REGOLITH SURFACE CREEP ON ASTEROID BENNU: PRELIMINARY RESULTS FROM IMAGE ANALYSIS, SOIL-STRESS MODELING, AND LABORATORY EXPERIMENTS.
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Introduction: Bennu is a rubble-pile asteroid with an equatorial bulge that suggests a rotational (centrifugally-driven) distortion of the asteroid at some time in its history [1-3]. The bulge could be an equatorial accumulation of regolith that has drifted latitudinally to the equator, but primarily of near-surface material, or it could be an expression of pseudo-plastic distortion of the whole asteroid, or both (re-accumulation from a debris disk is a third possibility).

If surface creep of regolith is involved, we would expect it to be expressed by alignment of elongate rocks and boulders parallel with the direction of transport towards the equator. This assertion is based on the idea that orientation occurs in order to minimize flow resistance of an object in a streaming medium of similar material. This alignment would be weak or absent at the poles, strong at mid latitudes, and jumbled in equatorial regions owing to the collision of two opposing (N and S) drift directions (Fig. 1).

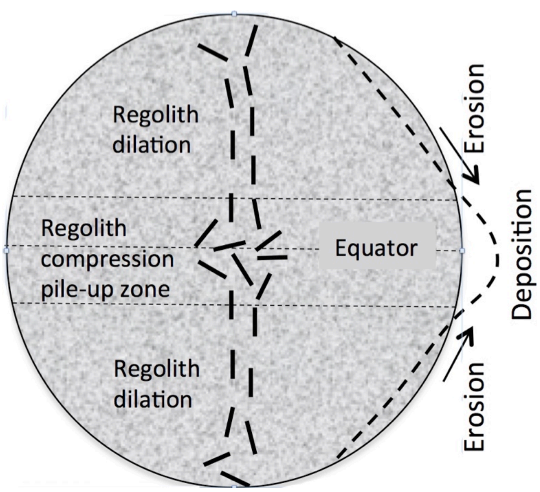

Figure 1: *Notional model for orientation of boulders.*

To test this alignment hypothesis, we examined OSIRIS-REx spacecraft photographic imagery and compared it with results from laboratory experiments and the predictions of a geometrically-based stress-vector model.

Geometrical Model: The geometrical model was set with centrifugal forces equal to gravity at the equator as the maximum asteroid rotational condition before centrifugal shedding of material into space. Resolved force vectors for this predefined condition indicate a maximum of horizontal soil stress at mid latitudes and no significant net horizontal (creep-inducing) component of stress at the poles or equator.

Negligible stresses at the poles predict a lack of boulder alignment. Mid latitudes should express maximum alignment, increasing with equatorward transport distance. Compressive collisions of north and south equatorward drifts predict a realignment of boulders on the equatorial bulge to an E-W trend.

Image Analysis: These model predictions are supported by direct photographic imagery of Bennu's surface, although we stress that our database is preliminary, consisting to date of five analyzed sites in total. The sites were selected at arbitrary locations on Bennu's surface at equatorial latitudes and mid northern and southern latitudes. Many tens of boulders were measured at each location using elliptical fitting of boulder long axes. Locations were chosen to avoid major features such as craters and boulder fields where localized soil movements could overprint any general global alignment trend.

In order to deal with shadowing and other illumination issues, we analyzed images with low incidence angles, and therefore little shadow. In the locations where some shadows were present, we only measured boulders with visible boundaries.

Rose diagrams expressing boulder alignment trends are shown in Fig. 2. Diagrams A and B are from mid northern latitudes and show prominent (roughly) N-S alignment trends. Similarly, diagram C from a southern mid latitude shows a north-south trend. Diagrams D and E are from equatorial locations; the N-S trend is absent. Whilst there is general agreement between observed boulder alignments and modeled expectations, there are also unexplained NW-SE and NE-SW trends seen in four of the five diagrams (southern mid latitude being the exception).

Although boulder alignment trends are quite recognizable in the rose diagrams, they are not recognizable by eye; the trends are very subtle and are only exposed statistically be multiple alignment measurements. We note that Schwartz et al. [4] have also observed N-S alignment trends of boulders which they associate with Bennu's contemporary global slope directions that are also aligned north-south.

Laboratory Experiments: These corroborated the results of image analysis. We physically simulated Bennu's boulder motion in the laboratory by horizon-

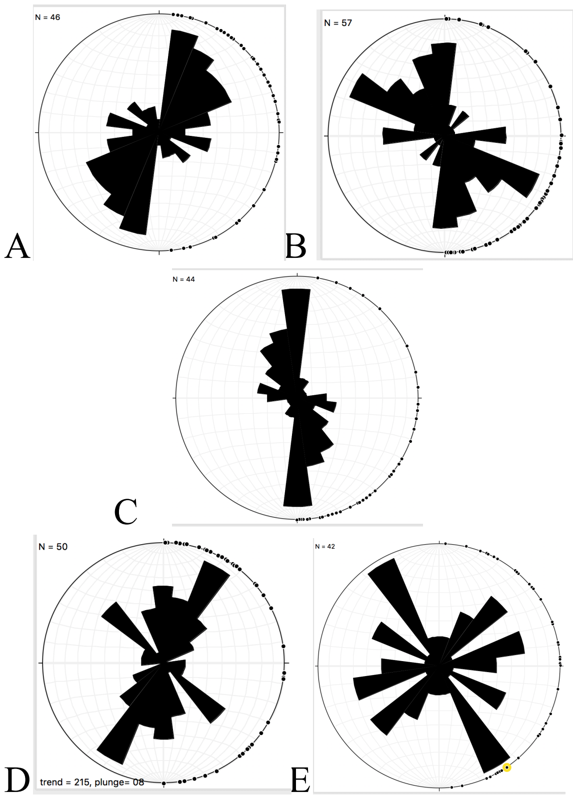

***Figure 2**: Rose diagrams of boulder alignment (north is up). **A:** Northern mid-latitude, PolyCam image 20190223t123627s932. **B**: Northern mid-latitude, PolyCam image 20190225t023628s059. **C:** Southern mid latitude PolyCam image 20190321t194439s822. **D:** Equatorial, PolyCam image 20190226t062628s068. **E:** Equatorial, PolyCam image 20190321t190115s293*.

tally shearing thin layers of loose granular materials. The materials were light weight in order to reproduce the low frictional relationships in a low gravity environment. The grain inertia/friction ratio was the experimental similitude parameter.

Spherical/equant grains (peppercorns), disk-shaped grains (lentils), and elongated grains (rice) of ~0.5 cm were made into mixtures and spread with random orientations in a plume or channel and then subjected to horizontal shear by mechanically dragging the top layer across the base layer. This induced a boundary-layer shear through the body of the grain mass down to a depth of several grain diameters. We postulate a similar boundary layer structure on Bennu, with unconfined surface material entraining material just beneath, but effective drag ceasing at some small depth on the order of a few boulder diameters.

The lentil disks became imbricated with their overlap in the direction of drag. At the same time, a significant fraction of the rice population became aligned with the shearing direction (long grain axis parallel with drag). Rose diagrams will be made of the grain alignments for comparison with our image analysis.

Next Steps: Our database is small and many more boulder alignment measurements are planned. The lab experiments are in their infancy and the test matrix will be expanded, in particular, to test the travel distance required to generate alignment, the effect of different mixtures (relative proportions of grain types), and the way in which multiple alignment trends are able to co-exist in a mobile granular mass.

Conclusions: The modeling, photographic image analysis, and laboratory experiments are consistent with a drift of near-surface material towards the equator, but they do not preclude concomitant bulk distortion of the whole asteroid due to the same centrifugal influence.

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References: [1] Walsh K. et al. (2019) *Nature Geoscience 12.4, 242.* [2] Barnouin O.S. et al. (2018) *AGU Fall Meeting Abstracts, #P33C-3835*. [3] Michel P. et al. (2018) *AGU Fall Meeting Abstracts, #P33C-3850*. [4] Schwartz et al. (2019) LPSC Vol. 50, No. 2132.