Low core-mantle boundary temperature inferred from the solidus of pyrolite

The Earth's interior can be divided into layers by chemical composition and physical properties (Fig. 1). The interface between the mantle (silicate rock) and the outer core (liquid iron alloy) is located at a depth of 2900 km (136 GPa for pressure). The melting temperature of the mantle provides key constraints on the thermal and chemical structure of the core. The temperature at the top of the core should be lower than the solidus (onset of melting) temperature of a primitive mantle to avoid global melting above the core-mantle boundary (CMB). On the other hand, the temperature on the core side of the CMB should be higher than the liquidus (complete melting) temperature of the liquid outer core. The temperature at the CMB is often believed to be about 4000 K, which is higher than the liquidus temperature of most of the plausible outer core compositions. A laser-heated diamond anvil cell (DAC) can achieve such high pressure and temperature conditions. Previous experiments using laser-heated DAC techniques have shown that the solidus temperature of a primitive mantle is about 4200 K at the CMB [1], supporting a high T_{CMB} around 4000 K. The determination of the solidus temperature using the DAC is, however, challenging because detecting a small amount of partial melt at the onset of melting by X-ray diffuse scattering [1] is difficult, especially for silicates.

We determined the solidus temperature of the lower mantle on the basis of the textural and chemical characterizations of quenched samples after subjecting them to a high-pressure environment like that of the CMB. Our previous melting experiments showed that a partial melt of the mantle material is highly enriched with iron under all mantle pressure conditions [2]. The 3D distribution of iron can be obtained by imaging the sample at X-ray energies of 7 and 8 keV (*K*-absorption edge of Fe is 7.11 keV) using analytical dual-energy microtomography with a high spatial resolution of ~200 nm (pixel size: ~70 nm) and a 110-μm field of view under the typical conditions at beamline **BL47XU** [3], which are sufficient to image the internal structure of small DAC samples (typically about 40 μm) at the CMB pressure. This suggests that the detection of iron enrichment can be used as a tracer for a tiny partial melt at the onset of melting.

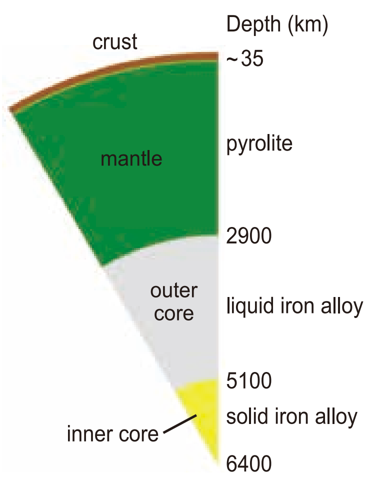

Fig. 1. Schematic illustration of the Earth's interior.

Our starting material possessed a natural primitive mantle (pyrolite) composition with about 400 parts per million (ppm) H_2O. High pressure and temperature experiments were conducted using laser-heated DAC techniques. The starting material was heated to 2100-3900 K at 25-169 GPa in a DAC, which covers the entire pressure range of the lower mantle. The pressure was determined on the basis of the Raman shift of diamond after the experiments and correction for the thermal pressure determined by the unit-cell volume of $MgSiO_3$-rich perovskite at beamline **BL10XU**. The temperature, which was measured using a spectroradiometric method with a spatial resolution of 1 μm, was quenched to room temperature by turning off the heating laser once the temperature reached the targeted value. The highest temperature with the 1-μm spatial resolution during heating was adopted as the experimental temperature in each run because melting occurs once the sample exceeds the solidus temperature. The temperature spatial resolution is higher than the size of the observed melt pocket by subsequent X-ray microtomographic imaging.

We also collected the X-ray microtomographic images of the recovered samples to explore the three-dimensional (3D) internal structure of all samples at beamline **BL47XU**. Some of the samples exhibit a round shaped Fe-enriched pocket at the center, which corresponds to the hottest part during laser heating (Fig. 2). Subsequent electron microprobe analyses confirmed that consistent with earlier melting experiment [2], such iron-rich regions represent quenched partial melts with nonstoichiometric compositions. Due to its high spatial resolution, the present microtomography imaging detected quenched melt pockets about 3 μm in size, which are formed by ~3 vol% partial melting at 142 GPa and 3690 K, but not at 151 GPa and 3680 K (Fig. 2). Thus, the solidus curve of pyrolite is bracketed as low as 3570(200) K at the CMB [3]. The solidus curve obtained in this study is consistent with the results of

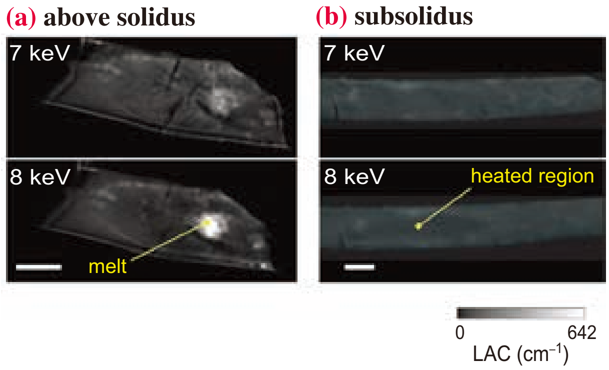

Fig. 2. Computed tomography images of a pyrolitic material quenched from the deep mantle conditions [4]. Brightness contrast is based on the X-ray linear attenuation coefficient (LAC) of an object. Comparison between the images obtained at 7 and 8 keV energies shows an Fe-rich melt pocket at the hottest part of the sample in A (142 GPa/3690 K) but not in B (151 GPa/3680 K). Scale bars represent 5 μm.

multi-anvil experiments below 25 GPa but is lower than those of recent laser-heated DAC studies combined with *in situ* X-ray diffraction measurements [1].

A lower solidus temperature helps explain the present day thermal and chemical structure of the mantle and the core. Although seismic observations may suggest the presence of a partial melt above the CMB, the possible partial melting is local feature not global one. Because the CMB temperature is isothermal, such a local occurrence indicates that these regions have distinct chemical compositions with lower melting temperatures. The solidus temperature of the mantle directly above the core is constrained by the upper limit on the CMB temperature to 3570 (200) K, which is much lower than the conventional estimate of around 4000 K. Pure iron cannot melt at such low temperatures. The outer core is known to contain about 10 wt% light elements in addition to iron and nickel. An alloy with the appropriate amount of sulfur, silicon, and oxygen, which are the most plausible candidates for the light elements from cosmochemical and geochemical aspect of views, cannot melt the outer core. However, the 0.6 weight% (25 atomic%) hydrogen (Fig. 3) may have been incorporated into the core from the hydrous magma ocean, which is thought to have existed on Earth during core formation [5].

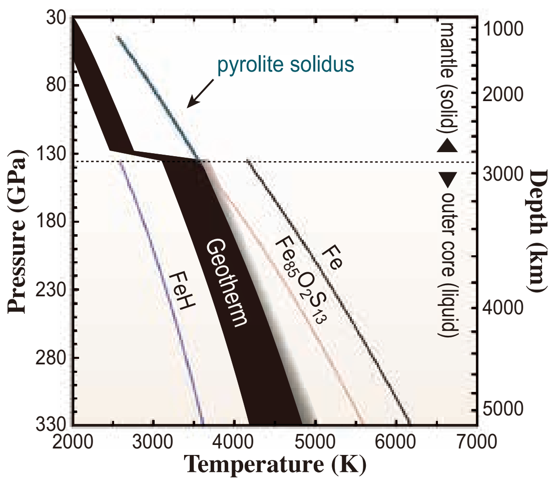

Fig. 3. Temperature profile (geotherm) in the lower mantle and the outer core [4]. Dark green curve depicts the solidus of pyrolite determined in this study. Melting (liquidus) temperatures of pure iron, Fe-O-S alloy, and FeH are shown by black, pink, and blue lines, respectively.

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