X-ray nano-tomography for obtaining deep understanding of Earth's interior

An X-ray nano-tomography system using a full-field x-ray microscope has been open to public users since 2006 at BL47XU in SPring-8. The system now has a spatial resolution of 200 nm (pixel size: ~75 nm/pixel) with a large-diameter Fresnel zone plate (310 μm) and a 110 μm field of view under typical conditions. The X-ray image detector has been changed from a CCD-based system to a high-definition sCMOS-based system to shorten the measurement time. As a result of these modifications, we have achieved a measurement time of 300 s for 900 projections. The X-ray energy can be selected between 6 and 10 keV to obtain high contrast for various samples.

In the field of planetary science, the nano-tomography system has been used for the analysis of small particles provided by Stardust (NASA's comet sample return mission) and Hayabusa (JAXA's asteroid Itokawa sample return mission). Specifically for the initial analysis of Itokawa particles, Tsuchiyama et al. developed a new technique named analytical dual-energy microtomography. The 3D distribution and shape of the minerals were obtained by imaging samples from Itokawa at X-ray energies of 7 and 8 keV using Fe as the index element (the K-absorption edge of Fe is 7.11 keV) [1]. This information greatly contributed to later destructive measurements of the same samples such as an analysis of the oxygen isotopic composition by secondary ion mass spectrometry.

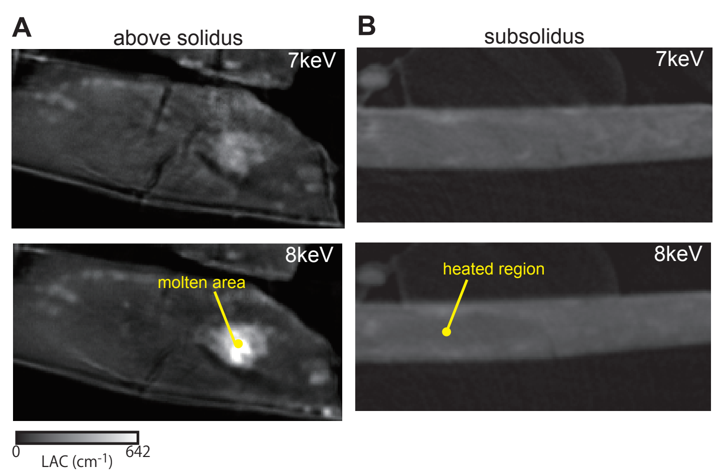
Recently, Nomura et al. showed that the temperature at the Earth's core-mantle boundary (CMB) is as low as 3570 ± 200 K using the nano-tomography technique. This temperature was lower than those estimated in previous studies [2]. The CMB is located at a depth of 2900 km inside the Earth (~130 GPa) and it is the interface between molten metal and rock. Only a laser-heated diamond-anvil cell (DAC) is known to achieve such a high pressure and temperature. The solidus temperature of the lower mantle was determined from X-ray diffraction patterns in previous research. However, this technique did not have sufficient sensitivity to detect the start of melting, i.e., partial melting. Therefore, Nomura et al. determined the solidus temperature of the lower mantle by textural and chemical characterizations of quenched samples using nano-tomography after pressurizing and heating them to approximately the CMB conditions.

Using the AD-CT technique with Fe as an index element, iron-rich regions were detected in tomographic images of some samples (see figure). The starting material was synthesized with a pyrolitic mantle composition and confirmed to be a mixture of olivine, pyroxenes, plagioclase and 400 ppm H_2O.The sample was heated to 2100 - 3900 K at a pressure of 25 - 169 GPa in a DAC at BL10XU in SPring-8,which covered the entire pressure range of the Earth's lower mantle. The existence of such iron-rich regions shows that the sample was previously molten. The melted area in the figure has a diameter of about 3 μm, corresponding to only 3% partial melting of the sample. The lower solidus temperature found in this research is attributed to both the effect of water and the high detection sensitivity to the onset of melting.

The low temperature at the CMB requires the melting temperature of the outer core to be much lower than the previous estimations. This low temperature may be due to the presence of light elements such as hydrogen. It may also help explain the complex seismic evidence regarding the nature of the CMB. This study demonstrates that nano-tomography can be used as a tool to observe the deep interior of the Earth.

These findings were the results of a close collaboration among Tokyo Institute of Technology, Kyoto University and SPring-8.

[1] Tsuchiyama et al., "Analytical dual-energy microtomography: A new method for obtaining three-dimensional mineral phase images and its application to Hayabusa samples", Geochim. Cosmochim. Acta. **116** (2013) 5
[2] Nomura et al., "Low Core-Mantle Boundary Temperature Inferred from the Solidus of Pyrolite", Science **343** (2014) 522



Computed tomography images of a pyrolitic material quenched from deep-lower-mantle conditions. Comparison between the images obtained at energies of 7 and 8 keV shows an Fe-rich melt pocket at the hottest part of the sample in A but not in B. The scale bars represent 5 μm.