LITHOSPHERE (RUSSIA), 2018, volume 18, No. 5A, pp. 78–89

GEO-PETROLOGICAL MODEL FOR THE FORMATION OF DIAMOND-BEARING FLUID-EXPLOSIVE BRECCIA STRUCTURES (URAL TYPE)

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Received 26.12.2017, accepted 06.06.2018

The geo-petrological model of diamond-bearing fluid-explosive breccia formations constitutes a well-structured system of features that are typical of several similar formations in the Cis-Ural and West Ural areas of the Perm Territory. The model reflects a number of basic common factors associated with the morphology of these structures, their rock composition and the conditions for their formation. In this paper, the authors characterise regional and local geological positions featuring diamond-bearing formations, as well as the parameters common for the areas of their development. The necessity of mineralogical and geochemical studies of black sand, while prospecting for diamond-bearing targets is highlighted. This will help identify specific mineral associations and geochemical anomalies typical of these widespread formation areas. The description of a geological structure associated with the best-studied deposit (Efimovsky) is given in detail. The description of this deposit is used as an example to illustrate the shape of breccia bodies and their polyphase structure, as well as show their texture and rock structure specifics. Special attention is paid to the petrographic characteristics of all kinds of fluid-explosive breccias, which to a different extent contain clastic, protomagmatic and newly formed fluidogenic material. The paper gives the characteristics and specifics of mineral grains of various origin, many of which are abundant in gas-liquid inclusions characterised by block extinction, while quartz possess planar elements. The authors examined the differences in the diamond potential of rocks belonging to different successive evolution phases of fluidogenic breccia formations. When studying newly discovered breccia structures that have a limited number of features, the model considered in the paper will help to predict the missing features and assessment criteria for diamond potential.

Keywords: *geo-petrological model, Cis-Ural and West Ural areas of the Perm Territory, diamond-bearing fluid-explosive breccia formations, Efimovsky deposit, petrographic and mineralogical characteristics of breccias, diamond potential*

INTRODUCTION

Diamond-bearing breccias, as well as structures formed by them, developed in the Cis-Ural and West Ural parts of the Perm Territory, constitute the prototype of Ural fluid-explosive formations. To date, 19 such features (2 deposits and 17 occurrences) have been identified here, with their total resource base being estimated at 5270 thousand carats. The model is based on the most studied deposits and occurrences in the Efimovsky, Rybyakov, Vishera and Yayva areas. In the course of work, we obtained documentation of natural outcrops, mine workings, the core samples of boreholes and quarries for these sites. In addition, to build a complete model, we used material on other features of this region (Malaya Porozhnaya, Yuzhnaya Rassolnaya, Ilya-Vozh, Volynka, etc.), as well as on similar features of some other regions in Russia and abroad [Diamond-bearing…, 2011].

GEOLOGICAL STRUCTURE OF THE VISHERA DIAMOND-BEARING AREA

Tectonically, the ore areas under study are located at the junction of large tectonic structures of the Urals, Timan and the eastern border of the East European Platform. Geologically and structurally, they are confined to the diamond-bearing West-Ural megazone located between the Ural foredeep and the Central Ural megazone. The West Ural structure is composed mainly of Paleozoic and, to a lesser extent, Precambrian heavily displaced sedimentary formations, thrust over to the west and, in turn, overlain by large allochthons displaced from the Central Ural megazone. It is characterised by the presence of the Archean-Early Proterozoic crystalline basement of the East European platform, which is established using geophysical data and confirmed by deep-hole prospecting. According to geophysical parameters, the crust of the zone belongs to the intracratonic subtype formed in the Archean – Early Proterozoic [Berlyand, 2007]. The basement is composed of deeply metamorphosed and dislocated sedimentary and igneous rocks of the Archean and Lower Proterozoic. It has a block structure characterised by intense fragmentation by deep-seated faults, including by strike-slip and thrust faults, and occurs at a depth of 4–6 km [Grinson, 1971].

Like other diamond-bearing regions of the Perm Cis-Urals, the Vishera area is confined to the marginal zones of the platform having a rigid shallowly occurring Precambrian basement complicated by actively moving zones [Luk'yanova et al., 1997, 2005; Berlyand, 2007; Petrov et al., 2012]. It is characterised by the gradient zones of the gravitational field – negative gravimetric anomalies, including specific zones in the form of 'chains' of negative discontinuous anomalies, as well as anomalies in the endogenous heat flux. In addition to gravimetric anomalies, it exhibits a qualitative geomagnetic feature characteristic of the region – the presence of subvertical inhomogeneities in petromagnetic and density sections along with local magnetic anomalies of low intensity (3–20 nT). They are detected using the method of spectral-spatial analysis of geomagnetic lateral fields, and, as shown by studies in the Vishera and Yayva areas [Petrova, Mavrichev, 2004; Diamond-bearing..., 2011], are presumably associated with fluid-explosive diamond-bearing rocks. The movement of fluidogenic material containing xenogenic clasts of various compositions along weakened zones from depth to the surface is also reflected in the petromagnetic section in the form of magnetisation inhomogeneities. Detailed geophysical works (gravity survey, scale 1:10,000; electrical prospecting using vertical electrical sounding) showed that in the gravity field fluid-explosive breccia bodies are characterised by negative anomalies often fixing linear zones. In geoelectric sections, 'mudded' (argillizite) breccia varieties yield $\rho_к$ values of 200–600 ohm·m, whereas 'sandy', essentially quartz varieties, show values of 900–1500 ohm·m.

The characterisation of diamond-bearing areas should be supplemented by the results of the following studies.

– Identification of mineralogical associations indicative of the diamond potential [Zhukov et al., 1978]. They are characterised by the constant presence of limonite, hematite, kyanite, staurolite, tourmaline, rutile, corundum, pyrope, almandine pyrope, chrome spinels, spinel and native metals in various quantitative proportions. The granulometric feature of these associations consists in their heterogeneity, whereas the morphogenetic feature is the constant presence of rounded grains (spherites) having a smooth shiny and finely-rough (corroded) surface (limonite, hematite and carbonates).

– Detection of geochemical anomalies in such elements as Co, Ni, Cr, Ce, Be, Ba, Ti, Pb, Zn, As, Y and Ag using primary and secondary dispersion halos.

According to the regional geological-and-structural position, the following features are characteristic of diamond-bearing regions.

1. Significant thicknesses of the sedimentary cover overlying the basement (4.0–7.0 km) and of the Earth's crust (from 35–40 to 45–50 km).

2. Gradient zones of the gravitational field (negative gravimetric anomalies, including specific zones in the form of 'chains' of negative discontinuous anomalies), as well as anomalies in the endogenous heat flux.

3. The fragmentation of the basement by the zones of deep-seated faults, which are favourable for the penetration of endogenous fluids into the earth's crust, as well as the presence of so-called structural 'traps' on the path of fluid movement to the surface, especially promising in terms of fluid unloading. They include the intersections of deep-seated faults; the junctions of faults with the sides of large subsidence structures (aulacogens) or rises of Precambrian complexes; zones of thrust fault planes at the contacts with heterochronous (Precambrian and Paleozoic) complexes; anticlinal cores and large forms of relief lowering complicated by crushed zones.

4. The manifestation of epeirogenic movements of various directions and amplitudes at certain stages in the development of the mobile system, contributing to the forward movement and introduction of deep fluids.

5. The widespread development of the following sedimentary deposits in the cover: *sandy* – a favourable environment for the localisation of penetrating fluids with the formation of sheet-like bodies, veins, stockwork zones and other breccia structures; *silty-clay*, which constitute a screen that impedes the movement of fluids to the surface and contributes to their concentration in a closed system.

6. The manifestations of basic-ultrabasic magmatism in the area, which is an indirect sign of possible diamond-bearing breccias, given that there is supposed to be some link with these rocks – an inherited paragenetic connection in the absence of a genetic one.

7. The increased diamond potential of the territory along with the discovery in the area of predominantly curved-faced rounded (Ural or Brazilian type) diamonds with specific geochemical and mineralogical anomalies.

The main and largest tectonic structure of the Vishera diamond-bearing area is the Polyudovo-Kolchim anticlinorium, which in the southwest and northeast is confined by deep-seated steeply dipping faults manifested in geophysical fields and overlain by allochthonous plates of large thrust and oblique-slip faults of various ages (Fig. 1). The anticlinal core is represented by Upper Riphean-Vendian carbonate and terrigenous deposits, with the sides being composed of Paleozoic rocks and with Upper Ordovician quartz sandstones and conglomerates or Upper Silurian carbonate rocks occurring at its base. It should be noted that the whole set of faults creates the key-like structure of the region, formed by a network of subparallel oblique-slip fault structures. At the intersection points of the faults complicated by crushed zones, a network of fractures develops – weakened zones that serve as the pathways for the products of endogenous processes, including the transfer and redeposition of ore material, the introduction of magma with the formation of plagioperidotite-essexite and dolerite hypabyssal formations, as well as diamond-bearing fluid-explosive rocks.

The Polyudovo-Kolchim anticlinorium is divided into two large anticlines separated by a synclinal saddle: Kolchim in the northwest and Tulym-Parma in the southeast. Anticlinal cores are formed by carbonate and terrigenous rather contorted Lower Riphean–Ordovician rocks of the platform cover, which descend to the northeast accompanied by the complications of dip-slip and oblique fault nature. Paleozoic (Silurian – Permian), also terrigenous-carbonate, weakly displaced deposits of the upper structural layer of the cover occur in the sides of anticlines. In the southwest and northeast, the anticlinorium is confined by deep-seated

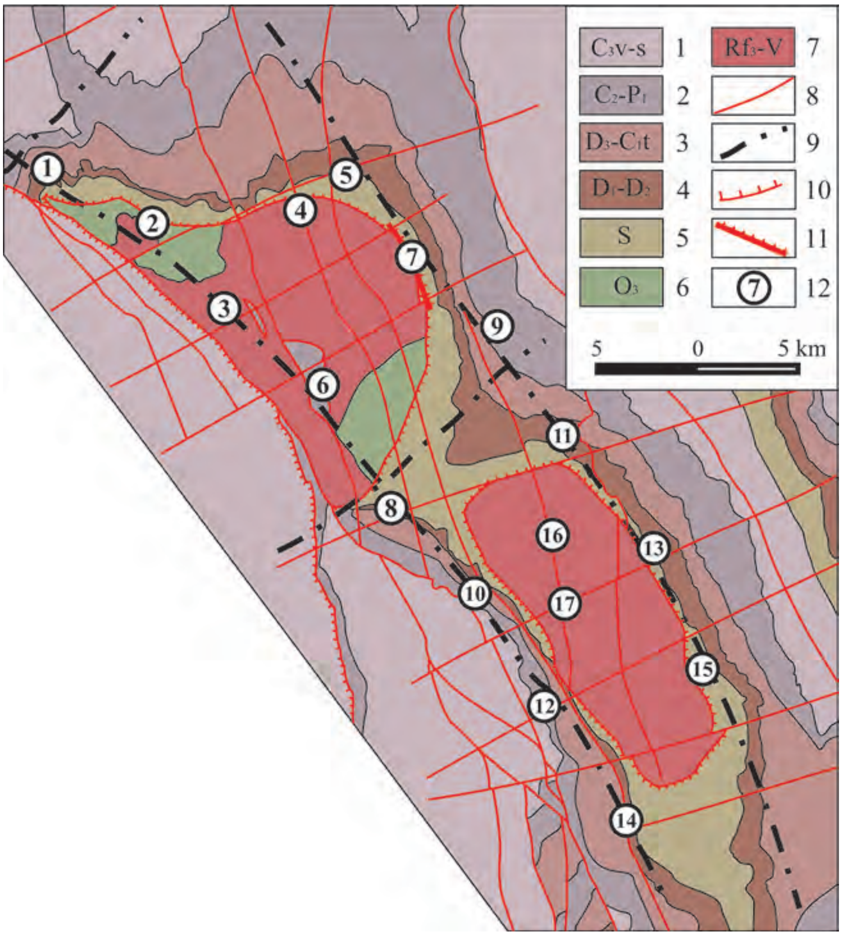

Fig. 1. Geological and structural scheme of the Polyudovo-Kolchim anticlinorium [Diamond-bearing…, 2011].

1–5 – Paleozoic sediments: 1 – Visean-Serpukhovian, 2 – Middle Carboniferous–Lower Permian, 3 – Upper Devonian–Tournaisian, 4 – Lower to Middle Devonian, 5 – Silurian; 6–7 – Riphean–Lower Paleozoic sediments: 6 – Ordovician, 7 – Riphean-Vendian; 8 – tectonic faults; 9 – regional deep faults hidden under overlying sediments; 10 – boundaries of structural tectonic levels; 11 – fragment of the Kolchim thrust; 12 – ore clusters: 1 – Storozhevsky, 2 – Klyuchevskoy, 3 – Dresvyanaya Steppe, 4 – Churochinsky, 5 – Zhalinsky, 6 – Burkochimsky, 7 – Efimovsky, 8 – Svetlinsky, 9 – Volynka, 10 – Ilya-Vozh, 11 – Vodorazdelny, 12 – Poludenno-Kolchim, 13 – Kocheshor, 14 – North Kolchim, 15 – Verkhny-Tulym, 16 – Bystrinsk, 17 – Lower Kocheshor.

faults. They were manifested in physical fields; however, in most cases, they were overlain by Paleozoic deposits, including by thrusts. It is along these deep-seated faults that the manifestations of diamond-bearing fluid-explosive breccia formations are located (or projected onto them). Only a few of them gravitate towards lower-order en echelon faults.

Fluid-explosive formations of the Efimovsky deposit, which is the most studied one, are confined to the northeastern part of the Kolchim anticline. Here, Vendian terrigenous deposits occur under gently dipping Silurian-Carboniferous terrigenous-carbonate deposits with the complications of strike-slip nature (Fig. 2). The boundary between them is tectonic – along the area of the Kolchim thrust of the northwest strike with a moderate northeast dip (17°) of the fault plane, which was established by drilling activities. In addition, to the northeast of the Kolchim thrust the deposit gravitates to the section of the hidden Ishkov fault having a steep east dip (75–80°) of the fault plane and a vertical amplitude of movement (40–60 m).

GEOLOGIC ASPECTS OF STRUCTURES AND COMPOSITION FLUID-EXPLOSIVE BRECCIA (FEB) FORMATIONS

The position of fluidogenic breccias in the given scheme indicates that the fluid explosions occurred along the zones of these major tectonic displacements, including along the interformational thrusts. Using all possible ways to head to the surface and penetrate into the host rocks, as a result of explosions fluids formed dyke-, sill-, cone-, vein- and sometimes stockwork-like breccia bodies. The most numerous dyke-like bodies are confined to steeply dipping faults of predominantly the northeast strike (see Fig. 2) at a thickness of

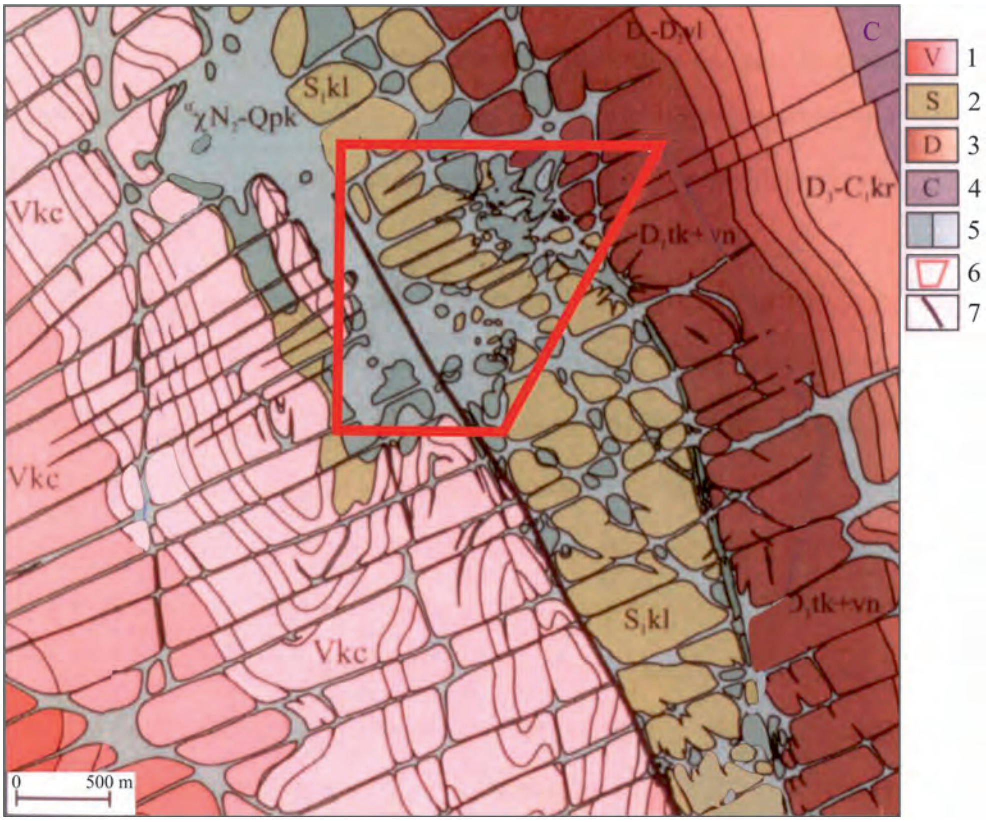

Fig. 2. Geological scheme of the Efimovsky deposit (by I.P. Teterin et al., unpublished report ‘Permgeologodobycha’, 2009).

1 – Vendian system (V kc – Kocheshor Formation, lower and upper strata); 2 – Silurian system (S kl – Kolchim Fm); 3 – Devonian system (D_1tk + vn – Takatin and Vanyashin Fm, D_1-D_2 vl – Volynka stratum, D_3-C_1 kr – siliceous stratum); 4 – Carboniferous system (C – West-Uralian Fm); 5 – fluid-explosive breccias (dark grey – the Polyudovo-Kolchim complex, light grey – the Efimovsky complex); 6 – contours of the Efimovsky deposit; 7 – fragment of the Kolchim thrust.

100–500 m. However, the Efimovsky deposit is formed mainly by two subtabular and sill-like bodies, injecting fault planes of the northwest strike, with a thickness of up to 70 m and a length of up to 7 km. They are predominantly associated with the Kolchim thrust; divided by the stratum of Lower Silurian dolomites; and transected by the dyke-like breccia bodies. The size of breccia bodies, which rarely have a cone-shaped form, varies from fractions of a meter to 400 m and more, and they usually form dyke-, sill- and vein-like apophyses into the basement rocks, creating a complex stockwork form.

The contacts of breccia bodies are usually indistinct, given that central parts of the bodies having a low number of clasts are enriched by them to their periphery and finally replaced by authigenic breccias. In addition, all the variety of fluidogenic breccia bodies are characterised by uneven contours of body walls and tree-like junctions, apophyses and veins, whose thickness, gradually decreasing, often reaches 1–2 mm at a length of tens of centimetres (Fig. 3).

The size of breccia bodies also varies; however the vast majority of them average tens of meters across reaching up to 2 km in length; they can usually be observed up to 200–300 m, rarely up to 500–600 m. The FEB bodies (all the diversity of which in the Urals and in some other regions is often called tuffisites) are very specific, having a spotted-mottled-yellowish-, greenish-or greyish-brown colouring. Macroscopically, they have the appearance of clay, sandy-clay, sandy, conglomerate-like rocks with unevenly dispersed fragments and sometimes implicitly manifested stratification and fluidisation. They contain a different number of fragments (from 20 to 60–70%), varying in size (from fractions of a millimetre to several metres), composition (usually polymictic) and form.

The nature of clasts undoubtedly constitutes an important indicator of diamond-bearing breccias. As in all breccias, angular clasts are constantly present and sometimes predominate. Due to explosive processes, as a rule, they are to some degree exposed to fragmentation and disintegration. However, the specificity of fluidogenic breccia, in particular, the rocks of the Efimovsky deposit, is that, along with angular clasts, almost constantly there are rounded clasts in them, sometimes with a shell-like cleavage. These clasts got their

Fig. 3. Different forms of fluid-explosive breccias [Diamond-bearing…, 2011].

shape after being in a mobile solid-gas stream, where they underwent abrasive, tumbling processing, rather than as a result of rolling, like in the case of sedimentary rocks. In addition, fluid-explosive breccia contains disintegrated ‘shadowy’ clasts, as well as the clasts of mineral grains with microexplosive fragmentation, reflecting a sharp drop of pressure with decompression, which constitutes their reliable identification feature. There are also shock-induced transformations of the fragments in the breccias under consideration manifested predominantly in the grains of the fragmented quartz of planar deformation features, sometimes shock-induced twinning, radial jointing, changes in refraction values, etc. Lithoclasts (terrigenous and carbonate rocks) and their mineral components (mostly quartz, rarer feldspar and dolomite) dominate the composition of clasts. There are also constant clasts of metamorphic rocks of the basement, alien to the host rocks, and of the cover engulfed and carried by the fluid flow. The borders of clasts with the binder mass differ in character – they can be both clear and indistinct, corrosion or reaction ones. The marginal zones of clasts are heavily fractured, filled with a cementing mass or gas-liquid inclusions, as they constitute the areas of their most syngenetic transformations. In some cases, the clasts in whole may be replaced by a fluidogenic mineral association or recrystallised.

The appearance of FEBs having a variety of fragments is complemented by the constant presence (in different ratios) of mineral grains of different origin. Some of them are minerals – for example, quartz – formed during the regeneration or granulation of clastic grains, while others are newly formed. The latter (quartz, carbonates, biotite, muscovite, hematite, goethite, etc.) crystallize mainly at the final stage in breccia formation and are not deformed if they have not been exposed to repeated explosions; they are often idiomorphic and do not contain gas-liquid inclusions. In addition, fluid flows are characterised by the discharge of the ore components of the fluid into the forming breccias (extraction during decompression), which leads to mineralisation, as well as diamond content [Endogenic..., 2018].

A characteristic feature of diamond-bearing breccias is the presence in them of protomagmatic minerals and magmatic mineral inclusions (xenoliths?) – outliers from the fluid-generating medium. These minerals and inclusions are rare, in many cases replaced by a mineral association similar to breccia cement, in which case they are identified by the morphology of grains and inclusions or detected in the heavy rock fraction. In general, phlogopite, olivine (serpentine), pyroxenes, pseudoleucite, leucoxene, pyrope (sometimes having a kelyphite rim), picroilmenite, chrome spinel and other minerals are found in diamond-bearing breccias, which suggests a deep-seated, possibly mantle, origin of the fluid. In thin sections, these minerals are rare, they are mainly observed in areas with porphyritic textures, within which breccias, in accordance with the classification, look like magmatogenic-fluidogenic ones.

Protomagmatic mineral grains are replaced to varying degrees by potassium feldspar, hydromica, quartz, carbonate, pyrite or an illite-smectite aggregate, often being predominant in the binder mass of the rock. In addition, in recent years, lenticular-striated inclusions of the magmatic lamproite component are found in them, which are close to orendites and madupites in composition [Luk’yanova, Sharpenok, 2004]. A microprobe study of the binder mass of these breccias carried out in thin sections, as well as using X-ray phase analysis, helped to detect microlites of sanidine (10–300 μm), whose amount sometimes reaches 5% of the mass and composition corresponds to the composition of lamproitic sanidine [Luk’yanova et al., 2005].

The diamond mineral association in Ural FEBs includes diamond, pyrope, chrome spinel, picroilmenite, chromium-bearing diopside, moissanite, native Pt, Hg, Fu, Bi, oxide (Mn-Fe-Ti) and silicate spherules and slags, kimberlite zircon, florencite and senaite [Chaikovskii, 2004]. The diamonds of this association have specific features uniting them with diamonds from Brazil, South-West Africa and Northeast Yakutia. Among them, curved-faced colourless (less often very light golden, pink or greenish-blue) dodecahedrons having a smooth relief, strong lustre and high transparency predominate; with about 80% of them being gemstones.

In general, the characterised diamond-bearing breccias, as a rule, have a heterogeneous breccia-taxite appearance in the absence, in most cases, of clastic material sorting. At the same time, along with mottled ataxite, mottled banded, banded (pseudo-layered) and fluid textures, which are close to eutaxitic texture, are noted in them. In some cases, they are due to sorting, kinetic redistribution of the material, rather than sedimentation; in other cases, however, matter suspended in the fluid is differentiated according to its size and concentrated during the laminar flow of a solid-gas flow or disintegrated clasts are pulled in the direction of the fluid flow with the formation of elongated layers, gradually merging with cement. Finally, both ataxitic and eutaxitic textures may be due to the coexistence of inclusions or streams of immiscible phases in the fluid. The decrystallisation of these phases during explosive phenomena leads to a mottled or oriented, flow-like arrangement of fluid components. Thus, it is the emulsion nature of the fluid that determines the mottled, lenticular-banded or fluid textures of FEBs, including ignimbrite- or even lava-like ones.

Indistinct borders and transitions are often noted between all structural varieties. So, in the case of a sequential increase in the binder mass of quartz-micaceous, illite-smectite striae, tuff-like breccias gradually acquire an ignimbrite shape. Resorption and reaction relationships of the binder mass with mineral grains (signs of the multi-stage manifestations of the fluid phase), as well as granulation and recrystallisation of minerals, most often quartz, are also characteristic. The high porosity and gas saturation of rocks, as well as clusters and minerals contained in them, also constitutes a very important and almost constant indicator of these breccias.

Like the rocks in general, the binder mass of fluidogenic breccias is also heterogeneous, consisting of fluidogenic cement, which contains this or that amount of a finely fragmented fraction. As a rule, it comprises a wide variety of structures. Tuff-like structure (sometimes called sandy, tuffisite, ashy) is the most common, with streaky-fluid, fluid, ignimbrite, lava-like structures, etc. being observed less frequently.

For fluidogenic breccias, it is natural that within bodies and even within the same thin section, various structural and compositional varieties (generations) of breccias are combined, between which – along with gradual, indistinct transitions – injection relationships are often established. This indicates their polyimpulse formation, whereas the relationships between the generations reflect close in time, but, most likely, successive pulses of the fluid-explosive process. Explosive manifestations can also be replaced by pneumatolitic, pneumatolite-metasomatic and hydrothermal-metasomatic, including dolomitisation.

Geological mapping and a large amount of mining work carried out in separate areas of diamond-bearing breccia formations revealed that their internal structure is heterogeneous. Thus, if we exclude from consideration authigenic breccias (sandstones, carbonate rocks, etc.), then at least three main generations of rocks (with internal facies and sometimes phase varieties), differing in their material composition, texture and structural features and, finally, diamond potential, exist as part of separate bodies (for example, the northern section of the Efimovsky deposit; Fig. 4).

In the early phase of the fluid-explosive process, polymodal (small-coarse clastic) tuff-like FEBs rich in clasts were formed. The different-sized fragments of Devonian sandstones and Silurian dolomites are immersed in a binder mass consisting of fragments of small and finely clastic fraction cemented by a fibrogranular quartz-micaceous cement. These breccias are associated with a low and very inhomogeneous diamond content.

The binder mass of these breccias can have two generations. The first is characterised by the filling of spaces between quartz crystalloclasts by mica-clay aggregate. The binder mass of the second generation includes both fragments of individual crystals and breccias with the cement of the first generation (Fig. 5). It is also characterised by a mica-clay composition with a high content of fine-grained sericite and a significant amount of ore mineral (iron oxides and hydroxides).

It should be noted that quartz crystalloclasts joined by a binder mass of the first generation have mainly angular facets. A distinctive feature of similar grains – already concentrated in the second-generation binder mass – is the predominance of rounded shapes in faceting (Fig. 6).

The grain borders of quartz are strongly corroded; reaction relationships with the cement are often observed (Fig. 7). Relatively large clasts of quartz are broken by a system of differently oriented fractures, often including gas-liquid chains. Both large and relatively smaller quartz crystalloclasts in most cases are characterised by undulose or block extinction.

The second phase of the explosive process (see Fig. 7) resulted in the formation of breccias moderately and inhomogeneously rich in the clastic basement rocks of breccia and finer dimension, as well as mineral grains cemented by smectite-hydromica fluidogenic mineral association.

Rock clasts are characterised by different morphology. Lithoclastic formations characterised by rounded and sometimes indistinct or transitional borders with respect to the binder mass are widespread. The formation of such borders in lithoclasts is caused by the pene-

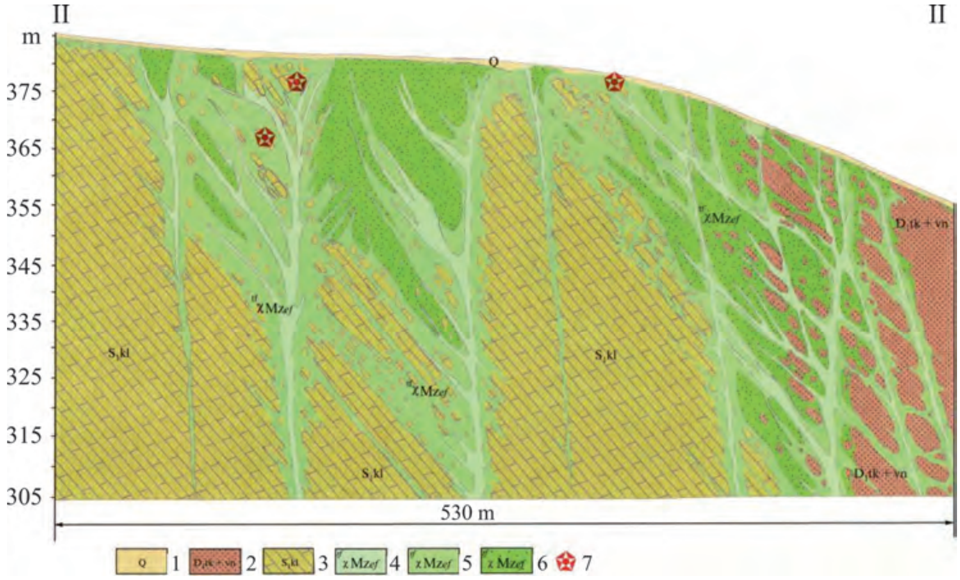

Fig. 4. Geological cross section of the northern area of the Efimovsky deposit [Diamond-bearing…, 2011].

1 – Quaternary deposits (clays, crushed stone and blocks of bedrock); 2 – Takatin and Vanyashin Devonian formations (sandstones); 3 – Silurian Kolchim suite (dolomites); 4–6 – Efimovsky complex: 4 – argillizite fluid-explosive breccias of the third phase, 5 – fluid-explosive breccias of the second phase, 6 – fluid-explosive breccias of the first phase; 7 – diamond finds.

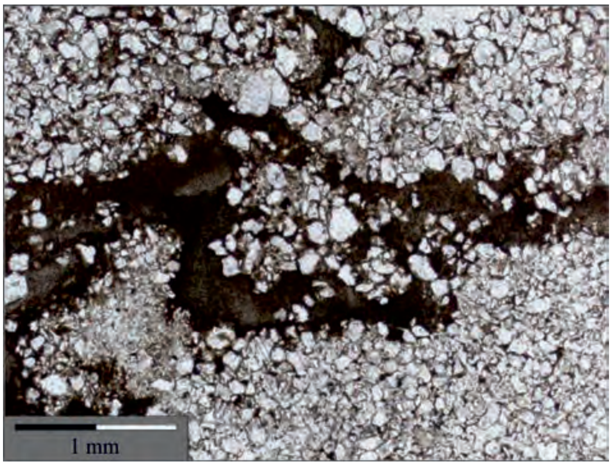

Fig. 5. Clasts of aposandstone breccia, cemented by first-generation binder mass and enclosed in second-generation cement.

tration of cement minerals through the various types of fractures: both those formed during brecciation processes and along the primary fractures of bedding, with the replacement of brecciated sedimentary rocks. The predominant aggregates developing from rock clasts include quartz-sericite-clay (in the case of substitution of quartz sandstones, less often argillites) and clay-ore ones (in the case of the substitution of clasts, presumably, of the main effusive rocks), in which iron oxides and hydroxides predominate (Fig. 8).

Breccias are characterised by a fairly significant distribution of crystalloclasts enclosed in a cementitious mass. Quartz grains are most often found among the crystal clasts. In most cases, they have rounded, largely corroded borders. A lot of, especially large, grains of the mineral are broken by a differently oriented system of fractures, along which the development of gas-liquid inclusions is observed. Almost all quartz crystalloclasts are characterised by block extinction and a lot of them have planar features (Fig. 9).

Breccias of this generation are characterised by the maximum diamond content for the Efimovsky deposit; however, like for the early breccias, it is inhomogeneous. The shape of productive bodies is diverse. They include simple and complex lenses, pockets, steeply dipping columns consisting of pocket-like and lenticular inclusions, veins and irregularly shaped injections. As a result of studying some of the bodies in detail, up to 5–7 varieties of breccias having both phase and facies relationships have been identified. It is not possible to reliably assess the diamond potential of each of them; however, the maximum diamond contents gravitate toward the lower parts of the sill.

The final stage in the formation of the sill-like breccia body of the Efimovsky deposit is fixed by the formation of very dense argillizites with a small amount of xenogenic material. The diamond content of these rocks is extremely low.

Lithoclasts immersed in a quartz-mica-clay cementitious mass make up no more than 30–35% of the total breccia. Among the rock clasts, argillites and siltstones predominate, with quartz sandstones being relatively rare. Elongated lithoclasts with rounded smooth, often indistinct borders are very widespread (Fig. 10). The smoothest transitions are observed between the bind-

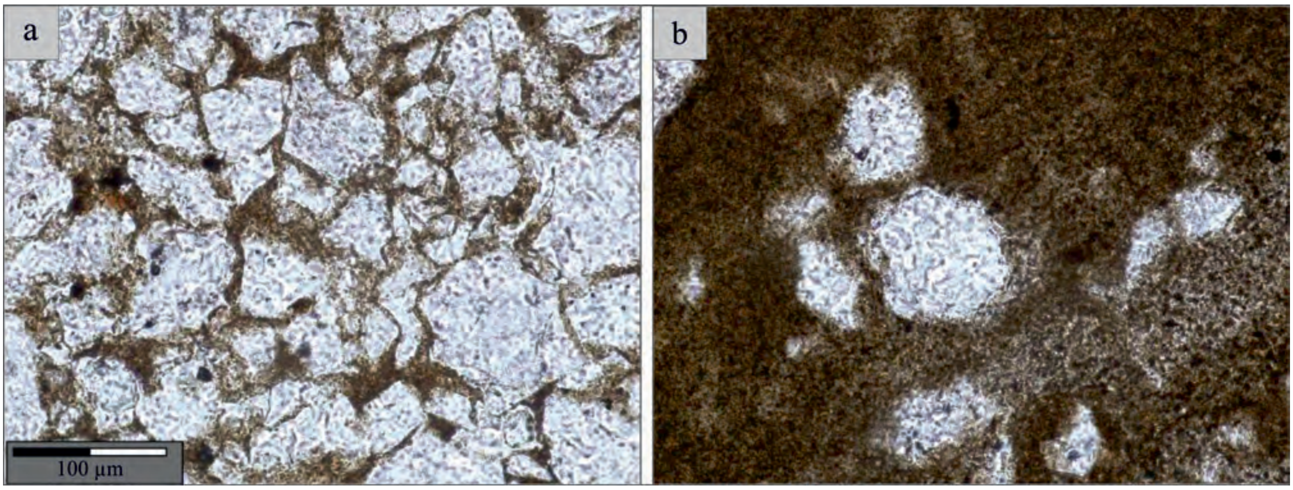

Fig. 6. Grains of quartz characterised by different morphology, enclosed in the cementing mass of the first (a) and second (b) generations.

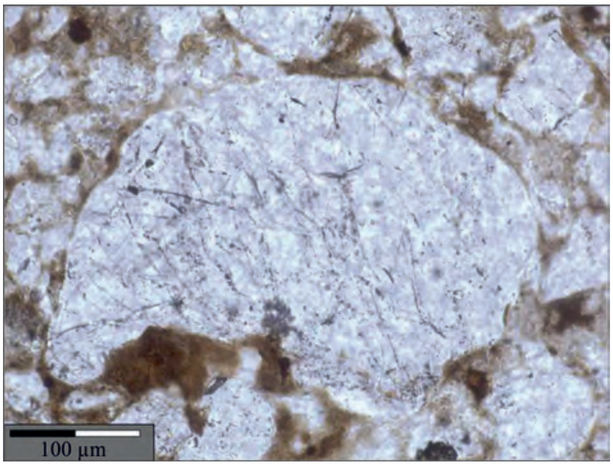

Fig. 7. Quartz grain having rounded corroded borders, broken by a system of differently oriented fractures with gas-liquid inclusions.

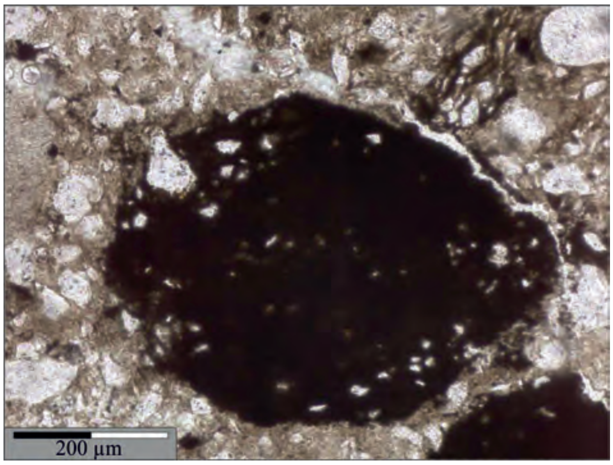

Fig. 8. Crystalloclast (olivine) replaced by an aggregate of ore minerals.

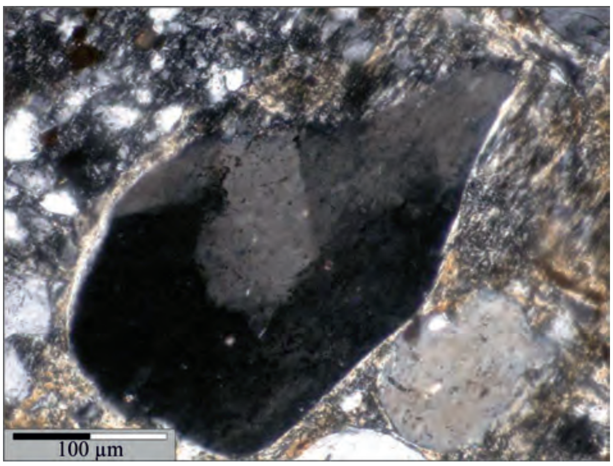

Fig. 9. Quartz grain characterised by distinctive block extinction.

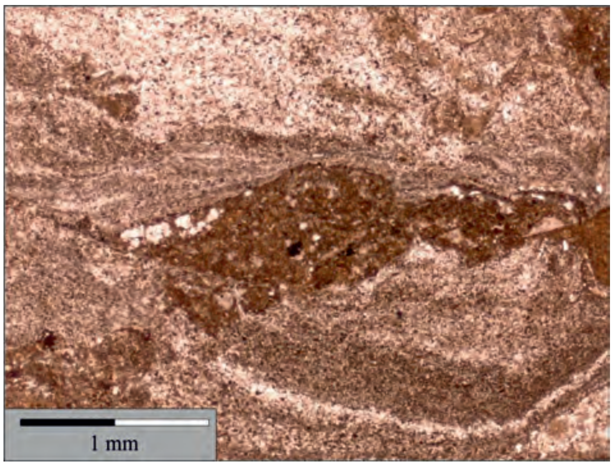

Fig. 10. A clast of rock in the binder mass.

er mass and clasts of argillites, which, apparently, are largely replaced by cement minerals during fluidisation processes.

Crystalloclasts are rarely present in these breccias. Among them, different-sized clasts of quartz grains predominate, which in most cases have rounded corroded borders. Quite often, the chains of quartz grains oriented along the flow structures are observed. Individual quartz grains are often broken by variously oriented fractures along which chains of gas-liquid inclusions develop, and have a pronounced block extinction.

Cementing mass constitutes a fine-grained quartz-sericite-clay aggregate exhibiting quite significant variations in the mineral composition and well-marked traces of the flow. The binder mass minerals include both newly formed minerals (sericite, newly formed quartz and partly clay minerals) and finely crushed grain fragments formed during brecciation. Relatively rarely, the general fine-grained background of cement reveals individual rather large, in many cases strongly curved, newly formed grains of biotite and muscovite. Finely-dispersed aggregates of ore minerals characterised by a predominance of iron oxides and hydroxides have a significant and very uneven development in the binder mass.

In the breccias of predominantly the first and second phases of brecciation, protomagmatic minerals sometimes occur along with newly formed minerals and clastic material in the binder mass in thin sections. Of these, the most common is zircon. In most cases, these are fragments of individual grains, less commonly, individual minerals having prismatic or long-prismatic idiomorphic faceting. According to [Zhukov et al., 1978; Diamond-bearing..., 2011], a fairly wide spectrum of protomagmatic minerals is distinguished in crushed and stream-sediment samples for fluid-explosive formations of the Efimovsky deposit; however, in thin sections these minerals are extremely rare and are significantly susceptible to secondary changes, which greatly complicates their identification.

FEBs have some specific chemical characteristics. Given that these rocks constitute an additive result of the interaction and coexistence of components of various origins, the chemistry of diamond-bearing FEBs can be considered only in a comparative aspect. The studies on the chemical characteristics of these rocks in the Vishera area of the Urals [Landa, Luk'yanova, 2003; Diamond-bearing..., 2011] revealed their dual nature. Being similar to the upper crustal formations in a number of parameters, which is primarily due to the presence of absorbed substance of the host rocks in them, they at the same time possess certain characteristics that reflect their deep-seated origin and similarity with rocks classified, for example, in Central Italy as madupite lamproites. They are similar in terms of their elevated contents of titanium, phosphorus, magnesium, potassium, trace and rare-earth elements, as well as the specific distribution of petrogenic elements, REEs and refractory lithophiles. The level of ratios of indicative elements (Rb/Sr, U/Th, etc.), as well as the nature of the variability in the contents of elements are shown on a number of charts [Diamond-bearing..., 2011].

In general, FEBs under consideration exhibit a potassium specificity. Their potassium content correlates with the content of titanium, phosphorus, chromium, manganese, iron, sometimes barium, strontium and vanadium. In addition, the rocks are usually abnormally enriched with silicon and ore minerals, which, according to F.A. Letnikov [1992], is the effect of exceptionally high extraction of silica and ore minerals from fluid. Thus, the petrogeochemical features of the breccia rocks in question allow us to consider the composition and depth of the primary fluid source, generating breccia, which is rather relative than definite and depends on the composition of the components of magmatic origin present in them, including protomagmatic minerals (phlogopite, pseudoleucite, sanidine, olivine, pyroxenes, alkaline amphiboles, chrome spinels, etc.).

CONDITIONS FOR THE FORMATION OF FLUID EXPLOSIVE BRECCIAS

Briefly given diverse compositional characteristics of the diamond-bearing FEBs of the West Urals, as well as the injective nature of the bodies formed by them (in a closed system), allowed their researchers to validate both their endogenous origin and the deep-seated (mantle?) origin of the fluid flow. This flow was formed as a result of fluid explosions, similar in composition to their magmatic (rock and mineral) components – lamproites [Luk'yanova, Sharpenok, 2004].

Clearly, the formation of a diamond-bearing fluid thermodynamic system [Zhukov, 2000] occurred under unstable PT-conditions. These conditions existed both during its genesis at the deep-seated (mantle?) level and during its subsequent evolution and formation at the crustal and surface levels. The instability of *P-T* conditions in the thermodynamic system generating these breccias at the mantle level caused, first of all, the discreteness of the crystallisation medium of barophilic minerals, in particular diamonds. In accordance with this, the processes of their predominant growth in the melt alternated with the predominance of dissolution. This led to the formation of crystals with a zoned distribution of table-cut and curved-faced shapes [Shafranovskii, 2001]. The curved habit of a diamond is a more stable form when dissolution processes dominate in the crystallisation medium. It is this fact that predetermined the sharp predominance of relatively large curved-faced diamonds (Ural or Brazilian type) with a small content of table-cut crystals in fluidogenic diamond-bearing breccias. Thus, the discovery of curved-faced diamonds in the area under study constitutes a direct qualitative criterion for the identification of diamond-bearing fluidogenic breccias.

Further development of the fluid thermodynamic system was associated with the pulsed movement of the fluid under periodically repeated stretching conditions at the subcrustal and crustal levels. Under these conditions, a specific flow, which constituted a solid-liquid-gas phase, moved towards the earth's surface along deep-seated faults accompanied by a complex system of oblique-slip faults in active mobile zones. This forward movement, with the processes of stretching and compression alternating, also had a pulsating character, which led to the existence of a multitude, often the thinnest (hairy-like) apophyses into the host rocks with them being crushed (Fig. 11).

The liquid-gas phases of the fluid were transformed by the way of extraction and pneumatolysis during explosions predominantly into mineral masses, as well as into newly formed grains of minerals. Mineral masses cement primary protomagmatic mineral formations, including pseudomorphs after them, various xenoliths and mineral grains trapped during explosions, resulting in the formation of FEBs. Recurring pulses of these phenomena lead to the formation of complex diamond-bearing structures.

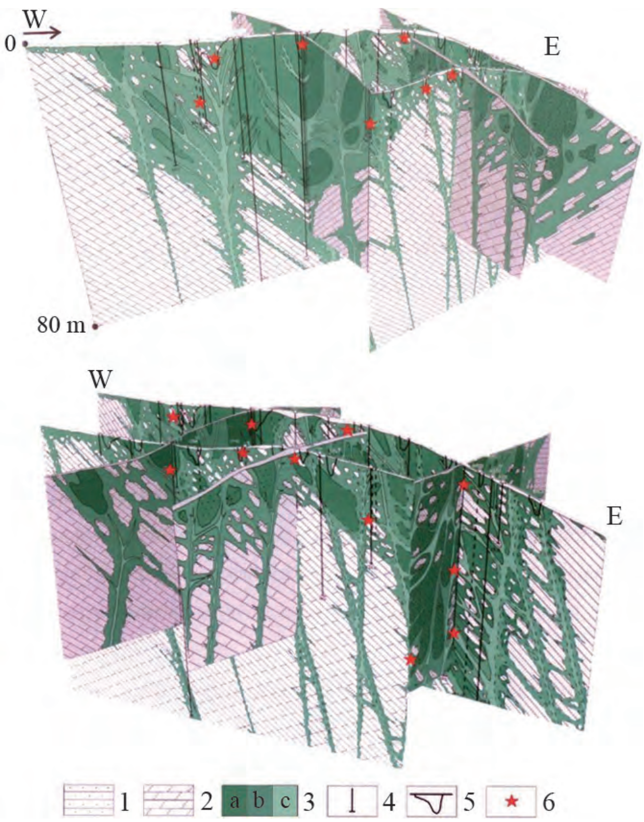

Fig. 11. Three-dimensional model of the northern part of the Efimovsky deposit [Korotchenkova, 2012] built drawing on the materials of [Petukhov, Teterin, 2007].

1 – sandstones of the Takatin suite; 2 – dolomites of the Kolchim suite; 3 – fluid-explosive breccias: a – the first phase, b – the second phase, c – the third phase; 4 – boreholes, 5 – excavation ditches, 6 – diamond finds.

The above-listed features of a typical ore-bearing diamondiferous breccia structure allow us to validate a working geological and petrological model, whose main components are presented in Table 1.

CONCLUSIONS

The model for the formation of a fluid-explosive diamond-bearing structure includes the following main elements:

– the position of the diamond-bearing structure in the marginal zone of the ancient platform and its location at the junction of two large structures (Timan and Urals) explains the significant development of heat and mass transfer of matter, as well as of the general high-energy state of the system, resulting in melt-fluid formations at the upper mantle or lower crustal levels;

– the fragmentation of the basement by deep-seated faults, including strike-slip and thrust faults, the development of numerous discontinuous faults in the rocks of the platform cover; they cause a significant flow of deep-seated solid-gas-liquid fluids to the surface, where, due to the existence of structural traps, fluid mixes with low-temperature meteorite waters and interacts with overlying rocks, thus causing explosive processes that lead to the formation of fluid-explosive structures;

– compression and decompression phenomena, leading to the crushing of the clasts of host rocks, the solid components of the fluid flow, the mineral grains of various origin and the breccias of the previous phases with the formation of fluidogenic breccia rocks characterised by specific mineral formation (explosion-extraction-pneumatolysis);

– the polyphase (polyimpulse) development of the breccia complex, the interaction of fluid with the basement rocks, meteorite waters and the substance of highly mineralised brines led to the formation of three types of fluid-explosive breccias having different diamond potential: early – medium-large crystal-lithoclastic breccias having a small amount of cement (aposandstone breccias); mature – small-medium lithocrystalloclastic polyfacies breccias ('sandy-clay') with a significant amount of binder mass consisting of micaceous-quartz-clay cement and clasts of rocks and minerals of a fine fraction; late – small, finely clastic, predominantly crystalloclastic argillizite breccias; fluid-explosive breccias of the second type are the richest in diamonds, whereas the first type of breccias reveal little diamond potential and diamonds are practically absent in breccias belonging to the third type.

Table 1. Main characteristics of diamond-bearing fluid-explosive breccia formation

Diamond-bearing breccia formations		Characteristics – criteria							Examples of deposits and occurrences
		Geological and structural		Geophysical	Compositional				
		Regional	Local		Petrographic	Mineralogical	Geochemical	Mineralisation	
FEBs of hidden fluid explosions, spatially separated from t he source of fluids	Diamond-bearing fluid-explosive breccias (Ural type)	1. Confinement to the marginal parts of ancient platforms complicated by mobile zones 2. Fragmentation of the basement by deep-seated faults, including oblique-slip faults 3. Widespread development of sandy, clay and carbonate deposits in the cover 4. Occurrences of basic and ultrabasic magmatism 5. Increased diamond potential of the territory	1. Widespread development of faults, excessive fracturing 2. Discordant rocks, intervals in sedimentation 3. Presence of erosion depressions 4. Placers of curved-faced diamonds 5. Discovery of fluid-explosive breccia formations	I. Regional homogeneities 1. The gradient zones of gravimetric anomalies, as well as the 'chains' of negative discontinuous anomalies 2. Anomalies in the endogenous heat flux Subvertical inhomogeneities in petromagnetic and density sections along with local magnetic anomalies of low intensity (3–20 nT) II. Local heterogeneities In the gravity field, fluid-explosive breccia bodies are characterised by negative anomalies. In geoelectric sections, argillizite breccia varieties yield $\rho_к$ values of 200–600 ohm·m, whereas essentially quartz varieties show values of 900–1500 ohm·m	Highly heterogeneous appearance of rocks: tuff-like and argillizite breccias (often conglomerate-like, sandy) Ataxitic breccia, structures with micaceous-quartz-clay, argillizite and tuff-like cement A variety of xenoclasts, including deep-seated ones exhibiting signs of explosive crushing The combination of mineral grains of various origin: xenogenic and newly formed (quartz, mica and carbonates)	Indicative mineralogical association: limonite, hematite, kyanite, staurolite, tourmaline, rutile, corundum, pyrope- almandine, spinels and native metals The constant presence of spherites (limonite, hematite and carbonates), pyrite, barite, manganese, occasional diopside and hornblende There are also pyropes, diamonds, picroilmenites chrome-diopsides, chrome spinels	1. Abnormally high levels of correlatable Ni, Mn, Zn, Pb, Cd, Ag, Y and Yb. Of the listed elements, the combination of Ni, Mn, Zn and Pb is the optimal indicator of diamond potential 2. Potassium petrochemical specificity. The correlation of K_2O content with Ti, P, Cr, Mn and Fe	Specific non-metallic, diamond: dodecahedrons, their clasts, crystals having a transitional habit; cluster crystal	Efimovsky, Malaya Porozhnaya, Rybyakov, Ilya-Vozh, Volynka (Perm Territory); Luzhsky District, Leningrad Region; Minas Gerais, Brazil

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