MODELING THE GROWTH OF REGOLITH ON THE MOON: IMPLICATION FOR THE EVOLUTION OF CRATER AND IMPACTOR POPULATIONS.

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Introduction: Lunar regolith is defined as fragmental materials covering the lunar surface [1], and it is the product of long period of meteoritic bombardment [2]. Regolith covers virtually the entire lunar surface, providing critical information about lunar geologyand the space environment. In the study of lunar regolith, thickness is one of the most important parameters, since it is directly related with engineering and other scientific problems, such as its connections with the age of underlying terrain and the quantities of implanted solar wind volatiles.

The Apollo 11, 12, 15 [3], 14, 16 and 17 [4] missions have carried out *in situ* seismic experiments, which can be used to determin the regolith thickness atthe landing sites Figure 1 shows the relationship between the surface ages of the landing sites [5] and the regolith thicknesses measured by seismic experiments. The regolith thickness values are consistent with the median regolith thicknesses calculated based on the 3D morphology of small fresh craters [6]. Figure 1 shows that in general, older surfaces bear thicker regolith. Based on the fact that lunar regolith is mainly formed by constant bombardments of small impact craters, the growth of regolith has been simulated using crater accumulation models. Shoemaker et al. [1] utilized crater size-frequency distribution (i.e., CSFD) to predict the lunar regolith thickness as a function of surface age (Shoemaker's model hereafter), whereas Oberbeck et al. [7] established a more complicated model to simulate regolith growth by a Monte Carlo simulation, which considered the relation between crater type (i.e., the geometry of craters can be concentric, central-mound and flat-bottomed) and the volume of ejected material to model regolith evolution. Melosh [2] showed that these two models predict consistent results when using the same production function (i.e., PF). Therefore, here we focus on Shoemaker's model for simplicity. Choosing proper values of parameters, Shoemaker's model matches the regolith thicknesses at Apollo 12 and 15 (see Figure 1), but this model constantly fails to fit the regolith thicknesses observed at the other Apollo landing sites. This poor fit is mainly due to the fact that the observed regolith thickness is almost unchanged between 3.3 and 3.8 Ga with a thickness of ~4 m, whereas using a constant (i.e., unchanged with time) PF with slope of ~-3 would predict that the regolith thickness increase almost linearly with cratering rate [2]. For example, according to the chronology function of Neukum et al. [8], the regolith thickness of a 3.8 Ga-old unit should be ~5 times larger than that of a 3.3 Ga-old unit due to the larger impact flux at 3.8 Ga. This is in contradiction to the *in situ* measurements as shown in Figure 1. Therefore, the near zero vertical growth of lunar regolith requires either a different PF during 3.3 to 3.8 Ga, or other surface geological activity during this time have prohibited the vertical growth.

Crater production population might have changed around 3.85 Ga possibly due to the migration of the outer planets [9]. In addition, the possible present of a transient atmosphere due to lunar volcanism [10] can also change the size-frequency distribution (i.e., SFD) of craters formed on the lunar surface due to atmospheric screening effect similar to that on Mars. Here we first revise Shoemaker's model to constrain the possible changes of PF, and then investigate the mechanism causing the PF changes.

Method: The widely used lunar production functions NPF and HPF possess both steep but different slopes for craters smaller than ~1 km (-3 to -3.8 for NPF depending on the diameter range of interest and -3.8 for HPF). The discrepancy in slope between NPF and HPF can be explained by the effect of topography degradation from a production population, and the true PF has a slope of -3.2 (see Xie et al. [11] for details). Here, we assume an abrupt change of CSFD from shallower slope (b) to -3.2 at time t_c.

The equilibrium onset diameter (i.e., the largest diameter in equilibrium), D_{eq}, can be determined from the intersection between the PF and the equilibrium population. Here we adopt the 6% of the geometry saturation level as the SFD distribution of craters in equilibrium. Cumulative coverage is the fraction of area covered by craters with diameter from D to D_{eq}, and the mutually overlap of craters is taken into account [12]. When cumulative coverages are 75th, 50th (i.e., median) and 25th percentiles, respectively, the regolith thicknesses are assumed to be M times the apparent depth (measured from pre-impact surface [11]) of craters with diameter D.

Resutls: Figure 1 shows that, when b = -2.1, t_c = 3.3 Ga and M = 2.8, our model-predicted median regolith thickness is consistent well with the *in situ* measurements at Apollo landing sites. Actually, for all $b \leq$ -2.1, the model-predicted regolith thickness is almost the same for ages older than 3.3 Ga (not shown for clarity), because for the shallow-sloped PF, the change of density of small craters (<~20 m) is minor compared to that after 3.3 Ga, although the value of $N(1)$ has increased by a factor up to ~6 from 3.3 to 3.8 Ga [8]. Regolith thicknesses at the Apollos 14 and 16 landing sites are excluded from the model fit, because our model cannot be applied to the scenario where ejecta blanketing from large craters (especially for basins) becomes important. The 75th percentile thickness is almost the same as the minimum thickness given by Shoemaker's model with 100th percentile coverage, because our model considered mutually overlap, which reduces the coverage level reported by Shoemaker.

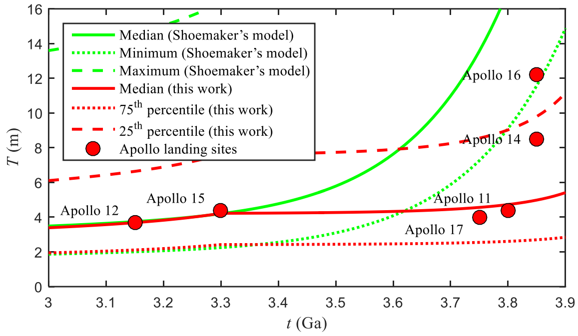

Figure 1 Regolith thickness versus surface age t. The PF slope of -3.22, 6% of the geometry saturation, and chronology function of Neukum et al. [8] are used in Shoemaker's model.

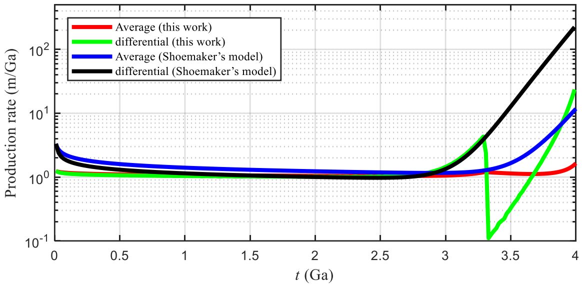

Figure 2 The average and differential regolith production rate (median thickness) versus surface age. The model-derived results of Shoemaker's model are shown for comparison (the values of parameters used is the same as Figure 1).

As shown in Figure 2, the average-median regolith production rate (i.e., the median regolith thickness at time t divided by t) is nearly constant (~1.1) at ages younger than ~3.8 Ga. However, the differential-median regolith production rate (i.e., the differential median regolith thickness at time t) shows a sawtooth-like variation trend: 1) the increase between 2.7 and 3.3 Ga is due to the increase in cratering rate; 2) the changing to shallower PF causes the abrupt decrease at 3.3 Ga towards older ages. The regolith growth rate at the beginning of the steeper-slope PF was as least ~30 times (this lower limit is corresponding to the upper PF slope limit of -2.1) higher than the immediately preceding period.

Discussion: Here, we consider that the migration of the giant planets and the possible presence of a transient atmosphere on the Mooncould cause a shallower-sloped PF compared with that later than 3.3 Ga. With the screening effect of smaller projectiles by the hypothiszed atmosphere, the PF slope needs to be shallower (i.e., larger) than -2.1 during ~3.3 – 3.8 Ga, thus the SFD slope of sub-km craters predicted from NEOs (whose SFD is the same as MBAs before 3.3 Ga) should be larger than ~-2.4 according to Popova et al. [13]. The slope derived here is shallower than that predicted from the modeling result of MBAs [14,15], whereas their results is consistent with the CSFD observed on asteroids (e.g., Vesta). However, because observed CSFD is steeper than the PF due to the effect of topography degradation [11], they may have overestimated the SFD slope of MBAs. In addition, the shallower-sloped PF is consistent with the observation of Strom et al. [9].

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