MARS EJECTA IN THE REGOLITH OF PHOBOS: IMPLICATIONS FOR GROOVE FORMATION FROM SECONDARY IMPACTS.

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Introduction: The bulk concentration of Mars ejecta in the regolith of Phobos is narrowly constrained by two studies that predict nearly identical values using substantially different analytical methods. By modeling primary impacts on Mars and the resulting volume of ejecta that would intersect Phobos, Chappaz et al., (2012) [1] predict that *500 ppm* of Mars ejecta has been deposited into the Phobos regolith during the last 3.5 Gyrs. By comparing the flux rate of solar system projectiles that directly intersect Phobos to the proportion of ejecta that is produced from Mars by the same solar system flux rate, Ramsley and Head, (2013b) [2] predict that *250 ppm* is deposited into the Phobos regolith since the Stickney Crater impact.

More than 95% of Mars ejecta that impacts Phobos is re-ejected into Mars orbits and subsequently accumulates as new regolith on Phobos [2]. Consequently, the bulk volume of Mars ejecta deposits in the upper regolith of Phobos [1,2] closely corresponds to the total volume of Mars ejecta that has intersected Phobos during the last few Gyrs. This constraint offers an opportunity to further refine *Conclusion #13* from Ramsley and Head, (2013a) [3] where we compare the volume of Mars ejecta that intersects Phobos to the volume of projectiles that would be required to produce grooves on Phobos as secondary impacts, according to the hypothesis of Murray et al., (1992–2014) [4–11].

Methods and Key Parameters: The hypothesis of Murray et al. [4–11] asserts that grooves on Phobos are younger than Stickney Crater. Observations by Thomas et al., (2000) [12] of boulders that were produced by the Stickney impact suggest that, at most, a few meters of regolith has accumulated on Phobos since the deposition of Stickney ejecta boulders (typically ~5 m in diameter). Consequently, the volume of Mars ejecta on Phobos that was deposited during the time frame of groove formation is concentrated in the upper few meters of the Phobos regolith. Further, Phobos has orbited close to Mars during only the most recent ~500 Myrs [13], suggesting that >90% of Mars ejecta since the Stickney impact is concentrated in the upper 0.4–1.0 m of Phobos regolith [2]. By multiplying the 250 ppm concentration of Mars ejecta times the volume of the upper 1 m of regolith and adjusting for particulate voids [14] we compute the total volume of Mars ejecta projectiles that have intersected Phobos since the time of the Stickney Crater impact.

The volume of projectiles that would be required to produce grooves from secondary impacts may also be computed. The typical impact velocity of Mars ejecta fragments that intersect Phobos is ~2–3 km/s [2,3] and groove pits are typically ~150 m in diameter [3]. Based on crater scaling equations, this requires a projectile diameter of ~15 m [15], or a projectile volume of ~1,800 m^3. The grooves are composed of ~2 x 10^5 pits (observed and inferred) [3] and would require an equal number of secondary craters. We compute the required total volume of groove-forming projectiles by multiplying the volume of a single projectile by the total number of groove pits.

We then compare the predicted volume of Mars ejecta in the upper 1 m of Phobos [2] to the volume of projectiles that are required to produce grooves from impacts.

We also compute the volume of regolith that would be produced by groove-forming impacts [2] and compare this to the post-Stickney impact regolith accumulation [12].

Predictions: The mean radius of Phobos is 11.1 km [16]. This works out to a surface area of 1.55 x 10^9 m^2, and an upper 1 m of regolith volume of 1.55 x 10^9 m^3 (1.55 x 10^9 m^2 x 1 m). With a 50% porosity [14] and 250 ppm for the bulk concentration of Mars ejecta, the total predicted volume of Mars ejecta projectile fragments that have impacted Phobos during the time frame of groove formation is 2 x 10^5 m^3 (1.55 x 10^9 m^3 x 250 ppm x 50%).

Multiplying the volume of a single groove-forming projectile by the number of pits on Phobos works out to a total projectile volume of 4 x 10^8 m^3 (1,800 m^3 x 2 x 10^5). When we compare this to the total volume of Mars ejecta that has intersected Phobos during the time frame of groove formation (2 x 10^5 m^3), the available volume of Mars ejecta is *insufficient by more than three orders of magnitude* to produce the grooves as secondary impacts.

The Murray hypothesis [4–11] categorizes ~12 groove families and interprets that these were produced by grid patterns of same-sized Mars ejecta fragments from ~12 primary impact events on the surface of Mars (a mean of ~16,000 same-sized secondary impacts on Phobos per groove-family). A single 150 m secondary crater would produce 2 x 10^5 m^3 of Phobos ejecta [15]. In total, groove-forming secondary craters would produce a volume of Phobos ejecta equal to 4 x 10^{10} m^3 (2 x 10^5 [craters] x 2 x 10^5 m^3 [ejecta volume per crater]).

Because >95% of impact ejecta from Phobos returns to Phobos from Mars orbits [2], groove-forming secondary impacts would globally add new regolith on Phobos to a depth of ~25–50 m (4 x 10^{10} m^3 / 1.55 x 10^9 m^2 / porosity [14]). This introduces two observational discrepancies that further disallow the Murray hypothesis [4–11]:

1. The Murray hypothesis [4–11] asserts that grooves were formed after the Stickney Crater impact. However, regolith deposits of ~25–50 m would bury 5 m Stickney boulders that are observed in the present day [12,17].

2. In a review paper, Pieters et al., (2014)[18] describe the distinct "blue" and "red" spectral color units mapped on Phobos. These geological units would not be so distinctly observed if buried under a ~25–50 m global deposit of new regolith.

Related Problems with the Murray Hypothesis: Murray and Heggie [4] attempt to address several lines of contradictory evidence regarding grooves from secondary impacts. To add to our previous negative findings about the origin of grooves on Phobos as secondary impacts from primary impacts on Mars (the Murray hypothesis [4–11]), we offer the following points:

1. Ramsley and Head [3] refer to a 1997 three dimensional NASA model of Phobos [19]. Although local surface features (such as small craters) have been added to more recent digital models of Phobos, the basic overall shape of the models are unchanged since 1997, and there is no basis to suggest that recent 3D models of Phobos undermine the conclusions of Ramsley and Head [3].

2. In order to test the full extent of impact exposure of Phobos to Mars ejecta, Ramsley and Head [3] model a *complete set* of physically possible trajectories from Mars. Murray and Heggie [4] suggest that the upper velocities in the Ramsley and Head model [3] are unlikely, and indeed they are less likely. By limiting the model to only *plausible* ejecta trajectories (per Murray and Heggie [4]), the surface area of Phobos that is exposed to Mars ejecta is *greatly* reduced, and as a consequence, segments of *nearly all* grooves fall within a larger trajectory-defined impact exclusion zone, thereby ruling out secondary impact chains as the origin for most grooves.

3. Starting at the sub-Mars hemisphere, the east-to-west distribution of impact exposure to Mars ejecta on Phobos is *flight-time-dependent* by a temporal factor of at least 10 (and a maximum of ~20) [3]. Because ejecta disperses with increasing flight times, this strongly suggests that pit pattern disorganization and pit-to-pit emplacement spacing on the anti-Mars hemisphere of Phobos would be *10 to 20 times* greater than on the sub-Mars hemisphere of Phobos – *which is not observed*.

Murray and Heggie [4] challenge this by stating that Ramsley and Head [3] do not supply images of Phobos in their paper that show the organization of grooves. However, spacecraft images of Phobos are *widely available* throughout the literature and images of Phobos grooves clearly demonstrate that there is *no substantial decrease* in groove-pit organization or pit spacing east to west.

The absence of a hemispheric dichotomy in pit organization sets two physically impossible limits: First, the cratering process on Mars must adjust fragment dispersion rates to match ejecta flight times to Phobos that vary by ~ 20 to ~180 minutes. Secondly, the *same ejecta trajectory* may intersect Phobos outbound or inbound with two entirely different flight times and the primary crater on Mars must also compensate for the location of Phobos in space.

4. The Murray hypothesis [4–11] suggests that ejecta grid patterns are produced from parallel fluidized columns of ejecta that break up into thousands of same-sized blocks during the flight from Mars to Phobos. Ramsley and Head [3] show that even a *minuscule* dispersion rate among ejecta fragments (>1 mm/s or >1 microradians) is sufficient to produce excessive groove pit-to-pit spacing on Phobos. However, even if Mars produced same-sized fragments in a *perfect* grid pattern with a *zero* dispersion rate, the operation of orbital mechanics would break up the grid pattern prior to the intersection with Phobos. [3]

Conclusions:

1. The volume of Mars ejecta that has intersected Phobos during the period of groove formations is at least *three orders of magnitude* less than what would be required to produce the grooves as secondary impacts.

2. Groove-forming secondary impacts would produce ~25–50 m of new regolith on Phobos and bury features that are clearly observed in the present day (Stickney boulders and regional "blue" and "red" spectral units).

3. Minor refinements in computed shape models of Phobos since 1997 have no material effect on the conclusions of Ramsley and Head [3].

4. Modeling only *plausible* trajectories of Mars ejecta rules out most grooves due to groove segments that are observed within the consequentially larger trajectory-defined exposure exclusion zone [3].

5. There is no observed increase in east-to-west groove pit disorganization on Phobos. To produce the observed uniformity of groove morphology, the primary crater on Mars must modify ejecta grid dispersion rates to match flight times to Phobos [3].

6. A *minuscule* dispersion rate among ejecta fragments (>1 mm/s or >1 microradians) is sufficient to produce excessive pit-to-pit spacing on Phobos [3]. Further, due to orbital mechanics, even a *perfect* ejecta grid pattern would disintegrate during the flight to Phobos [3].

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