FATIGUE-DRIVEN BOULDER EXFOLIATION AND PARTICLE EJECTION ON BENNU.

J. L. Molaro[1], C. W. Hergenrother[2], S. R. Chesley[3], R.D. Hanna[4], C.W. Haberle[5], R.-L. Ballouz[2], S. R. Schwartz[2], W. F. Bottke[6], K.J. Walsh[6], H. Campins[7], and D.S. Lauretta[2]. [1]Planetary Science Institute, Tucson, AZ, USA (jmolaro@psi.edu). [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA. [3]Jet Propulsion Laboratory, Caltech Institute of Technology, Pasadena, CA, USA. [4]Jackson School of Geosciences, University of Texas, Austin, TX, USA. [5]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA. [6]Southwest Research Institute, Boulder, CO, USA. [7]University of Central Florida, Orlando, FL, USA.

Introduction: Thermally driven fracture processes, such as thermal fatigue, have been hypothesized to drive rock breakdown and regolith production on asteroid surfaces [e.g., 1-7]. Thermal cycling induces mechanical stresses in rocks that drive the propagation of microcracks, which may grow into larger scale features. The rock properties and rotation period of the body, along with the interaction between stresses generated at micro- and macroscopic scales, control the size and shape of disaggregated material [e.g., 1–2, 4], which in turn affects the distribution of rocks and regolith on these surfaces. Understanding how this process operates is critical to characterizing landscape evolution on asteroid surfaces, however observational evidence of its action beyond Earth is extremely limited.

Images from the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft of the surface of Bennu provide the opportunity to search for *in situ* evidence of thermal breakdown over a wide range of scales. We show observations of boulder morphologies consistent with both terrestrial observations [e.g., 8] and models of fatigue-driven boulder exfoliation [e.g., 9]. Exfoliation occurs as one or more surface-parallel fractures that cause layers or flakes of material to disaggregate from boulder surfaces. We relate these observations to 3D simulations of thermally induced stress fields in boulders and describe how these stress fields lead to their development. On Earth, exfoliation is also known to cause mobilization of disaggregated rock fragments [9], suggesting it may be capable of ejecting material from Bennu's surface. We also quantify the characteristic spacing of exfoliation cracks and estimate the speeds of particles that may be ejected during an exfoliation event.

Observations: In 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 characterize 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. 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 boulder embedded in unconsolidated, fine-grained material with a thermal inertia matching the measured, disk-integrated value (~350 $J/m^2\ K\ s^{1/2}$) [10]. We imposed a solar flux over one day at an equatorial location at Bennu's semi-major 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 carbonaceous chondrite, with bulk material properties comparable to terrestrial serpentine-group phyllosilicates [e.g., 11].

Thermal strain energy is stored energy in the boulder as it undergoes elastic deformation, which can go into crack propagation and particle mobilization. We predict the characteristic spacing of exfoliation cracks by assuming that a crack develops at a depth where the accumulated energy is equal to the energy needed to create the new crack walls. Exfoliation cracks are limited to depths of ~30 cm into the boulder surfaces. Assuming that each exfoliation flake disaggregates into equally sized particles with dimensions of the flake thickness, we can also predict the size-frequency distribution of the particle population that exfoliation is expected to produce. Alternately, by assuming that a single crack develops at an arbitrary depth, we can quantify the excess energy available to mobilize particles during an exfoliation event. We compare our results to observations [7] of particle ejection events from Bennu's surface.

Results: The magnitude of exfoliating stresses (peak tensile stress at the location where exfoliation occurs) ranges from ~0.3-3 MPa for boulders 0.2 to 6 m in diameter. These stresses are comparable to the tensile strengths of terrestrial phyllosilicate rocks (e.g., serpentinite) and similar soft, anisotropic 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, indicating that fatigue is possible on Bennu. The thickness of resulting exfoliation layers are predicted to range from ~1 mm to 10 cm (Figure 1),

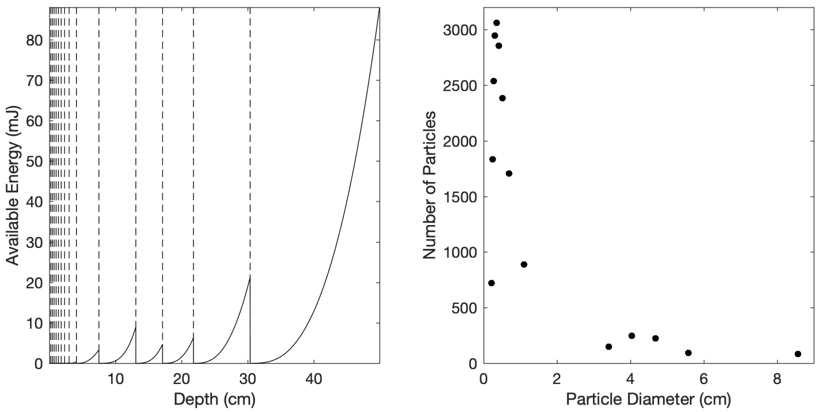

Figure 1. (left) Available strain energy with depth from the surface of a 1 m boulder during the time at which peak strain energy (and peak exfoliating stress) occurs. The dashed lines show depths at which enough energy has accumulated to form a crack, dropping the available energy to zero. (right) The number of particles into which each exfoliation layer disaggregates.

which is consistent with terrestrial observations of exfoliation cracks [8] and with the thicknesses of exfoliation layers observed on Bennu's boulders.

We have observed particle ejection events from Bennu's surface repeatedly since first entering orbit in January 2019 [7]. Observed particles range in size from <1 cm to 10 cm [7], consistent with our predictions for exfoliation. While the mass of material that may be ejected during a given exfoliation event is unknown, the observed particles are also consistent with the shape of the size-frequency distribution of the population of particles exfoliation is predicted to produce.

Figure 2 shows the energy per particle for material produced by an exfoliation crack at an arbitrary depth in a 1 m boulder. This energy is excess beyond what is needed to disaggregate the flake, and can be converted to kinetic energy to constrain the speed of ejected particles. We find particles may be ejected with speeds up to ~2 m/s for boulders smaller than or equal to 6 m in diameter, which is a reasonable match to the maximum observed particle speed of 3.3 m/s [7].

Conclusions: We find that the magnitude of stresses induced via thermal cycling is sufficient to drive thermal fatigue in Bennu's boulders, and that layered boulder morphologies observed are consistent with fatigue-driven exfoliation. We also find that the predicted sizes and speeds of particles that may be ejected during exfoliation events are consistent with observed particle ejection events at Bennu, indicating that thermal fatigue is a viable mechanism for generating these events and for, generally, producing asteroid activity.

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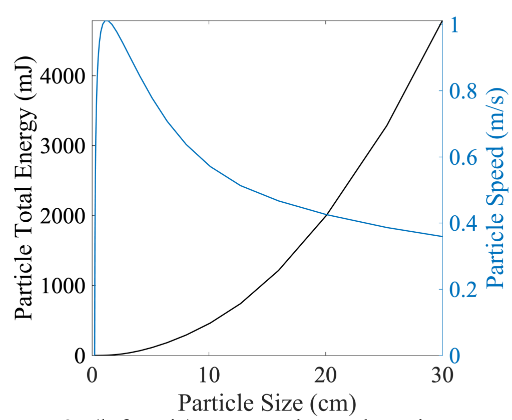

Figure 2. (left axis) Excess thermal strain energy in a cubic particle at the surface of a 1 m boulder with increasing size, and (right axis) predicted ejection speed.