**Longitudinal heterogeneity of Phobos' crater size-frequency distribution: Co-evolution of resurfacing and orbital dynamics.**

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**Introduction:** Phobos is tidally locked to its host planet, like Earth's Moon, making it a key comparative target for studying the satellite’s co-evolution of the resurfacing and the orbital dynamics. The heterogeneity of the satellite surface evolution under a host planet's gravity has advanced our understanding of such systems' evolution [1,2]. Furthermore, it provides insights into the dynamics and evolution of ejecta originating from Phobos and orbiting Mars.

Heterogeneity of the cumulative crater size-frequency distribution (CSFD) along the longitudinal direction of Phobos has been studied through simulations [1] and crater counting [3,4]. A simulation study [1] examined the heterogeneity of the CSFD by comparing the results with the previous crater-counting study [3]. However, they [3] did not observe the “kinks” in the CSFD, which appeared as the characteristic knees in the CSFD in another crater-counting study [4]. The possible reason for this absence of the kinks was that the study area [3] included regions with varying cratering rates. Kinks in the CSFD provide insights into the scale of crater erasure and the impactor size-frequency distribution (SFD) [5,6]. Therefore, this study investigates the heterogeneity of the CSFD to understand the Phobos’ co-evolution of resurfacing and the orbital dynamics.

**Method:** To investigate the longitudinal heterogeneity in the surface evolutions around Phobos' spin axis, we divided the surface into four regions: leading, near, trailing, and far sides.

*Crater counting and the analysis of the CSFD:* We utilized three primary resources: (i) 109 images taken by the High Resolution Stereo Camera (HRSC) [7], (ii) 38 images taken by the Viking [8], and (iii) the latest Phobos shape model [9]. This research focuses on craters with diameters of 400 m or larger, based on the coarsest image resolution of 17.1 m/pixel. The coordinates and diameters of the craters were measured using the Small Body Mapping Tool [10].

We defined the best fit for the crater production function (PF) following the previous studies [5,11]. Separate analyses were performed for each isochron line at the kinks in the CSFD, using Craterstats 2.0. The PF is based on the crater formation rate and the impactor SFD model for the Martian region [4]. Through this fitting, we derived the cumulative crater frequency for a reference diameter of 1 km, denoted as $N(1)$. First, we fitted the PF to the CSFD, from the largest crater to the kink diameter. Next, we repeated the fitting process down to 400 m, applying resurfacing

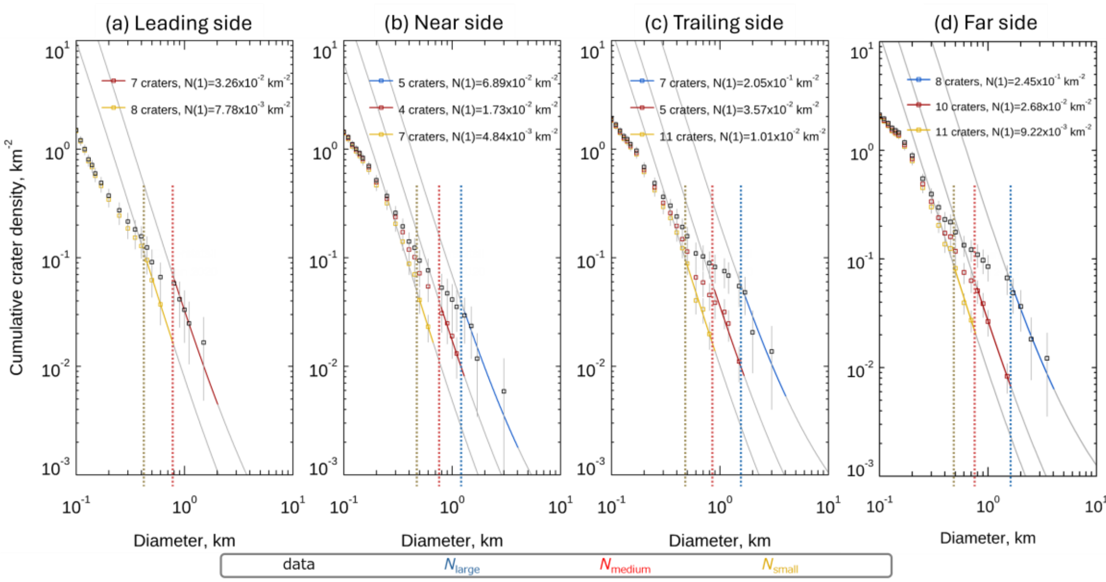


**Fig. 1** CSFD for each region. (a–d) CSFD results, with each fit represented by a distinct color. Kinks of 1.2–1.7 km with $N_{large}$ are shown in blue, kinks of 800 m with $N_{medium}$ in red, and kinks of 400 m with $N_{small}$ in yellow. For the leading side only, the fitting range of $N_{medium}$ includes craters from 800 m to the largest observed diameter.

corrections to the CSFD while considering the previously identified kink diameters [11]. This approach assumes that all craters of the fitting range were formed after a resurfacing event.

*Estimation of volume of the ejecta blanket:* The ejecta blanket refers to the regolith layer formed by the re-accretion of ejecta released during the formation of craters. We estimated the ejecta blanket thickness using the depth-diameter ratio of craters, which has been extensively studied for lunar craters [12]:

$$d = 0.036\, D^{1.014}.$$

where $d$ represents the depth of the crater (km), and $D$ is the crater diameter (km).

Next, we estimated the volume of the ejecta blanket for each of the four longitudinal quadrants—leading, near, trailing, and far, each covering 90° in longitude—by multiplying the surface area of each quadrant by the estimated thickness of the ejecta blanket.

**Results & Discussion:** The CSFDs obtained for the four study areas are summarized in Fig. 1. The kink diameters found at 400 m and 800 m were identical within the margin of error across all survey areas. The near, trailing, and far sides exhibited kinks in the 1.2–1.7 km range, whereas the leading side did not have any craters larger than 2 km. The volume of the ejecta blanket was estimated to be 52–91 $km^3$. Of the volume excavated by Stickney, the estimated amount re-accumulated to Phobos is 54–74 $km^3$ [13,14]. Whereas considering a uniform ejecta blanket extending to the polar regions may be an overestimate, the volumes appear consistent.

We interpret the heterogeneity in the CSFD and ejecta blanket thickness we found as follows: (1) The leading side experienced significant crater erasure, likely due to the thickest ejecta blanket. (2) The ejecta blanket was formed by material from the largest impact, Stickney, as the estimated volume is consistent with previous studies [13,14]. (3) The density of the craters larger than the kink of 1.2–1.7 km ($N_{\mathrm{large}}$) reflects pre-Stickney conditions, whereas the densities of craters measuring 0.8–1.5 km and 400–800 m ($N_{\mathrm{medium}}$ and $N_{\mathrm{small}}$) in diameter reflect post-Stickney surface evolution. (4) Crater number density on the near side was consistently lower than on the far side, likely due to planetary screening. This reduction in crater formation on the near side is particularly attributed to its proximity to Mars [1]. (5) Across all regions, the number of craters smaller than 800 m was lower than that predicted by the PF model, suggesting that the impactor SFD forming craters smaller than 800 m on Phobos is lower than that of lunar impactors.

Our results suggest that the leading side experienced the greatest deposition of the ejecta blanket on Phobos. This deposition likely occurred immediately after Stickney's formation, followed by global resurfacing facilitated by Phobos' post-Stickney impact spin [13,15] (Fig. 2). One possible mechanism for the scarcity of craters smaller than 800 m is that ejecta from impacts entered Martian orbit, where collisions fragmented the material, reducing the number of particles capable of forming craters smaller than 800 m on Phobos.

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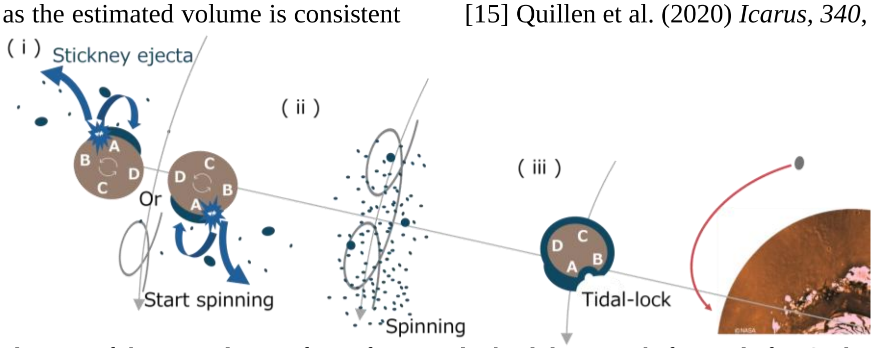


**Fig. 2** Conceptual diagram of the co-evolution of resurfacing and orbital dynamics before and after Stickney's formation, as Phobos gradually decreases in orbital altitude. The diagram illustrates the spin induced by the Stickney impact and the subsequent deposition of ejecta. (i) Stickney formation: Stickney forms, initiating Phobos' spin [13,15]. Since the initial direction before the tidal lock cannot be determined, both scenarios—Stickney forming on either the leading side or trailing side—are depicted. (ii) Interaction with Stickney ejecta: As Phobos spins, it intersects with the ejecta from Stickney, which enters Mars' orbital path [13]. Given that Phobos' spin period is longer than the lifetime of Stickney's ejecta in Mars' orbit, the ejecta accumulates globally across Phobos' surface [13]. (iii) Current tidal lock orientation: Phobos eventually becomes tidally locked in its current orientation. Due to Mars' screening effect, crater formation is reduced on Side B, as discussed by [1].