The Stickney Crater ejecta secondary impact crater spike on Phobos: Implications for the age of Stickney and the surface of Phobos

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Abstract:

The size-frequency distribution (SFD) of superposed craters inside Stickney Crater has been used by Schmedemann et al. (2014) to date Stickney Crater to ~2.8–4.2 Ga by assuming that all craters on Phobos were produced by background impacts. We hypothesize, however, that on Phobos, a global spike of secondary impact craters with diameters (D) <0.6 km and a portion of craters up to D 2 km were produced by Stickney Crater ejecta that returned from orbits around Mars. Thus, according to our model, the volume of ejecta that is produced by the Stickney impact on Phobos accounts for the superposed craters inside Stickney Crater, and also accounts for a sharp kink in the SFD of craters D <0.6 km in the Schmedemann et al. (2014) "Phobos average" counting area. In view of how the vast majority of craters on Phobos D <0.6 km and a portion of craters D <2 km were very likely produced by Stickney ejecta, the age of Stickney Crater may not be determined from the superposed craters inside Stickney Crater, and the entire surface age of Phobos may not be dated using craters D <2 km. In order to test our hypothesis, the following three questions are addressed: 1) Did the Stickney impact produce a sufficient impulse to desynchronize the orbital tidal lock of Phobos to produce a desynchronized secular rotation that exposed the entire surface of Phobos to Mars-orbiting Stickney ejecta? 2) Did the desynchronized secular rotation of Phobos persist for a sufficient length of time to expose Stickney Crater to secondary impacts until the volume of intersecting ejecta was fully depleted by secondary impacts? 3) Did the Stickney impact produce a sufficient volume of ejecta fragments to account for the superposed craters that are observed inside Stickney and the spike of ejecta that is observed in the "Phobos average" counting area of Schmedemann et al. (2014)?

To compute the impulse that desynchronized the tidal lock of Phobos we apply the Tsiolkovsky rocket equation and reduce its effect by considering the cone-shaped geometry of ejecta and the energy partitioning of impact processes that produce vapor, melt, and mechanically rework the target through compression, fracturing, and displacement. Based on our calculations, the Stickney Crater impact produced a sufficient impulse to desynchronize the tidal lock of Phobos and induced desynchronized secular rotation for a minimum time period of 5,000 years, and very likely *much longer*. In view of how Mars-orbiting ejecta from impacts on Phobos fully accumulates back onto Phobos within ~1,000 years, the ≲5,000-year period of desynchronized rotation was sufficient to fully expose Stickney Crater to its own secondary impacts. Other than a Stickney impact, there is no recent impact on Phobos that is capable of producing a SFD of secondary impacts that is consistent with a sharp kink in the SFD of craters D <0.6 km that are located west of Stickney Crater. In view of how our calculations predict that the Stickney impact produced a rotational desynchronization of Phobos that exposed the entire surface of Phobos to an intense spike of Stickney secondary impact ejecta *including the surface of Stickney Crater*, we predict that Stickney Crater would appear abnormally ancient due to Stickney secondary impacts that superpose the previous record of background craters on Phobos at D <0.6 km and a portion of craters up to D 2 km. The superposition of secondary craters consequently renders surface dating via crater counting unworkable based on craters D <2 km, and we conclude an alternate age for Stickney Crater of 0.1–0.5 Ga that is constrained by the boulder evidence of Thomas et al. (2000), the boulder destruction rate analysis of Basilevsky et al. (2013, 2015), and the observed space weathering of Phobos regolith (Pieters et al., 2014).

In related analyses we 1) predict the global equivalent thickness of deposits on Phobos from Stickney ejecta (Thomas et al., 2000) and accumulated Stickney secondary impact ejecta, 2) summarize the size frequency distribution (SFD) and temporal nature of the Stickney secondary impact spike on Phobos, 3) examine the hypothesis that the Stickney impact was a trailing hemisphere event on Phobos that reoriented Phobos to its present-day synchronous lock longitude, 4) set limits on the volume of low-velocity Stickney ejecta that is available to produce Phobos grooves (Wilson and Head, 2015) and subsequently degrade the grooves (Murchie et al., 1989), and 5) estimate the SFD of a meteor spike on Mars from a trailing hemisphere Stickney impact.

Index Terms: Phobos, Stickney Crater, tidal lock, secondary impacts, Tsiolkovsky rocket equation.

1. Introduction.

1.1. ***The age paradox of Stickney Crater.***

Studies of the age of Stickney Crater (D ~9 km), the largest crater on Phobos located ~50° west of the sub-Mars longitude (Fig. 1), have produced an unresolved paradox for the age of the crater, based on well-reasoned, yet conflicting, lines of evidence (see summary in Ramsley and Head, 2014).

On the one hand, Thomas et al. (2000) map thousands of boulders that are located proximally to the east of Stickney Crater and observe that the quantity and distribution of the boulders is morphologically consistent with ejecta from a large recent impact. The quantity, size, and preferential areal concentration of the boulders (all increase with closer proximity to Stickney Crater), strongly suggests that Stickney Crater is the source of the boulders. Furthermore, Basilevsky et al. (2013, 2015) calculate that small boulders on Phobos are destroyed by meteor bombardment in $\lesssim$0.5 Ga. Therefore, if the boulders are fragments of Stickney Crater ejecta, this would limit the age of Stickney Crater to $\lesssim$0.5 Ga.

On the other hand, in contrast to a boulder-supported age of $\lesssim$0.5 Ga for Stickney Crater, Schmedemann et al. (2014) count craters within Stickney Crater and derive two possible age ranges utilizing two different background flux regimes. Case A yields an age for Stickney Crater of 2.8–4.2 Ga by assuming that Phobos has orbited Mars during the entire period, and Case B derives an age of 38 Ma–3.4 Ga by assuming that Phobos is a recently captured asteroid that was previously exposed to the Main Belt flux (O'Brien and Greenberg, 2005). Because there is currently no viable model that supports a *recent* capture of Phobos into a sub-synchronous orbit around Mars, we consider only the age range of Case A.

In view of the age paradox inferred by 1) a young boulder age of $\lesssim$0.5 Ga, versus 2) an ancient age of up to 4.2 Ga based on the assumption of background superposed craters, either the boulder evidence is incorrectly interpreted or the assumption of superposed background craters is incorrect. The interpretation of the two lines of evidence, *cannot both be correct* (Ramsley and Head, 2014).

1.2. ***Stickney crater as a source of secondary impacts on Phobos.***

In order to address the paradox of younger and older ages for Stickney Crater, we first consider a source for the superposed craters inside Stickney that is consistent with the boulder evidence of Thomas et al. (2000). Other than the background flux of solar system projectiles, what other mechanism might produce the observed SFD of superposed craters inside Stickney?

Ramsley and Head (2013a, 2013b) suggest that ejecta from impacts on Phobos is trapped in orbits around Mars and returns to Phobos to produce secondary impacts. However, the studies of Ramsley and Head (2013a, 2013b) focus *only* on the fate of ejecta that intersects Phobos from primary impacts on Mars. Mars ejecta typically impacts Phobos with a velocity of 2–3 km/s (Ramsley and Head, 2013b) which produces ejecta from secondary impacts on Phobos with velocities that are generally <800 m/s. As a consequence 95-99% of the Phobos ejecta that is produced by impacts from Mars ejecta remains in orbit around Mars (Ramsley and Head, 2013b). In contrast, the higher launch velocities of ejecta that is produced by primary impacts on Phobos return a smaller proportion of secondary impacts to Phobos due to the limited gravitational capacity of Mars to trap the higher velocity ejecta.

Due to its diameter of ~9 km, Stickney Crater is most likely to be a primary crater. Depending on whether the pre-impact tidal lock of Phobos was similar to the present day, or rotated ~180°, the Stickney impact took place either on the *leading* hemisphere or the *trailing* hemisphere of Phobos.

If the Stickney impact took place on the *leading* hemisphere of Phobos, the average velocity of a solar system projectile impact is ~13 km/s. If the Stickney impact took place on the *trailing* hemisphere the average velocity of a solar system projectile impact is ~9 km/s (Neukum and Wise, 1976; Ivanov, 2001).

Due to the way in which the launch velocity of Phobos ejecta combines with or subtracts from the Mars-orbital velocity of Phobos, a portion of the higher-velocity *leading* hemisphere Stickney ejecta is lost to solar orbits, whereas a portion of the higher-velocity *trailing* hemisphere Stickney ejecta intersects Mars. Stickney ejecta that is not lost to solar orbits or to Mars is inserted into orbits around Mars where it intersects the orbit of Phobos (see video in SOM). According to our modeling of the fate of Stickney impact ejecta, ~40% of the ejecta from a *leading* hemisphere Stickney ejecta exits to solar orbits. From a *trailing* hemisphere impact, ~10% of the ejecta intersects the atmosphere of Mars and substantially <1% exits to solar orbits.

1.3. ***The pre-impact tidal lock orientation of Phobos.***

As we derive and describe in our SOM desynchronization calculations, our calculations show that the Stickney impact desynchronized the tidal lock of Phobos by increasing the rotational rate of Phobos to where Phobos rotated one extra sidereal rotation for every ~ 2.5 orbits of Phobos around Mars. Due to how Phobos had an equal chance to re-lock into one of two possible synchronous orientations at the conclusion of the desynchronized rotation, it is possible that the pre-impact orientation of Phobos was similar to its present-day longitude, which produced a Stickney impact on the *leading* hemisphere of Phobos **or**, prior to the Stickney impact, Phobos was oriented ~180° from the present day and the Stickney impact took place on the *trailing* hemisphere of Phobos. From an orbital mechanics standpoint, as long as the tidal lock of Phobos was desynchronized, a *leading* hemisphere Stickney impact **or** a *trailing* hemisphere Stickney impact are both equally plausible initial conditions (Fig. 1,2). Consequently, we analyze both scenarios that 1) the Stickney impact took place on the *leading* hemisphere of Phobos near its present-day longitude of ~50° W, and 2) that the Stickney impact took place on the *trailing* hemisphere of Phobos at ~130° E (~180° in longitude from the present day longitude of Stickney).

1.4. ***Special circumstances that facilitated the Stickney impact tidal lock desynchronization process.***

In our SOM desynchronization calculations, we calculate the acceleration components of the crater impulse that produced the desynchronization of the tidal lock of Phobos. Typically, a substantial alteration of the rotational angular momentum of a target body requires the special circumstances of a grazing impact from a very large projectile. Yet, it appears that the irregular shape of Phobos offers an alternative process where the Stickney impact may have intersected Phobos on the western equatorial slope of a large topographic high. As a consequence of the location of the Stickney impact, the angle of the cratering impulse was offset from the gravitational center of Phobos by 13.4°, and this offset produced an eastward vector component of acceleration impulse that added to the rotational angular momentum of Phobos in the direction of its pre-impact rotation (Fig. 2).

1.5. ***Tidally-locked moons shield impact sites from their own secondary impacts.***

Phobos ejecta that is trapped in orbits around Mars launches away from Phobos in one direction and comes around to intersect Phobos on the opposite hemisphere (Ramsley and Head, 2013b). When combined with the cone shaped pattern of ejecta fragments that disperses into orbits around Mars, this produces a distribution of intersecting orbits that exposes ~70% of the surface of Phobos to secondary impacts in a zone that is centered on the *opposite hemisphere* of Phobos from the location of the primary impact site. Consequently, the impact site and its surrounding region is shielded from its own secondary impacts (Ramsley and Head, 2013b).

If the tidal lock of Phobos had not been desynchronized by the Stickney impact, or if Phobos had de-spun rapidly back to its initial tidal lock orientation, secondary impacts from Stickney ejecta would not have significantly accumulated inside Stickney Crater or proximally to Stickney Crater. Therefore, in order for Stickney Crater to become fully exposed to its own secondary impacts, the impulse of the Stickney impact must be sufficient to produce a desynchronized secular rotation of Phobos that persisted for a sufficient time to expose Stickney Crater to the full duration of its own secondary impacts.

1.6. ***The exposure of Stickney Crater to its own secondary impacts and ejecta accumulation.***

Phobos and ejecta from Phobos orbit around Mars through a shared common volume of space at the location of the original impact event. For this reason there is a strong preferential focus that brings Phobos ejecta back into contact with Phobos (Fig. 3). Over time, the common region of intersection in space extends along the orbit of Phobos and the accumulation of ejecta on Phobos reduces the bombardment volume and intensity.

Dust $\lesssim 300\ \mu$m is typically deorbited to the atmosphere of Mars or to solar orbits within several years, whereas ejecta fragments $\gtrsim 300\ \mu$m tend to remain in orbit around Mars until they intersect the surface of Phobos over a period of up to ~1,000 years through a process of secondary, tertiary, and additional generations of impacts on Phobos until the fragment population is entirely depleted (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996; Ramsley and Head, 2013b). Consequently, in order for Stickney Crater to be fully exposed to its own secondary impacts the desynchronized rotation of Phobos, must persist for at least 1,000 years.

Over time, orbital parameters of ejecta become increasingly similar to Phobos due to the energy depletion of tertiary and additional generations of impacts on Phobos, and toward the end of the accumulation process ejecta globally settles onto Phobos without producing impact craters. The gradual lowering of impact velocities over time reduces the proportion of ejecta that is re-launched, which eventually drives the accumulation process to a conclusion. The process that began with a sharp punctuated spike of high-velocity secondary impacts diffuses over ~1,000 years into a stochastic distribution of low-velocity accumulation that slowly fills and mutes the distribution of previously emplaced craters and other features on Phobos (Ramsley and Head, 2013b).

1.7. *Stickney ejecta budget.*

To answer the question of whether or not there was a sufficient SFD of Stickney secondary crater impacts to account for the crater counting of Schmedemann et al. (2014), we work out the total volume of ejecta that was produced by the Stickney impact and then calculate the proportion of the fragments that were initially trapped in orbits around Mars with sufficient orbital velocities to produce secondary impact craters on Phobos. The budget is computed using the excavated volume of Stickney Crater and informed by the study of Wilson and Head (2015) who analyze the fate of low-velocity ejecta from Stickney (See "Stickney Ejecta.xlsx" in SOM).

On the Moon, the consequences of low-velocity and small-fragment-size ejecta is observable as continuous deposits that are emplaced proximally to craters. These low-velocity deposits accumulate as regolith but do not excavate craters (McGetchin et al., 1973). If the Stickney impact had taken place on the Moon, ~23% of the ejecta would have been emplaced as continuous deposits that were incapable of producing craters (McGetchin et al., 1973). Consequently, we subtract 23% of the total volume of the ejecta that was launched by the Stickney Crater impact and consider that only 77% of the ejecta from Stickney was *capable* of producing secondary craters on Phobos.

A portion of the higher-velocity ejecta is either lost to solar orbits or to the atmosphere of Mars and only a portion of the 77% of higher-velocity ejecta remains trapped in orbits around Mars and *available* to produce secondary impacts on Phobos. In contrast, most of the low-velocity "continuous deposit" ejecta is also trapped in orbits around Mars, however almost none of the low-velocity "continuous deposit" ejecta is lost to solar orbits or to Mars. Although we use the expression "continuous deposit" which typically has a strong proximal association with its source crater, all ejecta from Stickney Crater is generally deposited globally and uniformly on Phobos.

The lowest-velocity proportion of ejecta falls immediately onto the surface of Phobos, which suggest a mechanism that is capable of producing grooves on Phobos (Wilson and Head, 2015).

Our preliminary modeling suggests that only a minor proportion of ejecta fragments from Phobos intersect Deimos, though it is possible that Deimos intercepts a substantial proportion of dust $\lesssim 300\ \mu$m that slowly spirals out from Mars toward solar orbits.

1.8. *High-velocity ejecta from a leading or trailing hemisphere Stickney impact.*

The pre-impact synchronous tidal lock orientation of Phobos determines the proportion of crater-producing Stickney ejecta fragments that remain in orbit around Mars. According to our modeling, a solar system projectile impact on the *trailing* hemisphere of Phobos launches ~10% of available crater-producing fragments to the surface of Mars and substantially <1% to solar orbits. Therefore ~90% of the potential secondary crater-producing projectiles from a *trailing* hemisphere impact remain in Mars orbits.

In contrast, an impact on the *leading* hemisphere of Phobos produces ejecta where ~40% of the ejecta is launched to solar orbits and ~60% of the Stickney secondary crater-producing projectiles remain in Mars orbits.

1.9. ***Tidal lock stability and implication for pre-impact and post-impact tidal lock longitude.***

There are two potential stable longitude orientations for a synchronously-orbiting "tidally-locked" moon: one that points the major axis longitude of the moon toward the parent planet, and the same longitude pointed 180° in the opposite direction (Fig. 2). The major axis longitude is equally stable in either synchronous orientation, and therefore the sub-planet longitude may be swapped 180° to the opposite longitude with an impulse that desynchronizes the tidal lock (Burns, 1977). Two lines of evidence suggest that the orientation of Phobos prior to the Stickney impact was, in fact, rotated ~180° in longitude from the present day:

1. In view of the predicted higher impact velocity and the greater quantity of background impacts on the *leading* hemisphere of Phobos, the *leading* hemisphere should manifest a higher Size/frequency distribution (SFD) of craters compared to the *trailing* hemisphere. However, the opposite is the case; a greater SFD of craters on the present day *trailing* hemisphere of Phobos is observed compared to the *leading* hemisphere (Fig. 4). This strongly suggests that Phobos was reoriented ~180° from its present day tidal lock orientation during the majority of its earlier geological history.

2. In the crater count west of Stickney Crater of Schmedemann et al. (2014) we observe a sharp kink in the SFD data at D ~0.6 km (Figs. 5c, 6c, 7c). According to our model, Stickney secondary impacts superpose earlier background craters to produce a kink that is consistent with the higher flux of a Stickney impact from a *trailing* hemisphere Stickney impact, whereas the available crater-producing fragments from a *leading* hemisphere impact appears to be insufficient to fully account for the sharp kink in the SFD data.

Although neither of these two lines of evidence is entirely conclusive, the evidence, in total, suggests that the Stickney impact took place on the *trailing* hemisphere of Phobos, and as part of the Stickney Crater event, the tidal lock of Phobos was subsequently resynchronized ~180° from the previous tidal lock longitude to the longitude of the present day (Fig. 2).

1.10. ***The small target area of Phobos focuses secondary impacts and the accumulation of ejecta deposits.***

Due to the large size of the Earth's Moon, when a primary impact takes place on the Moon, most of the volume of the lunar impact ejecta is emplaced at distal impact sites far from the primary impact site. This observation is well-supported by our modeling of the Moon (McGetchin et al., 1973), which suggests that the vast majority of secondary impacts on the Moon are broadly and thinly dispersed (Fig. 8). However, the majority of secondary impacts on Phobos from Mars-orbiting ejecta impact onto an area that is ~25,000 times less than the surface area of the Moon.

To illustrate the extent to which Phobos is exposed to a much greater concentration of ejecta, the distribution of ejecta from the D 86 km Tycho Crater on the Moon was deposited onto the lunar surface to a global equivalent thickness of ~6 cm, whereas we calculate that the D ~9 km Stickney Crater on Phobos deposited either a ~15 m thick global equivalent distribution of accumulated Stickney ejecta from a *leading* hemisphere impact **or** a ~22 m thick global equivalent distribution of ejecta from a *trailing* hemisphere impact (see analysis in SOM "Stickney Ejecta.xlsx").

Consequently, the extent to which the small surface area of Phobos concentrates ejecta that returns from orbits around Mars strongly suggests that the surface of Phobos was substantially reworked by Stickney secondary impacts and accumulated deposits.

1.11. *The character of secondary impacts on Phobos.*

Although the notion of “secondary craters’ invokes images of proximal low-velocity and often low-incident angle impacts that produce distinctive herringbone crater patterns (Melosh, 1989), Phobos is potentially exposed to a stochastic distribution of ejecta that arrives from any angle at velocities up to ~4.7 km/s (beyond this velocity all Phobos ejecta escapes to solar orbits). As a result, a substantial proportion of Stickney secondary craters should be morphologically similar to circular-rimmed primary craters.

1.12. *Summary.*

In view of the evidence that we present in greater detail below, the craters that are observed inside Stickney Crater are secondary impacts from Stickney and therefore cannot be used to date Stickney. This, in fact, resolves the paradox of Stickney Crater where it appears “young” according to the boulder evidence of Thomas et al. (2000) and Basilevsky et al. (2013, 2015), and “old” according to crater-counting evidence of Schmedemann et al. (2014).

By removing the evidence that is based on crater counting, we are left with the evidence of the boulders with a survival limit of ~0.5 Ga, which suggests that Stickney Crater is no older than one half billion years. Because Phobos is also space weathered (Pieters et al., 2014), the Stickney impact must have taken place no more recently than ~0.1 Ga.

We therefor set a limit on the age of Stickney Crater of between ~0.1 Ga and ~0.5 Ga.

2. Analytical methods.

2.1. *The tidal lock of Phobos.*

In the present day, Phobos is a “tidally locked” body (Burns, 1972; Burns, 1977), and by this expression we observe that the same hemisphere of Phobos constantly faces Mars due to a synchronous rotational period that is the same as its orbital period. Because the orbital eccentricity of Phobos is not exactly circular, Phobos experiences a small extent of secular and non-secular libration. Yet on average, the same hemisphere of Phobos constantly faces Mars. Consequently, with respect to the orbital motion of Phobos, there is a fixed *leading* hemisphere and trailing hemisphere, and a fixed sub-Mars hemisphere and anti-Mars hemisphere

The tidal lock of Phobos is maintained by a gravitational gradient where Mars exerts a greater gravitational force at lower altitudes. As a consequence, the lowest gravitational energy state is achieved when Phobos is aligned along its major axis perpendicular to the surface of Mars. In our analytical system, we define the major axis of Phobos as the longest of the three axes of a triaxial ellipsoid where Phobos rotates on its shortest axis (Burns, 1977), (Fig. 9).

Tidally locked bodies are generally assumed to have been freely rotating earlier in their geological histories. Over time, there is a gradual conversion of rotational angular momentum to friction and heating as tidal forces between the parent planet and its moon interact. As the interaction dissipates heat to space, the moon loses rotational angular momentum until it reaches its lowest energy state and becomes locked along its major axis. If we provide the original orbit of a moon, its original rotational rate, and its mechanical dissipation properties, it is possible to compute the length of time that is required to de-spin the moon from its initial rotational rate to a tidally-locked synchronous-rotation state (Gladman et al., 1996).

If the synchronous-rotation state of Phobos is desynchronized, there is a 50% chance that Phobos will return to a synchronous-rotation with Mars at its pre-impact longitude **or** a synchronous-rotation that is rotated 180° from the original longitude. This suggests that if the Stickney impact desynchronized the tidal lock of Phobos, there was a 50% chance that the pre-impact orientation of Phobos was 180° in longitude from the present day. For this reason we model both a *leading* hemisphere Stickney impact that took place at its present day longitude and also a *trailing* hemisphere Stickney impact that took place 180° in longitude from its present-day longitude.

In our study we routinely refer to a *leading* hemisphere Stickney impact or a *trailing* hemisphere Stickney impact to distinguish the two possible pre-impact orientations of Phobos, though in reality, the Stickney impact is located ~40° east in longitude from the orbital apexes in either of the two possible pre-impact tidal lock orientations.

2.2. ***The exposure of Stickney Crater to its own secondary impacts.***

On a tidally-locked moon that is rotationally unaffected by an impact event, the impact ejecta that is launched from the moon travels away from the moon and returns to the opposite hemisphere of the moon. Consequently, if the rotation of Phobos were unaffected by the Stickney impact, Stickney Crater would not be exposed to its own secondary impacts. To test our hypothesis that Stickney Crater was exposed to its own secondary impacts, it is therefore necessary to calculate the modified rotational rate of Phobos due to the impulse of the Stickney impact and then compute the de-spin time until Phobos is relocked into a synchronous rotation by tidal forces.

While Phobos is rotating freely, the entire surface of Phobos is exposed to ejecta. However, if Phobos is relocked before the majority of the Stickney Crater ejecta intersects Phobos, *and* if the new locked orientation shields Stickney from additional secondary impacts, then simply desynchronizing the lock is not enough to support our hypothesis that Stickney Crater was fully exposed to its own secondaries.

Consequently, we compute the de-spin time to assess whether or not the secular rotation of Phobos remains desynchronized for at least 1,000 years, which is the length of time that is required for Mars-orbiting ejecta to substantially complete the process of accumulation back onto the surface of Phobos (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996; Ramsley and Head, 2013b).

2.3. ***Constraining uncertainties in the calculation of the Phobos de-spin rate.***

Due to the uncertainty of the evolution of orbits over time and the uncertainty of the early rotational rate of a primordial moon, the typical calculation of a de-spin time is substantially uncertain to at least ± one order of magnitude (Gladman et al., 1996). The uncertainty is primarily due to how the de-spin equation computes the semimajor axis of the moon to the sixth power (Gladman et al., 1996) and therefore uncertainty in the dimension of the semimajor axis has a substantial effect on the de-spin prediction time.

However, where we are testing the effect of a defined impulse at a specific time in the orbital history of Phobos (the Stickney impact at 0.5 Ga, and 0.1 Ga in SOM) it is possible to calculate the initial semimajor axis of Phobos to a close approximation. Also, because we compute the post-impact rotational rate of Phobos based on the impulse that produced Stickney Crater, we are able to further constrain the de-spin time prediction. Consequently, the initial semimajor axis and rotational rate that typically produce a wide range of uncertainty in the de-spin time are well constrained in our model, which reduces the error bar of our de-spin time prediction from at least ± one order of magnitude to a factor of ±2.

2.4. ***The impact impulse*.**

In order to assess the effect of the Stickney impact on the rotation and the orbit of Phobos, we first calculate the total available impulse that is delivered to Phobos by the Stickney impactor. From the scaling equations of Melosh, 1989, and the typical velocity of solar system impacts on Phobos (Neukum and Wise, 1976; Ivanov, 2001), we are able to compute the total acceleration impulse that is injected into the system in terms of the velocity and mass of the impactor. Using the Tsiolkovsky rocket equation, we assume that the total available impulse is equal to the velocity and mass of the impactor as though the projectile is the propellant mass and the impact velocity equals the nozzle velocity. Clearly, a crater is not a rocket engine. However the total available impulse is the same no matter what produces the mass × velocity input, and the only difference is the extent to which the crater formation process is inefficient in converting the total available impact energy into an acceleration impulse. The inefficiencies are mainly due to the cone shape of ejecta dispersion which is off-axis to the nadir-angle of the crater, and to a lesser extent, the energy that is lost to displacement, compression, melting, and vaporization of the target and projectile material (Melosh, 1989). Once we work out the total percent of the thrust inefficiency, the remaining energy is the *effective impulse* that is applied to Phobos by the Stickney impact.

2.5. *The effect of the Stickney impact on the rotation and orbit of Phobos.*

A substantial portion of our calculations focuses on the effect of the Stickney impact on the orbit and the rotation of Phobos. Calculations are explained in detail in SOM ("Desynchronization calculations at 7,300 km altitude.docx" and "Desynchronization calculations at 10,000 km altitude.docx"). Because the vector of the Stickney impact is offset from the gravitation center of Phobos by 13.4° (Fig. 2), the effective impulse is divided between the linear component that accelerates Phobos into a new orbit and a component that alters the rotation of Phobos. Using the effective impulse, the mass of Phobos, and the moment of inertia of a triaxial ellipsoid that approximates the shape of Phobos, it is then possible to calculate the new orbit of Phobos and the new rotational rate of Phobos that are produced by the Stickney impulse. In our SOM desynchronization calculations we compute the new orbits of Phobos that are produced by the Stickney impact (a *leading* versus *trailing* hemisphere impact produces a different orbital period). We also compute the increased rotational rate of Phobos due to the additional rotational angular momentum that is imparted by the impact (the same increase from a *leading* or *trailing* hemisphere Stickney impact). Also in SOM we compute the change in the rotational period of Phobos due to the compression and removal of target material that alters the moment of inertia and mass of Phobos.

The location of Stickney Crater is a special case that is located on the equator of Phobos and on the westward slope of a large topographic high. This, in fact, is the ideal location of an impact that produces the maximum rotational effect. For example, an impact away from the equator would have produced less torque, an impact on level ground would not have produced a preferential lateral impulse in any direction, and an impact on a northward or southward slope of a topographic high would have produced only a wobble in the motion of Phobos but no change in rotational rate.

In addition to the direct effect on the rotation of Phobos, two other Stickney impact mechanisms have an effect on the tidal lock of Phobos:

1. An impact on the *leading* hemisphere of Phobos reduces the angular momentum of the orbit and thereby reduces its semimajor axis and orbital period. An impact on the *trailing* hemisphere of Phobos *increases* the angular momentum of the orbit and thereby *increases* its semimajor axis and orbital period. Where we define a "tidal lock" to mean that the rotational period and orbital period are *synchronized*, any change in the orbital period has the effect of desynchronizing the tidal lock, even if the rotational period remains unchanged.

2. Target material is compressed by the Stickney impact toward the gravitational center of Phobos and redefines the moment of inertia of Phobos. As a consequence, the rotational rate of Phobos increases exactly the same way that an ice-skater spins faster on the ice when they draws their arms closer while spinning.

To work out the total extent of the desynchronization of the post-impact rotational period and post-impact orbital period of Phobos, we combine 1) the change in the rotational rate that is due to the preferentially eastward-directed impulse of the Stickney impact, 2) the change in the rotational rate due to the effect of crater material compression, and 3) the change in the orbital period of Phobos.

Due to the preferentially eastward-directed impulse, the Stickney impact increased the rotational rate of Phobos, and the compression of crater floor material further increased the rotational rate. However, depending on whether the Stickney impact took place on the *leading* or *trailing* hemisphere of Phobos, the new orbit of Phobos either added or subtracted from the total desynchronization of the rotational rate and orbital periods.

As it turns out, the eastward-directed impulse of the Stickney impact dominates the overall desynchronization effect, and the computed predictions for the desynchronization effects from a *leading* or *trailing* hemisphere Stickney impact are essentially the same.

Our calculations are explained in detail in SOM "Desynchronization calculations at 7,300 km altitude.docx" and "Desynchronization calculations at 10,000 km altitude.docx."

2.6. ***Available Stickney ejecta to produce secondary impacts on Phobos.***

We compute the volume of the Stickney ejecta that is available to produce secondary impacts by first working out the empty volume of the Stickney Crater. Our model that works out the volume of the available Stickney ejecta is available in SOM ("Stickney Ejecta.xlsx").

The crater has no appreciable rim and we model the crater volume by approximating the shape if the crater as observed. Because the volume of a simple crater is divided approximate equally between the target material that is excavated and ejected and the target material that is displaced into the floor and walls of the crater, our model assumes that the volume of Stickney ejecta that is launched from the crater is equal to 50% of the volume of the crater (Melosh, 1989).

Next we assume that a portion of the ejecta volume that is typically observed as a continuous deposit that encircle craters such as those on the Moon is produced by the Stickney impact (McGetchin et al., 1973; Lee et al., 1986; Hiesinger and Head, 2006; Wilson and Head, 2015). Due to the low gravity of Phobos, most of the "continuous deposit" material of a typical lunar impact is inserted into orbits around Mars from the Stickney impact, and the "continuous deposit" material from Stickney is unlikely to return to Phobos with sufficient velocity to produce secondary craters (Fig. 10), (Wilson and Head, 2015). We therefore subtract "continuous deposit" material from the total volume of Stickney ejecta that is produced by the Stickney impact in order to calculate the proportion that is capable of producing secondary impacts. McGetchin et al. (1973) describe a method for working out the total volume of the continuous deposit from craters on the Moon. When we apply the method of McGetchin et al. (1973) to Stickney Crater, the volume of the "continuous deposit" material represents ~23% of the total volume of the Stickney ejecta. (Our model for the volume of Stickney Crater "continuous deposits" is available in SOM: "Stickney Ejecta.xlsx").

A portion of the higher velocity ejecta fragments that are capable of producing secondary impacts on Phobos do not return to Phobos. To determine the proportion of ejecta that remains available to produce secondary impacts on Phobos, we constructed a physics model of Stickney ejecta that tests the fate of 10,000 test particles that are produced from both a *leading* and *trailing* hemisphere Stickney impact (Ramsley and Head, 2013a; Blender Foundation Team, 2015). Fig. 3 shows an example of the working model after approximately one orbit of Phobos since the Stickney impact. Once we observe that the test particles have either exited the Mars system or continue to remain in orbits around Mars, we count the number of test particles that are captured into orbit around Mars. According to the number of surviving particles in our model, ~40% of the ejecta that is launched from a *leading* hemisphere impact is lost to solar orbits, whereas only 10% is lost from a *trailing* hemisphere impact to the atmosphere of Mars and substantially <1% to solar orbits.

To work out the available proportion of ejecta that produces Stickney secondary impact craters on Phobos we assume that none of the "continuous deposit" material contributes to secondary impact craters on Phobos. Consequently, ~37% (100% – 23% – 40%) of Stickney ejecta is available to produce secondary impacts from a *leading* hemisphere Stickney impact (where 23% is “continuous deposit” material that does not produce secondary impacts and 40% is lost to solar orbits), whereas ~67% (100% – 23% – 10%) of Stickney ejecta is available to produce secondary impacts from a *trailing* hemisphere Stickney impact (where 23% is “continuous deposit” material and 10% is deorbited to Mars).

2.7. *The size/frequency distribution (SFD) of Stickney secondary impacts*.

Based on the available volume of high-velocity Stickney ejecta that returns from orbits around Mars to produce secondary impacts on Phobos, we distribute the ejecta fragments according to a global average sized/frequency distribution (Fig. 11). The available volume of ejecta sets narrow constraints on the model because, for example, if too much material is allocated to larger fragments there is insufficient ejecta to account for smaller fragments. Conversely, if we allocate too little material to larger fragments, we leave an inordinately excess volume of material that must be distributed into the bins of smaller fragments. Consequently, to a first order, the global SFD of Stickney ejecta fragments that we predict is likely to be consistent with the secondary craters that are emplaced globally on Phobos.

Our model predicts the SFD of secondary impacts, however, our prediction does not account for the subsequent over-printing of craters during the ~1,000-year accumulation period that would tend to lower the SFD slope overall and reduce the slope at small crater sizes. Nonetheless, as long as the supply of potential secondary impacts substantially exceeds the observed SFD craters inside Stickney, it is likely that the vast majority of superposed craters inside Stickney are secondary impacts from Stickney.

Our model of a *trailing* hemisphere Stickney impact is consistent with the abundance of the superposed craters inside Stickney, whereas a *leading* hemisphere Stickney impact emplaces only ~55% of the observed superposed craters inside Stickney Crater (Figs. 5-7). Nonetheless the secondary crater flux from a *leading* hemisphere Stickney impact is sufficient to produce an older age for Stickney Crater than would be produced by background craters alone. Consequently, the secondary impact flux from a Stickney impact on *either* hemisphere of Phobos is sufficient to nullify an age of Stickney Crater that is based on crater counting.

2.8. *The kink in the SFD of “Phobos average” craters west of Stickney Crater.*

To the west of the Stickney Crater rim inside the Schmedemann et al. (2014) “Phobos average” counting area we predict that a *trailing* hemisphere Stickney impact produces a sufficient SFD of superposed secondary craters to account for a kink in the SFD curve at D ~0.6 km where a recent spike of impacts D ≲0.6 km are clearly overprinted atop the older and larger SFD of background craters.

Conversely, we predict that the SFD flux from a *leading* hemisphere Stickney impact produces an insufficient supply of secondary impacts to account for the kink.

In view of the sufficient ejecta from a *trailing* hemisphere Stickney impact and the insufficient ejecta from a *leading* hemisphere Stickney impact to produce the kink, the manifestation of the kink is one line of evidence that supports our hypothesis that the Stickney impact took place on the *trailing* hemisphere of Phobos (Figs. 6c, 7c).

2.9. *Background craters.*

Our study does not suggest that there have been no background impacts on Phobos since the Stickney impact. The computed volume of Stickney ejecta only suggests that a *trailing* hemisphere Stickney impact on Phobos is sufficient to account for all craters on Phobos D ≲0.6 km and a portion D <2km. Background flux must have produced additional craters since the time of the Stickney impact that are superposed atop the Stickney secondaries. However, the sharp kink in the SFD that is observed in the Schmedemann et al. (2014) “Phobos average” counting area suggests that background flux has been insufficient to produce an observable reworking or overprinting of Stickney secondaries since the time of the Stickney impact, and therefore the vast majority of craters on Phobos D ≲0.6 km and a portion D <2 km are Stickney crater secondary impacts (Figs. 6c, 7c).

2.10. ***Pre-Stickney impact initial conditions.***

In view of the boulders that are observed proximal to Stickney Crater (Thomas et al., 2000) and the interpreted ≲0.5 Ga longevity of these boulders (Basilevsky et al., 2013, 2015), the initial conditions of our model places Phobos at a Mars altitude that is estimated for 0.5 Ga, which is 4,000 km higher than the present day (Burns, 1972; Lambeck, 1979; Bills et al., 2005; Jacobson, 2010). The sidereal orbital period of Phobos is computed using the formula:

$$\boldsymbol{T} = 2\boldsymbol{\pi}\,(a^3 / \boldsymbol{\mu})^{½}, \qquad 2.1$$

where, $\boldsymbol{T}$ is the sidereal orbital period of Phobos in seconds, $\boldsymbol{a}$ is the semimajor axis of Phobos, and $\boldsymbol{\mu}$ is the gravitational parameter of Mars (the coefficient of universal Gravity × the mass of Mars). The present-day semimajor axis $\boldsymbol{a}$ of Phobos is 9,376 km and the value of $\boldsymbol{\mu}$ for Mars is 4.283×10^4 km^3/s^2 (NASA, 2015a; NASA, 2015b; NASA/Jet Propulsion Laboratory, 2015). Using equation 2.1.1, the present-day sidereal period of Phobos computes to 27,563 seconds.

To compute the sidereal period of Phobos at an altitude that is 4,000 km greater than the present day, we add 4,000 km to the present-day semimajor axis, which equals 13,376 km. When we substitute 13,376 km to compute the sidereal orbital period of Phobos at the greater altitude using equation 2.1.1, this computes to a sidereal orbital period of 46,967 seconds.

3. Testing and implications.

In this section we describes the factors that control the increased rotational rate of Phobos due to the Stickney impact and the time to de-spin Phobos back to a tidal lock. Detailed calculations are available in SOM "Desynchronization calculations at 7,300 km altitude.docx" and "Desynchronization calculations at 10,000 km altitude.docx." Including the calculation in SOM, this section calculates the effect of an impact that takes place at an altitude that is 4,000 km greater than the present day at a semimajor axis of 13,376 km, which corresponds to the approximate altitude of Phobos at ≲0.5 Ga (Burns, 1972; Lambeck, 1979; Bills et al., 2005; Jacobson, 2010), which is the upper time limit for the Stickney impact suggested by Thomas et al. (2000) and Basilevsky et al. (2013, 2015). To further test the conclusions of our study, we repeat our calculations for the consequences of a Stickney impact that takes place at a near present-day orbital altitude of Phobos of 7,300 km which corresponds to a Stickney impact at ~0.1 Ga. The near present-day model at ~0.1 Ga, compared to ~0.5 Ga, desynchronizes the rotational period and orbital period of Phobos generally to the same extent. However, at the ~0.1 Ga altitude of Phobos, with a lower semimajor axis of 7,300 km, the de-spin process takes place more rapidly than at the higher ~0.5 Ga altitude of 10,000 km, and at the lower starting altitude of 7,300 km, this reduces the amount of time to resynchronize the its rotational and orbital periods.

3.1. ***What are the factors when partitioning the acceleration impulse that alters the orbit and rotational rate of Phobos?***

There are several components to this question that must be worked out in order to produce an answer. 1) What was the size and velocity of the projectile that produced Stickney Crater? 2) What is the nature of the inefficiencies of the Stickney impact process that reduces the conversion of the impact energy to an acceleration impulse? 3) Stickney Crater is tilted uphill to the east and suggests that a portion of the impact impulse is directed to the east which would increase the rotational rate of Phobos. What is the change in the rotational rate from this eastward impulse? 4) Because the Stickney impact is ~ 40° misaligned to the orbital motion of Phobos, only a portion of the Stickney impact impulse changes the orbit of Phobos (Fig. 2). What is the proportion of the altered orbital velocity of Phobos that changes its orbital period? 5) How does the compression and excavation of Phobos material during the Stickney impact alter the mass properties of the moon? Does this change the rotational rate?

3.2. *Total impact impulse.*

To calculate the altered rotational and orbital periods of Phobos, we first compute the *total* impulse of the Stickney impact, then reduce this impulse according to the inefficiencies of the crater formation process to work out the *available* impulse, and then calculate the vector that changes the rotational period and the vector that changes the orbit. To produce an accurate estimate of the total acceleration impulse that is available, we apply the Tsiolkovsky rocket equation, where we describe the mass of the impact projectile in terms of the rocket exhaust mass and the velocity of the impact projectile in terms of the rocket exhaust velocity. We apply the Tsiolkovsky rocket equation as follows:

$$\Delta v = v_e \ln(m_0/m_1), \qquad 3.1$$

where: Δv is the maximum change in the velocity of Phobos, v_e is the exhaust (projectile) velocity, $\ln$ is the natural logarithm function, m_0 is the initial total mass of Phobos plus the projectile, and m_1 is the final mass of Phobos, not including the projectile. In this initial model, we assume that the total mass and the velocity of the impactor produces an acceleration impulse on Phobos.

3.3. *Stickney projectile intersection velocity, projectile mass, and acceleration impulse efficiency.*

According to our solar system modeling of average meteor impact velocities on Phobos in the present day, the average impact velocity on the *leading* hemisphere of Phobos is 13,170 m/s and on the *trailing* hemisphere it is 9,025 m/s. This prediction is consistent with models of Neukum and Wise (1976) and Ivanov (2001). The difference in velocity between the *leading* and *trailing* hemispheres of Phobos is primarily due to the additive and subtractive effect of the orbital velocity of Phobos.

In both *leading* and *trailing* hemisphere Stickney impact models the effective impulse of the impact is *similar* since the same crater is produced in both models. However, compared to a *trailing* hemisphere impact, the higher impact velocity of a *leading* hemisphere impact requires a smaller projectile diameter, and due to the greater impact velocity of a *leading* hemisphere impact, the average crater ejection velocity is also slightly greater (Melosh, 1989).

At an orbit of Phobos that corresponds to ~0.5 Ga in the past that is 4,000 km greater in attitude than in the present day (Burns, 1972; Lambeck, 1979; Bills et al., 2005; Jacobson, 2010), in our solar system model we adjust the *leading* and *trailing* hemisphere meteor impact velocities on Phobos to account for effect of the greater semimajor axis of Phobos, which produces a lower orbital velocity. At ~0.5 Ga (10,000 km attitude), the average impact velocity on the *leading* hemisphere is ~12.9 km/s and on the *trailing* hemisphere it is ~8.7 km/s.

The Stickney Crater longitude is offset from the *leading* orbital apex (center of the *leading* hemisphere) of Phobos by ~40° and therefore the additive and subtractive effects of the Phobos orbital velocity are reduced by the vector angle of the offset longitude. When we take the 40° longitudinal offset into account, our predictions of a *trailing* hemisphere meteor impact velocity increases from 8.7 km/s to **9.1 km/s,** and from a *leading* hemisphere impact, the meteor impact velocity is reduced from 12.9 km/s to **12.5 km/s**.

3.4. *Trailing hemisphere impact, Stickney projectile diameter.*

Using the average of scaling equations 7.8.3 and 7.8.4 of Melosh (1989) we work out the mass and velocity properties of the *trailing* hemisphere impactor assuming a Phobos density of 1.86 kg/m^3 (NASA, 2015b; NASA/Jet Propulsion Laboratory, 2015), a meteor projectile density of 3,000 kg/m^3, a projectile velocity of 9.1 km/s (as worked out above), and a Stickney Crater diameter of ~9 km.

3.4.1. *Trailing hemisphere impact, Stickney projectile parameters from Melosh (1989) scaling equation 7.8.3:*

$$\boldsymbol{D} = 0.0133\ \boldsymbol{W}^{1/3.4} + 1.51 \text{ x } \boldsymbol{\rho_p}^{1/2}\ \boldsymbol{\rho_t}^{-1/2}\ \boldsymbol{L},$$

where $\boldsymbol{D}$ is the crater diameter, $\boldsymbol{W}$ = the kinetic energy of the projectile $\frac{1}{2}mv^2$, $\boldsymbol{\rho_p}$ is the projectile density, $\boldsymbol{\rho_t}$ is the target density and $\boldsymbol{L}$ is the projectile diameter. This computes to a project diameter of **810 m** and a projectile mass of **8.348 × 10^{11} kg**.

3.4.2. *Trailing hemisphere impact, Stickney projectile parameters from Melosh (1989) scaling equation 7.8.4:*

$$\boldsymbol{D} = 1.8\ \boldsymbol{\rho_p}^{0.11}\ \boldsymbol{\rho_t}^{-1/3}\ \boldsymbol{g}^{-0.22}\ \boldsymbol{L}^{0.13}\ \boldsymbol{W}^{0.22},$$

where $\boldsymbol{D}$ is the crater diameter, $\boldsymbol{\rho_p}$ is the projectile density, $\boldsymbol{\rho_t}$ is the target density, $\boldsymbol{g}$ is the difference in the gravity of the Earth compared to Phobos, $\boldsymbol{L}$ is the projectile diameter, $\boldsymbol{W}$ = the kinetic energy of the projectile $\frac{1}{2}mv^2$. This computes to a project diameter of **1,080 m** and a projectile mass of **1.979 × 10^{12} kg**.

3.4.3. *Trailing hemisphere impactor parameters, average of Melosh (1989) scaling equations 7.8.3 and 7.8.4:*

In our calculation we use the average of the Melosh (1989) scaling equations 7.8.3 and 7.8.4. (See SOM, "Stickney Ejecta.xlsx" for calculation details). An average of the two models works out to a *trailing* hemisphere projectile diameter of **945 m** and a projectile mass of **1.326 × 10^{12} kg**.

3.5. ***The ideal trailing hemisphere acceleration impulse.***

The mass of Phobos is computed using an average radius of 11,070 m and bulk density of 1.86 kg/m^3 (NASA, 2015a; NASA/Jet Propulsion Laboratory, 2015), which calculates to a Phobos mass of 1.0569 × 10^{16} kg. The total mass of Phobos plus the mass of the projectile of 1.326 × 10^{12} kg (from SOM, "Stickney Ejecta.xlsx") equals 1.0638145 × 10^{16} kg. Using the Tsiolkovsky rocket equation $\boldsymbol{\Delta v = v_e \ln(m_0/m_1)}$ (eq. 3.1), we calculate the ideal linear acceleration of Phobos from an impact on the *trailing* hemisphere of Phobos from a 945 m diameter projectile and a velocity of 9,100 m/s. For the present, we assume a 100% conversion of impact energy to linear acceleration impulse (the inefficiencies of the energy conversion to acceleration are removed in section 3.9.):

- Mass of Phobos is 1.0569 × 10^{16} kg ($\boldsymbol{m_1}$)
- Mass of Phobos plus the projectile is 1.0570326 × 10^{16} kg ($\boldsymbol{m_0}$)
- Natural log of ($\boldsymbol{m_0/m_1}$) = 0.00012545338
- Projectile velocity = 9,100 m/s ($\boldsymbol{v_e}$)
- Delta-v of Phobos = 9,100 m/s × 0.00012545338 = **1.1416 m/s**

3.6. ***The ideal leading hemisphere acceleration impulse.***

To produce the same crater diameter from a *leading* hemisphere Stickney impact with the higher impact velocity of 12.5 km/s, the *leading* hemisphere scenario includes the same projectile density of

3,000 kg/m^3 yet substitutes a smaller impact projectile diameter of **840 m** and a lower mass of **9.3102 x 10^{11} kg** that are worked out from Melosh (1989) scaling equations 7.8.3 and 7.8.4 (See SOM, "Stickney Ejecta.xlsx" for calculation details). Computing the *leading* hemisphere scenario using the Tsiolkovsky rocket equation $\Delta v = v_e \ln(m_0/m_1)$ (eq. 3.1), the following works out the ideal linear acceleration of Phobos (assuming a 100% conversion of impact impulse to linear acceleration with no conversion inefficiency):

- Mass of Phobos is 1.0569 × 10^{16} kg (m_1)
- Mass of Phobos plus the projectile is 1.056993102 ×10^{16} kg (m_0)
- Natural log of (m_0/ m_1) = 0.00008808581
- Projectile velocity = 12,500 m/s (v_e)
- Delta-v of Phobos = 12,500 m/s × 0.00008808581 = **1.1011 m/s**

According to Melosh (1989) the peak velocity of ejecta from a crater is ~10% of the impact velocity, and as a consequence, the greater impact velocity of a *leading* hemisphere impact on Phobos would produce a greater average ejecta velocity. According to the Tsiolkovsky rocket equation, as "rocket" exhaust (in this case Stickney ejecta) exits at a greater velocity, the same volume of exhaust produces a greater acceleration impulse. As a result, it is likely that a *leading* hemisphere impact would have produced a slightly greater acceleration impulse on Phobos than the 1.1011 m/s that we calculate here. However, for the sake of a conservative model we use the lower Phobos *leading* hemisphere delta-v of 1.1011 m/s in subsequent calculations.

3.7. *Cross-checking the acceleration impulse impact using Stickney ejecta mass and average ejecta velocity.*

Before impact energy conversion inefficiencies are applied, such as the cone shape launch of ejecta from the crater, the following is calculated as a cross-check for the delta-v results from above. As calculated in SOM, "Stickney Ejecta.xlsx," the total mass of Stickney ejecta is ~7.29 × 10^{13} kg. To estimate the average velocity of the ejecta, we accept from Melosh (1989) that the peak ejection velocity is between 1/3 and 1/5 of the shock velocity (which we conservatively take to be 1/5). We also accept that the shock velocity is equal to ~1/2 of the projectile velocity, or a peak ejection velocity that is ~10% of the projectile velocity (1/5 × 1/2).

To predict an average ejecta velocity, we assume that the ejection velocity at the conclusion of crater excavation is zero, and that the average ejecta velocity is mean of the peak velocity and zero velocity. This mean value is unlikely to produce a precise estimate of average ejecta velocity, yet where the Melosh (1989) model of ejecta velocity is an estimate, a simple mean is sufficient for a cross-check of our delta-v results from above.

For a projectile velocity of 9,100 m/s from a *trailing* hemisphere impact on Phobos, the average ejecta velocity works out as follows:

V_{ave} = 9,100 m/s × 0.5 (shock v) × 0.2 (peak ejecta v) × 0.5 (one half starting v) = **455 m/s,**

where, V_{ave} is the average velocity of ejecta from Stickney Crater that is produce by a *trailing* hemisphere impact on Phobos.

Using the Tsiolkovsky rocket equation $\Delta v = v_e \ln(m_0/m_1)$ (eq. 3.1), we calculate the total linear acceleration impulse from a *trailing* hemisphere Stickney impact on Phobos by applying the mass of Stickney ejecta (7.29 × 10^{13} kg, see SOM, "Stickney Ejecta.xlsx") and the average Stickney ejecta velocity (455 m/s, which is ½ of the peak ejecta velocity as discussed above):

- Mass of Phobos is 1.0569 × 10^{16} kg (m_1)
- Mass of Phobos plus Stickney ejecta is 1.06419 × 10^{16} kg (m_0)

- Natural log of ($\boldsymbol{m_0/m_1}$) = 0.00687
- Average ejecta velocity = 455 m/s ($\boldsymbol{v_e}$)
- Delta-v of Phobos = 455 m/s × 0.00687 = **3.13 m/s**

From a *leading* hemisphere impact on Phobos, the projectile velocity is 12,500 m/s and the average ejecta velocity works out as follows:

$$\boldsymbol{V_{ave}} = 12{,}500 \text{ m/s} \times 0.5 \text{ (shock v)} \times 0.2 \text{ (peak ejecta v)} \times 0.5 \text{ (one half starting v)} = \mathbf{625\ m/s,}$$

where, $\boldsymbol{V_{ave}}$ is the average velocity of ejecta from Stickney Crater that is produce by a *leading* hemisphere impact on Phobos.

Using the Tsiolkovsky rocket equation $\boldsymbol{\Delta v = v_e \ln(m_0/m_1)}$ (eq. 3.1), we once again calculate the total linear acceleration impulse from an impact on the *leading* hemisphere on Phobos using the mass of Stickney ejecta (7.29×10^{13} kg, see SOM, "Stickney Ejecta.xlsx) and the average ejecta velocity (625 m/s, which is ½ of the peak ejecta velocity as discussed above):

- Mass of Phobos is 1.0569×10^{16} kg ($\boldsymbol{m_1}$)
- Mass of Phobos plus Stickney ejecta is 1.06419×10^{16} kg ($\boldsymbol{m_0}$)
- Natural log of ($\boldsymbol{m_0/m_1}$) = 0.00687
- Average ejecta velocity = 655 m/s ($\boldsymbol{v_e}$)
- Delta-v of Phobos = 625 m/s × 0.00687 = **4.50 m/s**

Calculating the Stickney Crater impulse that produces Phobos delta-v based on an estimate of Stickney *ejecta mass* produces an estimate that is a factor of 3 to 4 times greater than computing the delta-v of Phobos based on an estimate of the Stickney *projectile mass* (3.13 m/s compared to 1.1416 m/s from a *trailing* hemisphere impact, and 4.50 m/s compared to 1.1011 m/s from a *leading* hemisphere impact). The higher delta-v calculation based on ejecta velocity (rather than projectile velocity) suggests that our calculations of the delta-v of Phobos that are based on the *projectile mass* is a conservative assumption in subsequent calculations.

3.8. *Analysis of the discrepancy of Phobos delta-v calculated from projectile velocity versus ejecta velocity.*

The discrepancy of the Phobos delta-v that is calculated from *projectile* velocity versus *ejecta* velocity may be due to how the mass distribution of ejecta is weighted toward larger ejecta fragments (Melosh, 1989). In view of how the delta-v calculations from ejecta velocity and projectile velocity should produce the same result, this suggests that the *average* velocity of Stickney ejecta may be ~3 to 4 times *less* than the ½ of the *peak* ejecta velocity that we estimate above, and closer to ~15% of the peak ejecta velocity (~½ / ~3 to 4). If this is true, and if we assume that the peak ejecta velocity is ~10% of the projectile velocity (Melosh, 1989), the *average* ejecta velocity from Stickney was only 1.5% of the projectile velocity (10% × 15%). Based on our predictions above of a *trailing* hemisphere meteor impact velocity of 9.1 km/s and from a *leading* hemisphere impact of 12.5 km/s, the average *trailing* hemisphere ejecta velocity may have been only **140 m/s** (9,100 m/s × 1.5%) and, the average *leading* hemisphere ejecta velocity may have been only **190 m/s** (12,500 m/s × 1.5%).

3.9 *Stickney impact acceleration efficiency: impact energy partitioning and losses.*

The calculations to this point only describe the total available acceleration impulse from the Stickney impact, as though 100% of the impact energy produces a delta-v in the orbital motion of Phobos. In fact, the conversion of impact energy to acceleration impulse during the cratering process is *inefficient* due to a number of factors. The impact energy is partitioned into several categories: 1) Processes that efficiently produce an acceleration impulse, 2) Processes that produce a non-optimal acceleration impulse, or 3) Processes that convert the energy in ways that consume the energy without contributing substantially to the total acceleration impulse. The following list summarizes the factors that limit the efficiency of the available impact energy to produce an acceleration impulse from an impact crater (Melosh, 1989; O'Keefe and Ahrens, 1977; Gault and Heitowit, 1963):

1. Due to the large mass fraction of solid target material that is excavated and launched from the crater, the flow of solid target material crater excavation is the primary source of the acceleration impulse. Excavated rock material is typically launched from the crater in a cone-shape. The cone-shaped pattern of target excavation includes a vertical vector component that applies an acceleration force to Phobos in a direction *normal* to the surface of Phobos. The cone-shaped pattern also includes a radial horizontal vector component that is *parallel* to the surface of Phobos and exits the impact site in an annular pattern from the crater and does not apply an acceleration force. A directional bias in the pattern of ejecta due to a low-angle oblique impact may produce a non-uniformity in the average vector angle of the ejecta (Melosh, 1989). However, Stickney Crater manifests no evidence to suggest that it was produced by a low-angle oblique impact, and we assume a uniform cone shaped for the launch of Stickney Crater ejecta.
2. The ejection angle of target rock material that exits via spallation is generally vertical and, according to the Tsiolkovsky rocket equation (eq. 3.1.1), contributes an acceleration impulse to Phobos that is mainly due to the high velocity of the spallation process (Melosh, 1989). However, the total volume of spalled target material is a small mass fraction of the total mass of ejecta that is produced by the impact and contributes less delta-v to Phobos than the ejection of excavated rock material.
3. Target material displacement and compression (Melosh, 1989) adds an acceleration impulse to the extent that the displacement and compression of the material is resisted by the target and the resistance is aligned normal to the target surface. Because the vector angles of displacement and compression range from normal to horizontal, only the normal vector component of the process produces an acceleration impulse.
4. The jetting of vaporized projectile and rock material exits Phobos in a radial pattern from the impact site at an angle that is nearly parallel to the horizontal target surface (Melosh, 1989). Because the combined radial vector angles of the jetted material tend to cancel, jetting contributes essentially zero acceleration impulse to Phobos.
5. Vaporization of projectile and target rock material absorbs impact energy and mostly disperses this energy into space as thermal radiation (Melosh, 1989). The heat of vaporization also causes the vapor plume to expand (Melosh, 1989), and as suggested by the Tsiolkovsky rocket equation (eq. 3.1.1), the high velocity of the ejected and expanding gas (Melosh, 1989) adds a slight acceleration impulse to Phobos. Due to the low ejecta mass fraction of the vapor (Melosh, 1989), the acceleration effect on the total delta-v of Phobos is minimal.
6. Melting of target and projectile material absorbs impact energy which is dispersed into space as thermal radiation. A portion of the melted rock is ejected from the crater and a portion remains in and near the crater, mostly below the floor of the crater (Melosh, 1989). The melting of the rock does not produce an acceleration impulse. Impact melt contributes to the delta-v of Phobos only by the excavation process that ejects the melt from the crater into space.
7. The heating of rock (without melting) absorbs impact energy which is radiated into space and does not produce an acceleration impulse to Phobos. The only contribution of heated rock to the delta-v of Phobos is produced by the ejection velocity of those heated rock fragments that are ejected from the crater into space.
8. Shock metamorphism consumes impact energy, and does not add an acceleration force to Phobos.
9. Fracturing of target rock consumes impact energy, and does not add an acceleration force to Phobos.

For a crater that is the size of Stickney that is produced on an airless moon that has essentially zero gravity from a flux of background meteor impact velocities of 9.1 km/s to 12.5 km/s that is typical of the vicinity of Mars (Neukum and Wise, 1976; Ivanov, 2001), approximately10% of the original impact energy of the Stickney impact is lost to vaporization, melting, heating, fracturing, shock metamorphosis, and jetting (Melosh, 1989; O'Keefe and Ahrens, 1977; Gault and Heitowit, 1963). In view of how ≲10% of the original impact energy is absorbed, consumed, or misdirected by processes that do not produce an acceleration impulse, ~90% of the total impact energy is potentially available as an acceleration impulse. This remaining ~90% of acceleration impulse is produced by vapor ejection and expansion, spallation, the launch of solid and melted ejecta, and the resistance of the target to displacement and compression. This 90% is the total *available* acceleration impulse.

Because of how most of the acceleration vectors are generally cone-shaped, we further reduce the 90% *available* acceleration impulse by assuming that the 90% *available* impulse is cone-shaped with an angle that is 45° from the zenith. This produces a downward-directed impulse efficiency that is ~71% of the total *available* impulse (sin of 45°). Combining the 71% efficiency with the 90% *available* acceleration impulse produces an *effective* acceleration impulse that is equal to **~64%** (71% × 90%). The *effective* acceleration impulse of 64% is the amount of impact energy that adds orbital angular momentum and rotational angular momentum to Phobos.

In order to account for uncertainties, we conservatively estimate that only **60%** of the Stickney impact energy is converted to an acceleration impulse. To accommodate this 60% factor, we reduce the *mass* of the projectiles in both scenarios to 60% (*trailing* and *leading* hemisphere impacts) as follows:

3.10 *Total available trailing hemisphere impact delta-v.*

To compute the acceleration impulse of the Stickney impact on the *trailing* hemisphere of Phobos, we reduce the projectile mass to 60% of the 945 m impactor. This reduces the projectile mass to 7.954×10^{11} kg, (1.326×10^{12} kg × 60%) and a total combined mass of Phobos plus the reduced-mass of the projectile of $1.05697954 \times 10^{16}$ kg (1.0569×10^{16} kg + 7.954×10^{11} kg). The *trailing* hemisphere Stickney impact velocity is unchanged at 9,100 m/s.

Using the Tsiolkovsky rocket equation $\boldsymbol{\Delta v = v_e \ln(m_0/m_1)}$ (eq. 3.1), we compute a linear acceleration of Phobos from a *trailing* hemisphere impact of Phobos as follows:

- Mass of Phobos is 1.0569×10^{16} kg ($\boldsymbol{m_1}$) (NASA, 2015b)
- Mass of Phobos plus the projectile is $1.05697954 \times 10^{16}$ kg ($\boldsymbol{m_0}$)
- Natural log of ($\boldsymbol{m_0/m_1}$) = 0.00007525499
- Projectile velocity = 9,100 m/s ($\boldsymbol{v_e}$)
- Delta-v of Phobos = 9,100 m/s × 0.00007525499 = **0.6848 m/s**

3.11 *Total available leading hemisphere impact delta-v.*

To compute the acceleration impulse of the Stickney impact on the *leading* hemisphere of Phobos, we reduce the effective projectile mass to 60% of the 840 m impactor. This reduces the projectile mass to 5.586×10^{11} kg, (9.310×10^{11} kg × 60%) and a total combined mass of Phobos plus the reduced-mass of the projectile of $1.05695586 \times 10^{16}$ kg (1.0569×10^{16} kg + 5.586×10^{11} kg). The *leading* hemisphere Stickney impact velocity is unchanged at 12,500 m/s.

Using the Tsiolkovsky rocket equation $\boldsymbol{\Delta v = v_e \ln(m_0/m_1)}$ (eq. 3.1), we compute a linear acceleration of Phobos from a *leading* hemisphere impact of Phobos as follows:

- Mass of Phobos is 1.0569×10^{16} kg ($\boldsymbol{m_1}$) (NASA, 2015b)
- Mass of Phobos plus the projectile is $1.05695586 \times 10^{16}$ kg ($\boldsymbol{m_0}$)
- Natural log of ($\boldsymbol{m_0/m_1}$) = 0. 00005285128
- Projectile velocity = 12,500 m/s ($\boldsymbol{v_e}$)
- Delta-v of Phobos = 12,500 m/s 0.00004701685 = **0.6606 m/s**

Because we do not know if the Stickney impact took place on the *leading* hemisphere of Phobos or on the *trailing* hemisphere, in all subsequent calculations we take the conservative approach and apply the calculation of the effective acceleration impulse from the Stickney impact on Phobos from a *leading* hemisphere impact of **0.6606 m/s** (compared to the slightly greater value of 0.6848 m/s from a *trailing* hemisphere impact).

3.12. ***Geometric Partitioning of Impulse Vectors.***

3.12.1. *The tilt in the orientation of Stickney Crater:*

The eastern rim of Stickney Crater has a higher geographic elevation than the western rim. Consequently, the bowl of the crater is misaligned with respect to the gravitational center (CG) of Phobos by 13.4° (Fig. 2). During the impact process, this misalignment produces a vectored impulse that is partitioned into two components – one vector component is directed linearly through the CG that alters the orbit of Phobos, and the other vector component is directed radially to the east, which increases the rotational rate of Phobos. The portion of the effective acceleration impulse of the Stickney impact on Phobos that is available to modify the orbit of Phobos is **0.6426 m/s** (Cos 13.4° × of 0.6606 m/s). The remainder of the effective acceleration impulse of the Stickney impact on Phobos is directed to the east and increases the rotational rate of Phobos.

3.12.2. *40° longitudinal offset of Stickney Crater.*

In both the *trailing* hemisphere and the *leading* hemisphere impact scenarios, the Stickney impact site is longitudinally offset from the orbital apexes of Phobos by 40° (Fig. 2). Consequently, the angle of the acceleration impulse that changes the orbit of Phobos is offset from the orbital motion of Phobos by 40°. For this reason, a portion of the acceleration impulse that changes the orbit of Phobos changes only the *eccentricity* of the orbit without altering its *semimajor axis* (the semimajor axis determines orbital period). Therefore only a portion of the impulse that alters the orbit of Phobos changes the orbital *period* of Phobos. Due to the 40° longitudinal offset of Stickney from the orbital motion of Phobos, Both the semimajor axis and eccentricity are altered. However, only the component of the impact that is aligned with the orbital motion alters the semimajor axis. The acceleration vector component that alters the semimajor axis of Phobos therefore equals **0.4923 m/s** (Cos 40° × **0.6426 m/s**), where 40° is the longitudinal offset of Stickney from the orbital motion of Phobos, and 0.6426 m/s is the total change in orbital velocity that is available to modify the semimajor axis of the Phobos orbit. In SOM, we include "Mars Satellite Orbital Calculator.xlsx," which is a calculator that can be used to observe the effects on a circular of Phobos around Mars due to instantaneous changes in the velocity of Phobos.

Detailed calculated of the effect on the orbital period and the rotational period of Phobos are produced in SOM: "Calculations for an orbit of 7,300 km altitude" and "Calculations for an orbit of 10,000 km altitude." At the greater ~0.5 Ga altitude above Mars of 10,000 km, the de-spin time back to a synchronized tidal lock of Phobos (where the orbital and rotational periods are the same) requires at least 16,000 years. At the lower ~0.1 Ga altitude above Mars of 7,300 km, the de-spin time back to synchronized tidal lock is at least 5,000 years. The more rapid de-spin at 7,300 km is due the greater tidal force closer to Mars. Because the ~0.1 Ga lower altitude of 7,300 km sets the most stringent limit on our model, we conclude that the de-spin time after the Stickney impact was at least 5,000 years, and very likely much longer. When we compare the minimum τ_{despin} time after the Stickney of ~5,000 years to the ≲1,000 years that is required to return all Stickney ejecta to Phobos (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996), we conclude that Phobos was globally and uniformly exposed to Stickney secondary impacts across all longitudes, including Stickney Crater and its immediate proximity.

4. Related analysis and additional discussion.

In this section we focus on the consequences of a desynchronized rotation of Phobos, particularly the reworking and degradation states of Phobos surface morphologies by primary and secondary ejecta that intersects and accumulates on Phobos up to 1,000 years after the Stickney impact. We also analyze and discuss the nature of low-velocity geological processes such as the emplacement of "continuous deposit" ejecta that accumulates on Phobos without producing craters, and the lowest velocity ejecta boulders that exit Stickney Crater with sufficiently low velocities to produce boulder-trail grooves on Phobos. We also calculate the SFD of Stickney secondary impacts on a region of Mars that would be exposed to Stickney ejecta from a *trailing* hemisphere Stickney impact.

4.1. ***Crater production SFD predictions versus manifested surface crater SFD.***

The SFD plots in Figs. 6-8 and Figs. 11-13 predict Stickney secondary impact flux in terms of *crater production* SFD, not the SFD that we would observe in the present day. Consequently, the plots do *not* account for the potential overprinting of newer-arriving Stickney secondary impacts (or background flux). However, in our study, we observe that the SFD of emplaced Stickney secondary craters does not approach saturation, and therefore the Stickney secondary crater production SFD is suitable for predicting the SFD of observed craters because, at most, the predicted flux of Stickney secondary impacts only slightly overstates the likely SFD of surviving Stickney secondary craters that would be observed.

4.2. ***Leading or trailing hemisphere Stickney Crater impact.***

According to our calculations, the rotation of Phobos was clearly desynchronized by the Stickney impact. At the conclusion of the de-spin period Phobos was relocked with its long "c" axis once again passing through the sub- and anti-Mars longitudes of Phobos. However, there is no preferential direction to this "c" axis reorientation with respect to the sub- and anti-Mars longitude of Phobos, and it is therefore equally likely that the pre-impact synchronization longitude of Phobos was restored *or* that Phobos was resynchronized at a rotational longitude that was ~180° from its pre-impact synchronization longitude.

Two lines of preferential evidence suggests that the pre-impact longitude was, in fact, oriented ~180° from the present day, and that, consequently, the Stickney impact took place on the *trailing* hemisphere of Phobos.

1. The observed SFDs of craters D $\lesssim$0.6 km in diameter that are counted by Schmedeman et al., 2014 in an area west of Stickney Crater and inside Stickney Crater are entirely consistent with our predicted SFD of secondary impacts from a *trailing* hemisphere impact, whereas there is insufficient flux from a *leading* hemisphere impact to produce the observed crater SFD at D $\lesssim$0.6 km (Figs. 5, 6, 7).
2. The SFD of craters on the present-day *trailing* orbital apex of Phobos suggests that the *trailing* apex has been exposed to a greater background meteor flux than the *leading* orbital apex (Fig. 4). However, due to the *higher* background meteor impact velocities on the *leading* hemisphere of Phobos, the lower meteor background impact velocities on the *trailing* hemisphere, and the manner in which the *leading* hemisphere sweeps a larger volume of space – we *should* instead observe evidence of a greater impact flux on the *leading* hemisphere of Phobos, not less. The observed reversal of crater SFD intensity on the orbital apexes of Phobos compared to the expected flux intensity suggests that Phobos was reoriented 180° to its present day tidally-locked synchronization longitude. Furthermore, in view of how evidence of a geologically early reorientation would have been reworked over time to reestablished the expected SFD pattern, this suggest that the 180° reorientation took place later in the geological history of Phobos.

Where background flux very likely accounts for *some* portion of craters on Phobos D $\lesssim$0.6 km in diameter, it is possible that a *leading* hemisphere Stickney impact *plus* the background flux accounts for the SFD of observed craters. Furthermore, it is possible that large impacts on Phobos other than Stickney

Crater have episodically desynchronized the rotation of Phobos. Consequently, there is insufficient evidence to rule out a *leading* hemisphere Stickney impact.

4.3. *Proportion of secondary impact ejecta from Phobos that is inserted into orbits around Mars.*

With respect to the central location of Mars in the martian system, Stickney ejecta that is launched from the *leading* orbital hemisphere of Phobos generally adds the ejecta launch velocity to the orbital velocity of Phobos. As a consequence, *leading* hemisphere Phobos ejecta generally attains a greater semimajor axis than Phobos, or even achieves escape velocity from the martian system.

Stickney ejecta that is launched from the *trailing* orbital hemisphere of Phobos subtracts the launch velocity of the ejecta from the orbital velocity of Phobos. Depending on the ejecta launch angle and velocity, the ejecta remains in a prograde orbit with a reduced semimajor axis compared to Phobos, or deorbits to Mars, or is inserted into a retrograde orbit, or reaches escape velocity in a retrograde direction.

According to our modeling ~60% of ejecta from a *leading* hemisphere Stickney impact on Phobos remains in orbit around Mars or falls immediately onto the surface of Phobos. Conversely, from the *trailing* hemisphere Stickney impact, ~90% remains in orbit around Mars or falls immediately onto the surface of Phobos.

4.3.1. *Universal statements on the fate of ejecta from Stickney Crater (assuming a 10,000 km altitude circular orbit of Phobos around Mars at ~0.5 Ga):*

1. The orbital velocity of Phobos produces a bias of 1,790 m/s in the orbital direction of all ejecta.
2. The escape velocity from any circular orbit equals the orbital velocity × square root of 2. At a martian 10,000 km altitude the escape velocity is 2,530 km/s relative to Mars.
3. Stickney ejecta with a launch velocity of ≲3 m/s remains on the surface of Phobos. A portion ≲8 m/s remains on the surface of Phobos. Stickney ejecta with a launch velocity of ≳8 m/s drifts into orbits around Mars.

4.3.2. *The fate of ejecta from a leading hemisphere impact (assuming a 10,000 km altitude of Phobos):*

1. Ejecta from a leading hemisphere impact that is launched from Phobos with a velocity <740 m/s remains in orbit around Mars or falls immediately onto the surface of Phobos.
2. Ejecta from a leading hemisphere impact that is launched with a velocity >1,790 m/s escapes to solar orbits.
3. A portion of ejecta from a leading hemisphere impact with launch velocities between 740 km/s and 1,790 m/s remains in orbit around Mars.
4. Due to the additive effect of the Phobos orbital velocity, no leading hemisphere Phobos ejecta deorbits to Mars.
5. Other than ejecta that returns to Phobos and a minor portion of ejecta (substantially < 1%) that deorbits to Mars, ejecta from a leading hemisphere impact is lost to solar orbits.

4.3.3. *The fate of ejecta from a trailing hemisphere impact (assuming a 10,000 km altitude of Phobos):*

1. Ejecta from a trailing hemisphere impact that is launched with a velocity ≲600 m/s enters prograde orbits around Mars or falls immediately onto the surface of Phobos.
2. A portion of ejecta from a trailing hemisphere impact that is launched with a velocity between ~600 and ~3,100 m/s deorbits to Mars.
3. A portion of ejecta from a trailing hemisphere impact with launch velocities >1,790 m/s escapes to solar orbits.
4. A portion of ejecta from a trailing hemisphere impact that is launched with a velocity between 3,100 m/s and 3,580 m/s enters retrograde orbits around Mars (inclination <90°).

5. All ejecta from a trailing hemisphere that launches with velocities >4,320 escapes to solar orbits.

6. Other than ejecta that returns to Phobos, ejecta from a trailing hemisphere impact deorbits to Mars, and only a minor portion escapes to solar orbits.

The overlapping fates of Stickney ejecta (particularly from a *trailing* hemisphere impact) require computational modeling to solve the portions of ejecta that remain in orbit around Mars. In our SOM video ("Phobos Returns to the Scene of the Crime"), we illustrate our modeling setup.

4.4. *Stickney Crater "continuous deposit" ejecta.*

Due to the distribution of ejecta launch velocities and the nature of ejecta fragments that are produced by a crater on Phobos, only a portion of the volume of Mars-orbiting ejecta returns to produce secondary impact craters on Phobos. The portion of the Mars-orbiting ejecta that does *not* produce secondary impact craters is consistent with the material that is typically observed on major planets proximal to primary craters in the form of a continuous deposit that does not typically manifest secondary impact craters, and are alternately referred to as ejecta blanket, circum-crater, crater rim, or proximally continuous deposits. (McGetchin et al., 1973; Oberbeck, 1975; Melosh, 1989, Wilson and Head, 2005, 2015). For the sake of a continuity of terms, we refer to the low-velocity ejecta from Stickney Crater that accumulates on Phobos and does not produce secondary craters as "continuous deposit" ejecta.

4.5. *The volume of ejecta that produces secondary impacts on Phobos from Stickney Crater.*

The volume of Mar-orbiting Phobos ejecta that is capable of producing secondary impact craters on Phobos is equivalent to the total volume of Mars-orbiting ejecta minus the low-velocity portion of continuous deposit ejecta that does not produce observable craters. Based on the work of McGetchin et al., 1973, the volume of low ejecta velocity continuous deposit material that does not produce secondary impact craters on Phobos from Stickney equals ~8.78×10^9 m^3 (See SOM, "Stickney Ejecta.xlsx," for details of our analysis). As discussed above (and worked out in detail in SOM), the total volume of Stickney ejecta equals 3.89×10^{10} m^3, which represents approximately ½ of the volume of the crater volume (Melosh, 1989; Housen and Holsapple, 2003, 2012). Consequently, the volume of ejecta that was launched into space from the Stickney impact is 3.01×10^{10} m^3 (3.89×10^{10} m^3 – 8.78×10^9 m^3). As discussed in Section 4.3., approximately ~60% of *leading* hemisphere Stickney ejecta volume returns to Phobos (including the low velocity continuous deposit ejecta), and approximately 90% from a *trailing* hemisphere impact. The available Stickney ejecta that produces secondary impacts from a *leading* hemisphere Stickney impact is calculated as: 3.89×10^{10} m^3 × 60% – 8.78×10^9 m^3 = **1.46×10^{10} m^3**, where 3.89×10^{10} m^3 is the total volume of Stickney Crater ejecta, 60% is the proportion of the Stickney ejecta that is *not* lost to solar orbits, and 8.78×10^9 m^3 is the volume of continuous deposit material that does not produce secondary impact craters on Phobos.

The available Stickney ejecta that produces secondary impacts from a *trailing* hemisphere Stickney impact is calculated as: 3.89×10^{10} m^3 × 90% – 8.78×10^9 m^3 = **2.62×10^{10} m^3**, where 3.89×10^{10} m^3 is the total volume of Stickney Crater ejecta, 90% is the proportion of the Stickney ejecta that is *not* lost to solar orbits or deorbits to Mars, and 8.78×10^9 m^3 is the volume of continuous deposit material that does not produce secondary impact craters on Phobos.

4.6. *Stickney secondary impacts on Phobos: Impact rates and Phobos global equivalent ejecta accumulation.*

The Stickney impact produced ejecta orbits that shared a common region of space with the orbit of Phobos at the location in space of the Stickney crater excavation process (Fig. 3). Because Phobos passed through this region of space only once per orbit, the intersection of Phobos with Mars-orbiting Stickney ejecta was episodic. The Stickney Crater excavation process required ~6 seconds to complete (Melosh, 1989). At an altitude of 10,000 km, Phobos traversed its own diameter once every ~12 seconds. During each subsequent orbit after the Stickney impact, Phobos passed through the 6-second excavation region in a total of ~18 seconds (~12 seconds of shared orbital intersection traverse through the region of ejecta production plus the ~6 seconds of excavation).

Over time, the orbits of Mars-orbiting ejecta were perturbed (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996), and the region of intersecting ejecta orbits extended along the orbit of Phobos such that the length of time duration of each subsequent episodic intersection of Phobos with Mars-orbiting ejecta increased. Also, due to the accumulation of ejecta on Phobos, the flux of subsequent episodic passages of Phobos through the region of intersecting orbits gradually diminished. Within ~1,000 years after the impact, Phobos fully accumulated the orbiting ejecta through a series of secondary, tertiary, and additional generations of impacts that gradually dissipated the ejecta velocity to the point where ejecta and mobilized regolith material remained below the escape velocity of Phobos and accumulated on Phobos (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996; Ramsley and Head, 2013b).

Figs. 12 and 13 plot the SFD of secondary impacts on Phobos during the early, middle, and late stages of the secondary impact process. In our model, the total volume of ejecta that produces secondary impacts is divided based on an estimate of the remaining volume of orbiting ejecta over time, where 50% of the Stickney secondary impacts take place during the first 10 years after the Stickney impact, 30% take place during the next 100 years, and the remaining 20% take place during the next 1000 years.

Because of the cone-shaped pattern of Stickney Crater ejecta, ~70% of the surface area of Phobos was initially exposed to each 18-second episodic impact intersection. Due to how the rotation of Phobos was desynchronized from its orbital period, which produced one extra Phobos rotation for every ~3 orbits of Phobos around Mars, each subsequent encounter with returning ejecta exposed a surface region of Phobos that was centered in longitude ~120° to the west of the previous encounter (See: Section 3.22. in SOM "Desynchronization calculations at 7,300 km altitude.docx" and "Desynchronization calculations at 10,000 km altitude.docx"). Due to the increasing perturbation of ejecta orbits, over time the orbital region of potential Stickney ejecta / Phobos intersections expanded along the orbit of Phobos and increased the time duration of each episodic intersection. Where Phobos was rotating independently from its pre-impact tidal lock due to its ongoing desynchronized secular rotation, and also due to the increasing time duration of each episodic intersection over time, a gradually increasing portion of the surface area of Phobos was exposed during each subsequent episodic impact encounter. The process of increased areal exposure during each episodic encounter with ejecta was further enhanced by secondary, tertiary, and subsequent impacts that produced additional ejecta that was randomized by stochastic incident angles to the point where Phobos was continuously exposed to returning ejecta across its entire surface (Ramsley and Head, 2103b).

What began as an intense spike of episodic impacts once every Phobos orbit with a duration of ~18 seconds eventually dissipated into a continuously fading infalling rain of impacts that decreased in intensity and velocity until the accumulation process was complete. Due to the orbital perturbations of the ejecta, the secular rotation of Phobos, and the randomization of the ejecta trajectory launch angles of secondary, tertiary, and subsequent impacts, Stickney-produced impact flux was uniformly distributed across all longitudes of Phobos.

Figs. 12 and 13 offer a window into the temporal aspects of the episodic intersections of Phobos with Stickney ejecta per unit surface area. For example, during the first 10 years after a *trailing* hemisphere Stickney impact, during *each orbital encounter* of Phobos with the ejecta stream across each km^2 of Phobos, one 2-m crater was produced, ten 0.8-m craters, one hundred 0.4-m craters, one thousand 0.2-m craters, and ten thousand 0.1-m craters – plus additional impacts of intermediate sizes and a host of smaller craters.

When we consider the *annualized* rate of Stickney secondary impacts on Phobos, (~671 encounters per year at an altitude of 10,000 km), the *annual accumulation rate* on Phobos during the first 10 years from a *trailing* hemisphere Stickney impact on each km^2 of Phobos produced one 43-m crater, ten 10-m craters, one hundred 4-m craters, one thousand 1.3-m craters, and ten thousand 0.5-m craters – plus additional impacts of intermediate sizes and a host of smaller craters (See SOM, "Stickney Ejecta.xlsx," for our analysis and a more complete sense of the SFD of Stickney secondary impacts).

As we see in Figs. 12 and 13, the secondary impact flux of ejecta from a *trailing* hemisphere Stickney impact is slightly greater than the flux from a *leading* hemisphere Stickney impact. However, an impact on either hemisphere of Phobos clearly produced an intense spike of secondary impacts. To fully appreciate the total bombardment effect, consider that the volume of ejecta from Stickney Crater that returned to Phobos was equivalent to a single 3–3.5 meter diameter impactor intersecting every square meter of the Phobos surface. In terms of a global equivalent layer thickness, the ejecta from Stickney Crater accumulated on Phobos to a global equivalent layer thickness of 15–22 meters.

A substantial volume of the pre-existing Phobos surface was also excavated, mobilized, and redistributed by Stickney secondary impacts (often referred to as "gardening"). The global equivalent layer thickness of deposits that were accumulated directly from Stickney ejecta *plus* the deposits that were produced by secondary impacts that excavated the pre-impact surface of Phobos produced a *total* global equivalent layer thickness of accumulated deposits that is substantially thicker than the 15–22 meter global equivalent layer thickness of Stickney ejecta deposits alone.

To calculate the additional volume of accumulated ejecta that was produced by Stickney *secondary impacts* that excavated the pre-impact surface of Phobos, we observe that Stickney secondary craters ≳400 meters in diameter account for >90% of the total crater volume of Stickney secondary impacts on Phobos. Craters with a diameter ≳400 are also likely to excavate preferentially from the pre-existing surface of Phobos, particularly soon after the Stickney impact when the gardening layer was thinnest.

However, apart from the very largest secondary impacts, the later-stage Stickney secondary impacts primarily remobilized recently accumulated deposits and did not add substantially to the total global equivalent layer thickness of gardened deposits. In view of how the average thickness during the accumulation process is ½ of the final thickness, as a conservative estimate we estimate that only ½ of the volume of ejecta that is launched from Stickney secondary impacts is produced from the pre-impact surface of Phobos and the other ½ is previously accumulated ejecta that is re-launched (a.k.a., gardened).

As worked out in SOM, "Stickney Ejecta.xlsx," secondary impacts from a *leading* hemisphere Stickney impact excavated a global equivalent layer thickness of ~27 m, and from a *trailing* hemisphere Stickney impact, ~45 m. Because we conservatively estimate that ½ of the secondary impact ejecta is produced from the pre-impact surface of Phobos, we conclude that secondary impacts from a *leading* hemisphere Stickney impact produced a global equivalent layer thickness of **~13 m** (27 m / 2), and from a *trailing* hemisphere Stickney impact, **~22 m** (45 m /2). The difference of 13 m and 22 m is due entirely to the greater flux of secondary impacts from a *trailing* hemisphere Stickney impact.

The global equivalent layer thickness of accumulated ejecta from Stickney Crater and from Stickney secondary impacts is summarized as follows:

4.6.1. *Leading hemisphere Stickney impact global equivalent layer thickness of ejecta:* Produced by Stickney primary ejecta: 15 m; Produced by Stickney secondary impact ejecta from the pre-impact surface of Phobos: 13 m; Total global equivalent layer thickness of newly deposited and gardened regolith: **28 m**

4.6.2. *Trailing hemisphere Stickney impact global equivalent layer thickness of ejecta:* Produced by Stickney primary ejecta: 22 m; Produced by Stickney secondary impact ejecta from the pre-impact surface of Phobos: 22 m; Total global equivalent layer thickness of newly deposited and gardened regolith: **44 m**

4.6.3. *Additional considerations:* Our 28 to 44 m prediction for a global equivalent layer thickness of accumulated primary and secondary Stickney impact ejecta is generally consistent with the observations of Thomas et al. (2000). Because of the stochastic distribution of secondary impacts in both target location and time, the thickness of accumulated ejecta deposits may be *locally* reduced by a large late-stage impact.

According to our analysis in SOM, "Stickney Ejecta.xlsx," Phobos Stickney secondary impacts approach crater-saturation at diameters $\lesssim$20 m, whereas secondary impact craters $\gtrsim$400 m are emplaced on ~54–84% of the Phobos surface which is a substantially lower SFD than is required to saturate a planetary surface (Hartmann and Gaskell, 1997). Some local regions may have avoided a large secondary impact, and these local regions are likely to therefore manifest a greater thickness of accumulated ejecta than the total global equivalent layer. However, because of how the gardening mechanism of Stickney ejecta and secondary, tertiary, and additional generations of impact ejecta is globally and stochastically distributed on Phobos, the impact flux of returning ejecta would have remobilized accumulated ejecta to some extent from all surfaces, and it is unlikely that regional Stickney deposits on Phobos deviate substantially in thickness from the total global equivalent layer thickness of Stickney deposits on Phobos (Ramsley and Head, 2013b).

Pre-Stickney-impact surface features that are not destroyed by large Stickney secondary impacts are muted by the effects of smaller secondary, tertiary, and additional generations of impacts that garden the surface via excavation and the accumulation of additional ejecta deposits. During the period of time when Phobos is exposed to secondary, tertiary, and additional generations of impacts, any features that were produced by this flux are also degraded by the same flux.

4.7. *Implications of Stickney ejecta in the production of grooves and groove degradation on Phobos.*

The model of Wilson and Head (2005, 2015) suggests that a process of rolling and bouncing Stickney ejecta boulders is the mechanism that produced many, if not all, of the grooves that are observed on Phobos. Where the boulders would have been mobilized by the impulse of the Stickney impact, the Wilson and Head (2005, 2015) model implies that the groove formation was woven into the events that immediately followed the Stickney impact. In particular, secondary impact cratering and the accumulation of ejecta deposits would have taken place after the grooves were produced by rolling and bouncing boulders.

This raises two central questions: 1) Did Stickney Crater produce a sufficient quantity of sufficiently large sub-escape-velocity boulders to support the model of Wilson and Head (2005, 2015)? 2) Murchie et al. (1989) categorize the widths of the grooves and their degradation states. Are the observed degradation states and width-distributions of the grooves consistent with our model of Stickney secondary impacts and accumulated ejecta deposition?

4.7.1. *Did Stickney Crater produce a sufficient quantity of large sub-escape velocity boulders to produce the grooves as boulder tracks per Wilson and Head, 2005, 2015?* If we apply the same method that we used to work out the SFD of Stickney secondary impact crater blocks to the SFD of low-velocity continuous deposit ejecta that does not produce craters, we observe a large reservoir of low-velocity Stickney ejecta (Table 1, see SOM "Stickney Ejecta.xlsx" for the full analysis). The total volume of continuous deposit ejecta is 8.78×10^9 km^2 represents 23% of the total volume of Stickney ejecta (discussed in Sections 1.3. and 2.6.), and is sufficient to account for several hundred boulders >200 meters in diameter and several thousand boulders with diameters between 100 and 200 meters. The low escape velocity from the rim of Stickney crater (Wilson and Head, 2005, 2015) suggests that most of these boulders were immediately inserted into orbits around Mars. However, as the crater excavation process progressed, there was a preferential reduction of ejection velocities and a preferential production of larger ejecta blocks (Oberbeck, 1975; Melosh, 1989; Wilson and Head, 2005, 2015). This suggests that the largest boulders exited from Stickney Crater with the lowest velocities (Wilson and Head, 2005, 2015). If 10% of the "continuous deposit ejecta" boulders with diameters greater than 100 m did not exit to orbits around Mars and instead remained in motion on the surface of Phobos, there was a sufficient size/frequency of boulders to support the model of Wilson and Head (2005, 2015) that rolling boulders from Stickney Crater produced the grooves of Phobos as boulder tracks.

4.7.2. *Is the observed degradation state of the grooves, per Murchie et al. (1989), consistent with the emplacement of Stickney secondary impacts and ejecta deposit accumulation?* Where the grooves would have been produced immediately at the conclusion of the Stickney impact (Wilson and Head, 2005, 2015), the grooves would have been fully exposed the subsequent degradation effects of flux from Stickney secondary, tertiary, and additional generations of impacts, and the mantling effects of accumulated ejecta deposits. Grooves with greater widths would be morphologically less affected by secondary impacts and the ejecta accumulation process due to their dimensions in comparison to the fixed scale of the degradation processes, whereas narrow grooves would be more greatly affected.

As observed by Murchie et al. (1989), the largest grooves (>400 m width) are, indeed, less morphologically modified, whereas grooves with narrower widths are more greatly muted in degradation state. The majority of grooves on Phobos are ~150 m in width and appear moderately muted, whereas grooves <80 m in width are not observed at all (Murchie et al., 1989). When we compare the observed groove degradation states at varying widths to our prediction of Stickney ejecta flux and to the accumulated thickness of a global equivalent layer deposit thickness of 28–44 m, our model is consistent with the observations of Murchie et al., 1989.

In addition to the mantling of accumulated deposits, Stickney secondary impact craters are likely to directly damage the grooves. However, in order to render a groove less visible, a Stickney secondary impact must destroy the groove levee, which is what most clearly defines a groove (Murray et al., 1994). Secondary impacts that are mostly (or entirely) emplaced within a groove or mostly (or entirely) emplaced outside of a groove are less likely to render the levee substantially unobservable. Further, a groove is a feature that extends in length for many km (Murray et al., 1994), and even if a short segment of a groove levee were entirely erased by a secondary impact, this would not remove the overall morphological sense of the entire groove and the groove would remain substantially observable, minus a missing segment. Entirely erasing the clear morphological definition of a groove with impact craters would, in fact, require multiple overlapping impacts along the entire length of the groove.

Stickney secondary impact crater diameters do not reach saturation at the width of the observed grooves (Hartmann and Gaskell, 1997; Murchie et al., 1989) and the vast majority of Stickney secondary impact craters consequently follow the contours of the pre-impact slopes of the groove walls. Apart from the very largest Stickney secondary impacts, most secondary impacts produced a muting effect on grooves with widths >80 m, rather than fully destroying the groove segment.

Because the size/frequency of low-velocity "continuous deposit" boulders that were produced by the Stickney impact (SOM, "Stickney Ejecta.xlsx"), there would have been no lower limit on the widths of the grooves that would have been produced as boulder tracks. However, accumulated deposits and Stickney secondary impacts preferentially affected the morphology of smaller features, and would have muted the grooves that were <80 m in width to the point where they are no longer observable.

In view of our predictions of the flux of Stickney secondary, tertiary, and additional generations of impacts and the global equivalent thickness of accumulated Stickney deposits on Phobos, the observed degradation states of the grooves of Phobos, as observed by Murchie et al. (1989), are consistent with our model.

4.8. *Implications of a change in the shape of Phobos: Previous versus present-day tidal lock longitude.*

The shape of Phobos changed slightly due to the Stickney Crater impact. Material from Stickney was excavated and distributed across the surface of Phobos. Other crater material was compressed into the floor and rim of Stickney. The crater formation process may also have preferentially raised the east rim of Stickney, thereby accentuating the naturally high elevation of Phobos at that longitude. Consequently, when Phobos was de-spun to its post-impact tidally-locked synchronous rotation longitude, the post-impact longitude ***c*** axis of Phobos was not exactly aligned with the pre-impact ***c*** axis.

The present-day ***c*** axis of Phobos, however, is located to the east of Stickney Crater, and the Stickney impact did not substantially alter the shape of Phobos to relocate the ***c*** axis by more than a few degrees. Consequently, the post-impact 0° sub-Mars longitude of Phobos may have been shifted a few degrees from its pre-impact 0° sub-Mars longitude, **or** a few degrees offset from 180° if Stickney Crater was a *trailing* hemisphere impact. Overall, a slight difference of a few degrees in the pre-impact and post-impact ***c*** axis of Phobos has no effect on the conclusions of our study.

4.9. *The origin of Limtoc Crater.*

Limtoc Crater (a D ~1.8 km diameter crater located in the southwest floor of Stickney Crater) is an outlier in diameter that is not easily explained as a secondary impact (Figs. 1, 5a, 5b). Limtoc may be a primary impact crater that post-dates Stickney Crater. However, where boulder evidence suggests that Stickney Crater is ≲0.5 Ga (Thomas et al., 2000; Basilevsky et al., 2013, 2015), the likelihood of a young superposed primary crater on Stickney that is the diameter of Limtoc Crater is relatively low (Melosh, 1989). Also, the required velocity and projectile diameter of a secondary impactor that would be required to produce Limtoc Crater tends to violate the size limits of secondary impacts on major planets (Melosh, 1989).

To explore the possibility that Limtoc Crater is a secondary impact from Stickney Crater, we consider the distribution of Mars-orbiting ejecta from a *trailing* hemisphere Stickney impact and observe that the ejecta volume is sufficient to account for ~5 secondary craters on Phobos that are equal in diameter to Limtoc (see SOM, “Stickney Ejecta”). Further, when we consider how only a small portion of secondary craters are typically associated with primary craters (Fig. 8) it is possible that oversized rogue secondaries are sometimes produced that may be misidentified as primary craters. Also, the internal structure of Phobos is very poorly understood, and we cannot rule out the excavation and mobilization of an inordinately large ejecta block, launched *intact* from the Stickney impact. We therefore conclude that it is *possible* that Limtoc is a secondary crater formed from Stickney Crater ejecta.

4.10. *The distribution of secondary impacts from a trailing hemisphere Stickney impact on the surface of Mars.*

If the Stickney impact took place on the *leading* hemisphere of Phobos, virtually no Stickney ejecta would have intersected Mars. However, according to our model (discussed in Sections 1.2. and 1.8.), approximately 10% of the ejecta from a *trailing* hemisphere Stickney ejecta would have intersected the atmosphere of Mars with a total meteor volume of ~3.9×10^9 m^3.

Assuming a *trailing* hemisphere Stickney impact on Phobos, the Stickney Crater ejecta arrived at Mars in a single continuous spike that persisted for several hours. A much lower volume of Stickney ejecta also passed close to the martian atmosphere and deorbited to Mars on subsequent orbits due to gradual orbital decay. The distribution of ejecta trajectories from Stickney Crater to Mars preferentially exposed martian equatorial latitudes with the highest concentration of Stickney ejecta flux and thinned in concentration at higher latitudes, north and south. The region of equatorial exposure extended east and west approximately 180° of longitude. Due to the rotation of Mars, the starting and ending longitudes of the distribution pattern are unknown. The total surface area of Stickney meteor exposure on Mars was ~10% of the martian surface. Because a higher volume of ejecta is produced from lower impact crater ejecta launch velocities (Melosh, 1989) and how the sorting of meteor emplacement on Mars was according to ejecta launch velocities from Phobos, Stickney meteor flux on Mars was preferentially concentrated in the east of the exposure region with the lowest flux in the west. Consequently, within the meteor exposure region the local SFD of impacts varied by up to an order of magnitude from the average of the entire region (high to low from east to west), with the highest SFD of Stickney meteor impacts focused toward the head of a cometary-shaped distribution pattern in the most eastern longitudes of the impact region.

Still assuming a *trailing* hemisphere Stickney impact, according to our model, during the flight of Stickney ejecta from Phobos to Mars, orbital mechanics accelerated Stickney ejecta to Mars-intersecting velocities between 4.15 km/s and 4.49 km/s from all potential Phobos altitudes between 7,300 km and 10,000 km (see SOM "Mars Satellite Orbital Calculator"). Fig. 14 plots the *average* SFD of Stickney Crater secondary impacts across the region of exposure on Mars assuming an average meteor impact velocity of 4.3 km/s. Within the impact exposure region (and during several hours of emplacement), Stickney ejecta meteors produced ~600 craters with diameters between 1 and 2 km, and ~10,000 craters between D 300 m and D 1 km in diameter. Overall, on average within every ~20 km^2 of the impact exposure region, Stickney ejecta produced one crater D >20 m (up to D 2 km).

Due to the high volume of Stickney projectiles that reached Mars and the deceleration effect of the atmosphere acting preferentially on smaller meteor particles, a portion of Stickney ejecta likely survived the atmospheric interface with the martian atmosphere and landed intact on the surface of Mars due to the same processes that retain meteorites from background meteor flux on Mars. However (as discussed in Section 1.12.), the Stickney impact likely took place between ~0.1–0.5 Ga, which suggests that it is unlikely that Stickney ejecta will be readily exposed or easily recognized on Mars. Nonetheless, if Stickney ejecta fragments are discovered on Mars, this would support the hypothesis that Stickney Crater was a *trailing* hemisphere impact, since, if the Stickney impact took place on the *leading* hemisphere of Phobos, virtually no Stickney ejecta would have intersected Mars.

5. Conclusions.

On the basis of our analyses, we reach the following conclusions:

1) ***Resolving the age paradox of Stickney Crater:*** In our study, we resolve the paradox of a ≲0.5 Ga Stickney age that is strongly suggested by the evidence of ejecta boulder ages ≲0.5 Ga (Thomas et al., 2000; Basilevsky et al., 2013, 2015) compared to the 2.8–4.2 Ga Stickney age of Schmedemann et al. (2014) which assumes that the counted craters inside Stickney and proximal to the west of Stickney are primary craters formed from projectiles representing the solar system background flux. When we account for Stickney secondary impacts on Phobos and calculate the de-spin time of Phobos after the Stickney impact, we show that Stickney Crater secondary impacts account for all of the craters that are counted by Schmedemann et al. (2014) to compute an older 2.8–4.2 Ga age for Stickney Crater. Due to the global presence of Stickney secondary craters on Phobos, crater counting to compute the age of Stickney, or any other feature on Phobos, based on craters D <2 km in diameter will produce an artificially older and inaccurate surface age.

2) *The SFD of Stickney secondary impacts on Phobos:* Our model of Stickney secondary impacts on Phobos that are produced by Stickney ejecta that is temporarily trapped in orbits around Mars is consistent with the observed SFD of craters on Phobos (as counted by Schmedemann et al., 2014) at diameters <0.6 km and a portion up to D 2 km. Our Stickney secondary impact SFD model that is produced from a *trailing* hemisphere impact is a close match to the SFD of craters that are counted by Schmedemann et al. (2014). Our Stickney secondary impact SFD model that is produced from a *leading* hemisphere impact is slightly lower, yet is generally consistent with the SFD of craters that are counted by Schmedemann et al. (2014).

3) *The Phobos global equivalent layer of accumulated ejecta from the Stickney impact event:* We predict a global equivalent layer thickness of accumulated primary and secondary Stickney impact ejecta of 28 to 44 meters. Approximately ½ of the deposit is derived from Stickney primary ejecta and the other ½ from larger Stickney secondary impacts that excavate the pre-impact surface of Phobos. Our prediction of a total global equivalent layer thickness of 28 to 44 meters is generally consistent with the observations of Thomas et al. (2000).

4) *The intensity of the impact spike on Phobos*: During the first 10 years after a *trailing* hemisphere Stickney impact, *each orbital encounter* of Phobos with the ejecta stream across each km^2 of Phobos, produced one 2-m crater, ten 0.8-m craters, one hundred 0.4-m craters, one thousand 0.2-m craters, and ten thousand 0.1-m craters – plus additional impacts of intermediate sizes and a host of smaller craters. The *annual* accumulation across each km^2 of Phobos was one 43-m crater, ten 10-m craters, one hundred 4-m craters, one thousand 1.3-m craters, and ten thousand 0.5-m craters – plus additional impacts of intermediate sizes and a host of smaller craters. Due to lower volume of available ejecta from a *leading* hemisphere impact, we also predict an impact rate that is slightly lower from a *leading* hemisphere impact. As the Stickney ejecta accumulation process continued, the time duration of the periodic intersections increased due to the orbital perturbation of the Stickney ejecta and the available flux also decreased due to the accumulation of the Stickney ejecta on Phobos until the process was complete ~1,000 years after the Stickney impact.

5) *The trailing hemisphere Stickney impact on Phobos:* The observed greater SFD of background impacts on the *trailing* orbital apex of Phobos compared to the *leading* orbital apex and the observed SFD of craters on Phobos that is more consistent with Stickney secondary impacts from a *trailing* hemisphere impact event suggest that the Stickney impact took place of the *trailing* hemisphere of Phobos. Once Phobos de-spun from the Stickney impact and was resynchronized into a tidal lock with Mars, the new tidal lock longitude of Phobos was rotated ~180° from its pre-impact orientation to the present-day longitude where Stickney Crater is now observed on the *leading* hemisphere of Phobos.

6) *The production and degradation state of Phobos grooves due to Stickney ejecta:* Our model of the volume and size/frequency of low-velocity ejecta boulders that were produced by the Stickney impact is consistent with the model of (Wilson and Head, 2005, 2015) which predicts that Stickney ejecta boulder tracks account for most, or all, of the grooves on Phobos. Further, our prediction of the SFD of secondary impacts and the accumulation of ejecta deposits on Phobos is consistent with the degradation states of the Phobos grooves as described by Murchie et al. (1989).

7) *Stickney secondary impacts on Mars:* If the Stickney impact took place on the *trailing* hemisphere of Phobos, a single spike of Stickney secondary impacts was emplaced along a portion of the equatorial latitudes of Mars. The region of Stickney secondary impact exposure on Mars was ~10% of the land area of Mars and was centered at equatorial latitudes across ~180° of longitude, though due to the rotation of Mars, the central longitude of the Stickney meteor exposure region on Mars is unknown. Intersections of Stickney ejecta with Mars took place in one continuous impact event distributed over several hours. During this time, within the exposed region on Mars, Stickney meteors produced ~600 craters with diameters between 1 and 2 km, and ~10,000 craters between D 300 m and D 1 km in diameter. On average, within every ~20 km^2 of the impact exposure region, Stickney ejecta produced one crater D >20 m (up to D 2 km). Due to the fate of Stickney ejecta that was produced from a *leading* hemisphere Stickney impact on Phobos, a *leading* hemisphere impact would not have produced a spike of Mars-intersecting Stickney ejecta. If Phobos meteorites are discovered on Mars that are consistent with Stickney ejecta, this would lend support to the hypothesis that the Stickney impact took place on the *trailing* hemisphere of Phobos.

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Figure and Table Captions:

Fig. 1: Phobos shown from the nadir viewpoint of ~30° W, ~0° N. The very low escape velocity from Phobos causes the majority of ejecta from the D ~9 km Stickney Crater to be inserted into orbits around Mars and return to Phobos as secondary impacts. Montage of Viking 1 visual imaging subsystem images F854A81, F854A82, and F854A83 (E. V. Bell, NSSDC/Raytheon ITSS).

Fig. 2: Nadir view from above the north pole of Phobos. Stickney Crater is tilted 13.4° west-to-east from an alignment with the geometric center of Phobos. Due to this offset, a portion of the Stickney impact impulse added rotational angular momentum to Phobos and desynchronized its rotational period from its orbital period. We compare the length of time required to de-spin the rotation of Phobos back to a synchronized tidal lock with the length of time required to accumulate Mars-orbiting Stickney ejecta back onto Phobos. The model is based on a set of shape coordinates computed and compiled by Thomas (1997) that are modeled and textured by Schrempp (2011) and visualized in Celestia solar system simulation software (Celestia Software Development Team, 2011).

Fig. 3: The orbital location of ejecta launched in all directions from Phobos at 800 m/s in a point in time ~4 hours after a simulated impact on Phobos, illustrating how Mars-orbiting ejecta returns to intersect the original location in space of the ejecta dispersion. Red test particles have the highest velocities, green have the lowest velocities, and yellow and orange are mid-range velocities. The orbital periods of ejecta fragments vary and this variation produces a continuous stream of ejecta at the point of

the original dispersion. Phobos passes through the ejecta stream during each subsequent orbit, and through this efficient focusing mechanism, over time Phobos accumulates the ejecta that is initially trapped in orbits around Mars. Ongoing orbital perturbation processes gradually alter the orbits of the ejecta and Phobos, which increases the accumulation time. Full narrated video is in SOM. (Blender/Bullet software: The Blender Foundation Development Team, 2015).

Fig. 4: The distribution of apex and antapex craters compared by Schmedemann et al., (2014). Due to how Phobos sweeps a larger volume of space with its *leading* apex hemisphere and how impacts on the *leading* hemisphere arrive at higher velocities, we expect to observe a greater SFD of craters on the *leading* hemisphere of Phobos than on its *trailing* hemisphere. The opposite is observed by Schmedemann et al., (2014). This suggests that during the majority of the early background impact history of Phobos, the synchronous tidal lock of Phobos was rotated ~180° from its present-day longitude. Figure from Schmedemann et al. (2014); the underlying image is the HRSC Phobos basemap (Wählisch et al., 2010) in equatorial equidistant projection.

Fig. 5: Superposed impact crater counting areas: The “S1”counting area **a.** covers the southern portion of Stickney Crater. The size/frequency distribution (SFD) for this area is plotted with red diamonds in Figs. 6a and 7a. The “S2”counting area **b.** covers the southeastern portion of Stickney Crater. The SFD for this area is plotted with red diamonds in Figs. 6b and 7b. The counting area west of Stickney Crater **c.** is counted as the “average” for Phobos. The SFD for this “Phobos average” area is plotted with red diamonds in Figs. 6c and 7c. From Schmedemann et al. (2014). Underlying images are from the HRSC basemap of Phobos (Wählisch et al., 2010) in Mercator projection.

Fig. 6: Size/frequency distribution (SFD) plots of superposed impact craters on Phobos. **a:** Red diamonds, derived from Schmedemann et al. (2014), plot the SFD of craters that correspond to the counting area “S1” inside the crater rim of Stickney (see Fig. 5a). The blue squares distribute the available ejecta from a *trailing* hemisphere Stickney impact (see SOM, “Stickney Ejecta.xlsx”). The predicted SFD production of secondary impacts from Stickney ejecta is sufficient to produce all of the “S1” craters from a *trailing* hemisphere Stickney impact on Phobos. **b:** Red diamonds, derived from Schmedemann et al. (2014), plot the size/frequency distribution (SFD) of the craters that correspond to the counting area “S2” inside the crater rim of Stickney (Fig. 5b). The blue squares distribute the available ejecta from a *trailing* hemisphere Stickney impact (see SOM, “Stickney Ejecta.xlsx”). Unlike the “S1” counting area, the “S2” counting area at smaller crater sizes produces a slightly higher SFD curve (red diamonds) compared to the available ejecta from a Stickney *trailing* hemisphere impact (blue squares). The slightly excessive number of counted craters in the “S2” area may be due to the limited areal size of the counting area or a combination of Stickney secondary impacts plus recent background flux. There is no sharp kink in the SFD in either the “S1” or “S2” counting areas, which suggests that the Stickney impact took place after the recent crater population spike shown in **c.** Red diamonds, derived from Schmedemann et al. (2014), plot the size/frequency distribution (SFD) of the craters that correspond to the “Phobos average” counting area to the west of the Stickney Crater rim (Fig. 5c). The blue squares distribute the available ejecta from a *trailing* hemisphere Stickney impact (see SOM, “Stickney Ejecta.xlsx”). The “Phobos average” counting area is selected by Schmedemann et al. (2014) for comparison with the two crater counting areas inside Stickney Crater, “S1” and “S2.” At a crater diameter of D ~0.6 km the “Phobos average” counting area shows a sharp kink in the SFD, which strongly suggests that a spike of impact flux was recently imprinted atop an older SFD of larger craters. The sharp kink at D ~0.6 km and the SFD of smaller craters that extend to smaller diameters from this

kink are consistent with our model of Stickney secondary impacts from a *trailing* hemisphere impact on Phobos.

Fig. 7: Red diamonds in **a.**, **b.**, and **c.** are derived from Schmedemann et al. (2014) and plot the size/frequency distribution (SFD) of the craters that correspond to the three counting areas shown in Fig. 5. From our model (see SOM, “Stickney Ejecta.xlsx”), the blue squares in **a.**, **b.**, and **c.** distribute the available ejecta from a *leading* hemisphere Stickney impact. The SFD of Stickney secondary impacts on Phobos from a *leading* hemisphere Stickney impact is slightly less than from a *trailing* hemisphere Stickney impact and is insufficient to account for the craters that are counted by Schmedemann et al. (2014). This *leading* hemisphere impact SFD deficiency suggests that Stickney secondary craters were more likely produced from a *trailing* hemisphere Stickney impact. However, the deficiency of the *leading* hemisphere impact SFD is insufficient to rule out a *leading* hemisphere Stickney impact.

Fig. 8: The size/frequency distribution (SFD) of observed secondary impacts from Tycho Crater on the Moon from Dundas and McEwen (2007) is derived and plotted in red squares. This is compared to lunar secondary impacts (blue diamonds) that are derived from our model which correspond to the SFD of Tycho secondary impacts that returned from orbits around the Earth (see SOM, “Stickney Ejecta.xlsx”). Due to the planetary diameter of the Moon, the vast majority of Tycho secondary craters are scattered across the global surface of the Moon. In contrast, secondary craters from Stickney Crater on Phobos are concentrated onto the small-body global surface area of Phobos, which suggests that the SFD concentration of secondary impacts on Phobos is substantially greater than on the Moon.

Fig. 9: Phobos approximates a triaxial ellipsoid (Burns, 1977). The three ideal principal axes **A**, **B**, and **C** of Phobos are shown overlaid atop a three-dimensional model of Phobos (after Ramsley and Head, 2013a). The three ideal principal axes are used to compute the mass properties of Phobos in our study. The 3D model shows a polar view of Phobos (left) and the *leading* orbital hemisphere view of Phobos (right). The model is based on a set of shape coordinates computed and compiled by Thomas (1997) that are modeled and textured by Schrempp (2011) and visualized in Celestia solar system simulation software (Celestia Software Development Team, 2011).

Fig. 10: This schematic diagram shows the trajectories of sub-orbital, orbital, and super-orbital ejecta from a large crater on Phobos and the geometry of the interaction of ejecta clasts with the regolith surface on Phobos. Transient crater stages and the various ejecta properties in relation to their position inside the transient crater cavity are also diagramed (from Wilson and Head, 2015).

Fig. 11: Comparison of the size/frequency distribution (SFD) of Stickney secondary impact production on Phobos from *leading* and *trailing* hemisphere Stickney impacts. Both distributions omit the ~23% of lower-velocity “continuous deposit” ejecta that is typically emplaced proximally to primary craters on major planets that do not produce secondary impacts, and the plots apportion only the higher-velocity Mars-orbiting Stickney ejecta that remains in orbit to produce secondary craters on Phobos. The two SFD plots differ due to how a *leading* hemisphere Stickney impact loses ~40% of Stickney ejecta to solar orbits, whereas a *trailing* hemisphere impact loses ~10% to the surface of Mars and substantially <1% to solar orbits.

Fig. 12: The size/frequency distribution (SFD) of **a.** *episodic* and **b.** *annual* Stickney secondary impacts on Phobos from a *trailing* hemisphere Stickney impact. The episodic plots ***a.*** show the spike of impacts during each translation of Phobos through the region of space where the original Stickney impact

took place (Fig. 3). The annual totals plot ***b.*** sum the total flux for a whole year of intersections. As Stickney ejecta accumulates on Phobos, less is available for future impacts, and as the orbits of Phobos and the ejecta evolve and diverge, the intersection process is increased in time and reduced in intensity. The plots show a high flux rate during the initial 10 years after the Stickney impact (red squares), a moderate flux rate during next 100 years (green diamonds), and a low flux rate during the final 1,000 years (blue triangles).

Fig. 13: The size/frequency distribution (SFD) of **a.** *episodic* and **b.** *annual* Stickney secondary impacts on Phobos from a *leading* hemisphere Stickney impact. As in Fig. 12, the episodic event and annual totals after the Stickney impact are shown during the first 10 years (red squares), the next 100 years (green diamonds), and the next 1,000 years (blue triangles).

Fig. 14: The average size/frequency distribution (SFD) of Stickney secondary impacts on the surface region of Mars that was exposed to Stickney secondary impacts from a *trailing* hemisphere impact. In this case, Mars was exposed to ~10% of the total volume of Stickney ejecta, and the deorbiting of Stickney ejecta onto Mars took place as a single continuous intersection spike over a period of several hours. If the Stickney impact took place on the *leading* hemisphere of Phobos, the vast majority of Stickney ejecta gained altitude around Mars and substantially <1% intersected Mars.

Table 1: The volume of “continuous deposit” ejecta from Stickney crater that intersects Phobos at velocities that are too low to produce secondary craters represents ~23% of all ejecta from Stickney Crater (McGetchin et al., 1973). In this table we distribute the volume of the continuous deposit ejecta into a size/frequency of fragment diameters. As discussed in Sections 3.7. and 3.8., the average of *all* Stickney ejecta velocities (including velocities that produce secondary impacts) may have been as low as 140 m/s, which suggests than an even lower average ejection velocity was imparted to the ~23% proportion of “continuous deposit” ejecta. As the excavation process approached its conclusion, there was a preferential reduction of ejection velocities and a preferential production of larger ejecta blocks (Oberbeck, 1975; Melosh, 1989; Wilson and Head, 2005, 2015). If $\gtrsim$10% of the continuous deposit fragments in this table remained on Phobos (~2% of all Stickney ejecta), there was a sufficient size/frequency of “continuous deposit” boulders to produce the grooves of Phobos as boulder tracks in accordance with the model of Wilson and Head (2005, 2015).