Mineralogy and surface modification of small grains recovered from the asteroid 162173 Ryugu

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Introduction: Surface material on airless bodies exposed to the interplanetary space experienced the bombardment by low-energy (~1 keV/nucleon) solar wind particles and micrometeoroid impacts. These processes, alongside the resultant surface modifications, and spectral darkening and reddening are called space weathering [1]. Space weathering of the Moon and the asteroid 25143 Itokawa belonging to S-type asteroids have been investigated intensively [e.g. 1-5]. The *Hayabusa 2* spacecraft returned samples from the asteroid 162173 Ryugu C-type asteroid. The Ryugu samples give us the first opportunity to investigate space weathering of C-type asteroids. The Mineralogy-Petrology Fine (M-P F or Sand) sub-team mainly investigates small grains (typically ~100 µm across). The main purposes of the M-P F sub-team are to understand the variation of mineralogy of the allocated grains and the nature of space weathering of the asteroid Ryugu. The M-P F sub-team is comprised of 51 members belonging to 25 universities and laboratories.

Sample and methods: Numerous small Ryugu grains, ~100 µm across on average, were allocated to the M-P F sub-team. Surface morphology of >350 grains from the chamber A of the sample canister have been observed by JEOL JSM-7001F field emission scanning electron microscope (FE-SEM) at Kyoto Univ. and by Thermo Scios focused ion beam (FIB)-SEM at Kyushu Univ. Elemental mapping analysis was also performed using Energy dispersive spectrometer (EDS) equipped on the FE-SEM. Most of the grains were attached to Au plates with small amounts of epoxy glue in N_2 filled glove box for SEM observation. Some grains were just placed on Pt plates without using any glue to make FIB sections in response to requests from some members. One sample was prepared by Reichelt Ultracut ultramicrotome at Kyoto Univ. In addition to the small grains, the Chemistry sub-team loaned a polished sample of a fragment originating from a large grain A0026 (~3 mm wide) because the sample has a bubble-rich material on its surface. Seven samples were able to be prepared for the detailed analysis. Up to now we have prepared ~80 FIB sections from 40 grains and >30 FIB sections have already been distributed to the members. To understand mineralogy and petrology down to the nanometer of these grains and to clarify the detailed mineralogical analyses of space weathering of the C-type asteroid Ryugu, we are now performing (scanning) transmission electron microscopy ((S)TEM), synchrotron radiation X-ray absorption fine structure (XANES and EXAFS) analysis, nano-tomography, and atom probe analysis at 15 universities and laboratories.

Results: Major minerals of the small Ryugu grains are phyllosilicates (saponite and serpentine), Fe-bearing sulfides, magnetite, dolomite, and a lesser amount of breunnerite. It is obvious that the asteroid Ryugu experienced severe aqueous alteration and did not experience heating enough to make secondary anhydrous minerals such as olivine, pyroxene and Fe metal, which are common in severely heated carbonaceous chondrites. Serpentine in these Ryugu grains may have better crystallinity than that in Orgueil and Ivuna CI chondrites [e.g., 6]. Typical spacing of (001) of saponite is ~1.0-1.3 nm, which suggests partial dehydration of interlayer H_2O molecules. Minor minerals so for observed are hydroxyapatite, ilmenite, magnesiochromite, manganochromite, Cr oxide, Cu-bearing ZnS, $(Fe, Ni)_2P$, $FeCr_2S_4$, cubanite, Na- and Mg-bearing phosphate, forsteritic olivine, and Fe-free low-Ca pigeonite. A moissanite crystal was also identified, which could be a presolar grain.

The surfaces of the most Ryugu grains investigated have highly euhedral pyrrhotite crystals. Their surfaces preserve quite sharp steps, which may reflect growth or dissolution in aqueous solutions. Magnetite crystals that form framboidal aggregates have shapes as rounded as those in Orgueil and Ivuna. In addition, some magnetite crystals have facets as sharp as those in

Tagish Lake C ungrouped meteorite. The presence of these Fe sulfide and oxide suggests that these surfaces did not experience enough exposure to the interplanetary space to degrade the surfaces of these minerals.

After scrutinizing >350 small Ryugu grains by FE-SEM and FIB-SEM, we found 10 small Ryugu grains having obviously different surface morphology. Figure 1 shows an example of such grains with abundant open bubbles. The bubble-rich surfaces form a continuous layer containing abundant bubbles. In Fig. 1(b), the bubble walls are as thick as ~0.5 µm at the thickest places. Most bubble-rich layers have ~50 - ~500 nm thick, but the layer of A0026 has up to ~3 µm thick. The bubble-rich layer in Fig. 1(b) is amorphous and contains abundant tiny Fe sulfide crystals based on selected area electron diffraction (SAED) patterns and electron diffraction mapping. Preliminary analysis of energy-loss near-edge structures of Fe L2, 3 edge of the bubble-rich layer and the subsurface phyllosilicate suggests that the former is much more enriched in Fe^{2+} than the latter. More detailed description of the rugged Fe sulfide and the other phases will be presented in another presentation [7].

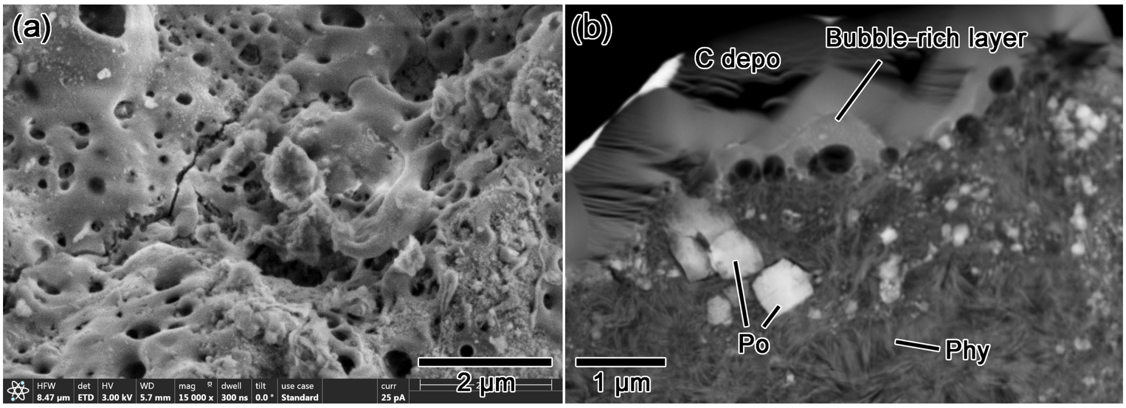

Fig. 1 Secondary electron and annular dark-field images of a small Ryugu grain with a bubble-rich surface. (a) The surface is covered by a gently rolling layer with abundant open bubbles. Abundant bright tiny speckles are on the surface. (b) A cross-section of the bubble-rich layer and the interior. Abbreviations: Po: pyrrhotite; Phy: phyllosilicate; depo: deposition.

Discussion and conclusion: These major minerals and the petrography of the small Ryugu grains indicate that the asteroid Ryugu experienced severe aqueous alteration that can be classified as C1. The mineralogy and petrology of these grains are similar to CI chondrites but these grains lack ferrihydrite and sulfates, both common among CI chondrites [e.g., 6, 8 and references therein]. The formation of ferrihydrite and sulfates may have occurred by terrestrial weathering. The spacing of (001) of saponite increased to ~1.3 nm on average by using ethylene glycol as the trough liquid during ultramicrotomy, which means that saponite in the Ryugu samples can rehydrate.

Morphology of the bubble-rich layers is apparently similar to melt sheets (Fig. 1a). However, it does not necessarily mean that all the layers were formed through melting by meteoroid impacts. The formation of similar bubble-rich amorphous layers by H^+ or He^+ ion irradiation has already been reported [9-11]. Although the size and number density of bubbles in the amorphous layer are different from the irradiation experiments and the natural samples, the difference can be interpreted by the different fluxes between them. Therefore, we believe that at least thin bubble-rich layers were related to solar wind irradiation. Unlike the irradiation experiments, the bubble-rich layer in Fig. 1(b) is more enriched in Fe, S, and Ca than the subsurface phyllosilicate. Recondensation of elements derived from the surrounding phases may have also played a role in the compositional difference. Because the thickness of the bubble containing layer is quite variable, the relative contribution of irradiation and micrometeoroid impacts that resulted in vaporization and recondensation of elements may be quite different at places. The M-P F sub-team continues to assess the role of recondensation in the space weathering of the Ryugu C-type asteroid. Although small Ryugu grains with the space weathering rims are quite rare among the investigated samples, it does not necessarily mean that such grains are rare on the surface of Ryugu because most of the surfaces are exposed to the interplanetary space may have been destroyed during the sampling sequence using Ta projectiles. If most of the space exposed surface had the bubble-rich amorphous layer on Ryugu, the bubble-rich amorphous surface layers might have affected the reflectance spectra of the asteroid Ryugu.

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