REGOLITH DEPTH ESTIMATIONS AROUND RADAR-DARK HALO CRATERS ON THE MOON. A. D. Thaker[1, 2] and C. D. Neish[1, 2], [1]Institute for Earth & Space Exploration, The University of Western Ontario, London, Canada. [2]Department of Earth Sciences, The University of Western Ontario, London, Canada. Email: athaker@uwo.ca

Introduction: The lunar regolith is a layer of unconsolidated material that covers the majority of the lunar surface. The physical properties of the regolith play a major role in understanding many aspects of lunar geology, including its history and evolution over time. Previous studies suggest that the regolith consistency varies spatially as well as vertically, becoming coarser at greater depths [1]. Moreover, impact craters on the Moon are largely responsible for creating and revealing this regolith layer [2].

Our aim in this work is to understand the properties of regolith around some unique impact craters on the Moon. These radar-dark halo craters (RDHCs) are surrounded by distinctive, ring-shaped structures, having unusually low radar return (Fig. 1). In addition to their darker appearance in radar images, these haloes also represent regions of low surface roughness estimates (low circular polarization ratio-CPR). Previous studies have hypothesized that these haloes are extended ejecta layers depleted in decimeter- to meter-scale blocks causing low radar returns and low CPR [3].

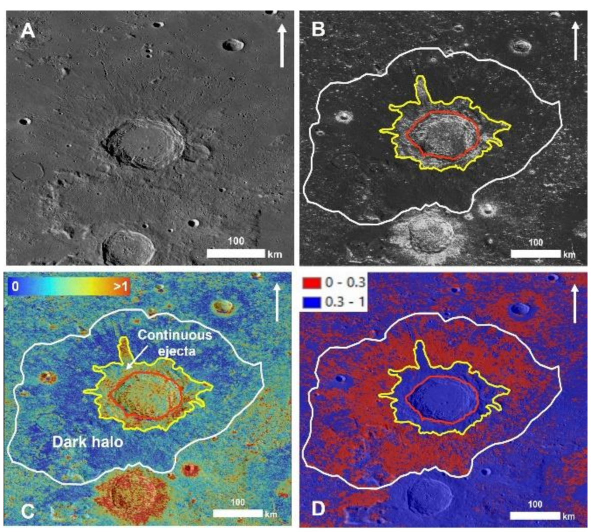

Fig 1: (A) LROC-WAC image, (B) Earth-based, P-band OC image, (C) Earth-based P-band CPR image, and (D) CPR threshold map of Aristoteles crater.

This study focuses on improving our understanding of the local regolith thickness around the RDHCs, and by extension, the physical properties of these unusual regions. Additionally, we compare the regolith thickness estimates for the radar-dark halo craters with "normal" craters without distinct dark haloes to check for any observable differences.

To measure the regolith thickness around these RDHCs, we use the morphology of small craters (D ~ 10-200 m) located there. Depending on the characteristics of the surface in which an impact occurs, different morphological features are formed. For instance, impacts that occur in a cohesive, uniform surface yield round, bowl-shaped craters [4]. Conversely, impacts that form in a less-cohesive, fragmented layer (i.e., regolith) overlying a coherent substrate, produce unique morphological features such as central mounds, concentric rings and flat-bottom floors (Fig. 2) [2, 4].

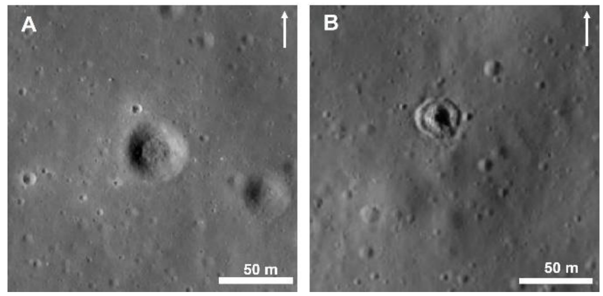

Fig 2: (A) Flat-bottom crater (NAC image M150667294LC) and (B) concentric crater (NAC image M1154350431LC) located in the continuous ejecta of Copernicus crater (an RDHC).

Previous studies have used the dimensions of such craters and their morphological features to estimate the global lunar regolith depth for mare and highland regions [2], as well as for Chang'E-5 landing site [5]. In our study, we focus on the local variations in the regolith depths, which may be helpful in better understanding the formation of the dark haloes.

Data and Methodology: To infer the depth of the regolith around these RDHCs, we measured small crater diameters and their internal feature (i.e. concentric rings, central mound, flat floor) diameters. This method is based on the finding that the ratio of the rim-to-rim diameter of the crater (D_A) to the diameter of the interior feature (D_F) is a function of the ratio of the crater diameter (D_A) to the regolith depth [2, 4, 5]. Hence, the depth can be calculated by using the following equation:

$$depth = (k - D_F/D_A) D_A \tan(\alpha)/2$$

Here, k is an empirically determined constant (0.86) and α is the angle of repose (~31°).

We use Lunar Reconnaissance Orbiter's (LRO) high resolution Narrow Angle Camera (NAC) images to study the parameters of these craters. We limit our NAC image selection to those with incidence angles between 71° and 45°, as the small craters are the most identifiable in this range. We use the LROC browsing interface *Quickmap* and the tools therein for our calculations. We measure the small crater morphological parameters from three different regions surrounding the RDHCs: (i) continuous ejecta around RDHCs, (ii) the dark haloes and (iii) a “typical” region beyond the halo for a reference value. We present our preliminary observations of two RDHCs - Aristoteles (50.2° N, 17.4° E) and Copernicus (9.62° N, 20.08° W) - and one normal crater - Piccolomini (29.7° S, 32.3° E) - in the next section.

Initial Observations: All the small craters observed during this study range in size from ~ 9m- 200m in diameter; however, the majority of them are around 35m-50m. Flat-bottom morphology is the most common for Aristoteles and Piccolomini, but concentric craters are the most common for Copernicus. It is important to note that any obviously secondary impact craters have been avoided in this study. Our overall observations for Aristoteles and Copernicus craters show greater regolith depth estimates for their dark halo regions compared to their continuous ejecta blankets. For Aristoteles, the estimated median regolith depths for the continuous ejecta and the dark halo are ~4.39 ± 0.29 m and ~6.87 ± 0.81 m respectively. Interestingly, the surrounding terrain has even higher regolith depth estimates (~12.22 ± 2.51 m), which might suggest that the regolith is thicker in the relatively undisturbed surrounding region. Similarly, for Copernicus crater the regolith depths are ~2.65 ± 0.15 m and ~4.05 ± 0.42 m respectively for continuous ejecta and the dark halo. Conversely, the ‘normal’ crater Piccolomini does not exhibit a noteworthy difference between its continuous (~4.19 ± 0.75 m) and discontinuous (~4.32 ± 0.51 m) ejecta estimates. Fig. 3 illustrates the distribution of regolith depths measured for the three craters and highlights the minimum, first quartile, median, third quartile, maximum and outlier values. With the exception of a few outliers, most of the values within each crater lie between 3 m and 15 m. The outlier estimates can be explained by the stochastic nature of the lunar regolith formation. As such, depending on the impact size variations, the nature of the regolith can vary even locally.

While our sample size is still quite small, it is intriguing that there is a noticeable difference in thickness between the regolith in the continuous ejecta and dark haloes for both Aristoteles and Copernicus, but none for Piccolomini. The increased regolith thickness estimations for the dark haloes indicate higher abundance of fine-grained, unconsolidated material in the area compared to the continuous ejecta blankets. We observe higher densities of small craters in the dark halo regions compared to the continuous ejecta layers of each crater. This observation compares favourably with a previous study indicating thinner regolith depths correlate with lower crater densities [2].

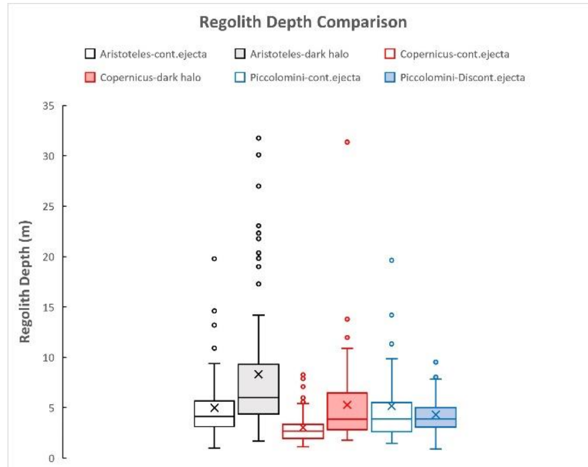

Fig 3: Regolith depth measurements in continuous ejecta and dark halo/discontinuous ejecta regions of all three craters

Our estimations for Copernicus crater also compare well with the average regolith thickness of the near side lunar mare regions (~2-4 m). However, it is interesting to note that despite being located on a mare boundary, Aristoteles shows regolith depths that are higher than the established mare average [2, 4]. Additionally, there are more small craters with unique morphologies surrounding Aristoteles (~2 craters/km^2) and Copernicus (~2 craters/km^2) than Piccolomini (~1 craters/km^2). However, our observations of Piccolomini’s discontinuous ejecta are somewhat limited due to the lack of NAC images in the desired incident angle range.

Future work: In the future, we plan to increase our sample size and expand this work for other known RDHCs. Additionally, we will compare our regolith thickness estimations of the RDHCs with additional ‘normal’ craters for further investigation. This work will provide further insight into the formation mechanism of radar-dark haloes.

References: [1] Shoemaker E. M. et al. (1969) *JGR, 74,* 6081. [2]] Bart G. D. et al. (2011) *Icarus, 215,* 485-490. [3] Ghent R. R. et al. (2005) *JGR, 110.* [4] Oberbeck V. R. and Quaide W. L. (1968) *Icarus, 9,* 446-465. [5] Yue Z. et al. (2019) *Icarus, 329,* 46-54.