# THE SIZE-FREQUENCY DISTRIBUTION OF ROCKY CRATERS AT THE CHANG'E 5 LANDING SITE: ROCK ABUNDANCE AS A PROBE FOR MECHANICAL PROPERTIES OF REGOLITH.

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**Introduction:** The lunar regolith is formed by the bombardment of micrometeorites that pulverize the lunar surface forming a poorly sorted layer of fragmental debris. Regions of thinner regolith on the Moon are naturally rockier because smaller impactors are able to penetrate the regolith and excavate bedrock.

The large age differences among mare units offers a controlled opportunity for understanding the effect of impact exposure on the rockiness of the surface owing to the similarity of the substrate. In this study, we take advantage of the very young mare surface of the Chang'e 5 (CE-5) landing site to compare mare regions widely differing in impact exposure [1, 2]. Crater counts at this site suggest this surface has undergone ~2.5-4 times less impact exposure than typical 3.5 Ga mare surfaces [1]. The comparison between young and old sites allows us to control for the mechanical properties of the regolith.

In this work we report on analysis of size-frequency distributions of craters with rocky ejecta collected from the CE-5 landing site and Mare Humorum. Our analysis features these controls: 1) substrate is limited to a single type (mare), 2) the regolith is thin enough such that all impactors in the study area penetrate to bedrock and have the capability of ejecting rocks, and 3) the surfaces differ widely in reported impact exposure time.

**Chang'e 5 Landing Site and Mare Humorum:** The first study area is in the northeast region of Oceanus Procellarum, which includes the CE-5 landing site (centered on 42.795N, 52.095W) and the second study area is in Mare Humorum (centered on 22.812S, 40.166W). Each study site is 60x60 km (3600 km$^2$). The model age of this region of Mare Humorum was reported to be 3.45 Ga [1] and the CE-5 site was estimated to be 1.21-2.07 Ga [3-7] with some regional locations up to 3.33 Ga [8].

**Data:** We use shaded relief imagery generated from the merged LOLA/Terrain camera DEM data set for the crater counting [9] and rock abundance or "rockiness" is quantified using thermal inertia data from LRO Diviner following Bandfield et al. (2011) [10]. From the rock abundance parameter we can then determine how crater size-frequency distributions vary with degree of rockiness.

**Methods:** All craters counted are larger than 200m in diameter, which ensures the impactor penetrated to bedrock. Secondaries are included in the counts to capture the entire crater population, as this study is not intended to determine absolute model ages for the CE-5 study area. Rock abundance is quantified as the average values of the ejecta from the crater rim to one crater radius from the rim. Crater size-frequency distributions are measured for the total crater population in each study area, and also each of 10 percentiles of ejecta rock abundance. To more directly compare the CE-5 study area to Mare Humorum, 90th percentile parameter minima for Humorum are applied to the CE-5 crater size-frequency distributions.

**Results:** We computed log-space histograms for rock abundance distributions (Figure 1). This parameter exhibits a roughly log-normal distribution at both sites, but is slightly skewed to higher values. For CE-5, the rock abundance distribution peaks at -2.35 (0.46% rock abundance) and has a full width at half maximum (FWHM) of 0.4. Rock abundance at Humorum peaks at -2.15 (0.71% rock abundance), but is broader, with a FWHM of 0.7.

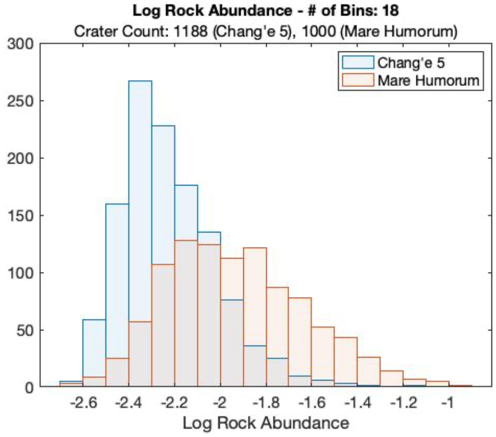

*Figure 1: Log histogram of CE-5 and Humorum ejecta rock abundance distribution.*

100 rocky ejecta craters, ranging from 3-13% rock abundance, comprise the 90th percentile rock abundance class at Humorum. Applying this range of values found for the Humorum's 90th percentile to the CE-5 craters, 6 craters are within the Humorum 90th percentile cutoff for rock abundance.

We computed crater size-frequency distributions (CFD) for both sites' total crater populations and the various percentiles. Slopes for the total population CFDs were -3.9 for both sites. The rock abundance CFD of the 90th percentile of Humorum (rocky CFD) shows a shallower slope than the total population CFD for both the Humorum and CE-5 (Figure 2).

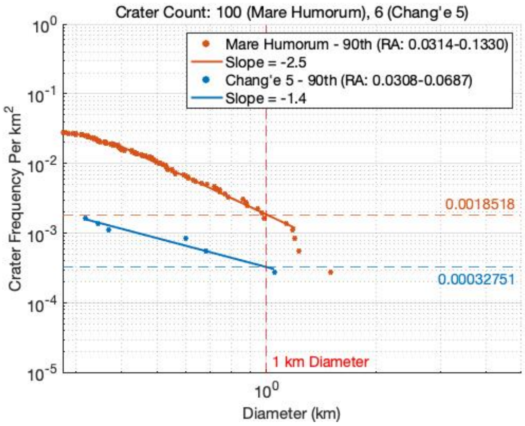

*Figure 2: CFD of rocky craters for the Mare Humorum study site. Minima from Humorum were applied to the CE-5 craters, with just 6 craters within range. N(D=1) plotted in dashed lines.*

Given the variability of reported ages in the region around the CE-5 site (ranging 1.21-3.33 Ga [3-8]), individual quadrants (900 km$^2$) within the study area were assessed to provide better spatial resolution and detect heterogeneity (Figure 3). We found variations in N(1)s between the quadrants as suspected.

Slopes for the total population CFDs average -3.92 among quadrants, but are somewhat inconsistent, differing by 0.02-0.59. Slopes for the rocky CFDs average -2.20 and are more consistent across quadrants, differing by 0.03-0.26. The slopes of the rocky CFDs are always shallower than those of the total population CFDs.

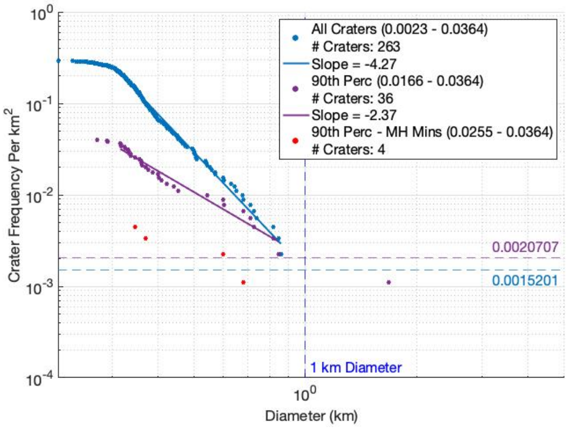

*Figure 3: Example of a quadrant CFD using NW quadrant of CE-5. In blue is the total crater population of CE-5 with a steep slope of -4.27. In purple is the 90$^{th}$ percentile of rocky craters in the CE-5 study area. And in red is the 90$^{th}$ percentile of rocky craters using Humorum minima for the CE-5 study area. N(D=1) plotted in dashed lines.*

**Discussion:** Impacts on the older Humorum surface are much more productive in excavating rocks than the younger CE-5 surface. We offer two hypotheses to explain this: The original mare surfaces may have developed different mechanical properties during emplacement [11]; or the somewhat older surfaces are more fragmented making it easier to expel rocks.

Further, Figure 2 and Figure 3 show consistent differences between the rocky CFD and the total population CFD. As expected, the total population CFDs exhibit a steep slope consistent with the inclusion of secondaries [12-14]. The rocky CFDs have shallower slopes, that could indicate that secondary impacts, being less energetic, are less effective at producing craters with rocky ejecta. However, the slopes are even shallower than expected for a primary cratering population [15].

All impactors included in this study are expected to excavate bedrock as counted crater diameters are 200m at minimum, which should penetrate nominal regolith depths of ~5 m [16]. However, our findings show that small impacts excavate rock less frequently or lose their rocks more efficiently. This phenomena may be the effect of irregular bedrock that results in variable regolith depth, leading to locally thick patches of regolith [e.g. 17]. Some small impactors will land in anomalously thick regolith and therefore not excavate rock. It is also possible that the small rocks excavated by small impacts are degraded faster than the large rocks excavated by large impacts (which must first become small rocks before becoming regolith) [18]. Additionally, the mechanical properties of substrate play an important role in whether smaller impactors are able to excavate rocks and immature materials.

**References:** [1] Hiesinger et al. (2000), *JGR*, 105(E12)., [2] Qian, Xiao, & Head et al. (2021), *EPSL*, 555, 116702., [3] Hiesinger et al. (2003), *JGR*, 108(E7)., [4] Hiesinger et al. (2011), *GSA Spec. Prs.*, 477, 1-51. [5] Morota et al. (2011), *EPSL*, 302, 255-266., [6] Jia et al. (2020), *EPSL*, 541, 116272., [7] Wu et al. (2018), *JGR*, 123(E12)., [8] Giguere et al. (2020), *LPSC 51*, #2356., [9] Barker et al. (2016), *Icarus*, 273, 346-355., [10] Bandfield et al. (2011), *JGR*, 116(E12)., [11] Head & Wilson (2020), *Geophys. Res. Letters*, 47(20)., [12] McEwen et al. (2005), *Icarus*, 176(2)., [13] McEwen & Bierhaus (2006)., *Ann. Rev. EPS*, 34(1)., [14] Bierhaus et al. (2018), *Meteoritics &Planetary Science*, 53(4)., [15] Brown et al. (2002), *Nature*, 420(6913). [16] McKay et al. (1991), *In Lunar Source-Book*, pp. 285-356., [17] Elder et al. (2019). *Journal of Geophysical Research: Planets*, *124*(12), 3373-3384. [18] Basilevsky, et al. (2015). *Planetary and Space Science*, *117*, 312-328.