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

Kenneth R. Ramsley a,b,⁎, James W. Head a

a Department of Earth, Environmental and Planetary Sciences, Brown University, Box 1846, Providence, RI 02912, USA
b School of Engineering, Brown University Box D, Providence, RI 01912, USA

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ABSTRACT

A global and uniformly distributed spike of secondary impact craters on Phobos with diameters (D) < 0.6 km and a portion of craters up to D 2 km were produced by Stickney Crater ejecta, including secondary craters within the surface area of Stickney Crater. The global exposure of Phobos to Stickney secondary impacts was facilitated by the desynchronized orbital/rotational period of Phobos that was produced by the impulse of the Stickney impact event. In our model we apply the Tsiolkovsky rocket equation to calculate the total available Stickney impact acceleration impulse delta-v (Δv) and further calculate the effective impulse by incorporating the energy conversion efficiencies of the crater formation process. We also calculate the pre- and post-impact Phobos moment of inertia that further contributes to the desynchronizing effect. The majority of the Stickney ejecta that exited from Phobos was trapped in orbits around Mars until it later accumulated back onto Phobos over a period of < 1000 years. However, Phobos de-spun back to a synchronous rotation after a much longer period of at least 5000 years. Therefore, a sufficient period of desynchronized rotation exposed the entire surface of Phobos to ejecta that returned from martian orbits. In view of how all or most craters observed inside Stickney Crater approximate the size/frequency distribution (SFD) of Stickney secondary impacts, it is infeasible to derive an age for Stickney Crater based on an assumption of background impacts (~2.8–4.2 Ga according to Schmedemann et al. (2014)). In view of how crater-counting is unworkable for age-dating Stickney Crater we conclude an alternate age for Stickney Crater of 0.1–0.5 Ga that is constrained instead 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 (Cipriani et al., 2011; Pieters et al., 2014). Assessing several implications of our model we 1) summarize the crater SFD and temporal nature of the Stickney secondary impact spike on Phobos, 2) predict the global equivalent thickness of deposits on Phobos from Stickney ejecta and subsequent secondary impact gardening, 3) examine the hypothesis that the Stickney impact was a trailing hemisphere event on Phobos that reoriented Phobos to its present-day synchronous “tidal lock” longitude, 4) set limits on the volume of low-velocity Stickney ejecta that is available to produce Phobos grooves from rolling boulders, and 5) estimate the crater SFD of a meteor spike on Mars from a trailing hemisphere Stickney impact.

1. Introduction

Based on well-reasoned yet conflicting lines of evidence, studies of the largest crater on Phobos, Stickney Crater (D ~ 9 km), have produced an unresolved discrepancy for the age of the crater (Ramsley and Head, 2014; Fig. 1). 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 these boulders is morphologically consistent with Stickney ejecta. In particular, the quantity, size, and preferential areal concentration of the boulders (increasing with closer proximity to Stickney Crater), strongly suggests that Stickney Crater is the source of the boulders. Basilevsky et al. (2013, 2015) calculate that meter-scale boulders on Phobos, including those associated with Stickney Crater, are destroyed by meteor impacts in ≤0.5 Ga. Therefore, based on the boulder destruction rates for Phobos, the age of Stickney Crater is ≤0.5 Ga.

Crater SFD is a method that is typically applied to date airless, or nearly airless, solar system body surfaces based on an assumption of a constant background impact crater flux from solar system projectiles (Hartmann, 1977, 1995; Hartmann and Gaskell, 1997). Forming the other half of the Stickney age discrepancy, Schmedemann et al. (2014) count craters within Stickney Crater and derive age ranges utilizing two...
different background impact flux regimes. Case A yields an age for Stickney Crater of 2.8–4.2 Ga by assuming that Phobos has always orbited around Mars, and Case B derives an age of 38 Ma–3.4 Ga by assuming that Phobos is a recently captured asteroid (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: 2.8–4.2 Ga.

In view of the large Stickney age discrepancy of \( \leq 0.5 \) Ga that is based on boulder evidence compared with an age that is based on background crater-counting of 2.8–4.2 Ga, the two models are mutually exclusive (Ramsley and Head, 2014). Both models are well-reasoned and well-supported, yet they conflict sharply, leaving an unresolved discrepancy.

Our hypothesis reconciles this discrepancy by concluding that most craters within Stickney are not produced by an influx of background meteor impacts, but rather the superposed craters within Stickney are secondary impacts that were produced by the Stickney impact event. Consequently, we ignore crater-counting age determinations for Stickney and accept the boulder model of Basilevsky et al. (2013, 2015) for the upper age limit of Stickney. Further, we infer a lower age limit based on space weathering, which requires \( \geq 0.1 \) Ga to manifest as observed on Phobos (Cipriani et al., 2011; Pieters et al., 2014).

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? 2) If so, did the desynchronized secular rotation of Phobos persist for a sufficient length of time to fully expose Stickney Crater to secondary impacts? 3) If so, did the Stickney impact produce a sufficient volume of ejecta to account for the superposed craters that are observed inside Stickney and the SFD spike that is observed in the “Phobos average” counting area of Schmedemann et al. (2014)?

In view of the intricately intertwined processes of the Stickney impact event, key results of our study are often introduced early in the text in order to fully explain the assumptions and methods of our model. We provide this context in order to assist the reader in assessing the relative merits of our introductory remarks, and we include references that direct the reader to later sections for the detailed analyses and discussions that underpin our stated conclusions.

1.1. Stickney crater as a source of secondary impacts on Phobos

Due to its size, we assume that the \( D \approx 9 \) km Stickney Crater is very likely a primary solar system impact crater (not a secondary impact from a primary crater on Mars), and also that the velocity of the projectile that produced Stickney was similar to the typical intersection velocities of solar system projectiles in the vicinity of Phobos (Neukum and Wise, 1976; Ivanov, 2001). Based on our model, we further assume that a portion of Stickney ejecta that exits from Phobos remains temporarily trapped in orbits around Mars where it continues to intersect the orbit of Phobos at the location of the original impact in cis-martian space (SOM video: “Phobos Returns to the Scene of the Crime”).

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Over the course of < 1000 years, and mostly within the first few hundred years (Nayak et al., 2016), Mars-orbiting Phobos ejecta returns to Phobos in a series of impact and gardening events that gradually deposits the original impact ejecta back onto Phobos (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996; Ramsley and Head, 2013b).

Higher-velocity ejecta fragments return to Phobos to produce secondary impact craters (Burns, 1972; Thomas, 1998; Ramsley and Head, 2013a, 2013b). Lower-velocity ejecta accumulates on Phobos without producing craters, and the very lowest velocity ejecta flows and rolls on the surface of Phobos without immediately exiting from the gravity well of Phobos (Wilson and Head, 2005, 2015; Syal et al., 2016). Nayak and Asphaug (2016) further suggest an intermediate category of clustered collisional features “sesquinary catenae” on Phobos that are produced from ejecta that rapidly returns to Phobos.

For nomenclature consistency with our previous reports, we do not use the term sesquinary to describe impact craters that are produced by Mars-orbiting ejecta, and in this report our use of the more generic expression “secondary craters” describes the first-generation of impact craters on Phobos that are produced by ejecta from any primary crater (Ramsley and Head, 2013a, 2013b).

1.2. Implications of the two possible pre-impact tidal lock orientations of Phobos

Assuming that the Stickney impact desynchronized the rotation of Phobos, i.e. “broke the tidal lock,” Phobos either de-spun back to its original pre-impact longitude or was reoriented \( \sim 180^\circ \) (Fig. 2). If Phobos de-spun back to its pre-impact orientation, the Stickney impact took place on the leading hemisphere of Phobos (where we observe...
Stickney Crater in the present day). If Phobos was reoriented ~180° by the Stickney impact event, the impact took place on the trailing hemisphere of Phobos. With respect to the most likely end-state synchronous orientations of Phobos, there is no dynamic preference to either scenario (Burns, 1972). Consequently, throughout our calculations, we analyze for both scenarios: 1) A leading hemisphere impact at the present-day Stickney longitude of ~50°W, and 2) a Stickney impact on the trailing hemisphere of Phobos at ~130°E, ~180° opposite from the present-day longitude of Stickney. In order to clearly distinguish between the two main branches of our model (based on either a leading or trailing hemisphere impact), our report routinely italicizes the two words leading and trailing.

Taking the gravitational focus of Mars and the orbital velocity of Phobos into account, if a meteor impact takes place on the leading hemisphere of Phobos, the average impact velocity at Phobos is ~13 km/s, and if the impact takes place on the trailing hemisphere of Phobos, the average velocity is ~9 km/s (Neukum and Wise, 1976; Ivanov, 2001).

According to our model, due to the way in which the launch velocity of Phobos ejecta combines with or subtracts from the orbital velocity of Phobos, ~40% of the ejecta that is produced by a leading hemisphere Stickney impact exits to solar orbits, whereas from a trailing hemisphere impact, ~10% interacts the atmosphere of Mars and substantially < 1% exits to solar orbits (Section 2.6).

### 1.3. The fate of Stickney ejecta that is inserted into Mars-centric orbits

Immediately after the Stickney impact, ejecta that remains trapped in orbits around Mars intersects the orbit of Phobos at the location of the Stickney impact in cis martian space (Fig. 3, SOM Video: “Phobos Returns to the Scene of the Crime”). This intersection consequently produces a strong initial preferential orbital focus that brings a portion of Mars-orbiting Stickney ejecta back into contact with Phobos during each subsequent orbit of Phobos.

Combining the gradual depletion of orbiting ejecta with the evolution of Mars-centric orbits, the flux of Stickney ejecta at Phobos decays over time. Solar photon pressure deorbits ejecta fragments ≤300 μm to the atmosphere of Mars or to solar orbits within several years, whereas ejecta fragments ≥300 μm tend to remain in Keplerian orbits around Mars until they intersect the surface of Phobos through a process of secondary, tertiary, and additional impact generations of Phobos until the fragment population is entirely depleted. Due to the initial post-impact alignment of Phobos with Mars-orbiting ejecta, the vast majority of Stickney ejecta preferentially returns to Phobos within a few hundred years (Dobrovolskis and Burns, 1980; Juhász et al., 1993; Hamilton and Krivov, 1996; Krivov et al., 1996; Ramsley and Head, 2013b; Nayak et al., 2016).

The model of Nayak et al. (2016) further suggests that a small mass fraction of Phobos ejecta may intersect Deimos. We accept the conclusions of Nayak et al. (2016) and note that their mass fraction predictions of Phobos ejecta accumulation on Deimos has no material effect on the conclusions of our study. Comparing this to our model, immediately post-impact, we observe that virtually 100% of the Mars-orbiting Phobos ejecta intersects the orbit of Phobos and essentially 0% is initially aligned with the orbit of Deimos. It is likely that Deimos intercepts a fraction of Phobos ejecta fragments ≤300 μm that spirals toward solar orbits, and where Keplerian orbits evolve, Phobos ejecta may shift to orbits that intersect Deimos over time. Overall, the likelihood of a Phobos ejecta transfer to Deimos is strongly dependent on the location of the impact on Phobos. For example, the likelihood of a Deimos intersection is particularly improbable from a trailing hemisphere impact on Phobos where > 99% of the Mars-orbiting Phobos ejecta is inserted into orbits that are below the orbital altitude of Deimos.

### 1.4. Tidally-locked moons typically shield primary 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 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 from the location of the primary impact site. Consequently, the primary impact site is typically shielded from its own secondary impacts (Ramsley and Head, 2013b).

However, if the rotation of Phobos is desynchronized from its tidal lock, the entire global surface of Phobos is periodically exposed to secondary impacts, including the crater that produced the desynchronization event.

In our model, we calculate the de-spin time of Phobos to determine whether or not Stickney Crater is fully exposed to its own Mars-orbiting ejecta (SOM: “Desynchronization calculations at 7300 km altitude” and “Desynchronization calculations at 10,000 km altitude”). In order for Phobos to be globally and uniformly exposed to all available returning ejecta, the de-spin time of Phobos must equal or exceed the period of time when ejecta remains in orbit around Mars.

### 1.5. Factors that contribute to desynchronizing the tidal lock of Phobos

A tidal lock requires that both rotational and orbital periods remain the same. If the orbital period changes – this alone may desynchronize the orbital/rotational periods of a tidally-locked body sufficiently to produce “free” rotation. In addition to directly altering the orbit of the target, the impact event and resulting crater morphology may also alter the rotational rate of the target through: 1) a grazing collision angle that imparts a preferential acceleration vector, 2) the removal and displacement of target material that alters the target body’s moment of inertia, 3) deformation of the target body that also alters the moment of inertia, and/or 4) an impact onto a non-spherical target body that produces a crater that is tilted from the gravitational center (CG) of the target (producing an effect similar to factor 1). Further, all four of these factors operate...
with greater efficiency when the impact takes place on or near the target's equatorial latitude.

Where we do not observe evidence of a low-angle Stickney impact event, we do not include factor 1 in our model. We also do not calculate for factor 3 because we do not know if the Stickney impact event substantially altered the pre-impact shape of Phobos beyond the crater itself. We do, however, calculate the effect on the moment of inertia of Phobos due to material that is displaced and removed from Stickney Crater (factor 2), and we account for the desynchronizing effect that is produced by the location of Stickney Crater on the western slope of a substantial topographical elevation that is located almost exactly on the equator of Phobos (factor 4). Stickney Crater is tilted uphill to the east as a consequence of its emplacement location, thereby shifting the crater orientation away from the CG of Phobos by 13.4° (Fig. 2). This tilted offset, combined with its equatorial latitude, produces a strong preferentially directed acceleration vector component that increases the rotational angular momentum of Phobos.

In our model, we calculate the change in orbit from leading and trailing hemisphere Stickney impacts at altitudes that correspond to an impact at ~0.1 Ga and ~0.5 Ga.

1.6. The conversion of Stickney impact energy to a Phobos acceleration impulse

Our model conservatively accounts for impact-to-impulse acceleration conversion losses where ~40% of the impact energy is dissipated to no effect by a host of factors (listed in Section 3.8) and only ~60% of the projectile impact energy is translated into an acceleration impulse.

When we partition the total desynchronizing effect, ~0.4% is produced by a change in the orbit of Phobos, ~10% is produced by the displacement and removal of target material from the crater, and ~90% is produced by a direct eastward impulse vector component (SOM: “Desynchronization calculations at 7300 km altitude” and “Desynchronization calculations at 10,000 km altitude”).

In fact, due to the alteration in the moment of inertia of Phobos, the displacement and removal of target material from Stickney Crater alone would have produced at least 500 years of de-spin time—sufficient de-spin time to support our hypothesis of globally-emplaced Stickney secondary impacts on Phobos (Section 3.5.5).

1.7. Stickney secondary crater SFD budget

To answer the question of whether or not there is a sufficient global SFD of Stickney secondary craters on Phobos to account for the crater counting of Schmedemann et al. (2014), we calculate the total volume of ejecta that is produced by the Stickney impact and then calculate the fraction that was initially trapped in orbits around Mars with sufficient orbital velocities to produce secondary craters on Phobos. The budget is calculated using the excavated volume of Stickney Crater (SOM: “Stickney Ejecta”).

Phobos gravity has essentially no effect on crater excavation and launch velocities from Phobos >20 m/s. Phobos gravity also has essentially no effect on the diameters of observed craters on Phobos. Consequently, we utilize orbital and crater scaling models that ignore the consequences of local Phobos gravitation (Melosh, 1989), (SOM: “Stickney Ejecta”).

1.8. Earth’s Moon as an analog for low-velocity Phobos ejecta

On the Moon, the process of low-velocity ejecta emplacement is observable as a continuous deposit that is located proximally to lunar craters. Due to the low ejection and emplacement velocities, continuous ejecta deposits on the Moon accumulate as featureless regolith (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 proximally to the crater. Consequently, we assume that only 77% of Stickney ejecta was capable of producing secondary craters on Phobos (McGetchin et al., 1973), (SOM: “Stickney Ejecta”).

Although the process of low-velocity ejecta accumulation at Phobos may include an intervening step (orbiting Mars), for the sake of a continuity of terms, we nonetheless define low-velocity Phobos ejecta that does not produce secondary impact craters on Phobos as “continuous deposit ejecta.” We further assume that a portion of the lowest-velocity ejecta is mobilized to flow across the surface of Phobos without exiting to martian orbits, which suggest a mechanism that is capable of producing grooves from rolling and bouncing boulders (Wilson and Head, 2005, 2015; Syal et al., 2016).

1.9. The most likely pre-impact tidal lock longitude of Phobos

Two lines of evidence suggest that the orientation of Phobos prior to the Stickney impact was rotated ~180° in longitude from the present day (also why we preferentially analyze this orientation):

1. Typically, due to a greater impact flux and greater impact velocities, background impacts are preferentially emplaced on the leading hemisphere of a tidally-locked body to produce a greater SFD of craters compared to the trailing hemisphere. However, on Phobos we observe a greater SFD of craters on the present-day trailing hemisphere (Fig. 4). This strongly suggests that Phobos was reoriented ~180° from its present-day tidal lock orientation after the majority of its earlier geological history.

2. In the “Phobos Average” crater-counting area of Schmedemann et al. (2014) located to the west of Stickney Crater, we observe a

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Fig. 4. The distribution of Phobos 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. However, the SFD of craters shown in this plot is reversed from our expectation, which suggests that Phobos orbited around Mars during much of its earlier geological history ~180° from its present-day tidal lock orientation.
sharp kink in the SFD data at $D \sim 0.6$ km (Figs. 5c, 6c, 7c). According to our model, this kink is consistent with the higher flux of Stickney ejecta that returns from a trailing hemisphere impact.

Although neither of these lines of evidence are entirely conclusive, they nonetheless suggest that Stickney Crater was produced on the trailing hemisphere of Phobos, and Phobos was subsequently resynchronized ~180° from the pre-impact tidal lock longitude to the longitude of the present day.

1.10. The small target area of Phobos concentrates the areal density of secondary impacts

Due to the large surface area of the Earth's Moon, when a lunar primary impact takes place, most of the secondary impacts are emplaced far from the primary impact site. This observation is well-supported by our modeling of the Moon (SOM: “Stickney Ejecta”), which suggests that the vast majority of secondary impacts on the Moon are broadly and thinly dispersed across the lunar surface, and only a small proportion are observed in association with the primary impact (Fig. 8). However, Phobos does not have a large area to distribute its secondary impacts, and as a consequence, secondary impacts on Phobos from Mars-orbiting ejecta are concentrated into an area that is ~25,000 times smaller than the surface area of the Moon. Apart from any other analysis, the process where Mars-orbiting ejecta is concentrated onto Phobos due to the small body size of Phobos strongly suggests that the surface of Phobos was substantially reworked by Stickney secondary impacts and accumulating deposits.

1.11. The character of secondary impacts on Phobos

Although the notion of “secondary craters’ typically invokes images of proximal low-velocity and often low-incidence angle impacts that produce distinctive herringbone crater patterns (Melosh, 1989), Phobos is exposed to a stochastic distribution of Mars-orbiting ejecta that may arrive from any angle at any velocity up to ~4.7 km/s (beyond this velocity Phobos ejecta escapes to solar orbits from all scenarios). As a result, a substantial proportion of Stickney secondary craters are likely to appear morphologically similar to circular-rimmed primary craters.

2. Analytical methods, concepts, and assumptions

We begin with a shape model of Phobos. From this model we measure the location and surface orientation of Stickney Crater...
Based on the mass properties of Phobos and predictions of the Stickney impactor's mass and velocity, we apply the Tsiolkovsky rocket equation to calculate the total available acceleration impulse that is produced by the Stickney impact. Accounting for impact-to-impulse crater formation inefficiencies and the location of the impact site on Phobos, we predict the post-impact orbital velocity of Phobos and its altered rotational period.

As a cross-check, we compare our prediction of the post-impact Phobos $\Delta v$ to Ivanov (1991) who lists three alternate methods. The fact that our $\Delta v$ prediction is fully consistent with Ivanov (1991) strongly suggests that our application of the Tsiolkovsky rocket equation is valid.

We assume a triaxial ellipsoid to calculate the extent of orbital/rotational period desynchronization and also as part of our de-spin calculations (Burns, 1977; Fig. 9). To calculate the post-impact de-spin period of Phobos, we apply the formulae of Gladman et al. (1996) and Burns (1977). Calculations are repeated for both leading and trailing hemisphere pre-impact orientations of Phobos and for altitudes of Phobos above the martian surface of 7300 km and 10,000 km that correspond to ~0.1 Ga and ~0.5 Ga. In order to limit rounding errors, during many of our calculations we often include a large number of significant digits. Key results and conclusions are reported using a reasonable number of significant digits.
2.1. The tidal lock of Phobos

In the present day, Phobos is a “tidally locked” body (Burns, 1972, 1977), and by this expression we observe that the same hemisphere of Phobos faces Mars due to a synchronous rotational 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 faces Mars at all times. 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 energy rotational state is achieved when Phobos is aligned along its major axis perpendicular to the surface of Mars and rotates on its shortest axis (Burns, 1977, Fig. 9).

Tidally locked bodies are typically 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 tides between the parent planet and moon interact, and the moon loses rotational angular momentum until it reaches its lowest energy state and becomes locked along its major axis. Based on the post-Stickney impact orbit of Phobos, its post-impact rotation, and its energy dissipation properties, it is possible to calculate the length of time that is required to de-spin Phobos from its post-Stickney impact rotational rate back to a tidally-locked synchronous-rotation (Burns, 1977; Gladman et al., 1996).

2.2. Secular libration rather than desynchronized rotation?

Notionally, it is reasonable to imagine that the Stickney impact may have produced an increase in the secular libration of Phobos, rather than desynchronized rotation. As it turns out, this hypothesis may be directly calculated using the de-spin formulae of Burns (1977) and Gladman et al. (1996).

The total libration time period is one orbit. If the de-spin time is less than the orbital period, the de-spin process will be completed before one rotation takes place, and in effect, Phobos will oscillate until the residual impulse is dissipated through the motion of secular libration. However, if the de-spin time is substantially longer than the orbital period of Phobos (as we calculate), in effect, the de-spin period exceeds the orbital period and subsequent orbits that include free rotation will be required before tidal forces reestablish a synchronous lock.

During the final stages of resynchronization, Phobos would manifest a substantial degree of secular libration. However, we do not calculate the end-stage period of secular libration or consider this time period in our model.

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

Due to poorly estimated initial states of the orbit and rotational rate of a primordial moon, the typical calculation of a de-spin time to a tidal lock 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 calculates the semimajor axis of the moon to the sixth power (Gladman et al., 1996) and consequently how the uncertainty in the primordial 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 0.1 Ga: 7300 km altitude, and 0.5 Ga: 10,000 km altitude (Burns, 1972; Lambeck, 1979; Bills et al., 2005; Jacobson, 2010), we begin with a semimajor axis that offers a close approximation. Also, because we calculate the post-impact rotational rate of Phobos based on the impulse that produced Stickney Crater, we are able to supply a reliable initial rotation rate. Consequently, the initial semimajor axis and rotational rate that typically produce a wide range of uncertainties in de-spin time calculations are well constrained in our model, which reduces the error bar of our de-spin time prediction from ± one order of magnitude to a factor of ± 2.

2.4. Impact impulse and the application of the Tsiolkovsky rocket equation

Where Stickney Crater is inconsistent with morphological features that are typically associated with low collision angle impacts (Melosh, 1989), our model assumes a Stickney projectile impact angle between 20° and 90° (near-horizontal to perpendicular). From a non-grazing impact angle of 20–90°, the vast majority of impact energy is translated into a centralized core of shock-driven dynamic pressure that excavates and launches ejecta into a generally uniform cone-shaped distribution pattern that is normal to the target surface (Melosh, 1989). For this reason, we assume that the collisional angle of the Stickney impact did not contribute significantly to the post-impact angular momentum of Phobos (Section 1.5).

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 based on the typical velocity of solar system impacts at Phobos (Neukum and Wise, 1976; Ivanov, 2001), and the scaling equations of Melosh (1989) to calculate the impactor mass. Applying the Tsiolkovsky rocket equation, we assume that the total available impulse is equal to the velocity and mass of the impactor. The projectile mass is the “propellant” mass and the impact velocity is equal to the “nozzle” velocity (in essence, our “rocket” engine is running backwards).

The most energetic portion of the Stickney Crater excavation process likely took place during the first ~6 s after the beginning of the impact event (Melosh, 1989). Although a brief process, this length of time is consistent with many rocket engine maneuvers. Obviously, a crater formation process is not a rocket engine. Nonetheless, the total available impulse is the same no matter what produces the mass × velocity input, and the only difference is the extent to which a crater formation process is inefficient in converting the total available impact energy into a vectored acceleration impulse. The main inefficiency of a crater formation compared to a rocket engine stems from the ~45° cone-angle of crater ejecta which deviates ~2°–5° from an ideal rocket nozzle vector. Once we consider all conversion inefficiencies, the remaining impact energy is the effective impulse applied to Phobos by the Stickney impact. (A detailed list of inefficiencies is discussed in Section 3.8).

2.5. The altered orbital and rotational periods of Phobos produced by the Stickney impact

Where Stickney Crater is tilted from the CG of Phobos by ~13.4° and is also longitudinally offset from the orbital apex of Phobos by ~40° (Fig. 2), we partition the impulse vector component that accelerates Phobos into a new orbit and the component that directly alters the rotational period of Phobos. Further, we calculate 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, much like how ice-skaters spin faster on the ice when they draw their arms closer while spinning.

The preferentially eastward-directed impulse of the Stickney impact increased the rotational rate of Phobos, and the compression and removal of crater floor material further increased the rotational rate due to the change in the moment of inertia of Phobos. These effects are the same from either a leading or trailing hemisphere Stickney impact.

Conversely, depending on whether the Stickney impact took place on the leading or trailing hemisphere of Phobos, the post-impact orbit of Phobos either adds or subtracts from the total desynchronization effect. However, the contribution to the overall desynchronization effect from either orbital alteration is negligible (∼<0.4%), and our calculated predictions for the desynchronization effects from a leading or trailing
ejecta initially orbits around Mars (Fig. 10), and it returns to Phobos at the gravitational force of Phobos, most of the low-velocity continuous deposit ends up being incorporated into the target material that is removed and the target material that is displaced. A simple crater (in this case, Stickney) is divided equally between the areas impacted by the impacting particle and the surrounding regolith. The volume of Stickney ejecta launched from the crater is equal to 50% of the total volume of Stickney ejecta (SOM: “Stickney Ejecta”).

For detailed calculations, see SOM: “Desynchronization calculations at 7300 km altitude” and “Desynchronization calculations at 10,000 km altitude.”

2.6. Available Stickney ejecta to produce secondary impacts on Phobos

We calculate the volume of Stickney ejecta that is available to produce secondary impacts by analyzing the interior volume of Stickney Crater (SOM: “Stickney Ejecta”). The interior volume of a simple crater (in this case, Stickney) is divided equally between the target material that is removed and the target material that is displaced into the floor and walls of the crater. Our model therefore assumes that the volume of Stickney ejecta launched from the crater is equal to 50% of the observed empty 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 encircles a primary crater on the Moon is also produced by the Stickney impact (McGetchin et al., 1973; Lee et al., 1986; Hiesinger and Head, 2006; Wilson and Head, 2005, 2015; Fig. 10). Applying the method of McGetchin et al. (1973) to Stickney Crater, the volume of the “continuous deposit” material represents ~23% of the total volume of Stickney ejecta (SOM: “Stickney Ejecta”). We define the remaining ~77% as “higher velocity” ejecta that is capable of producing secondary impact craters on Phobos (Section 1.8 and SOM: “Stickney Ejecta”). Due to the low surface gravitation of Phobos, most of the low-velocity continuous deposit ejecta initially orbits around Mars (Fig. 10), and it returns to Phobos at velocities that are too low to produce secondary impact craters. Instead, it accumulates as a global deposit of gardened regolith.

A portion of the higher velocity ejecta does not remain in orbit around Mars, and it is therefore unavailable to produce secondary impacts on Phobos. To determine the proportion of ejecta that remains available to produce secondary impacts on Phobos, we simulate the orbits of Stickney ejecta with a physics model that tests the fate of 10,000 particles from both leading and trailing hemisphere Stickney impacts (Ramsley and Head, 2013a; Blender Foundation Development Team, 2015).

Fig. 3 shows the state of the model after approximately one orbit of Phobos since the time of the Stickney impact. After several orbits, we observe the total number of test particles that remain in orbit around Mars. According to the quantity of remaining test particles, ~40% of the ejecta that is produced by a leading hemisphere Stickney impact is lost to solar orbits, whereas ~10% is lost from a trailing hemisphere impact to the atmosphere of Mars, and substantially < 1% to solar orbits.

Consequently, ~37% of Stickney ejecta is available to produce secondary impacts from a leading hemisphere impact (the 60% that remains in orbit around Mars minus the 23% that produces low velocity continuous deposits), whereas ~67% is available to produce secondary impacts from a trailing hemisphere Stickney impact (the 90% that remains in orbit around Mars minus the 23% that produces low velocity continuous deposits).

2.7. The exposure of Phobos to a uniformly global accumulation of Stickney ejecta

We calculate the de-spin time of Phobos in order to compare this period to the period of time that is required to return Stickney ejecta to Phobos. If the de-spin time exceeds the period of accumulating ejecta, Phobos is globally exposed to returning Stickney ejecta. On the other hand, if the de-spin period ends prior to the end of the ejecta accumulation period, Stickney Crater may be partially excluded from its own returning ejecta or preferentially exposed, depending on the end-state tidal lock longitude of Phobos (either facing the incoming ejecta flux, or shielded from it), (Section 1.4). Where the de-spin period, in fact, greatly exceeds the ejecta accumulation period, we do not calculate regional scenarios of excluded or preferential ejecta accumulation, and instead assume a uniformly global accumulation of ejecta.

2.8. Method for distributing the SFD of Stickney secondary impacts on Phobos

Assuming a desynchronized rotation of Phobos throughout the period of returning ejecta, we globally distribute high-velocity Stickney ejecta secondary impacts on Phobos according to a typically-observed SFD pattern (Fig. 11). From a common source of impact flux, there is a generally best fit logarithmic distribution of crater sizes versus crater frequencies (Hartmann, 1977, 1995; Hartmann and Gaskell, 2003).

Fig. 11. The size/frequency distribution of Stickney secondary impact production on Phobos from leading and trailing hemisphere Stickney impacts are compared.
For example, an under-abundance of production at one end of the plot will produce an obvious overabundance at the other end.

Our SFD plot of Stickney secondary impacts on Phobos is further constrained by an expected upper-limit diameter of secondary impacts compared with the diameter of the primary crater (Melosh, 1989). Our model slightly exceeds this limit, however the volume of ejecta requires at least several over-sized outliers in order to account for the total volume of Stickney secondary impact ejecta (Fig. 11).

Where we are constrained by the requirements for a balanced plot and an upper-limit crater diameter, our SFD model is the most likely distribution of Stickney secondary impacts. Our complete model includes secondary impacts as small as D 1 mm. However, secondary craters $\geq 100$ m account for $> 99\%$ of the high velocity Mars-orbiting Stickney ejecta volume, and Fig. 11 accounts for essentially all high-velocity ejecta that returns to Phobos from orbits around Mars.

Figs. 12 and 13 plot the accumulation of secondary impacts over
time by assuming a decreasing impact flux. The production rate decay stems mainly from a general depletion of orbiting material over time and the distribution of orbits where favorable intersections are consumed early and less favorable orbits are consumed at a lower rate (requiring additional time to deplete). Orbits also evolve, which further reduces the likelihood of intersections over time.

3. Breaking the tidal lock of Phobos and the fate of Stickney ejecta

In this section we describe 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.

3.1. What are the factors that alter the orbit and rotational rate of Phobos?

There are several components to this question that must be worked out. 1) What was the size and velocity of the projectile that produced Stickney Crater? 2) What are the inefficiencies of the Stickney crater formation process that attenuate the conversion of impact energy to an acceleration impulse? 3) Stickney Crater is tilted uphill to the east which suggests that a portion of the impact impulse directly increased the rotational rate of Phobos. What is the change in the rotational rate from this eastward impulse? 4) Stickney Crater is offset in longitude from the orbital motion of Phobos by ~40° (Fig. 2). What is the effect of this misalignment? 5) To what extent does the compression and excavation of material during the Stickney impact event alter the moment of inertia and consequently the post-impact rotational rate of Phobos?

3.2. The impact impulse

We calculate the total available impulse of the Stickney impact using the Tsiolokovsky rocket equation:

\[ \Delta v = v_e \ln(m_0/m_1), \]  
(3.1)

where: \( \Delta v \) is the change in the velocity of Phobos, \( v_e \) is the projectile velocity, \( \ln \) is the natural logarithm function, \( m_0 \) is the initial total mass of Phobos plus the projectile mass, and \( m_1 \) is the post-impact mass of Phobos. In Section 3.8 we adjust this calculation based on the attenuating effects of energy conversion inefficiencies during the impact process.

3.3. The pre-Stickney impact orbit of Phobos

In view of Stickney Crater boulders that are observed by Thomas et al. (2000) and the ≤0.5 Ga meteor destruction rate of meter-scale boulders on Phobos that is predicted by Basilevsky et al. (2013, 2015), our model places Phobos at a Mars altitude that is consistent with 0.5 Ga – or a semimajor axis 4000 km greater than the present day. In view of the lower-limit Stickney Crater age of ~0.1 Ga based on observations of space weathering (Cipriani et al., 2011; Pieters et al., 2014), in a second test, we also model the orbit of Phobos with a semimajor axis that is 1300 km greater than the present-day orbit of Phobos. (Burns, 1972; Lambeck, 1979; Bills et al., 2005; Jacobson, 2010).

At our two modeled semimajor axes (13,376 km and 10,698 km), we calculate the sidereal orbital period of Phobos using the formula:

\[ T = 2\pi(\alpha^3/\mu)^{1/2} \]  
(3.2)

where, \( T \) is the sidereal orbital period of Phobos in seconds, \( \alpha \) is the semimajor axis of Phobos, and \( \mu \) is the gravitational parameter of Mars (a coefficient of universal Gravity \( \times \) mass of Mars). At a Mars-centric semimajor axis of 13,376 km, \( T = 47,042 \) s. At 10,698 km, \( T = 33,563 \) s. And in the present day, where Phobos orbits with a semimajor axis of 9,376 km, \( T = 27,563 \) s.

3.4. Stickney projectile intersection velocity, projectile mass, and acceleration impulse efficiency

Consistent with Neukum and Wise (1976) and Ivanov (2001), we adjust the leading and trailing hemisphere Stickney impact velocities to account for the greater semimajor axis of Phobos at higher altitudes. Further, we include the effect of how the Stickney Crater longitude is offset from the orbital apex (center of the hemisphere) of Phobos by ~40°. When we take all dynamic and geometric effects into account, we model the Stickney leading hemisphere impact with a velocity of 12.5 km/s, and from a trailing hemisphere impact, 9.1 km/s. Where the impact velocities of 12.5 km/s and 9.1 km/s are similar, differences in secondary effects such as the proportion of impact energy that is partitioned into vaporization and melting can be ignored (Melosh, 1989).

Where post-impact calculations of \( \Delta v \) may be made with precision from a known impulse using the Tsiolkovsky rocket equation, it turns out that the reliability of predictions related to the post-impact effect are almost entirely governed by the scaling uncertainties of impact crater formation processes. For example, if the actual Stickney impactor was ½ the mass that we utilize in our model, the impact event produced ½ as much desynchronizing impulse and the de-spin back to a tidal lock required ½ as much time. However, in view of how we predict a de-spin time > 5000 years, a Stickney impactor mass as low as 10% of the mass predicted based on Melosh (1989) nonetheless supports our hypothesis that Phobos was globally exposed to Stickney ejecta.

3.5. The Stickney projectile mass

Averaging the scaling equations 7.8.3 and 7.8.4 of Melosh (1989) we calculate the trailing hemisphere Stickney projectile mass assuming a Phobos density of 1.86 kg/m³ (NASA/Jet Propulsion Laboratory, 2015), a meteor projectile density of 3000 kg/m³, a projectile velocity of 9.1 km/s, and a Stickney Crater diameter of ~9 km. Equation 7.8.4 of Melosh (1989) includes a gravity parameter, and we set this to the surface gravity of Phobos, which is essentially zero. We then average the results from both Melosh (1989) equations 7.8.3 and 7.8.4.

3.5.1. Trailing hemisphere Stickney projectile diameter and mass calculated from Melosh (1989) scaling equation 7.8.3:

\[ D = 0.0133 \cdot W^{1/3} + 1.51 \cdot \rho_p^{1/2} \cdot R^{-1/2} \cdot L \]  
(3.3)

where \( D \) is the crater diameter, \( W \) is the kinetic energy of the projectile \( \frac{1}{2} m v^2 \), \( \rho_p \) is the projectile density, \( R \) is the target density and \( L \) is the projectile diameter. Melosh (1989) equation 7.8.3 predicts a projectile diameter of 810 m and a projectile mass of \( 8.35 \times 10^{11} \) kg.

3.5.2. Trailing hemisphere Stickney projectile diameter and mass calculated from Melosh (1989) scaling equation 7.8.4:

\[ D = 1.8 \cdot \rho_p^{0.11} \cdot R^{-1.3} \cdot \rho_t \cdot L^{3.22} \cdot W^{0.22} \]  
(3.4)

where \( D \) is the crater diameter, \( \rho_p \) is the projectile density, \( \rho_t \) is the target density, \( g \) is the difference in the gravity of the Earth compared to Phobos, \( L \) is the projectile diameter, \( W \) is the kinetic energy of the projectile \( \frac{1}{2} m v^2 \). Melosh (1989) equation 7.8.4 predicts a projectile diameter of 1080 m and a projectile mass of \( 1.98 \times 10^{12} \) kg.

3.5.3. Based on an average of results from Eqs. (3.3) and (3.4) (Melosh, 1989, eq. 7.8.3 and 7.8.4) we predict a trailing hemisphere Stickney impact projectile diameter of 945 m and a projectile mass of \( 1.326 \times 10^{12} \) kg.

3.5.4. Repeating the calculations for a leading hemisphere Stickney impact, we calculate a projectile diameter of 810 m and a projectile mass of \( 9.3102 \times 10^{11} \) kg.
3.5.5. Asphaug and Melosh (1993) estimate that the Stickney projectile may have been as small as D 170 m (~66 times less than the diameter of Stickney Crater). The mechanical properties of Stickney ejecta and Phobos as a target body are both unknown, and in the end, we are faced with a choice between the evidence of Ivanov (1991) that strongly suggests a more conventionally-sized impactor diameter – versus the model of Asphaug and Melosh (1993) that suggests an extraordinarily small impactor.

Based on the required amount of total impact energy to produce the range of Δv impulse predictions of 0.3–3.0 m/s reported by Ivanov (1991), and where we calculate a total Δv of ~1.1 m/s (calculated and discussed in the remainder of Section 3), the Stickney impactor mass was very likely comparable to our predictions. We do not reject the possibility that the Stickney impactor was smaller than our predictions. However, the three lines of evidence from Ivanov (1991) suggest that the diameter of the projectile was much closer to our model.

Ultimately, even if the Stickney impact added zero Δv to Phobos, the newly formed morphology of Stickney Crater alone would have been sufficient to desynchronize the tidal lock of Phobos for > 500 years due solely to the effect on the Phobos moment of inertia (Section 1.6). (SOM: “Desynchronization calculations at 7,300 km altitude” and “Desynchronization calculations at 10,000 km altitude”). Consequently, our Δv calculations suggest only that the de-spin time was vastly greater than required to support our hypothesis of global Phobos exposure to Stickney ejecta, and even if Phobos fully absorbed the energy of the Stickney impact without any Δv, our hypothesis is nonetheless well supported. (In reality, material is missing from the crater, zero Δv is highly unlikely).

3.6. The total available trailing hemisphere acceleration impulse (100% conversion efficiency)

The mass of Phobos is calculated using an average radius of 11,070 m and bulk density of 1.86 kg/m^3 (NASA/NASA/Jet Propulsion Laboratory, 2015), which calculates to the 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 (an average of results from Eqs. 3.3 and 3.4) equals 1.0638145 × 10^16 kg. Using the Tsiolkovsky rocket equation Δv = v_e ln(m_0/m_1) (Eq. 3.1), we calculate the linear acceleration of Phobos from an impact on the trailing hemisphere of Phobos from a D 945 m projectile and a velocity of 9.1 km/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 considered in Sections 3.8–3.11.):

- Mass of Phobos is 1.0569 × 10^16 kg (m_1)
- Mass of Phobos plus the projectile is 1.0570326 × 10^16 kg (m_0)
- Natural log of (m_0/m_1) = 0.00012545338
- Projectile velocity = 9100 m/s (v_e)
- Δv of Phobos = 9100 m/s × 0.00012545338 = 1.14 m/s.

3.7. The total available leading hemisphere acceleration impulse (100% conversion efficiency)

When applied to a leading hemisphere Stickney impact, the Tsiolkovsky rocket equation (Eq. (3.1)) produces a similar result as seen in Section 3.6. The small difference is due to scaling laws at different impact velocities that produce slightly nonlinear crater-scaling predations.

- 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)
- Δv of Phobos = 12,500 m/s × 0.00008808581 = 1.10 m/s.

The Tsiolkovsky rocket equation calculates the available impulse. Sections 3.8–3.11 describe the inefficiencies that produce an effective impulse and how the effective impulse is partitioned into orbital and rotational acceleration vectors.

3.8. Stickney impact energy partitioning and losses

Our calculations to this point describe the total available acceleration impulse from the Stickney impact, as though 100% of the impact energy produces a post-impact Δv in the orbital motion of Phobos. However, the conversion of impact energy to acceleration impulse during the cratering process is inefficient due to a number of factors.

Impact energy is partitioned into several categories: 1) Processes that produce an efficient acceleration impulse, 2) Processes that produce an inefficient acceleration impulse, 3) Processes that convert energy in ways that do not contribute to the total acceleration impulse, or 4) processes that cancel out the acceleration impulse of other processes (such as how a change in the orbit of Phobos may combine to reduce the overall desynchronizing effect). The following list summarizes the factors that limit the efficiency of the available impact energy to produce an acceleration impulse from an impact crater (Gault and Heitowit, 1963; O’Keefe and Ahrens, 1977; Melosh, 1989):

1. Due to the large mass fraction of target material that is excavated and launched from the crater, the flow of excavated target material is the primary source of the acceleration impulse. Excavated material is typically launched in a cone-shaped distribution (Melosh, 1989). The cone-shaped pattern averages to a preferential vertical vector component that applies an acceleration force to Phobos in a direction normal to the target surface. The cone-shaped pattern also includes a radial component that is parallel to the surface of Phobos. A directional bias in the pattern of ejecta due to a low collision angle impact may produce a non-uniformity in the average radial vector of the ejecta (Melosh, 1989). However, Stickney Crater manifests no evidence to suggest that it was produced by a low angle collision, and we assume a uniform cone shaped for the launch of Stickney Crater ejecta. Where the radial force is equal in all directions, on average the radial force does not produce an acceleration vector.

2. The ejection angle of target rock material that exits via spallation is generally vertical and contributes an acceleration impulse to Phobos due mainly to the high velocity of the ejecta (Melosh, 1989). However, the total volume of spalled material is a minor mass fraction of the total mass of ejecta that is produced by the impact event and contributes far less Δv to Phobos than the ejection of excavated 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. Because resistance is radially distributed, only the normal angle vector component of the resistance produces an acceleration impulse – similar to the vector partitioning of the ejecta cone.

4. Typically described as “jetting,” at the moment of first contact, high-velocity vaporized projectile and rock material exits the impact site in a radial pattern that is nearly parallel to the target surface (Melosh, 1989). Because the combined radial vector angles of the jetted material tend to cancel, jetting contributes essentially zero Δv.

5. Vaporization of projectile and target rock material consumes impact energy that is gradually dispersed as thermal radiation (Melosh, 1989). The heat of vaporization also causes a vapor plume to expand and exit the newly forming crater. However, due to the low mass fraction of the vapor (Melosh, 1989), the contribution of vapor to the post-impact Δv is negligible.

6. Melting of target and projectile material consumes impact energy which is dispersed as thermal radiation. A portion of the melted material is ejected from the crater and a portion remains in, near,
and below the floor of the crater (Melosh, 1989). The ejection of melt adds to the Δv. The melting process itself consumes impact energy and contributes nothing to the Δv.

7. The heating of rock (without melting), shock metamorphism, and the fracturing of target rock all absorb impact energy without producing any acceleration impulse.

8. Overall, ~10% of the available energy is lost to melting, heating, fracturing, shock metamorphism, and jetting (Gault and Heitowit, 1963; O’Keefe and Ahrens, 1977; Melosh, 1989). The remaining ~90% produces an acceleration impulse from vapor ejection, spallation, the launch of solid and melted ejecta, and the resistance of the target to displacement and compression.

However, due to the non-ideal shape of Stickney Crater as a rocket nozzle, the remaining acceleration impulse is applied inefficiently. To calculate the geometric inefficiency, we assume that the vast majority of the impulse is cone-shaped with an ejecta launch angle that averages to 45° from the zenith. This produces a cone-angle efficiency of ~71% (sin of 45°). Combining the 71% cone-angle efficiency with the 90% impulse conversion efficiency equals ~64% (71% × 90%).

To account for uncertainties, we conservatively estimate that 60% of the Stickney impact energy is converted to an effective acceleration impulse. For a full discussion of small-body properties that may affect the conversion of impact energy to Δv impulse, see Housen and Holsapple, (2003, 2012).

3.9. The effect of a trailing hemisphere impact on delta-v

To account for all inefficiencies involved in producing a trailing hemisphere acceleration impulse on Phobos, we reduce the projectile mass to 60% of the actual impactor. This reduces the projectile mass to 7.954 × 10¹¹ kg, (1.326 × 10¹² kg × 60%) and a total combined mass of Phobos plus the projectile of 1.05697954 × 10¹⁶ kg (1.0569 × 10¹⁶ kg + 7.954 × 10¹¹ kg). The trailing hemisphere Stickney impact velocity is unchanged at 9.1 km/s.

Applying the Tsiolkovsky rocket equation Δv = vₑ ln(mₒ/m₁) (Eq. (3.1)), we calculate a linear acceleration of Phobos from a trailing hemisphere impact of Phobos as follows:

- Mass of Phobos is 1.0569 × 10¹⁶ kg (m₁) (NASA/NASA/Jet Propulsion Laboratory, 2015)
- Mass of Phobos plus the projectile is 1.05697954 × 10¹⁶ kg (mₒ)
- Natural log of (mₒ/m₁) = 0.00007525499
- Projectile velocity = 9100 m/s (vₑ)
- Δv of Phobos = 9100 m/s × 0.00007525499 = 0.68 m/s.

3.10. The effect of a leading hemisphere impact on delta-v

The same way that we compute in Section 3.9, to account for inefficiencies involved in producing the acceleration impulse on the leading hemisphere of Phobos, we reduce the projectile mass to 60% of the actual impactor. This reduces the projectile mass to 5.586 × 10¹¹ kg, (9.310 × 10¹¹ kg × 60%) and a total combined mass of Phobos plus the reduced-mass of the projectile of 1.05695586 × 10¹⁶ kg (1.0569 × 10¹⁶ kg + 5.586 × 10¹¹ kg). The leading hemisphere Stickney impact velocity is unchanged at 12.5 km/s.

Applying the Tsiolkovsky rocket equation Δv = vₑ ln(mₒ/m₁) (Eq. (3.1)), we calculate a linear acceleration of Phobos from a leading hemisphere impact of Phobos as follows:

- Mass of Phobos is 1.0569 × 10¹⁶ kg (m₁) (NASA/NASA/Jet Propulsion Laboratory, 2015)
- Mass of Phobos plus the projectile is 1.05695586 × 10¹⁶ kg (mₒ)
- Natural log of (mₒ/m₁) = 0.00005285128
- Projectile velocity = 12,500 m/s (vₑ)
- Δv of Phobos = 12,500 m/s × 0.00005285128 = 0.66 m/s.

In subsequent calculations we conservatively apply the slightly lower Δv from a leading hemisphere impact of 0.66 m/s (compared to the slightly greater value of 0.68 m/s from a trailing hemisphere impact).

In view of how the total effective acceleration impulse of 0.66 m/s falls within the lower Δv range reported by Ivanov (1991) – between 0.3 m/s and 3.0 m/s – we are confident that our application of the Tsiolkovsky rocket equation is both accurate and conservatively applied.

3.11. Geometric partitioning of impulse vectors

3.11.1. The east-west geographic tilt in the orientation of Stickney Crater

The eastern rim of Stickney Crater has a higher geographical elevation than the western rim. Consequently, the bowl of the crater is misaligned with respect to the CG of Phobos by 13.4° (Fig. 2). During the impact process, this misalignment produces an impulse vector that is partitioned into two components – one impulse vector component that is directed linearly through the CG that alters the orbit of Phobos, and the other impulse vector component that is directed to the east, which increases the rotational rate of Phobos. Working out the Δv partitioning, the CG impulse vector is 0.64 m/s (cos 13.4° × 0.66 m/s). The remaining eastward impulse vector component adds rotational angular momentum to Phobos (SOM: “Desynchronization calculations at 7300 km altitude” and “Desynchronization calculations at 10,000 km altitude”).

3.11.2. 40° longitudinal offset of Stickney Crater

In both trailing and 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 alters only the eccentricity of the orbit without altering its semimajor axis (the semimajor axis determines the orbital period). The acceleration vector component that alters the semimajor axis equals 0.49 m/s (cos 40° × 0.64 m/s).

Detailed calculations of the effect on the orbital period and the rotational period of Phobos from the Stickney impact impulse are included in SOM: “Calculations for an orbit of 7300 km altitude” and “Calculations for an orbit of 10,000 km altitude.”

3.11.3. Summarizing our detailed SOM calculations

At a 10,000 km martian altitude (0.5 Ga), the period of Phobos de-spins back to a synchronized tidal lock after a Stickney impact requires at least 16,000 years. At a 7300 km altitude (0.1 Ga), the de-spin time is at least 5000 years. Because the 7300 km altitude sets the most stringent time limit on our model, we report that the de-spin time after the Stickney impact was > 5000 years. In reality, the de-spin time may have been as long as ~64,000 years (SOM: “Calculations for an orbit of 10,000 km altitude”” and “Calculations for an orbit of 10,000 km altitude”).

3.12. The fate of Stickney impact ejecta

With respect to its post-impact cis Mars orbital velocity, Phobos ejecta that exits from a trailing hemisphere impact subtracts the orbital velocity of Phobos from the launch velocity of the ejecta. Conversely, Phobos ejecta that exits from a leading hemisphere impact adds the orbital velocity of Phobos to the launch velocity of the ejecta.

3.12.1. The escape of Stickney ejecta to solar orbits (assuming a 10,000 km altitude circular orbit of Phobos around Mars at ~0.5 Ga)

The orbit of Phobos produces an orbital velocity bias of 1790 m/s in the launch of all ejecta. Where the escape velocity from a circular orbit equals the orbital velocity ×2½, at a martian orbital altitude of
10,000 km, the escape velocity from the martian system is 2,530 m/s relative to Mars. Consequently, leading hemisphere ejecta that launches with velocities as low as 740 m/s (2530–1790 m/s) may escape to solar orbits, whereas, trailing hemisphere ejecta that launches with velocities as high as 4329 m/s (2530 m/s + 1790 m/s) may remain trapped in martian orbits.

3.12.2. The specific fate of ejecta from a leading hemisphere impact (assuming a 10,000 km altitude of Phobos)

From a leading hemisphere, ejecta that is launched from Phobos with a velocity < 740 m/s is inserted into orbits around Mars or remains on the surface of Phobos. Ejecta from a leading hemisphere impact that is launched with a velocity > 1790 m/s escapes to solar orbits. A portion of ejecta from a leading hemisphere impact with launch velocities between 740 m/s and 1790 m/s remains in orbit around Mars. Due to the additive effect of the Phobos orbital velocity, < 1% of leading hemisphere Phobos ejecta deorbits to Mars.

3.12.3. The specific fate of ejecta from a trailing hemisphere impact (assuming a 10,000 km altitude of Phobos)

Ejecta from a trailing hemisphere impact that is launched with a velocity < 600 m/s enters prograde orbits around Mars or remains on the surface of Phobos. A portion of the ejecta that is launched at velocities between ~600 m/s and ~3100 m/s deorbits to Mars. Ejecta that is launched with velocities between 3100 m/s and 4320 m/s enters retrograde orbits around Mars, and ejecta launched with velocities > 4320 m/s escapes to solar orbits.

4. Implications of the Stickney event

In this section we focus on the surface morphologies that are produced by primary and secondary Stickney ejecta. A portion of Stickney ejecta produces secondary impacts on Phobos and we calculate the secondary crater SFD for both leading and trailing hemisphere impact scenarios. A portion of Stickney ejecta also accumulates without producing craters, and we analyze the nature of low-velocity geological processes that produce a substantial layer of newly-gardened regolith and calculate the ejecta volume and boulder SFD that would be required to produce grooves on Phobos from rolling boulders (Wilson and Head, 2005, 2015; Syal et al., 2016; Fig. 10). Lastly, we discuss the resynchronized longitude of Phobos and the fate of Stickney ejecta that intersects Mars.

4.1. Predicted versus observed Stickney secondary crater SFDs on Phobos

Figs. 6, 7, 11, 12, and 13 include predictions of the Stickney secondary crater SFD in terms of production flux. Our SFD predictions do not account for the potential overprinting and destruction of existing craters by newer-arriving impacts. However, in our study, we observe that the SFD of emplaced Stickney secondary craters approaches full surface saturation at D ≤20 m (SOM: “Stickney Ejecta”), which are generally unobservable crater diameters in present-day spacecraft images of Phobos (Schmedemann et al., 2014; Figs. 6 and 7). Consequently, the flux of Stickney secondary crater production at Phobos is a suitable analog for predicting the observed SFD of Stickney secondary craters.

4.2. The kink in the SFD of craters west of Stickney Crater

Immediately to the west of Stickney Crater, Schmedemann et al. (2014) count craters in a “Phobos average” counting area (Figs. 6c, 7c). In this counting area we observe a kink in the SFD curve at D ~0.6 km where a recent spike of impacts D ≤0.6 km are clearly superposed atop an SFD of larger background craters. SFD patterns with a kink of this type suggest a resurfacing spike that substantially exceeds the steady flux of background impacts (Michael and Neukum, 2010).

From our model we predict the global SFD of Stickney secondary craters that should be emplaced on Phobos and observe whether or not this prediction is consistent with the kink that appears in the crater counting data of Schmedemann et al. (2014). Both leading and trailing hemisphere Stickney impacts produce reasonably close fits. However, based on the greater SFD production from a trailing hemisphere impact, a trailing hemisphere impact is more generally consistent with the observed crater counting kink in the data of Schmedemann et al. (2014), (Figs. 6c, 7c).

Where the kink plotted from the Schmedemann et al. (2014) “Phobos average” counting area is predicted by our model of Stickney secondary impacts, this strongly suggests that the vast majority of D ≤0.6 km craters on Phobos were produced by the Stickney impact event, and the contribution of background craters D ≤0.6 to the crater population of Phobos is negligible.

4.3. Calculating the volume of ejecta that produces secondary impacts on Phobos from Stickney Crater

The total volume of Stickney ejecta equals 3.89 × 10¹⁰ m³ (SOM: “Stickney Ejecta”). Based on the work of McGetchin et al. (1973), the volume of low velocity continuous deposit Stickney ejecta that does not produce secondary impact craters on Phobos equals 8.78 × 10⁹ m³ (Sections 1.8 and 2.6, SOM: “Stickney Ejecta”). As discussed in Section 2.6, 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 volume of Stickney ejecta that produces secondary craters from a leading hemisphere impact is calculated as: 3.89 × 10¹⁰ m³ × 60% – 8.78 × 10⁹ m³ = 1.46 × 10¹⁰ m³, where 3.89 × 10¹⁰ m³ is the total volume of Stickney Crater ejecta, 60% is the proportion of the Stickney ejecta that returns to Phobos, and 8.78 × 10⁹ m³ is the volume of continuous deposit ejecta that does not produce secondary impacts.

The volume of Stickney ejecta that produces secondary craters from a trailing hemisphere impact is calculated as: 3.89 × 10¹⁰ m³ × 90% – 8.78 × 10⁹ m³ = 2.62 × 10¹⁰ m³, where 3.89 × 10¹⁰ m³ is the total volume of Stickney Crater ejecta, 90% is the proportion of the Stickney ejecta that returns to Phobos, and 8.78 × 10⁹ m³ is the volume of continuous deposit ejecta that does not produce secondary impacts.

4.4. Stickney secondary impact flux on Phobos and global equivalent deposit thickness

The Stickney Crater event may be characterized as a “spike” of activity that involved a complex and intertwined process that persisted for up to a thousand years. Immediately after the Stickney impact, the orbit of Phobos and the orbits of Stickney ejecta intersected at a common region of cis martian space (Fig. 3). Where Phobos passed through this region of space once per orbit, the intersection of Phobos with Mars-orbiting Stickney ejecta was episodic (once per Phobos orbit). During each intersection, only a small portion of ejecta arrived at the same location in cis martian space when Phobos was present. Consequently, ~7 × 10⁶ orbits of Phobos were required before Stickney ejecta fully accumulated back onto Phobos (~1000 years × ~700 orbits per year).

The Stickney Crater excavation process required ~6 s to complete (Melosh, 1989), which spread the event into 6 s of Phobos orbital motion (~1/2 diameter of Phobos). Due to the elongated region of common orbital volume, the shape and size of Phobos, and the orbital velocity of Phobos – during each subsequent post-impact intersection, Phobos encountered Stickney ejecta during an ~18-second window (~12 s of shared orbital intersection traverse plus ~6 s of crater excavation).

Over time, Mars-orbiting Stickney ejecta was perturbed, which produced a growing region of intersection that extended along the orbit of Phobos and into less favorable orbital alignments. Also, as
impact on each km² of Phobos produced one 43-m crater, ten 10-m craters, one thousand 0.2-m craters, and ten thousand 0.1-m craters. The secondary impact ejecta is produced from the pre-impact surface of the target. The cumulative volume of pre-existing Phobos regolith (a process often described as "gardening") was distributed globally on Phobos (Ramsley and Head, 2013b). In addition to delivering ejecta from orbit, Stickney secondary impacts delivered secondary craters, many with sizes greater than 400 meters in diameter, that are observed on Phobos. The model of Wilson and Head (2005, 2015) suggests that low-velocity rolling and bouncing Stickney ejecta boulders produced most, if not all, of the grooves on Phobos in a process that took place during the hours immediately following the Stickney impact, (Fig. 10). In our model, we observe a large reservoir of low-velocity continuous deposit ejecta that are required to saturate a planetary surface (Hartmann and Gaskell, 1997). Consequently, localized regions of Phobos may have avoided larger secondary impacts, and these regions are likely to manifest a locally greater thickness of accumulated deposits than the global equivalent thickness. Nonetheless, because of how the gardening mechanism of Stickney ejecta included secondary, tertiary, and additional generations of impacts, primary and secondary Stickney ejecta was distributed globally on Phobos (Ramsley and Head, 2013b).

4.5. Stickney ejecta that produces grooves and groove degradation on Phobos

The model of Wilson and Head (2005, 2015) suggests that low-velocity rolling and bouncing Stickney ejecta boulders produced most, if not all, of the grooves on Phobos in a process that took place during the hours immediately following the Stickney impact, (Fig. 10). In our model, we observe a large reservoir of low-velocity continuous deposit ejecta (McGetchin et al., 1973; Table 1), (SOM: "Stickney Ejecta") that is equal to ~23% of the total volume of Stickney ejecta (discussed in Sections 1.8. and 2.6.). When we distribute the volume of continuous deposit ejecta (8.78×10⁹ km³) into an SFD of boulder-scale and smaller fragments, we predict that the continuous deposit ejecta contains several hundred boulders > 200 m in diameter and several thousand with diameters between 100 and 200 m. The escape velocity of ejecta from Phobos further suggests that most of these boulders were immediately inserted into orbits around Mars (Wilson and Head, 2005, 2015; Syal et al., 2016; Fig. 10).

While crater excavation progresses and draws to a close, there is a preferential reduction in ejection velocities and a production of larger ejecta blocks (Oberbeck, 1975; Melosh, 1989; Wilson and Head, 2005, 2015). If just 10% of the continuous deposit ejecta boulders with diameters greater than 200 m remained in motion on the surface of Phobos and ½ from recently deposited Stickney primary ejecta, we conclude that secondary impacts from a leading hemisphere Stickney impact produced a newly-excavated 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 compared to a leading hemisphere Stickney impact.

Our calculated primary impact Stickney ejecta deposit thicknesses are generally consistent with predictions of Weidenschilling (1979), Thomas (1998), and Thomas et al. (2000). When we combine the volume of primary and secondary Stickney ejecta, we calculate that the Stickney impact produced a new global equivalent layer of Phobos regolith deposits 28–44 m thick, which is slightly greater than previous models that do not also account for ejecta from secondary impacts.

According to our analysis in SOM: “Stickney Ejecta,” Stickney secondary impacts approach crater-saturation on Phobos at diameters ≤20 m, whereas secondary impact craters ≥400 m are emplaced onto ~54–84% of the Phobos surface – substantially less than the flux of impacts that are required to saturate a planetary surface (Hartmann and Gaskell, 1997). Consequently, localized regions of Phobos may have avoided larger secondary impacts, and these regions are likely to manifest a locally greater thickness of accumulated deposits than the global equivalent thickness. Nonetheless, because of how the gardening mechanism of Stickney ejecta included secondary, tertiary, and additional generations of impacts, primary and secondary Stickney ejecta was distributed globally on Phobos (Ramsley and Head, 2013b).

4.4.1. The intensity of the Stickney secondary impact spike

To illustrate the effect of ejecta depletion, Figs. 12 and 13 plot the SFD of secondary impacts on Phobos during the early, middle, and late stages of the secondary impact process. What began as an intense spike of episodic impacts once every Phobos orbit with a duration of ~18 s eventually dissipated into a continuously fading rain of impacts that decreased in intensity and velocity until the accumulation process was complete. Due to the orbital perturbations of Mars-orbiting ejecta, the secular rotation of Phobos, and the randomization of ejecta launch angles – secondary, tertiary, and subsequent impacts produced an impact flux that was uniformly distributed across all longitudes of Phobos (Ramsley and Head, 2013b).

Figs. 12 and 13 offer a temporal sense of the episodic intersections of Phobos with Stickney ejecta. For example, during the first 10 years after a trailing hemisphere Stickney impact and during each orbital encounter (compressed into as little as 18 s) each km² of Phobos received 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.

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 flux during the first 10 years from a trailing hemisphere Stickney impact on each km² 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.

Comparing 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, a Stickney impact on either hemisphere of Phobos clearly produces 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 m diameter projectile intersecting every square meter of Phobos. (SOM: “Stickney Ejecta”).

4.4.2. The production and gardening of Stickney secondary impact regolith

In addition to delivering ejecta from orbit, Stickney secondary impacts also excavated, mobilized, and redistributed a substantial volume of pre-existing Phobos regolith (a process often described as “gardening”). To calculate the additional volume of accumulated ejecta that was produced by Stickney secondary impacts, we observe from our model that Stickney secondary craters ≥400 m in diameter account for > 90% of the total crater volume of Stickney secondary impacts on Phobos (SOM: “Stickney Ejecta”). Also, secondary craters with a diameter ≥400 are likely to excavate preferentially from the pre-existing surface of Phobos rather than recently returned Stickney ejecta, particularly soon after the Stickney impact when the gardening process was newly underway. Conversely, apart from the very largest secondary impacts, later-stage Stickney secondary impacts primarily remobilized accumulated Stickney ejecta deposits, and most of the later-stage impacts did not add substantially to the total global equivalent layer thickness of newly gardened deposits.

As we calculate in SOM (“Stickney Ejecta”), secondary craters from a leading hemisphere Stickney impact excavated a global equivalent layer thickness of ~28 m, and from a trailing hemisphere Stickney impact, ~44 m. Because we conservatively estimate that ½ of the secondary impact ejecta is produced from the pre-impact surface of Phobos and ½ from recently deposited Stickney primary ejecta, we conclude that secondary impacts from a leading hemisphere Stickney impact produced a newly-excavated 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 compared to a leading hemisphere Stickney impact.

Our calculated primary impact Stickney ejecta deposit thicknesses are generally consistent with predictions of Weidenschilling (1979), Thomas (1998), and Thomas et al. (2000). When we combine the volume of primary and secondary Stickney ejecta, we calculate that the Stickney impact produced a new global equivalent layer of Phobos regolith deposits 28–44 m thick, which is slightly greater than previous models that do not also account for ejecta from secondary impacts.

According to our analysis in SOM: “Stickney Ejecta,” Stickney secondary impacts approach crater-saturation on Phobos at diameters ≤20 m, whereas secondary impact craters ≥400 m are emplaced onto ~54–84% of the Phobos surface – substantially less than the flux of impacts that are required to saturate a planetary surface (Hartmann and Gaskell, 1997). Consequently, localized regions of Phobos may have avoided larger secondary impacts, and these regions are likely to manifest a locally greater thickness of accumulated deposits than the global equivalent thickness. Nonetheless, because of how the gardening mechanism of Stickney ejecta included secondary, tertiary, and additional generations of impacts, primary and secondary Stickney ejecta was distributed globally on Phobos (Ramsley and Head, 2013b).
Phobos without exiting to orbits around Mars (~2% of the total volume of Stickney ejecta), there is a sufficient SFD of rolling and bouncing boulders to support the model of Wilson and Head (2005, 2015). Such a low percentage of ejecta volume suggests that the model of Wilson and Head (2005, 2015) is plausible, and in view of the evidence of Thomas (1998) and Thomas et al. (2000), it appears that ejecta boulders from Stickney Crater are sufficiently competent to produce grooves (Wilson and Head, 2005, 2015).

4.5.2. 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 by rolling boulders immediately at the conclusion of the Stickney impact (Wilson and Head, 2005, 2015), the grooves would have been fully exposed to the degradation effects of flux from Stickney secondary, tertiary, and additional generations of impacts, and the mantling effects of accumulated ejecta deposits (Ramsley and Head, 2013b).

In order to render a groove less visible, a secondary impact must destroy the groove levee – the feature that most clearly defines a groove (Murray et al., 1994). Secondary impacts that are emplaced mostly within or beside a groove would not substantially damage the groove morphology. Further, a groove is a feature that extends in length for many km (Murray et al., 1994), and even if a short levee segment were entirely erased by a secondary impact, this would not remove evidence of the overall morphological sense of the entire groove, and the groove would remain substantially observable, minus a missing segment. To entirely erase a groove, the flux of secondary impacts would require multiple overlapping impacts along the entire length of the groove.

Grooves with greater widths would be less degraded due to their scale in comparison to the scale of the degradation process, whereas narrower grooves would be more greatly affected, and the narrowest grooves would be destroyed. According to our model, Stickney secondary impact crater diameters do not reach saturation at the ~80 m minimum observed widths of the grooves (Hartmann and Gaskell, 1997; Murchie et al., 1989). Consequently, the observed grooves (>80 m in width) survived the Stickney ejecta spike because they exceeded the scale of the degradation process, whereas grooves <80 m in width are not observed on Phobos because they were narrower than the scale of the degradation process.

4.5.3. Where are the groove-producing boulders?

In answer to the oft-asked question regarding the fate of large groove-producing Stickney ejecta boulders that are no longer observed on Phobos (Murray et al., 1994), Wilson and Head (2005, 2015) suggest that the groove-producing boulders were lost to martian orbits. However, at the same low velocities, the same boulders would rapidly return to Phobos mostly intact. According to our model that calculates the spike of returning high-velocity Stickney ejecta (Section 4.4.1; Figs. 11–13) the intensity of the flux combined with the large target diameters of groove-producing boulders would have repeatedly bombarded every groove-producing boulder present on the surface of Phobos – very likely breaking groove-producing boulders into smaller fragments (Basilevsky et al., 2013, 2015). If the groove-producing boulders were generally fragmented to the 5–10 m diameter scale of boulders that are typically observed by Lee et al. (1986) and Thomas et al. (2000), the post-Stickney impact gardening process was sufficient to bury most of the boulder fragments beneath newly-produced regolith, particularly in view of a global equivalent thickness of Stickney-produced regolith of up to 44 m (Section 4.4.2). In the same way as all other Stickney ejecta that remained on Phobos or rapidly returned to Phobos, our model of the Stickney impact event suggests that the groove-producing boulders were repeatedly bombarded, fragmented, and gardened into the regolith of Phobos.

4.6. The origin of Limtoc Crater

Limboc Crater, a D ~1.8 km feature located on the southwest floor of Stickney Crater, is consistent with our model of Stickney secondary craters on Phobos (SOM: “Stickney Ejecta”), (Figs. 1, 5a, 5b). Nevertheless, the diameter of Limtoc as a secondary crater is generally inconsistent with the observed size-ratio of a secondary crater compared to its primary (Melosh, 1989). On the other hand, the likelihood of a ~0.1–0.5 Ga superposed background crater D ~1.8 km that is
emplaced within the relatively small target area of Stickney is also very low (Hartmann, 1977, 1995; Hartmann and Gaskell, 1997).

When we consider how only a small portion of secondary craters are typically observed in association with their primary crater (Fig. 8) it is possible that larger-than-expected secondary crater diameters are misidentified as primary craters. Further, the internal structure of Phobos is essentially unknown, and we cannot rule out a process where an oversized block was excavated and launched intact at a relatively high velocity. We therefore conclude that it is possible that Lunitoc is a secondary crater formed from Stickney Crater ejecta.

4.7. Leading or trailing hemisphere Stickney Crater impact. Which is the most likely scenario?

According to our calculations, the rotation of Phobos was desynchronized by the Stickney impact for at least 5000 years and probably much longer (SOM: “Desynchronization calculations at 7300 km altitude” and “Desynchronization calculations at 10,000 km altitude”). At the conclusion of the de-spin period Phobos relocked with its long “c” axis once again passing through the sub- and anti-Mars longitudes of Phobos (Fig. 9). Dynamically, there is no preferential direction to this subsequent tidal lock, and it is equally likely that the pre-impact synchronization longitude of Phobos was restored or Phobos was resynchronized at a rotational longitude ~180° from the pre-impact longitude (Burns, 1972). Two lines of evidence suggest that the synchronous longitude was reoriented ~180° from the present day, and as a consequence, the Stickney impact took place on the trailing hemisphere of Phobos.

1. The observed SFDs of craters D ≤0.6 km that are counted by Schmedemann et al. (2014) in an area west of Stickney Crater and inside Stickney Crater are more generally 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 ≤0.6 km (Figs. 5–7).

2. According to our model of impact flux at Phobos (based on Basilevsky et al. (2015)), a greater SFD of background flux should be observed on the leading orbital apex of Phobos. Instead, we observe a greater SFD on the trailing apex (Fig. 4). This suggests that during most of its earlier geological history, Phobos orbited around Mars in a tidally locked longitude that was ~180° from the present day.

It is possible that impacts on Phobos other than Stickney Crater episodically desynchronized the rotation of Phobos, and Phobos has been reoriented several times. Consequently, although our observations suggest the higher likelihood of a trailing hemisphere Stickney impact, there is insufficient evidence to rule out a leading hemisphere Stickney impact.

4.8. The post-impact de-spun c-axis longitude of Phobos

Due to the Stickney Crater impact, the resulting change in the shape of Phobos may have slightly altered the post-impact c-axis longitude of Phobos. Target material from Stickney was excavated and redistributed across the surface of Phobos. Target material was also compressed into the floor and rim of Stickney Crater, and a portion was removed to solar orbits or to the surface of Mars.

Consequently, when Phobos resynchronized to a post-impact tidally-locked longitude, the end-state orientation of Phobos may not have been precisely realigned with the pre-impact c-axis of Phobos. However, in view of the limited extent of post-impact morphological modifications to Phobos compared with the total sized and mass of Phobos, very likely the post-impact c-axis tidal lock longitude shifted no more than a few degrees to the east from the pre-impact c-axis longitude (Fig. 9).

4.9. Secondary craters on the surface of Mars from a trailing hemisphere Stickney impact

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, 2.6 and 3.12), approximately 10% of the ejecta from a trailing hemisphere Stickney impact would have intersected the atmosphere of Mars with a total meteor volume of ~3.9×10⁶ m³ (SOM: “Stickney Ejecta”).

Assuming a trailing hemisphere Stickney impact, Stickney ejecta arrived at Mars in a single continuous spike that persisted for several hours. During subsequent orbits, a much lower volume of ejecta also passed close to the martian atmosphere and deorbited to Mars. Due to the rotation of Mars, the starting and ending longitudes of the distribution pattern cannot be calculated. However, our model reveals the distribution of trajectories from Phobos to Mars that preferentially exposed martian equatorial latitudes to higher concentrations of Stickney ejecta flux and less flux at higher latitudes, north and south.

The total surface area of Stickney meteor exposure on Mars was ~10% of the martian surface, and the region of exposure extended east and west approximately 180° in longitude. Because a higher volume of ejecta is produced from lower impact crater ejecta launch velocities (Melosh, 1989) and due to 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.

Still assuming a trailing hemisphere Stickney impact, according to our model, during the flight of Stickney ejecta from Phobos to Mars, the effect of orbital mechanics accelerated Stickney ejecta to Mars-intersecting velocities between 4.1 km/s and 4.5 km/s (SOM: “Mars Satellite Orbital Calculator”). Assuming an average meteor impact velocity of 4.3 km/s, Fig. 14 plots the average SFD of secondary impacts on Mars from Stickney ejecta. Within the impact exposure region on Mars,
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, plus a host of smaller crater diameters.

Still assuming a trailing hemisphere Stickney impact, due to the volume of Stickney projectiles that intersected Mars and the deceleration effect of the atmosphere acting preferentially on smaller meteor particles, a portion of Stickney ejecta likely survived the martian atmospheric interface and landed intact on the surface of Mars. However, according to our model, the Stickney impact likely took place between ~0.1–0.5 Ga, which suggests that it is unlikely that Stickney ejecta would be easily recognized on Mars.

5. Conclusions

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

1) The age of Stickney Crater: In view of how most or all craters that are counted within Stickney Crater by Schmedemann et al. (2014) are Stickney secondary impacts, the superposed craters are invalid for calculating an age for Stickney Crater. Consequently, we predict a Stickney age of 0.1–0.5 Ga based on the evidence of Thomas et al. (2000), Basilevsky et al. (2013, 2015), and space weathering (Ciprani et al., 2011; Pieters et al., 2014).

2) The global SFD of Stickney secondary impacts on Phobos: According to our model, the vast majority of craters on Phobos D ≤0.6 and a portion up to D 2 km are Stickney secondary impacts. Stickney secondary craters D ≤0.6 km are directly observable in an SFD kink at D ~0.6 km plotted by Schmedemann et al. (2014) “Phobos average” counting area (Figs. 5c, 6c, 7c) that superposes the background crater flux. The clearly observed SFD kink further suggests that the contribution of background craters D ≤0.6 to the crater population of Phobos is negligible.

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 28–44 m on Phobos. 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 28–44 m is generally consistent with the observations of Thomas (1998) and Thomas et al. (2000).

4) The production and degradation state of Phobos grooves and groove-producing boulders: In support of the model of (Wilson and Head, 2005, 2015) that predicts groove-production from low-velocity Stickney ejecta boulders, our model suggests that a sufficient SFD of low-velocity ejecta boulder blocks were produced by the Stickney impact. Further, our prediction of the Stickney secondary impact spike and the accumulation of regolith on Phobos is consistent with the degradation state of the observed Phobos grooves as described by Murchie et al. (1989), and the intensity of the impact spike flux suggests that groove-producing boulders were fragmented and gardened into newly produced Stickney regolith.

5) The likelihood of a 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 (Fig. 4) and the intensity of the observed SFD kink of craters D ≤0.6 km on Phobos to the west of Stickney Crater (Figs. 5c, 6c, 7c) are consistent with a trailing hemisphere Stickney impact, suggesting that Phobos de-spun to its present-day tidal lock ~180° in longitude from its pre-impact orientation.

6) Stickney secondary impacts on Mars: If the Stickney impact took place on the trailing hemisphere of Phobos, a spike of Stickney secondary meteor flux was emplaced along a portion of the equatorial latitudes of Mars. Where a leading hemisphere impact would not have produced a spike of Mars-intersecting Phobos ejecta, the identification of Phobos meteorites on Mars would suggest that the Phobos impact took place on the trailing hemisphere of Phobos.

7) Application of the Tsiolkovsky rocket equation to estimate post-impact target delta-v: In view of how our application of the Tsiolkovsky rocket equation predicts a post-Stickney impact Δv that is consistent with three alternate methods (Ivanov, 1991), an application of the rocket equation offers a novel, universal, simple, scalable, and reliable method for calculating the total acceleration impulse produced by impact events on planetary bodies.

8) The resilience of our hypothesis: Mostly due to the Δv impulse of the Stickney impact, our model predicts a total post-Stickney-impact de-spin period of > 5000 years. Nonetheless, due to the post-impact moment of inertia of Phobos, material that is removed and compressed into the crater alone would have produced at least 500 years of de-spin time, and there would have been a sufficient period of desynchronization to support our hypothesis of globally-emplaced Stickney secondary impacts on Phobos even if Phobos absorbed 100% of the impulse energy without converting any of the impact energy to Δv. In short, the manifested existence of Stickney Crater alone is sufficient to support our hypothesis.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.pss.2017.02.004.

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