Kimberlite Genesis According to Data on Hot Accretion of the Earth

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Abstract. Analysis of modern geological and planetological data indicates hot accretion of the Earth. Impact melting during its formation led to origin of layered global magma ocean. Kimberlites were formed from residual melts of its lower peridotite latyer. This explains high content of meltphylic (lithophytic) components in kimberlites. Prolonged cooling and crystallization of magma ocean from top to bottom in the Earth’s history is the cause of mainly the Phanerozoic age of kimberlites. Moving apart of lithosphere and products of magma ocean fractionation contained therein when oceanic areas are formed, explains absence of kimberlites in these areas and Clifford rule nature. Low temperature of kimberlite magmas and high content of volatile component in them was caused by formation from residual melts. Increased temperature of crystallization of volatile-poor melts and emission of volatile components from magmas at shallow stages of upwelling led to solidification of upper parts of magmatic columns and their explosion during further upwelling under impact of high pressure of gas phase preserved by solidification. This explains the fact that, kimberlites formed mostly explosion pipes, and that kimberlite lavas are lacking. Diamonds were crystallized as a result of carbon accumulation in residual melt. Evolution of its composition during crystallization from peridotite through eclogite to kimberlite was responsible for existence of xenoliths of the same composition in kimberlites and inclusions in diamonds, and decrease of their average isotope age in this sequence. Degree of the saturation of the melt with carbon during its fractionation increased. Due to that, layer growth was followed by radial one, and morphology of originating diamond crystals was evolved from octahedrons to dodecahedrons and then to cubes and aggregates, and sculptures were formed on them. Accumulation of meltphylic components in residual melts is causes increase of nitrogen, light carbon isotope and other admixtures content in later diamonds.

1. Introduction
At present time, it is usually assumed that, kimberlite magmas were formed by partial melting of peridotites ≈ 0.1% in emerging mantle plumes. Diamonds were crystallized in the Archean time and were mechanically captured by kimberlite magmas when upwelled through diamondiferous mantle [1–3]. But these suggestions are not consistent with more regularly spaced distribution of diamonds in kimberlite bodies, that might be expected in case of xenogenic origin of this mineral. More often, it is contradictory to the Post Archean isotope age of diamonds (line BA on Fig. 1) and numerous signs of their crystallization in melts [4]. With such origin of kimberlites, it is unclear how kimberlite melt is separated from peridotites, since with an insignificant degree of melting, they almost do not differ in
viscosity form solid rocks. That is why, according to calculations [4, 5], melts in slightly melted rocks could not be separated. This is confirmed by experimental data [6] and results of studies of ultrametamorphism zones [5], indicating that, melts are not separated even at with content 30 – 35 %. Furthermore, mineral equilibriums in mantle xenoliths indicate the fact, that upper mantle cooled approximately by 200° every billion years, and that it lacked processes of heating and melting (line T on Figure 1). Reason of kimberlite absence in oceanic areas is unclear, although they recorded mass upwelling of plumes and decompression melting of their substance.

2. Evidence of hot heterogenic accretion of the Earth

Potential energy release during accretion of the Earth was 9000 cal/g, that is why it could be heated by 34 000 °C during formation [7]. In this connection, O.Y. Shmidt [8] – supporter of hypothesis of cold accretion – supposed that, accretion lasted over billion years. During that time, the Earth’s material had time to lose released impact heat. But modern isotope data [9, 10] indicate that, planets were formed in less than 10 million years. This indicates their hot accretion.

This conclusion is confirmed by trends of magmatic fractionation in mantle xenoliths from kimberlites of different regions (line MgO on Figure 1) and in the Early Precambrian complexes of the Aldan shield (Figure 2), increase of isotope age and temperature of crystallization of different rocks in them according to sequence of these rocks formation during fractionation (lines B and T on Figure 1). Hot accretion is also indicated by signs of very hot temperature on the Earth’s surface in the Early Archean (up to 900 – 1000 °C), existed in the Early Precambrian crystalline complexes and xenocrysts, clinopyroxene from kimberlites, of very low (2 – 3.5 °/km) geothermal gradients, close to adiabatic gradient for the melts (0.3 °/km) and sharply different from modern gradients (up to 150 °/km) [5].

![Figure 1. Average isotope ages of mantle rocks from xenoliths in kimberlites (line R), inclusions in diamonds (line A), average temperature of rock formation at 5 GPa (line T), and average MgO content (line MgO). Composition of inclusions in diamonds and rocks: E – eclogite, F – phlogopite-bearing, G – harzburgite, K – kimberlite, Ka – carbonatite, L – lherzolite, P – peridotite, V – verlite and websterite.](image)

All these and many other data indicate formation of mantle and ancient crystalline crust by fractionation of compositionally layered global magma ocean with maximum depth ≈ 240 km [4], formed mainly under influence of impact heat release during accretion. Sharp nonequilibrium of mantle rocks with metallic iron and H2O and CO2, rather than H2 and CO2, distribution on the Earth [7] indicate that, metallic and iron particles were never mixed within the Earth interior. When protoplanetary disk cooled below Curie temperature (1043 K), iron particles were aggregated very
rapidly under the influence of magnetic forces, because the bodies had centimetric dimensions and forces were billions times bigger than gravity forces [5]. Therefore, accretion was heterogeneous. Conclusion on hot heterogeneous accretion of the Earth explains the nature of all features of kimberlites and diamond contained therein.

**Figure 2.** Position of composition fields of different orthogneisses and schists of the Olekmensky (1), Fedorovsky (2) and Kurultinsky (3) complexes of the Aldan shield along single trend of magmatic fractionation. Fields: L – leucogranites (73 – 78 % SiO$_2$); G – granites (68 – 73 % SiO$_2$); GD – granodiorites (63 – 68 % SiO$_2$); D – diorites (53 – 63 % SiO$_2$); B – basites (44 – 53 % SiO$_2$). Data used [11, 12].

3. Fractionation of magma ocean and kimberlite origin
Calculations [4] indicate that, due to density increase with depth (from 2.3 to 2.8 g/cm$^3$), wide convection was not developed on the layered magma ocean after termination of accretion during cooling, and the ocean long-term solidified from top to bottom. From 4.6 to $\approx$ 3.8 billion years ago, surface was fully melt-covered and there were no solid rocks on it. It explains absence on the Earth of rocks of the age of more than 4.0 Ga and craters of giant meteorite bombardment, completed on the Moon $\approx$ 3.8 billion years ago. Before $\approx$ 2.6 billion years ago, crystallization of acid layer of magma ocean took place, as well as formation of predominantly orthogneiss complexes, granitoids of felsic crystalline crust (Figure 3) and small amount of the bodies of para-rocks on the surface of solidified acid layer.

**Figure 3.** Diagram of crystallization of post-accretion layered magma ocean and evolution of magmatism on the continents. Composition of the formed magmas: 1 – acid; 2 – subalkaline; 3 – anorthosite; 4 – alkaline-ultramafic; 5 – lamproite; 6 – kimberlite.
Later on, autonomous anorthosites and subalkaline and alkaline igneous rocks were formed from plagioclase cumulates and residual melts of the layer of magma ocean of basic composition. Crystallization of picrite layer led to formation of alkali-submafic and carbonatite melts. Solidification of the near-bottom peridotite layer caused termination of intrusion of komatiite magmas into greenstone belts. According to experimental data [13], over-pressured fractionation of peridotite layer, in case of carbon dioxide proportion in fluid is over 0.6 mole, led to origin of kimberlite residual melts. Isotope age of anorthosites, carbonatites and kimberlites on average is correspondingly 1.8 [4], 0.688 and 0.136 Ga (Figure 1). It illustrates clear lowering of the solidification level in post-accretion magma ocean in process of time. It is related to its cooling mainly as a result of conductive heat losses upwards.

Figure 4. P-T diagram of the phase composition and evolution of kimberlite magmas with 10% H₂O and 10% CO₂. Lines with arrows – evolution of kimberlite magmas during upwelling. Lines of evolution: 0 – Precambrian stage, 1 and 2 – stages of correspondingly friction and decompression-friction melting; 3, 4 and 5 – stages of decompression melting, decompression solidification and explosive disintegration of magmas. Fig. of crystals – morphology of the originated diamonds. Cb – solid phases of carbonatite in solidus conditions; F – fluid; Fl – phlogopite; Ga – garnet; Gf – graphite; Kl and K – solid phases of kimberlite in primary (liquidus) and lower temperature conditions; L – melt; indices – content of water (lower) and carbon dioxide (upper) in the melt; Sp – spinel [14].

According to content of light rare-earths (up to thousand chondrite norms) in kimberlites, kimberlite residual melts were formed after crystallization of peridotite layer in about 99.9 – 99.99 %. That is why they contain high content of meltphylic chemical components (light rare-earths, H₂O, CO₂, K₂O), insignificant amount of kimberlite melts in the mantle and small bodies formed by them in the Earth’s crust (usually tens – hundred meters), and their magmas have low temperature (about 500 °C after explosion). With low degree of peridotite layer crystallization, residual melts had alkali-mafic, but not kimberlite composition. This explains almost complete lack of the early Precambrian kimberlites.

Due to low density, residual melts floated and were pressed out along extension zones. Low temperature led to rapid solidification (by vitrification or crystallization) of kimberlite magmas at late
stages of upwelling (sectors 4 on lines of magma upwelling, Figure 4) due to emission of volatiles from them during decompression. Further upwelling involved explosion of upper parts of kimberlite columns (sectors 5 on lines of upwelling) under influence of high inner pressure of gas phase, preserved by solidification. This explains the fact that, kimberlite magmas formed mainly volcanic pipes and breccias, usual lack of kimberlite lavas on the earth surface, processes of magmatic fractionation and sedimentation of high-density diamond and garnet in pipes. Spreading of peridotite layer fractionation products below ocean areas of upwelled plume substance during formation of these areas is a reason of enigmatic lack of kimberlites in them, and explains nature of Clifford’s rule.

4. Diamond genesis

According to isotope data (Figure 1), diamond began crystallizing 3 – 3.5 billion years ago, when melt composition was peridotitic, due to increase of free carbon concentration in residual melts, because this component was slightly captured by originated rock-forming minerals. This explains occurrence of inclusions of peridotite paragenesis in diamonds and their isotope age, well in excess of age of kimberlite pipes (first hundred million years). This age difference is major argument in favor of hypothesis of xenogenic origin of diamonds in kimberlites. But in the studied case of hot origin of the Earth, it reflects just earlier beginning of diamond formation in comparison with kimberlite residual melts (Figure 1).

Sunagava [15] concluded that, when degree of supersaturation of crystallization conditions with carbon increased, morphology of crystallized diamond changed from octahedrons to rhombic dodecahedrons, and then to cubes. At the beginning of crystallization of peridotite layer of the magma ocean, degree of supersaturation of the melts with carbon was relatively insignificant. At that time, its cooling was slow due to still very hot overlying layers (Figure 3). Due to slow crystallization, carbon atoms added mainly to the end of growth layers on the facets of diamond crystals, because more covalent free bonds were exposed here, than on the layer planes. That is why diamonds grew by tangential layer growth with formation of perfect sharp-ribbed octahedrons with mirror smooth facets (crystal 1 on Figure 5). Long-lived crystallization at the early stage of magma ocean cooling explains occurrence of single giant diamonds (tens-hundreds carats) and predominantly octahedral form of their crystal (93 – 94 %, [16]). Insignificant amount of dissolved free carbon in the melts is a reason of insignificant content of diamonds in kimberlites (usually < 1 g/t).

SiO$_2$ content in kimberlites varies from 24 to 55 %, and in melted inclusions in diamond reaches 70 %. Such increase of silicic acid concentration in residual melts with fractionation led to increase of their viscosity from $10^1$ to $5\cdot10^5$ N/m·sec, i.e. five million times [4]. The Stokes-Einstein equation $D=\frac{RT\pi}{6\eta r}$ suggests that, the diffusion coefficient D in liquids is directly proportional to temperature T and is inversely proportional to medium viscosity $\eta$ ($R=8,31\cdot10^3$ J/kmol·grad, $\rho$ – medium density, $\pi=3.14$, $r$ – radius of diffusible molecules). The equation shows that, increase of residual melt viscosity led to the same decrease of carbon diffusion rate in them and increase of degree of supersaturation of them with this component (Figure 5). The latter followed by faster origin of new crystallization centers and growth layers on diamond crystals and led to decrease of their area. Layered crystals transitional in form (from octahedrons to rhombic dodecahedrons), widely spread in kimberlites, were formed (crystals 3 – 7).

In case when growth layers originated in center of crystal facets, and they increasingly did not reach their ribs and apexes, rounded-stepped crystals were formed (7, 8 on Figure 5). Due to decrease of carbon diffusion rate in viscous melts rich in silicic acid, originated growth layers became thinner. It caused formation of spread thin-layered rounded crystals (6, 9, 10 on Figure 5).

Nature of rounded diamonds is discussed for more than a century. It is most often assumed that they were formed by dissolution of flat-faced crystals. Proof of this are supposedly observed phenomena of “cutting” inner lamination by rounded surface of crystals [17]. However, there is an obvious substitution of notions in this statement. Modern observer can see only geometric disruption of the growth layers, but not the process of “cutting”. Disruption may be related to local growth termination due to decrease of atom inflow to the layer during origin of new layers as a result of
crystal inclusion into cumulate aggregate of rock-forming minerals. Existence of rounded inner zoning in some diamonds, and very often less size of table-facet crystals in the same pipes and placers [4] indicate growth origin of rounded diamonds.

![Figure 5](image_url)

**Figure 5.** Ratio of value of specific intensity of X-ray luminescence (I/m) and diamond properties and crystallization conditions. Points indicate average values I/m during formation of flat-faced (P), splinter-layered (PL), polycentric (P), rounded-stepped (RS) and block (B) octahedrons; rhombic dodecahedrons (D) and rounded dodecahedroid (O); colorless (C), green (G), yellow (Y) and brown (B) diamonds; with blue (B), green (G), yellow (Y), orange (O) photoluminescence and non-luminescent crystals (N). Ca and La lines – crystal in kimberlites with respectively carbonatite and lamproite trend of differentiation, intermediate line – crystals, occurring in different kimberlites. Crystal photos: 1 – flat-faced, 2 – thin-layered, 3 – coarse-layered, 4 – polycentric, 7 and 8 – rounded-step-cut octahedrons; 5 – rhombic dodecahedron, 6, 9 and 10 – rounded dodecahedroids relatively flat-faced, with lumpy and tiled sculptures; 11 – cube; 12 – aggregate.

Accumulation of meltphric components in residual melts led to increase of impurity content in diamonds and increase of related defects of their crystal lattice. Defects caused quenching of (I) diamond X-ray luminescence. That is why specific intensity value of X-ray luminescence I/m (m –
radiation path in crystal) is a good indicator of relative sequence of diamond formation in fractionating magma.

Figure 5 illustrates that, specific intensity luminescence lower values (0.4 – 1.0) are typical for rounded diamonds, in comparison with table-facet crystals (1.0 – 1.8). This indicates higher content of impurities and defects in rounded crystals, and consequently their later formation during fractionation of peridotite layer of magma ocean. Increase of proportion of rounded diamonds on average from 0 to 77% with increase of SiO₂ content respectively from 24 to 55% in kimberlites and lamproites (Figure 6), corresponding to the melt viscosity from $10^{-1}$ to $10^{3}$ N/m·sек, confirms crystallization of rounded diamonds influenced by decrease of carbon diffusion rate in residual melts.

Chemical activity of carbon was directly proportional to its concentration in the melt. That is why when degree of supersaturation of the melts with carbon significantly increases, most atoms of the latter could not find ends of the growth layers. Its high chemical activity made atoms adding themselves to crystal facets. It caused gradual reducing the role of layer-by-layer growth and increasing the role of normal radial growth during diamond crystallization. Radial growth led to crystallization of cubes, spheroids and diamond aggregates and to formation big amount of different sculptures on diamonds. In block crystals, decrease of carbon diffusion rate was followed by decrease of the area of growing outer parts of the blocks and origin of deep crack-like cavernes, sometimes reaching center of the crystals, between them.

![Figure 6. Ratio of rounded crystals among diamonds with silica acid content in kimberlites.](image)

Examined time sequence of formation of diamond crystals of different morphology is supported by typical (natural) decrease of the specific intensity value of X-ray luminescence from octahedrons to dodecahedroids and then to cubes and diamond aggregates, shown on Figure 5 according to K.P. Argounov [16]. It is also supported by decrease of average proportion of octahedrons from 41 to 7% and increase of proportion of dodecahedroids from 21 to 80% with increase of SiO₂ content in kimberlites and lamproites from 22 to 60% (Figure 7).

Change of the melt content during fractionation caused change of peridotite paragenesis of captured inclusions to eclogite paragenesis and then to kimberlite one (carbonates, phlogopite). It is confirmed by decrease of isotope age of inclusions in this direction on average from 3.1 billion years for harzburgite inclusions, up to 2.8 billion years for peridotite undissected inclusions, 2 billion years for lherzolite inclusions, 1.1 billion years for eclogite ones and 0.4 billion years for kimberlite inclusions (Figure 1).
Figure 7. Ratio of average SiO$_2$ content in kimberlites and lamproites with proportion of octahedrons (1), dodecahedroids and sum of cubes and varieties II – VIII according to Y.L. Orlov (3) [14].

Figure 8. N average total content in varieties of diamonds (1; O – octahedrons; D – dodecahedroids; Fr – framesite; F – fibrous), in diamonds from mantle xenoliths (2; G – harzburgite; L – lherzolite; E – eclogite) and with different paragenesis of inclusions (3; P – peridotite; EP – eclogite paragenesis) [14].

Accumulation of meltphyles components in residual melts was a reason of gradual increase of average content of impurities in late diamonds from 0.001% in colorless octahedrons up to 0.1% in dark-brown and 1% in carbonado, and consequently occurrence of different color in them [4]. Nitrogen, as all gases, was intensively accumulated in residual melts. It caused increase of its average content from 200 ppm in octahedrons up to 420 ppm in dodecahedroids and up to more than 1000 ppm in fibrous cuboids (Figure 8). Right slope of curves of rare earths distribution in magmatic rocks indicates more intensive accumulation of light elements in residual melts in comparison with heavy elements. That is why light carbon isotope should be accumulated more in residual melts and in diamonds, crystallized in them, in comparison with heavy isotope. It is supported by results of general conclusion of much (1641 determinations) of published data. They indicate change of the $\delta^{13}$C value on average from -3‰ in octahedrons, up to -3.5‰ in dodecahedroids, up to -5‰ in cores of cubic crystals, up to -7‰ in their mantles and up to -27‰ in carbonado (Figure 9).
Figure 9. Average contents of $\delta^{13}$C in diamond varieties (1; O – octahedrons; D – dodecahedroids; Ke – cores of cubic diamonds in coating; S – in coatings of these diamonds; F – framesites; C – carbonado) and in diamonds with different paragenesies of inclusions (2; P – with peridotite; E – eclogite; V – websterite) [4].

Content of nitrogen, light carbon isotope and other impurities more often increases from central parts of crystals to their rims. But opposite cases are often enough. Their presence is natural and should be caused by inevitable existence of local movements of the material in thick (about 80 km) crystallized layer of primarily peridotite magma. It appears that, in its parts cooling from the top, originated diamonds and rock-forming minerals due to their increased density could sink into slightly differentiated deeper parts with decreased content of nitrogen, light carbon isotope and other impurities. Due to pressure increase during putting down, diamond continued to crystallize, but originated new zones had more high-temperature features than cores. Many zones enriched and depleted in impurities, sometimes occurred in diamond crystals indicate that, some diamonds put down and up repeatedly during the growth process.

In case of upwelling of magma flows, removed deep diamond crystals could occur in shallow conditions of its thermodynamic instability and undergo dissolution with formation of amoeba-like grains with wide pits in them. Such partially dissolved diamonds occur in kimberlites very rarely. Rounded diamonds and deep crack-like cavities in them, which were supposedly formed by dissolution, as mentioned above, have signs of growth origin.

Large proportion of diamond octahedrons in kimberlites, formed at early stages of fractionation of peridotite layer of the magma ocean, indicates their burial among cumulates of rock-forming minerals and in this connection their isolation from fractionating melt. That is why they did not experience intumescence of later diamond substance. Diamonds of xenoliths and eclogites have the same origin. Sharp qualitative predominance of octahedrons in peridotite xenoliths confirms their early crystallization. When kimberlite residual melts upwelled, cumulates were captured by them, slightly melted at early and middle stages of upwelling (Figure 4) as a result of huge decompression and partially disintegrated with release of diamond crystals. Content of mantle xenoliths in kimberlite more often is caused by origin of their rocks from cumulates of peridotite magma during formation of kimberlite magmas, but not in the Archean mantle as usually is assumed.

Octahedrons, bordered by younger diamond substance, are widely distributed in kimberlites sometimes. These include diamonds in coating according to Y.L. Orlov [17], which octahedral core is surrounded by cubic coating. Such diamonds were not isolated by cumulates from residual melt and grew in it. Often fibrous structure of this coating is specified by its formation by radial growth due to very supersturation of the residual melt with carbon. Lumpy surface of the cubes (crystal 11 on Figure 5) reflects such growth.
5. Conclusions

Thus, taking into account existence of the processes of global magmatic fractionation allows explaining origin of numerous features of kimberlites and diamonds contained in them. Kimberlites were formed from the last residual melts of lower peridotite layer of magma ocean. This explains high content of meltphyle components in them, occurrence mostly in volcanic pipes, predominantly Phanerozoic age and distribution in regions with continental lithosphere. Diamonds were crystallized as a result of accumulation of free carbon in residual melts. Increase of the degree of supersaturation of these melts with carbon is a reason of the change tangential growth of diamonds to radial one, and evolution of morphology of originated crystals. Accumulation of meltphyle components in the melts caused increase of content of nitrogen and other impurities in late diamonds.

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