LIFETIME OF SMALL LUNAR CRATERS AND SATURATION EQUILIBIUM CONSTRAINTS ON THE SCALE DEPENDENCE OF DIFFUSIVITY.
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Introduction: Here we discuss a recent calculation of the connection between crater degradation, crater lifetime, and the observed population of craters in saturation equilibrium [1]. A population of craters is said to be in equilibrium at some particular size if the production of craters balances with the removal of craters at that size [e.g., 2, 3]. The balance of crater production and destruction in equilibrium controls the crater lifetime (or the time period within which craters are detectable) at a given crater size.

In other words, if we know the production rate of craters and the number of craters typically observed in equilibrium, the lifetime of craters can then be directly calculated. One can think about this geometrically on a cumulative size-frequency distribution (SFD) plot as the intersection between the observed equilibrium curve and an isochron at a particular size: the intersection point provides the average crater lifetime.

From crater lifetimes at different sizes, with knowledge of the fresh crater shapes and an estimate for when craters are so shallow that they are erased, we can assess the scale-dependence of crater degradation and variation in effective diffusivity as a function of scale.

Crater Equilibrium Lifetimes: For the Moon, established models for both the production rate [e.g., 4] and equilibrium SFD exist [5,6], at least at crater diameters D≥10 m. Using the Neukum production function [4] and equilibrium functions from Trask [5] or Hartmann [6] gives the lifetimes given in **Fig. 1**.

For diameters <10 m, the Neukum production function is undefined so we use pi-scaling to calculate a production rate from Grün et al. [7] (see [1] for details). This scaled Grün et al. production function has a steep, –4 cumulative form, which produces the break in slope in **Fig. 1**.

Diffusivities Consistent with Equilibrium Lifetimes: From the crater lifetimes given in **Fig. 1**, it is straightforward to infer the effective diffusivity at a given size with two other inputs: (a) the shapes of fresh craters when they form on the Moon; and (b) a visibility threshold for when craters become unrecognizable. With these inputs, we can simply take the initial shape, apply a diffusion model until the visibility threshold is attained, and compare how much diffusion is needed over the crater's estimated lifetime at that size.

When making this calculation, it is important to note that neither the initial shape nor the visibility threshold is known with much certainty, especially in the meter-to-decameter size range. Observations from LROC DTMs show that small fresh craters (D~30 m and below) on the Moon rarely have as high initial depth/Diameter $(d/D)_{initial}$ as their larger counterparts [8–10]. Here, we assume that craters are reduced from

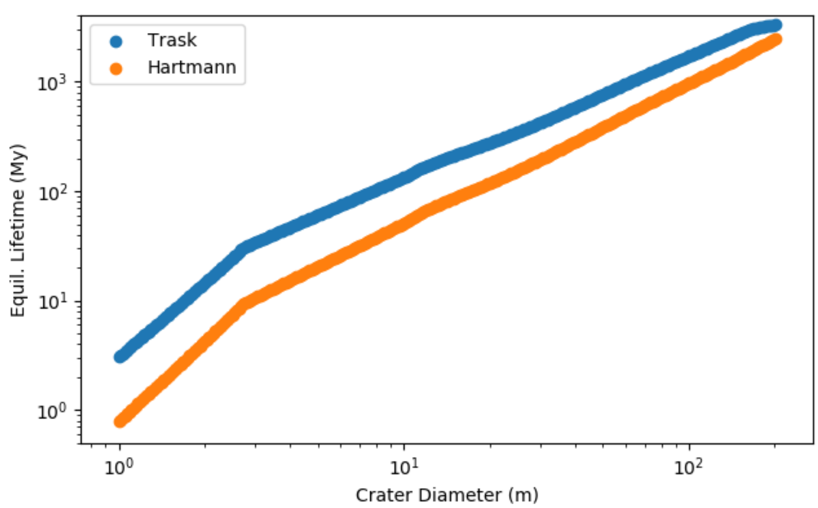

Fig. 1. Calculated lifetime of craters of different sizes assuming Trask [5] and Hartmann [6] equilibrium. The lifetime of small craters (D≤20–30 m) must be short, <500 Ma. The slope on these equilibrium-derived lifetimes τ generally follow a power law with $\tau \sim D^{1.1}$ to $\tau \sim D^{1.3}$. The fact that these lifetimes do not scale with a power-law exponent of 2 is symptomatic of anomalous diffusion.

$d/D_{initial}$=0.21 at D=400 m to $d/D_{initial}$=0.1 for sizes D≤10 m (see [1], Table 2).

For the visibility threshold, we chose to use a single cutoff value for d/D, following [11]. We selected $(d/D)_{cutoff}$=0.04 as the nominal case based on the left tail of the probability density functions (PDFs) for d/D in [9]. Choice of the $(d/D)_{cutoff}$ has an appreciable effect on the absolute diffusivities, but not on the qualitative behavior or relative diffusivities at different scales. Higher visibility thresholds need lower diffusivities and vice versa because less diffusion is needed to erase craters. In reality, the visibility threshold may be size-dependent (i.e. $(d/D)_{cutoff}$ varies with size), but assessing that carefully is challenging and left for future work.

Taking the assumed initial shape and visibility threshold, **Fig. 2** gives our estimates for effective diffusivity at different scale. The results of this calculation are consistent with earlier studies [e.g., 11–14] that imply the effective diffusivity must decrease with increasing crater size and length scale.

Limitations: Two limitations are worth mentioning here. First, this analysis only applies to areas with low background slopes where the equilibrium functions are valid. From past measurements, it is well-established that crater lifetimes are greatly reduced in areas of appreciable topographic slope. Consequently, the lifetimes given here are likely upper bounds on crater lifetimes for areas with higher background slopes.

Second, the diffusivities (**Fig. 2**) computed here are samples of different time periods. This arises because craters of distinct sizes have such different lifetimes (**Fig. 1**). Because we assume a constant diffusivity over the course of craters' lifetimes, changes in diffusivity with time that are independent of scale could end up expressed in these effective diffusivities as a scale-dependence. This effect is minor if the impact flux on the Moon was constant since ~3 Ga [e.g., 4], but that is uncertain [e.g., 15, 16].

Implications for Volatile Exploration: Our results in **Fig. 1** help provide limits on the maximum age of volatiles found within recognizable craters at specific sizes, at least where volatiles were deposited after crater formation and were not excavated during the impact event. With surface measurements of crater morphometry and the distribution of volatiles, we may be able to get more direct estimates for the timing of volatile deposition rather than just upper limits.

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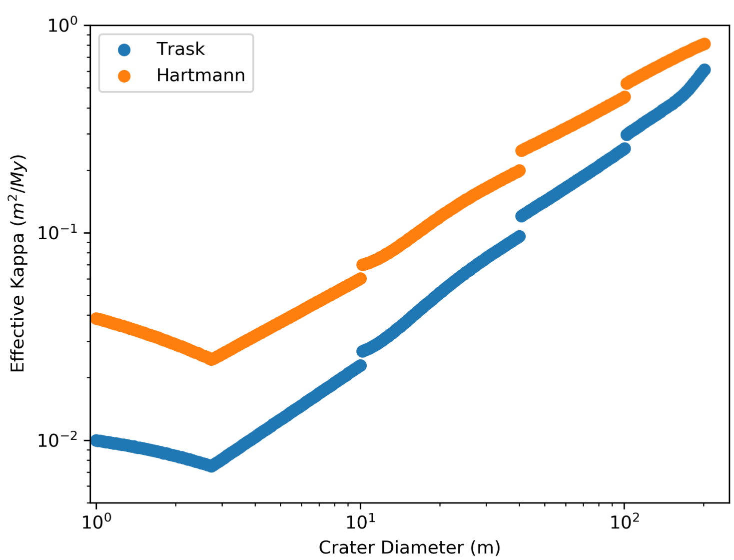

Fig. 2. Effective diffusivity required for maintaining crater equilibrium over the timescales given lifetime from Fig. 1 Trask (blue) [5] and Hartmann (orange) [6] equilibrium differ here because the Hartmann equilibrium-implied lifetimes are shorter (Fig. 1). The step discontinuities are a result of the changes in the presumed crater shape. Above 5-m, the effective diffusivity implied by the Hartmann equilibrium function can be approximated by a power-law $\kappa_{eff}\cong 3.6D^{0.87}$, and the Trask diffusivity has $\kappa_{eff}\cong 3.1\ D^{1.05}$ for D in km and κ_{eff} in m^2/My.