THE REPRESENTATIVENESS OF RYUGU SAMPLES ESTIMATED FROM STATISTICAL ANAYSIS OF BOULDER COLOR DISTRIBUTION. S. Sugita[1,2], K. Yumoto[1], T. Ebihara[1], T. Morota[1], E. Tatsumi[3,1], D. N. DellaGiustina[4], H. Kobayashi[5], R. Honda[7], S. Kameda[6], N. Sakatani[6], Y. Cho[1], Y. Yokota[8], T. Kouyama[9], M. Yamada[2], M. Hayakawa[8], M. Matsuoka[10], H. Suzuki[11], C. Honda[12], K. Ogawa[8], K. Yoshioka[1], and H. Sawada[8], [1]Dept. Earth and Planet. Sci., Univ. of Tokyo, 7-3-1 Hongo, Tokyo, Japan (sugita@eps.s.u-tokyo.ac.jp), [2]Chiba Inst. Tech., [3]Inst. de Astrofísica de Canarias, [4]Univ. of Arizona, [5]Nagoya Univ., [6]Rikkyo Univ., [7]Kochi Univ, [8]JAXA/ISAS, [9]AIST, 10 Paris Univ., [11]Meiji Univ., [9]Univ. of Aizu.

Introduction: Global observations by JAXA's Hayabusa2 has shown that the Cb-type asteroid 162173 Ryugu is very homogeneous in reflectance spectra at both visible [1,2] and near-infrared wavelengths [3]. This homogeneity on Ryugu played an important role in selecting sampling sites [4,5]. Subsequent higher resolution (0.9 – 19 cm/pix) observations, however, detected much greater spectral variety on its surface, such as bright boulders [6-8], some of which coincide with low-porosity boulders (i.e., so-called cold boulders) [9], and high-porosity (> 70%) boulders, which possess reflectance ~20% lower than the Ryugu average and are called "darker boulders" [10]. Furthermore, >1000 bright boulders have been found [7]. Bright boulders have spectral diversity much greater than boulders with near-average reflectance; their range of spectral slope (–0.4 to +0.6 μm^{-1}) [8] are about 10 times that (0.1 to 0.2 μm^{-1}) of Ryugu's global low-resolution (2 m/pix) observations [1], in which only a few bright boulders were discerned. Despite these great variety, nevertheless, the rarity of these brighter and darker boulders indicate that the degree of parent-body heterogeneity is limited. The degree of heterogeneity manifested in remote-sensing data on Hayabusa2 has not been quantitatively examined extensively.

Because Ryugu is a rubble pile likely formed by re-accumulation of fragments from impact-induced catastrophic disruption of a parent body [1,11], these observed spectral variety among boulders on Ryugu would reflect the heterogeneity of its parent body. Furthermore, high-precision spectral and geochemical analyses of returned samples allow parent-body processes in great details [e.g., 12-14]. These studies will allow us to understand the evolution of C-complex asteroids in the Solar System greatly. However, linking between Ryugu samples to main-belt asteroids (MBAs) requires comparison through widely observed spectral properties, such as spectral slope and reflectance, which account for a large portion of spectral characteristics of C-complex asteroids [e.g., 15]. In order to meet these needs, we quantitatively investigate the heterogeneity of Ryugu boulders in this study.

Data and Analysis: We used multi-band images obtained by the telescopic optical navigation camera (ONC-T) of Hayabusa2 for asteroid Ryugu and identified 8,077 boulders ≥3 m in diameter on Ryugu (Fig. 1). For comparison, 1,483 boulders on Bennu identified in images taken by MapCam of OSIRIS-REx by [16] have been analyzed. We applied the results of cross calibration between ONC-T and MapCam based on the lunar observation and minimized inter-instrument bias [17].

Color and Albedo Distribution: The large numbers of analyzed boulders allowed us to obtain reflectance and spectral slope distribution down to ~0.01% of boulders on both asteroids. Analysis results shown in Figs. 2A and B indicate that the reflectance at standard geometry (30° incidence angle and 0° emission angle) of 95% of Ryugu boulders are distributed within a narrow range (0.019±0.003); the brightest 2.5% boulders are only 15% brighter than the average. Similarly, 95% of Bennu boulders are distributed also within a narrow range (0.02±0.007); the brightest 2.5% boulders are only 35% brighter than the average.

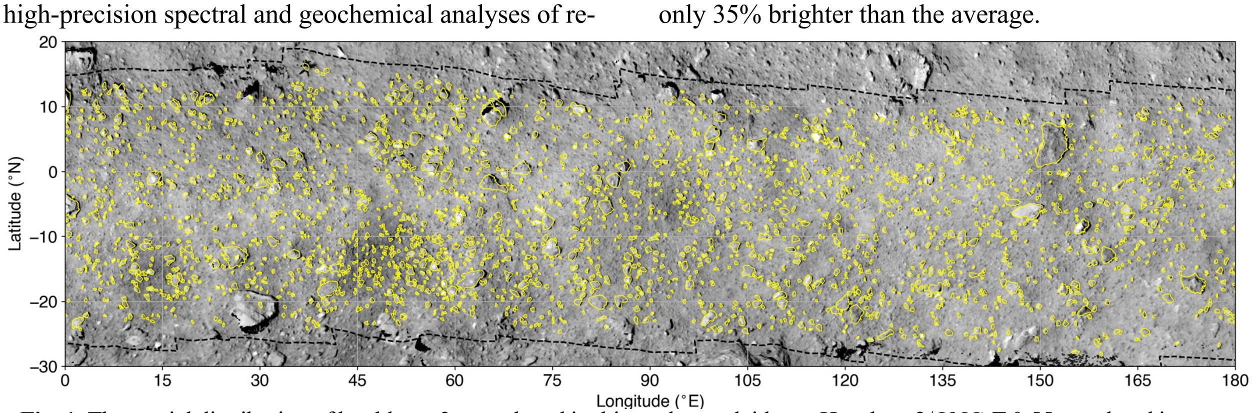

Fig. 1. The spatial distribution of boulders ≥3 m analyzed in this study overlaid on a Hayabusa2/ONC-T 0.55-mm-band images of the equatorial region of Ryugu. Only easter hemisphere (0 – 180°) is shown. See [15,24] for more details of boulder counting.

More detailed analysis revealed that bright boulders (i.e., brighter than the average by 50% [6]) is only ~0.01% on Ryugu and ~0.1% on Bennu (Fig. 1A). Boulders with 15% brighter than the average is 1% on Ryugu and those with 40% brighter than the average is 1% on Bennu. "Darker boulders" is <0.01% on both Ryugu and Bennu (Fig. 1A). Similar analysis on spectral slope distribution reveals narrow spectral variations on the two asteroids. Although the average spectral slopes of the two asteroids are significantly different (0.18 μm^{-1} for Ryugu and -0.10 μm^{-1} for Bennu), their distribution widths are similar (Fig. 1B).

Comparison with Meteorite Spectra: Then, we compared the obtained spectral and reflectance heterogeneity with those of CM and CI samples treated with heating and space weathering experiments [18,19]. Examples of results are shown in Figs. 2C and 2D. The ranges of spectral slope and reflectance observed for boulders on Ryugu can be reproduced well by a narrow temperature range ΔT of heating (40 K and 120K for CI and CM, respectively). This result suggests that Ryugu materials experienced heating at temperatures more than 40 K and 120 K different from its average heating temperature would be only 0.01% of its mass if its composition is CI and CM, respectively. Although the reflectance range of Bennu is wider than Ryugu [20], materials with similar reflectance difference account for only about 0.1% of mass (Fig. 2A). The spectral slope range is about the same as Ryugu. Thus, Bennu materials must also have experienced very homogeneous parent-body processes.

Variations in spectra and reflectance due to those in composition and the degree of aqueous alteration are difficult to assess quantitatively because systematic investigation on changes in meteoritic spectra due to these effects has not been conducted extensively. However, the range of variation in spectra and reflectance in C-complex asteroids are estimated to be on the same order of magnitude as those caused by heating experiments with ΔT ~ 1000K [18]. Thus, if the main cause of the variation in spectra and reflectance of Ryugu materials is those in composition or the degree of aqueous alteration, their heterogeneity in Ryugu's parent body also needs to be very limited. This great homogeneity and supports that Ryugu and Bennu are from large parent bodies, such as parent bodies (~100 km) of Polana and Eulalia families, more than smaller background asteroids (e.g., ~10 km).

Implications for Parent Body Processes: Large parent body size alone may not be able to account for the combination between great homogeneity and rare occurrence of anomalous color of boulders observed on Ryugu and Bennu. For example, 0.1% and 0.01% of volumes correspond to only 17 m and 1.7 m of surface layers for a 100-km-diameter parent body, respectively. These are much thinner than thermal boundary layers on ^{26}Al-heated bodies [21] and pore closing depth [22].

These results might suggest other homogenizing factors other than large parent body size may exist. One possibility may be combination of impact fragmentation, mixing, and breccia formation. Such processes may be able to generate macroscopically homogenous boulders from heterogeneous fragments. In fact, many boulders on Ryugu and Bennu exhibit breccias properties [8, 23].

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References: [1] Sugita et al. (2019) *Science*, *364*, eaaw0422 [2] Tatsumi et al. (2020) *A&A*, 639, A83 [3] Kitazato et al. (2019) *Science 364*, 272, [4] Morota et al. (2020) *Science*, 368, 654-659. [5] Tachibana et al., *Science*, in review. [6] Tatsumi et al. (2021) *Nat. Astron. 5*, 39, [7] Sugimoto et al. (2021a) *Icarus* 114529. [8] Sugimoto et al. (2021b) *Icarus* 114591. [9] Okada et al. (2020) *Nature*, 579, 518. [10] Sakatani et al. (2021) *Nat. Astron. 5*, 766, [11] Watanabe et al. (2019) *Science*, *364*, 267. [12] Yada et al. (2021) *Nat. Astron.* [13] Nakamura et al. *Science* submitted. [14] Yokoyama et al. *Science* submitted. [15] DeMeo et al. (2009) *Icarus*, *202*, 160. [16] DellaGiustina et al. (2020) *Science*, *370*, eabc3660. [17] Yumoto et al. (2021) 52nd *LPSC*, #1370. [18] Hiroi et al. *MAPS*, *31*, 551. [19] Matsuoka et al., (2015) *Icarus*, *254*, 135. [20] Lauretta et al., *Nature*, *568*, 7. [21] Grimm and McSween (1992) *Science*, *259*, 653, [22] Neumann et al. (2021) *Icarus*, *358*, 114166, [23] DellaGiustina et al. et al. (2021) *Nat. Aston.*, *5*, 31. [24] Ebihara et al. (2021) 52nd *LPSC*, #1902.

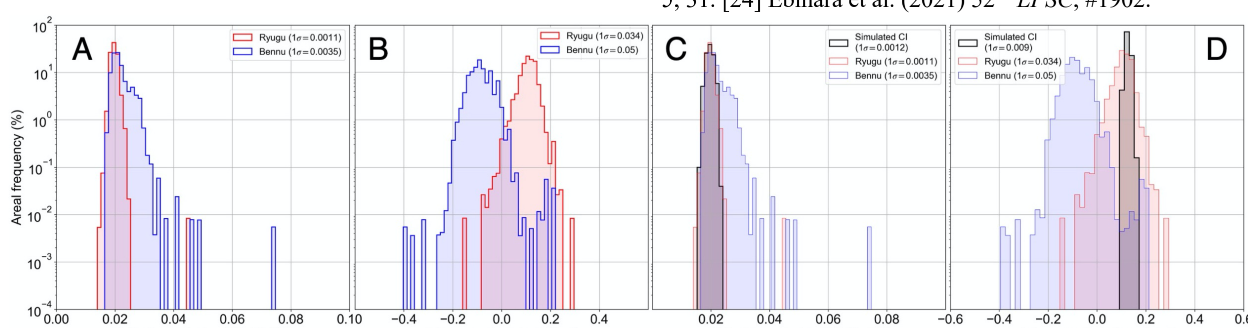

Fig. 2. Spectral distribution of boulders 3m in diameter or larger on Ryugu and Bennu and comparison with heated CI chondrite samples. (A) 0.55-μm reflectance, (B) b-to-x (0.48 – 0.86 μm) spectral slope, (C) comparison with heated CI reflectance, and (D) comparison with heated CI b-to-x slope.