PHOBOS GROOVES FROM STICKNEY IMPACT BOULDER EJECTA: TESTING THE HYPOTHESIS.

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Introduction: Stickney boulder ejecta that slides, rolls, and/or bounces across the surface of Phobos is proposed as the source of many grooves on Phobos [1]. Reservations that are raised regarding the Stickney boulder hypothesis include [2,3]: 1) The non-radial distribution of the grooves with respect to the rim of Stickney Crater, 2) The parallelism of the grooves, 3) Intersecting grooves that suggest an episodic process, 4) Grooves that crosscut Stickney Crater, which suggests that Stickney is older than the grooves, 5) The absence of grooves on the trailing orbital apex of Phobos, 6) Grooves that appear to pass through craters with little or no change in morphology, and, 7) The absence of large boulders on Phobos at the observed scale of the grooves. To assess the viability of reservations 1-6, our study observes a model of simulated suborbital, orbital, and supraorbital boulder motions [1]. To assess reservation 7, we refer to previous work [4,5,6].

Methods and Assumptions: We insert a three-dimensional shape model of Phobos based on data from Thomas (1997) [7] into orbit around Mars, then place simulated Stickney Crater ejecta boulders in motion at velocities that remain predominantly under the gravitational influence of Phobos [1]. Due to the secular orbital decay of Phobos, we test the model at three semimajor axes *(a)*: 10,000 km, 12,000 km, and 14,000 km (Phobos at ~100 Ma, ~200 Ma, and ~500 Ma respectively). Due to the impulse of the Stickney impact that breaks the tidal lock of Phobos [4], the shape model rotates at a slightly faster desynchronized rate. Where desynchronization may reverse the tidal lock phase of Phobos [4], we initiate tests in present-day and 180° tidal lock phases.

We assume a Stickney impact event that radially distributes boulder ejecta from the rim of the crater in equal volume. To produce a realistic distribution, our boulder injection mechanism slightly randomizes individual blocks into a variety of launch vectors and velocities. Based on the software limitations of our model, we launch a maximum of 82 test boulders at once. In order to focus our observations, we study test boulder motions collectively, in smaller groups, and individually [Figs 1-6]. Due to limitations in our collision-detection software, we simulate boulders at D800 m, which is larger than the hypothesis of Wilson and Head (2015) (D150-400 m) [1]. Nonetheless, we assume that gravitational forces and the rotation of Phobos equally influence and guide the motion of boulders D150-800 m. Where boulders tend to roll, we refer to boulder surface motion on Phobos as "rolling."

Observations: A system of Mars/Phobos gravity and Phobos rotation translates the motion of Stickney boulder ejecta vectors into non-radial and generally parallel patterns.

Ejecta boulders may travel >360° around Phobos to closely align their motions with grooves from both directions, crosscut grooves at a variety of angles, produce solitary non-linear grooves, and/or return to Stickney Crater [Figs. 3-6].

The intersection of Stickney ejecta boulder motions strongly suggests that crosscutting grooves may be produced by a single ejecta event.

Sudden regional changes in slope produce suborbital test boulder flight, particularly above the Phobos trailing hemisphere. Apart from regional changes in slope, rolling boulders tend to maintain continuous contact with preexisting terrain.

Supraorbital boulders return to Phobos from martian orbits across a wide range of times, incident angles, velocities, and locations [8] and do not produce groove-like patterns.

The spike of high-velocity Stickney ejecta that returns from martian orbits [4] is sufficient to disintegrate groove-producing boulders to D≲8 m that are observed on Phobos [5,6]. Further, at a scale that retains the morphology of grooves ≳80 m in width, Stickney secondary impact gardening is sufficient to bury many D≲8 m boulder fragments [4].

Our model at a = 12,000 km (shown and discussed in Figs. 1-6) produces a pattern of boulder motions that closely align to previously documented grooves [2]. Martian gravity at a = 10,000 km preferentially ejects boulders. Boulder motions at a = 14,000 km tend not to produce linear and parallel grooves.

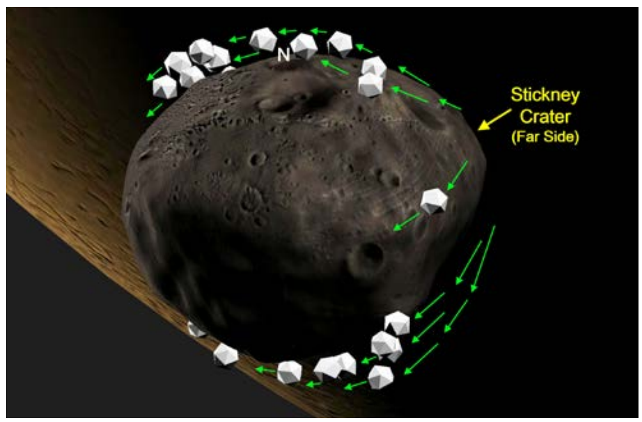

Fig 1. In this view, rolling boulders exit Stickney Crater to the northwest, west, and southwest. Due to gravitational and rotational effects, northwest boulders turn to the right and a similar number of southwest boulders turn to the left. A smaller proportion of westward boulders continue to the west.

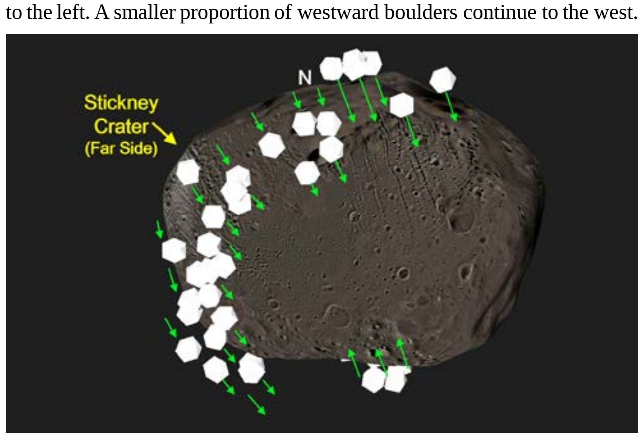

Fig 2. In this view, Stickney Crater ejecta boulders roll on the Phobos surface to the east and north of Stickney. Above the surface of Phobos, several test boulders are also moving south-to-north from the southern hemisphere. Boulders rolling across the northern hemisphere and east of Stickney Crater follow patterns of previously documented grooves [2].

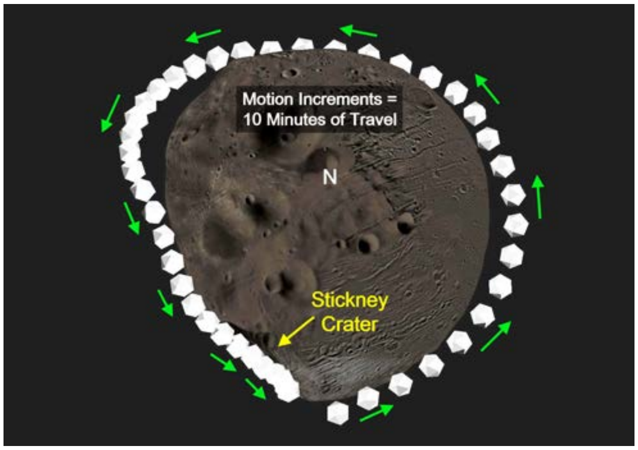

Fig 3. A test boulder exits Stickney Crater and rolls to the east, drifts into suborbital motion over the trailing hemisphere of Phobos, bounces once, again briefly rolls on the surface of Phobos, returns to suborbital motion, then rolls across the leading orbital apex of Phobos and through Stickney Crater where it comes to rest on the east rim. The total motion of this test block strongly suggests that a Stickney ejecta boulder is able to produce a groove on the floor of Stickney Crater.

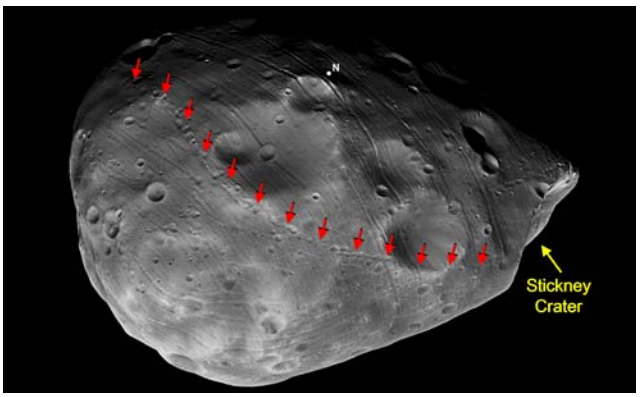

Fig 4. Image of the northern hemisphere of Phobos [9]. Red arrows indicate a prominent non-linear groove. The non-linear groove is fully consistent with the motion of the test boulder shown in Fig. 5.

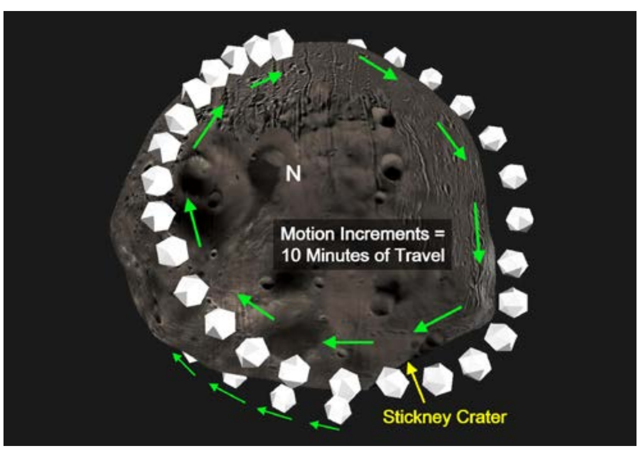

Fig 5. A test boulder from Stickney Crater moves in a series of rolling and suborbital motions around Phobos. After a brief suborbital flight that passes over Stickney Crater, the test block rolls across the northern hemisphere of Phobos. The motion across the northern hemisphere closely follows the observed pattern of the non-linear groove indicated in Fig 4. The motion of test blocks that circle Phobos up to 360° (and more) suggests a mechanism that accounts for non-linear and non-parallel grooves.

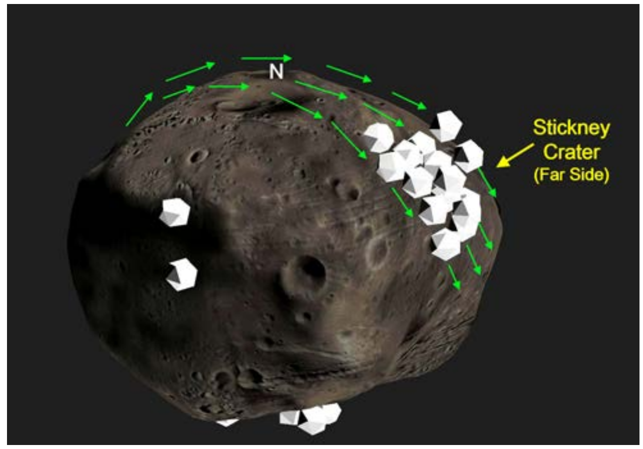

Fig 6. A portion of test boulders launched generally to the south from Stickney Crater pass in suborbital motion over the southern and trailing hemispheres of Phobos, then roll across the northern hemisphere. This motion adds to the northern pattern shown in Figs. 1 and 2. Further, this motion orthogonally crosscuts earlier east-west Stickney boulder motions, consistent with previously documented crosscutting grooves [2,3].

Conclusions: We describe a system of Stickney boulder ejecta motions under the influence of Phobos' rotation and the gravity of Mars and Phobos. From our study, we conclude the following: 1) At a = 12,000 km, the rotation of Phobos, and the gravity of Phobos and Mars, guide Stickney ejecta boulder motions that are consistent with the general and specific patterns of observed grooves on Phobos. 2) Test boulders exit radially from Stickney Crater and typically move in parallel motions thereafter. 3) Boulders may travel 360° or more around Phobos to produce crosscutting grooves. Consequently, Stickney ejecta boulder motions are able to produce what appear to be episodic events. 4) Stickney ejecta boulders, launched to the east, may travel more than 360° around Phobos to crosscut the floor of Stickney Crater. 5) Sudden regional changes in slope produce suborbital flight. Due to suborbital motion, Stickney ejecta boulders do not roll across the trailing orbital apex of Phobos. 6) Rolling boulders tend to maintain continuous contact with local terrain contours. 7) Due to gravitational symmetry, our model is unable to predict the pre-Stickney impact tidal lock orientation of Phobos. 8) When testing our model at a = 12,000 km, the observed motion of Stickney boulders is consistent with the observed pattern of grooves. Boulder motions at a = 10,000 km and a = 14,000 km are inconsistent with the grooves as observed. 9) The flux of later-arriving high-velocity Stickney ejecta is sufficient to disintegrate and bury groove-producing boulders. Grooves $\gtrsim$80 m in width survive this process [4]. 10) At a = 12,000 km, we observe no instances of grooves that are inconsistent with a model of formation by boulders from Stickney Crater as proposed by Wilson and Head (2015) [1].

References: **[1]** Wilson and Head (2015) *Planet. Space Sci., 105*, 26-42. **[2]** Murray and Heggie (2014) *Planet. Space Sci., 102*, 119-143. **[3]** Basilevsky et al., (2014) *Planet. Space Sci., 102*, 95-118. **[4]** Ramsley and Head (2015) *Lunar and Planetary Science Conference*, 1414. **[5]** Thomas et al. (2000) *J. GeoPhys. Res., 105*, 15,091–15,106. **[6]** Thomas (1998) *Icarus, 131*, 78-106. **[7]** Thomas (1997) *Phobos Optical Shape Model*. . **[8]** Ramsley and Head (2013) *Planet. Space Sci., 87*, 115-129. **[9]** Neukum (2010) *Mars Express HRSC Camera ESA/DLR/FU.*