THE ABUNDANCE OF ROCKS ON THE LUNAR MARIA IS NOT A FUNCTION OF SURFACE AGE.

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Introduction: The Moon's surface is covered by a regolith that is developed as meteorites bombard the lunar surface, forming a poorly sorted layer of fragmental debris. New rocks are excavated and thrown onto the surface when an impactor of a large enough size and high enough velocity penetrates the regolith, reaching the underlying competent material. As the regolith thickens, the smaller impacts are confined within the regolith, leaving only larger impactors able to excavate rocks [1]. Remote sensing studies of the local variations in the abundance of rocks on the lunar surface can illuminate our understanding of the thickness of the regolith [e.g., 2].

Older surfaces are expected to have thicker regolith, therefore there would be fewer rocks exposed. We can test this notion by measuring the abundance of rocks as a function of time. The mare offers a uniquely wide range of well-dated volcanic deposits. Hiesinger et al. [3, 4, 5] constrained the ages of mare units using crater counting techniques and found ages ranging from 1.2-4.2 Gyr [6]. Older surfaces should theoretically have fewer rocks exposed as the regolith is more developed. The mare's wide range of surface ages offers the ability to control the relationship between regolith development and the abundance of rocks in a crater's ejecta blanket. We report on each dated surface's productivity in exposing rocks as a function of impactor size using crater size-frequency distributions.

Site Selection: This study features rocky crater counts of 15 lunar mare sites. These sites overlap with Hiesinger et al. counted areas [3, 4, 5] but are larger to collect adequate statistics on rocky craters that are less abundant than the total population. Counted areas range in size from 3,200 - 3,700 km^2. Sites include seven locations within Oceanus Procellarum, two in Mare Imbrium, two in Mare Nubium, one in Mare Serenitatis, one in Mare Humorum, and two in Mare Tranquillitatis.

Data: We use shaded relief imagery generated from the merged LOLA/Terrain camera DEM data set for the crater counting [7] and rock abundance or "rockiness" is quantified using thermal inertia data from LRO Diviner following Bandfield et al., 2011 [8]. From the rock abundance parameter, we can then determine how crater size-frequency distributions vary with degree of rockiness.

Methods: The CraterTools plug-in for ArcMap [9] was used to count craters, all of which are greater than 200 m in diameter to ensure penetration to bedrock. Secondary impact craters were included in the crater counts to capture the entirety of the crater population. CraterPy [10] was used to extract rock abundance statistics from the crater ejecta, which is defined from 1.1 to 2 crater radii. The average rock abundance of the ejecta was used to develop rock abundance binning for the crater size-frequency distributions. The bins are defined by 1% increments of rock abundance. A crater is added to every bin where its ejecta rock abundance is greater than or equal to that bin.

Results: A qualitative inspection of the data revealed that Mare Humorum is the rockiest of the study areas. To compare among mare sites, we define a rocky crater as having the minimum rock abundance of the top 10% of rocky craters in Mare Humorum: 2.9% coverage of rocks. Applying the 2.9% rock abundance cutoff value to all other sites (Figure 1), we find that Humorum has the rockiest craters, followed by two sites in Procellarum, and a scattered, but low distribution throughout the rest of the lunar sites. Further, Figure 1 also shows that there is a weak correlation between age and rockiness with a correlation value (r) of 0.22.

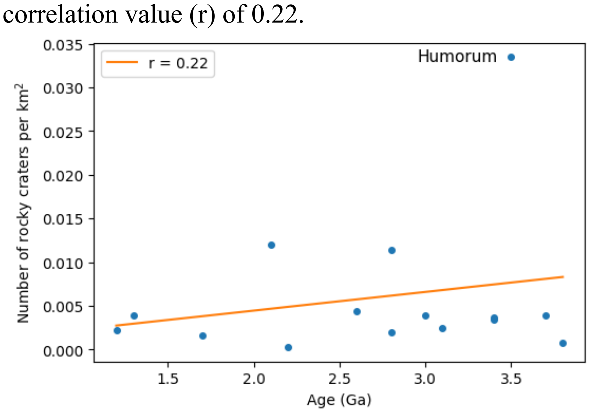

Figure 1: The relationship between mare surface ages and the number of craters with greater than 2.9% rock abundance in their ejecta.

We computed size-frequency distributions for each site's total population and the various degrees of rock abundance. Humorum, for example, encompasses a wide range of ejecta rock abundance. Figure 2 shows the various phases of the relationship between crater size and rock abundance. Larger craters are generally more rocky than smaller craters at this site, which results in a "pinching" appearance of the size-frequency distribution. Essentially, the converging behavior indicates that at a certain diameter and above all craters have high rock concentrations. At a certain level of rock abundance and above, the size-frequency distributions begin to show a parallel behavior.

The crater size-frequency distribution for Mare Imbrium (Figure 3) features the parallel behavior throughout all levels of rock abundance. There is a wide gap between the size-frequency distributions at each step. The rockiest craters at this site are a size-representative subset of the total crater population.

All counted sites exhibit variable behavior in their size-frequency distributions. Some sites show strong departures from the slope of the total population as rock abundance cutoffs are increased, and others show the parallel slope behavior with increasing rock abundance.

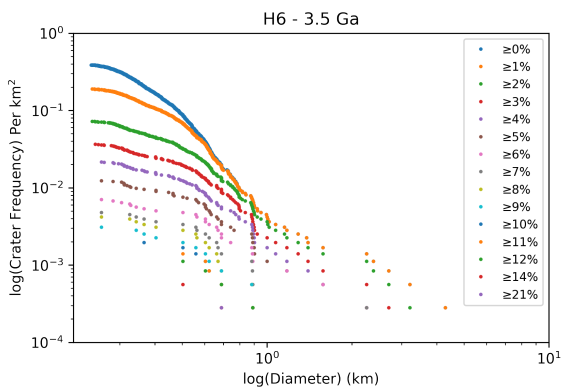

Figure 2: Size-frequency distribution of craters at Mare Humorum increasing in rockiness.

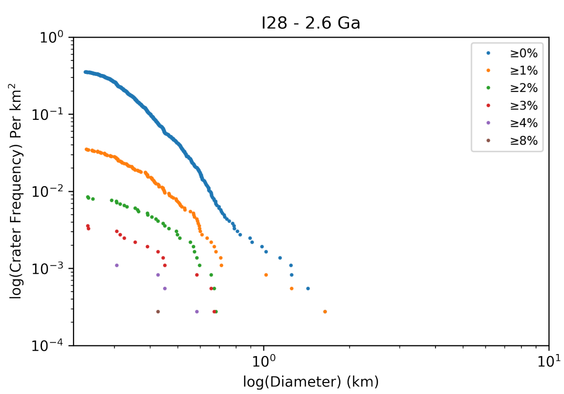

Figure 3: Size-frequency distribution of craters at Mare Imbrium increasing in rockiness.

Discussion: Our original notion was that the abundance of rocks in the ejecta has a relationship with age. The distribution of ejecta rocks shows that there is a poor correlation between age and rock abundance (Figure 1). When we exclude the outlier, Humorum, we find that whatever weak correlation exists between rock abundance and age disappears. Some sites are much more rocky than others with no clear control by age, so there may be other limiting factors in a surface's ability to expose rocks and retain them on its surface. Perhaps, mechanical properties of these mare units were developed upon emplacement as proposed by Head & Wilson, 2020 [11]. Properties such as vesicularity, crystallinity, density, among others, may influence an impactor's ability to break up and eject rock beneath the regolith. These protolith features may be responsible for the anomalously rocky surface of Humorum. The regolith itself may have local variability in thickness causing smaller impactors to exhume powdery regolith rather than the competent basalts buried deep.

The varying degrees in pinching of the size-frequency distributions (Figures 2 and 3) may illuminate local variations in regolith thickness. These distributions are uniquely sensitive to rockiness as a function of size, so for variable regolith thicknesses, we would indiscriminately lose craters of all sizes with increasing rock abundance. The more irregular the contact between regolith and underlying mare basalts, the more small craters will have the ability to excavate rock. This behavior is shown in the more parallel size-frequency distributions (Figure 3). In the case of the converging size-frequency distributions (Figure 2), the slope shallows with increasing rock abundance. Thus, the pinching behavior is indicative of a loss of small craters. As the pinching behavior starts to exhibit more parallel characteristics, the size-representative population of rocky craters indicates that the regolith is somewhat irregularly thick. In summary, the parallel behavior is indicative of a highly irregular regolith thickness compared to size-frequency distributions featuring a pinching behavior.

We have determined that rocks on the lunar surface are not dependent on the surface's age but may be due to the nature of the regolith and underlying mare basalts. To probe the thickness of the regolith and the competence of mare basalts, we can examine the behavior of crater size-frequency distributions. Therefore, this tool may be used to explore the complexities of the lunar subsurface.

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