DISRUPTED BOULDERS ON THE SURFACES OF NEAR-EARTH ASTEROIDS BENNU, RYUGU, AND DIMORPHOS. R.-L. Ballouz[1], O.S. Barnouin[1], R.T. Daly[1], C.M. Ernst[1], S. Sugita[2], K.J. Walsh[3], M. Pajola[4], A. Lucchetti[4], S. Raducan[5], M. Jutzi[5], S.R. Schwartz[6], S. Cambioni[7], E. Asphaug[8], M. C. Nolan[8], T. Kohout[9]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, ronald.ballouz@jhuapl.edu, [2]University of Tokyo, Tokyo, Japan, [3]Southwest Research Institute, Boulder, CO, USA. [4]INAF, Padua, Italy, [5]University of Bern, Bern, Switzerland, [6]Planetary Science Institute, Tucson, AZ, USA. [7]MIT, Cambridge, MA, USA, [8]LPL, University of Arizona, Tucson, AZ, [9]University of Helsinki, Helsinki, Finland.

Introduction: Spacecraft exploration of small near-Earth asteroids (NEAs) have revealed the rubble-pile nature of these small objects. The arrival of the OSIRIS-REx and Hayabusa2 spacecraft to the C-complex asteroids Bennu (490-m-diameter) and Ryugu (900-m-diameter), respectively, came with the surprise discovery of surfaces dominated by large boulders [1, 2]. The boulder-rich surfaces of Bennu and Ryugu provided an opportunity to study in detail the constituent building blocks of rubble pile asteroids. The detailed study of the boulder populations on both asteroids have led to insights into their thermal and physical properties and the dynamical and surface evolution of their host asteroids [3-5].

The combined census of boulders and craters on Bennu showed that boulders effectively armor the surface against impacts, frustrating the formation of small (<~ 2 m) craters [6]. The effect of the armoring process is also evident in high-resolution images of small craters formed on the surfaces of Bennu boulders [3]. Here, we present evidence for *in situ* collisional processing of boulders across C- and S-complex NEAs. These observations inform our understanding of regolith development on small solar system bodies.

Collisionally Processed Boulders on NEAs: We first focus on boulders that appear to have been collisionally disrupted on the asteroids Bennu and Ryugu. We leverage the high-resolution images and altimetry data from OSIRIS-REx to better understand the boulder disruption process on the surfaces of NEAs in general. We are working towards establishing guidelines that will facilitate the identification of collisionally processed boulders on the surfaces of asteroids that may not be as well characterized as the targets of sample return missions. Then, we apply our set of preliminary guidelines to a candidate disrupted boulder on the surface of 160-m-diameter Dimorphos, the target of NASA's DART mission and binary companion of the S-type NEA Didymos.

***Bennu Observations*:** For Bennu, we used high-resolution PolyCam images with global coverage (>5 cm/px), returned by OSIRIS-REx, projected on to a shape model of Bennu using the Small Body Mapping Tool (SBMT) [7]. Candidate disrupted boulders are identified by the appearance of an impact feature, such as a crater that is as large as the boulder itself, the presence of clear cleavage planes, and through-going fractures. Fig. 1a-c shows a prominent example of a disrupted boulder candidate on Bennu that is located at the center of a 128-m-diameter crater that has a depth-to-diameter ratio of 0.06 [8]. This particular case may be an example of a catastrophic impact onto a large (>20m) diameter boulder that disrupted the boulder while still forming an under-lying crater [9]. If so, the impactor was likely > ~0.5 m based on the estimated strength of Bennu boulders [3].

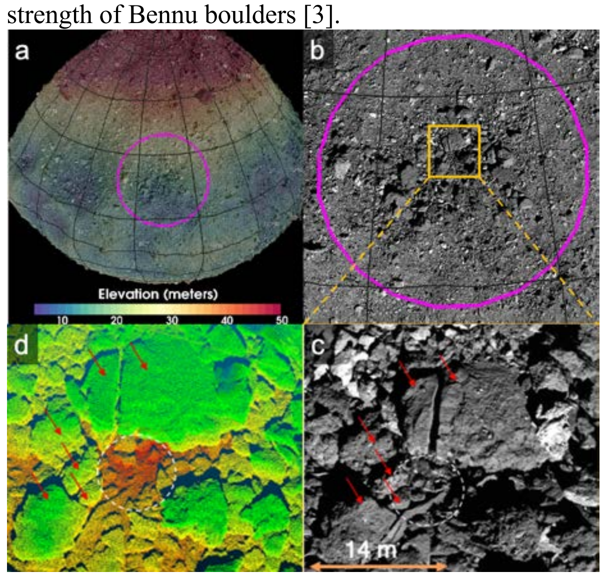

Figure 1. Example of a candidate disrupted boulder on Bennu located at the center of a 128-m-diameter crater (21ºN,189ºE) shown as a magenta circle on a basemap [10] projected on to the Bennu shape model [7] (**a**&**b**). **c,** PolyCam image of the candidate disrupted boulder, identified by radial concentric through-going fracture pattern. **d**, OLA DTM of **c**, revealing a central pit (red=lowest point) at the point of origin of the radial fractures. Red arrows in **c** and **d** highlight the same fragments in each panel.

Follow-up morphological characterization of these candidate disrupted boulders was made using topographic data returned by the OSIRIS-REx Laser Altimer (OLA), which surveyed Bennu at 2 cm ground-sample distance. OLA-based digital terrain models (DTMs) were created for each disrupted boulders in order to verify the nature of the disrupted boulder by measuring and identifying the aforementioned characteristics, such as the presence of a crater or depression, inter-boulder radial through-going fractures originating from the depression, and the number and size frequency distribution of fragments. Fig. 1d shows an OLA DTM of the same candidate disrupted boulder as in Fig. 1c.

***Ryugu Observations*:** For Ryugu, we performed a similar search for disrupted boulders, using our aforementioned process. We used high-resolution ONC-T images taken during proximity and sampling operations of Hayabusa2 projected onto a SPC shape model of Ryugu [4] using SBMT. The ONC-T images that have ground sample distances of 18 and 29 cm/px, which cover ~ 40% and 19% of Ryugu's surface, respectively, supplemented by ONC-T images (> 1mm/px) taken during descents by the Hayabusa2 spacecraft for sampling and small sat deployment. Fig. 2a,b show examples of candidate disrupted and cratered boulders found on the Ryugu. In Fig. 2a, radial through-going fractures separate the fragments, while Fig. 2b shows a single coherent boulder with radial concentric fractures on the boulder surface. These two examples may be suggestive of an evolutionary path for boulder fragmentation on asteroids, where: i) an impact generates widespread fractures and flaws within the target (Fig. 2b), and ii) subsequent processing by a lower strain-rate process (e.g., thermal fatigue [11]) allows for the complete fracturing of the boulder, while allowing the fragments to be retained on a micro-gravity surface.

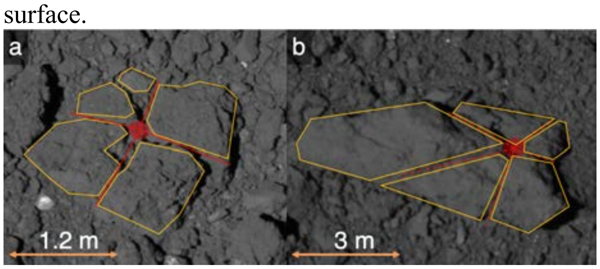

Figure 2. Candidate disrupted and cratered boulders on Ryugu. **a**, 2.5-m-diamter disrupted boulder (5N, 310E) exhibiting through-going concentric radial fractures (red solid lines) from a central point (red circle) separating fragments (orange polygons). **b**, 7.6-m-diameter cratered boulder (5.5N, 330E) with radial concentric fractures (red dashed lines) that separate a coherent boulder into segments (orange polygons).

***Dimorphos Observations*:** We apply our knowledge of boulder disruption on asteroid surfaces, as informed by Bennu and Ryugu data, to the surface of Dimorphos (Fig. 3a), the target of NASA's DART mission [12]. We use images returned by DART's Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO). DRACO images of Dimorphos with pixel scales between 6-50 cm/px were used to search for disrupted boulders candidates. These resolved images cover ~23% of the surface of Dimorphos. So far, we have identified one candidate disrupted boulder on Dimorphos, shown in Fig. 3b. The cluster of boulders resembles that seen in Fig. 1&2 on Bennu and Ryugu, with indications of a radial through-going fracture pattern originating at the center of the cluster, and fractures on the surface of the individual fragments. We measured the sizes of the individual boulders that make up the cluster, and find a size-frequency distribution (SFD) that resembles that of some catastrophic disruption simulations [13]. The largest boulder has approximately half the total volume of the cluster, and the SFD of the remaining fragments can be described by a power law with a cumulative SFD slope of -1.5 in volume. In situ collisional disruption of boulders, such as in Fig. 3, may explain the scarcity of craters on Dimorphos [14], suggesting an effective armoring process on its surface.

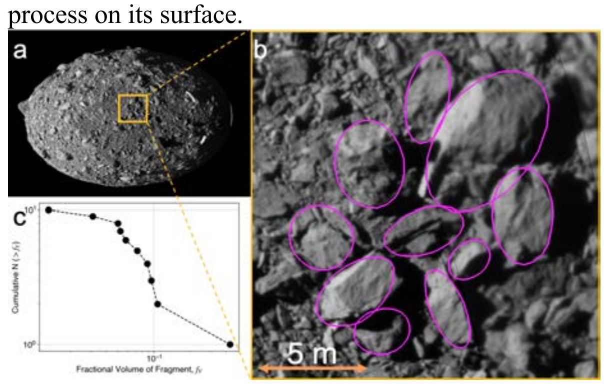

Figure 3. A cluster of boulders on Dimorphos (**a**) identified as candidate disrupted boulder. **b**, The fragments (magenta ellipses) exhibit morphological patterns similar to that identified on candidate disrupted boulders on Bennu and Ryugu (Fig. 1&2). **c,** The fragment SFD is reminiscent of that found in numerical simulations of catastrophic disruption [13].

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