THE ROLE OF VERTICAL MIXING PROCESS ACROSS MARE AND HIGHLAND CONTACTS. Y. H. Huang[1], D. A. Minton[1], J. Elliott[1], T. Hirabayashi[1], A.M. Freed[1], C.I. Fassett[2], and J.E. Richardson[3] [1]Department of Earth, Atmopsheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907 (huang474@purdue.edu), [2]Department of Astronomy, Mount Holyoke College, South Hadley, MA 01075[3], Arecibo Observatory, Arecibo, PR 00612.

Introduction: Impacts transport material in two ways on the lunar surface: laterally and vertically. As Tycho crater's rays show, material can be transported laterally to large distances. Of course, the excavation of a crater also causes vertical transport. The lunar surface is mainly composed of darker mare basalt and brighter highland anorthosite, which makes the boundary between these terrains an ideal place to study how mixing processes work. Li and Mustard [1] suggested that lateral mixing is the more important process on these geological contacts and argued that vertical mixing is less significant.

We will investigate this mixing problem using a three dimensional mixing model based on the Cratered Terrain Evolution Model (CTEM). Figure 1 shows the preliminary result of a CTEM simulation across Grimaldi crater's mare/highland contact. It shows that a model with only lateral mixing results a large amount of transport of material on both the mare and highland side. We also clearly see that including a crude model of vertical mixing with depth, which buries lateral-transported material, significantly affects the surface abundance of transported material across the contact.

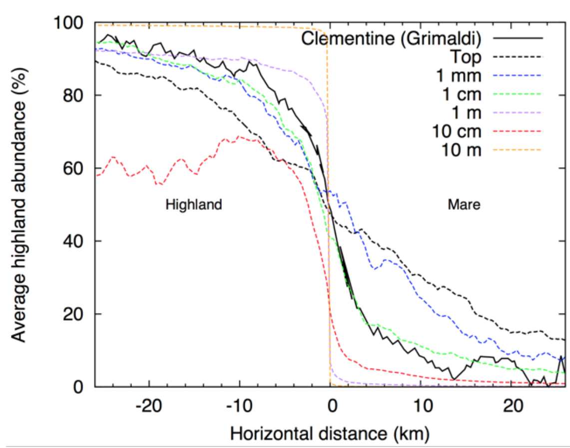

Figure 1: The average highland abundance with varying distance from the geological contact of southwestern Grimaldi crater. The solid line is Clementine data taken from Li and Mustard [1], and dashed lines are our simulation results from CTEM. The black dashed line is data without any vertical mixing (labeled by "Top"), but the rest of dashed lines are calculated by included vertical mixing at the end of each simulation. The legend for dashed lines are the vertical mixing depth that is mixed down at the end of the simulation.

Observations and Constraints: Figure 1 shows that vertical mixing may be as important as lateral mixing. Small craters under the resolution of CTEM are responsible for developing the lunar reworking zone. Threfore we need a realistic vertical mixing model that is calibrated with observational data in order to properly model this sub-pixel process in our code.

The vertical mixing process is observed in many millimeter scaled regolith layers with homogeneous texture in Apollo drilling core samples [2], and was modeled by Gault [3]. He used the concept of turnover to model the reworking zone, which is based on the idea that the excavation of the impact crater is the driving force that mixes material from depth up to the surface. The larger an impact crater, the deeper the vertical mixing. The degree of mixing for a surface depends on how long it takes for every bit of the surface to be turn over at least once. He used well-formulated crater production functions for different impact flux models to derive a relationship between mixing time and mixing depth. He predicted that the surface would be turned over to a depth of 0.5 mm at least 100 times in one million years, and for 10 cm depth, would be turned over at least once per billion years.

Unfortunately, the observed time scale for vertical mixing varies depending on what technique is applied to date lunar soils. Cosmic ray exposure ages from the Apollo 17 soil samples, 70181, the very mature soil from the Valley Floor in the landing site, shows an exposure time of ~100 My in the upper 5 cm of regolith [4]. Also, cosmic ray-derived dates of the Luna 24 drill core has average exposure ages of 600 My and 450 My for the upper zone (1 m) and lower zone (40 cm), respectively [5, 6]. These two exposure times are consistent with the cosmogenetic ages of lithic fragments found in the core [7,8]. However, it appears that the time scale measured in the Luna-24 and Apollo 17 drilling core samples shows that what appears to be much shorter times for forming thicker layers. This is inconsistent with Gault's numerical result, which showed ~1 Gy for 5 cm turnover depth. This inconsistency motivates us to re-examine Gault's study.

Method: We adopted the concept of turnover by Gault but modeled this time-dependent turnover numerically. We used 1 m^2 of the surface area to investigate how much time or how many craters it takes to cover 100% of the surface, defined as true saturation. Due to the random nature of impact cratering, it takes more craters to reach true saturation than to reach geometric saturation (efficient packing of circles). Gault estimated that the vertical mixing depth of a crater was

1/8 of its diameter. This assumes that mixing is primarily due to excavation of material from the target location to the proximal ejecta blanket. From a crater production function, for a given size of a crater, the required time for turnover was obtained. The value of 1/8 of a crater diameter as the mixing depth for a given size of a crater is based on the depth that the deepest excavation flow can go, but it would assume that the center of a projectile sits at the surface as the excavation stage starts.

However, there are at least two studies suggesting that the extent of vertical mixing zone would be deeper than 1/8 D. Pierazzo [9] found that if the projectile is equivalent to a buried charge, rather than sitting at the surface, it would result in deeper excavation flow where material from greater depth is mixed. Hirabayashi [10] pointed out that the regolith becomes more porous as the regolith thickness increases. More importantly, the region between the floor of the transient crater and the floor of the final crater may itself be mixed during a cratering event, becoming a porous regime which appears as a negative gravity anomaly for simple craters. Fieldwork observations show slightly mixed material in this porous regime [11]. Also, numerical simulations show a chaotic motion of excavation flows in this region [12].

Results: If the vertical mixing by a crater is capable of mixing deeper, not only excavated material but also brecciated material underneath the final crater, we expect to see faster mixing. Assuming that the mixing depth by a crater is one radius of the final crater, the 5 cm thick layer in our simulation takes about 100-200 My to reach true saturation, which is consistent with the exposure time of Apollo Valley Floor mature soil sample, 100 My. Yet, the average exposure times for developing two thicker columns in the Luna 24 drill core, 1 m and 40 cm, are estimated as the same order as Apollo 17 sample, million years. This can be explained by an episode of thick ejecta excavated from a large cratering event, in which this thick layer is mixed but has shorter exposure time. This is also supported by the report of that varying degrees of soil maturity in a single sampled layer [13]. The mixing time or exposure time is thus at least partially independent of the mixing depth or the thickness of a mixed layer. Whether a cratering event recycles or reworks material or incorporates deeper fresh material appears to be stochastic due to the random nature of impact cratering. Figure 2 shows that the required time for a surface to reach different mixing depth for 100% and 50% coverage of a surface. For example, by 10 Ma a surface down to 3 mm of depth would be fully mixed, and a surface down to 10 cm would have a 50% probability of being mixed.

Our work suggests much more vertical impact-driven mixing at the lunar surface and subsurface, in contrast to the findings of Li and Mustard [1]. This finding is important for helping to resolve how material is transported across mare and highland contacts.

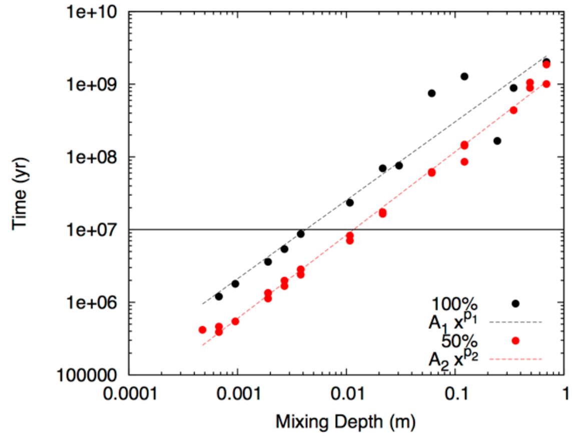

Figure 2: The required mixing time for a surface to get mixed down to different mixing depth. The black and red solid dots are for 100% and 50% true saturation case respectively. The dashed line with black and red color are fitting curves in a power las for 100% and 50% true saturation case: $A_1=10^{9.56178}$, $p_1=1.07949$, $A_2=10^{9.21741}$, and $p_2=1.14684$.

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