

CONSTRAINING DEGRADATION OF LUNAR CRATER EJECTA USING MULTIPLE REMOTE SENSING DATASETS

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Introduction: Impact craters dominate the surface of Earth's Moon and are present in a variety of degradational states. Some impact ejecta deposits on the lunar maria have higher than average values in Mini-RF circular polarization ratio (CPR) images [1] and Diviner thermal-IR-derived rock abundance (RA) maps [2], indicating significant levels of roughness or rockiness in the surface and subsurface. Other craters are not distinguishable in radar brightness from the background, indicating that they are similar to the average maria in terms of surface and subsurface roughness or rockiness at the scale of the S-band wavelength (12.6 cm). This observation has led to our driving science question: At what rate do rough, rocky crater ejecta systematically evolve to smooth, uniform regolith? We hypothesize that rocks that are exposed at the lunar surface erode at a more rapid rate than the rocks in the subsurface which are partially shielded from micrometeoroid bombardment. Here, we use Mini-RF CPR and Diviner RA data to test this hypothesis by comparing crater ejecta deposits in these two remotely sensed datasets with different depth sensitivities. Rock abundance estimates from thermal IR (TIR) data are sensitive to meter-scale rocks at the lunar surface, whereas S-band CPR data are sensitive to decimeter-scale rocks at the surface and buried rocks in the near subsurface. Hence, our hypothesis would be supported if TIR rock abundance values from lunar ejecta deposits fade to background values more quickly than radar signatures associated with crater ejecta deposits.

Background: The visual remnants of an impact on the Moon typically are a roughly circular crater with a raised rim as well as proximal and distal ejecta that was thrown outward upon creation of the crater [3]. This crater described above is commonly referred to as a simple crater as opposed to a complex crater which is typically much larger with terraced walls and a central peak or pit. The ejecta deposits of simple craters are emplaced as heterogeneous mixtures of centimeter-scale rocks, meter-scale boulders, and fine-grained regolith [e.g., 3,4]. The former two of these three constituents cause craters to possess elevated CPR and RA values based on their respective size sensitivities. Previous analysis of both thermal and radar data shows that these ejecta constituents evolve and erode over geologic time due to prolonged exposure to micrometeoroid bombardment [e.g., 5–10].

Data: The radar data used in this study are S-band (12.6 cm) synthetic aperture radar (SAR) CPR data from the Lunar Reconnaissance Orbiter (LRO) Mini-RF

instrument [1]. CPR is defined as the ratio of backscattered energy reflected in the same sense circular (SC) polarization as that transmitted to the energy in the opposite sense circular (OC) polarization [e.g., 11]. CPR data represent a change in signal polarization state caused by backscattering off of surface or subsurface scatterers; single scattering from smooth surfaces produces OC polarization, while multiple scattering from rough surfaces produces equal values of SC and OC polarization. The rock abundance (RA) data used in this study are derived from three of the seven spectral channels (6, 7, and 8) of the Diviner instrument [2]. RA data represent the percentage of sub-meter to meter-scale rocks that are exposed at the surface [2, 12]. The derivation of RA data accounts for multiple regolith temperatures present within a given field of view and estimates the distribution of these various temperatures on the basis of the degree to which a composition-dependent anisothermality exists at the lunar surface [2].

The model age values for each crater in this study were derived from crater topography and degradation state by [6], in which a hillslope diffusion model was applied to topographic profiles of ~13,000 simple (0.8–5.0 km in diameter) impact craters. Using the model, each crater was assigned a degradation value ($\kappa\tau$) and local crater density was then correlated to the Neukum production function [13] to obtain an approximate age value for that degradation state.

Methods: This work examines 72 simple impact craters in the size range of 1.5–2.0 km in diameter on the lunar mare. All craters chosen for analysis were previously identified and documented with a $\kappa\tau$ value and age in the Fassett and Thomson crater database [6]. Once a subset of craters was chosen for analysis, the RA global mosaic and corresponding level 1 Mini-RF images were downloaded from the Planetary Data System (PDS) and ingested into the USGS ISIS3 software. Mini-RF images were orthorectified using an ISIS3 processing routine following that used in [14].

Characterization of craters in both Mini-RF CPR and Diviner RA images was completed by first extracting 360° radial median profiles of CPR and RA pixel values out to a distance of four crater radii from the center of the crater. Power law curves were then fit to these data for the ejecta of each crater only (i.e. interior data was excluded), and the coefficients of each curve equation were recorded for comparison with age. Once extracted, curve-fit parameters are plotted directly against age for analysis of age versus CPR and RA intensity.

Summary: We analyzed 102 craters using the methods described above and found that both CPR and RA values associated with small impact craters fade with time (**Fig. 1, Fig. 2**). Results of our analysis show that the rates at which CPR values and RA values fade to background values are not readily distinguishable. The lack of a strong separation between these two rates is likely due to variance in our data. Further work, such as image projection control and assessing size or geographic dependencies on roughness, may be required to reduce data scatter and determine if it is possible to distinguish these rates (**Fig. 1**). Our results are inconsistent with previous work which show that RA values fade at a rapid rate and CPR values fade much more slowly [5, 7, 15]. Specifically, [5] found that blocks in the top 10 cm of ejecta associated with large (>18km) craters are completely eroded in ~1 Ga. We found that RA values associated with the ejecta deposits in our study remain elevated for 3.5–3.8 Ga, e.g., for the lifetime of the maria.

The finding that RA and CPR values fade over billions of years indicates that rocks in and on lunar ejecta deposits are eroding over extended periods of time. Moreover, rocks that are inferred from CPR images to

be present in the subsurface appear to erode at a rate that is indistinguishable from the rate at which rocks which are present at the surface erode. Elevated RA values at ages of 3.2–3.4 Ga indicates that there are rocks present at the lunar surface erode over extended timescales.

References: [1] Raney K. R. et al. (2011) *Proc. IEEE*, 99, 808-823. [2] Bandfield J. L. et al. (2011) *JGR*, 116, E00H02. [3] Oberbeck V. R. (1975) *Rev. Geophys.*, 13, 337-362. [4] Melosh J. (1996) *Impact Cratering: A Geologic Process*, Oxford UP, 89-100. [5] R. R. Ghent et al. (2016) *Icarus*, 273, 182-195. [6] Fassett C. I. and B. J. Thomson (2014) *JGR*, 119, 2255-2271. [7] Bell S. W. et al. (2012) *JGR*, 117, E00H30. [8] Jawin E. R. et al. (2014), *JGR*, 119, 2331-2348. [9] Patterson, G. W. et al. (2017) *Icarus*, 283, 2-19. [10] Fassett C. I. et al. (2018) *JGR*, 123 [11] Campbell B. A. (2012) *JGR*, 117, E06008. [12] Bandfield J. L. et al. (2015) *Icarus*, 248, 357-352. [13] Neukum G. et al. (2001) *Space Sci. Rev.*, 96, 55-86. [14] Cahill J. T. et al. (2014) *Icarus*, 243, 173-190. [15] Neisch C. D. et al. (2013) *JGR*, 118, 2247-2261.

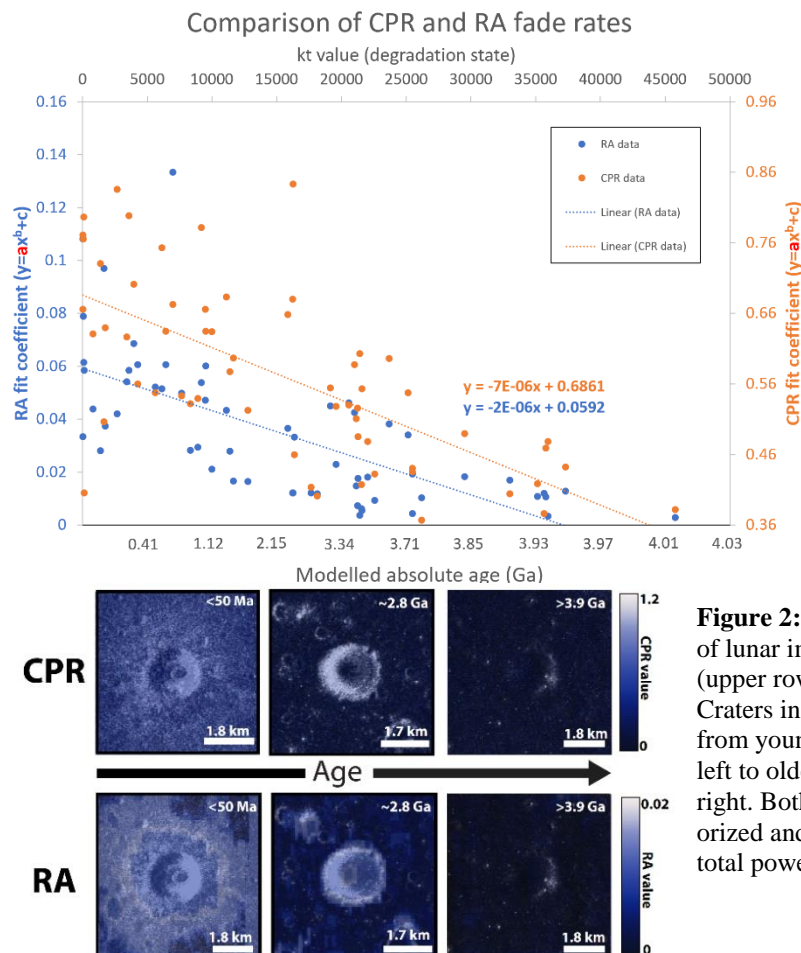


Figure 1: Plot showing crater fit coefficients (primary y-axis) and CPR fit coefficients (secondary y-axis) with age on the lower x-axis and kt (degradation state) on the upper x-axis. The orange dotted line represents the rate of CPR decrease over time and, therefore, subsurface rock erosion, while the blue dotted line represents the rate of RA decrease over time and therefore, surface rock erosion.

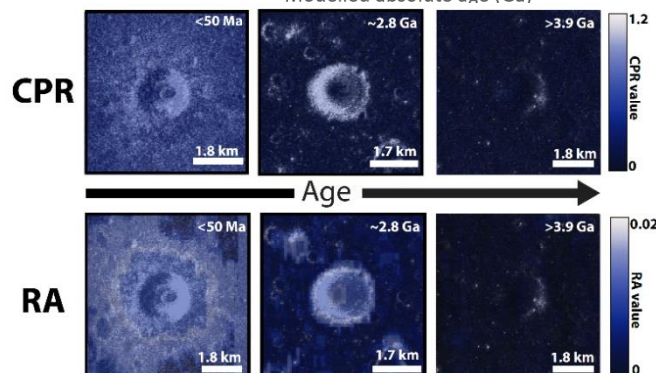


Figure 2: Evolutionary sequence of lunar impact craters in CPR (upper row) and RA (lower row). Craters in both sequences evolve from young and rougher on the left to older and degraded on the right. Both RA and CPR are colorized and overlaid onto Mini-RF total power images.