The Variance of Regolith Depth in the Lunar Highlands Versus the Maria in the Mare Crisium

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Abstract:

Regolith is the unconsolidated fine-grained substrate that covers the lunar surface. Regolith depth is important because it is related to the geologic history of the lunar surface. Below regolith, there is rock. The main process currently altering the lunar surface is impact cratering: the process of impacts forming craters in the lunar surface. Cold spot craters are a relatively newly discovered category of craters, which are distinguished by their relatively young ages and the low thermal inertia (low night-time temperatures) material surrounding the craters. Utilizing the mapping software ArcGis, we were able to record data with unparalleled accuracy.

In the past, research has been done using crater sizes to determine regolith depth, but the use of cold spot craters is relatively new. Cold spot craters' young age leads to crater ejecta that has not yet been homogenized, allowing for inspection of blocks around craters. By comparing the size of craters that did and did not excavate blocks, regolith depth can be estimated. We found that the highlands surrounding Mare Crisium had significantly deeper regolith than Maria Crisium itself through the use of this relationship. Due to this difference in regolith depth, the Maria's surface is significantly rockier than the highlands due to a higher frequency of craters excavating blocks. This is consistent with the more recent volcanic resurfacing of the maria. These findings help endorse the use of cold spot craters in future research.

Introduction:

In 1897, Merrill defined regolith for the first time and stated "In places this covering is made up of material originating through rock-weathering or plant growth in situ. In other instances, it is of fragmental and more or less decomposed matter drifted by wind, water or ice from other sources. This entire mantle of unconsolidated material, whatever its nature or origin, it is proposed to call the regolith." [Merrill, 1897] On the Moon, regolith has been defined as a layer of fragmental debris [Shoemaker et al. 1967]. It forms and evolves over a long period of time by a many individual events [Shoemaker et al. 1969]. Regolith thickness should directly correlate with crater abundance due to regolith being produced by impacts on the Moon. Because of this, regolith depth has been estimated by examining the size-frequency distribution of crater populations (Shoemaker, 1969). Another indicator of regolith depth is based on the occurrence or lack of blocks produced by an impact event. It was suggested by Rennilson et al. (1966) that regolith depth could be estimated from the depth of the smallest crater with a blocky rim. This is based off the assumption that an impact has to penetrate through the regolith in order to fracture a lower layer of a more coherent substrate into blocks. This method assumes that in general, there are small age differences (Rennilson, 1966). The blocky crater method looks at these craters with blocks, and has been used to figure out that regolith in an area with an age of 2.5 Gyr is roughly 8-31 meters in depth, which is similar to the 8-33 meters in depth estimated by the equilibrium diameter method for areas similar in age (Wilcox, 2005). Another method of estimating lunar regolith depth has been through the study of the morphology of craters with diameters of less than 250 meters. The morphology was shown to be dependent on the nature and depth of the substrate, and that strength boundaries control interior morphology [Oberbeck and Quade, 1967]. However, more recent work has shown that even a slight difference in strength between two layers of regolith is enough to result in this distinct morphology and bedrock is not required (Prieur et al., 2018; Wilcox et al., 2005).

Impactors are the initiator of transport of material on the Moon, as they are the main factor that affects the regolith. Small impacts generally only mix the top layer of lunar regolith, but larger impacts have the ability to excavate rock, depending on the thickness of the regolith at that location and the size of the impact. Crater rays, which are distal ejecta, cause substantial heterogeneity in surface materials [Huang et al., 2017]. Regolith depth is a key indicator of patterns in lunar evolution, and the depth varies throughout various areas of the Moon. Roughly the top ten centimeters of regolith is homogenized on a time scale of less than one billion years, which provides evidence for regolith formation being a relatively rapid process. Additionally, there is no observed difference in the general regolith thermal inertia between the maria and the highlands [Hayne et al., 2017].

Mare Crisium is located between 10° and 30° N and 50° and 70° E on the lunar nearside. The Mare Crisium basin contains three major basalt groups: the soils formed from a Fe- and Mg-rich high Ti basalt (Group I), a very low Ti ferrobasalt (Group II), and a low Ti ferrobasalt (Group III). Group I appears to be the oldest basalt. Group II basalts are primarily located in two regions: The Northeast edges (Group IIA) and the North-Northeast half of the basin (Group IIB). [Heisinger et al., 2011a]. Lunar mare basalts cover roughly 17% of the whole lunar surface [Head, 1977]. The ages of the surfaces in the Crisium basin range from 2.71-3.61 Gya [Heisinger et al., 2011a]. The majority of volcanism on the Moon ended around 3.0 Gya [Haruyama et al., 2009, Hiesinger et al., 2011b], but some volcanism continued until ~1.2 bya [Hiesinger et al., 2011b].

Cold spot craters are a relatively newly identified class of craters, which are distinguished by their cold nighttime surface temperatures compared to surrounding material [Bandfield et al., 2014]. Cold spot craters are one of the only variations in the lunar surface’s thermophysical properties, as they are relatively uniform throughout the rest of the surface [Hayne et al., 2017].

These cold spots can be used as markers to identify the most recent impacts on the lunar surface [Williams et al., 2018].

Methods:

The H-Parameter is extremely important in locating cold spot craters. It defines a diurnal night-time cooling curve, which allows for easier to spot visuals of a cold spot crater. The H-Parameter determines the increase of density and thermal conductivity with depth. Larger H-Parameter values corresponds to a lower thermal inertia of material in the top ~10 cm, and smaller values correspond to denser material with higher thermal inertias. Regolith H-Parameter and thermal inertia correlate with rock abundance because small rocks are frequently in high concentrations near larger rocks and reradiation from rocks may cause differences in nighttime regolith temperatures, specifically in rocky regions. The H-parameter can be used to describe the temperature independent depth-profiles of thermophysical properties [Hayne, 2017].

For data collection, we used Arizona State University's Lunar Reconnaissance Orbiter (LRO) Camera (LROC) Quickmap of the Moon. We used cold spot craters exclusively, because they formed recently and blocks have not had time to break down or become buried. The data collected about each crater includes its coordinates, diameter, number of rocks, image resolution, incidence angle, and Narrow Angle Camera (NAC) image used. All cold spot craters examined were already discovered to be cold spot craters (Williams et al. (2018). Since previous coordinates were often approximate and the craters are small compared to the cold-spot surrounding them, we first needed to determine which crater was the source of the cold-spot. One of the primary methods used was the H-parameter map. The H-parameter quantifies the increase of density and thermal conductivity with depth [Hayne et al., 2017], so low thermal inertia cold-spot craters are easily visible as regions of high H-parameter (Figure 1). The H-parameter information was obtained by the LRO Diviner Lunar Radiometer Experiment (Diviner).

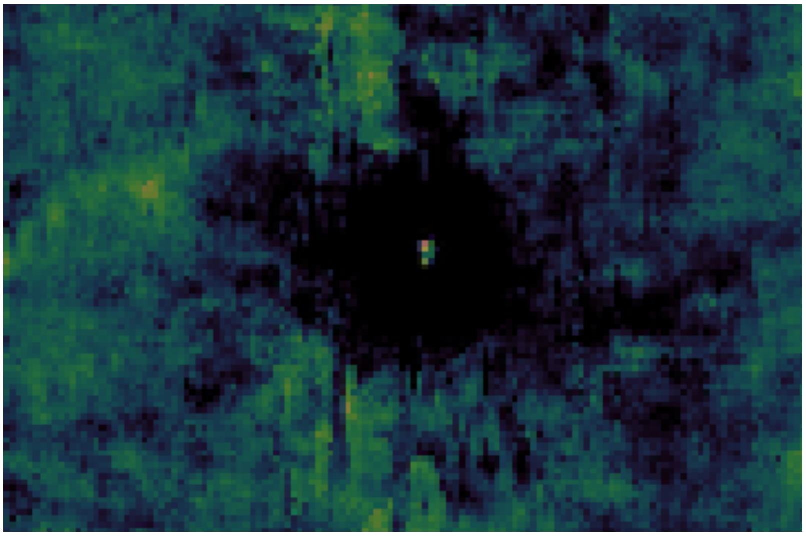


Figure 1: The H-Parameter map of a cold spot crater.

To confirm that we had identified the correct crater, we used NAC images with low incidence angles to look at ejecta patterns. Very young impact craters have distinctive ejecta patterns that fade quickly. Additionally, we recalculated the diameter to confirm previous findings. In order to do this, we used Quickmap to measure three or more diameters across the crater, and the point at the intersection of these three lines was used as the coordinates of the crater center. To recalculate the diameter, we calculated the average of the transects. We then searched for rocks by closely inspecting the area around the crater at different incidence angles. By using different incidence angles, we were able to ensure that the inspected rocks were indeed rocks. The smallest size for a rock was defined as two bright pixels and four dark pixels, which would mean an approximately one-meter wide rock. The shadows of rocks face in the opposite direction of the craters, showing a protrusion rather than indentation. After inspecting a crater, the NAC image was recorded, which also gave information about the incidence angle and image resolution of that image, which were kept for records.

After the initial search for cold spot craters using LROC Quickmap, we used the mapping software ArcGis 10.6 and reprocessed all of the images to have the same resolutions in order to keep the definition of what qualifies as a rock standardized. We utilized two add-ons: Crater Helper Tools and Crater Tools. For each crater, we inserted the image into a blank template, then set the spatial reference to lunar sinusoidal, allowing for the software to adjust to the flattening effect of a 2D image. We created a new shapefile on top of the crater image layer, where we recorded crater diameter and position, and then also the dimensions and number of boulders surrounding the craters. The recorded data was exported as text tables.

Once all data was collected, we divided the craters into the two different groups of craters: craters located in the maria, and craters located in the highlands. The map shape file defining the boundary between the maria and the highlands were made by Nelson et al. (2014) based on the LROC Wide Angle Camera (WAC) and Clemintine image data. Next we created two percentage bar charts for the maria and lunar highlands in order to display the differences between various crater sizes and the number of blocks excavated by craters of different sizes. This relationship was used in order to determine the smallest crater which did not excavate any rocks. The chart design is similar to those used in Wilcox et al. (2005). I used the language of Octave (open source version of MATLAB) and the Octave Forge Mapping package to conduct this analysis.

The transient crater scaling law is being used, where the diameter is multiplied by 0.084 to determine excavation depth [Melosh, 1989]. This will allow for the calculation of regolith depth to compare the maria and highlands of Mare Crisium.

Figure 2

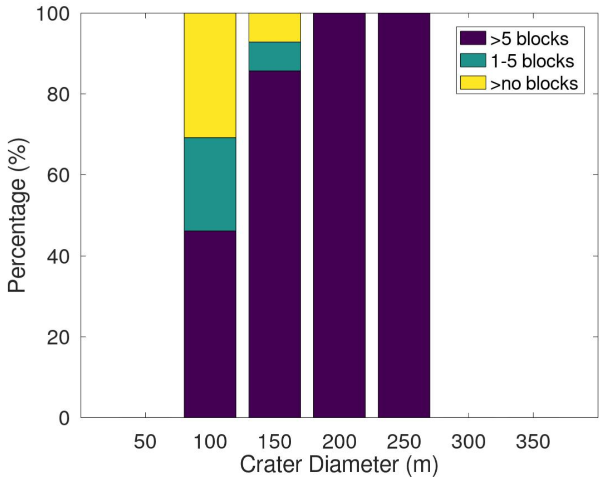
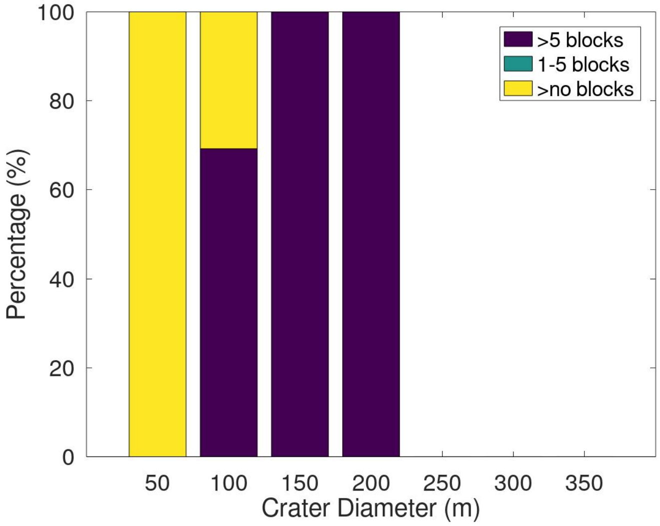


Figure 3



Results and Discussion:

We looked at 76 cold spot craters in the lunar maria and the lunar highlands, with a relatively even distribution of craters in each. Figures 2 and 3 display the number of blocks excavated by various crater diameters in the highlands and maria respectively. The reasoning for there to be a category between one to five blocks is because when there are not over five blocks, there is a sense of uncertainty whether the crater excavated the blocks. Each number in the x-axis label represents the craters of that diameter ± 25 meters. In the highlands (Figure 2), 44% of craters between 75 and 125 m in diameter excavated more than 5 blocks, while in the maria (Figure 3) roughly 67% of the craters between 75 and 125 m in diameter excavated more than 5 blocks, which suggests that the regolith is less than 10.5 m thick in 67% of Mare Crisium. Roughly 85% of craters between 125 m and 175 m in diameter in the highlands excavated more than 5 blocks, while in the maria, this crater size excavated more than 5 blocks 100% of the time. In the maria all craters larger than 125 m in diameter excavated over 5 blocks 100% of the time. This suggests that the regolith is less than 10.5 m thick everywhere in maria crisium. In the highlands, roughly 10% of craters between 125 m and 175 m in diameter excavated no rocks, which suggests that the regolith could be up to 14.7 m deep in some places. Overall, the data shows that more blocks are excavated by smaller impact craters in the maria than the highlands, which is consistent with a thicker regolith layer in the highlands.

Using the information from the data analysis, we are able to determine the depth of the regolith in both regions. Cold spot craters are transient craters and relatively newly formed, rather than the final crater diameter. The excavation of blocks is important, as by using that factor, we are able to determine how deep the regolith is. The regolith depth of the highlands ranged from roughly 7.98 meters to 11.5 meters. The regolith depth of the Maria is roughly 6.80 meters to 8.48 meters. The smallest crater to excavate rock in the highlands had a diameter of 95 meters, and the largest crater to not excavate rock in this region had a diameter of 137 meters. The smallest crater to excavate rock in the maria had a diameter of 81 meters, and the largest crater to not excavate rock in this region had a diameter of 101 meters.

Conclusion:

Regolith in the highlands is deeper than the regolith in Mare Crisium. The difference in depth is roughly between 0.50 meters to 4.70 meters. This is important because it reveals that Mare Crisium is more likely to have a less rocky surface than the highlands. Since impact cratering is essentially the only method of regolith transport currently, this displays that the maria subsurface will be significantly rockier as it requires relatively smaller impacts to excavate rocks. This means that a smaller crater is more likely to excavate blocks in the maria than if it impacted in the highlands. And vice versa, a larger crater is less likely to excavate blocks in the highlands than if it impacted in the maria. By the increased frequency of excavation in the maria, it is much more likely that the surface is much less homogenous than that of the highlands. Cold spot craters were used because since they are young relative to the geologic history of the Moon, their ejecta blankets have not yet been homogenized. For future research, cold spot craters could be important in identifying spatial variability in the rockiness of the lunar subsurface and understanding the geologic history of the Moon.

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