

MINERALOGY OF HAYABUSA2 PARTICLE A0064 DETERMINED BY FIB-TEM: INSIGHTS INTO AQUEOUS ALTERATION PROCESSES ON ASTEROID RYUGU. A. J. Brearley¹, T. Nakamura², T. Morita², M. Kikuri², K. Amano², E. Kagawa², H. Yurimoto³, T. Noguchi⁴, R. Okazaki⁵, H. Yabuta⁶, H. Naraoka⁵, K. Sakamoto⁷, S. Tachibana^{7,8}, S.-I. Watanabe⁹, and Y. Tsuda⁷. ¹Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM87131 (brearley@unm.edu), ²Tohoku University, Sendai 980-8578, Japan, ³Hokkaido University, Sapporo 060-0810, Japan, ⁴Kyoto University, Kyoto 606-8502, Japan, ⁵Kyushu University, Fukuoka 812-8581, Japan, ⁶Hiroshima University, Higashi-Hiroshima 739-8526, Japan, ⁷ISAS/JAXA, Sagami-hara 252-5210, Japan, ⁸The University of Tokyo, Tokyo 113-0033, Japan, ⁹Nagoya University, Nagoya 464-8601, Japan.

Introduction: In December 2020, the Hayabusa2 spacecraft successfully returned samples of the regolith of asteroid Ryugu to Earth. These samples represent the first materials collected from the surface of a carbonaceous asteroid and the most pristine extraterrestrial samples of asteroidal materials available for study in the laboratory. The spacecraft collected samples from two different locations, one being the undisturbed regolith (Chamber A) and a second sample (Chamber C) consisting of original regolith material and fall-out deposits from the artificial impact crater. The spectral characteristics of Ryugu show that it has very low reflectance and has affinities to CI carbonaceous chondrites [1]. As such, these samples provide a remarkable opportunity to gain new insights into the characteristics of the surface materials of carbonaceous asteroids, including for example, the nature of pristine solar system materials, the role of aqueous alteration in asteroid evolution and the effects of regolith and space weathering process on these materials [1,2].

During the preliminary analysis period of the Hayabusa2 mission the Stone team was tasked with the petrologic and mineralogic analysis of selected samples from the Hayabusa2 sample collection. Here we report SEM and FIB/TEM observations from one sample A0064, collected in Chamber A.

Samples and Methods. Sample A0064 consists of four (FO001-004) ~50-90 μm -sized, irregularly-shaped fragments that were dispersed around the large sample. These fragments are presumed to be either grains broken off the larger particle or smaller particles that were original attached to the surface of the main A0064 particle. The fragments were pressed gently into indium foil prior to shipment and were analyzed as is, with no carbon coating. SEM imaging and X-ray mapping were carried out on a FEI Quanta DualBeam SEM/FIB and a FEI Helios NanoLab 650 DualBeam SEM/FIB. Focused ion beam samples of selected areas of each sample were prepared using both instruments. Transmission electron microscopy was performed on a JEOL NEOARM 200CF aberration corrected STEM instrument equipped with dual JEOL 100 mm² EDS detectors controlled using Oxford Instruments AZtec software.

Observations. SEM imaging (SE and BSE) of the as-is surfaces of the four particles showed that the

sample is uniformly fine-grained. The mineralogy consists of coarser-grained, μm -sized sulfide, carbonate, and magnetite grains set in matrix of submicron material. The sulfide grains range up to 5 μm in size with morphologies that vary from euhedral

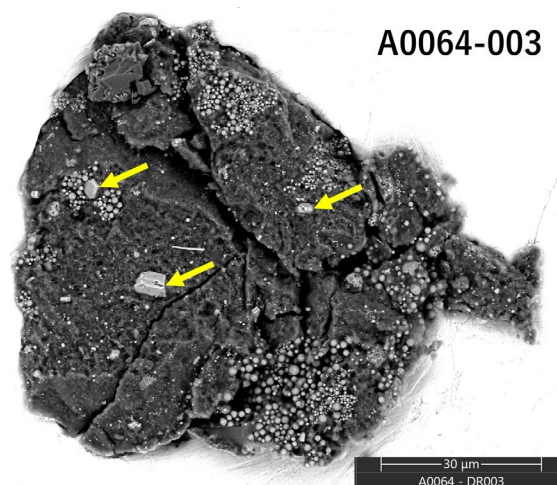


Figure 1 – SEM-BSE image of fragment A0064-FO003, showing abundant magnetite framboids set in a very fine-grained matrix. Rare sulfide grains (yellow arrows) are also present.

to anhedral, including distinct hexagonal morphologies, whereas magnetite occurs as both magnetite framboids and plaquettes (Fig. 1). Carbonate grains are relatively rare in the four particles studied, occurring as subhedral grains, up to 4 μm in size. The abundance of magnetite, especially framboids, varies significantly among the four particles, suggesting that there are distinct lithologies within the larger particle. A0064-FO003 is particularly magnetite-rich, with several framboids ranging from 5 to 30 μm in size (Fig. 1). No anhydrous silicates were observed in any of the particles.

Several FIB sections of A0064-FO001 were prepared of different areas of the sample, including carbonate and sulfide grains. TEM analysis of the fine-grained matrix shows that it is dominated by a groundmass of phyllosilicates in which submicron magnetite and sulfide grains. Two occurrences of phyllosilicates are present: coarser-grained phyllosilicates occur in irregularly-shaped domains, 1 to 2 μm in size consisting of fibrous, parallel to subparallel

grains with lengths up to 250 nm and widths from 10-25 nm. These domains are free of sulfide and magnetite and have well-defined boundaries with the adjacent fine-grained material. The dominant phyllosilicate component is finer grained with grain sizes of 10-30 nm in length and few nanometers in width and is intimately intergrown with sulfide and magnetite. High-resolution TEM shows that both coarse and finer-grained phyllosilicates consist of coherent intergrowths with basal spacings of ~0.7 nm and 1.0-1.2 nm, consistent with serpentine and smectite group minerals, respectively. Based on STEM EDS analyses the phyllosilicates have compositions consistent with Mg-rich serpentine and saponite ($\text{Mg}/(\text{Mg}+\text{Fe}) \times 100 = 74-92$). The phyllosilicates analyzed from four FIB sections have slight compositional differences between them.

In several of the FIB sections, regions of phyllosilicates are present with textures that indicate they are pseudomorphic replacement products of preexisting minerals. These regions have well-defined boundaries with adjacent fine-grained matrix. One example consists of layered texture with an outer rim (<0.45 μm thick) of very fine-grained phyllosilicates, surrounding a core of coarse-grained phyllosilicates. This texture is completely different from the occurrence of phyllosilicates in the fine-grained matrix and appears to be indicative of two stages of replacement of a primary silicate phase such as an olivine or pyroxene.

Sulfides in the fine-grained matrix are variable in terms of their distribution, morphology, grain size and composition. The finest grained sulfides are distributed heterogeneously within the phyllosilicate groundmass and range in grain size from <20 to ~200 nm in size, with anhedral to euhedral morphologies. Both pyrrhotite and pentlandite are present in this size range commonly occurring as clusters. Micron-sized, irregularly-shaped sulfide-rich and sulfide-free domains are present. An usual feature of this sample is the occurrence of an Fe-sulfide mineral with a unique texture. Numerous grains are present with subhedral morphologies and grain sizes of 0.1-0.6 μm that are characterized by crystallographically-controlled fractures that segment the grains into elongate subgrains (Fig. 2). The identify of this phase has not yet been established, but electron diffraction patterns are not consistent with pyrrhotite.

Discussion: The mineralogy of the four particles demonstrate that these materials have close affinities to CI chondrites, but also show some notable differences. The occurrence of fine-grained phyllosilicates (serpentine and saponite), magnetite framboids and plaquettes, and carbonates (Mn-bearing dolomite) demonstrate the close link to CI chondrites, rather than CM chondrites [3,4]. The mineral assemblage clearly represents a very advanced state of aqueous alteration

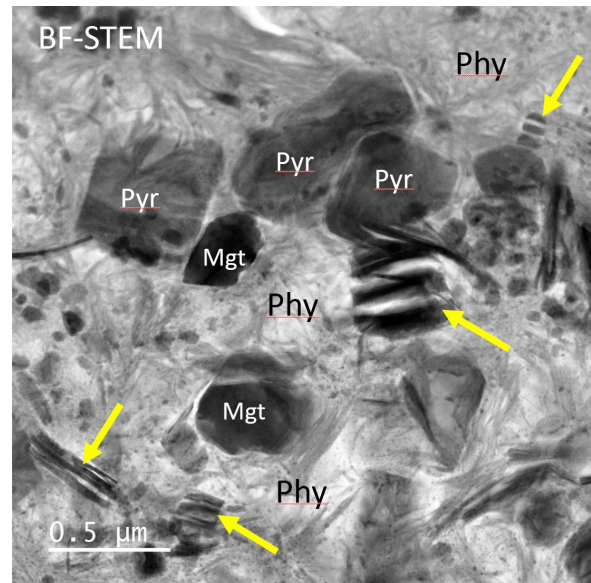


Figure 2. Bright-field STEM image of region of phyllosilicates (Phy), pyrrhotite (Pyr), magnetite (Mgt) and unidentified Fe-sulfide phase (yellow arrows) with distinct parallel fractures.

indicated by the high abundance of hydrated phases and the absence of anhydrous silicates. However, the presence of pseudomorphic replacement textures does suggest that anhydrous silicates were likely present in the precursor material, consistent with the observations of olivine and pyroxene in less altered lithologies from Ryugu [2]. There are, however, notable differences between these samples and CI chondrites, that show that the Hayabusa2 samples record different alteration conditions or alternatively have not been modified by terrestrial alteration. Ferrihydrite, one of the most common Fe^{3+} -bearing minerals in CI chondrites [3,4] is absent in Ryugu samples whereas nanophase pyrrhotite and pentlandite, which are absent in CI chondrites, are very widespread. The phyllosilicate compositions are also more Mg-rich than those in CI chondrites [2]. In general, sulfides are significantly more abundant in the Ryugu samples than in CI chondrites, where sulfides are rare and relatively coarse-grained. These observations are consistent with alteration of the Ryugu samples under more reducing conditions [2] than CI chondrites or alternatively, that CI chondrite falls have undergone significant modification due to interaction with the terrestrial atmosphere following their collection [5].

Acknowledgments: This research was funded by NASA Grant 80NSSC18K0731 to PI Adrian Brearley.

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