THE SECONDARY IMPACT SPIKE ON PHOBOS FROM STICKNEY CRATER EJECTA. K. R. Ramsley[1,2] and J. W. Head[1]. [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA. [2]School of Engineering, Brown University, Providence, RI 02912 USA, Kenneth_Ramsley@brown.edu.

Introduction: Utilizing two different planetary background flux estimates and counting craters where the Mars Express HRSC camera offers sufficient image resolution, Schmedemann et al. (2014) [1] derive two possible age ranges for the largest impact feature of Phobos, Stickney Crater. Case A derives 2.8–4.2 Ga by assuming that Phobos has orbited Mars during the entire period. Case B derives an age of 38 Ma – 3.4 Ga by assuming that Phobos is a recently captured asteroid that was exposed to Main Belt flux. Our model investigates a third option where we explore the possibility that a young Stickney impact produced a spike in the impact flux in the form of secondary impact projectiles that make its surface look prematurely ancient by forming the vast majority of the counted superposed craters < 0.6 km and a lesser population up to 2 km due to extreme ejecta volume and velocity.

Stickney blocks: Small boulders on Phobos are degraded and destroyed by meteor impact flux subsequent to their emplacement/exposure at a rate that suggests that these boulders have been exposed for ≤ 0.5 Ga [2]. Consequently, an ancient age for Stickney of 2.8–4.2 Ga is unlikely in view of the work of Thomas (2000) [3] who mapped thousands of blocks that are located proximally to the east of Stickney Crater, and further observes that the quantity and distribution of the blocks is morphologically consistent with ejecta from a large recent impact. Based on their quantity, size, and preferential areal concentration that increases with closer proximity to Stickney Crater, this strongly suggests that Stickney Crater is the source of the blocks [3]. Apart from invoking the substantially uncertain crater-counting age of a recent asteroid capture of Phobos [1], how can one reconcile an age of ≤ 0.5 Ga for Stickney-related boulders [2,3] and a crater-counting age prediction of 2.8–4.2 Ga [1]? Either the boulders are produced by an alternate source or the craters that are used for counting are produced by an alternate mechanism other than the background impact flux [4]. We investigate the latter case.

Stickney ejecta: The vast majority of ejecta from Stickney is trapped in orbits around Mars, and because the orbits of the ejecta are altered at a common origin in space, they continue to intersect the common origin during each orbit. Eventually, Stickney ejecta fragments and Phobos pass through the same location in space at the same time [9]. Within dozens to hundreds of years (≤ 200,000 orbits of Phobos) ≥ 95% of Stickney ejecta intersects and impacts onto Phobos. [5–9].

Although ejecta from Stickney returns to Phobos, there is a rule of orbital mechanics that precludes secondary impacts on primary impact sites when the target is a tidally-locked body. Primary impact ejecta on tidally-locked bodies intersects the target body generally on the opposite hemisphere of the primary impact site [9]. Consequently, a primary crater that is produced on a tidally-locked body remains *unexposed* to its own secondary impacts.

Breaking the tidal lock of Phobos: The rule of celestial mechanics that shields a primary crater on a tidally-locked body from its own secondary impacts is violated when the impact event breaks the tidal lock. If the Stickney impact broke the tidal lock of Phobos, the entire surface of Phobos would be exposed to Stickney ejecta, including Stickney Crater and its proximal regions.

Does the Stickney impact produce an impulse that breaks the tidal lock? First, we assume that the boulder evidence sets an upper limit of 0.5 Ga for the age of Stickney [2,3]. In view of the increasing orbital decay rate of Phobos, an orbital altitude that is 4,000 km above the present day is selected for our model [10–13]. At this altitude, the Stickney impact increases the rotation rate of Phobos such that it rotates ~ 6 times for every 5 orbits around Mars. In fact, a Stickney impact at *any* orbital altitude, including the present-day altitude, produces an impulse that is sufficient to break the tidal lock of Phobos.

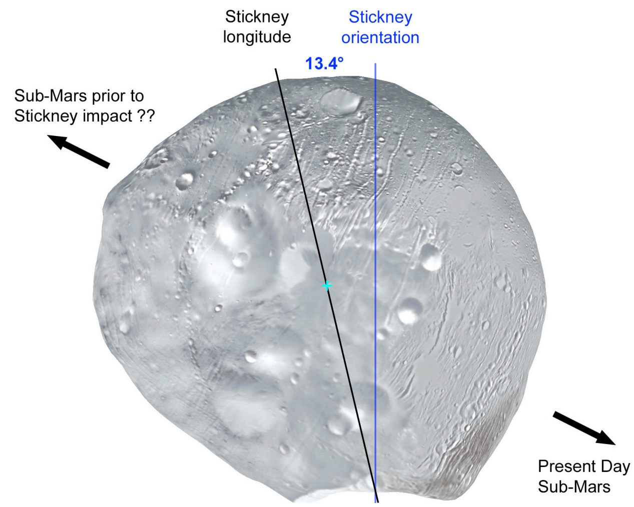

Fig 1. Stickney Crater is misaligned with the CG of Phobos by 13.4°. Ejecta that is preferentially directed to the west from the tilted crater provides a mechanical advantage to break the tidal lock of Phobos. The original tidal lock may have been 180° out of phase from the present day or the same as the present-day.

The Stickney impact is able to break the tidal lock of Phobos because the impact takes place on a western hillside of a high-elevation equatorial region of Phobos. Consequently, a large impulse vector component is directed to the east (Fig. 1). The impulse is analyzed using the Tsiolkovsky rocket equation. The analysis takes into account the inefficiencies of the crater formation process where ~ 40% of the impact impulse is lost to heating, compression, and the inefficiencies of a cone-shaped "rocket exhaust." By supplying the Stickney impact projectile mass, its velocity, and the impulse inefficiency factor, it is possible to accurately predict the added rotational angular momentum that is produced by the Stickney impact event.

The additional angular momentum breaks the tidal lock if the de-spin time is substantially longer than the time that is required for Phobos to rotate more than ¼ phase from its tidal lock orientation. Beyond this point, Phobos will continue to rotate until it regains its original tidal lock orientation or is relocked 180° out of phase from the original tidal lock orientation. For this reason, the Stickney impact could have taken place in the present-day orientation of Phobos or 180° out of phase from the present day. Further, if the lock is broken, the duration of the time when Phobos continues to rotate faster than its orbital period must be sufficient to expose the entire global surface of Phobos to returning Stickney ejecta (at least several hundred years).

Does Phobos rotate freely for a sufficient period of time? Based on equations from Gladman et al. (1996) [14] and Burns (1977) [15], Phobos de-spins back to a tidal lock after 56,800 years with a lower limit of 14,000 years. Typically, the computation of the de-spin time lacks state information about the initial rotation rate and the orbital altitude of the satellite. However, these variables are supplied by our model. The Love number k_2 and the value of Q also contribute uncertainty. Yet, they may be estimated within factors of ~ 2X, and we are therefore confident in our prediction of a lower limit of 14,000 years for the de-spin time of Phobos after a Stickney impact at 0.5 Ga. 14,000 years is clearly a sufficient length of time to permit Phobos to be globally and uniformly exposed to Stickney secondary impacts.

The Stickney secondary impact spike. The Stickney impact impulse produces a counterforce. Approximately 10% of the counterforce vaporizes, melts, shocks, and compresses target material. The remaining ~ 90% of the counterforce is launched as ejecta. During the next several dozen to hundreds years, approximately 95% of the Stickney ejecta returns to Phobos in the form of secondary impacts that stochastically impact across the entire global surface of Phobos [9]. Based on the mass of the ejecta from Stickney Crater and the kinetic energy of the Stickney ejecta counterforce, it is possible to accurately compute the average secondary impact velocity of returning Stickney ejecta onto Phobos. This works out to an average velocity of 1.1 km/s.

Assuming that ~ 95% of the Stickney Crater ejecta returns from orbits around Mars, the volume of projectiles from Stickney that impacts onto Phobos is 3.7×10^{10} m^3 with a mass of ~ 6.9×10^{13} kg. With a Phobos surface area of ~ 1.54×10^9 m^2, the volume of secondary impact flux that is distributed across the geographic surface of Phobos is equal to a projectile material depth of ~ 24 m; this phase of reimpact would have taken place over the course of several dozen to several hundred years. The Stickney secondary impact storm on Phobos may be imagined as 3.6 m diameter projectiles impacting onto every square meter of Phobos at a velocity of 1.1 km/s.

When we distribute the impacting ejecta from Stickney Crater on Phobos according to the typical size/frequency curve of a crater population, we predict a sharp spike in the number of craters on Phobos < 0.6 km plus a lesser population up to 2 km due impact velocities ≤ 4.6 km/s and the extraordinary volume of ejecta that returns. This distribution is entirely consistent with the size/frequency curves of Schmedemann et al. (2014) [1] where the counting area *outside* of Stickney Crater produces a size/frequency curve of large degraded primary craters with a clearly superposed population of younger craters < 0.6 km and a sharp kink in the curve that strongly suggests two separate populations of impact flux.

Furthermore, when Schmedemann et al. (2014) [1] counts craters *inside* Stickney, this reveals no older flux of larger primaries and no sharp kink in the size/frequency curve. Inside Stickney only one population of craters is observed and this population is generally consistent with the population of younger craters that are plotted outside of Stickney. This suggests that the source of the craters inside Stickney is produced by the same flux that produced the superposed population of younger craters outside of Stickney.

Because the crater-counting curve inside Stickney Crater is not exactly smooth, a recent sub-population of primary craters has likely been emplaced inside Stickney since the time of the Stickney impact. Yet, in consideration of the predicted storm of secondary impacts from Stickney and the clearly observed sharp kink in the size/frequency curve in the counting area outside of Stickney, most of the craters inside Stickney are secondary impacts from Stickney.

Conclusions: We conclude that the vast majority of the present-day distribution of craters on Phobos < 0.6 km and a portion of the population ≤ 2.0 km are unrelated to the background meteorite flux of Phobos and are instead consistent with an over-printing of secondary craters from Stickney ejecta that were produced during a brief secondary impact spike during the most recent 0.5 Ga. The emplacement of secondary impacts from Stickney Crater across Phobos severely disrupted the crater-counting clock and produced a crater size-frequency distribution that is consistent with the apparent "ancient ages" that are interpreted by Schmedemann et al. (2014) [1]. Thus, caution must be exercised when determining surface ages by crater-counting in cases where significant ejecta can return to the surface, but may not be recognized as secondary impact craters.

Our analysis suggests that secondary ejecta impacts from a relatively young (≤ 0.5Ga) Stickney Crater can reconcile 1) the observation of Stickney-related boulders by Thomas (2000) [3], 2) the inferred boulder survival lifetimes of Basilevsky et al., (2014) [2] and 3) an apparently ancient age of Stickney of 2.8–4.2 Ga [1].

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