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Electron Microscopy Investigations of Organic-Mineral Relationships in Returned Samples from Asteroid Ryugu

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The JAXA Hayabusa2 mission successfully returned a total of 5.4g of regolith material from two separate sampling sites on the surface of the C-type asteroid Ryugu [1]. These samples provide an unprecedented opportunity for direct laboratory analysis of early solar system materials from which the Earth and life eventually evolved, with greatly reduced levels of alteration from interaction with terrestrial contaminants compared to terrestrially collected samples. The Initial Analysis of the Hayabusa2 samples began in June of 2021 and will conclude in June of 2022. Based on remote sensing measurements made by the Hayabusa2 spacecraft while in orbit around Ryugu, the returned samples were expected to show evidence for pervasive heating and loss of volatiles, including water [2]. However, the initial laboratory studies have shown that hydrated silicates and primitive organic matter are abundant [3].

The goals of the Organic Macromolecule, a.k.a "IOM", and Mineralogy and Petrology Finescale, a.k.a "Sand" Initial Analysis teams were to characterize the insoluble organic matter, and the mineralogy and space weathering features of the Ryugu samples through varied microanalysis measurements, respectively. This study will summarize results from the intersection of the work of the two teams on interactions of the organics and fine-grained minerals, with a focus on transmission electron microscopy results. The samples studied by the two teams included whole particles (10s to 100s of μm), extracted focused ion beam particle cross-sections, ultramicrotome slices of particles, and acid-insoluble macromolecular organic isolates. The distribution of samples to the international team allowed for the use of wide-ranging instrument configurations and conditions, from 60 kV UHV aberration-corrected scanning transmission electron microscopy to 300 kV cryo transmission electron microscopes, including energy dispersive x-ray spectroscopy and electron energy loss spectroscopy for determination of elemental composition and bonding states.

The initial analyses show that organic matter is abundant in the Ryugu samples, and that it is pervasively intermixed with the μm to sub-μm mineral components (Figure 1). Diffuse organic matter is present throughout a matrix rich in Mg-rich phyllosilicates, magnetite, carbonates and sulfides. In addition, nanoglobules, i.e., discrete round blebs of organic carbon typically < 400 nm diameter, appear as isolated inclusions and in clusters, surrounded by phyllosilicates, and in some cases associated with magnetite. Larger nanoglobules, and dense, irregularly shaped organic particles up to 2 μm in size are present, but rare. At least one carbonate grain with internal vesicles containing diffuse organics has been observed. Nanodiamonds, ~ 3 nm diameter appear, encased in amorphous organic carbon. The near edge fine structure of the C K-edge of the organic particles shows significant heterogeneity of both the diffuse and globular organics, broadly consistent with prior studies of organic matter in the Orgueil meteorite (Figure 2).

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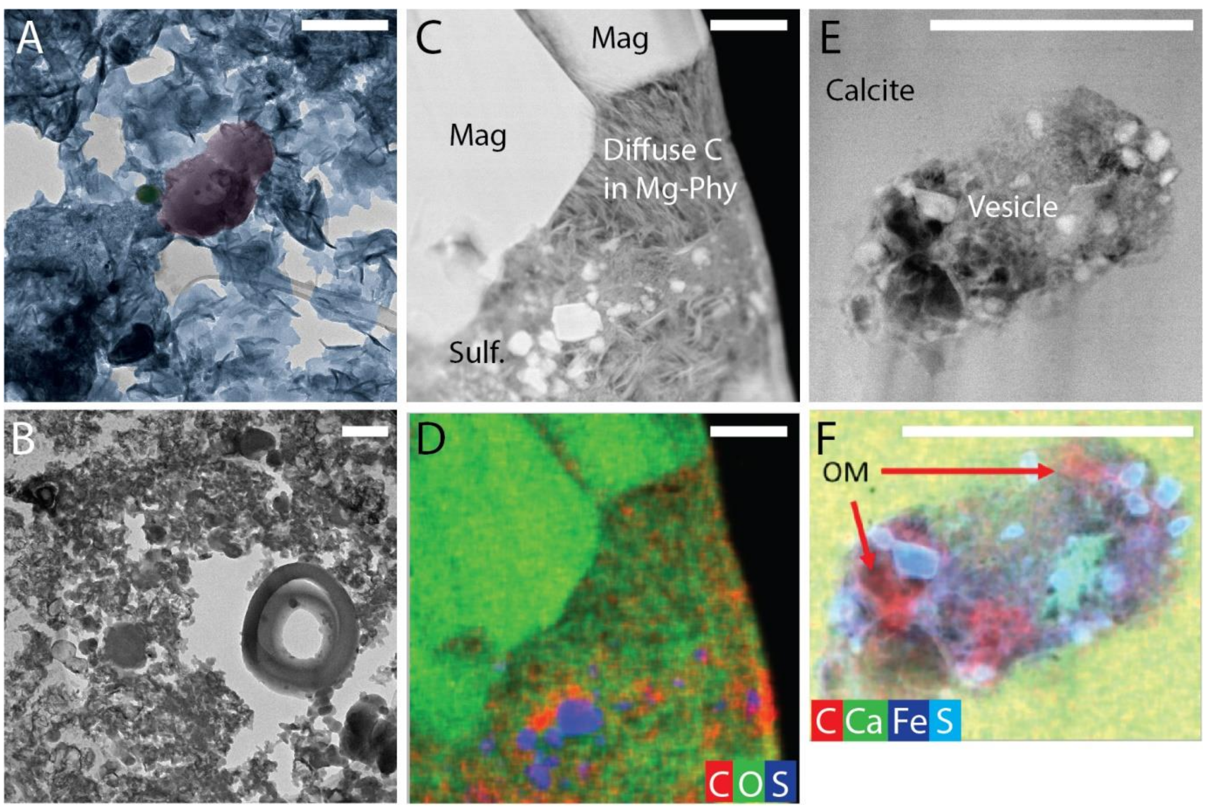

Figure 1. (A) False color BF TEM image of microtomed particle with nanoglobule in purples, sulfide in green and phyllosilicates in blue. (B) BF TEM of acid insoluble residue. (C) DF STEM image of particle FIB section with diffuse carbon interspersed with Mg-rich phyllosilicates, Fe, Ni sulfides (Sulf.), and

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magnetite (Mag). (D) C, O, N EDS raw count RGB map of area shown in (C). DF STEM image (E) and EDS map (F) of a vesicle in calcite with internal organics and sulfides. All scale bars are 500 nm.

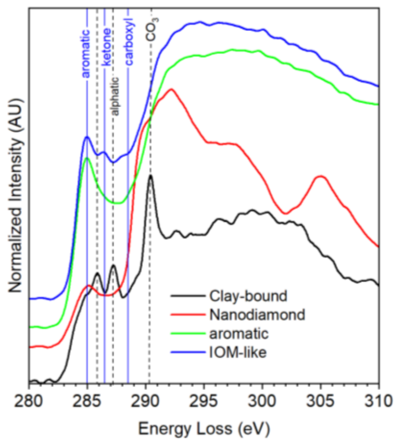

Figure 2. Example C K-edge EELS data from C-rich Ryugu grains.

[1] T. Yada, et al. Nature Astronomy **6** (2022), p. 214. doi:10.1038/s41550-021-01550-6.
[2] S. Sugita, et al. Science **354** (2019), p. 252 doi: 10.1126/science.aaw0422.
[3] C. Pilogret, et al. Nature Astronomy **6** (2022), p. 221. doi:10.1038/s41550-021-01549-z.

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