MORPHOLOGICAL ANAYSIS OF BOULDERS ON ASTEROID RYUGU. S. Sugita[1,7], R. Honda[2], T. Morota[3], S. Kameda[4], E. Tatsumi[19,1], K. Yumoto[1], C. Sugimoto[1], C. Honda[5], Y. Yokota[6], M. Yamada[7], T. Kouyama[8], N. Sakatani[6], H. Suzuki[9], K. Yoshioka[1], Y. Cho[1], M. Matsuoka[6], K. Ogawa[10], D. Domingue[11], H. Miyamoto[1], O. S. Barnouin[12], P. Michel[13], C. M. Ernst[12], T. Hiroi[14], T. Nakamura[15], H. Sawada[6], M. Hayakawa[6], N. Hirata[5], N. Hirata[10], H. Kikuchi[1], R. Hemmi[1], T. Michikami[16], M. Hirabayashi[17], G. Komatsu[19], K. Shirai[6], S. Tanaka[6], M. Yoshikawa[6], S. Watanabe[3], Y. Tsuda[6], [1]U. of Tokyo (sugita@eps.s.u-tokyo.ac.jp), [2]Kochi U., [3]Nagoya U., [4]Rikkyo U., [5]U. of Aizu, [6]JAXA, [7]PERC CIT, [8]AIST, [9]Meiji U., [10]Kobe U., [11]PSI, [12]APL/JHU, [13]Obs. de la Cote d'Azur, [14]Brown U., [15]Tohoku U. [16]Kindai U. [17]Auburn U., [18]U. d'Annunzio, [19]Inst. de Astrofisica de Canarias

Introduction: Hayabusa2 observations have revealed that the spectra of Ryugu is consistent with moderately dehydrated state [1,2]. This state is ambivalent in the sense that it could preserve the state before aqueous alteration or could be resulted from dehydration after alteration. Depending on the nature of this state, what Ryugu samples represent would be drastically different.

A key for this problem may lie in the physical properties of the boulders. They exhibit surprisingly low thermal inertia, as low as regolith [2-4], suggesting very high porosity. Furthermore, many Ryugu boulders are too large to produce with impact fragmentation on Ryugu, indicating their origin on a parent body [2,5]. Thus, understanding the nature of this high porosity would help us understand parent-body processes. In particular, there is possibility that extremely porous structures was formed during dust accretion in the solar nebula. If Ryugu boulders preserve such fluffy structure, it would mean that Ryugu materials did not experience extensive alteration, metamorphism, or compaction.

However, high-resolution images (<1 cm/pix) obtained by the optical navigation cameras (ONC) onboard Hayabusa2 during touchdown rehearsals show that Ryugu boulders contain many angular clasts with contrasting colors, suggesting polymict breccias [2]. In fact, Bennu boulders also exhibit breccia-like morphologies [6,7]. It is also noted that high ratio (~100%) of low-albedo carbonaceous chondrites, such as CI, CM, CR, are known to be impact breccias [8].

In this study, we examine the physical state and evolution of boulders via morphological examinations using optical images obtained by Hayabusa2/ONC to understand the nature of the porosity of Ryugu boulders.

Ryugu Boulder Types: The Hayabusa2 global observations have revealed that Ryugu have multiple types of boulders based on spectral, albedo, and morphologies [2]. Type-1 boulders, which are dark and rugged, account for the majority of Ryugu's boulders. Although type-2 (smooth and bright) boulders do not exhibit obvious breccia-like structure at scales discernible with Hayabusa2/ONC (e.g., ≥1 mm/pix). The thermal inertia of type-2 boulders is much lower than typical solid rocks leaving the possibility for a large porosity [1,9].

The presence of such different morphologies and spectral properties of boulders was subsequently confirmed with much higher resolution (<1 mm) images obtained during the landing observations of MASCOT [10]. Cauliflower-like complex structures were seen on the surfaces of dark and rugged boulders.

Several different processes could be possible for high porosity and complex rugged structures: 1) impact brecciation, 2) drainage channel structure made during dehydration, 3) pores between grains accreted from primordial Solar nebula. Although all these three processes could make a wide variety of porosity particularly if subsequent compaction is permitted. However, there pore size distribution should not be changed and could be used to distinguish among the three or other candidates. More specifically, impact breccia would have a power-law grain/pore size distribution because impact fragmentation would produce a power-law size distribution. In contrast, drainage structure would form pores and cracks along mineral boundaries and minerals that destructed by dehydration reaction. This, the typical size should be comparable to the typical mineral grain sizes, which is typically millimeters to sub millimeter. Finally, the grain size of dust grains accreted from solar nebula is estimated to be micron range [e.g.,11, 12].

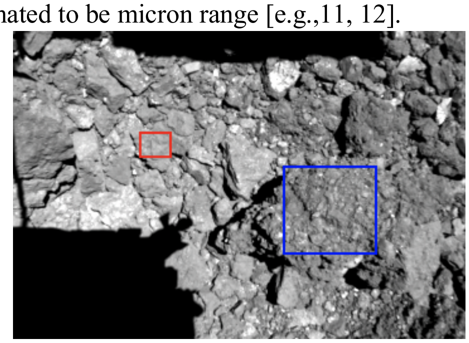

Fig. 1. High-resolution (~1mm/pix) image immediately prior to the first touchdown by Hayabusa2 on asteroid Ryugu (hyb2_onc_20190221_222855_w1f_l2d). The type-1 and type-2 bounders used for analysis are indicated with blue and red squares. The top black shadow of Hayabusa2's solar array panel is about 1 m.

Morphology Comparison at Different Scales: In order to investigate the nature of boulder surface texture and the grain size distribution, we performed a Fourier transform on individual boulders at drastically different scales. One is the 18 cm/pix images obtained during crater search observations, and the other is high-resolution (~1 mm/pix) images observed during a touchdown descent (Fig. 1). For comparison, we chose the same boulders used in the analysis of 18cm/pix by [13].

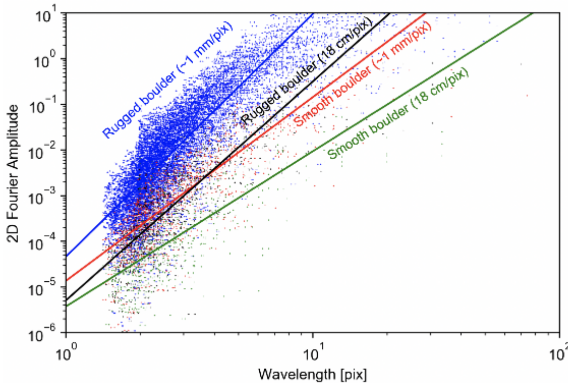

Fig. 2. Power spectra of boulder surface images. Dots are individual Fourier amplitude and solid lines are the best-fit power-law functions. Type-1 (dark and rugged), 2 (bright and smooth) boulders observed at very different resolution are compared.

Our preliminary analysis results (Fig. 2) show that image-texture power spectra for all the boulders follow power-law functions and that rugged type-1 boulders exhibit steeper slopes (larger amplitudes at longer wavelengths) than neighboring smooth type-2 boulders at both resolutions. The fact that the image texture power spectra are similar at extremely different scales might reflect that their textural structures have fractal structures. This is more consistent with impact fragments rather than other two possible candidates discussed above.

Xenolith in Type-1 Boulders: Among anomalously bright boulders found on Ryugu exhibit both S- and C-type spectra [14]. The former is likely fragments from an impactor to Ryugu's parent body, and the latter may be from different parts of the parent body that experienced different degrees of either aqueous alteration or thermal metamorphism. These may be a cause for brightness variation in clasts in polymict breccia.

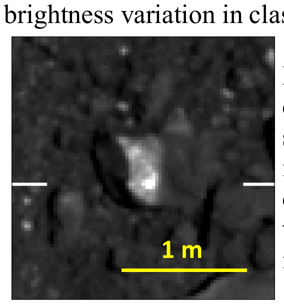

Fig. 3. A C-type bright boulder on Ryugu. Multiple small bright clasts are seen inside a large clast with medium average brightness, which is possibly embedded in a larger dark boulder.

Furthermore, detailed observations of the occurrence of bright boulders suggest that they may be embedded in the substrate boulders. Although it is difficult to judge whether they are simply sitting on the substrate boulders or mechanically adhered in the substrate boulders, some of the bright boulders occur as clusters on the substrate boulders (Fig. 3 and [15]. Furthermore, one of the S-type boulders exhibit very particular occurrence: a elongate bright boulder is sticking out from the substrate boulder, and its shadow and the body are clearly separated from each other [15]. Because the length of unsupported portion of the bright boulders is longer than that supported by the substrate, this can be gravitationally unstable, strongly suggesting that a fragment unadhered to the substrate would be unlikely.

This finding suggest that type-1 boulders were formed after major collisional activities, which would be after the formation of Ryugu's parent body. This is more consistent with impact breccia nature of type-1 boulders than with extremely primitive materials, such as accreted dust structure.

Parent Body Evolution: Timing relation between cementation of boulders and xenolith embedding would provide a very important constraint on the parent-body evolution. If the presence of liquid water is required for cementation between clasts within breccia, the S-type impactor is less likely to have disrupted the Ryugu's parent body because a rubble pile is unlikely able to host liquid water. Then, either impact melt or adherence of organic matter contained in carbonaceous chondrites may have played the central role. If the impact did not disrupt the parent body, it still had to have occurred very early in the Solar System, early enough to have liquid water present in these parent body. Thus, the disrupter would have different from the S-type fragments.

Conclusions: Our preliminary results suggest that a large fraction of Ryugu boulders could be impact breccia. The occurrence of bright boulders suggests that S- and C-type fragments have to be embedded in Ryugu's parent body before the boulder were cemented together.

Relative timing between ordinary chondrite (OC)-like xenoliths embedding and cementation of the bulk materials of Ryugu boulders would place an important constraint on the evolution of Ryugu's parent body. If OC-like fragments are found in Hayabusa2 samples, the thermal and aqueous alteration state of such fragments would be extremely important to analyze.

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