INVESTIGATING THE PHYSICAL MODIFICATION OF THE BENNU SAMPLE DURING ENTRY, DESCENT, AND LANDING.

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Introduction: On September 24, 2023, the OSIRIS-REx Sample Return Capsule (SRC) entered Earth's atmosphere and landed in the Utah Test and Training Range (UTTR). Preliminary examination of the returned Bennu sample has confirmed that OSIRIS-REx sample mass exceeds the mission requirement of 60 g of material. The sample consists of particles that range from a few centimeters to microscopic fines. During the SRC's entry, descent, and landing (EDL) sequence, it may have experienced (i) peak decelerations of 10s of *g* [1] (ii) tumbling, and (iii) touchdown at approximately 10 m/s, which could have induced physical modification of the sample. In addition, the act of sampling may have altered or biased the physical properties of the collected materials [2]. Here, we investigate the likelihood and extent of physical modification of the sample between collection and return using observations and modeling. This work addresses the mission's hypothesis 12, which concerns, in part, the modification of the sample during collection and Earth entry.

Motivation: The OSIRIS-REx team is investigating the physical and thermal properties of the sample to better understand the evolution of Bennu's surface [3], in part by comparing sample properties to those derived from remote observations [4]. However, to understand the representativeness of the sample and the link between physical features and asteroid *in situ* processes (such as impacts, thermal fatigue, and space weathering [5-7]), we need to evaluate and isolate the effects of EDL on the sample physical properties (e.g., shape, size distribution, and porosity).

Evidence for artificial physical modification: Preliminary examination of the Bennu sample at NASA Johnson Space Center (JSC) has revealed direct and indirect evidence for artificially induced physical modification. At the largest scales, the sample is dominated by particles with smooth angular faces that suggest relatively recent fracturing. Through image analysis, we are able to show that at least two stones can be fit together like puzzle pieces (Fig. 1), indicating a recent fracturing event. This stands in contrast to rocks on Bennu, where smooth and angular rocks are a minor lithology; though, we note the disparate length scales in this comparison [8]. Preliminary analysis of the mass distribution of particles, derived from a combination of mass measurements and particle size measurements in images, indicates that most of the mass is in particles smaller than 5 mm, with a particle mass index of approximately 0.85. Bennu's surface was relatively dust-poor, in comparison [9]. Furthermore, some particles have been observed to break down when handled with standard sample manipulation tools, like tweezers, by JSC processors.

Modeling approach: Here, we will model the free motion of Bennu particles inside TAGSAM during EDL using a numerical collisional code, *pkdgrav*, that has been used to reconstruct spacecraft-surface interactions [10,11]. We model and track the accumulated stress on particles as they collide with each other and the TAGSAM interior to constrain the degree of breakdown that may have occurred. The modeling is separated into three phases: (i) SRC shaking due to atmospheric entry and descent, (ii) SRC tumbling, and (iii) SRC impacting the UTTR. For each of these phases, we will analyze the extent of physical modification of the sample due to the accumulated stress of mechanical agitation.

For the preliminary modeling presented here, we use sample particle parameters (size distribution, volume, mass, etc.) based on preliminary examination data, and EDL parameters derived from seismo-acoustic modeling of Stardust SRC EDL [2], combined with images taken of the OSIRIS-REx SRC at UTTR during environmental sampling. EDL parameters may be updated in the future with improved knowledge of the OSIRIS-REx SRC re-entry [12]. The ultimate goal of this effort is to investigate the extent of sample physical modification given our current understanding of the strength of Bennu material [5, 9], which will be updated through a suite of strength measurements [3,13]. Future work will evaluate other potential contributions to sample physical modification, such as the vibrational environment during transport from UTTR to JSC.

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References: [1] Revelle D.O. & Edwards, W.N. (2007) *M&PS* 42, 271-299. [2] Lauretta D.S. et al. (2022) *Science* 377, 285-291. [3] Lauretta D.S. et al. (2023) *arXiv*:2308.11794 [4] Ryan A.J. et al. (2024) this conference. [5] Ballouz R.-L. et al. (2020) *Nature* 587, 205-209. [6] Molaro J.L. et al. (2020) *Nat. Commun.* 11, 2913. [7] DellaGiustina D.N. et al. (2020) *Science* 370, eabc3660. [8] Jawin E.R. et al. (2023) *JGR Planets* 128, e2023JE008019. [9] Rozitis B. et al. (2020) *Sci. Adv.* 6, eabc3699. [10] Ballouz R.-L. et al. (2021) MNRAS, 507. [11] Walsh K.J. et al. (2022) *Sci. Adv.* 8, eabm6229. [12] Witze A. (2023) *Nature* 623, 230-231. [13] Hoover C.G et al. (2024) this conference.

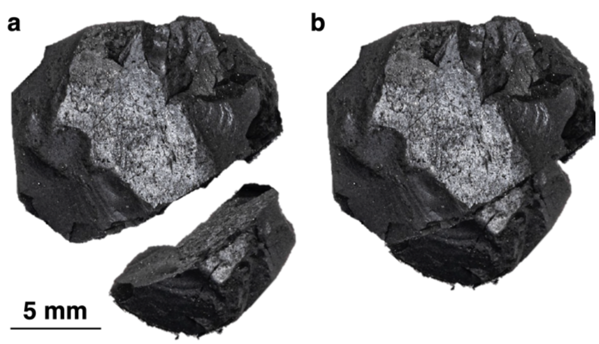

Figure 1. a, Advanced Imaging and Visualization of Astromaterials (AIVA) mosaic of two Bennu particles. The larger stone is OREX-800016-0 and measures 15.6 mm in its longest dimension. The smaller stone was deposited in a separate container. **b,** Visual analysis of AIVA images show that these two stones fit together like puzzle pieces, suggesting a recent fracturing of the parent stone.