COLLISIONAL AND THERMAL EVOLUTION OF RYUGU'S PARENT BODY INFFERRED FROM BRIGHT BOULDERS. S. Sugita[1], C. Sugimoto[1], E. Tatsumi[2,1], Y. Yokota[3], T. Morota[1], R. Honda[4], S. Kameda[5], Y. Cho[1], K. Yoshioka[1], H. Sawada[3], N. Sakatani[3], M. Hayakawa[3], M. Matsuoka[3], M. Yamada[6], T. Kouyama[7], H. Suzuki[8], C. Honda[9], K. Ogawa[3], ONC team, [1]Dept. Earth and Planet. Sci., Univ. of Tokyo, 7-3-1 Hongo, Tokyo, Japan (sugita@eps.s.u-tokyo.ac.jp), [2]Inst. de Astrofísica de Canarias, [3]JAXA/ISAS, [4]Kochi Univ., [5]Rikkyo Univ., [6]Chiba Inst. Tech., [7]AIST, [8]Meiji Univ., [9]Univ. of Aizu.

Introduction: The near-Earth asteroid 162173 Ryugu exhibit a flat average spectrum (Cb-type) and a very low (0.04) average normal albedo [1,2]. Although the majority of boulders on Ryugu have reflectance spectra and albedo similar to the Ryugu average, a small fraction of boulders exhibit anomalously high albedo and distinctively different spectra [1,3]. Detailed analysis of images obtained before the first touchdown (TD1) and found that the spectra of these anomalous boulders (i.e., bright boulders or BBs) can be classified into two groups (S- and C-types) [3]. The former is most likely exogenic and from impactor(s) that collided with Ryugu's parent body. The latter may be endogenic and from portions of Ryugu's parent body that experienced a different thermal history from the majority of Ryugu boulders. A subsequent study [4] found that many S-type BBs follow trends consistent with space weathering of ordinary chondrites and are often found as clasts embedded in larger dark boulder forming polymict breccia.

In this study, we expand our analysis to images obtained after TD1 to determine the quantitative properties of BBs on Ryugu. We measured the sizes of >1000 BBs and characterized the morphologic and spectral properties of the larger (~meter) BBs.

Data and Analysis: The details of the data and analysis are given by [5,6] Here, we provide a brief summary. We used v-band (0.55 μm) images captured by the telescopic Optical Navigation Camera (ONC-T) onboard Hayabusa2 [1,7] for our analysis. We analyzed the data used in [3,4] as well as those obtained later in the mission. The former was obtained during hovering operations after MASCOT deployment at ~2.7 km in altitude (~0.29 m/pixel). The latter includes two sets of high-resolution (~0.18 m/pixel) images captured during the artificial crater search observations before (CRA1) and after (CRA2) the SCI operations [8]. The latter also includes descent observation images (≥ 3.8 mm/pixel).

Spatial and Size Frequency Distribution: The number density of BBs in the equatorial region exhibit a west/east dichotomy. This longitudinal pattern is the same as the pattern found for large dark boulders by [1, 9]. This observation suggest that the BBs are well mixed with the dark boulders.

The size frequency distribution (SFD) of BBs on Ryugu is shown in Fig. 1. S-type BBs from 0.3–3 m follows a power law with a shallow exponent (-1.6±1.2). Comparisons in SFD between S-type BBs and darker general boulders [1,9] indicate that the volume ratio of the former to the latter is only $3^{+3}_{-1} \times 10^{-6}$.

The SFD of C-type BBs from 0.02 – 2 m follows a power law with a steep exponent (-3.1±0.7). Comparisons in SFDs between C-type BBs and general boulders indicate the volume ratio of the former to the latter is $4^{+23}_{-3.2} \times 10^{-5}$.

C-type Clasts in Breccia: Careful observations found that many C-type BBs are embedded in large substrate boulders (Fig. 2) similarly to S-type embedded clasts found by [4]. The fact that C-type BBs are included in breccia suggests that the cementation process may have continued on Ryugu's parent body until after the cessation of thermal metamorphism, and perhaps until catastrophic disruption of the parent body, resulting in a very large number of breccias. Such breccias would have a very high porosity and may have contributed to the globally low thermal inertia observed for Ryugu [1,10,11].

Visible Spectra: Spectral analysis of BBs on Ryugu shown in Figs. 3 and 4 provide important constraints on the evolution of Ryugu's parent body.

First, S-type BBs turned out to follow two space-weathering trends of two different initial spectra of ordinary chondrites (Fig. 3A). We were initially skeptical about this interpretation because there are a lot of mechanisms that could influence the reflectance spectra of S-type asteroid materials [4]. However, thorough examination of spectral modification process of S-type BBs supports that the apparent two trends parallel to the space weathering trend is real [5], suggesting that more than one projectile may collided its parent body (Fig. 3B). Fragments from multiple projectiles suggest that Ryugu may not have been formed directly from Polana's parent body or Eulalia's, but it may have been formed from the catastrophic disruption of a member of the Polana or Eulalia family [1, 12].

Second, comparison between S-type BBs on Ryugu and meteoritic samples indicate that at least one group of S-type BBs on Ryugu is ordinary chondrite (OD) and unlikely HED (Fig. 3BC), which supports the analysis by [3]. This makes a significant contrast with Bennu's BBs, which are likely to be basaltic (i.e., HED-like) [13].

Third, C-type BBs exhibit a continuous spectral trend similar to the heating track of low-albedo carbonaceous chondrites, such as CM and CI. Other processes, such as space weathering and grain size effects, cannot primarily account for their spectral variation (Fig. 4). This suggests that thermal metamorphism might be the dominant cause for the spectral variety among the C-type BBs on Ryugu and that general boulders on Ryugu may have experienced thermal metamorphism under a much narrower range of conditions than the C-type BBs. This supports the hypothesis that Ryugu's parent body experienced uniform heating due to radiogenic energy [1].

Prospect to returned Ryugu samples: When the above power law is extrapolated to millimeter scales, which is the size range of samples that can be captured by the Hayabusa2 sampler, the abundance of C-type BB materials is estimated to be >0.2%. Because >5g of Ryugu samples have been returned to Earth [14,15], >10 mg of C-type BBs could be contained in the samples. Because this amount is much more than the total Itokawa samples brought by Hayabusa [16], substantial geochemical analyses could be conducted for C-types BBs. In contrast, S-type BBs would be much more difficult to find because of their much steeper SFD.

Acknowledgments: This study was supported by JSPS Core-to-Core program "International Network of Planetary Sciences".

References: [1] Sugita et al. (2019) *Science*, *364*, eaaw0422. [2] Tatsumi et al. (2020), *A&A.*, *639*, A83. [3] Tatsumi et al., 2020, *Nature Astron.*, 10.1038/s41550-020-1179-z [4] Sugimoto et al. (2020) *LPSC* #1770 [5] Sugimoto et al. (2021a) submitted to *Icarus*. [6] Sugimoto et al. (2021b) submitted to *Icarus*. [7] Kameda et al. (2017). *SSR, 208*, 17–31. [8] Arakawa et al., *Science*, *368,* 67-71. [9] Michikami et al. (2019) *Icarus*, 331, 179-191. [10] Grott et al., (2019), *Nature Astron*. *3*, 971-976. [11] Okada et al. (2020) *Nature*, 579, 518-522. [12] Walsh et al. (2020) *LPSC*, #2253. [13] DellaGiustina et al. *Nature Astron*., 10.1038/s41550-020-1195-z. [14] Tachibana et al. (2021) *LPSC*. [15] Yada et al. (2021) *LPSC*. [16] Tsuchiyama et al. (2011) *Science*, *333*, 1125-1128. [17] Bus and Binzel (2002) *Icarus*, *158*, 146–77.

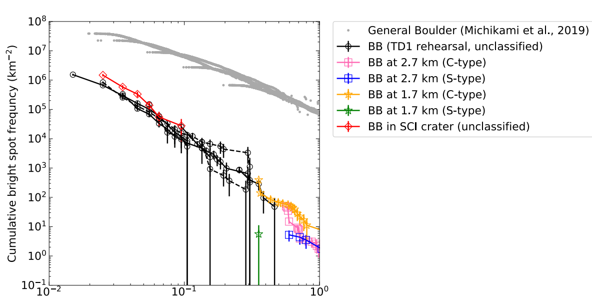

Fig. 1. The SFD of bright boulders (color symbols) and general dark boulders (grey symbols) on Ryugu.

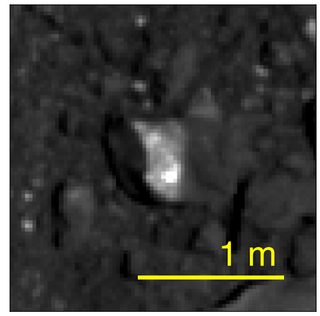

Fig. 2. Intra-boulder bright clasts embedded in a larger dark boulder on Ryugu (hyb2_onc_20181015_130705).

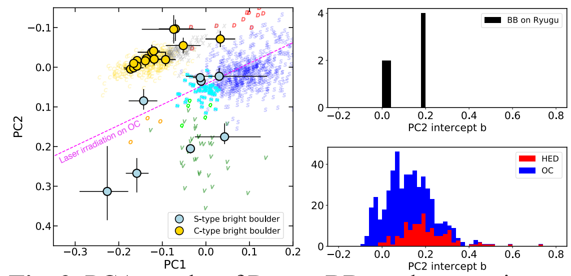

Fig. 3. PCA results of Ryugu BBs and comparison with main-belt asteroids (MBAs [17]) and meteorites. (A) Comparison of PC1-PC2 between S- and C-type BBs and MBAs. Note that S-type BBs follow the space weathering trend reproduced with laser irradiation experiments (Relab at Brown Univ.) shown as a blue dashed line. (B) Histogram of PC2 intercepts (*b*) of S-type BBs projected parallel to the space weathering trend. All the S-type BBs belong to either Trends I or II. (C) Histogram of *b* of HED meteorites and OCs. Only 6% of HEDs have *b* values the same or lower than trend I, but as much as ~30% of OCs exhibit *b* values the same or lower than trend I.

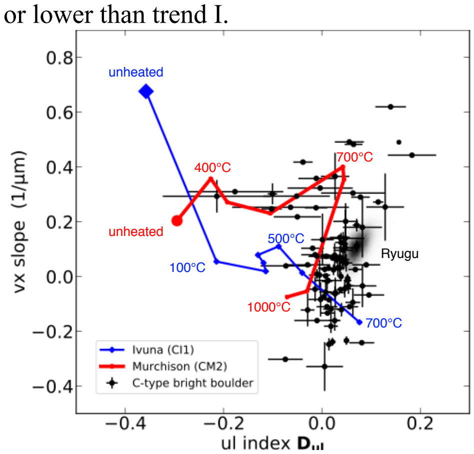

Fig. 4. Comparison of ul-index and spectral slope between C-type bright boulders on Ryugu and heated carbonaceous chondrites. Red circles are C-type BBs. Colored lines indicate the heating tracks of carbonaceous chondrites (Ivuna and Murchison). The black cloud indicates the spectral distribution for the surface of Ryugu.