Anomalous Compression of Basaltic Magma: Implications to Pressure-induced Structural Change in Silicate Melt

The transportation of magmas, which are generated by the partial melting of deep-seated mantle rocks, in the planetary interior is driven by buoyant force. The relative density between magmas and surrounding rocks controls whether magma ascends to the surface or remains in the deep interior. Density also controls the gravitational separation of crystals from the deep magma ocean in the earliest Earth, which could generate chemical stratification of the Earth's interior. Magmas are normally less dense than coexisting crystals at atmospheric pressure, but they are more compressible than crystals (Fig. 1). More than two decades of experimental studies have shown that the density of magmas can be higher than that of coexisting crystals at high pressure (e.g., Ref. [1]). Density crossover could have notable effects not only on the chemical stratification in the early Earth but also on recent volcanic activities.

Experimental studies on the compressibility of magmas have been carried out by static compression sink/float experiments, in which the flotation or settling of crystal in the magma is recognized from a quenched sample, yielding the density of magma at a fixed pressure. The equation of state for magma evaluated from one or two density data is, however, highly ambiguous. The structural change of magma with pressure also makes it difficult to represent the compression property of magma by a single equation of state. An alternative technique is expected to solve this problem. The X-ray absorption method [2,3] is advantageous because it can measure directly the density of magma at the desired pressure and can yield an accurate equation of state for magma. We have studied the density of the basaltic magma, which is the most abundant magma on Earth and other Earth-like planets such as Mars and the Moon, at high pressure using X-ray absorption method.

X-ray absorption experiments were carried out using the large-volume high-pressure apparatus SMAP-1 installed at beamline **BL22XU**, where a highly brilliant monochromatic X-ray is available (Fig. 2). The basaltic magma was confined in the single-crystal diamond capsule that is X-ray transparent rather than in silicate, the hardest material, which is uniformly deformed under pressure and is chemically inert with magma. The absorption of X-ray from the basaltic magma was measured up to 4.6 GPa and 1900 K, and the density was calculated from the Lambert-Beer law, $I/I_0 = \exp(-\mu\rho t)$.

X-ray absorption measurements provide the density of basaltic magma along its melting curve. Density data are normalized to 1673 K to draw an isothermal compression curve, which shows that the density of basaltic magma rapidly increases with pressure (Fig. 3). Fitting the Birch-Murnaghan equation of state to density data yields an anomalous

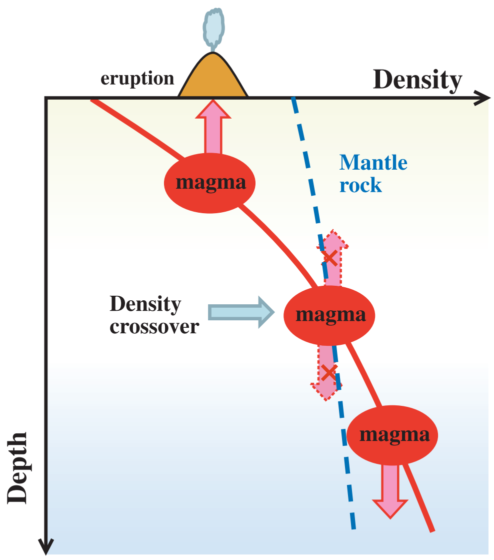

Fig. 1. Density profiles of magma and mantle rock as a function of depth. Transport of magma within the mantle is controlled by its density. Pressure corresponding to density crossover determines the critical depth at which magma can ascend.

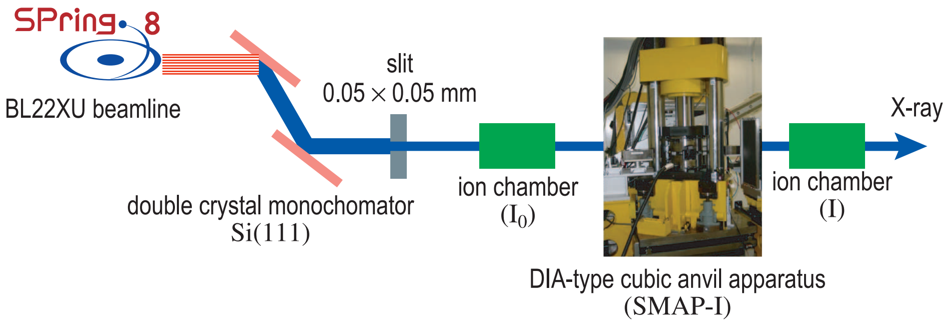

Fig. 2. Experimental setup for X-ray absorption measurements of magma at high-pressure and high-temperature at BL22XU.

negative pressure derivative of the bulk modulus of the basaltic magma (Birch-Murnaghan equation of state is a constitutive equation that provides a mathematical relationship between pressure, temperature and volume). This means that the basaltic magma becomes more compressible at higher pressure, in contrast to the normal crystalline solid. This result strongly indicates that the structure of basaltic magma changes with increasing pressure, including the shrinkage of networks of SiO_4 and AlO_4 tetrahedra and the increase in the coordination number of aluminum ions. Although Agee [1] predicted the equation of state for the basaltic magma on the basis of his sink/float experiments as shown in Fig. 3, his analysis cannot explain the complex compression behavior of basaltic magma. A linear extrapolation of our data, if correct, may shift the pressure of density crossover toward a pressure lower than that of the previous estimation. Compared with the density of olivine, which is the crystalline phase coexisting with basaltic magma in the mantle, the density of the basaltic magma would exceed that of olivine at approximately 7 GPa, which is lower than the pressure of density crossover predicted by Agee [1] by 1 GPa. The basaltic magma could not ascend from a position deeper than 200 km in the Earth's interior.

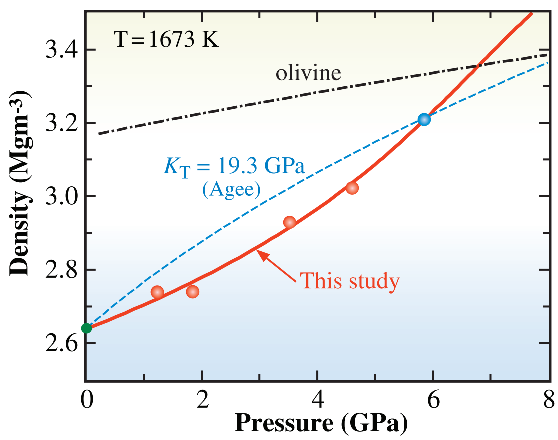

Fig. 3. Pressure *vs.* density diagram showing the compression curves of basaltic magma and coexisting olivine crystal. The red curve with density data is for basaltic magma determined in this study. The densities of basaltic magma are normalized to 1673 K. The blue dashed line is the calculated compression curve fitted to the density data at 5.8 GPa obtained by Agee [1].

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