crystals

MDPI

Article

Specific Internal Structure of Diamonds from Zarnitsa Kimberlite Pipe

Alexey Ragozin [1,2,*], Dmitry Zedgenizov [1,2], Konstantin Kuper [3] and Yuri Palyanov [1,2]

1 V. S. Sobolev Institute of Geology and Mineralogy, Siberian Branch Russian Academy of Sciences, Novosibirsk 630090, Russia; zed@igm.nsc.ru (D.Z.); palyanov@igm.nsc.ru (Y.P.)
2 Department of Geology and Geophysics, Novosibirsk State University, Novosibirsk 630090, Russia
3 Budker Institute of Nuclear Physics, Siberian Branch Russian Academy of Sciences, Novosibirsk 630090, Russia; k.e.kuper@inp.nsk.su
* Correspondence: ragoz@igm.nsc.ru; Tel.: +7-383-330-8015

Academic Editor: Helmut Cölfen
Received: 30 March 2017; Accepted: 7 May 2017; Published: 11 May 2017

Abstract: The Zarnitsa kimberlite pipe is one of the largest pipes of the Yakutian diamondiferous province. Currently, some limited published data exists on the diamonds from this deposit. Among the diamond population of this pipe there is a specific series of dark gray to black diamonds with transition morphologies between octahedron and rounded rhombic dodecahedron. These diamonds have specific zonal and sectorial mosaic-block internal structures. The inner parts of these crystals have polycrystalline structure with significant misorientations between sub-individuals. The high consistency of the mechanical admixtures (inclusions) in the diamonds cores can cause a high grid stress of the crystal structure and promote the block (polycrystalline) structure of the core components. These diamond crystals have subsequently been formed due to crystallization of bigger sub-individuals on the polycrystalline cores according to the geometric selection law.

Keywords: diamond; internal structure; diffraction of backscattered electrons; radial mosaic pattern; Zarnitsa kimberlite pipe

1. Introduction

The first diamondiferous kimberlite pipe found on the Siberian Platform was named Zarnitsa (Dawn). It was discovered by L.A. Popugaeva in 1954 [1] in the Daldyn-Alakit kimberlite field of the Yakutian diamondiferous province. The Zarnitsa kimberlite pipe is one of the largest pipe in Yakutia, having a surface size of 535 $\times$ 480 m. Currently, only limited data has been published on the diamonds excavated from this deposit. According to [2], most of the diamond crystals (96%) in this pipe are octahedral (23%), laminar rhombic dodecahedral (20%), and rounded dodecahedral (29%) with transitional habits between octahedron and dodecahedron (17%). Less common are the grey polycrystalline diamonds (bort), cuboids and coated diamonds.

In this work, we have studied a specific series of individual diamonds and their aggregates which were representing the dark gray- to black-coloured crystals of transitional octahedron and rhombic dodecahedron habits. These diamonds have similar morphological features to the dark grey rounded diamonds which are widespread in the alluvial placers of the northeastern part of the Siberian platform [3–7]. They are classified as variety V with aggregates of variety VII, according to the Yu. Orlov classification [8]. The similarity between the crystals studied in the current work and the rounded diamonds from alluvial deposits can be seen primarily in the presence of many black inclusions, which are unevenly distributed along the samples' volume. The rounded morphology of the diamonds from the Zarnitsa kimberlite pipe, the transition between octahedron and rhombic dodecahedron habits, and the presence of the specific micro-relief surface structure may also be found in the alluvial diamonds of the Siberian Platform [3]. Previous studies demonstrate that rounded alluvial diamonds from these placers are characterized by the radial mosaic internal structure that is unusual for natural diamonds as this structure is formed by the splitting crystal growth mechanism [9]. Until recently, similar diamonds have not been found in kimberlite pipes closer to the alluvial placers nor in any other known kimberlite pipes of the Yakutian diamondiferous province. In the current work, we provide a detailed study of the internal diamond structure found in Zarnitsa kimberlite pipe diamonds. We then compare this structure to the structure of authentic crystals of variety V and VII found in alluvial placers.

2. Results

2.1. Morphology

In the current work, 16 grey- to black-diamonds from Zarnitsa kimberlite pipe were selected for internal structure study (Figure 1). The samples include rounded or half-rounded diamonds, with octahedron and rounded rhombic dodecahedron crystal habits, and the aggregates of such crystals (Figure 2). The yellowish and brownish hue of some diamonds is due to secondary iron oxides/hydroxides deposits that developed on thin cracks in the external parts of the crystals. The dark grey-to-black colour is explained by the presence of numerous black inclusions, within the matrix of the diamond itself which is typically characterized by a colourless and transparent crystal.

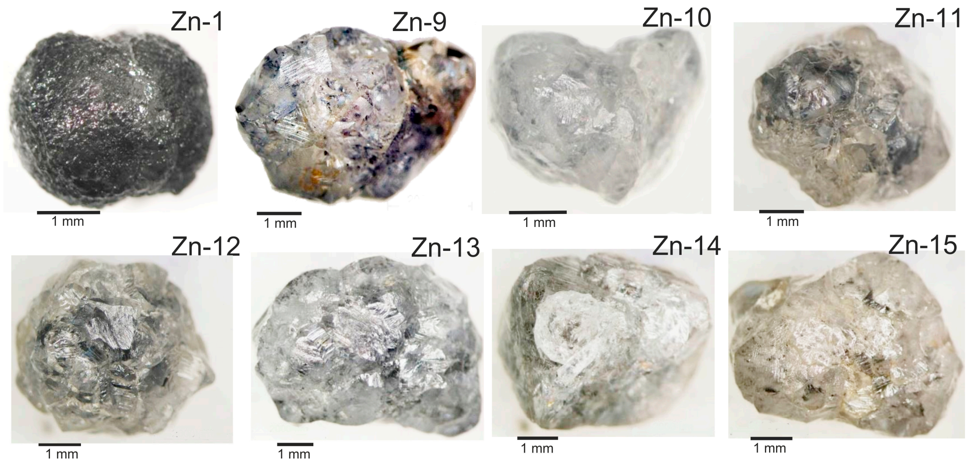

Figure 1. Rounded rough diamonds from Zarnitsa kimberlite pipe (optical microphotographs).

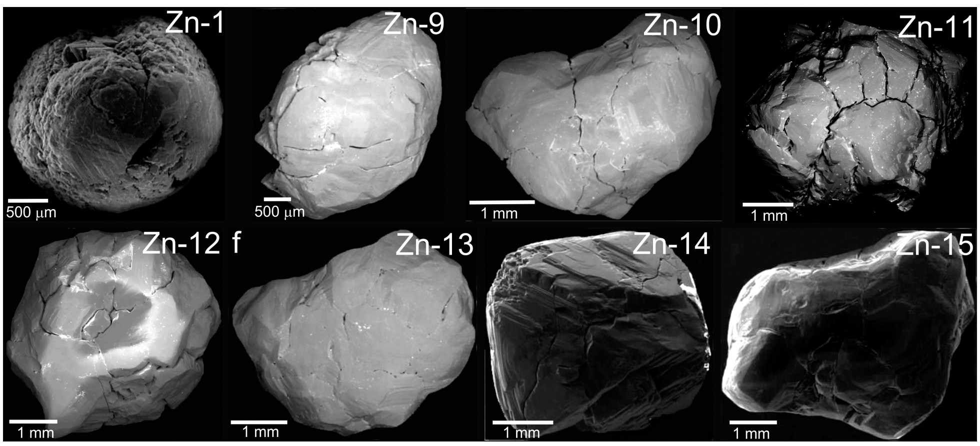

Figure 2. Morphology of diamonds (SEM images).

Morphological features specific to the so-called half-rounded diamonds [10] can be seen in the studied kimberlite pipe diamonds. The crystal morphology includes (1) laminar octahedral faces with clear laminar structure and ditrigonal layers, decreasing in size in a step-by-step pattern towards the periphery; (2) convex rounded surfaces at the octahedral edges with sheaf-like striations produced by the ditrigonal layered-steps of the octahedral faces; and (3) in some crystals, a smooth rounded surface close to the (111) apex is located hypsometrically lower than the combination surfaces and ditrigonal layers. In some cases, the morphology of the diamonds is complicated by: rounded apexes; elongated, drop-shaped hillocks on the dodecahedral crystal faces; etch channels; and a great number of small rounded holes.

The morphology of a Zn-14 diamond is characterized by laminar octahedral edges with clear laminar structure (Figure 2, Sample Zn-1). The vestiges of octahedral edges are also often seen on other crystal types; they are distinguished by ditrigonal layers of varying thickness that diminish step-wise towards the periphery. Triangular pits, which are generally called trigons [11], are a very common and distinctive feature of the octahedral crystal faces of these diamonds. Trigons vary in size up to 300 μm; a single diamond is commonly comprised of many trigons with a wide range of sizes. Even octahedral crystal faces, which visually appear pristine and smooth, can often contain microscopic trigons. Trigons have flat bottoms and are oriented in the direction opposite the underlying crystal face. These trigons are referred to as negative trigons and are typical microrelief features found on the surface reflecting the dissolution processes [12].

In addition to the laminar octahedral faces, the habitus of the crystals includes rounded surfaces. There are usually arched combination surfaces at the octahedral edges, which are sculptured by sheaf-like striation. The striation is a complex of edges found on ditrigonal layers in octahedron faces. These combination surfaces are not true crystal faces (110) but are close enough to the face that the dodecahedral diamond habit is sometimes described as a dodecahedroid. These surfaces also have many microrelief elements. such as drop-shaped hillocks and disc sculptures. The development stage of these combination surfaces varies from sample to sample. Thus, in the Zn-14 sample (Figures 1 and 2), they are weakly developed, which is why the habit of this diamond is mostly octahedral. In some cases (Zn-9 and Zn-10 samples), rounded surfaces prevail in the external morphology (Figures 1 and 2). In these samples, only the remaining laminar octahedral faces are fixed. The Zn-1 sample (Figures 1 and 2) has an almost spherical shape, as in the surface sculpture specific for diamond spherulites (ballas diamonds).

In some crystals (Zn-10, Zn-13, Zn-15 samples), convex rounded surfaces are fixed close to the (111) apex, located hypsometrically below combination surfaces and octahedral ditrigonal layers. On these surfaces, shagreen and round drop-shaped hillocks are occasionally seen. These surfaces have round dodecahedral shape which is the final dissolution form of primarily octahedral crystals. Sometimes the morphology of such crystals is complicated by rounded apexes, rock coatings, deep-etched channels and cracks (see Figure 2c–e). Such features are specific to diamond crystals that have undergone intensive dissolution [12–17].

2.2. Internal Structure

2.2.1. Optical Microscopy

The interference pattern of anomalous birefringence is not expected for crystals of cubic syngony. Diamonds belongs to the cubic crystal system and should therefore exhibit isotropic optical properties. However, many research studies on diamonds often show weak birefringence [18,19]. The appearance of anomalous birefringence may indicate a high degree of crystal structure deformation. High interference colours with cross polarizers indicate that a strong deformation exists within the crystalline structure. Internal stress in diamonds may be caused by (i) dislocations; (ii) lattice parameter deviations (caused by lattice impurities); (iii) inclusions; (iv) cracks; and (v) plastic deformation [20,21].

The optical microscopy-based observations of polished plates reveal zonal and sectorial internal structure in the diamond samples. In the core of the Zarnitsa kimberlite pipe diamond crystals, the highest concentration of black coatings and cracks are usually visible, making them almost non-transparent in most cases (Figure 3). In some cases, high inclusion concentrations are not visible in the central region of the diamond; though, the high-order interference colours (bright colours), from the central diamond region, are visible on the periphery. Thus, in the external zones of a Zn-14 crystal (Figures 3 and 4), only the regions with wavy extinction and birefringence pattern indicates a lack of stress in the crystalline structure. Moreover, diamonds with sectoral inhomogeneity are primarily expressed by the different concentrations of mechanical impurities (inclusions) in the various growth sectors. As seen in Figure 3, some growth sectors contain little three-dimensional defects while other sectors are rich with inclusions. In the Zn-1 sample (Figure 3), black microinclusions are located along the radial fibrous lines and develop from the inner parts of the crystal to its periphery. In addition, birefringence patterns show the various growth sector structures. The areas in the crystals associated with the growth sectors with a small quantity of black inclusions is quantified by fewer deformations compared to the other volume of diamonds. Unlike crystal volumes with abundant inclusions, only the wavy extinction or the specific tatami-like patterns are visible in the crossed polarizers (Figure 3). Such patterns are usually explained by a plastic deformation and fibrous internal structures specific to diamonds with cubic habits [22,23]. In the volume of crystals with abundant inclusions, strong interference is fixed which indicates a high deformation of the crystal structure. Such an interference pattern is a result of the uneven stress distribution within the crystal volume.

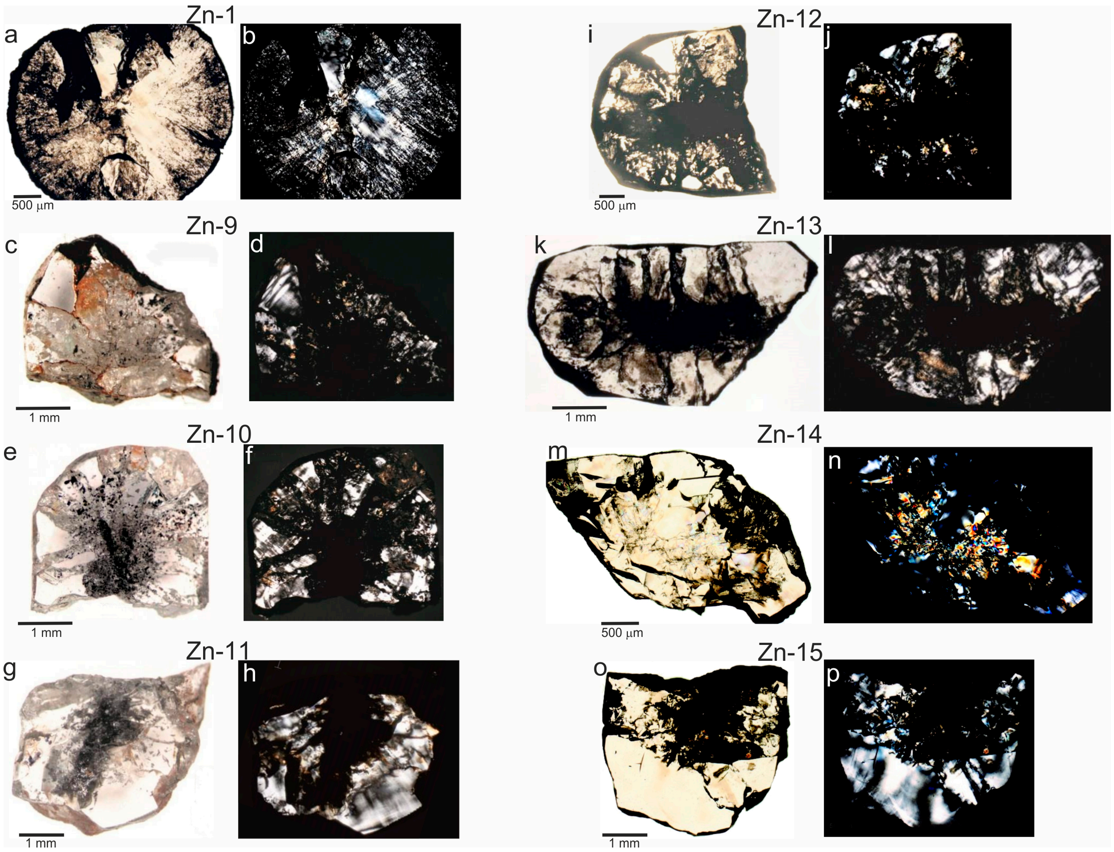

Figure 3. Internal morphology of double-polished diamond plates ((**a**,**c**,**e**,**g**,**i**,**k**,**m**,**o**)—transmitted polarized light; (**b**,**d**,**f**,**h**,**j**,**l**,**n**,**p**)—birefringence pattern).

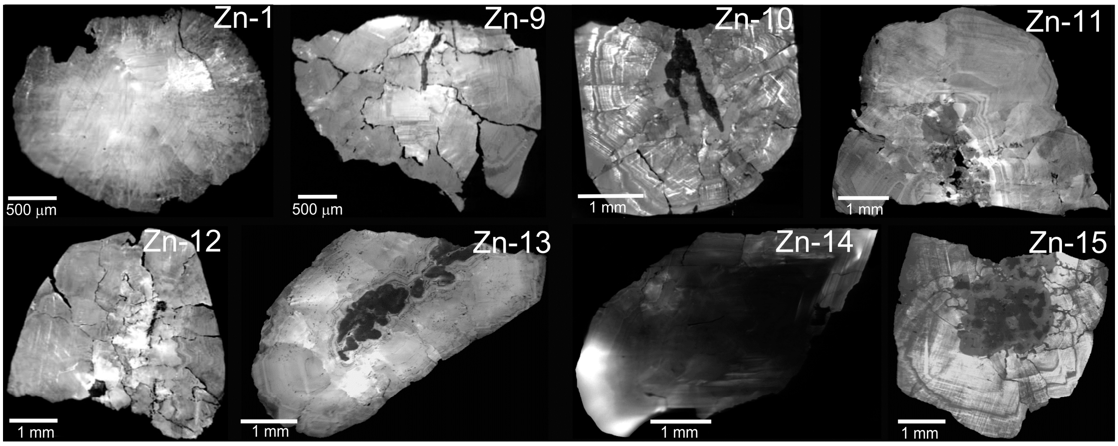

Figure 4. Cathodoluminescence images of polished plates from diamond showing zoning structures, and irregularly shaped polycrystalline cores with dark luminescence.

2.2.2. Cathodoluminescence Imagery

Cathodoluminescence (CL) is one of techniques that allows direct visual observation of crystal growth patterns, zonality and sectorality. The borders of diamond zones and sectors are visible by CL due to the uneven distribution of impurities (isomorphic nitrogen impurities in the form of a defect or microinclusion) found in the crystal volumes [24,25]. Zonal structure is noticed clearly on the CL topographs of diamonds from the Zarnitsa kimberlite pipe (Figure 4). Weak core luminescence is a specific feature of most diamond cores with complicated structures and irregular morphologies. Diamond cores complicate the mosaic structure of the crystal because central parts of the crystals with dark luminescence contain numerous blocks that tightly coalescence with each other, which is specific to polycrystalline bodies (Figure 4, Samples Zn-11, Zn-13, Zn-15). External zones have brighter luminescence on CL topographs. Concentric zonal structures are also seen at the external zones. The shape of growth-zonality close to the diamond centre repeats the contour aggregations in the core (Figure 4, Sample Zn-13). Such zonal structure reflects the primary irregular core morphology. Peripheral parts of the crystal samples also show rounded shapes in some cases; however, in most cases, straight linear octahedral zones are seen.

2.2.3. Electron Backscatter Diffraction (EBSD)

The EBSD technique is capable of precisely determining the textural features of the crystals, expressed as lattice orientation relationships between the macroblocks (subgrains). The EBSD technique reveals that the Zarnitsa kimberlite pipe diamonds have a mosaic block internal structure (Figure 5). The EBSD images show that the diamonds consist of numerous (up to 37) blocks of different size (subindividual), which are disoriented between each other. The disorientation angle of the blocks reach significant values up to 47° (Figure 5). The size of the block increases from the crystal core to the periphery because subindividuals originate at the centre and extend to its surface. Finally, such subindividual systems form the radial structure. At the same time, a bigger quantity of small disoriented blocks is seen in the diamond center. The significant disorientation angle of the block points to elements of polycrystalline structure in the diamond samples. Microscopically, the diamond samples either have the form of single crystals or consist of several (up to 4) monocrystals.

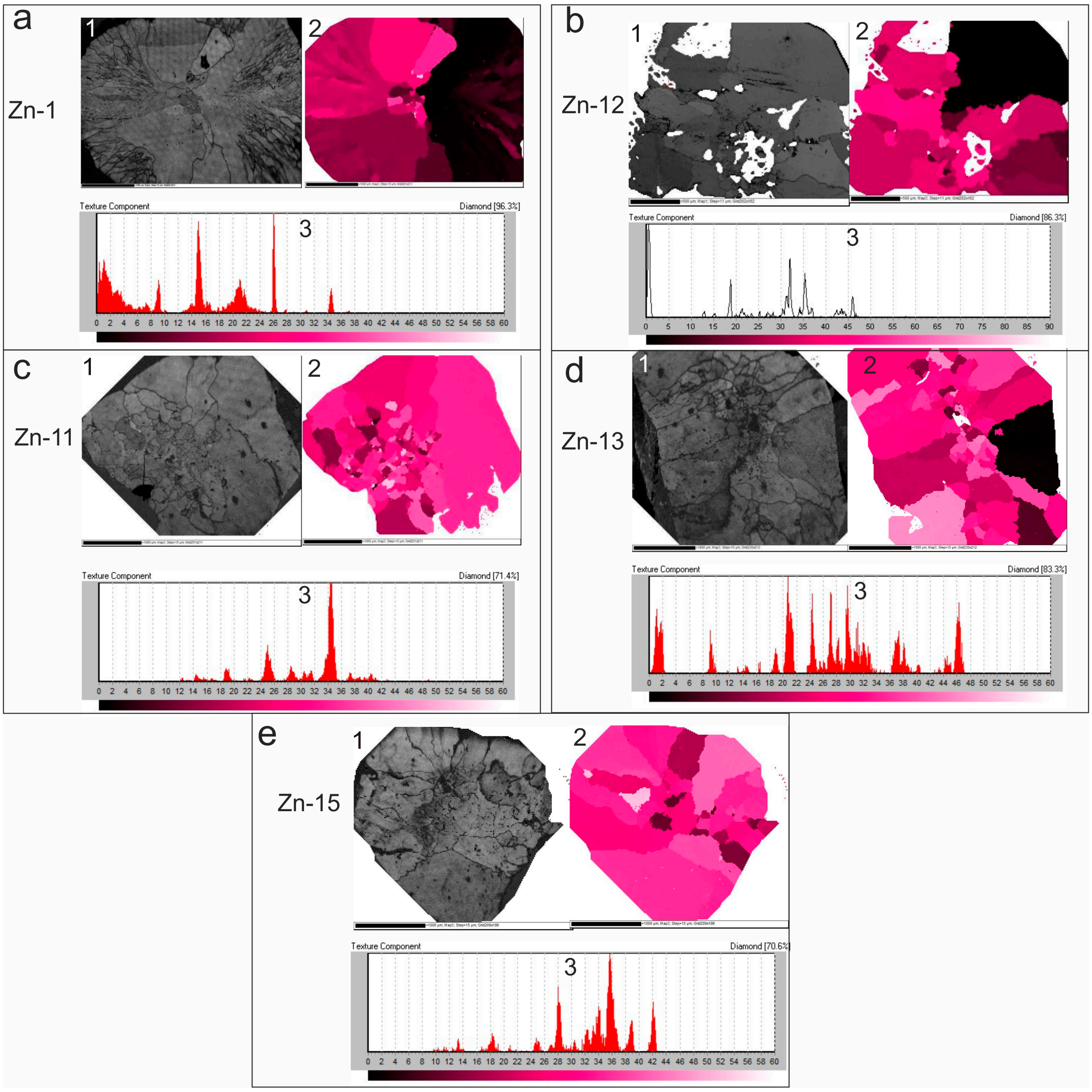

Figure 5. Mosaic-block internal structures of diamonds consisting of subgrains (subindividuals) misorientated relative to each other (1—reflected light, 2—EBSD image, 3—misorientation degrees) (**a**) Sample Zn-1; (**b**) Sample Zn-12; (**c**) Sample Zn-11; (**d**) Sample Zn-13; (**e**) Sample Zn-15.

3. Discussion

The morphological features of diamonds have not been correlated to the geological features of natural diamond formation. This can probably be explained by the fact that the external morphology reflects only characteristics of the latest growth stages which is mainly defined by dissolution and regeneration processes. A large amount of data now shows the deep-seated (mantle) origin of most natural diamonds, while kimberlites and lamproites only bring natural diamonds to the Earth's surface [26–29]. Recently X-ray topography showed that a diamond morphology may be imposed to a full-grown (protogenetic) olivine during their encapsulation, suggesting that the bulk of the inclusion is protogenetic, whereas its more external regions, close to the diamond-inclusion interface, could be syngenetic [30]. Physical and chemical changes in kimberlite melts (changes in pressure, temperature, oxygen fugacity etc.) can lead to the change in the morphology of diamond crystals, which are likely the result of dissolution and magmatic corrosion processes. The high occurrence of dissolution processes has a great influence on many natural diamonds; this is demonstrated by the many micromorphological-based details, such as etch channels, triangular etch pits, dissolution layers, etc. [31,32]. Curved rounded crystal with rhombic dodecahedral habit (dodecahedroid) is the final form of the diamond dissolution [8,13]. Simulated diamond crystal dissolution data, generated by using natural paragenesis system modelling [12–16], shows that the formation of ditrigonal layers in the dissolution process occurs with a pressure range of 2.5–5.7 GPa and a temperature range of 1100–1450 °C. Despite the differences in the simulated data and the natural processes, the main common factors of the morphological evolution of diamonds are likely to be the same. The diamond samples and the partially dissolved simulated diamond crystals have similar complex morphological features. The similarity is seen with the presence of ditrigonal (pseudo-hexagonal) shapes of layers on the (111) faces, negative trigons, deep etch channels, hillocks on rounded surfaces, sheaf-like striations and smooth rounded surfaces near the crystal apexes. Such morphological similarity, combined with the changing crystal habit of each diamond sample (from octahedral to rounded rhombic dodecahedral), results in the development of the various morphological features exhibited in the shape of the diamond samples. This result is likely to be due to the various degrees of dissolution of the primary octahedral crystals and their aggregates. On the other hand, mosaic fibrous internal structures were revealed by X-Ray topograhy in the so-called diamond spherocrystals [33]. Diamond spherocrystals have oriented radial structures: in the cubic sectors elongated subindividuals oriented along the [100] directions and in octahedral sectors along the [111] directions. The habit of diamond spherocrystals was shown to depend on the subindividual growth rate along the [100] and [111] directions; they become close to rhombic dodecahedral or octahedral as the rate increases. A similar structure, in this study, was defined for the Zn-1 diamond. The growth shape of the diamond spherocrystals differs from the dissolution shape via a lack of additional edges. The description "rounded rhombic dodecahedron" is clearly an oversimplification since a rhombus that is divided into two curved surfaces can only be divided by an additional edge that is always the shorter diagonal of the rhombus [34]. Thus, the whole crystal surface is divided into 24 curved surfaces, which in the ideally symmetric specimen would be identical triangular sheets. The polyhedron which best represents this topology is the tetrahexahedron. The additional edges are not seen clearly in the Zarnitsa kimberlite pipe diamond samples, though it can possibly be explained by the rough sculptures of the rounded surfaces.

Morphological features of the diamond samples are similar to V and VII diamond varieties which are wide spread in alluvial deposits of the north-east Siberian Platform [3]. Primary sources of these diamonds have not been discovered yet. The presence of numerous black inclusions, unevenly spread within the crystal volume, in Zarnitsa kimberlite pipe diamond samples makes them similar to rounded diamonds from alluvial placers. At the same time, the maximum concentration of three-dimensional defects are mostly seen in the core of Zarnitsa diamonds, while the inclusions are spread within the whole crystalline volume of the diamonds from alluvial placers, excluding some growth sectors (100) [3]. We noticed sectoral distribution of inclusions in some diamonds from Zarnitsa kimberlite pipe; but in most cases, such inclusions are concentrated in centre region of the crystal. As the birefringence patterns show, the centre crystal regions with the darkest inclusions have significantly more stress inside the crystal structure compared to the external diamond zones. There are likely to be many mechanical admixtures (inclusions) which cause high stress and promote the block (polycrystalline) structure of crystal interiors. External diamond zones have more perfect internal structure compared to their core parts; this is clearly seen in the internal structure found in the Zn-14 sample. Even though this crystal is morphologically represented by a well-faceted octahedron with laminar faces, a high-stress mosaic-block structure was found in the sample.

Thus, the internal structure of some diamonds from the Zarnitsa kimberlite pipe are close to the rounded diamonds from the alluvial placers [3]; despite these similarities, diamonds from the Zarnitsa kimberlite pipe essentially have another mechanism of internal structure formation. Dark grey round diamonds from the Zarnitsa kimberlite pipe have specific zonal and sectorial mosaic-block internal structures visualised by the CD and EBSD techniques. The central regions of the diamond samples have clear polycrystalline structure with significant subindividual disorientation. Large subindividuals develop from the interior and increasing in size outward towards the periphery. Such subindividual systems form the radial structure.

X-Ray diffraction, CL, and birefringence studies have revealed the specific internal structures of rounded V-variety diamonds from alluvial placers of the Northeastern Siberian platform [3]. Although diamonds are single crystals, their volume is separated into slightly misoriented subindividuals, intimately intergrown with each other. The diamonds of the V variety have radial mosaic-block internal structures consisting of slightly misorientated (up 20′) subindividuals. The system of subindividuals forms a radial structure consisting of several larger blocks (subgrains) which are also misoriented to one another by up to 5°; while some of them are split into smaller parts. These internal structures may develop by the splitting crystal growth mechanisms [9]. In this case, crystallography is filled with branched forms. The branching that allows spherulites to fill spherical volumes is called noncrystallographic branching. This branching is distinct from the crystallographic branching of snowflakes, for example, where every branch is in single-crystal register with every other branch [9].

Unlike the rounded V variety diamonds, the internal structure formed by splitting crystal growth mechanisms and the formation of diamonds from Zarnitsa kimberlite pipe, which are in many ways similar, can be explained by different reasons. As shown earlier, diamond centres have clear polycrystalline structure with numerous (>15) subindividuals. According to A.V. Shubnikov's geometric selection law, the enlargement of subindivials, from the centre to the periphery, and the formation of the radial mosaic internal structure are likely to be the result of primarily polycrystalline core development [35]. This law primarily states that single crystals with different orientations grow on the polycrystalline core and crowd over each other when growing before beginning to suppress each other. In other words, the primary development belongs to the crystals (individuals) with the maximum growth rate direction that is perpendicular to the polycrystalline base. It is suggested that the development of spherulitic morphologies may be controlled by growth rate anisotropy and geometrical selection law as well [35]. The geometrical selection law may proceed through competitive or trans-crystalline growth of polycrystalline aggregates [9]. The survival of individual crystals in an aggregate is determined by crystal orientation to the nucleation surface and its relative growth rate. In this case, only radial directions can provide continuous growth of surviving subindividuals.

4. Methods

The morphological features of crystals were studied by optical Zeiss Stemi SV 6 stereo microscope and the scanning electron microscope Leo-1430VP SEM, which has an accelerating voltage of 15 kV, with a working distance of 15 mm. In the past, the 300–500 µm polished plates were made from diamonds. CL diamonds plate patterns were studied using an Oxford Centaurus detector on the Leo-1430VP SEM (accelerating voltages of 12–15 kV and the electron beam current of ~0.5 mA). The deviation from the basic orientation in the diamond grain was mapped by EBSD [36]. The EBSD analysis was performed with the use of the Oxford Instruments HKL detector mounted to a Hitachi S-3400 N scanning electron microscope (SEM). Kikuchi patterns formed by back-scattered electrons were automatically indexed by the Oxford data collection software. The accuracy of determination of the angles of misorientation by this method was 0.5°–1.0°.

Analytical investigations were carried out in the Analytical Center for multi-element and isotope research SB RAS. The part of the work (EBSD) was done using the infrastructure of the Shared-Use Center "Siberian Synchrotron and Terahertz Radiation Center (SSTRC)" based on VEPP-3/VEPP-4M/NovoFEL of BINP SB RAS.

5. Conclusions

Rounded diamonds from Zarnitsa kimberlite pipe have specific zonal and sectorial mosaic-block internal structures. The central sections of the diamond samples have clear polycrystalline structure with significant subindividual disorientation. The high consistency of mechanical admixtures (inclusions) in diamond cores cause high lattice stress of the crystalline structure and promote block (polycrystalline) core structures. Such internal structures in the Zarnitsa kimberlite pipe diamonds are derived from the crystallization of the polycrystalline cores, according to the geometric selection rule. Unlike the mosaic block structure of similar diamonds, described before and after the placers of the north-east of the Siberian platform, which were formed by the splitting crystal growth mechanism. Thus, despite the physical resemblance and the similarity of the internal structure, diamond crystals from the Zarnitsa kimberlite pipe and the rounded diamonds from the alluvial placers were formed due to essentially different processes. Diamonds from the Zarnitsa kimberlite pipe evolve from polycrystalline cores to monocrystals, while an alluvial placer diamond splits up the spherulite-like structure.

Acknowledgments: The research was supported by state assignment project (project No. 0330-2016-0007), and in part by RFBR (project No. 16-05-00614).

Author Contributions: Alexey Ragozin studied samples by optical and scanning electron microscopy, made the polished plates from diamonds; Dmitry Zedgenizov conducted the cathodoluminescence experiments and analyzed the data; Konstantin Kuper performed the electron backscatter diffraction experiments; Yuri Palyanov analyzed the data and discussed the results; Alexey Ragozin and Dmitry Zedgenizov contributed equally by writing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sarsadskikh, N.N.; Popugayeva, L.A. New data about manifestation ultramafic-alkaline magmatism within Siberian Platform. *Razvedka I Okhrana Nedr.* **1955**, *5*, 11–20. (In Russian).
2. Kostrovitskiy, S.I.; Spetsius, Z.V.; Yakovlev, D.A.; Fon-der-Flaas, G.S.; Suvorova, L.F.; Bogush, I.N. *Atlas of the Primary Diamond Deposits of the Yakutian Kimberlite Province*; NIGP SC "ALROSA" (PAO): Mirny, Russia, 2015; p. 480. (In Russian)
3. Ragozin, A.L.; Zedgenizov, D.A.; Kuper, K.E.; Shatsky, V.S. Radial mosaic internal structure of rounded diamond crystals from alluvial placers of Siberian Platform. *Mineral. Petrol.* **2016**, *110*, 861–875. [CrossRef]
4. Ragozin, A.L.; Shatsky, V.S.; Rylov, G.M.; Goryainov, S.V. Coesite inclusions in rounded diamonds from placers of the northeastern siberian platform. *Dokl. Earth Sci.* **2002**, *384*, 385–389.
5. Ragozin, A.L.; Shatskii, V.S.; Zedgenizov, D.A. New data on the growth environment of diamonds of the variety V from placers of the northeastern Siberian Platform. *Dokl. Earth Sci.* **2009**, *425*, 436–440. [CrossRef]
6. Afanasyev, V.P.; Agashev, A.M.; Orihashi, Y.; Pokhilenko, N.P.; Sobolev, N.V. Paleozoic U–Pb age of rutile inclusions in diamonds of the V–VII variety from placers of the northeast Siberian Platform. *Dokl. Earth Sci.* **2009**, *428*, 1151–1155. [CrossRef]
7. Smith, E.M.; Kopylova, M.G.; Frezzotti, M.L.; Afanasiev, V.P. Fluid inclusions in Ebelyakh diamonds: Evidence of CO_2 liberation in eclogite and the effect of H_2O on diamond habit. *Lithos* **2015**, *216–217*, 106–117. [CrossRef]
8. Orlov, Y.L. *The Mineralogy of Diamond*; John Wiley: New York, NY, USA, 1977; p. 233.
9. Shtukenberg, A.G.; Punin, Y.O.; Gunn, E.; Kahr, B. Spherulites. *Chem. Rev.* **2012**, *112*, 1805–1838. [CrossRef] [PubMed]
10. Bartoshinskii, Z.V.; Kvasnitsa, V.N. *Crystallomorphology of a Diamond from Kimberlite*; Naukova Dumka: Kiev, Ukraine, 1991; p. 172. (In Russian)
11. Frank, F.C.; Puttick, K.E.; Wilks, E.M. Etch pits and trigons on diamond: I. *Philos. Mag.* **1958**, *3*, 1262–1272. [CrossRef]
12. Khokhryakov, A.F.; Pal'yanov, Y.N. The evolution of diamond morphology in the process of dissolution: Experimental data. *Am. Mineral.* **2007**, *92*, 909–917. [CrossRef]
13. Khokhryakov, A.F.; Pal'yanov, Y.N. The dissolution forms of diamond crystals in $CaCO_3$ melt at 7 GPa. *Russ. Geol. Geophys.* **2000**, *41*, 705–711.
14. Khokhryakov, A.F.; Pal'yanov, Y.N. Evolution of diamond morphology in the processes of mantle dissolution. *Lithos* **2004**, *73*, S57.
15. Khokhryakov, A.F.; Palyanov, Y.N. Effect of crystal defects on diamond morphology during dissolution in the mantle. *Am. Mineral.* **2015**, *100*, 1528–1532. [CrossRef]

16. Khokhryakov, A.F.; Pal'yanov, Y.N.; Sobolev, N.V. Evolution of crystal morphology of natural diamond in dissolution processes: Experimental data. *Dokl. Earth Sci.* **2001**, *381*, 884–888.
17. Khokhryakov, A.F.; Pal'yanov, Y.N. Influence of the fluid composition on diamond dissolution forms in carbonate melts. *Am. Mineral.* **2010**, *95*, 1508–1514. [CrossRef]
18. Howell, D. Strain-induced birefringence in natural diamond: A review. *Eur. J. Mineral.* **2012**, *24*, 575–585. [CrossRef]
19. Howell, D.; Wood, I.G.; Nestola, F.; Nimis, P.; Nasdala, L. Inclusions under remnant pressure in diamond: A multi-technique approach. *Eur. J. Mineral.* **2012**, *24*, 563–573. [CrossRef]
20. Lang, A. Causes of birefringence in diamond. *Nature* **1967**, *213*, 248–251. [CrossRef]
21. Tolansky, S. Birefringence of diamond. *Nature* **1966**, *211*, 158–160. [CrossRef]
22. Frank, F.C. On the x-ray diffraction spikes of diamond. *Proc. R. Soc. Lond. A Math. Phys. Sci.* **1956**, *237*, 168–174. [CrossRef]
23. Moore, M.; Lang, A.R. On the internal structure of natural diamonds of cubic habit. *Philos. Mag.* **1972**, *26*, 1313–1325. [CrossRef]
24. Götze, J.; Kempe, U. Physical principles of cathodoluminescence (CL) and its applications in geosciences. In *Cathodoluminescence and Its Application in the Planetary Sciences*; Gucsik, A., Ed.; Springer: Berlin/Heildelberg, Germany, 2009; pp. 1–22.
25. Lang, A.R. Topographic methods for studying defects in diamonds. *Diam. Relat. Mater.* **1993**, *2*, 106–114. [CrossRef]
26. Sobolev, N.V. *Deep Seated Inclusions in Kimberlites and the Problem of the Composition of the Upper Mantle*; AGU: Washington, DC, USA, 1977; p. 279.
27. Meyer, H.O.A. Genesis of diamond—A mantle saga. *Am. Miner.* **1985**, *70*, 344–355.
28. Meyer, H.O.A. Inclusions in diamond. In *Mantle Xenoliths*; Nixon, P.H., Ed.; Wiley and Sons: New York, NY, USA, 1987; pp. 501–523.
29. Harris, J.W. Diamond geology. In *The Properties of Natural and Synthetic Diamond*; Field, J.E., Ed.; Academic Press: London, UK, 1992; pp. 345–393.
30. Agrosì, G.; Nestola, F.; Tempesta, G.; Bruno, M.; Scandale, E.; Harris, J. X-ray topographic study of a diamond from Udachnaya: Implications for the genetic nature of inclusions. *Lithos* **2016**, *248*, 153–159. [CrossRef]
31. Orlov, Y.L. *Diamond Morphology*; AS USSR: Moscow, Russia, 1963; p. 235.
32. Khokhryakov, A.F.; Pal'yanov, Y.N.; Sobolev, N.V. Crystal morphology as an indicator of redox conditions of natural diamond dissolution at the mantle PT parameters. *Dokl. Earth Sci.* **2002**, *385*, 534–537.
33. Orlov, Y.L.; Bulienkov, N.A.; Martovitsky, V.P. The spherocrystals of diamond—New type of natural single crystals having a fibrous structure. *Dokl. Akad. Nauk SSSR* **1980**, *252*, 703–707.
34. Moore, M.; Lang, A.R. On the origin of the rounded dodecahedral habit of natural diamond. *J. Cryst. Growth* **1974**, *26*, 133–139. [CrossRef]
35. Shubnikov, A.V. About geometric selection law in the formation of a crystalline aggregate. *Dokl. Akad. Nauk SSSR* **1946**, *51*, 679–681.
36. Humphreys, F.J. Review grain and subgrain characterisation by electron backscatter diffraction. *J. Mater. Sci.* **2001**, *36*, 3833–3854. [CrossRef]