EPSC Abstracts
Vol. 13, EPSC-DPS2019-105-1, 2019
EPSC-DPS Joint Meeting 2019

EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

Exposed inclusions or fallback? A closer look at Bennu's weathered boulders

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Preliminary observations of Bennu by the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) Camera Suite (OCAMS) [1][2] reveal a diverse geology with multiple craters, surface lineaments, and ubiquitous dark and bright boulders, many of which are fractured [3][4][5]. The asteroid exhibits regional structures, extensive weathering, and brecciation on every size scale yet observed. A size range of 5 to 10 cm diameter is favored in the constituent units of many of the darker boulders, whose texture gives the appearance of a pitted and cellular structure reminiscent of cauliflower [6]. Most boulder matrixes on Bennu have this property, while those with a smoother, finer-grained texture appear to be in the minority.

Through 2- to 6-cm/pixel images obtained between February and April 2019 during the Detailed Survey Baseball Diamond (BBD) mission phase, it has been possible to observe Bennu's boulders with much higher spatial detail and at a substantially different phase angle (~90°) than images from both previous and subsequent campaigns. A novel feature observed in addition to Bennu's profuse boulder diversity is the presence of cobbles and pebbles perched on the boulders' surfaces in orientations that exhibit no alignment with the underlying boulder's texture. We have interpreted their origin as either (a) inclusions revealed by weathering over geological timescales or (b) externally sourced cobbles/pebbles that have settled upon the boulder surface, guided by Bennu's low gravity. The latter interpretation has been recently motivated after particles ejected from Bennu's surface were observed to fall back to the asteroid's surface [7].

Bennu's rich surface geology appears to support both possibilities (Figure 1, A and B). Based on the criteria listed below, we have assembled and classified a list of apparent inclusions in high-resolution BBD PolyCam and MapCam images as either (a) true inclusions of the underlying boulder, whether exhumed or embedded, or (b) fallback particulates traveling from an external source to the underlying boulder. The criteria we employed to guide our classification include:

1. If the underlying boulder shows little evidence of extensive weathering over the rest of its surface, then it may be more likely that the cobble or pebble is external and not an exhumed inclusion.
2. A strong reflectance disparity between the cobble or pebble and the underlying boulder may be indicative of an external source (i.e., bright fallback and dark inclusions); nevertheless, it is possible to identify inclusions that are brighter than their underlying boulder (Fig. 1A). As in this example, though, the disparity appears to be muted by comparison to the evident bright fallback (Fig. 1B).
3. Considerable shadowing and even shadow overhangs indicating a sharp separation between pebble/protrusion and underlying boulder may be indicative of fallback (Fig. 1B).
4. Alignment of the putative inclusion seems unrelated to that of the boulder matrix (fallback) or aligned with the boulder matrix (weathered inclusion) (Fig. 2).
5. Disparity between neighboring boulders and underlying boulder, especially a strong brightness difference of the inclusion with respect to neighboring boulders.
6. Presence of discoloration or brightness pattern suggests unresolved dust or powder that may be the aftermath of a settling particle shattering event.
7. Cluster of inclusions present on the boulder support the action of a settling particle shattering event.
8. Samples of pebbles and cobbles around the boulder can be evidence of either inclusions (if the underlying boulder shows definitive signs of weathering such as

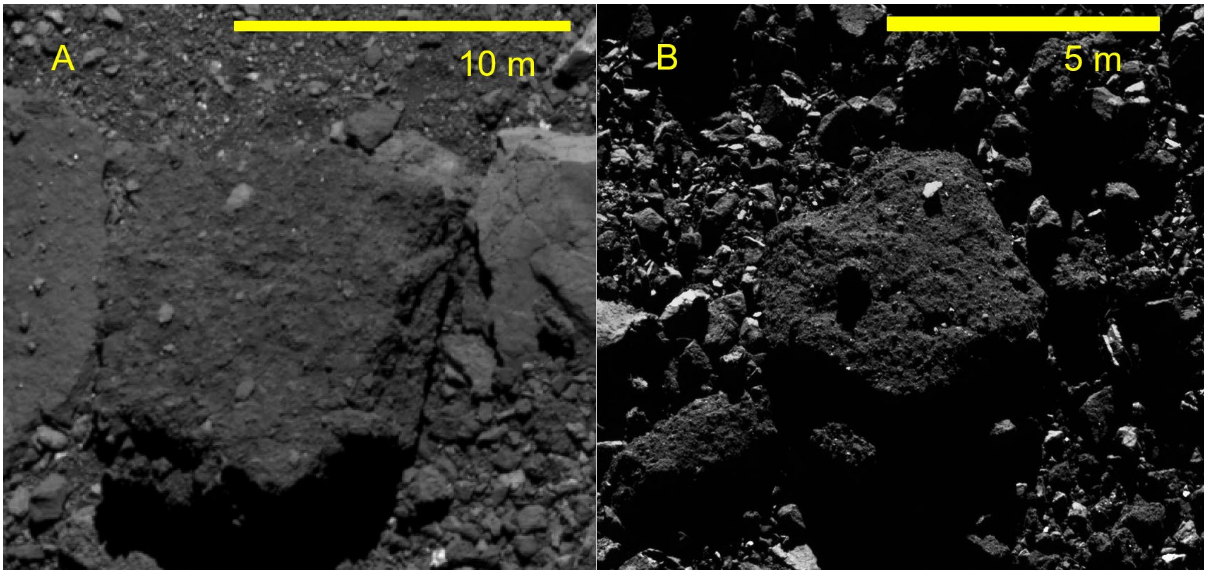

Figure 1: A) INCLUSION: A PolyCam image from April 05, 2019 (20190405T205240S260_pol, phase angle = 37°, scale = 0.038 m/pixel, (lon,lat) = 74, –23°) provides an example of evident inclusions (brighter areas embedded within or in the process of exhuming from the boulder). B) FALLBACK: A PolyCam image from February 24, 2019 (20190224T084628S456_pol, phase angle = 92°, scale = 0.018 m/pixel, (lon,lat) = 237, –70°) shows what is evidently an externally sourced cobble lying on top of a boulder. Both boulders exhibit the roughened, cauliflower-like texture that characterizes most of Bennu's boulders. The different brightness disparities and shadowing characteristics between putative inclusion or fallback cobble and underlying boulders contribute to the classifications.

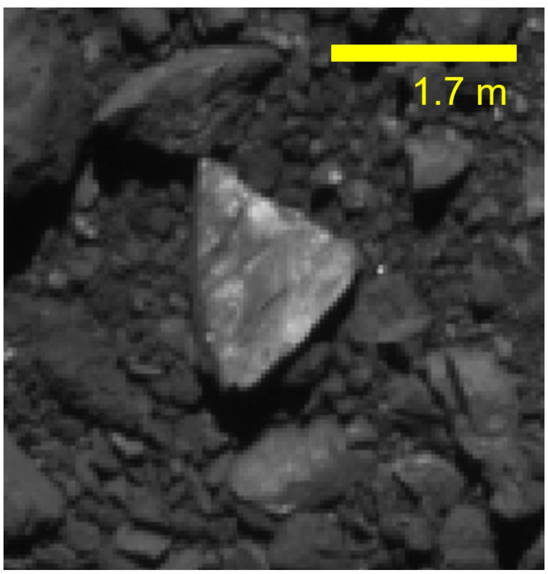

Figure 2: INCLUSION: A PolyCam image from April 05, 2019 (20190405T183058S145_pol, phase angle = 46.7°, Scale = .046 m/pix, (lon,lat) = 273, –29.4°) provides an example of the alignment of evident bright inclusions with the underlying boulder matrix (Criterion 4).

pits and a misshapen appearance) or fallback (if the underlying boulder is smooth).

Of the dozens of examples present in our list, the majority seem to represent weathered inclusions exposed on the surface, but external deposition is evidently responsible for ~10% of initially reviewed cases. This adornment of Bennu's surface may be a general phenomenon of carbonaceous microgravity bodies.

Acknowledgements

This material is based upon work supported by NASA under Contracts NNM10AA11C and NNG12FD66C issued through the New Frontiers Program. Maurizio Pajola was supported for this research by the Italian Space Agency (ASI) under the ASI-INAF agreement no. 2017-37-H.0. Marco Delbo acknowledges support from the Centre National d'Études Spatiales, as well as the Academies of Excellence on Complex Systems and Space, Environment, Risk and Resilience of the Initiative d'EXcellence 'Joint, Excellent, and Dynamic Initiative' (IDEX JEDI) of the Université Côte d'Azur.

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