SPACE WEATHERING OF ANHYDROUS MINERALS IN REGOLITH SAMPLES FROM THE C-TYPE ASTEROID RYUGU.
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Introduction: Asteroids are building blocks of planet formation and provide information of the evolution of the early solar system. C-type asteroids are among the major asteroid types and have been expected to be parent bodies of carbonaceous chondrites. JAXA's Hayabusa2 spacecraft explored the C-type asteroid Ryugu and recovered 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 Hayabusa2 sample container revealed that millimeter pebbles and fine grains were successfully collected by the spacecraft [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]. Materials exposed to the space environment are expected to exhibit modified optical, physical, or chemical properties. This process is called as space weathering and is caused mainly by micrometeoroid bombardments and solar wind implantation [4]. Thus far, the space weathering of carbonaceous asteroids has not been well understood. Ryugu samples will offer insights into the ongoing alteration of the regolith of Ryugu. In this study, we examined the space weathering of Ryugu samples as the initial analysis by the Mineralogy-Petrology Fine (Sand) sub-team. We investigated the modification of anhydrous minerals including iron sulfides, magnetite, and carbonates, which are major reservoirs of volatiles including carbon, oxygen, and sulfur in Ryugu materials.

Samples and Methods: Ryugu samples from the two sampling sites were preserved in chambers A and C of the sample catcher inside a 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: JEOL JSM-7001F). We then extracted electron-transparent sections of the regions of interest on the Ryugu grains for transmission/scanning transmission electron microscopy (TEM/STEM) studies, using a focused ion beam (FIB) system (Thermo Fisher Scientific Helios NanoLab G3 CX at Kyoto University, Thermo Scios at Kyushu University). We performed TEM analysis at Kyoto University using STEM/TEM (JEOL JEM-2100F, JEOL monochromated JEM-ARM200F)

Results: We identified the space-exposed surfaces of Ryugu grains by the appearance of impact craters, melted drops, splashes, melt sheets, and glassy spherules on the grain surfaces. The abundance of these impact products varies from grain to grain. Phyllosilicates on the grain surfaces show modified morphologies with tiny voids [5].

Most sulfides in the Ryugu grains are apparently pyrrhotite and pentlandite. They occur on the grain surfaces as hexagonal plates, cuboids, and irregular shapes with sizes of up to a few tens of micrometers. Pyrrhotite plates often exhibit sharp growth steps on their surface. We identified the modified pyrrhotite and pentlandite having shallow depressions or porous textures (Fig. 1a, b). Iron metals are developed on the iron sulfide surfaces, and some are in the form of curved whiskers (Fig. 1a, b). The iron whiskers contain small amounts of nickel. TEM analysis shows that the iron metals have the structures of body-centered-cubic (bcc) iron.

Magnetite on Ryugu grains appears as framboidal aggregates, plaquettes, spherulites, and irregular shapes. These morphologies are closely similar to those of magnetite found in aqueously altered carbonaceous chondrites, such as CI chondrite [6]. We found the modified surface of magnetite exhibiting a porous texture (Fig. 1c). TEM observation shows that bcc metallic iron particles cover the magnetite surface (Fig. 1d). This metal-rich layer extends to approximately 60 nm from the surface. Beneath the metal-rich layer, we identified crystallographic misorientations that extend to a depth of 120 nm.

The modified surface of carbonates has a rough texture. The breunnerite grain we examined by TEM is covered by ferropericlase [(Mg,Fe)O] -rich rim. Crystallographic misorientations appear in the substrate breunnerite within 130 nm below the surface. Dolomite has a vesicular rim with crystallographic misorientations. Carbon and oxygen are depleted the surface of these carbonates.

The outermost surfaces of the iron sulfides, magnetite, and carbonates are covered by 10–15 nm thick layers rich in Si. The Si-rich layers also contain O, Mg, and S.

Discussion: Metallic iron whiskers on iron sulfides have been found as space weathering products in lunar soils and regolith particles from the S-type asteroid Itokawa [7, 8]. The metallic iron might have formed through selective sulfur loss, accumulation of excess iron atoms, and subsequent growth of iron metals. These alteration processes are likely caused by various phenomena including solar wind implantation, thermal effects produced by micrometeoroid bombardments, and solar heating [8]. The occurrence 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 lattice misorientations and vesicles identified in the modified magnetite and carbonates may correspond to typical damage structures in crystals irradiated by ion-beam [9]. The iron metals on magnetite may have been produced via selective escape of oxygen by ion sputtering, and by the thermal effects of micro-impacts that assist atomic diffusion. Similarly, the solar wind sputtering and micrometeorite bombardments may have caused selective escape of carbon and oxygen at the carbonate surfaces, leading to the formation of the periclase-rich rim on breunnerite. The outermost Si-rich layers on sulfides, magnetite, and carbonates, are chemically distinct from the substrates and probably consist of vapor-deposited materials produced by ion sputtering and/or vaporization of micrometeorite impacts [11].

Thus, the loss of volatiles and the resultant reduction of iron may represent the major modification of space weathering ongoing on the surface of Ryugu. We suggest that these modifications are distinct indicators of regolith maturity on volatile-rich airless bodies.

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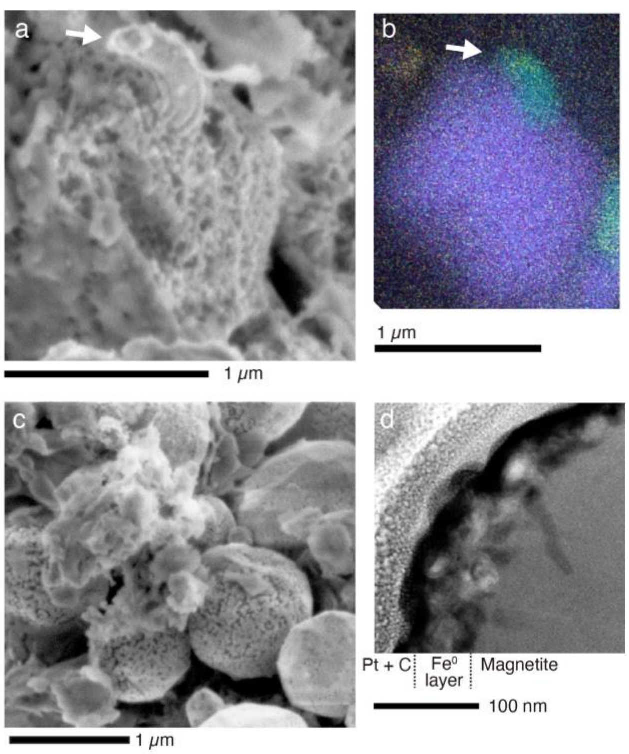

Figure 1. Space-weathered iron compounds in Ryugu samples. (a) Secondary electron image of space-weathered iron sulfides on a Ryugu grain. (b) Elemental map of iron (green), sulfur (cyan), and nickel (yellow), corresponding to the sulfide grain in (a). Arrows in (a, b) indicate an iron metallic whisker on the sulfide grain. (c) Secondary electron image of space-weathered magnetite on a Ryugu grain. (d) Annular-dark-field image of magnetite in an FIB section picked up from the surface shown in (c).