Primitive liquid water of the solar system in an aqueous altered carbonaceous chondrite.

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Non-destructive 3D observation of the aqueous altered CM chondrite Sutter's Mill using scanning-imaging x-ray microscopy (SIXM) showed that some of calcite and enstatite grains contain two-phase inclusion, which is most probably composed of liquid water and bubbles. This water should be primitive water responsible for aqueous alteration in an asteroid in the early solar system.

We have developed a new technique for 3D observation of fine aggregates of mineral-water-organics for application to carbonaceous chondrites. As a first step of this technique, sections (usually polished thin sections) of samples are observed with an optical microscope and SEM and regions of interest (ROIs) are chosen for further 3D analysis. If required, detailed observation is made by an FE-SEM with high spatial resolution, elemental mapping and/or EBSD analysis. Then, a block 20-30 μm in size ("house" similar to a cube with a roof or cylinder with a roof) is picked up from a ROI by FIB [1]. 3D structure of the block is observed with the spatial resolution of >~100 nm by a SR-based imaging absorption micro-tomography and scanning-imaging x-ray microscopy (SIXM) at SPring-8 [2].

In the absorption tomography, if a sample is imaged at two x-ray energies, 7 and 8 keV, mineral phases can be discriminated based on the x-ray linear absorption coefficients at the two energies (dual-energy tomography: DET) [3]. However, it is difficult to discriminate materials, which are composed of light elements such as water and organic materials, from voids based on the absorption contrast. If we use phase contrast, which is related to the x-ray refractive index and thus the density of a material, they can be discriminated. Phase and absorption contrast images can be simultaneously obtained in 3D by SIXM.

We applied this technique to carbonaceous chondrites (Sutter's Mill, Ivuna, Orgueil and Tagish Lake meteorites). We found many inclusions with various morphologies in carbonate grains, which were formed by aqueous alteration. At this moment, we cannot detect any aqueous fluids inside the inclusions based on the phase contrasts except for one, which may contain fluid with a bubble. We do not know whether fluids have been escaped from the host mineral grains or they were not originally included from the time of the carbonate formation. We also observed vacant hexagonal platelets in the matrix of the Ivuna meteorite as well as in calcite grains in the Sutter's Mill meteorite. Candidates of organic materials were also observed in the matrix of the Ivuna meteorite.

We are currently making a sample in the shape of a pillar, which is used for TEM tomography, with FIB from a block sample ("house") that has been imaged by DET and SIXM. During the FIB micro-processing, 3D observation with FE-SEM was also made by serial sectioning. The goal of this technique is three-dimensional observation of samples in multi-scale with spatial resolutions from the orders of μm to nm. This is useful not only for carbonaceous chondrites but also samples returned from C-type asteroids by the HAYABUSA-2 and OSIRIS-REx missions.

Reference: [1] Miyake et al. 2014, *Microscopy*, 63: i24. [2] Takeuchi et al. 2013, *J. Synch. Rad.*, 20: 793. [3] Tsuchiyama et al. 2013. *GCA*, 116: 5.

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