Ultrabasic-basic differentiation of mantle magmas and natural diamond-parental melts by evidence of physico-chemical experiments

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Experimentally at 7 GPa phase relations in two sections of the system garnet peridotite–eclogite–carbonatite are studied in connection with the problem of physico-chemical conditions of differentiation of the upper mantle ultrabasic-basic magmas and formation of continuous series of peridotite–eclogite rocks as well as the syngenesis of diamond and primary inclusions of peridotitic and eclogitic parageneses. Diagrams of equilibrium and fractional crystallization of the boundary silicate multicomponent system peridotite–eclogite are constructed. As a result, a new effect of "peridotite–eclogite tunnel" is established. The tunnel provides formation of the continuous series of peridotite–eclogite rocks of the Earth's upper mantle. Also, diagrams of equilibrium and fractional crystallization for the polythermal section peridotite$_{30}$carbonatite$_{70}$–eclogite$_{35}$carbonatite$_{65}$ are constructed. As a result, a combined action of the effects of peridotite–eclogite tunnel and carbonatization of peridotitic magnesian phases is recognized. The effects provide consecutive formation of the phases of peridotitic and eclogitic parageneses in the natural processes of diamond origin.

Key words: upper mantle, mantle magmatism, diamond genesis, peridotite, eclogite, carbonatite, syngenetic inclusions, fractional crystallization, peridotite–eclogite tunnel, experiment

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1. Melting relations of the upper-mantle peridotite-eclogite system

Xenoliths of peridotite-pyroxenite and eclogite-grospydite series in kimberlites are basic for the conception of primary garnet peridotitic or pyrholitic by *A. Ringwood* [*1962*] rocks of the upper mantle. Garnet peridotites and eclogites are the major rocks of the Earth's upper mantle [*Ringwood, 1975*]. Peridotites dominate statistically (95%) in respect to eclogites (5%). However, the inverse relationship is ascertained for the Roberts Victor (80% eclogites and 20% peridotites), Bobbeyan, Ritfontein (SA), Orapa (Botswana), Garnet-Ridge, Moses-Rock (USA), Zagadochnaya (RF) and some other pipes. 63% of eclogites are presented by bimineral Cpx–Grt rocks. Mineral phases of peridotite and eclogite parageneses represent most of primary inclusions in natural diamonds [*Sobolev, 1974*]. With rare exception, minerals of both the parageneses are not coexisted in the same crystal. Petrochemical trends demonstrate continuous transitions between peridotitic and eclogitic rocks [*Marakushev, 1984*] and compositions of mineral inclusions in diamonds [*Sobolev, 1974*]. But direct petrogenetic relations of peridotites and eclogites are physico-chemically poorly substantiated.

Formation of primary ultrabasic magma in garnet peridotite system Ol–Opx–Cpx–Grt is under control of quasi-invariant peritectics Ol+Opx+Cpx+Gr+L [*Litvin, 1991*]. Based on experimental evidence, a topology of the diagram of equilibrium melting relations of peridotite-eclogite system Ol–Cpx–Crn–Cs has been determined. This makes possible to identify principal details of structure of its liquidus [*Litvin, 1991*]. It has been found that Ol–Opx–Cpx–Gr–peridotite and Cs–Opx–Cpx–Grt–eclogite peritectics are physico-chemically bounded up by univariant curve Opx+Cpx+Grt+L that has

a temperature maximum at the "piercing point" of the boundary plane Opx–Cpx–Grt between peridotitic (olivine-saturated) and eclogitic (silica-saturated) composition tetrahedra. The maximum represents a thermal eclogitic barrier between Ol-saturated peridotitic and SiO_2-saturated Opx–Qtz/Cs- and Ky–Crn-eclogitic compositions. It is an insuperable obstacle for ultrabasic-basic differentiation in case of equilibrium so fractional crystallization of ultrabasic magma. The "eclogitic barrier" will hold its importance for less deep conditions and was discussed in the context of basaltic magmatism [*O'Hara, 1968*].

Another univariant curve Ol+Cpx+Grt+L links the Ol–Opx–Cpx–Grt peridotite peritectics and the eutectics of rarely occurring olivine eclogites in temperature-lowering way without a thermal maximum. It is known that olivine eclogites are extremely rare among the xenolith of mantle rocks in kimberlites [*Dawson, 1980*] but frequent among xenoliths in alkaline basalts [*O'Hara, 1968*]. An existence of the univariant curve Ol+Cpx+Grt+L without a temperature maximum that links the garnet–peridotitic and olivine–eclogitic simplexes is of principal interest in view of the fact that Ol can disappear in reaction with Jd components while Grt, Opx and Na-Mg-silicate are formed above 4.5 GPa [*Gasparik, Litvin, 1997*]. The reaction of "olivine garnetization" is minimizied and can not show itself appreciably in equilibrium process of ultrabasic melt crystallization. Moreover, figurative point ot the system composition is not able go out the limits of the peridotitic composition simplex. But one would expect that effectiveness of the reaction is significantly increased under the conditions of fractional crystallization due to accumulation of jadeitic component in the residual melts. As this takes place, it is important that the figurative point of the system composition is able to transfer into the olivine–eclogitic composition simplex by a natural physico-chemical way, i.e. go out the limits of the peridotitic composition simplex.

Experimental searching of physico-chemical mechanism, that is capable of carrying out a continuous ultrabasic-basic differentiation of the mantle magmas and thus provide petrogenetic links for formation of the rocks of peridotite-eclogite series, has acquired a meaning after experimental discovering of the reaction between olivine and jadeite that gives rise to olivine disappearing [*Gasparik, Litvin, 1997*]. The question of physico-chemical conditions of formation of the mineral phases of peridotitic and eclogitic parageneses from primary inclusions in natural diamonds has assumed an actual significance in connection with elaboration of the mantle-carbonatite theory of diamond genesis [*Litvin, 2007, 2009*] and its progression [*Litvin, 2010; Litvin et al., 2012*]. Beyond any doubt, the problem can be only solved in physico-chemical experiment.

This work is devoted to investigation of physico-chemical conditions of diamond formation in the upper mantle peridotite–eclogite–carbonatite–carbon parental media of multicomponent and changeable compositions. The limits of the parental basic compositions is characterized by the system peridotite$_{30}$carbonatite–eclogite$_{35}$carbonatite$_{65}$–carbonatite [*Litvin, 2010b; Litvin et al., 2012*] (Fig. 1).
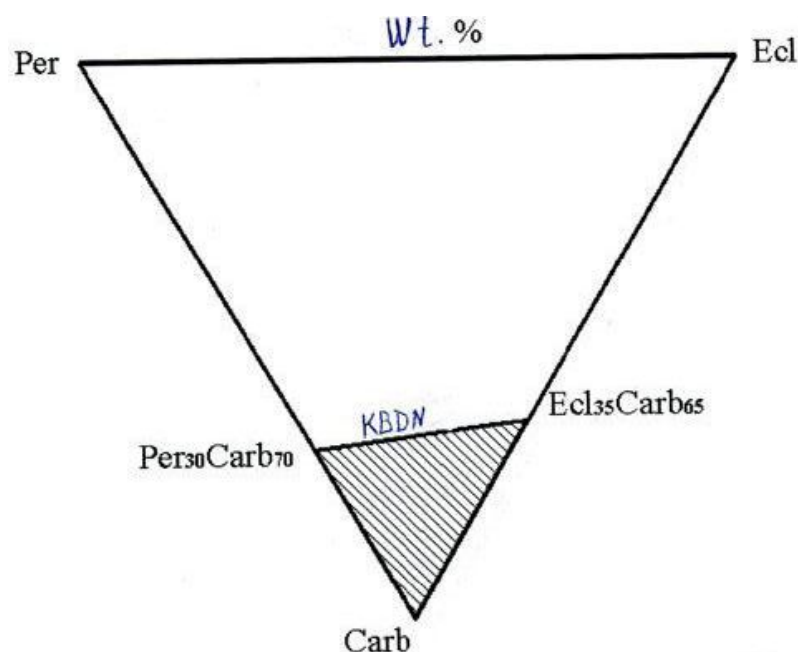
Fig. 1. Composition triangle of the peridotite Per–eclogite Ecl–carbonatite Carb - system. The line of concentration barrier of diamond nucleation (CBDN) restricts the field of parental media for natural diamonds and primary mineral inclusions therein [*Litvin, 2010b*]. Note: for compositions of the boundary phase see Figs. 2 and 5

2.**"Peridotite-to-eclogite tunnel" mechanism**

Fractional crystallization of primary komatiitic magma is accompanied by increasing concentration of jadeite component at residual melts. This activates the mechanism of ultrabasic-basic magma differentiation with formation of continuous peridotite-eclogite series. By experimental evidence, "peridotite-to-eclogite tunnel" mechanism is under control of reaction between Ol- and Jd-components [*Gasparik, Litvin, 1997; Litvin et al., 2000*]. Over liquidus of peridotite-eclogite system, reaction point Ol+Jd–Cpx=Grt+L [*Butvina, Litvin, 2010*] operates effectively in Ol elimination along the univariant curve Ol+Cpx+Grt+L. Under temperature lowering, the reaction brings figurative point of composition of the ultrabasic-basic magma out of peridotite Fo + Di–Jd–Cpx + L divariant field into the eclogitic one Grt + Jd–Di–Cpx + L.

The work of the "peridotite-to-eclogite tunnel" under fractional crystallization of ultrabasic-basic magmas is clearly disclosed by equilibrium phase diagram of the system peridotite $(Ol_{60}Opx_{16}Cpx_{12}Grt_{12})$–eclogite $(Cpx_{50}Grt_{50})$ studied experimentally at 7 GPa (Fig. 2) as well as by diagram of fractional crystallization (Fig. 3) constructed on the base of the equilibrium one. At both cases, olivine is the liquidus phase.
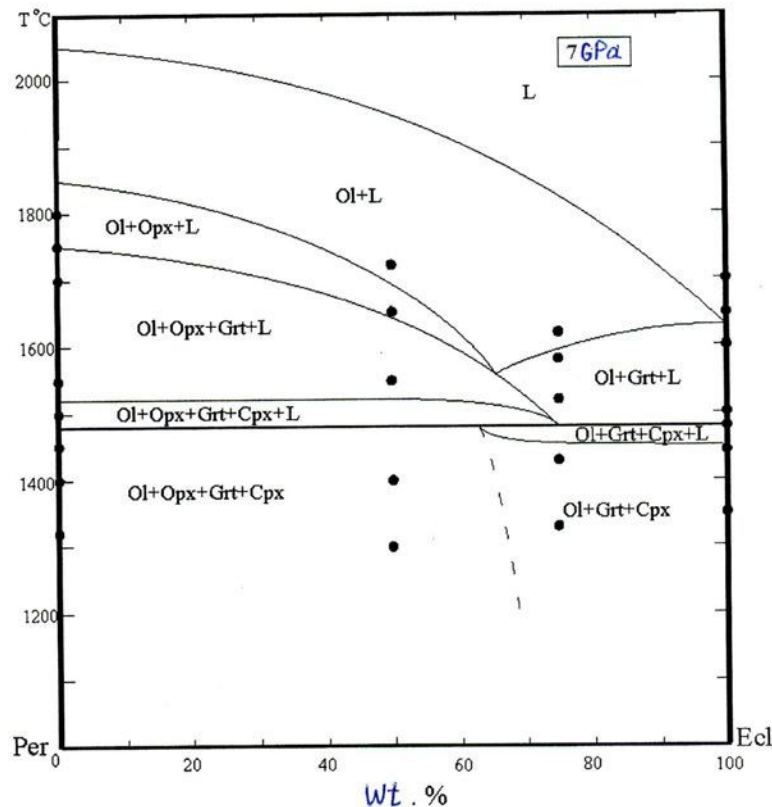

Fig. 2. Diagram of equilibrium crystallization of the system peridotite – eclogite at 7 GPa; starting compositions: Per $(Ol_{60}Opx_{16}Cpx_{12}Grt_{12})$ = Na_2O 0.52, MgO 37.12, FeO 11.35, CaO 2.49, Al_2O_3 3.48, SiO_2 45.04 and, respectively, peridotitic olivine Ol = MgO 45.63, FeO 14.35, SiO_2 40.02, orthopyroxene Opx = Na_2O 0.30, MgO 33.34, FeO 7.26, CaO 0.21, Al_2O_3 0.49, SiO_2 57.80, clinopyroxene Cpx = Na_2O 2.60, MgO 16.88, FeO 4.68, CaO 15.66, Al_2O_3 4.28, SiO_2 55.92, garnet Grt = MgO 20.93, FeO 8.48, CaO 3.97, Al_2O_3 24.07, SiO_2 42.55;(2) eclogite Ecl $(Cpx_{50}Grt_{50})$ = Na_2O 3.71, MgO 8.51, FeO 15.24, CaO 9.04, Al_2O_3 15.76, SiO_2 47.74 and, respectively, eclogitic clinopyroxene Cpx = Na_2O 7.41, MgO 8.50, FeO 6.40, CaO 12.09, Al_2O_3 9.52, SiO_2 56.31, garnet Grt = MgO 8.51, FeO 24.08, CaO 5.98, Al_2O_3 22.19, SiO_2 39.23 Black circles - experimental points
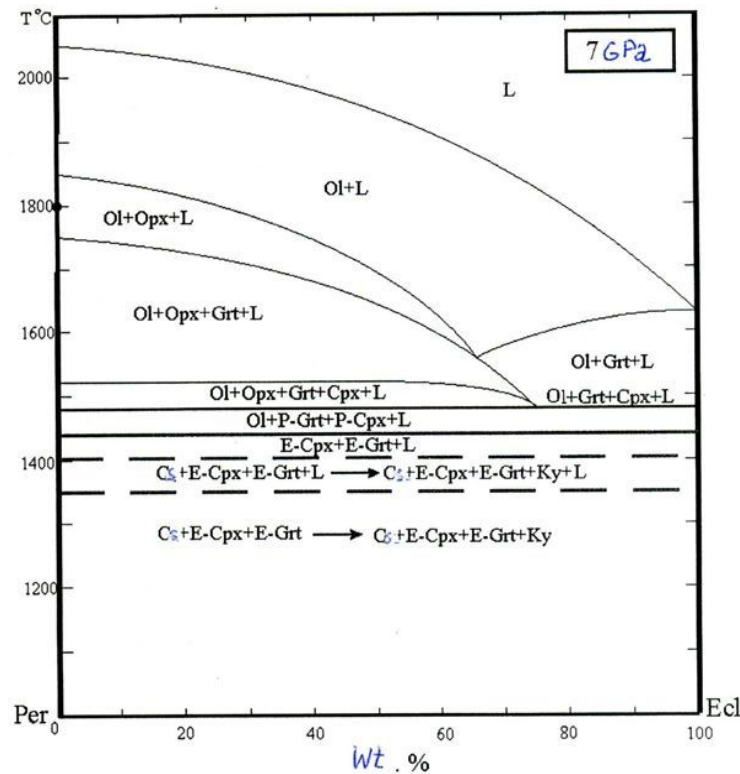
Fig. 3. Diagram of fractional crystallization of the system peridotite($Ol_{60}Opx_{16}Cpx_{12}Grt_{12}$)–eclogite ($Cpx_{50}Grt_{50}$) at 7 GPa under conditions of the peridotite–eclogite tunnel. Note:signs P and E concerns, respectively, to decignation of peridotitic and eclogitic phases of the same name

For the equilibrium case, orthopyroxene is lost in solidus peritectic point, and subsolidus is presented as result by two assemblies with olivine – Ol+Opx+Cpx+Grt and Ol+Cpx+Grt. For the case of fractional crystallization, olivine is also lost under action of "peridotite-eclogite tunnel", and following crystallization of the residual melts is determined by the transfer of figurative point of melt from the line Cpx–Grt along the liquidus elements of SiO_2-saturated eclogitic systems.

Fig. 4 is schematically presented liquidus surface of the upper mantle peridotite-eclogite system as a projection onto the boundary plane Ol–Cs–Crn of the complex tetrahedron Ol–Cs–Crn–Cpx in such way that the composition line Cpx–Gr tis perpendicularly oriented in respect to the plane Ol–Cs–Crn. The line Cpx – Grt is commonplace for all the peridotitic and eclogitic composition tetrahera (simplexes) of the system Ol–Cs–Crn–Cpx being a place where all the tetrahedra are contiguous.

Fig. 4 demonstrate that figurative points of residual melt compositions transfer towards to the join Cpx–Grt due to olivine-jadeite reaction. Direction of the transfer of the composition points from the quazi-invariant point Ol+Opx+Cpx+Grt to the composition line Cpx–Grt is marked by thick distorted line over the hatched region of the garnet peridotite liquidus surface. By doing so, a way for transfer of the melt figurative point over liquidus surface of any silica-saturated eclogitic cystem is opened. In this case, a choice of direction of further fractional crystallization is determined by component ratio in starting composition of ultrabasic melt in the very beginning of its fractional crystallization. Thus, the "peridotite-to-eclogite tunnel" mechanism makes the round the thermal eclogitic barrier and, correspondingly, paves the way for continuous fractional crystallization of ultrabasic-basic magmas with transfer in formation from Ol-bearing peridotite to Cs-bearing eclogite rocks
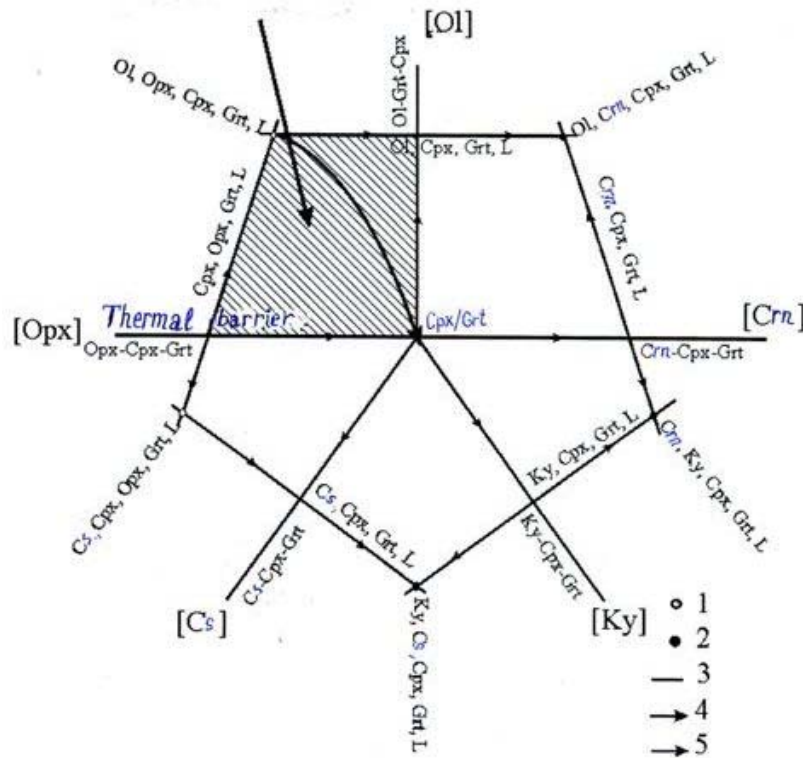
Fig. 4. Divariant liquidus field Cpx+Grt+L (view from the apex Cpx). Conventional signs: 1 – quazi invariant peritectic points; 2 – quazi invariant eutectic points; 3 – thin lines – univariant curves with arrows 4 pointed out directions of temperature lowering; 5 – thick line with arrow contacting the Cpx-Grt line is pointed out a change in direction of the univariant curve Ol+Cpx+Grt+L under conditions of fractional crystallization and acting the mechanism of "peridotite-eclogite tunnel".

3. Differentiation of silicate-carbonate melts parental for diamond and minerals of peridotite and eclogite parageneses

By experimental evidence, a changeable composition of the peridotite–eclogite–carbonatite parental melts for diamond and mineral inclusions therein is based on the peridotite$_{30}$carbonatite$_{70}$-eclogite$_{35}$carbonatite$_{65}$-carbonatite system [*Litvin, 2010b; Litvin et al., 2012*]. Diagrams of equilibrium and fractional crystallization of the boundary system peridotite$_{30}$carbonatite$_{70}$-eclogite$_{35}$carbonatite$_{65}$ are presented at Fig. 5 and 6, respectively.

By preliminary evidence, differentiation of the parental melts is under definite influence of the mechanism of "peridotite–eclogite tunnel". But an additional factor connected with the effects of carbonatization of peridotiticMg-components is coming into play. For the both equilibrium and fractional crystallization cases, olivine, orthopyroxene and garnet are liquidus phases and action of the carbonatization processes are shown up. For the equilibrium case, olivine is lost at the first peritectic point, and orthopyroxene – at the second one; as a result, subsolidus is presented by one assembly with olivine Ol + Opx + Cpx + Grt + Ms + Carb* and two assemblies without olivine – Opx + Cpx + Grt + Ms + Carb* and Cpx + Grt + Ms + Carb*. Nevertheless, in the case of equilibrium crystallization clinopyroxenes and garnets are characterized by peridotitic specialization and, perhaps, these regain eclogitic compositions only under conditions of fractional crystallization. Finaly, coesite and kyanite are formed among sublolidus assemblies as the result of fractional crystallization.

Fig. 5. Preliminary diagram of equilibrium crystallization of the system peridotite$_{30}$carbonatite$_{70}$-eclogite$_{35}$carbonatite$_{65}$ at 7 GPa; starting compositions: (1) carbonatite – K$_2$O 18.55, Na$_2$O 1.69, MgO 8.30, FeO 15.89, CaO 15.08, CO$_2$ 40.49, (2) peridotite (Ol$_{60}$Opx$_{16}$Cpx$_{12}$Grt$_{12}$) – for composition of the boundary phase see Figs. 2; eclogite (Cpx$_{50}$Grt$_{50}$) – for composition of the boundary phase see Fig. 2. Black circles - experimental points. For carbonate phases, magnesite Ms is separately shown but the other Ca, Fe, Na and K carbonates are symbolized by Carb* to simplify the diagram

Fig. 6. Preliminary diagram of fractional crystallization of the system peridotite$_{30}$carbonatite$_{70}$-eclogite$_{35}$carbonatite$_{65}$ at 7 GPa

Schematic liquidus diagram of the system peridotite–eclogite–carbonatite is presented at Fig. 7 and indicates that the role of carbonatization process is growing in importance with increase of content

of carbonate constituent, whereas the role of the mechanism of "peridotite–eclogite tunnel" – with increase of content of silicate constituent.
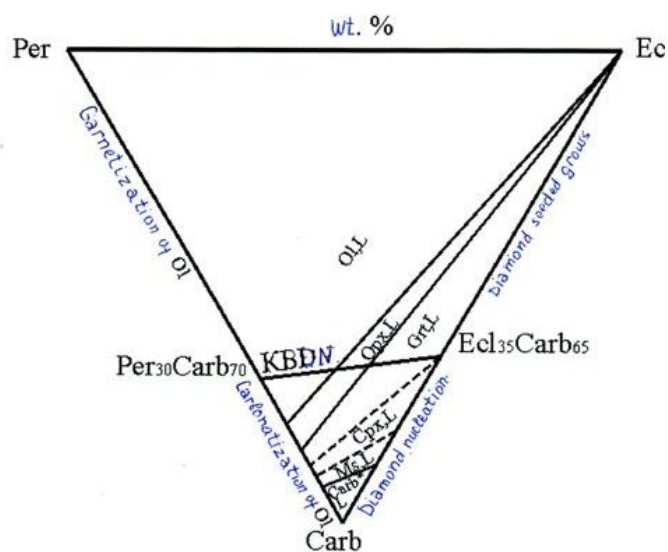

Fig. 7. Schematic liquidus of the system peridotite – eclogite – carbonatite

Fractional differentiation is responsible for formation of diamond-hosted mineral inclusions for both the peridotite and eclogite parageneses. Nevertheless, the existence of regular transition from peridotitic paragenesis to eclogitic one under fractional crystallization of syngenetic minerals testifies that a change of corresponding conditions is sequential. This excludes the paragenetic superposition for minerals and as a sequence the coincidental trap by growing diamonds of phases belonging to different parageneses. Mineral inclusions of different paragenetic relation within the same diamond crystal has to be regarded as result of accidental events without physico-chemical basement.

Figs. 8 and 9 demonstrate examples of syngenetic crystallization of diamond and minerals of peridotitic and eclogitic parageneses, respectively, by results of testing experiments at 8.5 GPa.

Fig. 8. Syngenetic crystallization of diamond with olivine in peridotite–carbonatite system: D = diamond; Ol = olivine
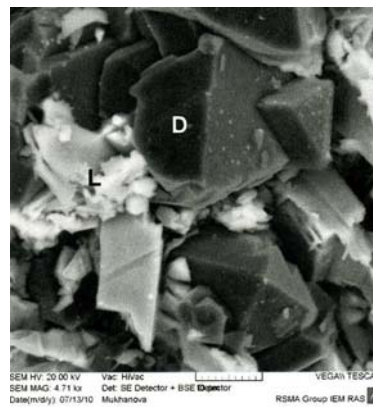

Fig. 9. Syngenetic crystallization of diamond with Cpx and Grt in eclogite-carbonatite system [*Pokrovskaya, Litvin, 2011*]: D = diamond, Cpx = clinopyroxene, Grt = garnet, L = melt

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