Analysis and Simulation of Boulder Mass Movement Sites on Asteroid Bennu Y. Tang[1], D.S. Lauretta[1], R.-L. Ballouz[1], D.N. DellaGiustina[1], C.A. Bennett[1], and K.J. Walsh[2], [1]Lunar and Planetary Laboratory, University of Arizona (tangy14@lpl.arizona.edu), [2]Department of Space Studies, Southwest Research Institute, Boulder, CO, USA.

Introduction: Surface processes dictate how a planetary surface evolved to its current state. Over the past two years, NASA's OSIRIS-REx sample return mission has been investigating the near-Earth asteroid (101955) Bennu [1], revealing a boulder-dominated surface with diverse morphologies [2]. Past asteroid missions have found evidence of seismic shaking and mass movement (the transport of materials largely through downslope forces) being major contributors to surface evolution on small, airless bodies [3,4]. The same is expected for Bennu, which shows globally distributed evidence of mass movement [5]. This study aims to provide understanding of mass movement on Bennu through detailed analysis of specific features on the asteroid surface.

Methodology: Surface forces on Bennu include, in addition to gravity, centrifugal force due to Bennu's rotation, creating a large geopotential difference between highs at the poles and lows at the equator [6]. The centrifugal force changes over time due to Bennu's spin-up caused by the YORP effect [7–9]. Resistance to movement by boulders due to friction includes contributions from cohesive force.

We model the effects of these forces on boulders at Bennu's surface. We use pkdgrav [10] to simulate surface movement at potential sites of mass flow to help explain formation of large-scale features on Bennu, as well as how the surface responds to slope changes due to the YORP effect.

We identified candidate mass movement sites through visual inspection of boulder orientations, imbrication, and partial burials, as well as from [5]. We then conducted a census of the boulders at each site, with documentation of size, orientation, location, and albedo. We accomplished this using the Small Body Mapping Tool (SBMT) [11], which can project a ~5-cm global mosaic created using OCAMS images [12–14] onto a shape model using stereophotoclinometry (SPC) pointing [15,16]. Where available, higher-resolution images were used, such as for an area near the Sandpiper site (–47°N, 322°E) that was studied by the mission for possible sample collection.

Comprehensive morphological data and geophysical context of the areas of interest were also compiled. Elevation was extracted using the geopotential calculated at each relevant facet of a 3-million-facet SPC-derived global shape model (v42) [17] onto which the basemap of Bennu was projected. The geopotential includes a gravity term as well as centrifugal forces from the rotation of the asteroid [18].

The geophysical data provide the context and inputs to the boulder force model. The lateral forces on boulders are governed by the following equations:

$$F_{\text{lateral}} = F_{\text{surf}} \sin\theta_s - (F_{\text{surf}} \cos\theta_s + F_c) * k \quad (1)$$

$$F_{\text{surf}} = F_{\text{centrifugal}} + F_g = \vec{\nabla} V \quad (2)$$

Here, F_{surf} is the surface force, which is composed of the centrifugal force and gravity force, and is equal to the negative gradient of the geopotential. θ_s is the slope; F_c is the cohesive force; and k is the coefficient of friction. The parenthesis sums to the expected normal force from the surface.

In our modeling of boulder movement in pkdgrav, the surface is defined using data from the shape model. Pkdgrav provides a wide range of simulation scenarios, and allows us to change variables such as particle sizes and the strength of interactive forces such as cohesive forces, which data from the sampling event suggest are very low, nearly zero [19]. Seismic shaking can also be added to determine its importance in the initiation of such events. The same program can be used to simulate collisions between boulders, which can be represented by aggregations of smaller particles with high internal cohesion.

The simulation outputs the location and velocity of all the boulders, allowing comprehensive analysis of the motions as well as the final resting locations. These can be compared with the census data for potential mass movement sites on Bennu to determine the likely initial conditions for those sites. Changing slopes due to the YORP effect can also be added to comprehend the landscape changes that a changing slope may induce.

Preliminary Results: Here we report analysis of the area of interest that we designated site A, located at 15°–80° N and 295°–340° E (Fig. 1). This site has varying boulder distributions for different boulder sizes, with a relatively even distribution of smaller-sized boulders (<3m diameter) and a congregation of larger-sized boulders (>3m diameter) near the 35°–50° N latitudes (Fig. 2). One possible explanation is that the forces that a boulder experiences scale differently, with F_{surf}, composed of gravity and centrifugal force, proportional to the mass or volume of a boulder, whereas F_c is proportional to the surface area [16]. More simulations are planned to examine the necessary cohesive forces needed to induce the differing size distribution.

Future Work: Census of more potential mass movement sites is required to provide a better global study of the cohesive force and coefficients of friction, as well as cover the unique characteristics of each flow area. One mass movement site we are examining is near the Sandpiper candidate sample collection site, located at –47°N, 322° E. The crater in which Sandpiper is located presents evidence of mass movement such as partial burials, and a boulder distribution indicative of large stationary boulder disrupting the flow of small sized regolith. Due to Sandpiper's consideration by the mission as a candidate sample site, high-resolution imagery (1.3 cm/pixel; Recon A mission phase) of this site is available, enabling analysis at a different size regime than what is possible in the global mosaic.

In addition, simulations are required to better understand the nature of the flow. Preliminary results suggest that there is size differentiation in the mass movement, and one explanation could be the cohesive force. This will be tested in planned simulations using pkdgrav.

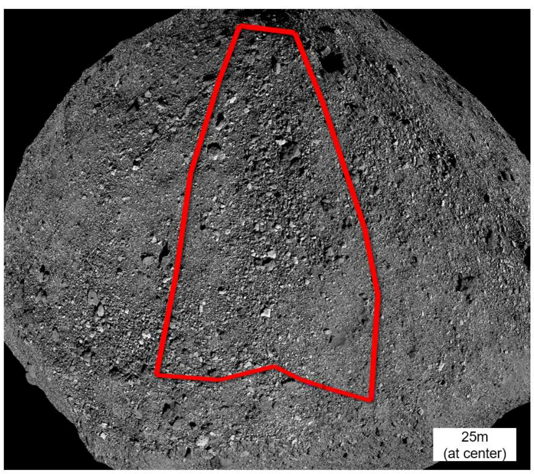

Figure 1: Mosaic of site A, with the potential mass flow area in the center, running top to bottom (N to S).

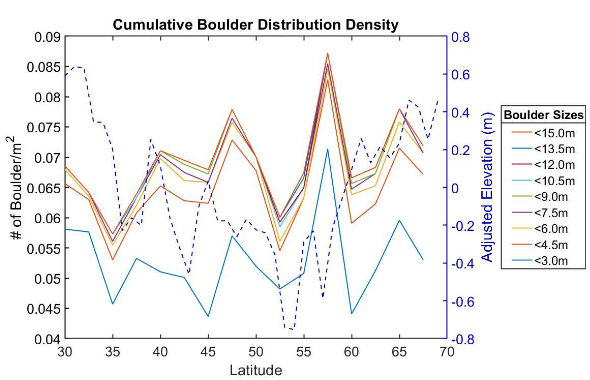

Figure 2: Concentration of boulders across different latitudes at site A, with each line representing cumulative concentrations below that boulder size. Although boulder concentration is similar across latitudes, different size regimes have slight latitudinal variance.

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