EVIDENCE FOR MICROMETEOROID BOMBARDMENT ON THE SURFACE OF ASTEROID RYUGU.

M. S. Thompson[1], P-M. Zanetta[2], T. J. Zega[2], T. Noguchi[3], H. Yurimoto[4], T. Nakamura[5], H. Yabuta[6], N. Naraoka[7], R. Okazaki[7], K. Sakamoto[8], S. Tachibana[9], S. Watanabe[10], Y. Tsuda[8], and the Hayabusa2 Min-Pet Fine Sub-team. [1]Depart of Earth, Atmospheric, and Planetary Sciences, Purdue University (mthompson@purdue.edu), [2]Lunar and Planetary Laboratory, University of Arizona, [3]Division of Earth and Planetary Sciences, Kyoto University, [4]Department of Earth and Planetary Sciences, Hokkaido University, [5]Department of Earth Science, Graduate School of Science, Tohoku University, [6]Earth and Planetary Systems Science Program, Hiroshima University, [7]Department of Earth and Planetary Sciences, Kyushu University, [8]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, [9]UTokyo Organization for Planetary and Space Science, University of Tokyo, [10]Department of Earth and Environmental Sciences, Nagoya University.

Introduction: The Japan Aerospace Exploration Agency (JAXA)'s Hayabusa2 mission successfully returned over 5 g of sample from asteroid Ryugu to Earth in December 2020 [1]. This return of the first samples from a carbonaceous asteroid provides an opportunity to understand how the surfaces of these airless bodies evolve through a process known as space weathering. Driven by solar wind irradiation and micrometeoroid bombardment, space weathering changes the morphology, microstructure, chemistry, and spectral properties of grains on airless surfaces [2]. Understanding how space weathering affects surface materials at the nanoscale is critical for interpreting remote sensing data collected by orbital spacecraft.

Our understanding of how space weathering operates on hydrated, organic-rich materials like those from Ryugu is still at an early stage. In advance of sample return, experiments simulating space weathering of carbonaceous materials were performed [3-7]. Laser irradiation was used to simulate the short-duration, high-temperature events associated with micrometeoroid bombardment on asteroid surfaces [3,4,6,7]. Similarly, H^+ and He^+ irradiation was employed to simulate exposure to the solar wind [5]. These experiments indicate that space weathering of carbonaceous materials is a complex phenomenon and that the analysis of returned samples is essential for building an understanding of how this process operates on the surface of Ryugu. Here we present evidence for space weathering on asteroid Ryugu through the analysis of Hayabusa2 samples and compare these results to our experimental simulations of space weathering of carbonaceous chondrites.

Samples and Methods: We performed transmission electron microscopy (TEM) on a sample of the A0058 particle collected in Chamber A during the first touchdown on asteroid Ryugu. This grain was mounted in epoxy and the Min-Pet Fine Sub-team prepared an electron transparent thin section through focused ion beam scanning electron microscopy (FIB-SEM) at Kyoto University. The TEM analyses were performed at the University of Arizona using the 200 keV Hitachi HF5000. The HF5000 is equipped cold-field emission gun, a third-order spherical aberration corrector for scanning TEM (STEM) analysis, bright- and annular-dark-field STEM imaging detectors, and twin Oxford 100 mm^2 silicon-drift detectors for energy dispersive X-ray spectroscopy (EDX). We analyzed the microstructural and chemical features of the A0058-T3 FIB section to identify evidence of space weathering.

Results and Discussion: The A0058-T3 FIB section is primarily composed of matrix material representative of aqueously altered carbonaceous chondrites, including phyllosilicates, Fe- and Fe-Ni-sulfide grains, and several prominent magnetite grains. Bright-field (BF) and high-angle annular-dark-field (HAADF) imaging of the section shows an amorphous layer of melt distributed heterogeneously across the surface of the sample, ranging in thickness between 300 nm and 3 µm (Fig. 1a). Distributed throughout the melt layer are submicroscopic Fe-bearing particles and vesicles. The vesicles range in size from a few 10s of nm to 300 nm and the nanoparticles range from a few nm to nearly 500 nm in diameter (Fig. 2).

EDX analysis shows that, compared to the matrix, the melt is enriched in elements including Fe and Ca, the latter of which is in very low abundance in the

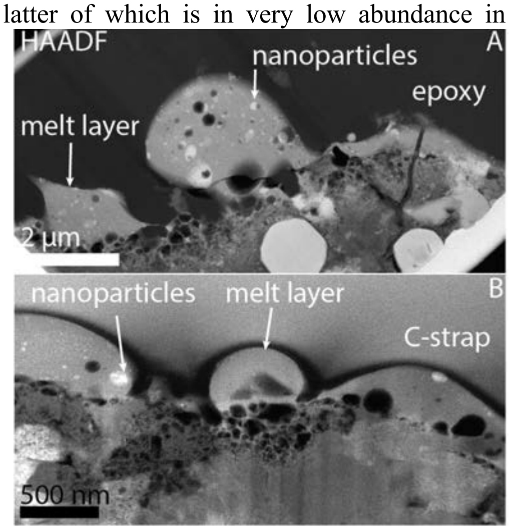

Figure 1: HAADF STEM images of A) Ryugu sample A0058-T3 and B) 1x lasered CM2 Murchison sample from [3] showing the similarity in melt thickness, and the size and distribution of vesicles and nanoparticles.

underlying matrix. We hypothesize that the melt is sourced from an adjacent Ca-bearing region of the grain. EDX maps also indicate nanoparticles throughout the melt are dominated by Fe-S and Fe-Ni-sulfide minerals.

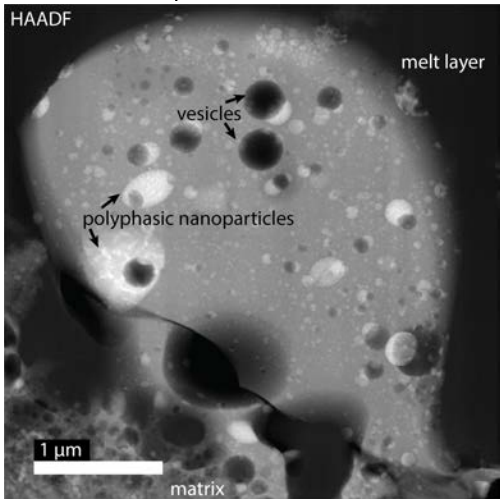

Figure 2: STEM-HAADF image of the amorphous melt droplet containing sulfide nanoparticles and vesicles.

High-resolution TEM (HRTEM) imaging of the nanoparticles reveal lattice fringes from which d-spacings can be measured. Images indicate several possible nanoparticle mineralogies including Fe-metal (Fe^0), pentlandite ($(Fe,Ni)_9S_8$), pyrrhotite ($Fe_{1-x}S$), and minor magnetite (Fe_3O_4). HRTEM images show that some nanoparticles are monomineralic while others are polyphasic, including both pentlandite and pyrrhotite (Fig. 3). These observations are also reflected in EDX maps in which the distribution of Fe and S in individual nanoparticles is uniform, while the Ni is heterogeneous.

At the interface between the melt and the underlying matrix material is a highly vesiculated layer that is ~500 nm in thickness. We hypothesize that this vesiculated region is from the outgassing of volatile species in the matrix, including water from hydrated phyllosilicates and possible S from sulfide minerals.

The melt textures observed in the Ryugu samples appear remarkably similar to laser irradiation experiments [3,4] performed to simulate micrometeoroid bombardment of carbonaceous chondrites (Fig. 1b), indicating this grain likely experienced a micrometeoroid impact(s) on the surface of Ryugu. The thickness, morphology, and composition of the melt deposit on the A0058 particle is similar to [3,4]. In addition, the mineralogy and size distribution of the nanoparticles mirrors experimental samples in [3,4]. Finally, the distribution of vesicles and their concentration at the interface between the melt and matrix is also reflected in [3,4].

Implications for Space Weathering on Ryugu: The observations made for sample A0058-T3 are consistent with micrometeoroid bombardment occurring on the surface of Ryugu. Microstructural and chemical features including melt layer morphology and thickness, vesicle size and distribution, and nanoparticle size and composition are all remarkably similar to laser irradiation experiments simulating progressive micrometeoroid bombardment of the Murchison meteorite. Compared with [4], this sample exhibits characteristics consistent with experiencing one or two individual impact events. Interestingly, the analysis of returned samples from asteroid Itokawa e.g., [9] indicated that solar wind irradiation was the predominant space weathering mechanism operating on small bodies. However, the results presented here demonstrate that micrometeoroid bombardment may play a more significant role in the space weathering of asteroids than previously thought. Finally, prior studies have shown that the effects of nano- and micro-phase sulfide particles on the spectral properties of airless surfaces are not uniform or well-understood [4], and future work should further investigate the role that these phases play in the remote sensing observations made for asteroid Ryugu.

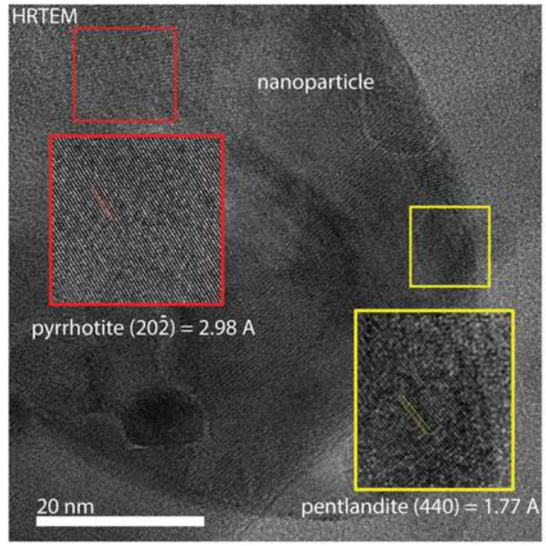

Figure 3: HRTEM image of a nanoparticle in the melt layer shown in Fig. 2. Lattice fringes are visible and d-spacings measured from different regions correspond to pyrrhotite (red box) and pentlandite (yellow box).

References: [1] Yada, T. et al. (2021) *Nat. Astr.,* 1-7. [2] Pieters C.M. and Noble S.K. (2016) *J. Geophys. Res-Planet., 121,* 1865-1884. [3] Thompson, M.S. et al. (2019) *Icarus 319,* 499-511. [4] Thompson, M.S. et al. (2020) *Icarus 346,* 113775. [5] Laczniak, D.L. et al. (2021) *Icarus 364,* 114479. [6] Lantz, C. et al. (2017) *Icarus 285,* 43-57. [7] Matsuoka M. et al. (2015) *Icarus, 254,* 135-143. [8] Gillis-Davis J.J. et al. (2017) *Icarus, 286,* 1-14. [9] Noguchi T. et al. (2011) *Science, 333*, 1121-1125.