3D-observation of matrix of MIL 090657 meteorite by absorption-phase tomography

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MIL 090657 meteorite (CR2.7) is one of the least altered primitive carbonaceous chondrites [1]. This meteorite has amorphous silicates like GEMS (glass with embedded metal and sulfide), which are characteristically contained in cometary dust, in matrix [2,3] as with the Paris meteorite [4]. Three lithologies have been recognized; lithology-1 (L1) dominated by submicron anhydrous silicates, lithology-2 (L2) by GEMS-like amorphous silicates and lithology-3 (L3) by phyllosilicates [2]. Organic materials are abundant in L1 and L2 [2,3]. L1 and L2 were further divided into sub-lithology respectively based on their textures and compositions [5]. These studies were performed by 2D SEM and TEM observations of sample surfaces and thin sections that are unable to reveal what constitute each lithology and how these lithologies are distributed and related to each other. This information will provide important insights into alteration and aggregation processes on asteroids and in the early solar nebula.
In this study, MIL 090657 matrix was examined in 3D using two types of X-ray tomography; DET (dual-energy tomography) [6] and SIXM (scanning-imaging X-ray microscopy) [7]. Mineral phases can be discriminated based on absorption contrasts at two different X-ray energies in DET. In SIXM, materials composed of light elements such as water or organic materials can be identified based on phase and absorption contrasts. By combining these methods, we can discriminate not only organic materials from voids but also hydrous alteration products, such as hydrated silicates and carbonates, from anhydrous minerals [8].
In this study, we first observed cross sections of MIL 090657 matrix fragments (~100 mm) in detail using FE-SEM/EDS. Based on the results, three house-shaped samples (30~50 mm) were extracted from L1, L2 and their boundary (H1, H3 and H5, respectively) using FIB. 3D imaging of these samples were conducted at BL47XU of SPring-8, a synchrotron radiation facility, with ~30-40 nm/voxel and ~70-80 nm/voxel at 7keV and 8keV in DET and ~100 nm/voxel at 8keV in SIXM.
We found new lithologies that we named L4, L5 and L6 in H1 and H3 in addition to L1 and L2. L4. L5 and L6 are mainly composed of probably phyllosilicates with different Fe contents. Sulfide and framboidal magnetite were recognized in L4. L5 includes magnetite and carbonate and L6 includes anhydrous silicates having cracks inside. L1, L2, L4 and L5 are porous while few voids were observed in L6. L4 adjoins to L1 with boundary, which is not very distinct. L2, L5 and L6 adjoin to each other, and the boundaries of L6 with L2 and L5 are clear. In H5, coarse mineral grains (~5-10 mm) such as Fe-metal and enstatite are present in L1 and L2. L1-L2 boundary is not sharp in 3D.
In conclusion, we found a variety of lithologies by 3D observation for the first time, suggesting that the MIL 090657 meteorite experienced complex alteration and aggregation histories. As L2 is dominated by amorphous silicates, which are extremely susceptible to aqueous alteration, this is presumed to be the most primitive lithology. The contact between L2 and phyllosilicate-bearing lithologies (L5 and L6) with clear boundaries indicates that they were aggregated after aqueous alteration of L5 and L6. The indistinct boundary between L1 and L2 is suggesting that these two lithologies might originally be the same aggregate composed of amorphous silicates and coarse mineral grains. L1 might have experienced weak aqueous alteration followed by mild thermal alteration [2], while L2 did not undergo aqueous alteration.

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