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Conditions of diamond crystallization in kimberlite melt: experimental data

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Abstract

Experiments on diamond crystallization in kimberlite melt were performed for 40 h at 6.3 GPa in the temperature range of 1300–1570 ºC and at 7.5 GPa in the temperature range of 1450–1570 ºC, using a multianvil high-pressure apparatus of split-sphere type. Group I kimberlite from the Udachnaya-East pipe and a synthetic multicomponent mixture modeling the average composition of group II kimberlites were used as starting materials. The experiments have shown that diamond growth on seed crystals in the kimberlite melt in equilibrium with olivine, pyroxene, and garnet starts from 1400 ºC at 7.5 GPa and from 1520 ºC at 6.3 GPa. Diamond nucleation requires higher temperature and pressure, 1570 ºC and 7.5 GPa. The alkali-enriched and silicate-depleted derivates of kimberlite melts ensure the growth and nucleation of diamond at lower *P* and *T* values: 1400 ºC at 7.5 GPa and 1520 ºC at 6.3 GPa. The results obtained evidence that temperature, pressure, and the composition of crystallization medium are the main factors controlling diamond formation processes in the kimberlite melts and their derivates.

Keywords: diamond formation; kimberlite melt; HP–HT experiment

Introduction

Kimberlites, known as rocks formed during the crystallization of the most deep-seated magmas and the main sources of diamonds, have been comprehensively studied since the 19th century. These researches show that kimberlite magmatism is one of the mantle evolution processes (Dawson, 1980; Kogarko, 2006, 2008; Mitchell, 1986, 2004, 2008; Ringwood et al., 1992; Sparks et al., 2006, 2009; Wyllie, 1977a,b, 1980; Wyllie and Ryabchikov, 2000) and is directly related to the deep carbon cycle (Shirey et al., 2013). Primary kimberlite magmas are regarded as volatile-rich carbonate–silicate melts with high MgO and rather low SiO_2, Al_2O_3, and alkali contents (Dawson, 1980; Kamenetsky et al., 2009; Kjarsgaard et al., 2009). Kimberlites are commonly subdivided into group I (basaltic kimberlites) and group II (micaceous kimberlites, or orangites), according to the classification of Smith et al. (1985). As shown by Kjarsgaard et al. (2009), primary kimberlite magmas were characterized by wide variations in the contents of CO_2 (0–16 wt.%) and H_2O (0–14 wt.%), but most of kimberlites had a molar ratio $H_2O/(CO_2 + H_2O) = 0.6–0.9$. Probably, some magmas were almost dry (<0.5 wt.% H_2O) (Kamenetsky et al., 2007, 2009). Since a small portion of kimberlites bears diamonds, the diamond-transporting magma during its separation was in equilibrium with elemental carbon, and its f_{O_2} was lower than that of the CCO buffer.

There are two main viewpoints of kimberlite genesis. According to the first, kimberlites form owing to the extremely low degree of melting (<1%) of carbonatized lherzolite in the asthenosphere (Canil and Scarfe, 1990; Dalton and Presnall, 1998; Dawson, 1980; Eggler and Wendlandt, 1979; Mitchell, 1986, 2004, 2008; Ringwood et al., 1992; Tainton and McKenzie, 1994). The second viewpoint regards kimberlites as products of the interaction between deep-mantle volatiles and lithospheric-mantle rocks (Foley et al., 2009; Green et al., 1988; Wyllie, 1977a,b, 1980). Brey et al. (2009) believe that volatile-rich fluids were responsible for the low degree of melting of the sublithospheric mantle. However, produced melts were poorly mobile under the subcontinental thermal regime, which led to the formation of metasomatized zones. The following geodynamic processes at the basement of lithosphere resulted in temperature growth by several hundred degrees and favored the formation of kimberlite melts. Ulmer and Sweeney (2002) think that kimberlites of group II formed

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in peridotite protoliths through alternating metasomatism by K-rich aqueous fluids or carbonatite melts.

Diamond, one of the main concentrators of carbon in the mantle, is the most crucial link in the deep carbon cycle (Shirey et al., 2013). Modern diamond formation models, based both on study of inclusions in diamonds and on experimental data, consider metasomatism of subcratonic lithosphere by carbonatite or kimberlite-like melts/fluids as a stage ensuring necessary prerequisites for diamond formation. As early as the 1970s, it was shown that part of diamonds surely crystallized from kimberlite melt at the mantle stage of its formation and evolution (Orlov, 1973; Sobolev, 1977). Later on, this conclusion was substantiated by the specific composition of inclusions in some diamonds (Jacob et al., 2000; Sobolev et al., 2009), the close ages of some diamonds and kimberlites (Foley, 2008; Jacob et al., 2000; Rege et al., 2008; Shimizu and Sobolev, 1995; Shimizu et al., 1997), and diamond morphology and degree of aggregation of nitrogen in the diamond structure (Boyd et al., 1994). Note that diamonds of the same kimberlite pipe usually belong to several populations.

The composition of high-density fluid/melt inclusions in fibrous diamonds from different world regions testifies to wide variations in the compositions of diamond-forming media differing in the proportions of carbonates, silicates, chlorides, and water (Klein-BenDavid et al., 2004, 2006, 2009; Logvinova et al., 2008; Miller et al., 2014; Navon, 1999; Shiryaev et al., 2005; Skuzovatov et al., 2011, 2012; Tomlinson et al., 2005, 2006; Weiss et al., 2008, 2009; Zedgenizov et al., 2004, 2009, 2011). The presence of carbonates in these inclusions as well as findings of carbonates in mineral inclusions in diamonds suggest a genetic relationship between the diamond-forming media and kimberlite melts, which is confirmed by geochemical data (Skuzovatov et al., 2012; Zedgenizov et al., 2009, 2011). The first findings of inclusions of high-density fluids/melts in single-crystal diamonds (Weiss et al., 2014) indicate a more crucial role of carbonate-containing media in the diamond formation.

Despite the active experimental studies of the processes and mechanisms of diamond crystallization in different model media carried out in recent two decades, there is only one work concerned with experimental research into diamond formation in kimberlite melt (Arima et al., 1993), performed at 1800–2200 ºC and 7.0–7.5 GPa.

Several series of experiments were carried out during a comprehensive study of the physicochemical conditions of kimberlite magma generation and the processes of diamond crystallization in kimberlite melts. One of the major tasks was elucidation of the phase composition of kimberlite-like systems near the liquidus (Sokol and Kruk, 2015). Near the liquidus, compositions of the relevant primary kimberlite magmas should be in equilibrium with a phase association similar to peridotite at a particular pressure (Ringwood et al., 1992). Therefore, to establish the genesis of the chosen samples, it was necessary to search for the fields of multiphase saturation of their melts near the liquidus. Another crucial problem was study of diamond crystallization processes in multiphase-saturated kimberlite melts near the liquidus. These experiments helped to reconstruct the pressure, temperature, f_{CO_2} and f_{H_2O} at which magma was separated from the protolith. The data obtained gave an insight into the main regularities and parameters of diamond formation processes in primary kimberlite magmas.

Methods

Experiments were carried out at 6.3 GPa in the temperature range of 1300–1570 ºC and at 7.5 GPa in the temperature range of 1450–1570 ºC, using a multianvil high-pressure apparatus of split-sphere type (BARS) (Palyanov et al., 2010). As starting materials, we used kimberlite of group I from the Udachnaya-East pipe, purified from xenogenous materials, and a synthetic multicomponent mixture modeling the average composition of kimberlites of group II (according to Smith et al. (1985)) with a slight correction of Na_2O content (after Ulmer and Sweeney (2002)) and, in some cases, CaO content. The initial composition of kimberlites is presented in Table 1. The preparation technique and composition of the samples were described by Sokol et al. (2013a, 2014).

Using Pt ampoules (6.0 mm in diameter and 3.2 mm in height) made it possible to perform the experiments at temperatures close to the liquidus of hydrous kimberlite melts, i.e., >1400 ºC. Protective graphite capsules (with a 0.5 mm thick wall) were used to prevent the interaction of the Pt ampoules with kimberlite melt and to minimize Fe loss from the samples. Moreover, the inner graphite capsule permitted control of f_{O_2}. Under equilibrium of carbon-saturated carbonate–silicate melt and graphite, the oxygen fugacity was close to or somewhat lower than that of the EMOG/D buffer (Stagno and Frost, 2010). The procedure of the ampoule assembling was described in more detail by Sokol et al. (2013a, 2014). Graphite of protective capsules was a source of carbon. Two flat faced cube-octahedral crystals of synthetic diamond and two crystals (dodecahedron and cuboid) of natural diamonds from Yakutian kimberlite pipes (all crystals measured 500–700 μm) were placed as seeds into each ampoule. After the experiments, the diamond and graphite crystals and the diamond seeds were examined by optical (Axio Imager Z2m) and electron microscopy (Tescan MIRA 3 LMU).

Phase composition was determined using Cameca Camebax and Jeol JXA-8100 electron microprobes. Analysis of silicate and carbonate phases was performed at accelerating voltage of 20 kV, current of 20 nA, and beam 1–2 μm in diameter. The composition of aggregates of dendritic phases produced after the melt quenching was examined by scanning 100×100 μm areas at accelerating voltage of 20 kV and current of 40 nA.

Results

Phase composition of kimberlites. To describe the physicochemical conditions of diamond and graphite crystallization