THERMALLY DRIVEN EXFOLIATION AND PARTICLE EJECTION ON BENNU.
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Introduction: Thermally driven fracture processes have been hypothesized to act on the Moon [1, 2], Mars [3, 4], Earth [e.g., 5], asteroids, [e.g., 1, 2, 6, 7] and comets [e.g., 8, 9], driving rock breakdown and regolith production on their surfaces. Thermal cycling induces mechanical stresses in rocks that drive the propagation of microcracks, which may grow into larger scale features. The interaction between stress fields generated at micro- and macroscopic scales controls the size and shape of disaggregated material [1–2, 4], which in turn affects the volume and distribution of rocks and regolith on these surfaces. Airless bodies in particular are thought to be highly susceptible to this process, and understanding how it operates is critical to characterizing their landscape evolution and surface properties.

While recent modeling and laboratory efforts have provided insight into how thermal breakdown may operate on airless bodies [1–5], observational evidence of its action beyond Earth is extremely limited. This is largely due to challenges distinguishing its signature from that of other weathering processes [e.g., 10], as well as the limited availability and resolution of spacecraft imagery on bodies it is likely to occur. Now, the Origins Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft has obtained images of the surface of asteroid (101955) Bennu at pixel scales down to 2-3 cm/px, providing an unprecedented opportunity to search over a wide range of scales for evidence of thermal breakdown occurring *in situ*.

We will show observations of boulder morphologies and fractures on Bennu consistent with both terrestrial observations and models of fatigue-driven boulder degradation. Specifically, we show evidence of boulder exfoliation, providing the strongest evidence yet that thermal fracturing plays an important role in airless body surface evolution. We will relate these observations to 3D simulations of thermally induced stress fields in boulders and describe how these stress fields lead to their development. We will also quantify the spacing of exfoliation cracks expected to develop on boulder surfaces, as well as estimate the range of speeds at which particles may be ejected from the surface due this process.

Observations: For this study, we use images acquired by the OSIRIS-REx PolyCam instrument over the period from March 21 to July 26, 2019. These images have pixel scales ranging from 3.8 to 8.8 cm/px, allowing us to identify and characterize fractures and boulder surface textures at the cm scale. We readily observe boulders with single and tiered exfoliation features over a range of latitudes in boulders ~0.7-18 m in diameter. Some observations are also made of other possible signs of fatigue, such as surface disaggregation and linear fractures.

Model: Following [1], we used COMSOL to perform 3D finite element simulations of the response of boulders on Bennu's surface to diurnal thermal cycling, allowing us to investigate the magnitude and distribution of resulting stresses. We modeled a boulders embedded in unconsolidated, fine-grained material with a thermal inertia matching observations from the OTES instrument. We imposed a solar flux over one day at an equatorial location at Bennu's semimajor axis (1.1 AU) and solved the heat and displacement equations, accounting for the radiative and conductive interaction between the boulder and regolith. The boulder is assumed to be a CI chondrite, with bulk material properties comparable to terrestrial serpentine-group phyllosilicates [e.g., 11].

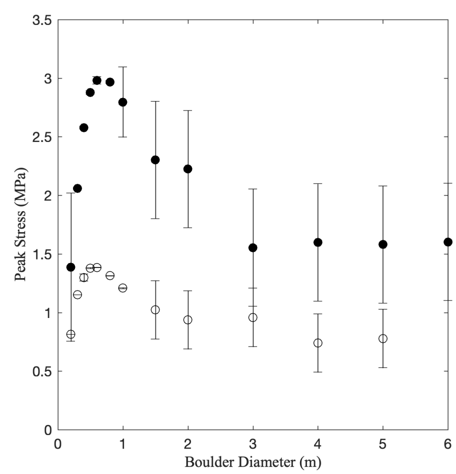

Figure 1. Peak exfoliating stresses in boulders of varying diameter with (solid) 10% and (open) 35% porosity. Quantified is the maximum principal stress, where positive stresses are always tensile.

Preliminary Results and Future Work: Figure 1 compares the magnitude of exfoliating stresses (using the maximum principal stress, where tensile stress is positive) induced in boulders with vary varying size, each simulated with bulk porosities of 10% and 35%. Magnitudes range from ~1-3 MPa, which are comparable to the tensile strengths of terrestrial phyllosilicate rocks (e.g., serpentinite) and similar soft, anistropic materials (e.g., sandstone), and exceed estimates of boulders on Ryugu [12]. On Earth, subcritical crack growth only requires a stress ~10% of the material's tensile strength to occur, suggesting that even if these idealized simulations represent an overestimate of stress magnitudes or higher stress is required to drive crack growth in vacuum environments, there is a reasonable likelihood that fatigue is possible on Bennu.

These stresses occur in the near-surface of boulders at depths of ~4-30 cm and drive crack propagation along surface-parallel planes. One or more exfoliation fractures may develop in this region, with crack spacing that is narrow near the surface and increasing with depth. The stored strain energy in these boulders represents the amount of energy available for crack propagation, which we can use to estimate the spacing of exfoliation layers. Figure 2 shows a preliminary estimate of the crack spacing in a 1 m boulder, with thicknesses ranging from mm scale up to ~10 cm.

We have observed particle ejection events from Bennu's surface at a regular cadence since first entering orbit in 2018 [13]. Since exfoliation fractures from fatigue develop progressively, excess thermal strain energy may be available during individual crack propagation events capable of mobilizing disaggregated fragments, which may be the driving mechanism for ejection events.

We will relate our simulated stresses to observations of exfoliation on Bennu's surface and demonstrate that our estimates of idealized crack spacing are consistent with observed layer thicknesses. We will also compare estimated ejection velocities to those observed by the spacecraft, and assess the extent to which thermal fracturing processes may contribute to asteroid activity.

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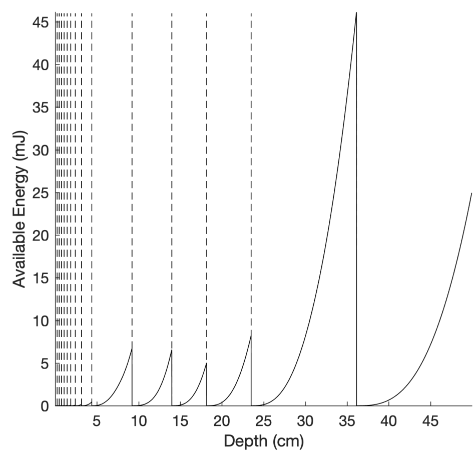

Figure 2. Available strain energy with depth in the surface of a 1 m boulder during the time at which peak strain energy (and peak exfoliating stress) occurs. The dashed lines show depths at which enough energy has accumulated to disaggregate a layer of material, dropping the available energy to zero.