

THE GEOLOGY OF (101955) BENNU FROM THE FIRST YEAR OF OSIRIS-REX OBSERVATIONS: DIVERSE BOULDERS AND RECENT MASS MOVEMENT. Erica R. Jawin¹, K.J. Walsh², T.J. McCoy¹, H.C. Connolly Jr.^{3,4}, A.J. Ryan⁴, R.-L. Ballouz⁴, D.N. DellaGiustina⁴, C.A. Bennett⁴, O.S. Barnouin⁵, J.P. Emery⁶, V.E. Hamilton², E.B. Bierhaus⁷, M.G. Daly⁸, M. Delbo⁹, J.L. Molaro¹⁰, M.C. Nolan⁴, J. Marshall¹¹, C. Beddingfield¹¹, M. Pajola¹², M.E. Perry⁵, B. Rizk⁴, D.J. Scheeres¹³, S.R. Schwartz⁴, B.E. Clark¹⁴, and D.S. Lauretta⁴, ¹Smithsonian Institution NMNH, Washington, DC (jawine@si.edu), ²Southwest Research Institute, Boulder, CO, ³Rowan University, Glassboro, NJ, ⁴Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, ⁵Johns Hopkins University Applied Physics Laboratory, Laurel, MD, ⁶Northern Arizona University, Flagstaff, AZ, ⁷Lockheed Martin Space, Littleton, CO, ⁸York University, Toronto, Canada, ⁹Laboratoire Lagrange, Nice, France, ¹⁰Planetary Science Institute, Tucson, AZ, ¹¹SETI Institute, Mountain View, CA, ¹²INAF - Astronomical Observatory of Padova, Italy, ¹³University of Colorado, Boulder, CO, ¹⁴Ithaca College, Ithaca, NY.

Introduction: NASA's OSIRIS-REx sample return mission has been investigating the B-type near-Earth asteroid (101955) Bennu [1] for the past year. Preliminary analyses showed that Bennu is a rubble-pile asteroid [2] that contains globally distributed hydrated materials [3]. Analyses of the global geology found impact craters and abundant boulders that varied in morphology, degree of burial [4], size and albedo [5]. These observations informed the selection of a primary and backup sample site, and sample collection is expected in August 2020. It is a mission priority to collect a sample of surface regolith to address fundamental scientific questions about the origin and evolution of Bennu.

This work summarizes progress made in understanding the global geology of Bennu over the past year. Two areas of focus include (i) analyses of boulder morphology to create a boulder classification scheme and (ii) documentation of global mass movement.

Boulder Classification: Analyses of global trends of boulder properties led to the creation of three morphologic groups—Type A, B, and C.

Type A boulders are dark-toned, hummocky, rounded, and have a clastic appearance (Fig. 1A). Clasts in Type A boulders are around ~10 cm in diameter. Type B boulders are intermediate-toned, smoother than Type A (but still have a rough, undulatory texture), rounded, and only rarely contain visible clasts (Fig. 1B). Type B boulders can contain exposures of Type A material underneath Type B material, suggesting the Type B texture could be a surficial rind or coating. Type C boulders are distinctly light-toned, smooth, angular, and contain no visible clasts (Fig. 1C). Type C boulders contain distinct fractures and pits, and the largest documented Type C boulder (~10 m) is much smaller than the largest A or B (~100 m and ~50 m).

Mass Movement: Morphologic evidence of mass movement was found to be globally distributed (Fig. 2). Several types of mass movement were identified including burial of upslope boulder faces by unresolved particles (and excavation of downslope faces), individual resolved boulders sitting on top of other boulders (“rocks on rocks”), and various examples of particle organization (imbrication, size sorting, long axis alignment).

All mass movement appears to be consistent with downslope movement according to the current slope distribution [6]. In the mid-latitudes movement is entirely towards the equator, and within the equatorial region movement is less ordered. Boulders may be the dominant mobile component, as accumulations of boulders are found in topographic lows.

The largest boulders on Bennu (>30 m) are buried to different degrees. In the equatorial regions large boulders are almost completely buried, while in the mid-latitudes up to tens of meters of surface relief are present. This observation, coupled with an unequal distribution of large boulders between the mid-latitudes and equator [5], suggests that large boulders are being exhumed in the mid-latitudes and buried in the equatorial region, presumably due to mass movement. The average maximum surface relief of these large mid-latitude boulders is ~9 m, which could correspond to the amount of surface deflation that has occurred in the mid-latitudes due to mass movement. The removal of several meters of

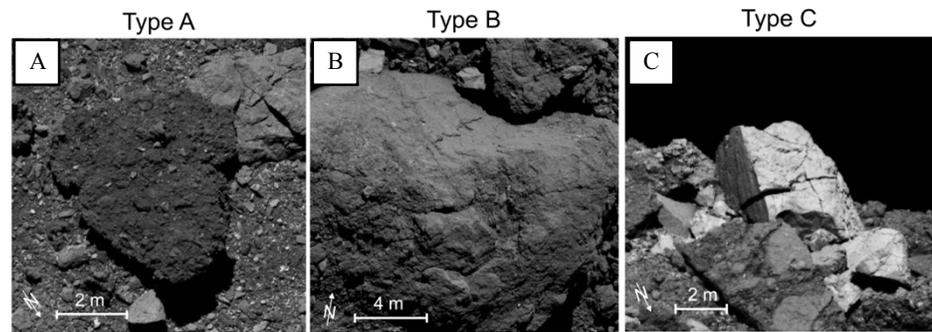


Figure 1. Examples of boulders from each group. (A) PolyCam image 20191012T220348S866. (B) PolyCam image 20191005T193302S098. (C) PolyCam image 20190412T174942S616.

material from the mid-latitudes and deposition in the equatorial region could have contributed to the construction of the equatorial ridge.

Discussion: Boulder Formation. Properties of boulders in the three groups can inform our understanding of their formation and evolution. The clastic texture of Type A boulders suggests they are impact breccias that most likely formed on the parent body, due to the energies required for brecciation [e.g., 7]. Brecciation would have been enhanced at or near the surface of the parent body, so we infer that Type A boulders could be regolith breccias. Type B boulders appear similar to Type A but with brighter, smoother surfaces, and the Type B material could be a rind or coating on Type A boulders. Processes such as micrometeorite bombardment could smooth the hummocky Type A boulders into a Type B morphology, given sufficient exposure at the surface. Variable exposure ages on the surface of Bennu could explain the difference in appearance and distribution of Type A and B boulders. Type C boulders do not contain visible clasts and appear more competent than Type A and B boulders. Type C boulders may therefore have originated deeper in the subsurface of the parent body than Type A boulders, where impact fragmentation and brecciation were less enhanced. The presence of Type C boulders on Bennu suggests that the disruption and reaccumulation events sampled different depths of the parent body and these materials are well-mixed on Bennu (as is also speculated on Ryugu [8]).

Era of Mass Movement. The current slope distribution is set by the spin period, and all documented locations of mass movement are in the local downslope direction—this suggests that the visible era of mass movement has occurred recently (during the present spin-period regime). Predictions of past spin-up (from 5 to 4.3 hr period) show where dynamic slopes would have

changed in the past—analyses of these slope changes show that mass movement has occurred in the mid-latitudes in regions with moderate slope increases ($\sim 5^\circ$ increase). These data suggest that mass movement has occurred globally on relatively recent timescales.

Comparison to Ryugu. Boulder morphologies and mass movement trends are similar in many ways to those found on Ryugu [8]: boulder morphologies on both asteroids include dark, hummocky, rounded boulders and bright, smooth, angular boulders. In addition, evidence of mass movement on both bodies includes partially buried large boulders and mass movement into crater interiors. However, differences are also present. There is no analogue for the weathered Type B morphology on Ryugu, suggesting differing exposure ages or weathering pathways for boulders on the two asteroids. In addition, different geopotentials have led to opposite directions of mass movement: towards the equator on Bennu, and away from it on Ryugu.

Conclusions: Continued geologic analyses of Bennu have led to improved understanding about the evolution of the surface, as well as the nature of the parent body. Upcoming sample collection in mid-2020 and later laboratory analyses will further inform our understanding about boulder diversity and exposure age.

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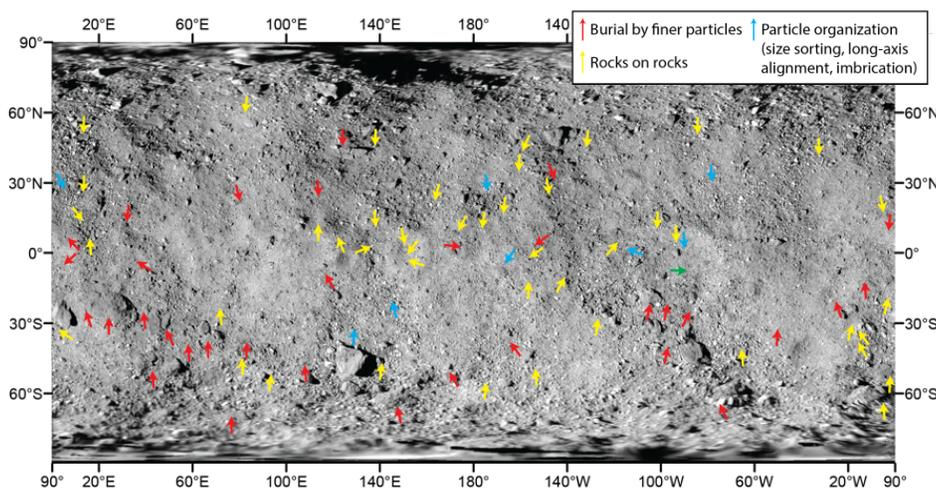


Figure 2. Documented locations of mass movement and inferred direction of movement. Basemap is the global mosaic from [5].