SURFACE RESIDENCE TIMES OF REGOLITH ON THE LUNAR MARIA. P. O'Brien[1] and S. Byrne[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721 (pob@lpl.arizona.edu)

Introduction: The surfaces of airless bodies like the Moon undergo microscopic chemical changes as a result of energetic processes operating in the space environment, collectively known as space weathering [1,2]. Despite returned lunar soil samples, the rate of space weathering on the Moon is not well understood. The amount of chemical weathering incurred in the lunar regolith depends critically on the rate at which regolith is excavated, transported, and buried by macroscopic impact processes. These physical processes control how long regolith spends on the surface where it is exposed to the space environment. We have developed a Monte Carlo model that simulates the evolution of lunar maria landscapes under topographic relief-creation from impact cratering and relief-reduction from micrometeorite gardening [3]. As synthetic model surfaces evolve over time, the positions of regolith tracer particles are tracked under the effects of these macroscopic physical processes. By comparing the particles' surface residence times to laboratory and remote-sensing measurements of soil maturity, this work links the physical and chemical evolution of lunar maria regolith to deduce its rate of space weathering.

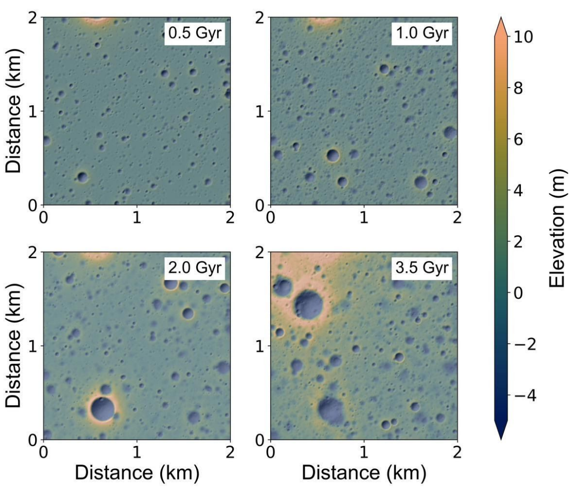

Figure 1. Example surface evolving over the age of a typical mare unit.

Landscape Evolution Model: The number of physical processes that have shaped the lunar landscape over the past few billion years is small. Large impacts form craters and break up solid bedrock, creating a layer of loose regolith. Micrometeorite impacts erode sharp features like crater rims and move regolith downslope in a transport process that can be modeled as topographic diffusion [4].

Our model simulates mare-like surfaces evolving over time from flat surfaces to cratered landscapes. Impacts are randomly sampled from the present-day lunar impact flux [5] and the global population of secondary craters produced by these impacts is generated following empirical observations of secondary production on airless bodies [6,7]. At each timestep, we compute the downslope flux of regolith by solving the 2D diffusion equation [8]. The rate of diffusion is calibrated by matching the average roughness of the model landscapes to the observed roughness of the lunar maria, as measured by the median bidirectional slope at 4 m baselines [9]. Figure 1 shows how model surfaces subject to these physical processes become rougher and more heavily-cratered over time.

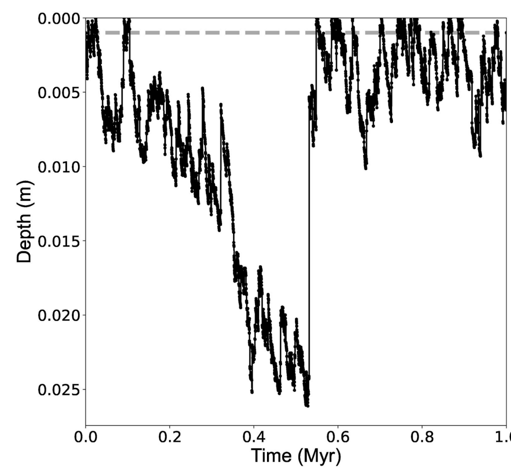

Figure 2. Vertical mixing of a particle due to sub-pixel resolution impacts (diameter < 8 m). The dashed line represents the "surface" layer at a depth of 1 mm.

Surface Residence Times: The 3D landscape evolution model is seeded with tracer particles to investigate the vertical and horizontal transport of lunar regolith. The same processes that influence the model grid elevations also influence the positions of the regolith tracer particles, which can be excavated, ejected, and buried by impacts or downslope mass movement. Particles are also vertically mixed by impacts occurring within the scale of a single 4 m x 4 m pixel on our model grid (Figure 2). The depth of each particle is stored at every timestep in order to determine how long regolith spends on the surface exposed to space weathering effects. Surface residence time is defined as the cumulative amount of time spent within a millimeter of the surface over 3.5 Gyr of surface evolution (the age of a typical mare unit [10]).

We measured surface residence times for thousands of regolith tracer particles in each of hundreds of Monte Carlo landscape evolution runs to characterize the distribution of surface exposure in lunar maria regolith (Figure 3).

We find that surface residence times are generally short due to rapid gardening by secondary impacts. The median surface residence time on the lunar maria is 6.42 Myr and 98% of regolith tracer particles spend less than 20 Myr within a millimeter of the surface. It is important to note that these short exposure ages are achieved over the entire 3.5 Gyr model runtime as particles are repeatedly buried and re-exposed by impacts. Another caveat is that these results refer only to the "observable regolith", tracer particles that end the model run at a depth of less than 10 cm (the average sampling depth of the Apollo astronauts). Most material in the ~5 m thick maria regolith layer spends even less time on the surface. The vigorous mixing of the upper regolith by secondaries is consistent with observations of fresh lunar impact "splotches" [11] and analytical overturn models [12].

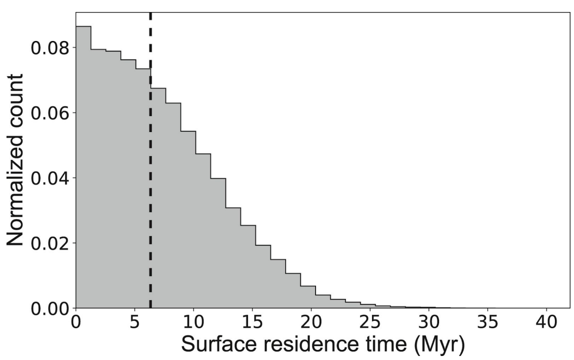

Figure 3. Distribution of surface residence times for regolith tracer particles, drawn from a sample of 300 Monte Carlo landscape evolution model runs. Dashed line indicates the median of the distribution.

Space Weathering Rates: Lunar soil maturity has previously been characterized using both laboratory sample analysis [13] and remote sensing datasets [14]. Metrics such as I_s/FeO and optical maturity (OMAT) quantify the amount of space weathering products like nanophase iron that have accumulated in a bulk soil sample. However, the timescale over which these chemical byproducts were accumulated has not been conclusively measured for all soil samples in [13]. Additionally, definitive exposure ages for the lunar surface cannot be measured globally with current orbital datasets.

The results of this work provide the first independent estimate of surface exposure ages for lunar maria regolith. We map the observed distribution of soil maturity onto the distribution of surface residence times (i.e. particles in the 99th percentile of surface residence are assumed to be in the 99th percentile of soil maturity). In Figure 4, I_s/FeO and OMAT are plotted against surface residence time. Regolith reaches maturity, defined as a bulk soil sample with an I_s/FeO value of 60 units [13], at a cumulative surface residence time of 7.15 Myr. The maturation timescale is sensitive to the impact rate, especially that of secondary impacts, which control how rapidly regolith grains are cycled from the surface into the subsurface. If the secondary crater size-frequency distribution is shallower than is commonly assumed (e.g. [11,12,15]), the cumulative exposure age needed to reach maturity could be longer by a factor of a few.

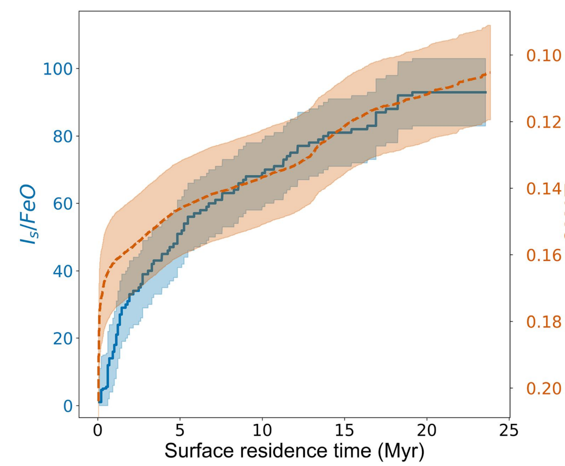

Figure 4. Dependence of soil maturity on surface residence time as measured by the ferromagnetic resonance metric, I_s/FeO (solid blue line) and the optical maturity parameter, OMAT (dashed orange line). The cumulative surface residence times needed for regolith to mature are achieved over billions of years of surface evolution.

References: [1] Hapke, B. (2001) *JGR: Planets*, *106(E5)*, 10039-10073. [2] Pieters, C. M. and Noble, S. K. (2016) *JGR: Planets*, *121(10)*, 1865-1884. [3] O'Brien, P. and Byrne, S. (2021) *JGR: Planets*, *126*, e2020JE006634. [4] Soderblom, L. A. (1970) JGR, 75(14), 2655-2661. [5] Marchi, S. et al. (2009) *AJ, 137*, 4936. [6] Vickery, A. M. (1986) *Icarus, 67(2)*, 224-236. [7] Singer, K. N. et al. (2013) *Icarus, 226(1)*, 865-884. [8] Pelletier, J. D. (2008) *Cambridge*. [9] Rosenburg, M. A. et al. (2011) *JGR: Planets, 116(E2)*. [10] Hiesinger, H. et al. (2011) *GSA, 477*. [11] Speyerer, E. J. et al. (2016) *Nature, 538*, 215-218. [12] Costello, E. S. et al. (2018) *Icarus, 314*, 327-344. [13] Morris, R. V. (1978) *LPSC IX*, 2287-2297. [14] Lucey, P. G. et al. (2000) *JGR: Planets, 105(E8)*, 20377-20386. [15] McEwen, A. S. et al. (2006) *Ann. Rev. of Earth and Plan. Sci., 34*, 535-567.