BOULDER CLASSIFICATION ON BENNU BASED ON MORPHOLOGY AND ALBEDO. Erica R. Jawin[1,2], T.J. McCoy[2], A.J. Ryan[3], H.H Kaplan[4], R.-L. Ballouz[5], K.J. Walsh[6], D.N. DellaGiustina[3], J.P. Emery[7], V.E. Hamilton [7], L.E. Melendez[2], H.C. Connolly Jr.[3,8], O.S. Barnouin[5], C.A. Bennett[3], J.L. Molaro[9], M. Pajola[10], D.R. Golish[3], B. Rizk[3], D.S. Lauretta[3] [1] Smithsonian National Air and Space Museum, Washington DC (jawine@si.edu). [2] Smithsonian National Museum of Natural History, Washington, DC, [3] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, [4] NASA Goddard, Greenbelt, MD, [5] Johns Hopkins Applied Physics Laboratory, Columbia, MD, [6] Southwest Research Institute, Boulder, CO, [7] Northern Arizona University, Flagstaff, AZ, [8] Department of Geology, School of Earth and Environment, Rowan University, Glassboro, NJ, [9] Planetary Science Institute, Tucson, AZ, [10] INAF - Astronomical Observatory of Padova, Padova, Italy

Introduction: NASA's OSIRIS-REx sample return mission is investigating asteroid (101955) Bennu [*1*] and is currently in the process of returning a sample of the asteroid to Earth, scheduled to arrive in 2023. Preliminary analyses upon arrival at Bennu found that it is a rubble-pile asteroid [*2*] containing hydrated materials [*3*], implying Bennu formed from a disrupted "parent body" which experienced extensive aqueous alteration. It was immediately obvious that Bennu is covered in thousands of boulders varying in size from under a meter to over 90 m which vary in morphology, size, and albedo [*4*, *5*], characteristics which were inherited from the parent body (or potentially bodies).

Further investigation found that boulders could be sorted into at least two populations based on normal reflectance: "dark boulders" (less than Bennu's median reflectance, 0.049) and "bright boulders" (brighter than the global median reflectance) [*6*]. Analyses of thermal data found variations following the same pattern, where dark boulders have low thermal inertia (~180 to 250 J m^{-2} K^{-1} $s^{-1/2}$) and inferred density and strength, while bright boulders have higher thermal inertia (~400 to 700 J m^{-2} K^{-1} $s^{-1/2}$), density, and strength [*7*]. Additionally, spectral analyses identified certain bright boulders containing bright veins or speckles to be associated with spectral signatures of carbonates [*8*].

These results suggest albedo is a major discriminator between boulders with distinct properties, and initial analyses suggest morphology is also a distinguishing factor between the bright and dark boulders [*6*, *7*]. We therefore examine how boulder morphology varies and use it to develop a classification scheme for boulders on Bennu. We then perform an analysis of albedo for boulders of different morphologic types to integrate our results with those of previous studies. These observations are useful in interpreting the diversity and structure of Bennu's parent body.

Data and Methods: We first analyzed all boulders >15 m in diameter (N=83), then analyzed a subset of the largest bright boulders (N=42), which are all between 7 and 12 m. Morphologic analyses were performed on radiometrically calibrated PolyCam images with a pixel scale of ~1–4 cm. We then quantified albedo using normal albedo maps from PolyCam and MapCam [*6*, *9*].

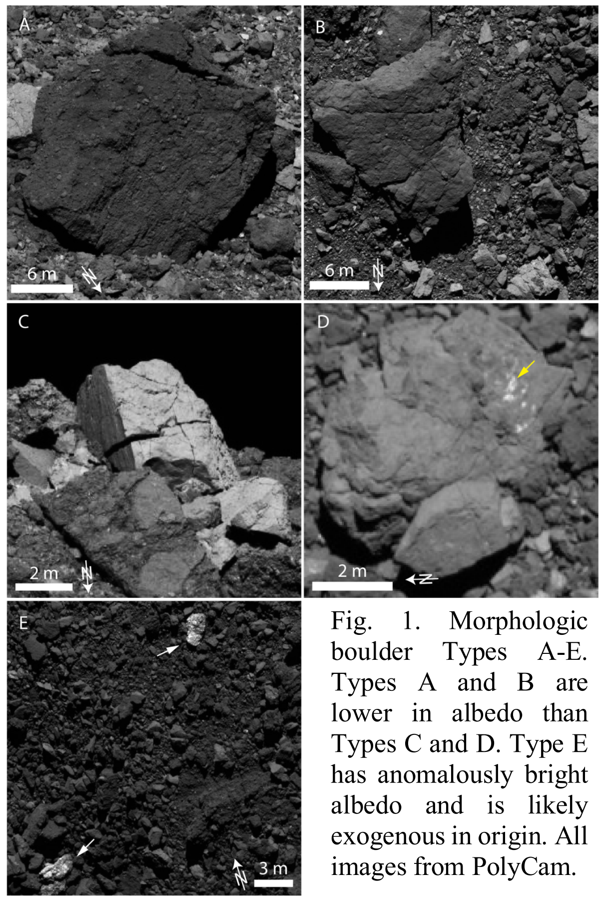

Fig. 1. Morphologic boulder Types A-E. Types A and B are lower in albedo than Types C and D. Type E has anomalously bright albedo and is likely exogenous in origin. All images from PolyCam.

Boulder Classification: We find that boulder morphologies tend to group into several categories, which we denote as Type A, B, C, D, and E (**Fig. 1**).

Type A: These boulders are dark toned with a hummocky surface texture and abundant clasts ~tens of cm large in a darker host matrix (**Fig. 1A**). Layering is present in many Type A boulders on the scale of tens of cm. 57% of boulders >15 m diameter are Type A, including Roc Saxum, the largest boulder on Bennu.

Type B: These boulders are intermediate in tone with an undulatory surface texture smoother than Type A and intersecting networks of polygonal fractures (**Fig. 1B**). Layering and clasts are rarely observed. 24% of boulders >15 m are Type B, including Benben Saxum.

Type A, A/B, B*:* 34% of boulders >15 m contain exposures of both Type A and B materials. Boulders that are approximately half A and B are labeled as Type

A/B, whereas a boulder with a dominant type (either A or B), with localized exposures of the other, is given a * designation. Most contacts between Type A and B are consistent with thin coatings of Type B material on the exterior of Type A boulders—although several boulders contain Type A and B material in discrete layers.

Type C: Within the population of bright boulders, 79% are angular with smooth surface texture, distinct fractures, and no visible clasts (**Fig. 1C**). The largest bright boulder is 12 m diameter, and as such no Type C boulders were found in the population >15 m.

Type D: The remaining 21% of bright boulders were slightly more rugged than Type C boulders with no visible clasts, but they contain small bright exposures (**Fig. 1D**). These boulders with bright exposures are consistent with the carbonate-bearing boulders of [*8*].

Type E: Several small (~1.5-4 m), anomalously bright boulders (13σ to 40σ above the mean) have been identified and determined to be exogenous in origin [*10*] (**Fig. 1E**). They vary morphologically but contain spectral signatures consistent with anhydrous silicates [*11*]. We did not perform an independent analysis of these boulders but refer the interested reader to [*10*, *11*].

Albedo: Morphology and albedo appear to be linked, as found by previous analyses (**Fig. 2**). The largest boulders on Bennu include only Type A and B (and A*, A/B, B*) and have albedos similar to average Bennu or darker. In contrast, the brightest boulders include only Type C and D, and do not contain any Type A or B morphologies. It is unclear if any morphologic overlap occurs in the albedo range between ~0.045 to 0.053, although this analysis is ongoing through an analysis of a large number of smaller boulders using very high-resolution data taken during the Recon phase of the mission. Normal albedo data from MapCam and PolyCam show good agreement, with $R^2 = 0.95$.

Implications for the parent body: The morphology and other characteristics of boulders can be used to determine their potential source regions on the parent body. Type A boulders are morphologically rugged, clastic, and layered, and thermal data suggest they have low thermal inertia, high porosity, and low density [*7*]. These data are consistent with Type A boulders being impact breccias, requiring they formed at or near the surface of the parent body (where impact processes dominate). Conversely, investigations are ongoing to determine whether these boulders could instead be formed via sediment deposition [*12*]. Type B boulders contain the distinct texture of intersecting polygonal fractures, reminiscent of a desiccated mud which may have been derived from impact heating and/or radiogenic heating in the first few Myr after Solar System formation. The close contacts between Type A and B boulders (in the form of A*, A/B, and B* boulders) suggest they formed in close contact on the parent body, implying that Type B boulders also formed

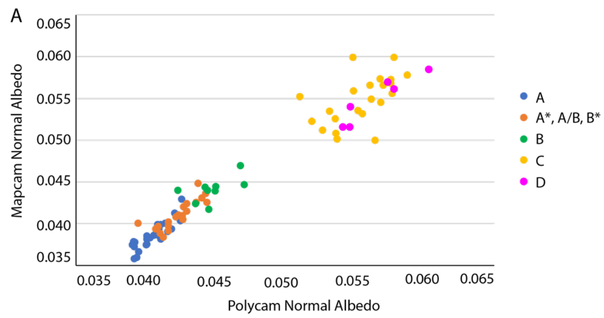

Fig. 2. Normal albedo of boulders. Albedo data from PolyCam and MapCam both show variation with morphologic type.

at or near the surface. The largest Type A boulder (Roc Saxum) is ~100 m diameter, which places a minimum on the depth of the brecciated zone of the parent body.

Type C and D boulders do not have any resolvable clasts, and thermal data suggest they are stronger, with lower porosity and higher thermal inertia [*7*], which suggests they originated beneath the brecciated zone of the parent body. The presence of carbonates in Type D (and potentially Type C) boulders requires a secondary period of aqueous alteration to have occurred in the region hosting these boulders, and that this alteratoin did not extend to the Type A and B regions (as Types A and B do not contain spectral evidence of carbonates). The Type C and D boulders therefore must have formed deeper than at least 100 m in the parent body, but potentially km deep in a ~100-km diameter parent body.

It is also possible that Bennu is formed of material from more than one parent body, and/or contains fragments of the impactor that destroyed the parent body. However, there is no spectral indication that the hydration band minimum position or depth is different for bright or dark boulders on Bennu that would indicate different parent bodies. We therefore favor a model of a single, heterogeneous parent body that was widely sampled during the catastrophic impact. Boulders generated by geologic processes of impacts and aqueous alteration at different depths in the parent body were fragmented and eventually coalesced into the rubble pile Bennu. Our analysis results in several hypotheses about the nature and diversity of the returned sample.

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