Surface morphologies and space weathering features of Ryugu samples

T. Matsumoto[1], T. Noguchi[1], A. Miyake[1], Y. Igami[1], M. Haruta[1], H. Saito[2], S. Hata[2], Y. Seto[3], M. Miyahara[4], N. Tomioka[5], H. A. Ishii[6], J. P. Bradley[6], K. Ohtaki[6], E. Dobrică[6], T. Nakamura[7], M. Matsumoto[7], A. Tsuchiyama[8, 9]; M. Yasutake[10], J. Matsuno[8], S. Okumura[1], K. Uesugi[10], M. Uesugi[10], A. Takeuchi[10], M. Sun[9], S. Enju[11], A. Takigawa[12], H. Leroux[13], C. Le Guillou[13], D. Jacob[13], M. Marinova[13], F. de la Peña[13], F. Langenhorst[14], D. Harries[14], P. Beck[15], T. H. Van Phan[15], R. Rebois[15], N. M. Abreu[16], T. Zega[17], P.-M. Zanetta[17], M. Thompson[18], M. Lee[19], L. Daly[19], P. Bland[20], R. Stroud[21], K. Burgess[21], J. C. Bridges[22], L. Hicks[22], M. E. Zolensky[23], D. R. Frank[6], J. Martinez[24], H. Yurimoto[25], K. Nagashima[6], N. Kawasaki[25], R. Okazaki[2], H. Yabuta[4], H. Naraoka[2], K. Sakamoto[26], S. Tachibana[12], S. Watanabe[27], Y. Tsuda[26], and the Hayabusa2 Initial Analysis Team

[1]Kyoto Univ., Japan; [2]Kyushu Univ., Japan; [3]Kobe Univ., Japan; [4]Hiroshima Univ., Japan; [5]Kochi Core Center, JAMSTEC, Japan; [6]Univ. of Hawaii, USA; [7]Tohoku Univ., Japan; [8]Ritsumeikan Univ., Japan; [9]Guangzhou Institute of Geochemistry, China; [10]JASRI, Japan; [11]Ehime Univ., Japan; [12]Univ. of Tokyo, Japan; [13]Univ. de Lille, France; [14]Univ. of Jena, Germany; [15]Univ. Grenoble Alpes, France; [16]Penn State, USA; [17]Univ. of Arizona, USA; [18]Purdue Univ., USA; [19]Univ. of Glasgow, UK; [20]Curtin Univ., Australia; [21]US Naval Research Laboratory, USA; [22]Univ. of Leicester, UK; [23]JSC/NASA, USA; [24]Jacobs Engineering, [25]USA, Hokkaido Univ., Japan; [26]JAXA/ISAS, Japan; [27]Nagoya Univ., Japan

Introduction: Asteroids are leftover remnants of planet formation and provide clues as to the origin and evolution of the early solar system. C-type asteroids have been expected to be parent bodies of carbonaceous chondrites, containing hydrated silicates and volatile compounds that could be the origin of water and life on the Earth. JAXA's *Hayabusa 2* spacecraft explored C-type asteroid Ryugu and collected surface materials at two landing sites on Ryugu [1]. The spacecraft delivered its re-entry capsule to the Earth, and subsequent initial investigation of the *Hayabusa 2* sample container found that millimeter pebbles and fine grains were successfully recovered from the surface of Ryugu [2]. Geologic maps and variations in the reflectance spectra of Ryugu's surface suggest that geologic activities and alteration of regolith occur over time [3]. Ryugu samples will provide an opportunity to understand the dynamic evolution of surface materials on C-type asteroids. Materials exposed to the space environment are expected to have altered optical, physical, or chemical properties. This process is defined as space weathering, which includes alteration by micrometeoroid bombardments, solar wind implantation, and solar radiation heating [4]. Analyses of lunar soils and regolith particles from S-type asteroid Itokawa have revealed that the uppermost surfaces of regolith grains record the space weathering features, such as amorphization, melting, and vapor-deposition [5,6]. Thus far, the space weathering of carbonaceous asteroids is not well understood. The surface microstructures of Ryugu samples will offer insight into the ongoing alteration of the regolith on Ryugu. In this study, we report the surface morphologies and mineral structures of Ryugu samples investigated in the initial analysis by the Mineralogy-Petrology Fine (Sand) sub-team.

Samples and methods: Ryugu samples from the two sampling sites were preserved in chambers A and C of the sample catcher inside the sample container [2]. We have mainly investigated the fine grains (< 300 μm) picked up from both chambers at the Extraterrestrial Sample Curation Center of JAXA. After the samples were allocated from JAXA, we handled them in a dry glove box filled with nitrogen at Kyoto University. For surface observation, the fine grains were fixed on gold plates using an Araldite adhesive. We examined the surface features of the Ryugu samples using a field emission scanning electron microscope (FE-SEM: JSM-7001F). We then extracted electron-transparent sections of regions of interest on the Ryugu grains for transmission/scanning transmission electron microscopy (TEM/STEM) studies, using a focused ion beam (FIB) system (Helios NanoLab G3 CX at Kyoto University, Thermo Scios at Kyushu University). We are now performing TEM/STEM analysis, synchrotron radiation X-ray absorption fine structure analysis, nano-tomography, and atom probe analysis.

Results: *Surface features of Ryugu grains*: Fine Ryugu grains have massive, platy, and granular shapes. The majority of the grain surfaces consist of phyllosilicates with rough surfaces. Coarse and fine surface textures are identified on the phyllosilicates. Cracks/gaps exist between phyllosilicates and other mineral phases. TEM analysis shows that the phyllosilicates are composed mainly of serpentine and saponite (detailed TEM observations are described in [7]). The second major mineral phases on the grain surfaces are sulfides, magnetite, and carbonates. These minerals are ubiquitous, although their abundance varies from grain to grain. Most of the sulfides are pyrrhotite crystals. They appear as hexagonal plates, cuboids, and irregular shapes with sizes up to a few tens of micrometers. The pyrrhotite plates exhibit sharp growth steps on their surfaces. Some pyrrhotite crystals with irregular surfaces have numerous voids. Pentlandite often coexists with pyrrhotite. Tiny sulfides (< 1μm), including zinc, chromium, and/or copper, occur as minor phases. Magnetite appears as framboidal aggregates, plaquettes, spherulites, and irregular shapes. The framboidal magnetite on Ryugu grains have distinct sharp edges, when compared to framboidal magnetites with rounded morphologies in thermally metamorphosed CI chondrites (e.g., Y980115) in which thermal sintering has likely occurred. The carbonate phases found on the Ryugu grains are mainly dolomite and minor magnesite-breunnerite. They have euhedral, fractured, and irregular surfaces. Calcium phosphate, oxides (chromite, ilmenite), and iron phosphides are found as minor phases. Na-Mg bearing phosphate with an irregular shape is present as a rare phase and is commonly attached loosely to the grain surfaces. Anhydrous minerals found on Ryugu grains are forsteritic olivine, low-calcium pyroxene and pure spinel with sizes up to a few micrometers. These phases are rare. Most of them have fractured surfaces.

Space weathering features: We found impact craters, melted drops, splashes, melt sheets, glassy spherules on Ryugu grains by SEM observation (Fig. 1). Studies of lunar soils and Itokawa particles have shown that these objects are likely products of micro-impacts on airless bodies [8, 9]; hence, the grain surfaces with the impact products may have been exposed to the space environment. The abundance of the impact products varies from grain to grain. Phyllosilicates on the grain surfaces are altered to have smooth surface textures with tiny voids (Fig. 1 in [7]). TEM analysis shows that the uppermost surface is surrounded by an amorphous rim with a thickness from 50 nm to 2-3 µm. Tiny vesicles and iron compounds appear in the rim. EDX analysis shows a change in chemical composition near the surface. The altered surfaces of pyrrhotite and pentlandite have shallow depressions (200 nm – 300 nm in depth) with rugged textures (Fig. 1). Iron metals protrude from the iron sulfide surfaces, and some are in the form of curved whiskers (Fig. 1). Dark-field TEM imaging suggests disordering of the lattice near the sulfide surface. Carbonates and magnetite have altered surfaces with rough textures. The breunnerite grain we examined by TEM has a distinct rim with disordered lattice and a thickness of approximately 90 nm. Selected area diffraction patterns obtained from the rim imply the appearance of periclase ((Mg,Fe)O) particles in the rim.

Discussion: The dominance of phyllosilicates and the scarcity of anhydrous minerals indicate that Ryugu samples have experienced a high degree of aqueous alteration. The morphologies of the major mineral phases, such as the unique shapes of magnetite, suggest a close similarity between Ryugu samples and CI chondrite [10].

Previous ion irradiation experiments simulating space weathering suggest that the uppermost surface of phyllosilicates can be modified by space weathering [11]. The altered phyllosilicate rim found in our analysis may have been formed by solar wind implantation and impact events [7]. Iron metallic whiskers on iron sulfides have recently been identified as space weathering products in lunar soils and Itokawa particles [12,13]. The iron metals are likely to have formed via selective sulfur loss, accumulation of excess iron atoms, and subsequent growth of iron metals. These alteration processes may be caused by various phenomena including solar wind implantation, thermal effects produced by micrometeoroid bombardments and solar heating [12]. The appearance of iron whiskers on Ryugu samples implies that the space weathering of iron sulfides on Ryugu is similar to that on the Moon and Itokawa. The thickness of the altered rim on breunnerite is roughly consistent with the maximum depth at which extensive atomic displacement is produced by implanted solar wind ions (~ 1 keV/nucleon) [6]. Hence, solar wind implantation may have contributed to the rim formation of the carbonate. Based on our initial analysis, we tentatively conclude that the Ryugu samples record the combined processes of space weathering on the aqueously altered asteroid, implying that remote sensing data should be reassessed considering the space weathering effect.

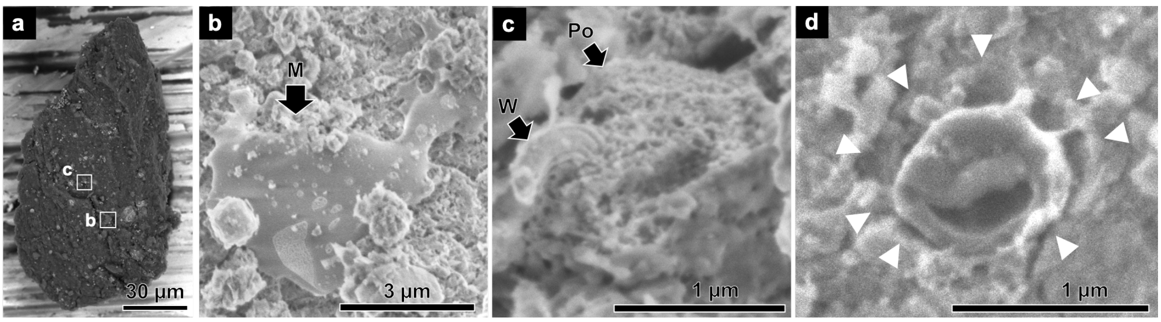

Fig. 1 Space weathered Ryugu grain. (a) Backscattered electron image of a fine Ryugu grain. (b-d) Secondary electron images of a melted drop (b), pyrrhotite with an iron whisker (c), and an impact crater with a residue on phyllosilicates (d). The image (d) was obtained from another fine Ryugu grain. M: melted drop, Po: pyrrhotite, W: iron whisker. Triangles in (d) indicate the crater rim.

References: [1] Watanabe S. et al. 2019. Science 364, 268-272. [2] Yada T. et al. 2021. Abstract# 2548 in 52nd LPSC. [3] Sugita S. et al. 2019 Science 364, 252. [4] Pieters C. and Noble S. K. 2016. J. Geophys. Res. Planet 121, 1865-1884. [5] Keller L. P. and McKay D. S. 1993 Science 261, 1305-1307. [6] Noguchi T. et al. Science 333, 1121-1125. [7] Noguchi T. et al. this symposium. [8] McKay D. S. et al. 1991. Lunar Sourcebook. [9] Matsumoto T. et al. 2018. Icarus 303, 22-33. [10] Brearley A. 2006, Meteorites and the early solar system *II*, 587-624. [11] Thompson M. et al. 2020. Icarus 346, 113775. [12] Matsumoto T. et al. 2020. Nat. Commun. 11, 1-8. [13] Matsumoto T. et al. 2021. Geochim. Cosmochim. Acta 299, 69-84.