MEASURING LUNAR EJECTA THICNKNESS AT SMALL COPERNICAN CRATERS.

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Introduction: Models of ejecta blanket thickness have a surprisingly broad impact on planetary geology. Interpretation of returned samples and in-situ measurements is intimately tied to crater ejecta thickness [1,2,3]. Models for impact gardening on the Moon and all airless bodies throughout the solar system are dependent on accurate knowledge of ejecta excavation and distribution. Lastly, the emplacement of resources such as lunar ice deposits may depend on burial rate under ejecta [4]. Despite its importance, ejecta thickness models up until now have been constructed using only semi-empirical methods.

Ejecta thickness can generally be described as:

$$\delta = f(R)(r/R)^{-B} \text{ for } r \geq 1, (1)$$

where $f(R)$ is ejecta thickness at the crater rim as a function of crater radius R, r is the distance from the center of the crater, and B is some constant (~3) [5]. Most models derive from predicting ejecta thickness at crater rims [6,7,8,9,10]. Previous works measured ejecta thickness as a function of radial distance from terrestrial experiments at explosion craters and in gas gun laboratories [5,6]. Extrapolating these studies to lunar ejecta blankets is complicated by differing gravity, atmosphere, material properties, and scale.

The most accurate method of deriving lunar ejecta thickness would be from direct measurements. Sharpton [9] and Kruger et al. [10] measure rim ejecta thickness through outcrop exposure on crater walls. However, this method requires an estimate of outcrop thickness in the overturned layer, ultimately derived from analogy to terrestrial craters. It is also limited to craters that were emplaced where outcrop lies near the surface and cannot be used to measure radial thickness variation.

Methods: We estimate ejecta blanket thickness as a function of radial distance by measuring the diameter and position of dark-haloed craters (Fig. 1) formed on Copernican ejecta blankets. Weathering darkens lunar regolith to a 50-200 cm depth [11]. Below this is brighter, immature material that an impact may excavate and deposit onto the surface (Fig. 2). Subsequent, smaller impacts on the ejecta blanket will excavate material from depth as a function of diameter. We assume that dark-haloed crater impacts penetrated the (much larger) parent crater ejecta and excavated material from below the pre-impact surface, thus allowing for point measurements of ejecta thickness. Maximum excavation depth is typically approximated using [5]:

$$d_e = 0.1D, (2)$$

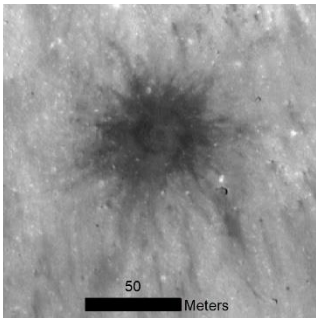

Figure 1: Dark child craters are prominent features on Copernican ejecta blankets.

Sharpton [9] suggests that excavation depth is shallower by a factor of ~3:

$$d_e \leq 0.03D, (3)$$

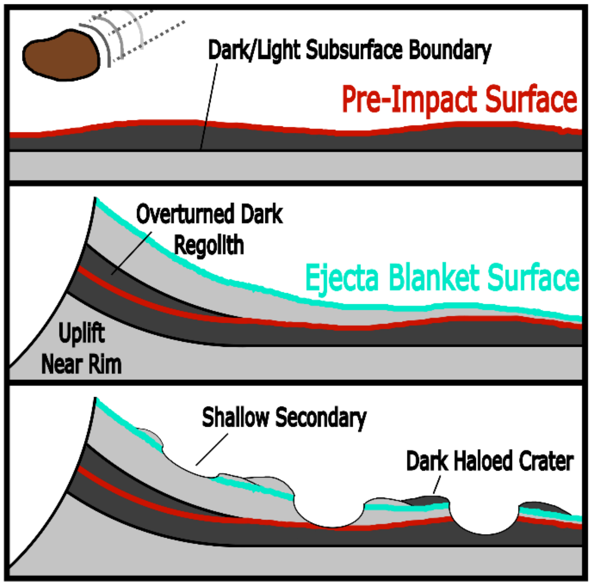

Figure 2: Cross-sections during a Copernican crater's formation; showing a pre-impact surface, nominal post-impact ejecta geometry, then excavation by subsequent impacts on the parent crater's ejecta blanket.

We used LROC NAC images [12] of 30 Copernican craters, 170 to 9000 meters in diameter. We selected craters based on albedo contrast with a mature background terrain, which biases our sample towards low latitudes, craters within the lunar highlands, and smaller-diameter craters. Image pixel scale ranged from 0.5 to 1.5 m. We used large- and small-incidence images for each crater to measure the position, diameter, and reflectance contact of craters formed on the parent ejecta blanket. Each "child" crater was categorized based on the reflectance of ejecta at its rim, dark or light, which can have maximum excavation depth approximated using either Eq. 2 or Eq. 3.

A few factors may introduce uncertainty with this method. Secondary impacts form at lower velocities, resulting in lower depth-to-diameter and shallower excavation [5,9]. Additionally, the nature of the contact between the ejecta and the pre-impact surface is not well understood. However, it is likely a zone of churned material on the order of centimeters to decimeters thick for craters in our sample range [13]. Lastly, some overturned mature regolith will be present in the ejecta blanket, most prominently within 0.5 radii of the parent rim. Dark-haloed craters near that rim may not represent excavation below the pre-impact surface.

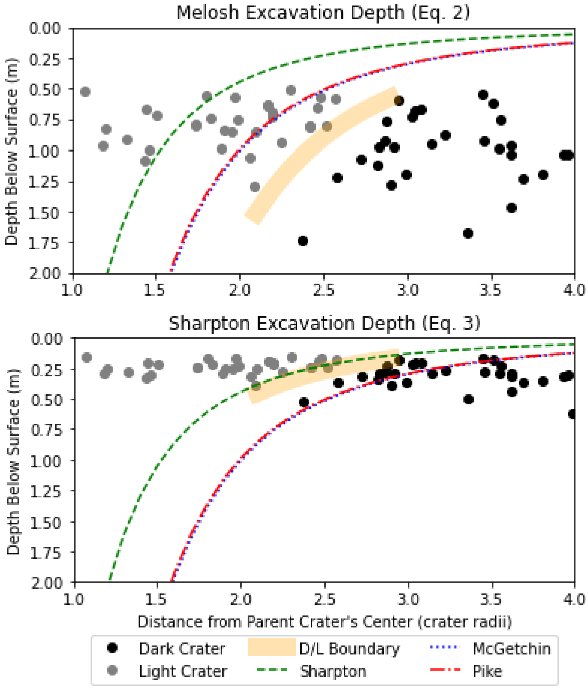

Figure 3: Radial position, color, and inferred subsurface depth of regolith on ejecta of a 480m diameter crater, assuming different excavation depths. We plot an approximate dark/light regolith boundary (the ejecta blanket's base) in our data against ejecta thickness models from Sharpton, McGetchin, and Pike. Sharpton's excavation depth and ejecta thickness are the only models that consistently align with our data.

Data and Results: We compare ejecta thickness equations from McGetchin et al. [6], Pike [7], and Sharpton [9] to estimates from our data at one representative parent crater (Fig. 3). Melosh's excavation depth (Eq. 2) projects an ejecta blanket significantly thicker than any of these models predict; this volume of regolith would violate conservation of mass with material ejected from the parent crater. Meanwhile, Sharpton's excavation depth (Eq. 3) projects an ejecta blanket consistent with Sharpton's ejecta thickness model.

Three of the craters we investigated suffer a lack of detectable child craters on their ejecta blankets and cannot be used in our analysis. The other 27 craters produce results comparable to Figure 3; an excavation depth $d_e=0.1D$ projects ejecta 20 to 100% thicker than the McGetchin or Pike ejecta thickness models. The Sharpton excavation depth $d_e=0.03D$ consistently projects an ejecta blanket that aligns with the Sharpton thickness equation.

Discussion and Conclusions: We examined the ejecta thickness of 30 lunar craters <9km diameter and found that our results are most consistent with the ejecta blanket thickness and excavation depth equations from Sharpton (2014), providing independent support for that paper's methods. At craters in this size range, the ejecta thickness can be as much as half of what is predicted by the commonly utilized McGetchin (1973) model. Since the McGetchin model has been widely used in past studies, reexamination of context for many lunar measurements or observations, including Apollo samples, may be warranted.

Our next step in advancing this analysis will be testing excavation depth. We can survey mature highlands surfaces and locate the smallest craters that excavate bright, immature regolith. We will use the known depth of the dark, mature layer from Apollo cores [11] to resynthesize equations for d_e. On a mature surface, Sharpton's excavation depth (Eq. 2) predicts the smallest bright craters will be ~1.7m, whereas Melosh's (Eq. 3) predicts a diameter of ~5m. With our dataset and an independently derived d_e equation, we can create an equation for ejecta thickness as a function of parent crater diameter and radial distance, which we expect to be comparable to the equations from Sharpton.

Future work will include measuring more diverse craters and examining other ejecta properties with our dataset. We will measure ejecta thickness at more mare craters, and the large, complex craters Byrgius A and Giordano Bruno via the methods in this study. We can also use our dataset to characterize the size and nature of the churned pre-impact contact with the ejecta. Our study of ejecta morphology will be relevant to many areas of planetary science, lunar resource utilization, and future missions to the Moon.

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