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Nanoscale characterization of carbonaceous materials in asteroid Ryugu regolith samples returned by Hayabusa2

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Asteroid regolith and comet coma dust are pristine samples of extraterrestrial materials that provide information about the early solar system. These samples are usually small, several mm down to less than 10 μm and require unique sample handling and processing procedures. Scanning-transmission X-ray microscopy (STXM) and scanning transmission electron microscopy (STEM) allow us to characterize the morphology and composition of the sub-μm components of these samples. A key analytical technique in these microscopes are their respective versions of absorption spectroscopy, X-ray absorption near edge spectroscopy (XANES) and electron energy-loss spectroscopy (EELS). Fresh samples from the asteroids Ryugu and Bennu require extra precautions due to their pristine nature, and we developed a combined focused ion beam (FIB) and ultramicrotomy approach to minimize the amount of sample volume needed for a consortium study of such grains. Embedding regolith grains in sulfur instead of epoxy is necessary to analyze carbonaceous phases within. We investigated organic matter in Ryugu samples as part of the Hayabusa2 Initial Analysis Team. Samples were prepared by both FIB and ultramicrotomy methods. STXM was performed at beamline 5.3.2.2 at the Advanced Light Source, and STEM was performed with an aberration-corrected Nion UltraSTEM 200 at the Naval Research Laboratory. C-XANES revealed a variety of organic functional groups, and hierarchical clustering of the spectral shapes found four main types of organic matter: IOM-like, highly aromatic, alkyl-aromatic, and molecular carbonate. These four types are confirmed by STEM imaging and C-EELS of the same C-rich features, many of which are nanoglobules. The molecular carbonate phase is associated with coarse-grained phyllosilicates such as saponite, which suggests it may be a secondary phase generated by exposure to interlayer sites. Subsequent XANES and EELS analysis of related (i.e., CI) carbonaceous meteorites also discovered molecular carbonate material distributed within coarse-grained phyllosilicates.