THE FREQUENCY OF PUTATIVE FALLBACK PARTICLES ATOP BENNU'S FIELDS OF BRECCIATED BOULDERS. B. Rizk[1], M. Pajola[2], K.J. Walsh[3], E.B. Bierhaus[4], D.N. DellaGiustina[1], C. Y. Drouet d'Aubigny[1], D.R. Golish[1], E.R. Jawin[5], M. Delbo[6], R.-L. Ballouz[1], J.L. Molaro[7], C.A. Bennett[1], K.N. Burke[1], P. Michel[6], L. Lim[8], J.P. Dworkin[8], H. Campins[9], H.C. Connolly, Jr.[10,1], T.J. McCoy[5], M.G. Daly[11], M.C. Nolan[1], D.S. Lauretta[1], [1]Lunar and Planetary Laboratory, 1415 N. Sixth Ave., University of Arizona, Tucson, AZ, USA 85705, (bashar@LPL.arizona.edu), [2]INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy, [3]Southwest Research Institute, Boulder, CO, USA, [4]Lockheed-Martin Space Systems, Littleton, CO, USA, [5]Smithsonian Institution, National Museum of Natural History, Washington, DC, USA, [6]Observatoire de la Côte d'Azur, Nice, France, [7]Planetary Science Institute, Tucson, AZ, USA, [8]NASA Goddard Space Flight Center, Greenbelt, MD, USA, [9]University of Central Florida, Orlando, FL, US, [10]Department of Geology, Rowan University, Glassboro, NJ, USA, [11]York University, Toronto, Canada

Introduction: Cobbles and pebbles perched on boulder surfaces that exhibit orientations and albedos divergent from the underlying boulder's texture and brightness is a novel feature of Bennu's boulder diversity. This phenomenon, dubbed 'rocks-on-rocks' by the mission team, has been recorded by the OSIRIS-REx Camera Suite (OCAMS) PolyCam and MapCam imagers since high-resolution imaging began in early 2019 [1][2][3][4]. Here, we interpret their origin as either (a) inclusions revealed by weathering or (b) externally sourced material that has landed on the boulder surface as particulate fallback. Bennu's surface geology supports both possibilities (Figure 1, A and B). The two phenomena may be related if ejection of particles from one boulder provides the source material for another boulder's fallback. The latter interpretation is recently motivated after particles ejected from Bennu's surface were observed to fall back to the asteroid's surface [5]. Here, we report a preliminary census and salient observations about putative fallback particles relative to exhumed inclusions with a goal of constraining both particle ejection and exhumation mechanisms.

Classification: Based on our counts, roughly two-thirds of boulders on Bennu are dark, brecciated, seemingly friable, and host inclusions. Many of these boulders are strongly weathered and exhibit clast shedding at various stages of completion (Figure 2, A-H). The texture of these cauliflower-like boulders appears to amalgamate brighter, angular, harder clasts within a darker, softer matrix. A set of several thousand high-resolution images—gathered mostly during the Orbital A and Orbital B global campaigns—has captured this process at various stages of its life cycle. Paradoxically, such extensive fragmentation makes it challenging to positively identify potential fallback particles.

We employed 8 criteria, [6], that analyzed weathering, reflectance, shadowing, alignment, morphology, discoloration, clustering and proliferation in order to

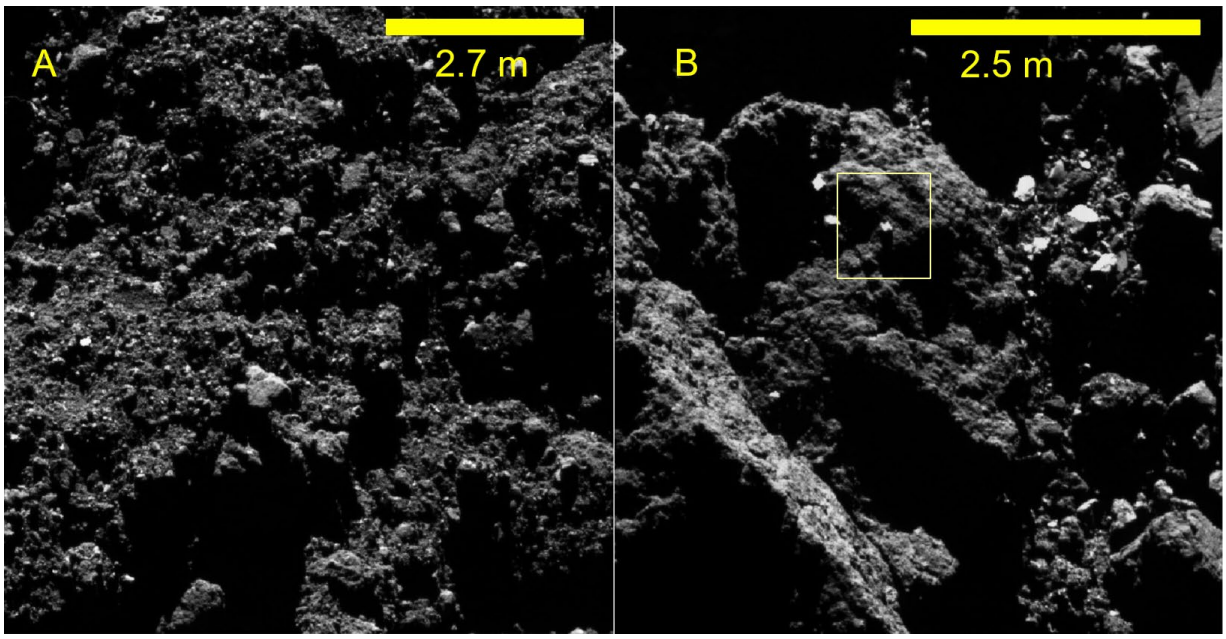

Figure 1: A) INCLUSION: A PolyCam image from July 3, 2019 (20190703T020207S725_pol, scale = 0.0087 m/pixel, (lon, lat) = 176, –83°) provides numerous examples of evident inclusions (typically brighter clasts embedded within or in the process of leaving the underlying boulder matrix). B) FALLBACK: A PolyCam image from July 15, 2019 (20190715T035524S809_pol, scale = 0.018 m/pixel, (lon,lat) = 4, –79°) shows what is evidently an externally sourced 10-cm-sized cobble lying on top of a boulder. Both images were acquired at 90° phase angles. This image pair demonstrates the occasional difficulty of the classification. Both boulders exhibit the roughened, cauliflower-like texture that characterizes many of Bennu's boulders. Brightness disparity, shadowing characteristics, matrix alignment and weathering context between putative inclusion or fallback cobble and underlying boulder contribute to the categorization.

divide candidate fallback and inclusions into either category. We estimated that in a sampling of almost 5000 meter-to-several meter–sized boulders some 5%, or almost 250 boulders, host pebbles and cobbles that could be classified as fallback particles. The rest—or 95%—host evident inclusions, i.e., clasts that began life embedded within the underlying boulder matrix and are now mechanically separated.

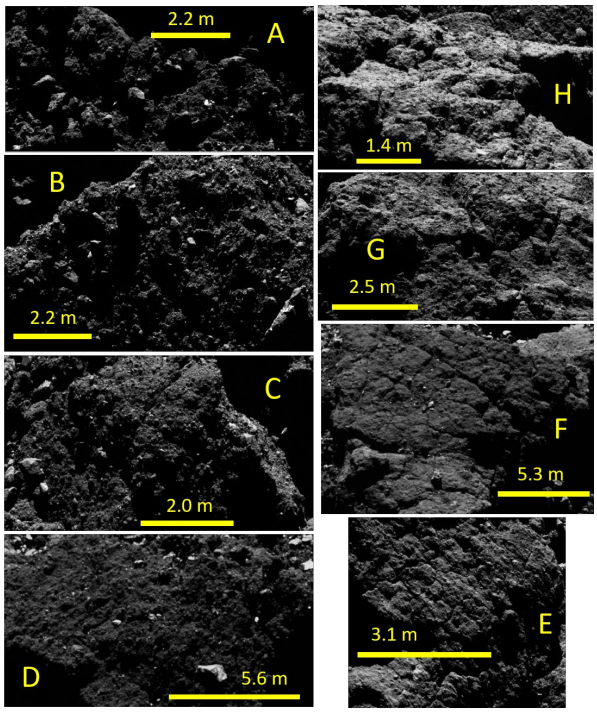

Figure 2: High-resolution high-phase-angle PolyCam images displayed in order of decreasing exhumation, clast shedding and textural weathering CCW starting from upper left. Image information [name, phase angle, scale (cm/pix), lon, lat & CW angle to North direction(°)]: A) 20190711T092848S026_pol, 90.6, 0.9, 221, -82, 278, B) 20190718T081041S737_pol, 90.7, 0.9, 108, 69, 83, C) 20190802T095005S980_pol, 84, 0.9, 212, 23, 269, D) 20190227T060627S854_pol, 93, 1.9, 257, -24, 92, E) 20190713T101830S351_pol, 88, 0.9, 258, -40, 87, F) 20190225T200127S887_pol, 92, 2.4, 120, 52, 286, G) 20190715T002243S946_pol, 91, 1.0 130, -46, 271, H) 20190711T124030S145_pol, 88, 0.9, 122, -47, 85

An Active Asteroid: One of the most exciting discoveries at Bennu, in its status as both a carbonaceous and a microgravity body, has been its evidently still active geology [5]. Several physical mechanisms seem plausible enough to be considered as capable of ejecting particles from Bennu's surface: micrometeoroid impacts, thermal cracking and abrupt pressure release from phyllosilicate dehydration ([7][8][9][10][11]). Images of evident micrometeoroid impacts are recorded in smooth boulder faces all over Bennu [7]. Images of cracking, both linear and network-like, abound [8]. And many of the darker boulders show pits that match the shape of nearby cobbles and grains that may have started out as clasts within these same boulders. These observed morphologies support the above mechanisms—micrometeoroid impact, thermal cracking and abrupt bound-water-driven release—respectively. The signature of electrostatic lofting has not been observed, despite searches during the Detailed Survey Equatorial Station campaigns of May 2-3 & 30, 2019, but the observation is a difficult one, and there is yet no observational reason to discount this mechanism.

In addition, all of these mechanisms may act in concert. For example, thermal stress may prepare a boulder to explosively release its clasts when struck by a micrometeoroid or may lower the pressure required to abruptly decompose a boulder [5]. Decomposing boulders could be more likely to retain fallback particles because their pitted, cracked surface provides more mechanical purchase for the particles to cling. In addition, the presence of externally-sourced clusters of particles may indicate that the process of impact (or ejection) fragments the external particles.

We hope to provide support for one or more of these, or any other, mechanisms in the observations of the morphologies of the putative fallback particles.

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