LUNAR CRATER POPULATIONS, EVOLUTION OF MEGAREGOLITH, AND INTERPRETATION OF LUNAR AND PLANETARY ROCK SAMPLES  
William K. Hartmann, Planetary Science Institute, 1700 E. Ft. Lowell Blvd., Tucson AZ 85710  
hartmann@psi.edu  and  
Alessandro Morbidelli, 1Université Côte d’Azur, CNRS-Lagrange, Observatoire de la Côte d’Azur,  
CS 34229–F 06304 Nice Cedex 4, France

Introduction: A significant paradigm shift [1] in planetary science resulted in a movement away from the terminal cataclysm or late heavy bombardment (LHB) scenarios [2]. Both of these terms, as originally defined and understood, pictured an early period of insignificant crater and basin formation, lasting from the end of lunar formation (ca. 4.5-4.45) to about 4.0 Gyr ago, followed by a period of intense cratering ca. 3.9 Gyr ago [3], with formation of most multi-ring impact basins within an interval of about 170 Myr.

As discussed in [2], dynamical models from about 2005 to 2015 concentrated on explaining the proposed gap in crater formation followed catastrophic spike in impacts. In 2018, however, Morbidelli et al. [4] produced an “accretion tail” dynamical model that returned to earlier models (see [2]) which pictured more or less monotonic decrease in impact rate as the debris of planetary formation were swept up. Included in [4] were quantitative data giving the impact rate as a function of time. The present abstract combines model data from [4] with techniques for converting the size-frequency distribution (SFD) of any given crater population into an estimate of the depth of material that has been extensively pulverized and converted into megaregolith materials. These techniques were initially developed in [5]. In other words, here we examine the question: If [4] is correct, what are the consequences regarding the evolution of lunar megaregolith? Our work is described in much more detail in a paper submitted by Hartmann and Morbidelli to Meteoritics and Planetary Science; that paper has been reviewed and is currently undergoing modest revisions [6].

Methodology. The basic idea of our technique begins with the log-incremental distribution of any particular SFD crater-count curve, such as a curve for a sparsely cratered lunar maria, or a curve for a crater saturated lunar upland surface. For any such curve it is possible to tabulate the area covered by the craters present in each diameter bin. (The bins in our plot being divided in $\sqrt{2}$ diameter intervals, i.e. 0.5 km, 0.707 km, 1 km, 1.414 km, 2 km, etc.) This area is

\[
\text{Area/\text{km}^2 \text{ per bin}} = (\text{no. craters/\text{km}^2} \times \pi r^2)
\]

where $r = \text{effective mean area of a crater in the bin}.$

The next step is to start with the bin with the largest craters and add up the cumulative area covered by craters in each bin, working bin by bin toward smaller sized craters. At some point a diameter $D_{100\%}$ is reached, where the sum of the areas of all craters an area equal to 100% of the area of the visible craters at $D > D_{100\%}$ is equal to 100% of the lunar surface. (See Fig. 1.) This is not the same as saying that 100% of the area has been excavated by such craters, because many of the craters overlap earlier craters, so that some areas have not yet been impacted. Thus we continue the process to reach a smaller diameter, $D_{200\%}$, where an area equal to 200% of the area of the visible craters at $D > D_{200\%}$ is covered. Let us define $d$ as the effective depth of excavation and ejection of material from a crater of diameter $D$. We take $d$ to be $\sim 1/3D$, being < transient cavity depth but > depth of the crater as observed today (consistent with a recent study of crater excavation [7]). Given that overlap still leaves uncratered areas when $D_{200\%}$ is reached, but also that when a given $D_i$ is reached, craters larger than $D_i$ and deeper than $d_i$ cover part of the area, we assume that depths of $d_{100\%}$ to $d_{200\%}$ give a rough estimate of the average depth excavated, with the most of ejecta being piled elsewhere. (A small percent of the ejecta is blown off the moon, with some of it re-accreting later). See Fig. 1 for further discussion.

Fig. 1. Lunar isochron diagram showing crater SFD for specified ages. Solid line show the saturation equilibrium curve, which tends to oscillate between dashed lines on either side. Heavy dotted line shows SFD for 2 x saturation. Numbers (“%”) show cumulative % of area covered by craters of specified $D$. As discussed in the text, this figure suggests that at twice the saturation level, megaregolith pulverization would reach depths of a few km to 20 km.
Certain parameters in the above discussion could be investigated in more detail, but precise information in some areas is not precisely known. In any case, we believe this system gives at least a first-order crude estimate of the average depth of megaregolith.

We also note that that this “average” result does not apply everywhere. For example enormous basins have been excavated here and there, while a few regions still escape overlap. For this reason, the megaregolith will be quite heterogeneous. For example the Imbrium basin, one of the last large impacts (~3.9 Ma ago) will have excavated and scattered the preexisting megaregolith from that are, creating a region of relatively shallow access to the primordial crust, under the layer of more lavas. Hence, as pointed out in [5], a crater like Copernicus, in the Imbrium area, probably ejected significant fragments of primordial crust.

Fig. 1 shows that by the time the total number of impacts reaches twice the number needed to reach the saturation equilibrium level, craters of D>4 km cover 200% of the area of the moon, and a megaregolith of a few to 20 km depth could have been reached. The quantitative results of [4], however, indicate that by 4.0 Ga ago, much higher crater densities, perhaps 10 x saturation, were reached. For more detail, see [6].

Conclusions. Our work suggests (1) the magma ocean solidified under intense bombardment. (2) This assures complex structure in magma-ocean layers, consistent with [8]. (3) Tens of kilometers of megaregolith formed. (4). The megaregolith is heterogeneous with “thin spots” where late basins such as Imbrium. (5). The thin spots allow large, recent impact craters, such as Copernicus, to access upper crustal layers and eject samples of the early crust, as found in the Apollo collections. (6). Because of the intense early cratering, the earliest multi-ring basins, such as South Polar Aiken and perhaps a giant Procellarum basin, have been badly degraded by hundreds of million years of subsequent large impacts. (7). Because impact melt lenses beneath even the largest surface impacts formed mostly in the upper (10? 20?) kilometers, most of the early impact melt lenses were intensely pulverized with remaining fragments mostly embedded in breccias, as observed. (8). Thus, the evolution of megaregolith is a critical factor in the nature of the rock samples found on the lunar surface today. (9). This is an effect under-appreciated in the dominant post-Apollo interpretations of lunar samples, until perhaps the early 2000s.

Connections with other new work. In addition to [5] and [6], similar results are being developed by recent authors. Wiggins et al. (2019, [7] modeled details of impact mechanics and state that “…impactors from 1 to 10 km in diameter can efficiently fragment the entire lunar crust to depths of ~20 km, implying that much of the modern day megaregolith can be created by single impacts rather than by multiple large impact events.” This suggests fragmentation to depths far below the depth, d, that we assumed for ejected material, although the penetration of bedrock fractures below craters is no doubt larger than the depth of excavation. We note, in addition, that the entire SFD crater diameter range must be considered to get an accurate picture of megaregolith evolution.

Richardson and Abramov (2020, [8]) also modeled megaregolith dividing it into three roughly defined layers: (1) Surface (loose fines and fragments), (2) upper megaregolith (mostly ejecta deposits of depositional breccias and melts, ~ 5 km deep) and (3) lower megaregolith fractured coherent layers at the base (~20 to ~25 km deep). The results similar to [5] and our results in [6].

Taken together, all these results from impact crater studies suggest new appreciation of megaregolith evolution and new progress in interpretation of rock samples from throughout the solar system.

[6] Hartmann, W. K. and Mordidelli, A. Submitted to MAPS, reviewed, and being revised.