrystals of refractory minerals. This explains an intensive thermal contact of bottom parts of pipes with host rocks.

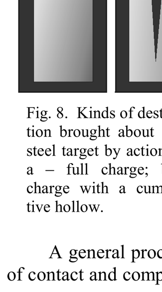

Fig. 8. Kinds of destruction brought about in a steel target by action of: a – full charge; b – charge with a cumulative hollow.

A general process of impact crater-formation takes place further on the surface (Fig. 9). At the stage of contact and compression, as a result of conversion of the meteoroid's kinetic energy into internal energy the substance of the meteoroid and terrestrial rocks is exposed to significant shift deformation, full or partial fusion. Subject to the sizes, mineral composition, structure and jointing of various meteoroid's parts the partial fusion comes about unevenly (the inside non-melted fragments further form xenoliths of "related" inclusions). The growth of external zones of diamond zonal crystals (4-th variety, after YU. L. Orlov) comes possibly about at the expense of meteoroid's carbonaceous matter, so does the formation of diamond crystals of 5-11-th variety the isotopic composition of which differs from the diamond groundmass and is cosistent with the dispersed carbon of the Earth's crust, at the expense of carbonic matter (graphite, coal, bitumen) of terrestrial rocks in the impact place. By effect the impact of a high-speed meteoroid looks like a nuclear explosion, and in this very moment does the expansion of the upper part of a pipe-shaped cavity with the formation of a funnel come about. At the stage of excavation a hot cloud consisting of vapor, small particles, melted refractory crystals and fragments of rocks (xenoliths) slowly rises acquiring a classical mushroom-shaped form. It is this cloud where such specific formations of kimberlites as silicate globules and autoliths take place. The filling of the cavity formed by a high-speed jet begins at the stage of modification. A mixture of shock-formed melt with fragments of crater-hosting rocks and related inclusions, sometimes with large blocks ("floating reefs") drains down into it from the bottom of the crater; the small particles, fragments and autoliths lifted by vapor fall down from top – a **kimberlite breccia** gets formed. Separate fluxes of such melt form the so-called kimberlite "columns" or "intrusion phases" observed in many pipes. The hybrid composition of kimberlites, the absence of distinct contact alterations of host rocks and xenoliths in the diatremic parts of pipes, the gliding planes on a contact with host rocks, the variety of forms of pipes in plan, the availability and composition of crater facies in the upper parts of pipes and many other things are also easily explained. Wide variations of the chemical composition of kimberlite bodies are explained by a variety of compositions of meteoroids and terrestrial rocks. The distribution of diamonds in the fragments of an outer space body was extremely irregular from what one may easily explain an availability of diamondiferous and non-diamondiferous kimberlite bodies. And the epochs of kimberlite origination are associated with the Earth's passing through swarms and flows of asteroids at certain periods of space time.

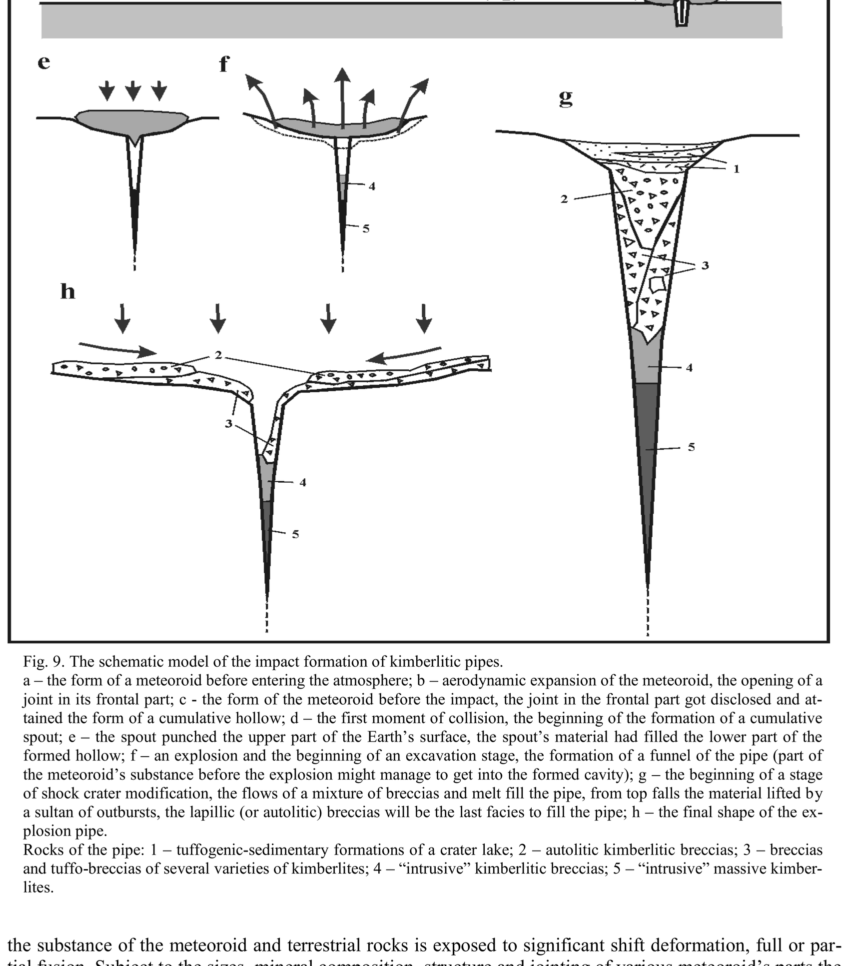

Fig. 9. The schematic model of the impact formation of kimberlitic pipes.
a – the form of a meteoroid before entering the atmosphere; b – aerodynamic expansion of the meteoroid, the opening of a joint in its frontal part; c - the form of the meteoroid before the impact, the joint in the frontal part got disclosed and attained the form of a cumulative hollow; d – the first moment of collision, the beginning of the formation of a cumulative spout; e – the spout punched the upper part of the Earth's surface, the spout's material had filled the lower part of the formed hollow; f – an explosion and the beginning of an excavation stage, the formation of a funnel of the pipe (part of the meteoroid's substance before the explosion might manage to get into the formed cavity); g – the beginning of a stage of shock crater modification, the flows of a mixture of breccias and melt fill the pipe, from top falls the material lifted by a sultan of outbursts, the lapillic (or autolitic) breccias will be the last facies to fill the pipe; h – the final shape of the explosion pipe.
Rocks of the pipe: 1 – tuffogenic-sedimentary formations of a crater lake; 2 – autolitic kimberlitic breccias; 3 – breccias and tuffo-breccias of several varieties of kimberlites; 4 – "intrusive" kimberlitic breccias; 5 – "intrusive" massive kimberlites.

The availability of dense atmosphere essentially changes the process of impact crater origination. The craters made by a destroyed intruder are small in comparison with those created by an undestroyed asteroid and are characterized by almost a flat floor. The "bushes" of kimberlite bodies and the kimberlite fields are likely to get originated from an impact interaction of such large (more than 1 km) stone meteoroids subjected to aerodynamic destruction with the Earth's surface (Fig. 10). Figuratively speaking, a kimberlite field is a preserved negative print of the surface of a meteoroid having collided with the Earth. The absence of any structural control over their location as well as an isometric and ellipse-like form in plan of the contours of kimberlite fields testify in favor of it. During tens and hundreds of millions of years the craters were destroyed by erosion, only the ring structures comparable with the craters' dimensions testify to their existence (Fig. 11). The estimations of speeds of formation of craters on the Earth indicate that the objects 10 km and more in diameter used to collide with the Earth as frequently as about once in a hundred million years [21]. Such objects could have formed kimberlite fields about 50 km in diameter, but there have been discovered single fields of such a diameter on the Earth. Most kimberlite fields have the sizes of 10-20 km, and a meteoroid of about 5 km in diameter would be enough to form such fields, but meteoroids of the size collided with the Earth rather more often.

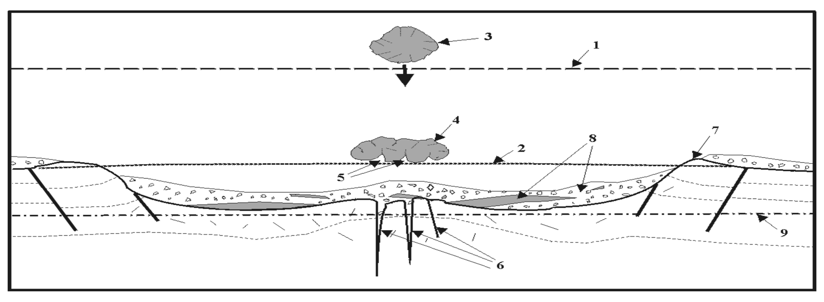

Fig. 10. The schematic model of kimberlite fild formation.
(1 – atmosphere's boundary; 2 – the Earth's initial surface; 3 – the shape of a meteoroid before entering the atmosphere; 4 – the shape of a meteoroid before the impact due to aerodynamic destruction; 5 cumulative hollows; 6 kimberlite pipes and dykes; 7 – arch of impact crater; 8 – impactites; 9 – the level of recent erosion section).

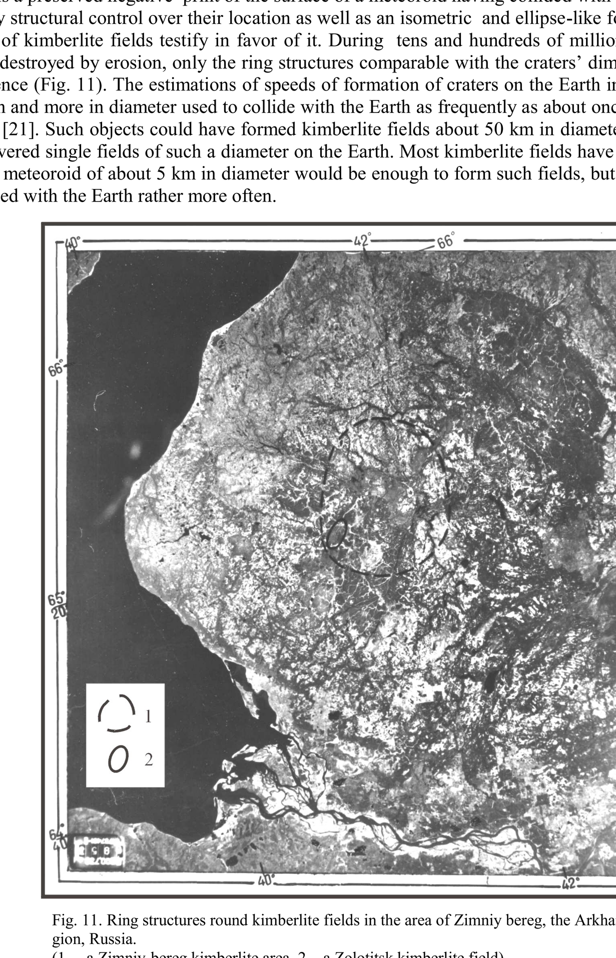

Fig. 11. Ring structures round kimberlite fields in the area of Zimniy bereg, the Arkhangelsk Region, Russia.
(1 – a Zimniy-bereg kimberlite area, 2 – a Zolotitsk kimberlite field).

The formation of explosion pipes is in direct association with the speed, dip angle and composition of meteoroids and they may be present not in all astroblems. Firstly, explosion pipes are likely to be absent in astroblems created by iron meteoroids. Secondly, pipes are not formed at oblique impacts (a cumulative effect at oblique angle impacts comes about in the form of creation of high-speed jet outbursts directed in line with a meteoroid's flight direction). Owing to washing out of outburst sediments rich diamondiferous placers such as Ebelyah in Yakutiya, the Visher placers in the Urals, fillites in the Brasilia and coastal-marine placers in the South-Western Africa further come into being (look an example) . During the movement of sediments of impact outbursts a partial solution of diamond crystals leading to the origination of rounded diamonds of the "Urals" type is brought about. Thirdly, at a high speed of impact (>15 km/sec.) and a dip angle close to being vertical, complete fusion and evaporation of a meteoroid's substance takes place, and the cavities in host rocks (dykes, pipes) formed at the moment of collision due to a cumulative effect will be filled with melted and brecciated matter only of host rocks or will remain hollow, and later will gradually be filled with lacustrine sediments (Bushmeland, SAR; Kerdakh, Syria). The above indicates that pipes get formed at close-to-vertical impacts of stone meteoroids running at a speed of up to 10 km/sec. and having been subjected to a considerable aerodynamic destruction. At such impacts only partial melting of a meteoroid's substance takes place, and a significant part of the substance is preserved at the stage of excavation.

Embarking upon the issue of a new "metamorphogenous" source of diamonds one may note the following. In various metamorphic rocks of the Kumdykol diamond field, planar structures in quartz have been identified what indisputably points out to the passing through these rocks of shock waves with peak pressures of 50 kbars and higher and to numerous inclusions of meteoritic substance represented by globules, small dump-bells, drop-like formations, flat casts, small snakes, wires and other fanciful forms brought about during the injection of melted substance of an asteroid into the fractures of a target's rocks (Fig. 12). The composition of these isolations – magnetite, hematite, iocite, troilite, α-iron, plessite [12]. At this field, apart from cubic diamond and hexagonal graphite modifications of carbon, transformable formations with structural elements of diamond, chaoite, α- and β-carbine, hexagonal, rhombohedral and cubic graphite, lonsdeilite as well as X-rays-amorphous differences of skeletal diamonds have been encountered [34]. Besides, the age of formation of an eclogite-gneiss-schistous complex of host rocks - the early Proterozoic, and the age of diamonds determined by zircons hosted in them - the Cambrian [16]. These data as well as: small sizes of diamond crystals (on the average 20-40 mcm); the confinement of a significant part of diamonds to the fractures in rock-forming minerals, especially in garnets; the prevalence of crystals of skeletal and curvi-faced spheroidal habit; the syngeneticity of diamond and graphite formation; the unprecedentedly high ratio of helium isotopes ($^{3}He/^{4}He$) in diamonds [16]; the inclusions of coesite in zircons; the pinching-out of productive bodies with depth - make it possible to assume that the indicated field came into being as a result of impact by a meteoroid small in size and rich in carbonaceous matter (probably, coaly chondrite or comet). At the stage of contact and compression the "injection" of evaporated substance of the meteoroid (or comet) into various metamorphic rocks and fractures of separate minerals with further simultaneous crystallization of diamond and graphite took place. The process was short-termed, probably, for the first seconds. This is why only very small crystals could have been formed.

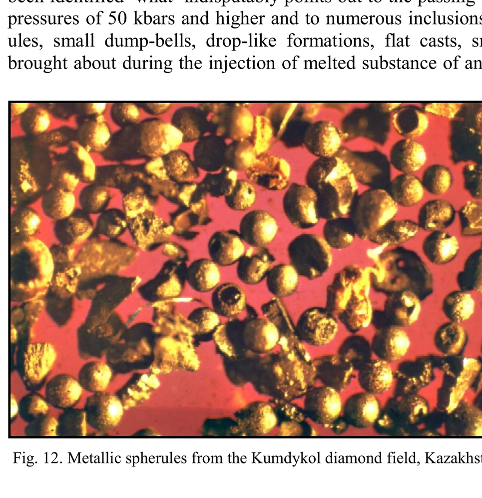
Fig. 12. Metallic spherules from the Kumdykol diamond field, Kazakhstan.

CONCLUSION

It is impossible to efficiently prospect for deposits of diamonds without knowledge of their genesis. The presented hypothesis makes it possible to work out an effective prognosis-prospecting conception of operations for bedrock and placer sources of diamonds. This should lead to a discovery of new big diamond fields, especially in those areas where their discovery was not presupposed at all due to the existing ideas of their origin.

The considered mechanism of kimberlites formation may undoubtedly be also applied to other numerous varieties of rocks localized in the bodies of likewise morphology – explosion pipes. The only difference is the composition of a meteoroid having formed them and that of local rocks. The single discoveries of diamonds in pipes of non-kimberlite composition can now be explained too.

In conclusion, the term itself – "pipes of explosion" – should be mentioned. In view of the origin from the Earth's depths, it did not correspond much to the facts and was often subjected to criticism. In view of the impact origin, one has to be surprised how much prophetic this name was since the impacts of supersonic meteoroids are really like explosions.

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