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On the possible origin of terraces on Bennu

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Abstract

We present evidence for latitudinal scarps or terraces across the northern and southern hemispheres of the asteroid Bennu at mid-to-high (40–70°) latitudes, and explore their geological characteristics. These features may be the result of surface creep due to YORP spin-up that leads to localized regional surface failure. Geotechnical analyses indicate that the latitude bands where the terraces are located are the most prone to failure. Simple laboratory experiments that attempt to simulate quasi-static failure of a blocky surface indicate that regional terracing as observed on Bennu is likely. The surface creep that produces the terraces could be geologically recent, also obscuring large high-latitude craters.

1. Introduction

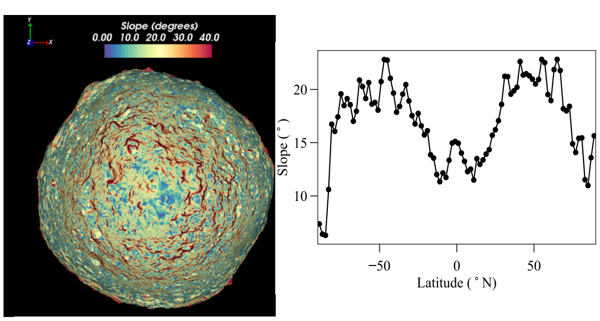

Figure 1. Regional high slopes circumventing the N (+Z) pole of Bennu terraces (top) indicate the presence of terraces. The median slope distribution in 1° latitudinal bins (bottom) shows evidence for these features on both hemispheres; their presence is also apparent in elevation. Some variability in terracing exists in longitude, but terracing remains a dominate feature in the mid-to-high latitudes.

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft arrived at (101955) Bennu in December 2018 [1]. A global digital terrain model (GDTM) of Bennu was derived from imaging and laser altimetry observations [2]. Initial assessment of the surface slope and elevation relative to gravity [3,4] indicates that Bennu possesses some interior stiffness, with significant evidence for surface mass-wasting.

Here, we explore manifestations of surface mass-wasting that result in terrace formation on Bennu. As in our earlier assessment [2], we use slope and elevation relative to gravity as well as simple laboratory investigations and a slope stability analysis to gain insights into the possible origin of these features.

2. Methods

The slope and elevation of Bennu are computed using a recent GDTM developed from all OSIRIS-REx Camera Suite (OCAMS) images [5] collected between late November 2018 and 2 February 2019, and the asteroid mass measured in January 2019 [3]. The RMS error of the model is <0.7 m. Individual OCAMS images and global imaging mosaics provide context for the slope and elevation results.

The slope stability analysis uses the "factor of safety" model for infinite slope [6], FS, that compares the ratio of resisting frictional and cohesive stresses to gravity

$$\boldsymbol{FS} = \frac{\tan\phi}{\tan\theta} + \frac{c}{\gamma_t T \sin\theta}$$

where θ is the slope angle, ϕ is the frictional angle of the surface material, c is the cohesion, $\boldsymbol{\gamma_t}$ is the depth-averaged total unit weight, and T is the thickness of the regolith/boulders that could fail. Values of $FS < 1$

imply the slope is prone to failure. We used the lowest-resolution shape model available for our analysis (average facet size of 12.5 m) to reduce local slope biases in our assessment. We set ϕ=40° for highly angular granular materials, and used c=1 Pa based on the minimum cohesion necessary to form the equatorial ridge of Bennu [3].

As a complement to the FS calculations, we carried out a series of simple laboratory experiments to form terraces in granular material. We make use of a gravel mixture composed of particles with three distinct colors with diameters near ~0.2 cm, ~0.5 cm, and ~1 cm. The coarse-grained material employed was intended as a proxy for the boulder-rich surface of Bennu. We placed the gravel in a clear-sided box, and slowly lifted one of its sides to mimic slope increases on Bennu due to YORP spin-up. We used a high speed (100 frames/s) camera to observe the displacement of the surface material.

3. Results

Terraces are evident in polar and latitudinal assessments of the slope and elevation of Bennu (Figure 1). They are most prevalent near latitudes of ±60° but span 30–80°. The OCAMS data indicate that many of the terraces are steep scarps, with an accompanied downslope ledge. The longest scarp spans over 120° of longitude. Although a statistical assessment is needed, the steep scarps appear to lack discernible boulders (except when a scarp itself is a boulder face). Some of the terraces are composed of rows of large step-faced boulders, with smaller rocks accumulating both above and below these rock faces as the surface material slowly creeps along and sometime precipitously fails to form the terraces.

This formation scenario is supported by our stability analysis. For the case where c=0, the slopes are the least stable at the current spin rates in the latitude bands where terraces are observed. Reducing ϕ to 32°, which is possibly a more reasonable friction angle for Bennu surface material, or continuing to increase the spin rate, we find regions that are at risk of slope failure today near where terraces are located. A cohesion of c=1 PA completely hinders any surface failure at current spin rates, which is inconsistent with observations; the failure would be deep-seated for such cohesion conditions.

Although under Earth gravity, the laboratory experiments provide some useful insights in understanding what to expect at Bennu. The experiments reveal that initially, as the slope steepens, individual boulders are the most likely to topple over. As the slope increases further, regional failures occur to produce many of the characteristic of the terraces seen on Bennu. The presence of smaller grain sizes in certain areas enhances the likelihood of surface mass-wasting, which may explain why some scarps on Bennu often lack coarse grains.

4. Discussion and Conclusion

We show that the formation of terraces on Bennu could be the result of slope instabilities generated by YORP spin-up. Their morphology and slope characteristic are consistent with laboratory-based assessments of regional slope failure, and the location of the observed terracing is consistent with expectations from slope stability analyses using the current spin-rates. At odds, however, with such an assessment is that YORP spin-up on Bennu is fairly slow [7], causing minute increases in slope with time. For such conditions, several studies [e.g., 8,9] indicate that slope failure should be global and catastrophic. But this is not observed. It is possible that on Bennu, large craters are long-lived, especially at the equator, but are slowly being obscured in the mid-latitudes where the terraces are present [4]. Some other seismic disturbance may need to be invoked to initiate the localized failure at time scales that are faster than catastrophic failure by YORP, such as micro-meteorite impacts or a dynamic form of thermal fracturing [1,10].

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