Back transformation kinetics of majoritic garnet and implication for ascending rate of diamond

Mineral inclusions in diamonds provide important information on the depth of diamond source regions and mineralogy of the Earth's deep interior. We have successfully presented the strongest constraint on the ascent speed of diamond from the deep interior of the Earth [1].

Majoritic garnet is a stable mineral in the Earth's deep mantle at a depth of ~400-700 km [2], which is discovered as diamond inclusions in several localities [3]. The presence of majoritic garnet in diamonds indicates that they have been formed in such extremely deep regions. Majoritic garnet should transform to other minerals (i.e., low-pressure minerals) during transportation to the Earth's surface because it is unstable at depths shallower than ~300-400 km. Therefore, diamonds containing majoritic garnet should have been transported quickly before the majoritic garnet inclusions were converted to other low-pressure-type minerals. We considered that the transformation rate of majoritic garnet can be potentially used as a unique speedometer of diamonds rising from a depth of ~400 km.

We determined the transformation rate of majoritic garnet into low-pressure minerals (back transformation of majoritic garnet) by time-resolved *in situ* synchrotron X-ray diffraction measurement at 3.0-7.5 GPa (depth of ~100-200 km) and 1020-1300°C using a Kawai-type high-pressure apparatus SPEED-1500 at beamline **BL04B1**. White X-rays from synchrotron radiation were used as the incident X-ray beam, which was collimated to 0.05 mm×0.2 mm. The diffracted beam was measured by the energy dispersive method with a fixed 2θ angle of 5.0° using a Ge solid state detector.

We observed the transformation kinetics of majoritic garnet to its low-pressure minerals (pyropic garnet + clinopyroxene) from the increase in integrated intensity of the diffraction line of clinopyroxene. The time dependence of the transformed volume fraction is shown in Fig. 1. Back-scattered electron image and element mappings of partially transformed sample after the transformation experiment are shown in Fig. 2. Textural observation revealed that decomposed low-pressure minerals (clinopyroxene and pyropic garnet) were formed along grain boundaries of parental majoritic garnet.

The kinetic data were analyzed on the basis of the one-dimensional growth of the reaction rim, which is observed to be a predominant process of the back transformation. In this case, the rate equation is given by [4]

$$V = 1 - \exp[-2SX(t)] \quad (1)$$
$$X(t) = kt^n \quad (2)$$

where V is the transformed volume fraction, S is the area of the grain boundary, $X(t)$ is the growth distance from the original grain boundary at time t, and k and n are constants. The area of the grain boundary S can be expressed as $3.35/d$, where d is the grain size of the parental phase. The k and n values were optimized by fitting of the kinetic data to these rate equations using a nonlinear least-squares procedure. Results of these fittings are shown in Fig. 1.

Figure 3 shows the time needed for 5 μm and 50 μm growths for the back transformation as a function of temperature. The kinetic parameters obtained at 6.7-7.5 GPa (~200 km depth) were used in the calculation ignoring the pressure effect on the diffusion rate. Figure 3 indicates that, if we consider the grain size of 100 μm for the parental

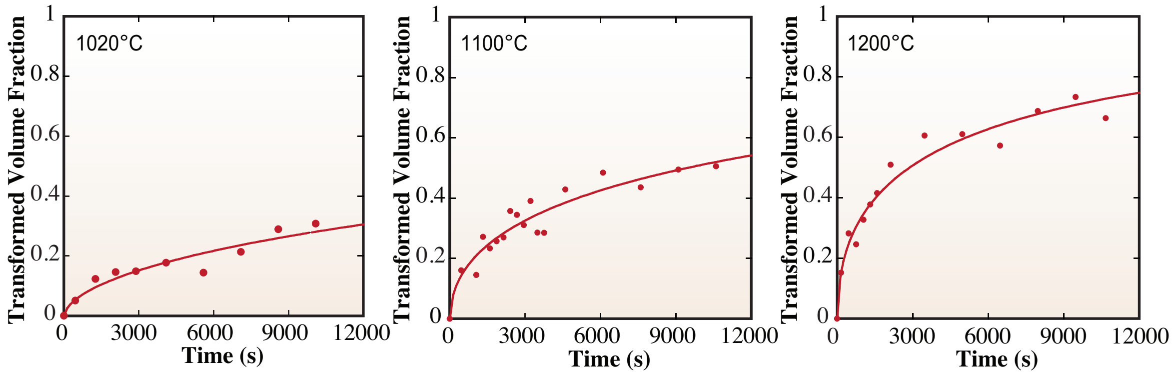

Fig. 1. Changes in the transformed volume fraction with time in the back transformation from majoritic garnet to clinopyroxene+majoritic garnet at 1020-1200°C. Curves obtained by least-squares fits of the kinetic data to eqs. (1) and (2) are also shown.

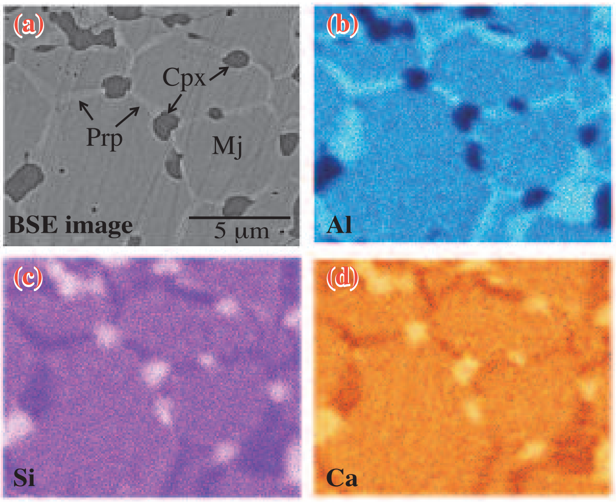

Fig. 2. **(a)** Back-scattered electron image and **(b)**-**(d)** element map of Al, Si and Fe showing textures of the recovered sample transformed at 3.0 GPa and 1100°C after 180 min of heating. Pyropic garnet (Prp, light gray) and clinopyroxene (Cpx, dark gray) precipitate along grain boundaries of parental majoritic garnet (Mj, gray).

majoritic garnet as typically observed in diamond, the majoritic garnet trapped in diamond can be brought to the Earth's surface through the upper mantle within ~600 hours at 1300°C. The average ascent rates of diamond are also shown in Fig. 3. When considering the temperature of 1300°C, the ascent rate of more than 60 km/h is required to preserve the untransformed majoritic garnet. In case that the ascent rate is slower than 0.6 km/h, the majoritic garnet completely transforms into pyropic garnet and clinopyroxene. We found that the velocity of the typical convective mantle flow (1-20 cm/year) is far too slow to satisfy the time limitation for the survival of majoritic garnet, indicating that such diamonds with majoritic garnet inclusions have been transported directly from the deep mantle by the rapid movement of "kimberlite" magma. Kimberlite magma is known to transport diamond to the surface quickly, but such activities have been considered to be restricted to the depths of the uppermost part (~150-200 km) of the Earth's mantle. Our experimental results suggest that such a rapid ascent mechanism as kimberlite magma activity may exist at greater depths than once thought.

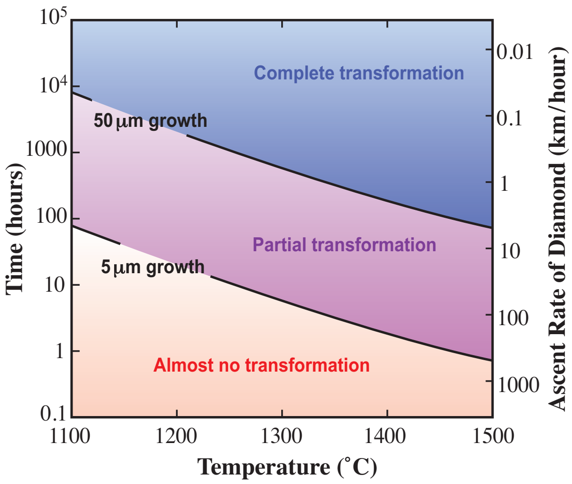

Fig. 3. Plots of the time needed for the 5 and 50 μm growths in the back transformation as a function of temperature based on the growth kinetics in this study. The ascent rates of diamond are also shown assuming that the back transformation proceeds at depth ranges of 50-400 km (right-hand scale).

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