NANO-PHASE OPAQUE MINERALS IN VAPOR DEPOSITED RIMS FOUND ON SAMPLES FROM C-TYPE ASTEROID RYUGU.

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Introduction: Solar wind irradiation and micrometeorite bombardments alter the physical, chemical, and optical properties of materials on airless bodies. These modifications are so called space weathering [1]. C-type carbonaceous Ryugue shows variations in reflectance spectra which are likely related to the geologic activity and surface exposure age [2]. Space weathering features in the returned samples will provide key information to interpret the surface evolution of Ryugu. One of the major causes to alter the reflectance spectra of airless bodies is considered to be nanometer-sized particles of opaque mineral phases (nanophase opaque minerals) produced by space weathering [1]. In this study, we examined the appearance of nanophase opaque minerals in Ryugu grains.

Methods: We analyzed two fine Ryugu grains, A104-021002 and A104-028098. These grains were fixed on gold plates with epoxy resin. After the grains were observed by scanning electron microscopy (SEM), electron-transparent sections were extracted from the grain surface using the focused ion beam system. The extracted sections were analyzed by scanning transmission electron microscopy (TEM/STEM). 4D-STEM imaging (electron diffraction mapping using nano-beam) was applied to identify nanometer-sized inclusions.

Results: The two Ryugu grains consist mainly of phyllosilicate-rich matrix, iron sulfides, magnetite, and carbonates. SEM observation shows that the phyllosilicate of the two grains have smooth surfaces with tiny bubbles, corresponding to the modified morphologies related to space weathering [3]. The magnetite and iron sulfides have porous surfaces indicative of space weathering [4]. TEM/STEM analysis shows that the phyllosilicate surfaces are coated by modified layers up to ~60 nm in depth (Fig. 1a). 4D-STEM imaging reveals that the surface modified layers are amorphous. Nanophase inclusions are rarely observed in the amorphous layers. STEM-EDS mapping of the phyllosilicate surfaces shows that outer 7-13 nm-wide zone is different in chemical composition from the phyllosilicate substrate (Fig. 1). The outermost rim of A104-021002 includes nanophase particles with high Z-contrast in HAADF-STEM image (Fig. 1b), and is rich in sulfur, iron, and nickel (Fig. 1c). 4D-STEM imaging of the outermost rim shows reflections corresponding to pentlandite and troilite with random orientations. The outermost rim of A104-028098 is rich in iron and has high Z-contrast. 4D-STEM data obtained from the rim shows reflections of troilite.

Discussion: The amorphous layers on phyllosilicate are probably produced by solar wind irradiation [3]. Studies of lunar soils and grains from S-type asteroid Itokawa has indicated that the outermost rims with distinct chemical composition correspond to materials deposited from vapors produced by micrometeorite bombardments and solar wind sputtering [1]. Thin deposits including nanophase iron sulfides, pentlandite, and magnetite were produced by the pulsed-laser experiment for carbonaceous chondrite simulating micrometeorite bombardments [5]. Therefore, the outermost rims on Ryugu grains are probably vapor-deposited materials. The nanometer-sized iron sulfides in the vapor deposits can be produced when the sulfur fugacity in the vapor cloud was high enough to condense sulfide minerals [5]. Plausible sulfur source for the high sulfur fugacity may be iron sulfide minerals, because iron sulfides are the second major minerals in Ryugu samples and the space-weathered iron sulfides show the evidence of sulfur loss [4]. The experimentally produced vapor-deposits showed a strongly reddened reflectance slope across the visible to near-infrared wavelengths, because of the opaque nano-particles [5]. The nanophase iron sulfides on Ryugu grains may contribute to the color variations of Ryugu, where surface materials are expected to be reddened with time [2]. The apparent scarcity of nanophase inclusions in the irradiation-damaged rim suggests that vapor deposition processes play an important role for the production of nanophase opaque minerals on Ryugu rather than solar wind irradiation.

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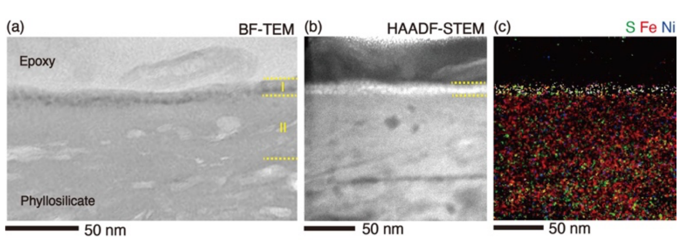

Figure 1. *Space weathered surface of Ryugu grain (A104-021002). (a) bright-field TEM image, (b) high-angle annular dark field (HAADF)-STEM image, (c) Elemental map including sulfur (green), iron (red), and nickel (blue). I: vapor deposited rim. II: irradiation-damaged rim.*