Morphological and spectral trends among boulders on asteroid 162173 Ryugu: implication for parent body processes

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The Optical Navigation Camera onboard the Hayabusa2 spacecraft revealed the abundance of m-scale boulders on a Cb-type asteroid Ryugu [1,2]. The boulder distribution, morphology, and spectrum should be related to the parent body processes and/or the evolutionary processes as a rubble-pile. Especially, the parent body processes on C-type asteroids are important in understanding the hydrothermal activity in primordial planets and the possible source of terrestrial water/organics. Initial reports have suggested a possible trend in boulder spectra and morphologies [1]. Such variety in boulders should partially be a manifestation of the parent body processes. However, the identification of the process responsible for creating the observed variation is not very straightforward. Our purpose is to determine such parent body processes by conducting a detailed investigation of the trend among boulders. In particular, analysis done by [1] cannot distinguish whether the trends reflect the presence of multiple clusters or one broad continuous cluster. Thus, to distinguish these two possibilities, statistical and quantitative analysis based on a thorough boulder counting is performed. Also, boulder spectra are affected by superficial processes, such as space weathering, solar heating, and grain size sorting [3]. The high-resolution images acquired after the initial reports are used to assess such effects. Also, we report new trends in boulder spectra and intra-boulder spectral variation revealed from high-resolution images.

Approximately 100 largest boulders within the range of 40˚N to 40˚S and 260˚E to 340˚E taken at ~0.2 m/pix were used for our analysis. The rims of boulders were marked manually, and spectra were measured within the outlines. Though the resolution of the shape model used for the photometrical correction was ~10-20 times lower than the image resolution, the error in the normalized spectra was confirmed to be small: the error in b-x slope is <~30% the global variation.

Our result show that the red-to-blue trend among boulders follows the spectral transition by heating experiments of CM chondrites with temperatures between 800 and 900 ˚C [4]. The same trend was seen with different observed phase angles, and thus is unlikely to be a manifestation of the phase reddening effect. The possible presence of multiple clusters in the spectral trend was investigated by conducting the k-means classification. The root-mean-square residual of the classification decreased with increasing number of classes, indicating no clear existence of large spectral clusters. This result is consistent with the existence of boulders which underwent different degrees of thermal metamorphism in the parent body. However, a small spectral class consistent with Type 3 boulders [1] exist, which particularly deviates from the thermal metamorphism trend. Also, the brighter half of the boulder population show a smaller size distribution. Thus, the darker boulders exhibit a volumetric preponderance over brighter boulders, which may also inherit the heterogeneity in the parent body.

We found that the power-law exponent of the 2D Fourier amplitude as a function of the spatial frequency could be an index for surface texture of boulders. The unimodal distribution of the exponent also shows

no clear presence of morphological clusters. Thus, the rugged morphologies are consistent with a genomict-type breccia, which indicates a well-mixed nature of the material at the timing of brecciation (e.g. impact melting, cementation under aqueous environments).

High resolution imaging of the boulders revealed the spectral variation within individual boulders. These variations tend to be associated with different facets. Similar color variation was previously reported for the largest boulder Otohime [1]. By calculating the direction of the bluer facet for each boulder, we found that bluer facets are likely to be directed toward the equator. This is consistent with the preferential vulnerability to space weathering and/or thermal degradation/exfoliation of facets facing a certain direction.

We conclude that majority of boulders on Ryugu exhibit a spectral and morphological trend within a single continuous cluster. The trend may have originated from boulders with different degree of thermal metamorphism together with the genomict-type brecciation processes on the parent body. In addition, observed intra-boulder spectral variation suggests superimposition of space weathering effects.

References
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