INVESTIGATING SPACE WEATHERING OF RYUGU GRAINS USING ELECTRON MICROSCOPY AND X-RAY COMPUTED TOMOGRAPHY.

L. E. Melendez[1], M. S. Thompson[1], L. P. Keller[2], S. A. Eckley[3], and C. J. Snead[2] [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA (melendl@purdue.edu); [2]ARES, NASA Johnson Space Center, Houston, TX. [3]Jacobs, NASA Johnson Space Center, Houston, TX.

Introduction: The effects of micrometeorite bombardment and solar wind ion irradiation – collectively known as *space weathering* – alter the microstructural, chemical, and spectral properties of airless surfaces. Characteristics of space weathering include vesiculated textures, amorphous grain rims (upper ~100 nm), and the production of Fe-bearing nanoparticles (npFe). The resulting modifications in the optical properties of the surface regolith include changes in spectral slope and overall reflectance of the surfaces as well as the attenuation of their characteristic absorption bands across VIS-NIR wavelengths. As the surface is continuously exposed to interplanetary space over time, the accrual of these features complicates the interpretation of remote sensing spectral data and the characterization of returned samples [1,2].

Laboratory experiments that simulate solar wind irradiation and micrometeoroid impacts using carbonaceous analogs have revealed novel and complex microstructural and chemical changes, including the decrease in organic species concentrations and the reduction of Fe^{3+} [3]. In 2020, the Japan Aerospace Exploration Agency (JAXA)'s Hayabusa2 mission returned over 5 g of regolith particles from near-Earth C-type asteroid (162173) Ryugu – a unique opportunity to study space weathering on carbonaceous materials [4]. Initial studies have established that the surface morphology and chemical signatures of space weathering in returned samples share characteristics with laser irradiation experiments simulating micrometeoroid bombardment, indicating that impacts are a significant space weathering mechanism operating on Ryugu [5].

Here, we seek to improve our understanding of space weathering of carbonaceous asteroidal regolith grains by characterizing its effects directly on returned samples to determine the nature of space weathering on Ryugu [3, 6]. To do so, we performed coordinated analyses using electron beam techniques and X-ray computed tomography (XCT) to examine the effects of space weathering on grains returned from the surface of Ryugu by the Hayabusa2 mission.

Methods: We were allocated five Hayabusa2 particles, three collected from the site of the first touchdown and two from the artificial impacting event of the second touchdown site (A0152, A0466, A0512, C0178, and C0428). The internal microstructure and mineralogy of two of the particles were examined using X-ray computed tomography (XCT) to scan the samples using the Nikon XTH 320 micro-XCT at NASA Johnson Space Center (JSC). Higher-resolution sub-volume scans were completed on the Zeiss Xradia 620 Versa at the University of Texas at Austin High Resolution X-ray CT Facility (UTCT) (Fig. 1, c and d). We transferred several <500 µm fragments to an SEM mount covered with carbon tape. The subparticles were carbon coated and examined using the Quanta 3D FEG focused ion beam

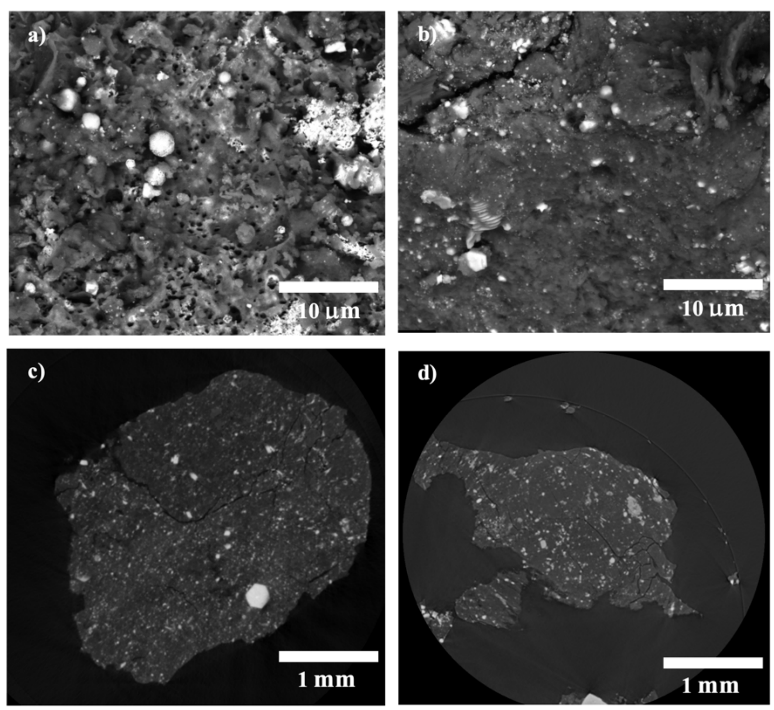

Figure 1. BSE images (a,b) of Ryugu subgrain surfaces: a) space-weathered region on A0152 with vesiculated textures and impact melt spherules, b) non-space-weathered region on C0178 with rough textures and no evident vesiculation. XCT images of the XY plane of c) A0152 and d) C0178.

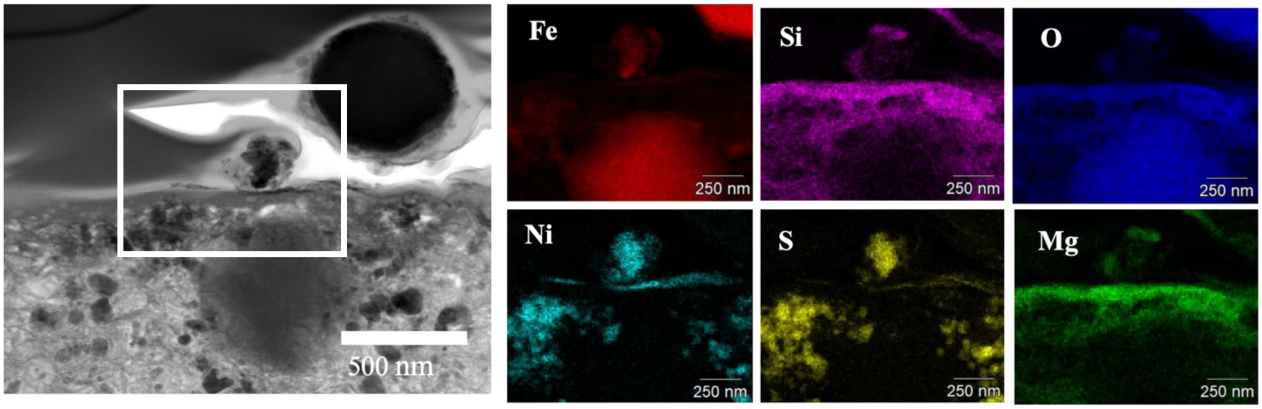

Figure 2. BF image of melt deposit identified on a subgrain in A0152 (Fig. 1a). EDS composition data (stamp shown in white rectangle) show two melt layers: a darker, thinner Ni-rich melt layer overlain a Mg-rich melt layer, indicative of multiple impacting events. The melt droplets, with their Fe-Ni-S composition, are likely pentlandite.

scanning electron microscope (FIB-SEM) at JSC to obtain backscatter (BSE) and secondary electron (SE) images from the fragments (Fig. 1, a and b). Particles that exhibited characteristic space weathering surface features were sectioned using the focused ion beam (FIB) for analysis using the scanning transmission electron microscope (STEM). Bright field (BF) and dark field (DF) STEM images and chemical maps of the FIB sections were acquired using the JEOL 2500SE STEM equipped with a 60 mm^2 ultra-thin window silicon drift energy-dispersive X-ray spectrometer (EDS) detector at JSC.

Results and Discussion: The XCT scans revealed a microbrecciated texture with hexagonal sulfide grains ~10 to ~200 µm in size distributed throughout a phyllosilicate and carbonate-rich matrix. There were multiple cracks throughout the inside of the particle, indicating a porous nature, following the high average microporosity measured in [7]. In the SEM we observed a rough surface texture with a matrix primarily composed of fine-grained phyllosilicates, FeNi sulfides, including hexagonal pyrrhotites 50 – 100 µm in diameter, along with several magnetite morphologies. Some subparticles from Chamber A exhibit numerous spherules and a highly vesiculated, frothy surface textures, indicative of volatile outgassing and melting via space weathering. These frothy layers are reminiscent of the deposits observed in laser-irradiation experiments that simulated shock heating by micrometeoroid impacts [6]. We prepared FIB sections from this impact site along with regions of the heterogeneous matrix. STEM imaging and analyses confirmed the presence of Mg-rich phyllosilicates, magnetite, sulfides, dolomite, and carbon nanoglobules, consistent with previous studies of Ryugu samples [8,9]. High resolution TEM (HRTEM) images indicate that the matrix is composed of intergrown serpentine and saponite. Analysis of the FIB section from the frothy melt region from the Chamber A sample, revealed impact spherules and amorphous, vesiculated melt layers ranging from 10 to 200 nm in thickness across the surface. EDS chemical maps (Fig. 2) indicate the nano- to microparticles (with diameters of 10 – 100 nm) embedded within the spherules and the melt layers have a composition consistent with nanophase Fe sulfides, Fe-O (magnetite) and Fe-Ni sulfides. The melt deposits have stratigraphy with superimposed layers of unique composition, (e.g., the S-rich melt layer superimposed on the Ni-rich melt layer in Fig. 2), which might be indicative of multiple impact events. We have not yet identified evidence for space weathering in Chamber C particles, though their composition is consistent with samples from Chamber A.

Conclusion: We used coordinated SEM and TEM analyses along with XCT to characterize the space weathering features on Hayabusa2 particles that formed as the result of impact processes on Ryugu. Additional analyses of this fragment will expand our understanding of space weathering on carbonaceous materials in preparation for future work on Bennu's samples, which were successfully returned by OSIRIS-REx on September 24^{th}, 2023.

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