MORPHOLOGICAL AND SPECTRAL PROPERTIES OF BOULDERS ON ASTEROID 162173 RYUGU.

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Introduction: Observations by the Optical Navigation Camera (ONC) onboard the Hayabusa2 spacecraft revealed that a C-type asteroid Ryugu is covered with a high abundance of large boulders [1, 2]. Initial report suggests that boulders have a correlation between morphologies and spectra; relatively bright boulders tend to have a smooth surface [1]. Such variation in boulder properties may reflect the heterogeneity in the parent body and its evolution processes. However, relations between spectra and morphologies of Ryugu boulders have not been studied extensively yet. In addition, the boulder spectra may also be influenced by more superficial processes, such as space weathering, solar heating, and grain sizes. Thus, detailed analyses are needed to obtain information on the parent-body processes.

Furthermore, the spectra and detailed morphologies of boulders have been catalogued for only ~20 boulders, which were chosen to represent the putative boulder groups (Type 1: dark/rugged, Type 2: bright/smooth, Type 3: bright/mottled) on Ryugu [1]. In addition, it is not clear yet whether the trends among different boulders types reflect the presence of multiple clusters or one broad continuous cluster. Distinction between these two possibilities would require a statistical analysis of morphologies and spectra of boulders.

For such statistical investigation, we analyzed the spectra of individual boulders using high-resolution images (~0.2 m/pix) acquired during crater-search observations and generated a spectral catalogue. Then we conducted clustering analysis. Furthermore, we conducted Fourier Transform analysis of morphologies of individual boulders.

Analytical Method: The overall footprint of the images taken during the crater search was from 40°N to 40°S and 260°E to 340°E. Approximately 100 largest boulders were used for our analyses. Pixels with shadows or high incidence/emission angles were removed from our analysis. Photometrical correction was performed with the Hapke model [5, 7]. It is noted that because the shape model resolution is much lower (~10 – 20 pix) than the image resolution, photometric correction is not accurate to the pixel level. Nevertheless, similar analyses on bright boulders indicate that uncertainty in normalized spectra from low-resolution shape models is small; error in b-x slope is only about 1/5 of the range of b-x slope variation over the Ryugu surface [Sugimoto+2020 LPSC].

Spectral properties: The spectral diversity among boulders has a trend similar to regolith-dominant surface (Fig. 2). Both boulders and regolith follow a trend similar to the heating transition of CM chondrites. The same trend was found with different observed phase angles. Thus, this is unlikely due to the phase reddening effect, suggesting that the variation in boulder spectra may reflect intrinsic difference in material properties of different types of boulders

Only weak correlation was found between the b-to-x spectral slope and albedo; the correlation coefficient is $R \sim -0.15$ (i.e. weak dark/red and bright/blue relation). No clear correlation was found between the location of boulders and the spectra either.

Furthermore, spectral clustering analysis based on the k-means method was conducted. However, the root-mean-square residuals of the classification continuously decreased with increasing number of classes. This shows that no clear clusters in boulder color could be found from our analytical accuracy.

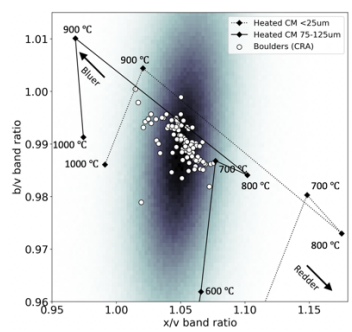

Fig. 2. Band ratios of b/v and x/v. The circles, dark cloud, and black lines show the spectra of boulders, surface of Ryugu, and heated CM chondrites [4] respectively.

Intra-boulder Spectral Variation: Some boulders exhibit significant spectral variation. Fig. 3 shows an example of boulders with one facet showing a high b-to-x slope (shown in red) while other facets exhibit moderate values compared to the Ryugu average (shown in green). The red facets tend to be steep with respect to the topology of Ryugu. Otohime, the largest boulder on Ryugu, also exhibit different spectra between facets [1].

This spectral variation between facets should be produced after the formation of Ryugu from contrasts

in processes, such as the heat-induced dehydration. Thus, the spectra of boulders could be superimposed by the effect of space weathering depending on its location and/or shape.

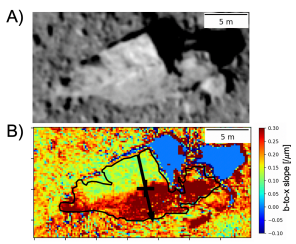

Fig. 3. A) Boulder situated at 19.5°N, 281.8°E. B) The b-to-x spectral slope of the same boulder. The dark arrow points to the direction which maximizes the variation in b-to-x slope.

Morphological properties: To understand the relations between spectra and morphologies, the surface ruggedness of boulders were investigated by a frequency analysis approach. The power-law exponent of the 2D Fourier amplitude as a function of spatial frequencies could serve as a measure for the surface ruggedness of boulders (Fig. 4). We found that dark and rugged (type 1) boulders have high power-law exponents, indicating that the ruggedness is dominated with large scale roughness in texture.

A histogram of power-law exponent in the analyzed ~100 boulders is shown in Fig. 5, indicating that the distribution is unimodal. This is consistent with the lack of clear clustering in spectra of boulders. Such unimodal distribution may be consistent with genomict-type breccia and well-mixed nature. Because brecciation would have occurred in the parent body owing to impact melting or cementation with aqueous environments [e.g., 6], such spectral variation within individual boulders may provide information on parent body processes.

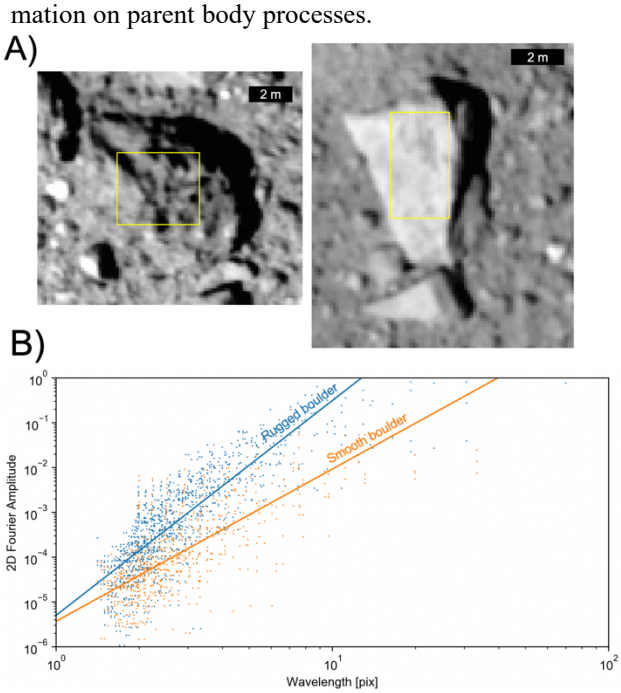

Fig. 4. A) Example of two boulders with a rugged (left) and smooth (right) surface situated at 22.4°N, 328°E and 12.2°N 311.9°E respectively. The box show the regions where Fourier analysis was performed. B) The Fourier amplitude as a function of spatial frequencies of the two boulders shown in Fig. 4A.

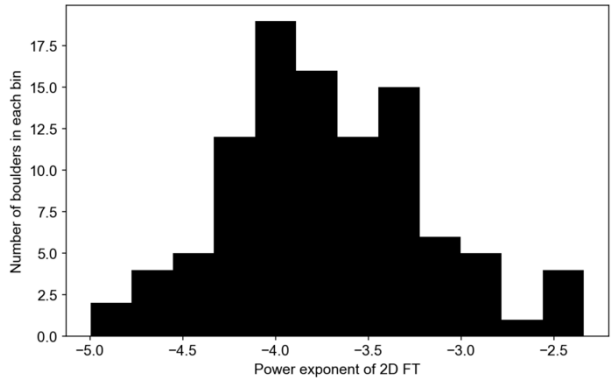

Fig. 5. Histogram of the power exponent of the 2D Fourier amplitude.

Concluding remarks: A trend from dark/rugged/red to bright/smooth/blue boulders were observed on Ryugu. These boulders do not exhibit multiple clusters, but is rather consistent with a continuous single cluster. Thus, such trends are consistent with endogenic processes on Ryugu's parent body. Comparison with spectra of heated CM chondrites suggests that the heterogeneity induced by different degrees of thermal metamorphism on the parent body may be the origin (bright/smooth/blue boulders experienced more intense thermal alteration). However, a caveat is that the change in spectra resulting from space weathering may play a substantial role in some of the boulder color variation [e.g, Morota et al., 2020]. Also, boulder with red facets is evidence that superimposition of space weathering effects has occurred to some extent.

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References: [1] Sugita, S. et al. (2019), *Science*, *364*, eaaw0422. [2] Michikami, T. et al. (2019), *Icarus*, *331*, 179-191. [3] DellaGiustina, D.N. et al. (2019), *Nature Astron.*, *3*, 341. [4] Pieters, C.M. (1983), *JGR*, *88*, 9534-9544. [5] Hapke, B. (1981), *JGR*, *86*, 3039-3054. [6] McCoy, T.J. et al. (2019), *82nd MetSoc Mtg.*#6428. [7] Tatsumi, E. et al. (2019), submitted. [8] Jaumann, R. et al. (2019), *Science*, *365*, 817-820.