SURFACE REDDENING OF RYUGU REVEALED FROM GLOBAL MAPPING AND TOUCHDOWN OPERATION OF HAYABUSA2. T. Morota[1,2], Y. Cho[1], M. Kanamaru[3], R. Honda[4], S. Kameda[5], E. Tatsumi[6,7,2], Y. Yokota[8], T. Kouyama[9], H. Suzuki[10], M. Yamada[11], N. Sakatani[8], C. Honda[12], M. Hayakawa[8], K. Yoshioka[1], M. Matsuoka[8], T. Michikami[13], H. Miyamoto[1], H. Kikuchi[8], R. Hemmi[1], M. Hirabayashi[14], C. M. Ernst[15], O. Barnouin[15], N. Hirata[16], N. Hirata[12], K. Ogawa[16], H. Sawada[8], S. Sugita[1], and Hayabusa2 team, [1]Univ. of Tokyo, Tokyo, Japan (morota@eps.s.u-tokyo.ac.jp), [2]Nagoya Univ., Nagoya, Japan, [3]Osaka Univ., Osaka, Japan, [4]Kochi Univ., Kochi, Japan, [5]Rikkyo Univ., Tokyo, Japan, [6]Univ. of La Laguna, Santa Cruz de Tenerife, Spain, [7]IAC, Tenerife, Spain, [8]JAXA, Sagamihara, Japan, [9]AIST, Tsukuba, Japan, [10]Meiji Univ., Kawasaki, Japan, [11]Chiba Institute of Technology, Narashino, Japan, [12]Univ. of Aizu, Aizu-Wakamatsu, Japan, [13]Kindai Univ., Higashi-Hiroshima, Japan, [14]Auburn Univ., Auburn, USA, [15]APL/JHU, Laurel, USA, [16]Kobe Univ., Kobe, Japan.

Introduction: Hayabusa2 arrived at the target near-Earth asteroid (NEA) Ryugu on June 27, 2019 [1]. It conducted global observations revealing a number of important properties of the asteroid, such as its top-shaped rubble pile nature [2, 3], the presence of a small amount of hydrous minerals [4], a young surface age, and color properties consistent with partially dehydrated carbonaceous chondrites [5]. Furthermore, more subtle properties, such as general spectral uniformity [4, 5] and variation in spectral slope [2, 5, 6] are observed by the telescopic optical navigation camera (ONC-T). The bluer materials are distributed at the equatorial ridge and in the polar regions, while the redder materials widely spread over the mid-latitude regions [5]. However, the nature of these spectral variations is still poorly understood.

On February 21, 2019, the Hayabusa2 spacecraft conducted its first touchdown on Ryugu. In the process of the touchdown operation, Hayabusa2 had an opportunity to take extremely high-resolution (~1 mm/pix) images of Ryugu's surface and to observe its response to the physical disturbances during the touchdown, including the sampling projectile collision and thruster gas jets. A series of touchdown observations revealed a number of important properties of Ryugu surface's, regarding space weathering, grain size distribution, mixing of different colors of materials, and stratigraphic relations among different materials. These properties are important for bridging the gap between meteoritic materials and asteroid surfaces. Furthermore, such characterization helps us in understanding the geologic context of samples captured in the capsule chambers of Hayabusa2. We discuss the stratigraphy and geology of the touchdown site, complex dynamic reactions of surface materials on Ryugu triggered by the physical contact of the Hayabsua2 spacecraft, and detailed textures and structures on pebbles and boulders captured in extremely high resolution images during the touchdown operations. Based on these proximity observations and global observations, we infer the nature of stratigraphy expressed in color and albedo of Ryugu.

Color and albedo changes observed in the touchdown operation: The touchdown site was selected based on both the established engineering safety criteria and the scientific merits for material sampling [2, 6]. Materials that contain both bluer and redder components substantially help understand the end-members of compositional elements in Ryugu. The spectral slope on Ryugu indicates regional variations in red/blue mixing ratios on Ryugu, but the presence of impact ejecta and mass wasting suggest Ryugu's surface has a well-mixed nature [5]. Furthermore, the spectral differences among different touchdown candidate sites are much smaller than the variation within each sites [2]. Thus, a touchdown to any of the candidate sites would have allowed us to obtain both redder and bluer components. However, because of the high boulder abundances [5, 7], the locations for safe landing were limited. [2]. We chose L08-B, one of the lowest boulder number density areas on Ryugu, as the primary lading site [2, 6] and deployed a target marker (TM). However, based on the location where the TM settled and the detailed search for areas without boulders taller than 65 cm, which could reach the reaction control system (RCS) of Hayabusa2 during a touchdown, we finally chose a smaller region L08-E1.

During multiple low-altitude (~40 m) descent maneuvers near the L08 region, we conducted high-resolution spectral and morphologic observations of this region. The touchdown spot is generally slightly bluer than the global average, but reddish spots are found within the L08-E1 region. These reddish spots tend to be darker than bluer areas, and this trend is the same as that found globally [2, 5]. The reddish spots are limited to a single flat surface of individual boulders or are not homogeneously distributed on surfaces of boulders. These observations suggest that the redder materials were created from bluer materials by some surface metamorphic processes such as space weathering, thermal metamorphism by solar heating and/or simple pulverization, but a large portion of the redder materials have been scraped off from the boulder surface by impact disruption and/or thermal fatigue. The fact that the surfaces of boulders remain unreddened means that the timescale of surface reddening at present is sufficiently slow compared with that of boulder resurfacing by impact disruption and/or thermal fatigue.

The combination of the impact of the projectile shot from the sampler system and the RCS thrust during the touchdown produced a large amount of debris below the Ryugu surface. The motion picture obtained by the nadir-viewing wide-angle optical navigation camera (ONC-W1) indicates that large boulders moved horizontally by more than 5 m. However, the majority of debris disturbed upon the touchdown was small pebbles and fine grains whose diameters are less than the pixel size (1 to a few mm) as observed within the highest resolution ONC-W1 images. The observed high mobility of regolith during the touchdown indicates that the inter-boulder/inter-pebble cohesion may be very weak. This high mobility is consistent with observations of Ryugu's extremely low number density of small craters suggesting active surface migration on Ryugu and mass wasting on crater walls [5].

Immediately after the RSC thrust upon touchdown, the entire field-of-view of ONC-W1 was darkened uniformly, while a dark ragged boulder nicknamed as "turtle rock" simultaneously became as bright as surrounding brighter boulders [6]. These observations suggest that dark fine grains were originally present on the surface and inside the pores of darker and redder boulders and were lifted up by the RSC thrusting. This process formed a cloud of dark fine grains radiating from the touchdown site that ended up extending ~10-m in diameter, centered at the touchdown site. The pre-touchdown color of this region was slightly bluer than the surrounding region but it became redder after the deposition of the lofted dark fine grains. These observations may suggest that the dark fines grains were created from the redder materials originally coated on boulder's surfaces.

Global Distribution of Spectral Slope and Stratigraphic Relationship Between Craters and Redder Materials: In addition to the latitudinal variation in spectral slope [5], it was found that the spatial variation in spectral slope correlates with the crater distribution. Stratigraphically upper craters larger than ~20 m in diameter have bluer interior compared to the surrounding materials. This means that the redder materials were covering the bluer materials and the underlying bluer materials were exposed by the crater formation, consistent with the stratigraphic relationship between the redder and bluer materials inferred from the global distribution of spectral slope. On the other hand, as stratigraphically lower craters tend to have redder interiors, the color of the crater interiors has no difference with that of surrounding materials. We investigated the contrasts in spectral slopes between crater interior surfaces and surrounding areas, defined as the area within a crater radius from the crater rim. The obtained histogram of the contrast in spectral spectral slope shows a bimodal distribution, indicating that craters on Ryugu can be divided into two groups: red craters whose interior has spectral slope similar to that of the surroundings and blue craters whose interior is bluer.

A probable explanation of the latitudinal variation in spectral slope is that while the exposure of Ryugu materials to space has led to their reddening, mass wasting from the equator and polar regions to the mid-latitude regions at the current spin of Ryugu exposed fresh bluer subsurface materials [2, 5]. The polar regions exhibit bluer spectra than the equatorial ridge, suggesting the reddening process by thermal metamorphism and/or space weathering by Sun. The color variation of crater interior can be explained by the stratigraphic relation; the craters with redder interiors were formed before the surface reddening and their interiors were discolored by the surface reddening, while the blue craters were formed after the surface reddening and the underlying bluer materials were exposed by the blue-crater-forming impacts. The bimodal distribution of the contrast in spectral spectral slope suggests that the surface reddening has not been active through Ryugu's history and occurred within a short time interval after the formation of redder craters and before the formation of bluer craters. These results are consistent with the interpretation that the surface reddening is not so active at present based on the distribution of spectral slope on the boulder surface.

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