STICKNEY CRATER: SECONDARY IMPACTS, BOULDERS, GROOVES, AND THE SURFACE AGE OF PHOBOS

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Introduction: We summarize our recent studies on the history of Phobos surface morphology subsequent to the time of the Stickney impact event, outline outstanding questions, and propose related scientific goals and objectives. Models, observations, and conclusions suggest a young age for the surface of Phobos and help test and account for the unique present-day surface morphologies [1-4].

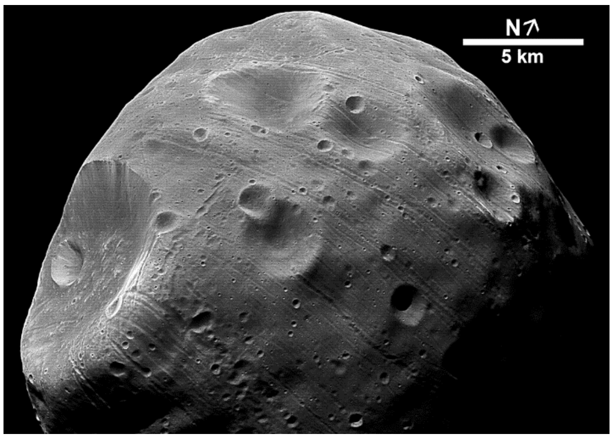

Fig 1. The Phobos northern hemisphere (Stickney Crater, left). Image: Mars Express HRSC camera, Orbit 756.

History of Phobos: Morphologically and spectrally similar to C-type asteroids, Phobos (average radius ~11 km) displays a shape modified by 1) a global background of large impacts, including the youngest of these, the D ~9 km Stickney Crater; 2) a layer of regolith up to several hundred meters thick [5]; 3) solitary and groupings of parallel, linear, pitted and uniformly wide grooves that cover and crosscut most of the Phobos surface [6]; 4) a recent substantial spike of craters D $\lesssim$0.6 km [3]; and 5) optical spectra that is consistent with heavily space-weathered regolith [7].

The orbit of Phobos is decaying, suggesting that this moon previously occupied higher orbital altitudes. Yet for all of its orbital history, Phobos has very likely remained below the synchronous altitude of Mars [8]. Due to its close proximity to Mars, models attempting to predict a Phobos asteroid-capture scenario are hard-pressed to construct a plausible mechanism [9].

Likely resolving the question of Phobos' origin, beginning with a Vesta-size impactor that collides with Mars early in the history of the Solar System, Canup et al., (2018) predict the present-day size, quantity, and orbits of the martian moons. According to the impact-formation model, Phobos and Deimos are not captured C-type bodies from the asteroid belt. Instead, they accreted from ejecta launched from a giant impact on Mars, and the moons have always orbited around Mars [10].

Assessing the volume and velocities of Stickney Crater ejecta that was launched into orbits around Mars, $\lesssim$1,000 years after the Stickney impact [3, 11-15] orbiting ejecta returned as secondary impacts to produce most present-day craters observed on Phobos D $\lesssim$0.6 km [3]. Modeling also suggests a deposition of new regolith 28-44 m thick from the Stickney event [3, 16]. Approximately half of this regolith is Stickney primary ejecta material and half was produced by high-velocity Stickney secondary impacts [3]. Due to the gardening effects of solar system impact flux, since the time of the Stickney impact, $\lesssim$0.5 m of new regolith has accumulated on the surface of Phobos [16].

Based on crater-counting methods that assume a background flux of solar system projectiles, Stickney Crater displays an age of 2.8-4.2 Ga [17]. However, where we observe an unambiguous kink in the crater size-frequency distribution of Phobos craters D $\lesssim$ 0.6 km that is consistent with secondary impacts from Stickney, and we observed no SFD kink inside Stickney, most Phobos craters D $\lesssim$ 0.6 km are Stickney secondary impacts [3].

Where crater-counting methods cannot assume that craters D $\lesssim$0.6 km on Phobos were produced by a steady flux of solar system projectiles, and where the Stickney crater interior contains only one crater larger than D ~0.6 km, crater-counting methods cannot yield an accurate age for the Stickney impact. [3].

Rather than crater-counting methods, we arrive at an age for Stickney Crater based on three factors: 1) Setting an upper limit of ~500 Ma, we observe small boulders that should not survive on the surface of Phobos more than 500 million years [3, 18, 19]; 2) Setting a lower limit, substantial space weathering suggests an age of at least ~100 Ma [3, 7]; and 3) applying a dynamical computer model when Phobos was orbiting Mars at three geologically earlier semimajor axis altitudes [4], at ~150 Ma [8] we observe traveling motions of rolling boulders from Stickney Crater that consistently align with observed patterns of Phobos grooves [4].

Phobos Groove Hypotheses: Since their discovery in the late 1970s, numerous hypotheses have been raised to explain the formation of Phobos grooves. These include: 1) Original primary stratigraphy [20]; 2) fracturing from the Stickney impact event [21], and subsequent regolith drainage [22]; 3) the close proximity of Mars gravitation that, through tidal forces, may be producing a pattern of fissures, and similar to the Stickney fracturing model, grooves via regolith drainage [23]; 4) Grooves as scouring marks produced during a process that captured Phobos into an orbit around Mars [9]; 5) Chains of craters from impacts on Phobos [24]; 6) a pattern of secondary impact craters from ejecta launched by a dozen impact events on the surface of Mars [6]; and 7) boulders rolling from Stickney Crater [25, 26]. Each of these groove-formation hypotheses faces objections:

Generally defined by large muted craters, the global morphology of Phobos is dominated by irregular impact-produced landforms. Superposed atop older features, we further observe a layer of regolith up to several hundred meters thick [5]. In view of a thick layer of regolith emplaced atop a substantial reworking of Phobos by large impacts, and a Phobos formation model that predicts a stochastic process of accretion [10], it is unlikely that original primary stratigraphic units are observable as grooves or any other morphologies on Phobos.

The Stickney impact may have produced fractures, yet many grooves observed on Phobos do not radiate from Stickney, and rather than observing generalized patterns of radially aligned grooves that continually diverge along predicted lines of impact-related stress, we instead observe orderly patterns of grooves in parallel and cross-cutting families [6].

Tidal stresses produce strain that might fracture Phobos, and in many locations these forces align with observed grooves. However, the tidal stress model does not account for all grooves, particularly crosscutting grooves [6].

Grooves as scouring marks produced during a process of asteroid capture face a daunting list of objections. Principally, these include an unlikely capture process that takes place early in solar system history, grooves emplaced atop a thick layer of regolith that accumulated *since that time*, and recent computer modeling that strongly supports the formation of Phobos following a large impact on Mars [10].

Grooves produced by ejecta returning from impacts on Phobos are limited to Stickney exit velocities of ≲8 m/s, which if exceeded, inserts boulders into orbits around Mars. At crater launch velocities ≲8 m/s, boulders do not produce impact craters. Instead, these velocities produce rolling and bouncing boulders.

Grooves as chains of secondary craters from a dozen impacts on Mars face similar constraints. Several hundred thousand identical fragments must launch into naturally constrained patterns of progressively changing velocities measured in millimeters per second, with progressively varying vector angles measured in microradians – every block adjusted to disperse according to the requirements of its final destination after flight times ranging from 20 minutes to several hours, all without a single interloper in size or wayward flight trajectory to disrupt a generally flawless pattern of observed grooves [1]. Further, since the time of the Stickney impact (an event that predates the grooves) by several orders of magnitude, the total volume of ejecta from Mars is insufficient to account for grooves as secondary impacts [1, 2].

The model of grooves from large slow-moving boulders produced by Stickney Crater faces the largest number of objections [4, 6]: Like the problem of Stickney impact fracturing, many grooves do not radiate from Stickney, and where we would expect to see boulder tracks dispersing from the crater rim and diverging without any intersections, grooves crosscut in many places. Further, grooves are observed *inside* Stickney, and considering the principle of geological superposition, this strongly suggests that Stickney Crater *predates* the grooves. Another objection points to a large region where grooves are absent from the Phobos trailing hemisphere. If boulders rolled across Phobos, why not here? Then there is the question of missing boulders. Where are they today? And if boulders were destroyed and buried by a spike of high-velocity Mars-orbiting Stickney ejecta [3], how did the grooves survive this process?

Testing the Rolling Boulder Model: Our computer model focuses on Phobos rolling boulders at a Phobos semimajor axis orbit of 12,000 km (a 14,000 km semimajor axis produces boulder motion patterns that are inconsistent with observed grooves, and at 10,000 km, boulders mostly drift into orbits around Mars).

Due to the close proximity of Mars and how the Stickney impact desynchronized the tidally-locked rotation of Phobos, rolling boulders from Stickney are subject to a complex array of non-intuitive rotational and gravitational forces [4].

Stickney Crater produced a sufficient volume of low velocity ejecta to account for many boulders with diameters up to D 400 m [3]. Boulders traveling on the Phobos surface with Stickney exit velocities ≳8 m/s preferentially exit to orbits around Mars. Boulders with exit velocities ~4-8 m/s tend to alternate between surface travel and ballistic flight, and apart from the trailing hemisphere of Phobos, boulders with exit velocities ≲4 m/s tend to remain in contact with the Phobos surface [4].

Low surface-travel velocities intuitively suggest limited travel distances. Yet with boulder bulk masses of up to 60 million tons and Phobos gravitation that is ~1,000 times less than Earth, there is very little impeding force to halt the traveling motions of Phobos boulders [26].

In our model, boulder motions initially radiate from Stickney and the radial pattern accounts for proximal grooves to the northeast, east, and southeast of Stickney. Almost immediately, however, a combination of Phobos and Mars gravitation and the rotation of Phobos translate the motions of boulders into generally linear and parallel patterns. Also, due to periods of suborbital flight, many boulders travel more than half way around Phobos, some 360° or more, and due to this process, we observe boulders that return to the vicinity of Stickney after traveling ~360° around Phobos in motions that align with parallel and tangential grooves to the west and northwest of Stickney, accounting for proximal non-radial grooves [4].

Due to travel distances >180°, boulder motion patterns intersect previous patterns, accounting for the observation of cross-cutting grooves [4]. Resolving the question of grooves inside Stickney Crater, approximately eight hours after the Stickney impact, we observe boulders returning to Stickney after 360° of travel. Entering Stickney, they roll down the crater wall, across the crater floor, and up the opposite wall [4].

Local suborbital boulder flights are typically driven by downhill terrain that gradually accelerates boulders. Encountering a persistent drop in elevation, boulders take flight. After brief suborbital transits, boulders return to Phobos. When approaching the generally low-elevation trailing hemisphere of Phobos, rolling boulders accelerate until they encounter a regionally pervasive reduction in topographical elevation, and in every test case in our model, boulders take flight, thereby accounting for an absence of grooves on the Phobos trailing hemisphere [4].

Our computer model addresses most objections to the rolling boulder model. However, two unresolved questions remain: At the conclusion of the Stickney impact event, a portion of large Stickney ejecta boulders remained on Phobos, and many other boulders subsequently returned from orbits around Mars. Why are larger boulders generally missing in the present day? To address this question, we calculate the size-frequency and velocity of Stickney impact ejecta fragments that returned to Phobos [3]. As it turns out, the spike of returning high velocity ejecta was sufficient to fragment and bury groove-producing boulders beneath a new layer of regolith 28-44 m thick [3, 16]. Yet this raises another question: How did the grooves survive the Stickney secondary impact spike? In short, when we predict the size-frequency-distribution of secondary Stickney impacts and gardening effects, *most Phobos grooves did not survive*. Instead, the spike destroyed all grooves ≲80 m wide, muted grooves 80-200 m wide, and minimally degraded the widest grooves [4].

Future Exploration of Phobos: Returned samples from Phobos will likely settle the question of whether Phobos is a captured asteroid or accreted ejecta from an impact on Mars, and samples will likely contain a concentration of Mars ejecta from impacts on Mars (we predict ~250 ppm [2]). Sampling surface boulders on the floor of Stickney Crater may definitively establish the age of Stickney and its associated processes. Active seismic imaging may detect (or rule out) groove-formation models that are based on Phobos cracks, and also offer evidence for buried boulder fragments. Core sampling might detect evidence of boulder-track regolith compression, and also sequestered volatiles. Ground penetrating radar may help to infer the total distribution and concentration of buried boulder fragments.

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