GLOBAL LUNAR REGOLITH DEPTHS REVEALED

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Introduction: Here we examine global lunar regolith depth averages in order to obtain a global understanding of the development of the lunar regolith.

We examine the lunar subsurface as revealed by no-cost, subsurface probes: naturally formed impact craters. Impacts into a surface with a weak layer (regolith) overlying a strong layer (substrate) produce unique crater morphologies that correlate well with the depth of the weak layer ([1, 2], see also Fig. 1). Impact caters both create and reveal the regolith layer.

Knowledge of the regolith depth informs us as to the possible source depth of surface rocks, and hence allows more accurate interpretation of the lunar surface observed via remote sensing. Knowledge of the lunar regolith depth is also important to learning about the impact cratering process. Bart and Melosh [3] found that a layer of regolith covering the lunar surface results in a portion of the high-velocity ejection phase occurring in the fine-grained regolith, reducing the population of large blocks available for ejection at high velocities. Bart and Melosh [4] also showed that the number of boulders ejected from an impact crater does not correlate with regolith depth.

Crater Morphology Method: To determine regolith depth, we used the results of the study by Quaide and Oberbeck [1]. A series of experimental impacts into both uniform targets and layered targets showed that the morphology of the experimental craters was correlated with the depth of regolith in which they formed. They found that the thickness of the regolith was given by $thickness = (k - D_F/D_A)D_A \tan(\alpha)/2$, where k is an empirically determined constant (0.86) and α is the angle of repose of the material (31°). By measuring D_F and D_A values for many lunar craters, we are able to calculate the regolith depth in each crater's location.

This technique requires meter-scale resolution of small craters for identification of the specific morphologies that indicate regolith depth. The new *Lunar Reconnaissance Orbiter* (LRO) Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) data suits this task, providing images at 50 cm/pixel across the lunar globe.

We examined 143 LROC images and measured the regolith depth as revealed by 10,663 individual craters from 5.2 m to 271.6 m in diameter. The latitudes of the craters studied range from 70.9°S to 60.0°N. Four examples of our measured craters are pictured in Fig. 1.

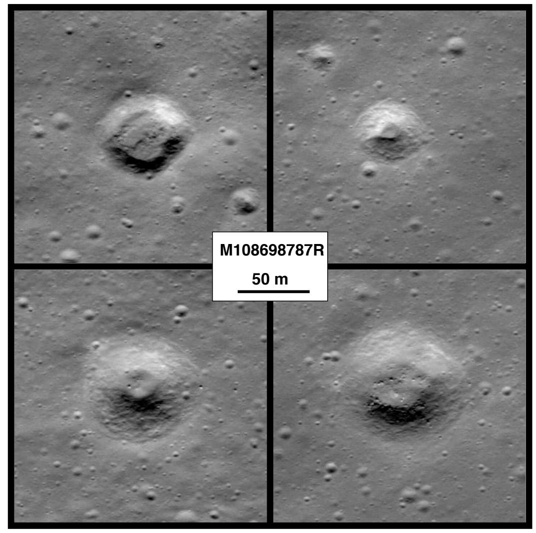

Figure 1: Examples of craters with distinct morphologies indicating impact into regolith. LROC NAC image M108698787R, 56.92°N, 80.63°E, in Mare Humboldtianum.

Regolith Depth Results: While individual measurements may be useful for interpreting local geologic landforms, the average regolith depth provides a regional picture of terrain evolution. Therefore we calculated the median regolith depth in each region. ([2] also examined the average regolith depth in the lunar regions they studied.) We group our 143 images into 30 different regions; 14 regions are located on the lunar nearside, and 16 regions are located on the lunar farside.

Fig. 2 presents our results. Median regolith depths are all less than 10 m, ranging ranging from 2.5 m in Mare Humorum to 8.7 m near the crater Landau on the farside. Fig. 2 also shows that the median regolith depths form a distinct pattern, with the thinnest regolith being located in the nearside maria, and most farside and higher latitude regions having thicker regolith.

Comparisons with other datasets: [2] estimated the regolith depths at 12 sites on the lunar equatorial nearside. Within our global survey of regolith depth, we carefully selected several regions near [2]'s 12 sites in order to compare our results.

[2] observed four characteristic regolith depths across their 12 sites: 3.3 m (which they designate type I), 4.6 m (type II), 7.5 m (type III), and 16 m

(type IV). Their thinnest regolith, type I, is located in the southern end of Oceanus Procellarum, near our data taken near the crater Letronne. We obtained a median regolith depth value of 2.9 m and [2] obtained a median value of 3.3 m. These values are in excellent agreement. Similarly, within Mare Tranquillitatis, we obtained a median value of 4.4 m, and [2] obtained a median value of 4.6 m (type II). These values are in excellent agreement.

Our data also concur with the lunar nearside regolith depth study of [5], who found that the southeastern nearside highlands have thicker regolith cover than the nearside mare. Their average highlands regolith thickness (12 m) is somewhat larger that what we found (6-8 m).

The recent study by [6] infers global regolith depths from the Chang-E 1 multi-channel microwave radiometer data. This study is the only other that examines regolith depth on the lunar farside. Similar to our results, they find mean regolith thickness of the maria is 5.3 m and the thickness of the highlands is 7.5 m.

We also compare our global results with the recent crater density map produced by [7, Fig.1B] from LRO Lunar Orbiter Laser Altimeter (LOLA) data. Because the regolith is generated over time by successive impacts, we expect areas of higher crater density to have deeper regolith. An overlay of our data with Fig.1B from [7] shows that our data are consistent with that idea.

Conclusions: We performed the first global survey of lunar regolith depths using Lunar Reconnaissance Orbiter Camera data and the crater morphology method for determining regolith depth. We find that on both the lunar farside and in nearside, non-mare regions, the regolith depth is twice as deep as it is within the lunar maria. We find that median regolith depths in the mare regions are typically 2-4 m, whereas median regolith depths on the farside and non-mare nearside areas are typically 6-8 m.

Our data compares favorably with the results of previous studies. We also find that regolith depth correlates well with density of large craters (>500 m diameter). This result is consistent with the gradual formation of regolith by rock fracture during impact events.

Understanding the current state of the lunar regolith is important for understanding the context and history of collected samples, as well as understanding of the impact history of the Moon and its connection to the formation of the regolith. Furthermore, knowing the depth of the regolith is important for both NASA's exploration mission, both in terms of designing exploration infrastructure and as context for samples collected by astronauts.

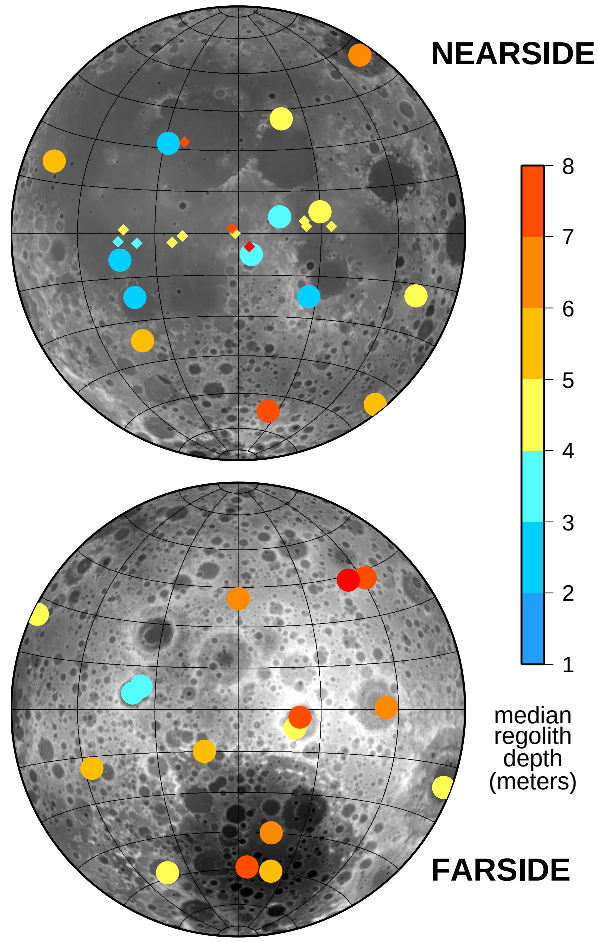

Figure 2: Plot of median regolith depth in meters for each region studied. Background grayscale indicates LOLA topography; lighter tones indicate higher terrain. Nearside mare regions have generally thinner regolith than other areas. The small diamonds are [2]'s results, many of which agree quite favorably with our results in that region.

References: [1] W. L. Quaide, et al. (1968) *J Geophys Res* 73(16):5247. [2] V. R. Oberbeck, et al. (1968) *Icarus* 9:446. [3] G. D. Bart, et al. (2010) *Journal of Geophysical Research (Planets)* 115:E08004 . [4] G. Bart, et al. (2010) *Icarus* 209:337 . [5] Y. G. Shkuratov, et al. (2001) *Icarus* 149:329 . [6] W. Fa, et al. (2010) *Icarus* 207:605 . [7] J. W. Head, et al. (2010) *Science* 329:1504 .