

REGOLITH THICKNESS OVER THE APOLLO LANDING SITES FROM MORPHOLOGY OF SMALL FRESH IMPACT CRATERS. Wenzhe Fa^{1,2}, Tiantian Liu¹, Minggang Xie², and Jun Du¹, ¹Institute of Remote Sensing and Geographical Information System, School of Earth and Space Sciences, Peking University, Beijing 100871, China (wzfa@pku.edu.cn), ²State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China.

Introduction: During the six Apollo landing missions, active and passive seismic stations were established at the landing sites. The observed seismic signals are characterized by gradual beginning and extremely gradual decay, indicating the presence of a regolith layer that is highly heterogeneous and lowly absorptive. Regolith thicknesses at the Apollo 14, 16 and 17 landing sites were observed to be 8.5, 12.2 and 4.0 m from the active seismic experiments [1], and those at the Apollo 11, 12, and 15 landing sites were estimated to be 4.4, 3.7 and 4.4 m based on the shear-wave resonance in the regolith layer as observed with the passive seismic experiments [2]. These numbers are extensively cited and frequently used as benchmarks when comparing with regolith thickness estimated from other techniques, such as those from radar and microwave radiometry inversion [3, 4].

Regolith thicknesses at the Apollo landing sites are for a small region where the seismometers were placed, and remote sensing inversions are usually for a large region with hundreds of meters to a few kilometers in size. Questions raised are that how regolith thickness varies across the Apollo landing sites and are the Apollo seismic experiment estimations representative? Impact craters with various morphology are ubiquitous across the lunar surface, providing a window to see the near surface structure of the Moon. In this study, we estimated regolith thickness over the six Apollo landing regions using the morphology and size-frequency distribution of the small fresh craters and compared them with the Apollo seismic experiment estimation.

Regolith Thickness Estimation Method: High-resolution optical images show that small craters (<250 m in diameter) usually exhibit four typical morphological types: normal, central mound, flat-bottomed, and concentric [5, 6]. Extensive laboratory impact experiments suggested that the morphology of crater depends mainly on the thickness of the regolith layer: a normal crater forms when D/d (D : crater diameter; d : regolith thickness) is smaller than 4, and a concentric crater forms when D/d is larger than 9 [5]. For a flat-bottomed (or central mound, concentric) crater, the regolith thickness is measured directly in topography data as the vertical distance between the pre-impact surface and the crater floor [6]. If one crater is used, an upper or lower limit of regolith thickness can be estimated. If a large number of craters over a region are investigated, cumulative distribution of regolith thick-

ness can be obtained by assuming that distributions of the four types of craters are uniform.

When a crater forms on the Moon, it begins to degrade because of various weathering processes (e.g., micrometeoroid bombardment). As a result, its diameter increases with time. We modeled crater degradation process for craters with diameters smaller than 500 m using the topographic diffusion theory [7], and found that the rim-to-rim diameter of a 3-Ga crater can be enlarged by a factor of ~ 2 . Regolith thickness will be biased to a larger value if all small craters with different degradation states are used in the estimation. Therefore, in our study, we only counted the freshest craters that are characterized by a well-defined rim, a steep inner-wall slope, and a pronounced blocky ejecta zone (for relatively larger craters) [8].

Regolith Thickness over the Apollo Landing Regions: In our study, we used high-resolution optical images from the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Cameras (NACs) with a spatial resolution of ~ 0.5 m/pixel for crater morphology identification and diameter measurement. To avoid misidentification of crater morphology, we only chose images with illumination angle that is slightly larger than 31° , which is the repose angle of regolith [9].

For each landing site, we selected a region with ~ 2.5 km \times 2.5 km in size. In total, we counted and identified 2511, 2654, 537, 1355, 1056, 1563 impact craters over the Apollo 11, 12, 14, 15, 16 and 17 landing sites, respectively. For each landing site, we also identified the freshest normal crater that is closest to the seismic station, which can give an estimate of the lower limit of the regolith thickness near the seismic station. Fig. 1 shows an example of the counted craters at the Apollo 11 landing site. From the nearest fresh crater to the seismic station, the lower limits of the regolith thickness at the Apollo 11, 12, 14, 15, 16 and 17 seismic stations are 3.8, 3.8, 3.3, 2.3, 2.3 and 2.3 m, respectively. These numbers are generally consistent with estimations based on the seismic experiments.

Fig. 2 shows the cumulative distributions of regolith thickness over the Apollo 11, 12, 14, 15, 16 and 17 landing sites. There are substantial variations in regolith thickness for each landing site. The median regolith thicknesses at these six regions are 5.0, 3.1, 4.8, 4.7, 6.8, and 4.7 m, respectively. The estimations

from crater morphology method cannot be compared directly with the Apollo seismic experiments, because regolith thickness estimated from crater morphology is for a large region whereas seismic experiment is only for the place where the seismometer was placed. For the Apollo 11, 12, 15, and 17 landing sites, regolith thicknesses from seismic experiment are within the range estimated from crater morphology. However, for the Apollo 14 and 16 landing sites, regolith thicknesses from seismic experiment are much larger than those estimated from the crater morphology. The Apollo 14 and 16 landing sites are located in highlands with a complex geological context. It is probably at these two landing sites, ejecta from the young fresh craters disturbed local variation of the regolith thickness. The seismic stations are probably located at the ejecta from the young fresh craters, and therefore the regolith thickness from the seismic experiment is much larger.

We also measured the regolith thickness from flat-bottomed craters with diameters larger than 4.2 times the thickest measured regolith [5]. The results show that regolith thicknesses from seismic experiments are all within the range of estimations from the flat-bottomed craters.

Conclusions: We estimated regolith thickness over the six Apollo landing regions using morphology and size-frequency distribution of small fresh impact craters. We found there are substantial variations in the regolith thickness over the six landing sites. Regolith

thicknesses from seismic experiments at the Apollo 11, 12, 15 and 17 landing sites are generally within the range of those estimated from the morphology of small craters. Our new estimation at the Apollo landing sites can be used as a calibration value for future regolith thickness estimation using remote sensing technique.

References: [1] Cooper M. R. et al. (1974) *Rev. Geophys.*, 12(3), 291–308. [2] Nakamura Y. et al. (1975) *Moon*, 13, 57–66. [3] Shkuratov Y. G. and Bondarenko N. V. (2001) *Icarus*, 149(2), 329–338. [4] Fa W. and Jin Y.-Q. (2010) *Icarus*, 207(2), 605–615. [5] Quaide W. L. and Oberbeck V. R. (1968) *JGR*, 73(16), 5247–5270. [6] Di K. et al. (2016) *Icarus* 267, 12–23. [7] Fassett C. I. and Thomson B. J. (2014) *JGR-Planets*, 119, 2255–2271. [8] Basilevsky A. T. (1976) *LPSC*, 7, 1005–1020. [9] Fa W. et al. (2014) *JGR-Planets*, 119, 1914–1935.

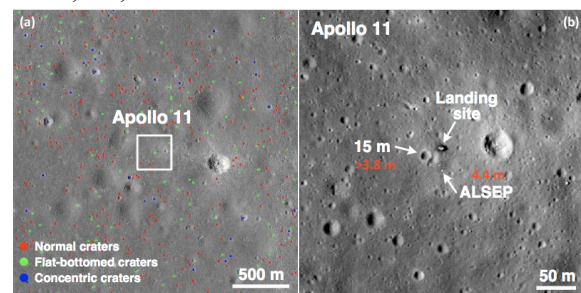


Figure 1. (a) All the counted small fresh craters over the Apollo 11 landing region. (b) A LROC image of the Apollo 11 landing region.

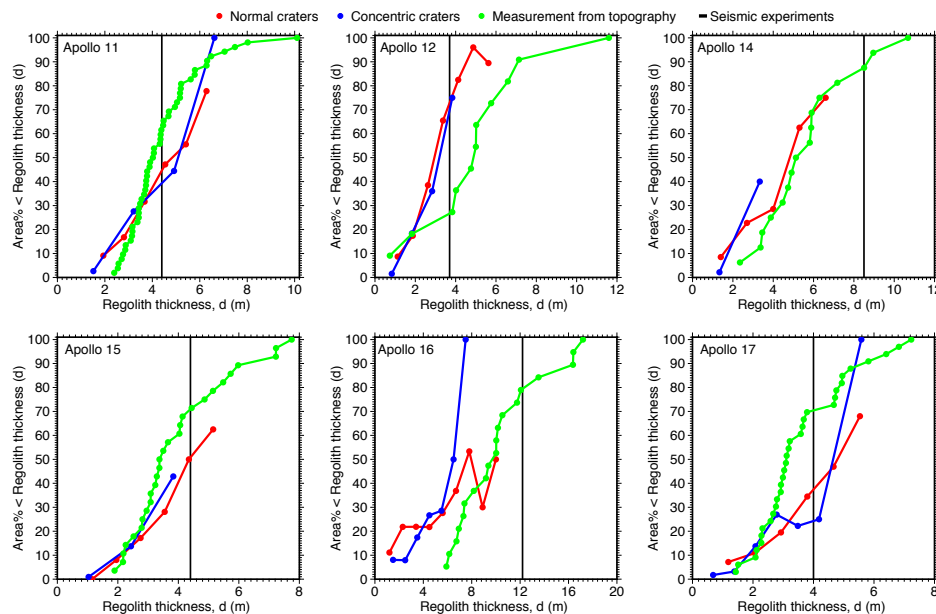


Figure 2. Cumulative distribution of regolith thickness (percentage of area with regolith thickness smaller than a given value) over the Apollo landing sites that are estimated from normal (red) and concentric (blue) craters, and direct measurement of the vertical distance between pre-impact surface and crater floor in topography data from flat-bottomed, center mound, and concentric craters (green). The vertical lines show the regolith thicknesses estimated from Apollo seismic experiments.