MORPHOLOGICAL AND SPECTRAL ANALYSIS OF S-TYPE BRIGHT BOULDERS ON RYUGU.

C. Sugimoto[1], E. Tatsumi[2,1], S. Sugita[1], Y. Yokota[3], T. Morota[1], M. Arakawa[4], R. Honda[5], S. Kameda[6], Y. Cho[1], K. Yoshioka[1], H. Sawada[3], N. Sakatani[3], M. Hayakawa[3], M. Matsuoka[3], M. Yamada[7], T. Kouyama[8], H. Suzuki[9], C. Honada[10], K. Ogawa[3], ONC team, SCI team, [1]Dept. Earth and Planetary Science, Univ. of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, Japan (chiosgmt@eps.s.u-tokyo.ac.jp), [2]Instituto de Astrofísica de Canarias, [3]JAXA/ISAS, [4]Kobe University, [5]Kochi University, [6]Rikkyo University, [7]Chiba Inst. Tech., [8]AIST, [9]Meiji Univ., [10]Univ. of Aizu.

Introduction: The initial global observations (~2 m/pix) of the near-Earth asteroid Ryugu with the telescopic Optical Navigation Camera (ONC-T) onboard Hayabusa2 revealed the presence of bright boulders on Ryugu [1]. Using higher resolution (~0.3 m/pix) images of Ryugu, spectral characterization of these bright boulders was conducted, revealing that there are two spectral types of bright boulders on Ryugu: 1) S-type bright boulders with strong absorption at ~1 μm and 2) C-type bright boulders with spectra that is featureless at ~1 μm [2]. Furthermore, large sizes of S-type bright boulders implies that they are more likely mixed during catastrophic disruption rather than be soft-landed on Ryugu. Furthermore, spectral comparison of C-type bright boulders and heated carbonaceous meteorites indicates that C-type bright boulders might have experienced partial dehydration to degrees different from the majority of Ryugu.

Although S-type bright boulders also have spectral variety in visible range and morphology, their variety and cause has not been investigated extensively yet. In this study, we investigate these variation in detail with the new observational facts on bright boulders and discuss about these unclarified topics.

Occurrence and morphologies: Because of their small size (≤ a few meters), most bright boulders cannot be spatially resolved in images taken at a few km of the altitude. In higher resolution images, we can observe the details occurrence of some bright boulders. Some of spatially resolved bright boulders are seen as small individual boulders (Fig.1 (a)) and others are seen as bright parts in darker boulders (Fig.1 (b)). Latter incorporated structure indicates that these xenolith-like materials have experienced mixing and agglomeration with darker fragments to be captured in host rock rather than have been soft-landed on Ryugu as exogenic materials.

One of the S-type bright boulders (M7 in [2]) is also seen as a bright part on a larger darker boulder (Fig. 2). In this image, the shadow of the S-type bright boulder can be seen in the west of the boulder, suggesting that a part of the bright boulder is extended out of the edge of the substrate boulder. The ratio of area indicated with red and green dashed lines in Fig. 2 is ~2:3. Thus, more than half of this bright boulder extends beyond the edge of the base boulder. This unstable mounting implies large cohesion between the bright boulder and the base boulder. This observation strongly suggests that it is mechanically adhered on the substrate boulder. This is consistent with the hypothesis that S-type bright boulders are more likely to be mixed during catastrophic disruption rather than be soft-landed on Ryugu after its formation period [2].

Furthermore, the Small Carry-on Impactor (SCI) onboard Hayabusa2 performed the first impact experiment on a small asteroid and successfully accomplished to form an artificial impact crater (SCI crater) on Ryugu [3]. Bright boulder are also observed on the floor of this SCI crater, suggesting that bright boulders exist not only on the surface of Ryugu but also in its interior.

Spectral variety of S-type bright boulders: Using the 7 color band filters (ul: 0.40 μm, b: 0.48 μm, v: 0.55 μm, Na: 0.59 μm, w: 0.70 μm, x: 0.86 μm, p: 0.95 μm) equipped on ONC-T, we extracted the visible spectra of six S-type bright boulders observed during hovering operation at ~3 km of the altitude (~0.3 m/pix) after MASCOT deployment [2].

The presence of implanted S-type bright boulders is consistent with theory that S-type bright boulders are likely to have been mixed before the formation of current Ryugu: during catastrophic disruption or earlier. Furthermore, their spectral variety also would be helpful for evaluating this idea. If their spectral variety is large enough to require the mixing of meteoritic materials from several types of asteroids, it may imply they are derived from several different projectiles. In contrast, if their spectral variety is consistent with spectral modification mechanisms with a single projectile, it suggest they came from a projectile.

For example, space weathering, grain size, and dust covering are the candidates to change the spectra of S-type bright boulders. In order to examine whether or not the spectral variety of S-type bright boulders can be explained by these effects, we conducted a principal component analysis (PCA) of the second phase of the Small Main-belt Asteroid Spectroscopic Survey (SMASSII, [4]) data and compared the spectra of the S-type bright boulders with those of meteorites.

In our PCA, the first principal component (PC1) and the second principal component (PC2) represent spectral slope up to 0.70 μm and longward absorption respectively. Thus, larger PC2 score means deeper absorption at ~1 μm. Range of 1-μm absorption depth of Six S-type bright is ranging from S- to V-types (Fig. 3). Although the error bars of some bright boulders are very large, their distribution range is much larger than these error bars. Also, a clear trend that bright boulders with bluer spectral slope (smaller PC1 score) have deeper 1-µm absorption is observed. Spectral properties of asteroids display similar continuous trend as they transition between Q-, Sq- and S-types, which is believed to be consistent with the increasing effects of space weathering [5]. Thus, this spectral variation may reflect differences in space weathering maturity of bright boulders.

Space weathering process. Ten ordinary chondrites (black dotted lines) with pulsed laser irradiation were compared with bright boulders. Almost all of these ordinary chondrites suggest that increasing laser energies results in redder spectral slope and shallower 1-µm absorption. These irradiation tracks are similar to the distribution of S-type bright boulders, but, no single tracks of ordinary chondrites cover all of six S-type bright boulders.

Grain size effect. Laboratory experiments suggest that increasing average grain size results in deeper absorption bands for ordinary chondrites [6]. However, the degree of this effect is not large enough to account for the observed spectral variety in S-type bright boulders on Ryugu. For example, the range of PC2 score (1-µm depth) of Sartov (L4) with different grain size is about half those of S-type bright boulders.

Dust covering effect. During the touchdown operation, dark fine grains with diameters of 1 to a few mm ware observed [7]. Because global average spectra of Ryugu is flat in the visible region, contamination by dust of Ryugu is expected to weaken absorption features. Thus, using the normalized spectra of S-type bright boulders (M7, M9) with deeper 1-µm absorptions and the global Ryugu average, we calculated the linear combinations with various mixing rates. To reproduce shallower 1-µm absorption of M13 and M20, contribution ratio as high as 50 – 75 % for the global average spectra of Ryugu is required. In contrast, these S-type bright boulders have reflectance not significantly different from each other. Thus, dust coating effect alone also cannot account for the spectral variety of bright boulders either.

Conclusion: The analysis results indicate that no single process can fully account for the spectral variety of S-type bright boulders. This may imply the variety in composition among several projectiles. However, the fact that laser irradiation tracks are similar to the distribution of bright boulders and that they cover most of the distribution range of bright boulders suggests that combination of a few process could explain the variety of all S-type bright boulders with a single projectile.

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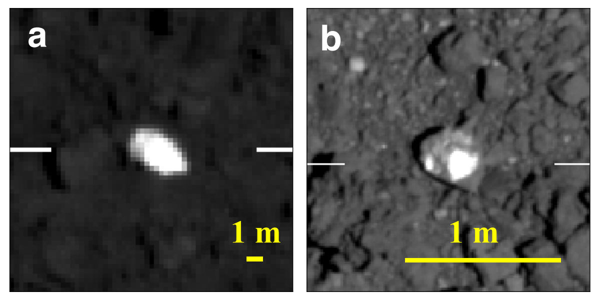

Fig. 1 (a) Individual bright boulders. (b) Unindividual bright boulders.

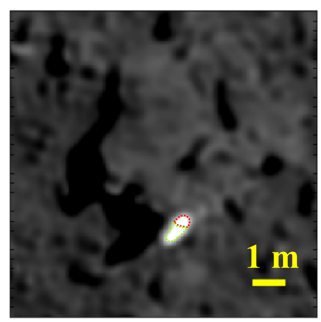

Fig. 2 Super-resolution image of M7 bright boulders (Second largest S-type bright boulder in [2]).

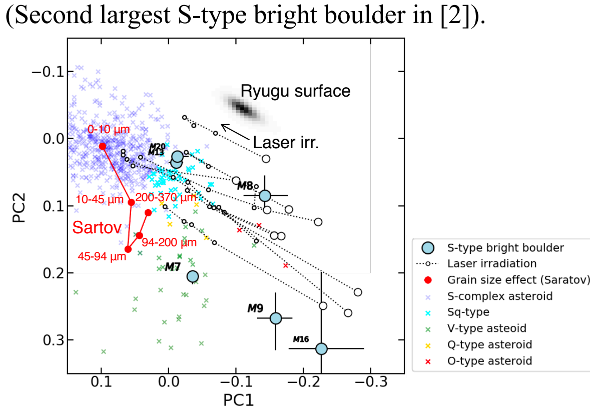

Fig. 3 Spectral comparison of S-type bright boulders, meteorites (Relab, Brown Univ.) and asteroids [4] [8].