DETAILED CHARACTERIZATION OF CRATER TYPES AND RELATIONSHIPS TO SURFACE AND SUB-SURFACE STRUCTURE ON BENNU.

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Introduction: Using high-resolution images from the OCAMS imagers [1] and high-resolution lidar scans from the OLA laser altimeter [2] onboard the OSIRIS-REx spacecraft, we provide a novel classification scheme for crater features and morphologies on asteroid Bennu, highlighting characteristics that are different from "classical" craters on larger planetary surfaces. In addition, aspects of crater morphology as a function of diameter provide insights to surface and sub-surface structure on Bennu, with implications for crater formation, crater erasure, and derived crater-retention surface ages.

Background: The first spacecraft exploration of asteroids revealed crater populations and morphologies that bore similarities to those seen on terrestrial surfaces, in particular, bowl-shaped craters (Figure 1). Galileo imaging of asteroids Gaspra and Ida revealed numerous, bowl-shaped craters and evidence of ejecta blankets [3-5]. The NEAR flyby of Mathilde showed multiple, large bowl-shaped craters; although the formation and preservation of multiple large craters was wholly unexpected, their morphologies were nonetheless similar to craters on terrestrial surfaces [6]. The NEAR mission to Eros achieved a global survey of the crater population, and there too found "classical" bowl-shaped morphologies [7].

The Hayabusa mission to Itokawa was the first spacecraft visit to a sub-km asteroid, and the craters observed on this surface are unlike those seen on larger asteroids [8]. Craters are more shallow, raised rims are generally absent, and there is variation in crater shape likely driven by the global shape of Itokawa itself. Comparison of the crater characteristics on Itokawa with larger asteroids suggests the onset of previously unseen dynamics of crater formation and evolution associated with a rubble-pile target.

OSIRIS-REx at Bennu: As of late summer in 2019, the OSIRIS-REx spacecraft completed multiple global surveys of asteroid Bennu, both via relatively close and slow flybys at 5-7 km distance, and from low-altitude orbits, roughly 800 m to 1300 m from Bennu's surface. Data collected during these phases include global imaging and spectroscopy at a variety of viewing and illumination geometries, as well as global OLA coverage. These data enable an unprecedented opportunity to both locate crater features and characterize their morphology, at crater scales from the largest observable on Bennu to sizes less than 1 m.

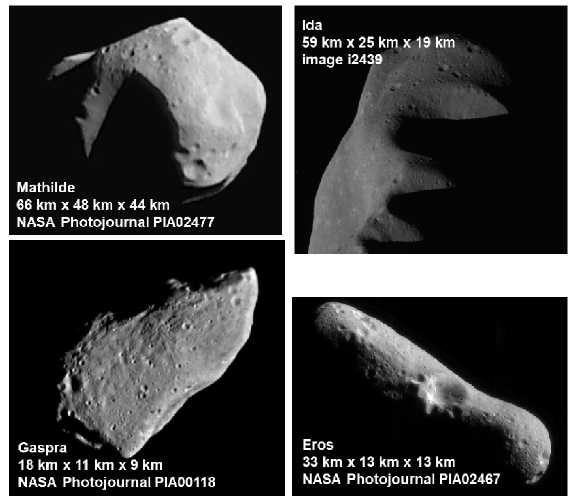

Figure 1. Asteroids with bowl-shaped craters that are recognizable by analogy to simple craters seen on larger planetary surfaces.

Development of Feature Descriptions: Bennu craters share similarities with features observed on Itokawa, larger asteroids, as well as perhaps new characteristics. To capture this variation in crater morphology, we are developing a feature-classification system based on four top-level categories: (1) rim and ejecta, (2) crater floor topography, (3) interior surface roughness relative to surrounding terrain, and (4) albedo and color. For each of these categories, there are several discrete items to consider. For example, when evaluating the rim and ejecta, we assess whether the rim is present in the crater shape itself (i.e. a classical "raised rim"), or if the rim consists of a complete or partial ring of surrounding boulders. For interior surface roughness, we assess both the contrast between the surrounding terrain and the crater interior, as well as the contrast in particle sizes and the smoothness of the interior itself.

Figure 2 shows a ~4 m diameter crater. In this case, the crater received a CRB label (rim composed of boulders), and a CPSS label (particle size smaller inside the crater than exterior to feature).

Figure 3 is another example. Like the crater in Figure 2, the crater rim consists of a ring of boulders.

Most of the resolvable particles inside the crater floor do not cast a shadow, suggesting the crater floor is generally smooth, and that the tops of the resolved particles are level with the crater floor.

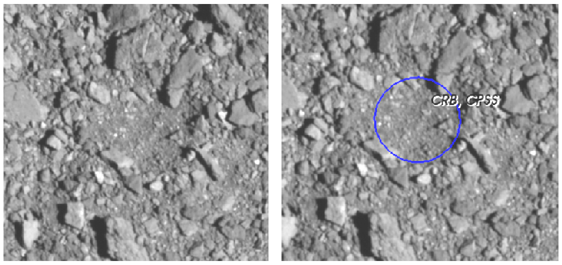

Figure 2. A roughly 4 m crater on Bennu, with a rim of displaced boulders and an interior with particle sizes smaller than the exterior. The left and right images in the figure are the same; the crater is circled in the right hand image.

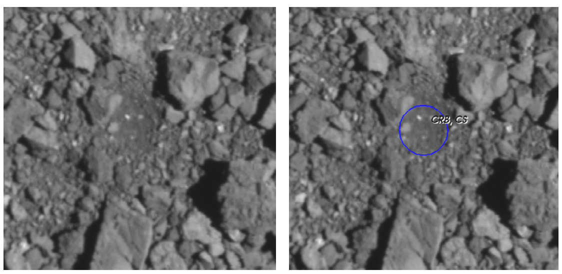

Figure 3. A ~1.6 m diameter crater with a smooth crater floor (most resolvable particles inside the crater floor do not cast a shadow). The left and right images in the figure are the same; the crater is circled in the right hand image.

The best OLA data for detailed topographic analysis, particularly for small craters, comes from the Orbital B mission phase, which is the most recently completed global measurement phase, and thus a global evaluation is still ongoing. Figure 4 is an example of a ~9 m diameter crater as seen in an OLA scan. This plot illustrates the boulder-rim morphology in “topographic space”, i.e. a traditional raised rim is replaced by a surrounding circle of boulders.

Discussion: The variation in crater morphology appears to be caused by several factors. Impact scale defines whether or not the pre-existing surface (the distribution of boulders) affects details of the crater morphology. At larger crater sizes, the excavation depth and crater diameter overwhelm the specifics of any particular pre-existing boulder population, and a more “traditional” crater shape forms, albeit with some differences from bowl-shaped craters seen on larger bodies. At smaller sizes, the crater morphology may become more sensitive to the specific pre-existing boulder population, and the relative efficiency of transforming the impactor energy and momentum into excavation of the surface to form a crater cavity, vs. disruption and/or displacement of the pre-existing boulder population. This behavior is very much like that found in the experiments of [9]. There appears to be a transition in crater morphology at ~20-25 m diameter, above which crater interiors are generally similar (with some exceptions) to the exterior, and below which the crater interior contrasts with the surrounding terrain. This suggests the presence of a sub-surface layer, potentially only a few meters thick, with a different particle size-frequency distribution than the bulk asteroid.

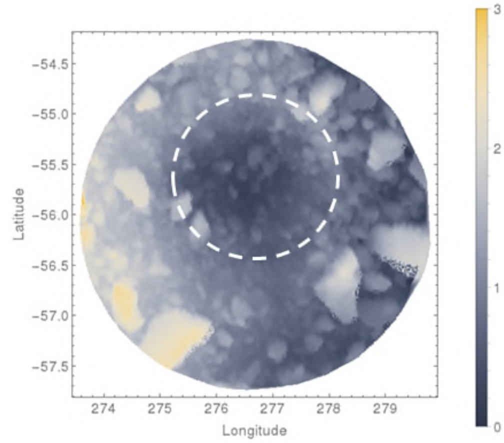

Figure 4. An OLA scan of a ~9 m crater (dashed outline) demonstrating the lack of a traditional crater rim. The scale bar is meters above lowest point inside the crater.

Summary: This data set will provide a map of crater sizes and locations across Bennu, as well as a means to define crater characteristics as a function of size and location. These analyses provide the foundation needed to understand the surface and sub-surface of Bennu, and apply the appropriate crater-scaling laws to invert the observed crater population to an impact history and surface age.

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