RE-ANALYSIS OF OBSERVATIONS OF CRATER DEGRADATION ON THE LUNAR MARIA ACCOUNTING FOR ANOMALOUS DIFFUSION.

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Introduction and Background: It has long been recognized that airless bodies like the Moon undergo a slow diffusion-like process of landscape evolution [e.g., 1-4] where the topography h can be described as evolving as $\frac{dh}{dt} = \kappa \nabla^2 h$, where κ is the diffusivity. This process slowly infills and erodes back the rims of craters [e.g., 5], and all landforms become softened over time (Fig. 1). Eventually, topographic diffusion leads to erasure of craters in heavily cratered terrains as an equilibrium population of craters is reached [e.g., 6,7].

The agent of diffusive degradation implicated in past studies was proximal ejecta mobilized by the innumerable small impacts that strike the lunar surface [2], which has a net-downslope bias on a slope, and is thus diffusive. However, calculations [8, 9] indicate that the mobilization of material locally by the proximal ejecta of small impacts is dramatically insufficient to explain either the observed diffusivity for km-scale craters or the density of craters in equilibrium [4,8,9].

Moreover, the effective diffusivity experienced by craters of different size must be size-dependent [5,8,10] to explain the slope of the equilibrium size-frequency-distribution. In other words, κ is not a constant and topography undergoes anomalous diffusion rather than classical linear diffusion. This arises because of the power-law nature of the impactor production function, which goes as $N_{cumulative} \propto D^{-3.2}$ for small lunar craters, coupled with the fact that larger cratering events do dramatically more diffusive work on the lunar surface. For consistency with the observed crater size-frequency distribution in equilibrium, the size dependence of the effective diffusivity needs to go as $\kappa_{eff} \propto D^{\varphi}$, where φ~0.8–1(at least for D<~2 km) [e.g., 8,9].

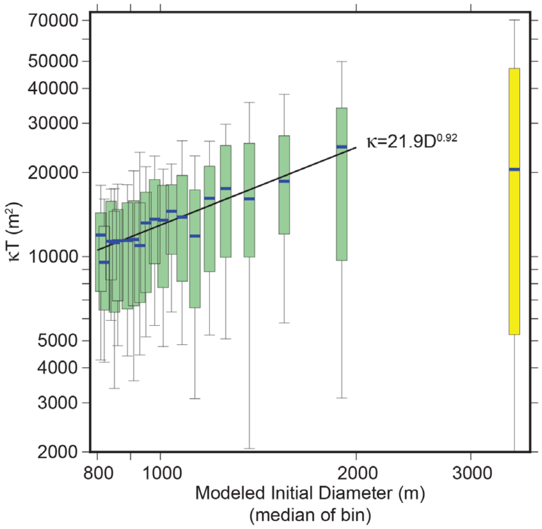

Fig. 2. Box-and-whisker plot of the 10-25-50-75-90% values of κt as a function of initial diameter; data from [4]. A power-law fit to the median values (blue lines) describes the data well for craters smaller than 2 km (green bins). This plot was constructed for craters whose modeled initial diameter was 800 m ≤ D_0 ≤ 4 km to avoid incomplete sampling at the edges of the crater size range that was measured.

In [4], the assumption was that crater degradation could be approximated using a linear diffusion model (a single value for κ). Such an assumption remains potentially viable because the data were gathered in a relatively narrow range of diameter (800m-5km, with 96% of the craters having observed D=800m and 2km). However, now that we better understand the size-dependence of diffusivity, it is worth reanalyzing data from that study, taking into account the anomalous nature of topographic diffusion on the Moon [8,9].

Signs of Size-Dependent Diffusivity in the Raw Data: Figure 2 shows the measured diffusion ages (κt) for craters on the maria as a function of diameter, with

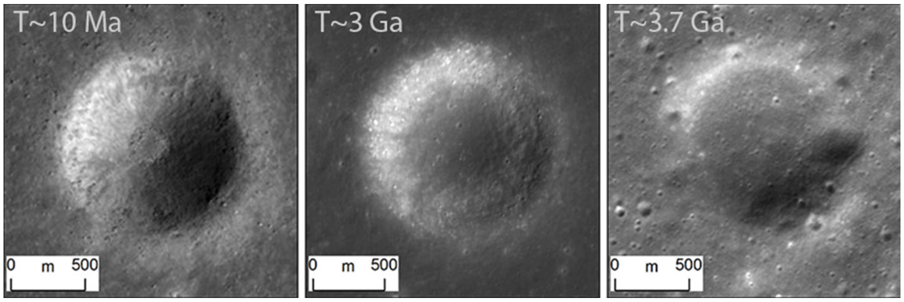

Fig. 1. Examples from the Kaguya Terrain Camera of how the appearance of craters changes as a function of time on the lunar surface. Craters progressively soften and infill with time. (Left, 22.51°E, 19.691°N; Center, 24.65°E, 26.02°N; Right, 26.10°E, 38.55°N).

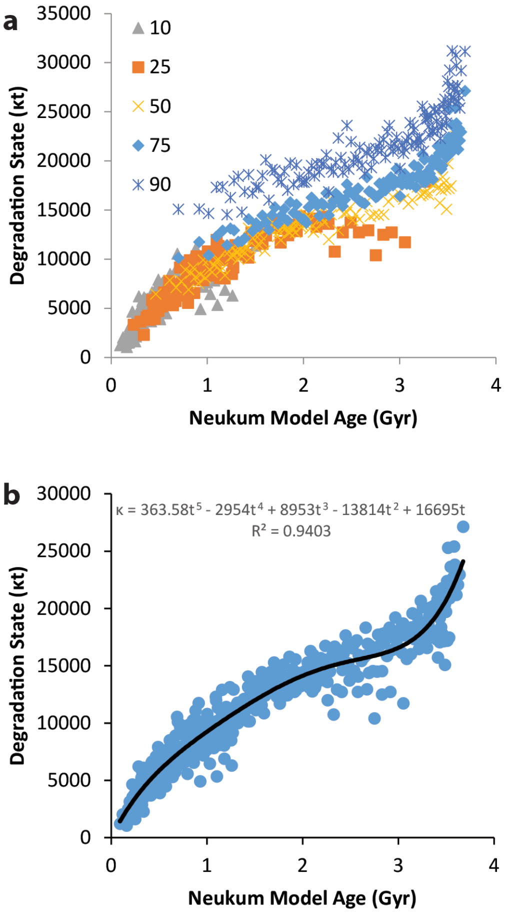

Fig. 3. (a) Plot of the 10th-25th-50th-75th-90th values of κt corrected to a common 1 km-equivalent size. The Neukum model age for each crater is derived based on the age of the terrain they formed, assuming they each formed in sequence equivalent to their relative degradation. (b) 1-km equivalent diffusivity as a function of age. This is quite close to the same as Fig. 11 in [4], though the R^2 has increased from 0.91 to 0.94.

a power-law fit to the median values (excluding the largest bin, which is an outlier). The best-fit power law exponent of φ~0.9 is closely in line with results of numerical experiments and expectations from the equilibrium behavior on the mare [9].

The observed behavior of largest craters ($1930 \leq D < 4000$ m; yellow bin in Fig. 2) is inconsistent with the rest of the data. There are several reasons that this might be the case. First, even considering anomalous diffusion, the largest craters alter with topographic diffusion relatively slowly, so their κt values are comparatively insensitive to the process and more difficult to accurately measure. Second, there are fewer large craters to work with and the dataset may simply not be adequate to characterize this part of the diameter distribution. Third, it is conceivable that this is a real deviation, and the size-dependence of diffusivity weakens at larger sizes.

Recalibrating the data by rescaling to a consistent 1-km scale diffusivity: Given our estimate for the size-dependence of diffusivity, it is possible to normalize the measured κt values in [4] to a reference diameter of 1 km by multiplying the observed κt for a crater of initial size D_0 (in km) by $(D_0)^{-\varphi}$ (Fig. 3). Here we take φ=0.9.

This enables recalculation of how κ varied on the Moon as a function of time (Fig. 3b). There are only small changes from [4], presumably because of the relatively narrow range of sizes dominated the initial analysis. The correction does modestly strengthen the power of the regression.

One element of interest in Fig. 3a is that this diameter correction did *not* solve an issue pointed out in [4] that the 90th percentile (most degraded) craters are more degraded than expected given the age of the units they are on. In the past [4], this was attributed to either unrecognized secondaries, which contaminate the data and start shallow, or perhaps craters that predated the last resurfacing episode but did not get buried so are older than the unit they are being assigned. These explanations remain viable, although with the jumps in degradation that are possible in anomalous diffusion, it may be a natural consequence of the long-tail of potential diffusivities in anomalous diffusion compared to linear diffusion. Future work that compares the spectrum of observed degradation states in the Cratered Terrain Evolution Model (CTEM) [e.g., 9] may shed light on this phenomenon.

Summary: Modeling and theoretical advancements imply that topographic degradation on the Moon can be treated as an anomalous diffusion process. The scale dependence of this process is both theoretically predicted [9] and observed (Fig. 2) to go as $\sim D^{0.9\pm0.1}$, at least for craters smaller than a few km. Re-normalizing the measured degradation states of ~km-scale craters on the Moon to a single effective size has only modest effect on the derived post-maria diffusivity history (Fig. 3).

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