Imaging fossil asteroidal ice in primitive meteorite by synchrotron radiation-based X-ray computed nanotomography

In the early Solar System, dust grains accreted to form planetesimals, and subsequent collisions and coalesce of planetesimals formed large planets. Some planetesimals that formed in the outer cold region are considered to have contained some ice upon formation. There are many meteorites showing evidence of aqueous alteration caused by ice melting in their parent bodies. However, researchers have yet to discover how the primordial ice was distributed in the meteorite parent bodies. This is largely due to complex secondary processes (e.g., aqueous alteration, brecciation) that affect most meteorites and destroy primordial information. Recently, we performed X-ray nano-computed tomography (XCT) of the Acfer 094 meteorite, which has been little affected by such modification, to determine the ice distribution in its parent body [1].

XCT was performed at SPring-8 **BL47XU**. We prepare two microsamples (~25×25×30 μm) from Acfer 094 meteorite chips by a focused ion beam technique. The samples were analyzed by two different XCT methods: dual energy tomography (DET) [2] and scanning imaging X-ray microtomography (SIXM) [3]. In the DET method, we obtained three-dimensional (3D) images with X-ray linear attenuation coefficients (LACs) at two different X-ray energies, one above and one below the *K*-absorption edge energy of iron: 7 and 8 keV, respectively. The images at 7 keV correspond closely to the compositional (*Z*) contrast, and those at 8 keV clearly show Fe-rich materials. In the SIXM method, we simultaneously obtained 3D images of both X-ray absorption contrast with LACs and X-ray phase contrast with refractive index decrements (RIDs), where the refractive index = 1−RID and RID corresponds to material density. These XCT images (Fig. 1) revealed three extremely porous regions in the two samples at a ~10 μm scale. We call these regions "ultraporous lithology (UPL)." The nondestructive observations ensure that the UPLs were originally present in this meteorite. 2D histogram plots of LAC and RID values indicate that the samples consist mainly of hydrous amorphous silicates (Fig. 2), which was confirmed by transmission electron microscopy observation of thin sections extracted from the CT samples. These suggest that the meteorite underwent aqueous alteration.

We performed scanning electron microscopy observation of polished surfaces of meteorite chips to search for more UPLs and found numerous UPLs. UPLs with abundant pores are fragile. Nevertheless, the UPLs showed no evidence of pore compaction, which was expected to have occurred during the parent body accretion. This suggests that the pores in UPLs were originally filled with some solid material(s). It is reasonable to consider that some ice, a major component in the early Solar System, once filled the pore spaces and subsequently disappeared owing to its evaporation and/or melting. That is, UPLs represent fossils of ice in the meteorite parent body. Melting of the ice is expected to have caused hydration of amorphous silicates. The ice abundance estimated on the basis of the pore fraction in UPLs is, however, too low to justify the observed aqueous alteration. This suggests that the distribution of ice was heterogeneous and that ice was much more abundant elsewhere in the parent body.

We propose that the inhomogeneous ice distribution originated during the meteorite parent body formation by dust agglomeration during radial migration from the outer to inner regions of the early Solar System

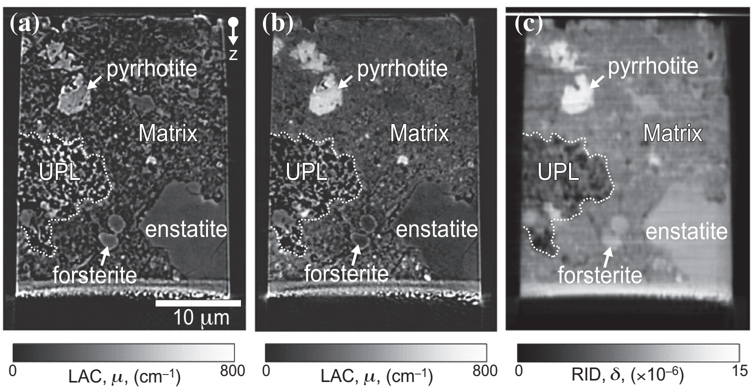

Fig. 1. XCT slice images of a microsample of the Acfer 094 meteorite. Absorption XCT images at 7 **(a)** and 8 keV **(b)**, and a phase XCT image **(c)** showing a UPL embedded in the matrix. Mineral names and compositions: pyrrhotite ($Fe_{1-x}S$); forsterite (Mg_2SiO_4); enstatite ($MgSiO_3$).

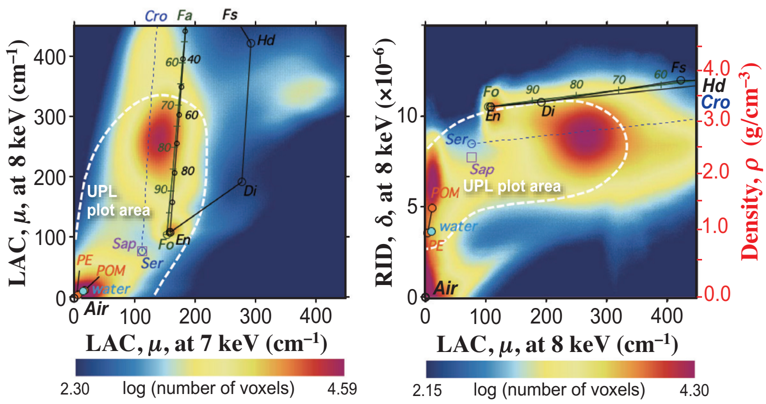

Fig. 2. 2D histograms of LAC and RID values of a microsample of the Acfer 094 meteorite at 7 and 8 keV. The histograms show peaks around air, resin, forsterite (Fo: Mg_2SiO_4), enstatite (En: $MgSiO_3$), and serpentine (Ser: $Mg_3Si_2O_5(OH)_4$) – cronstedtite (Cro: $Fe_2((Si,Fe)_2O_5)$). Other mineral names and compositions: Sap, saponite [$Ca_{0.25}(Mg,Fe)_3((Si,Al)_4O_{10})(OH)_2{\cdot}nH_2O$]; Fa, fayalite ($Fe_2SiO_4$); Di, diopside ($MgCaSi_2O_6$); Hd, hedenbergite ($FeCaSi_2O_6$); Fs, ferrosilite ($FeSiO_3$); PE, polyethylene [$(C_2H_4)_n$], POM, polyacetal [$(CH_2O)_n$].

across the H_2O snow line (SN). Recent theoretical studies [4] suggest that planetesimals and planets underwent such radial migration in the early stage of Solar System evolution. In the outer region beyond the SN, ice-rich dust accreted into the parent body first; subsequently, in the inner region, ice-free dust accreted. This process would produce a radial variation of ice abundance in the parent body.

On the basis of the above discussion, we propose the following model (Fig. 3). (i) The meteorite parent body grew from fluffy silicate dust with and without ice through radial migration from the outer to inner regions of the early Solar System across the SN. "Fluffy dust" denotes the general model of dust that formed the planets [5]. (ii) Around the SN, solid ice-silicate aggregates, which were formed by the sintering of ice in the fluffy dust, were incorporated into the meteorite parent body. The aggregates correspond to UPL precursors (ice-bearing UPLs). (iii) Subsequently, an aqueous alteration induced by ice melting took place in the parent body. A major part of the water was supplied from the ice-rich core.

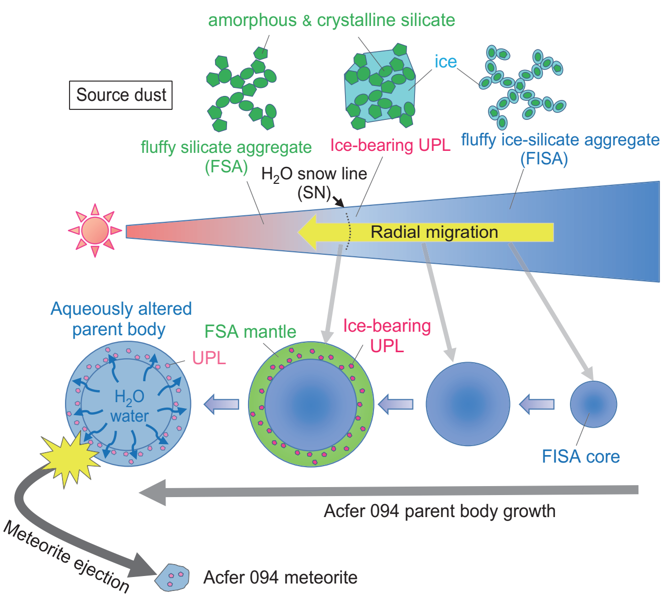

Fig. 3. Schematic illustration of the Acfer 094 meteorite parent body formation model. The parent body grew by agglomeration of fluffy dust with and without ice through its radial migration from the outer to inner regions of the solar nebula across the SN. The process produced a layered structure inside the parent body, with an ice-rich core and an ice-poor mantle. Around the SN, ice-bearing UPLs formed by sintering of ice were incorporated into the mantle. Subsequently, the melting of ice, mainly in the core, induced an aqueous alteration in the parent body.

The radial migrations of ice-bearing asteroids could have supplied some water to the inner forming region of the Earth. Therefore, our findings would be important to the understanding of not only icy asteroid formation but also the origin of water on the Earth.

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