REGOLITH LAYER DEPTHS AT APOLLO LANDING SITES AND EFFECTS ON CRATER SFDS.

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Introduction: The availability of very high resolution imaging of the Moon allows for craters with diameters (D) $\lesssim$ 1 km to be used in modern efforts to determine crater model ages of lunar terrains. However, changing terrain material properties both spatially and vertically can alter D $\lesssim$ 5 km crater distributions as shown by previous works [e.g., 1-3]. Since crater densities at D~1 km – traditionally used for determining model ages – are within this range, ages could be incorrectly estimated. Furthermore, ages derived from extrapolating to D=1 km from smaller diameters are even more susceptible to error.

In previous work [3], we fit expanded crater size-frequency distributions (SFDs) of Apollo terrains (D=10 m to several km) with the Model Production Function (MPF; [2]) in order to better understand the influence of spatially changing terrain properties on crater model age estimation. The MPF provides a lunar chronology that incorporates terrain properties by converting impactor distributions to crater distributions using modern impact scaling laws [1]. We found we could generally fit the Apollo SFDs and reproduce the reported radiometric ages [4] with appropriate terrain crater strengths and densities for the given site (e.g., Fig 1).

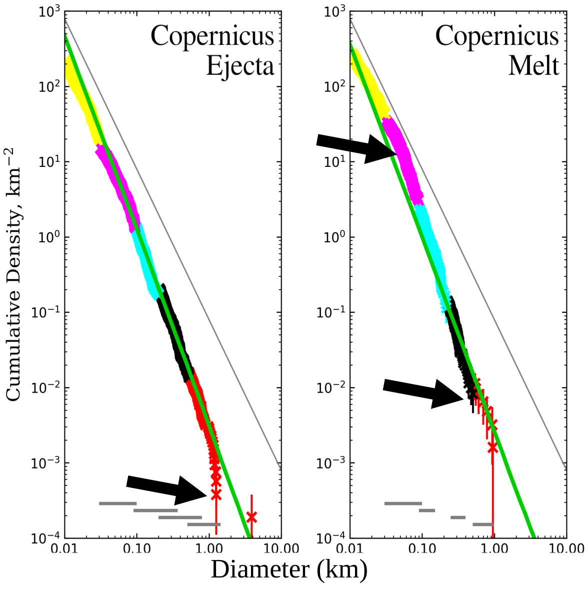

Figure 1. MPF best fits (green line) to crater SFDs (colored x's). Data are colored by source nest and horizontal gray lines indicate overlap diameters from nested technique [see 3]. Diagonal gray line is 2% geometric saturation [6]. Here we assess if deviations of SFDs from MPF (arrows) are caused by vertical variations in terrain properties.

Nevertheless, some terrains had minor deviations from the best fit MPF which may be caused by vertical variations in terrain properties with depth (e.g., Fig. 1, arrows). Often vertical variations in terrain properties are indicated by a "kink", or sudden, dramatic change in slope in the crater SFD (e.g., [5]; Fig. 1, left). We did not generally see such kinks in the Apollo SFDs [3; e.g., Fig. 1], but still wanted to assess if vertical variations in terrain properties could cause the deviations we observe. Therefore, we use common methods to assess the plausible regolith and other layer (e.g., volcanic) depths in several Apollo chronology calibration sites, including Copernicus.

Methods: Our approach to determine potential layer depths measures simple craters with unusual morphologies, such as central mounds, flat floors, and concentric rims, in Lunar Reconnaissance Orbiter Wide and Narrow Angle Camera (NAC) images, as it is proposed that vertically changing material properties cause these morphologies [7]. We use two common quantitative methods from the literature to determine layer depths (d). First, we use crater diameters and unusual feature diameters (D_f) of fresh craters with $D_f \geq 4$ m (limited by NAC image resolution) in each nested area with [8]:

$$d=(k-D_f/D)*D*\tan(\alpha)/2 \qquad (1)$$

where k is a constant weakly dependent on material properties (value of 0.86 works well for the Moon) and $\alpha=31°$ is the angle of repose. Second, we use crater diameter measurements and recorded unusual feature type (including normal) for all fresh craters D ≥ 40 m in the region with these relationships [7]:

$$\begin{gathered} d=D/4 \text{ for normal craters} \\ d=D/5.5 \text{ for mound/flat-floor craters} \\ d=D/9 \text{ for concentric craters} \end{gathered} \qquad (2)$$

The first method gives a more accurate depth, but is localized and limited by image resolution (numbers in Fig. 2), while the second method provides a less accurate depth, but covers the whole region (contours in Fig. 2). Thus, we combine the two methods to give more accurate, regional descriptions of depth for our Apollo landing site study areas.

Preliminary Results and Future Work: Fig. 2 shows layer depth results for Copernicus impact melt on its floor. Each panel shows results for a different depth range in meters and hot contour colors indicate where a layer of that depth range is concentrated (no contours indicates no craters of unusual morphology for those depths). The crater SFD in Fig. 1 right indicates the deviations from the MPF at D ~ 100-200 m and 500-800 m. First, we note that the unusual crater morphology analysis did not reach deep enough to observe the D ~ 500-800 m layer possibly indicated by the SFD. However, the last panel (d=50-400 m) is deep enough to analyze if vertical changes in terrain properties are important for the D ~ 100-200 m deviation. No values were gained using the first method because unusual morphology craters of the appropriate size were not observable. The second method indicates there may be a layer at this depth (bottom of the melt?) in the southwest portion of the study region, which may extend into the northern part of the region. Thus, it is currently unclear if this layer is broad enough to cause the deviation at D ~ 100-200 m seen in the crater SFD. Another uncertainty is due to the fact this deviation also occurs where the crater SFD may be entering saturation equilibrium (where the SFD parallels the diagonal gray line in Fig. 1).

Future work will start with applying a vertical variation in terrain properties to the MPF to see if we can reproduce the crater SFD deviations observed with reasonable parameters. We will apply this analysis to all the Apollo terrains we have examined in [3]. If vertical variations cannot provide an explanation, we will explore why that might be (e.g., incorrect incorporation of vertical property changes in the MPF, layers too thin...). Furthermore, we will compare our regolith depth results to previously published work [e.g., 7, 8, and many more] using a variety of methods to verify our calculations and better constrain the regolith depths in these areas, which has many applications beyond our work.

References: [1] Holsapple K.A. & Housen K.R. (2007) *Icarus*, *187*, 345–356. [2] Marchi S. et al. (2009) *AJ*, *137*, 4936–4948. [3] Kirchoff and Marchi (2023) *Icarus 391*, 115336, 10.1016/ j.icarus. 2022.115336. [4] Stöffler D. et al. (2006) *Rev. Min. Geo.*, *60*, 519–596. [5] Marchi S. et al. (2011) P*lanet. Space Sci. 59*, 1968–1980. [6] Hartmann W.K. (1984) *Icarus*, *60*, 56–74. [7] Quaide W.L. & Oberbeck V.R., (1968) *JGR, 73,* 5247–5270. [8] Bart G.D. (2014) *Icarus, 235*, 130–135.

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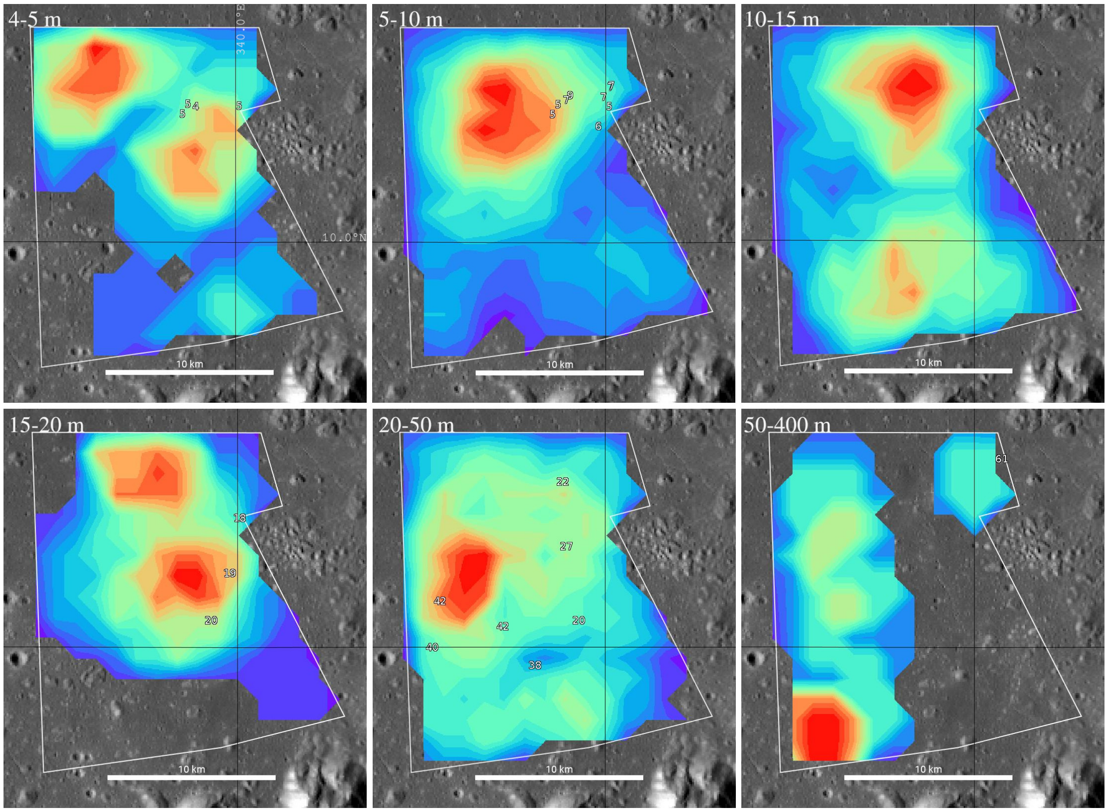

Figure 2. *Example layer thickness maps for Copernicus (floor) impact melt region for the depth ranges given in each panel. Numbers indicate thickness from the first method. Contour plots indicate layer thickness from the second method: hot colors indicate where a layer of the given depth range is likely located, cooler colors indicate less probability, and no contours indicates where data was unavailable. All values are in meters. Maps like these are made for each Apollo site examined in [3] and will be incorporated into vertical terrain property analyses.*