



On origin of lower-mantle diamonds and their primary inclusions



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ABSTRACT

Knowledge of mineralogy and petrology of unattainable lower mantle material is usually founded on high-pressure experiments with pyrolite ('*in situ*' material) and oceanic MORB basalt (subducted material). Primary inclusions in transition zone and lower-mantle 'super-deep' diamonds represent heterogeneous fragments of diamond-parental medium (not the unaltered lower mantle material). Inclusions of magnesiowustite and stishovite intergrowths ('stishovite paradox') give experimentally-supported evidence that stishovite, similarly to magnesiowustite, is not subducted but *in situ* lower mantle mineral. Primary Ca-, Mg-, Na-carbonate inclusions are symptomatic for multicomponent carbonatite (carbonate-oxide-silicate) parental melts for the lower-mantle diamonds and inclusions. We investigated melting phase relations of simple carbonates of Ca, Mg, Na and multicomponent Mg-Fe-Na-carbonate up to 60 GPa and 3500–4000 K (using multianvil press and diamond-anvil cell with laser heating) and determined a congruent melting of the carbonates and stability of *PT*-extended phase fields of the carbonate melts. 'Super-deep' diamonds are experimentally crystallized in melts of the lower mantle diamond-parental carbonate - magnesiowustite - Mg-perovskite - carbon system. Based on experimental and mineralogical evidence for the lower mantle diamonds inclusions, genetic links between diamonds and inclusions are determined and a generalized composition diagram of parental media for lower mantle diamonds and inclusions is constructed.

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1. Introduction

Lower mantle derived 'super-deep' diamonds are identified by indicatory magnesiowustite (Mg,Fe)O and Mg-perovskite (Mg,Fe)SiO₃ assemblage among their primary inclusions (Scott Smith et al., 1984; Harte and Harris, 1994; Stachel et al., 2000; Davies et al., 2004; Kaminsky, 2012). It is commonly supposed that heterogeneous primary inclusions in 'super-deep' diamonds are identical with original minerals of the lower mantle. By a typical concept, the inclusions represent ultrabasic minerals prevail in the lower mantle (to say, of *in situ* material source) and basic minerals of eclogite-like assemblages originated from subducting lithosphere (not of *in situ* material source). By alternative view (Litvin, 2007, 2013b, 2014), the lower-mantle mineral inclusions, both paragenetic and xenogenetic in respect to 'super-deep' diamonds, represent heterogeneous fragments of partially molten diamond-parental medium. This conclusion is based on rigid requirements of experimentally based criterium of diamond and inclusions syngensis (Litvin, 2007; Litvin et al., 2012): a natural diamond-parental medium has to be physicochemically capable for producing diamonds and formation of the whole complex of paragenetic

and xenogenetic phase-inclusions. By this is meant, that the lower mantle inclusions were trapped by growing 'super-deep' diamonds from heterogeneous parental medium. Therefore, the role of primary inclusions in determination of chemical and phase composition of heterogeneous parental medium of 'super-deep' diamonds becomes decisive and initiates the purposeful physicochemical experimental study.

Hence, it is beyond reason to identify mineral inclusions in 'super-deep' diamonds with phases of the surrounding mantle. In all probability, the mantle mineral components were initially involved in diamond-parental melts at their formation. The mantle-similar minerals were formed together with the host-diamonds, and their fragments were trapped by growing diamonds as paragenetic inclusions from parental melts. This also gives evidence on participation of magmatic melts at the lower mantle evolution. As a whole, the problem of lower mantle diamond genesis includes an elucidation of origin of parental media for lower mantle diamonds, physicochemical mechanisms of formation of diamonds and their primary inclusions in the parental melts, and physicochemical relations of parental media for diamonds and inclusions with the enclosing lower mantle rocks. The similar method of approach has successfully been taken at study of diamond genesis under the upper mantle conditions (Litvin, 2007, 2009, 2013a; Litvin et al., 2012). The data on the mineral-inclusion

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chemistry and high-pressure physicochemical experiments support the view that carbonate–silicate (carbonatite) melts with dissolved carbon are responsible for formation of most upper mantle derived diamonds. As a result, the mantle–carbonatite theory of diamond origin under the upper mantle conditions has been developed (Litvin, 2007, 2009). Compositions of primary inclusions in super-deep diamonds of the transition zone and lower mantle are not contradictory to the fact that a physicochemically uniform mechanism of diamond formation is operative for any depth.

1.1. Bulk lower mantle mineralogy by experimental evidence

The lower mantle material is unattainable for a direct analytical investigation. Present notions of its mineralogy and petrology have grown up on a basis of high-pressure phase reactions of garnet lherzolites (pyrolites) with realistic for the upper mantle compositions. A model pyrolite composition was experimentally studied at 10–40 GPa (Wood, 2000; Hirose, 2002; Nishiyama and Yagi, 2003; Akaogi, 2007). The high-pressure range includes 410-km ‘upper mantle – transition zone’ and 660-km ‘transition zone – lower mantle’ seismic discontinuities at about 13–14 and 23–24 GPa pressures, respectively. The upper mantle material consists of olivine $(\text{Mg,Fe})_2\text{SiO}_4$ (~60 vol. %), orthopyroxene, clinopyroxene and pyropic garnet. Olivine transforms into the more dense wadsleyite marking the 410-km ‘upper mantle – transition zone’ discontinuity. Polymorphic transition of wadsleyite into ringwoodite occurs at 520 discontinuity within the transition zone. At these conditions garnet solid solutions involving components of majorite $\text{Mg}_4\text{Si}_4\text{O}_{12}$ (Ringwood and Major, 1971) and $\text{Na}_2\text{MgSi}_5\text{O}_{12}$ -majorite (Dymshits et al., 2010) become the determining phases together with ringwoodite. At higher pressures, ringwoodite breaks up into magnesiowustite $(\text{Mg,Fe})\text{O}$ and perovskite $(\text{Mg,Fe})\text{SiO}_3$ marking the 660-km ‘transition zone – lower mantle’ discontinuity. Moreover, the ringwoodite transformation is responsible for *in situ* formation of over 60 vol. % petrological constitution for upper part of the lower mantle. Majoritic garnets transformations at 20–26 GPa are resulted in formation of (Mg,Fe,Al) -perovskite solid solution and exsolution of CaSiO_3 perovskite. By experimental evidence, the *in situ* mineralogical constitution of the lower mantle is mainly determined by magnesiowustite $(\text{Mg,Fe})\text{O}$, (Mg,Fe) - and Ca -perovskites. The plausible ‘subduction’ mineralogy for the lower mantle is elucidated in experimental phase transformation of mid-ocean-ridge basalt studied at high pressures (Irifune and Ringwood, 1993; Hirose et al., 1999; Ono et al., 2001; Akaogi, 2007). The subducting minerals are presented by stishovite, Ca -perovskite, Mg -perovskite and hexagonal aluminous $\text{Mg}_2\text{CaAl}_6\text{O}_{12}$ phase capable to host NaAlSiO_4 and KAlSiO_4 alkali components (Akaogi, 2007). The ‘subduction mineralogy’ must be supplementary to the *in situ* lower mantle mineralogy. By some assumptions (Stachel et al., 2005; Walter et al., 2008), origin of the ‘super-deep’ diamonds could be controlled by not *in situ* primitive but subducting material.

1.2. Primary inclusions in ‘super-deep’ diamonds

Primary mineral inclusions in ‘super-deep’ diamonds of the transition zone and lower mantle origin are of essential chemical variety and reviewed in (Kaminsky, 2012). For lower mantle conditions, the prevalent ultramafic minerals magnesiowustite $(\text{Mg,Fe})\text{O}$, (Mg,Fe) - and Ca -perovskites are accompanied by mafic phases of stishovite, associated with Fe-richer magnesiowustite $(\text{Mg,Fe})\text{O}$, CaSiO_3 -perovskite of sometime elevated Na and K contents, (Mg,Fe,Al) -perovskites and aluminous $\text{AlSiO}_3\cdot\text{OH}$ phase. Extraordinary stishovite $\text{SiO}_2 + \text{Fe}$ -richer magnesiowustite $(\text{Mg,Fe})\text{O}$ association, including closely related intergrowths, has been described among primary inclusions in ‘super-deep’ diamonds. On the one hand, the association is of a sort of ‘stishovite

paradox’ (Litvin, 2013b, 2014) because $\text{SiO}_2 + \text{MgO}$ paragenesis is forbidden for quartz and coesite. On the other, the paragenesis of stishovite and magnesiowustite gives evidence that stishovite is a definitely *in situ* lower mantle mineral similarly to magnesiowustite. This leads to the conclusion that not only ultramafic but also stishovite-bearing mafic material is drawn into the *in situ* lower mantle diamond-forming processes. Moreover, this has cast some doubt on the conclusions from experiments on ultramafic and mafic rocks transformation under high pressures and speculations on the role of subducting oceanic lithosphere in formation and evolution of the lower mantle material, including diamonds and their primary inclusions. Primary carbonate inclusions of aragonite CaCO_3 , dolomite $\text{CaMg}(\text{CO}_3)_2$, nyerereite $\text{Na}_2\text{Ca}(\text{CO}_3)_2$, nahcolite NaHCO_3 in transition zone and lower mantle diamonds are symptomatic for multicomponent carbonatite (carbonate–oxide–silicate) diamond–parental melts and feasibility of a mantle–carbonatite model to ‘super-deep’ diamond genesis.

1.3. Urgent objectives in study of lower-mantle diamond genesis

Mantle–carbonatite theory of upper-mantle diamonds and their inclusions origin (Litvin, 2007, 2009) takes into consideration that solely high-pressure carbonatite (carbonate–silicate) melts provide a formation of diamond–parental media with combination of the required and sufficient physicochemical properties. In the high-pressure process, the physicochemical possibilities are provided by congruent melting of carbonates, complete liquid miscibility of carbonate–silicate–(\pm oxide) melts and reasonably high diamond solubility in the melts.

Evidently, the reservoirs of parental magma for ‘super-deep’ diamonds and paragenetic inclusions were originated at lower-mantle ultrabasic rocks as the result of conjugated metasomatic and magmatic processes. Chemical and phase compositions of the diamond–parental melts were formed by components and products of interaction between CO_2 -bearing metasomatic agents and multicomponent multiphase lower-mantle oxide–silicate rocks. Credible sources of such metasomatic agents could be the mantle plumes and sizable magmatic reservoirs within the lower mantle. Carbonate melts are the key products of the metasomatic reactions. After formation, these carbonate melts are capable of dissolving the lower-mantle minerals, as major so accessory, as well as carbon and producing completely miscible carbonate–oxide–silicate–carbon parental magmas. Due to this, the magmas of variable composition and partial melting degree contain the wide range of components and minerals observed from their fragments included into ‘super-deep’ diamonds.

The main goals of this work are (1) physicochemical experimental studies of phase diagrams of simple and multicomponent carbonates representative for the primary inclusions in diamond under static PT-conditions of the lower mantle, (2) testing experiments at transition zone and lower mantle PT-conditions on diamond formation in melts of carbonate–oxide–silicate–carbon systems as indicator of high solubility of diamond in ‘super-deep’ carbonatite melts, and (3) construction of a generalized composition diagram of the parental medium for lower-mantle diamonds and their primary inclusions with considerations for their genetic links. The distinctive features of genetic classification of the primary inclusions in lower-mantle diamonds will be discussed on physicochemical experimental and analytical mineralogical foundations.

2. Experimental and analytical procedures

The experimental method is given in sufficient details by Spivak et al. (2012). A diamond anvil cell with the portable laser heating

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