MODELING THE EVOLUTION OF REGOLITH THICKNESS: IMPLICATIONS FOR GROWTH RATE AND SPATIAL DISTRIBUTION.

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Introduction: Lunar regolith is defined as a fine-grained layer of fragmental debris overlying the cohesive substrate bedrock and mainly formed by continuous impacts of large and small meteoroids with the lunar surface [1]. As a basic surface process on the Moon, the evolution of lunar regolith can provide key information about the transportation and mixing of material on the lunar surface and is significant for deciphering the bombardment history of the inner solar system. Until now, regolith thickness has been extensively studied by various methods and was estimated to be 2–8 m in the maria and more than 10 m in the highlands [1]. However, only a few models were developed to describe the regolith growth process [2, 3], which still requires further investigation.

Due to the changing impact flux over billions of years and the shielding effect of pre-existing regolith layer (i.e., impact flux trend and regolith buffering trend), regolith grows nonlinearly with time [4]. In this study, we developed a Monte Carlo based Lunar Topography and Regolith Evolution Model (LTREM) to simulate the growth of lunar regolith and the evolution of the cratered topography simultaneously. Using this model, we quantitatively investigated the growth rate and spatial distribution of regolith thickness in an area.

Lunar Topography and Regolith Evolution Model: LTREM characterizes the lunar surface as a two-layer target structure, with a fine-grained regolith layer atop the underlying cohesive bedrock. When an individual impact crater forms, our model considers the excavation and modification processes during impact cratering and the ejection and deposition of target materials. By modeling the formation of continuous stochastic bombardment of impact craters on the lunar surface and the erosion of impact craters due to topographic degradation [5], our model simulates the evolution of regolith thickness. Generally, LTREM consists of three parts. First, based on the impact flux [6], the size-frequency distribution of impactors striking the lunar surface is calculated, and the diameter of each impact crater is computed through the scaling law [7]. Second, depending on the crater diameter and pre-impact regolith thickness, the topographic profile of each crater is selected from the recently established shape models of fresh impact craters [8–10], which include four scale-dependent morphological types (normal, central mound, flat-bottomed and concentric). Each impact crater will be added onto the layered target at a random location in the simulated area. Finally, topographic degradation is modeled using the diffusion equation (i.e., $\partial h/\partial t = \kappa\nabla^2 h$; h: surface elevation, t: time, κ: diffusivity) [5], which describes the slope-dependent mass transport on the lunar surface and is numerically solved in our study.

In our model, new regolith is generated and pre-existing regolith is overturned as each impact crater is added onto the surface. Specifically, newly produced regolith includes both the ejecta blanket beyond the crater rim and the breccia lens on the crater interior. Simultaneously, topographic degradation will change the surface elevation and thus affect the spatial distribution of regolith thickness. In calculation, the regolith thickness is represented by the elevation difference of the surface and the top of the bedrock layer at any model run time.

Results: In this study, the area of the simulated surface is 10 km × 10 km and the spatial resolution is set to be 2 m. The minimum crater diameter is selected to be 4 m (i.e., twice the resolution). The surface age is set to be from 0 to 3.5 Gyr and Marchi's impact flux model is adopted [6]. Fig 1 shows the output from one typical simulation realization. With new craters accumulating on the surface, pre-existing craters are degraded over time and some small craters become invisible. As the simulated surface and bedrock elevation evolve, the regolith thickness grows, with median thicknesses of 2.26, 2.92 and 4.64 m at 1.0, 2.0, and 3.5 Gyr, respectively. The simulation results also show that the median regolith thickness averaged over a large number of realizations will stabilize after about 50 runs, with the variation less than 0.6% and a standard error no more than 0.1 m.

Fig. 2 shows the mean regolith growth rate as a function of model run time averaged over 100 Monte Carlo realizations. The colored dots represent the simulated results and the black line is the best fit of the mean regolith growth rate: $dT/dt_{\mathrm{m}} = Ae^{6.93(3.5-t_{\mathrm{m}})} - Bt + C$, where T is the regolith thickness, t_{m} is the model run time, and A, B and C are coefficients with the best fit values of 1.22×10^{-9}, -0.37 and 2.85, respectively. The exponent of the first term in this equation is set to be the same as that in the lunar chronology function [11]. During the first 0.5 Gyr (3.5–3 Ga), the regolith growth rate is quite high (> 5 m/Gyr) and drops rapidly, which is primarily ascribed to the decreasing cratering rate on the Moon before 3 Ga and known as the impact flux trend. While in the following 3 Gyr (3 Ga to present), regolith grows relatively slowly with a slightly decreasing rate (~3–1 m/Gyr). During this period, the impact flux keeps nearly constant and the shielding effect of the pre-existing regolith layer mainly affects the regolith growth rate, which is known as the buffering trend.

Fig. 3 shows the histograms of regolith thickness at different model run times. The left and right columns correspond to the results simulated with the constant and nonconstant (i.e., the time-derivative of the Neukum chronology function [11]) impact flux over 3.5 Ga. In general, regolith thickness exhibits a long-tailed distribution. Most areas are covered with a regolith layer of only several meters and a few areas exceeding 10 m or even thicker (e.g., 2.5% for 1 Gyr in Fig. 3a and 16% for 3.5 Gyr in Fig. 3b). This is consistent with the estimations of regolith distribution in an area by small crater morphology method [12, 13]. Our simulated results also show that regolith thickness exhibits a bimodal distribution when it is relatively thin, and gradually evolves into a single-peaked pattern as impact craters accumulate.

We further calculated the root-mean-square (RMS) thickness and the correlation length of regolith thickness with various window sizes. For a surface of 3.5 Ga, as the window size increases from 100 to 1000 m, the RMS thickness increases from 6.7 to 17 m and the correlation length ranges from ~20 to 100 m. These results show that there are substantial spatial variations in regolith thickness.

Conclusions: In this study, we developed a Monte Carlo based Lunar Topography and Regolith Evolution Model and simulated the evolution of regolith thickness. The results provide a quantitative constraint on the regolith growth rate and reveal significant lateral variations in regolith thickness. Our model and results contribute to a better understanding of the formation and growth process of lunar regolith and are helpful to decipher the impact history of the inner solar system.

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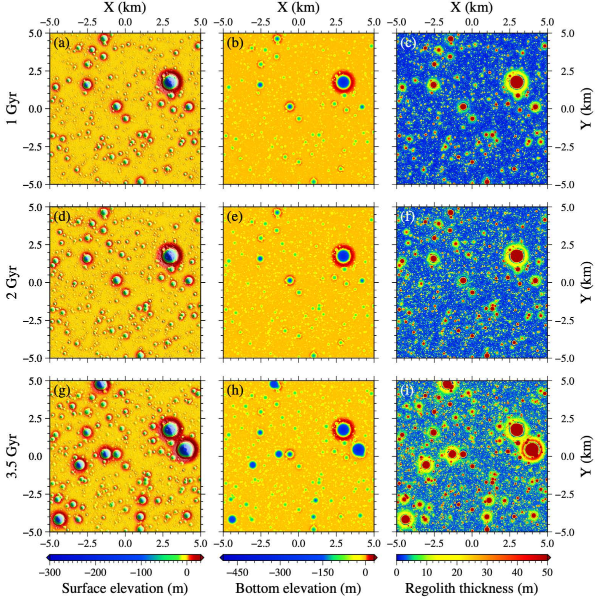

Figure 1. Simulated surface elevation (left), bottom elevation (middle), and regolith thickness (right) at 1 Gyr (top), 2 Gyr (middle), and 3.5 Gyr (bottom).

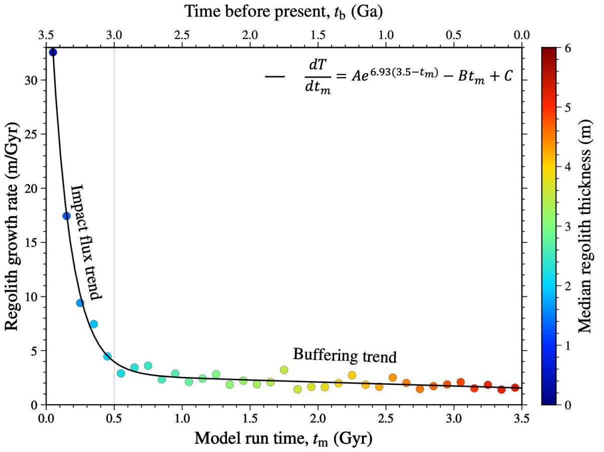

Figure 2. Mean regolith growth rate versus model run time. The dots represent averaged growth rate from 100 Monte Carlo simulations and the black line is the best fit result.

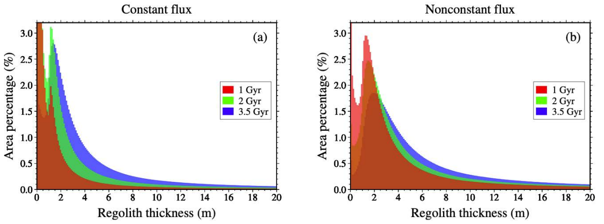

Figure 3. Area-weighted histograms showing the evolution of model regolith thickness (bin size: 0.1 m) with constant (a) and nonconstant (b) impact flux.