COLLISIONAL HISTORIES OF ASTEROIDS RYUGU AND BENNU INFERRED FROM THE ABUNDANCE OF EXOGENIC BOULDERS. S. Sugita[1], H. Kobayashi[2], K. Sugiura[3], H. Genda[3], E. Tatsumi[1,4], M. Jutzi[5], and P. Michel[6], [1]Dept. Earth and Planet. Sci., Univ. of Tokyo, Tokyo, Japan (sugita@eps.s.u-tokyo.ac.jp), [2]Nagoya Univ., Japan, [3]ELSI, Tokyo Inst. Tech., Japan, [4]Inst. de Astrofísica de Canarias, Spain, [5]Univ. of Bern, Switzerland, [6]Univ. Côte d'Azur, Obs. de la Côte d'Azur, CNRS, Laboratoire Lagrange, France.

Introduction: Relation between the parent body(s) of Near-Earth asteroids Ryugu and Bennu are a subject of great controversy and has important implications for interpretations of geochemical analyses of returned samples. Initial global observations have shown that Ryugu and Bennu possess similar albedo, visible spectra, and geologic properties [e.g., 1, 2] but have near infrared spectra with contrasting difference [3,4].

More recently, exogenic boulders with different spectral properties were found on the two asteroids, indicating that the two asteroids experienced different collisional histories [5,6] (Fig. 1). However, this does not rule out the common original parent body because the exogenic boulders could be implanted in collision events after the catastrophic disruption (CD) of the parent body forming its family. Nevertheless, further studies have estimated volumetric mixing ratios of these exogenic boulders ($7.1^{+6.3}_{-5.0} \times 10^{-6}$ for Ryugu [7] and ~3 × 10^{-4} for Bennu [8,9]), making it possible to assess what conditions of collisional history from the parent body(s) to the current km to sub-km bodies can quantitatively reproduce observed abundances of exogenic boulders.

In this study, we conduct such assessment in aid of 3-D impact simulations and Monte Carlo model calculations in order to place further constraints on the parent-body commonality of Ryugu and Bennu. Detailed discussions of this effort are given by [10].

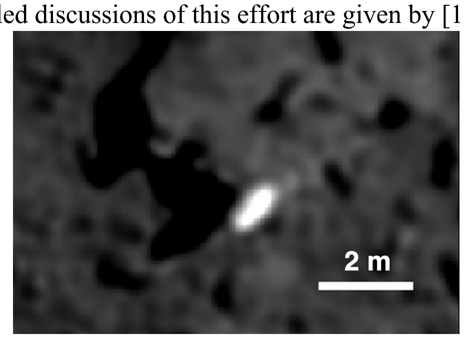

Fig. 1. An S-type bright boulders on Ryugu. This particular one occur as a clast within a breccia structured dark boulder [7].

3-D SPH Simulations: We used a three dimensional smoothed particle hydrodynamics (SPH) method for impact simulations using the code by [11], which includes self-gravity, size-dependent strength model (0.1 MPa for 100-km-diameter bodies), and friction angle (40°). We used the parameter sets of non-porous basalt in the Tillotson EOS [12].

To determine the impact conditions (impact angles θ and impact velocities v_{imp}) for making the largest asteroid (Polana or Eulalia) via a CD of the potential Ryugu's parent body, we first conducted a series of low-resolution simulations (2 × 10^4 SPH particles for the target body). As the parent body of Ryugu, we assumed a 100-km sized target body with mass M_{tar}, based on the estimates of the total masses of the Polana and Eulalia families [13]. We varied impactor mass (M_{imp}) for q (=M_{tar}/M_{imp}) = 4, 16, 32, and 64, and impact angle for θ = 15°, 30°, 37.5°, 45°, 50°, and 60° for various v_{imp}.

We analyzed the mass of the largest body (M_{lr}) after collision for various impact conditions. Because the largest body is estimated to have M_{lr}/M_{tar} ~ 0.1 for the collisions forming the Eulalia or Polana families, we looked for q-θ-v_{imp} combinations that can form families with ~0.1 of largest size fragment (clump) to the total family mass. We use the obtained q-θ-v_{imp} combinations for 20 higher-resolution impact simulations (up to 4 × 10^6 SPH particles for the target)

Fig. 2 shows snapshots for a CD due to an oblique collision. Upon contact, the impactor starts to elongate. Then, target materials near the impact point are ejected downwards forming an asymmetric ejecta curtain, in which target and impactor materials are mixed. However, the contact area between impactor and target is much smaller than near vertical cases. Thus, mixing ratio of impactor for resulting clumps decreases drastically as impact angle θ increases.

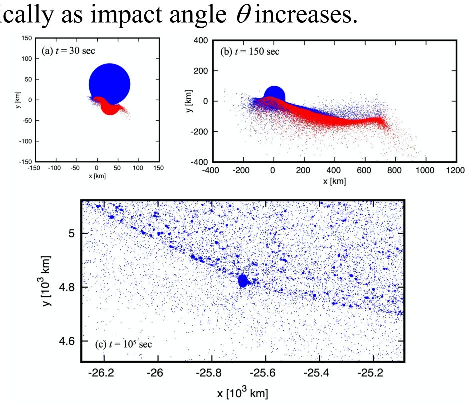

Fig. 2. Snapshots for an oblique catastrophic collision with q = 16, θ = 50° and v = 4.5 km/s. Blue and red dots are target and impactor materials, respectively.

Fig. 3 shows impactor mixing ratios for various θ and v_{imp} for q = 16. In low-θ collisions, impactor materials mix with target materials much more efficiently; resulting clumps have high impactor fractions. Although clump mass is distributed over a few orders of magnitude, their impactor mixing ratio is relatively constant (scatter is ten or less). The diagonal black thick line in the Fig. 3 shows the resolution limit in impactor fraction; only one impactor SPH particle in a clump. Below this line, we cannot resolve the impactor fraction. However, because impactor mixing ratio does not depend on clump mass very much, we can predict impactor mass fractions for smaller clumps based on those in larger clumps. For q = 16 and θ = 50° and 60°, a clump with the impactor fraction of ~ 10^{-6} is formed, although this clump is the largest one. There are smaller clumps which have zero impactor fraction due to the limitation of the numerical resolution, but those are expected to have the similar impactor fraction (~10^{-6}), when much higher-resolution simulations are carried out. On the other hand, clumps with impactor fraction ~10^{-6} should be rare for q < 16 or θ < 50° if the trend obtained for larger clamps continues to small clumps beyond the resolution limit of the current calculations.

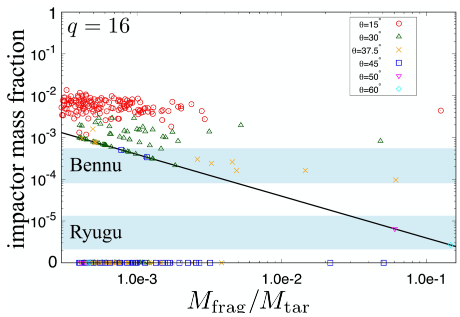

Fig. 3. Impactor mass fractions in each clump for the targe/impactor mass ratio q is 16. Impact velocity is chosen to make the largest clump mass is ~0.1 of the target. The mixing ratios of exogenic materials are shown with light blue hatch on Ryugu and Bennu.

Monte Carlo Simulations: Then, we performed a Monte Carlo simulation for collisional grinding with many collisions of a variety of normalized specific impact energy $e = Q/Q_D^*$ after the family-forming collision to Ryugu and Bennu sizes in the main belt using [14]. Here, Q_D^* is the specific impact energy to form a largest remnant of the half the parent body mass $Q_D^* = 7 \times 10^8$ $(D/100\mathrm{km})^{0.5}$ erg / g, and we assume that the first family-forming collision has e = 10 for the Eulalia or Polana families.

Fig. 4 shows the number of collisions with e > 0.1 during the subsequent collision evolution to become ~1 km or smaller asteroids after the family forming collision (red line). Our calculation results indicate that the most probable number of CDs ($e \geq 1$) and sub-CDs ($1 > e \geq 0.1$) to collisional grind down from a 100-km body to 1 km is three, while the probability distribution is widely extended. We further investigated the number of collisions with mixing (blue line). We did not count sub-CDs if materials to be a final 1-km body stays in the largest clump because such collision is not likely to mix impactor materials with the largest clump efficiently. Sub-CDs that eject out materials to be a final 1-km body is counted. Calculation results indicate that the number of moderate CDs with e < 10 and sub-CDs with mixing is most likely to be 2.

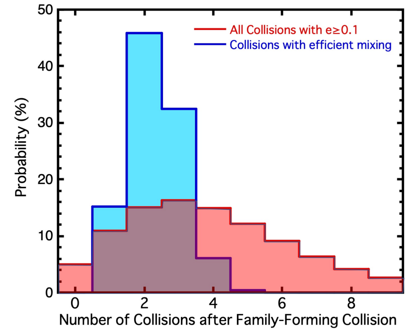

Fig. 4. Histogram for all collisions with e > 0.1 (red) and for collisions excluding with sub-CDs if materials to be a final 1-km body stays in the largest clump (blue).

Implications for Collision Histories: The calculations yielded an important implications for collisional evolution of Ryugu and Bennu.

(1) Oblique collisions (> 50º) of smaller impactors (q > 16) can reproduce a low mixing ratio ~10^{-6} – 10^{-5} on Ryugu, while near-head-on collisions can reproduce a high mixing ratio ~10^{-4} – 10^{-3} on Bennu. (2) Most clumps from a family-forming CD would experience one or two subsequent CDs or sub-CDs before they become ~1 km. (3) The observed difference in mixing ratios between Ryugu and Bennu is difficult to reproduce with a single CD on the same parent body assuming that the trend seen in our calculations holds at super high resolutions. Ryugu and Bennu may have originated either from two different parent bodies or from the same parent body via multiple CDs. (4) The Monte Carlo calculations show that the most probable number of CDs and sub-CDs including the family forming CD is two, which coincides with the number of spectral types of bright boulders on Ryugu [15].

In conclusion, our results indicate that possible exogenic boulders may retain information on complex collisional histories of Ryugu and Bennu, making search for impactor fragments in samples from these bodies more important.

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