

The Role of Vertical Mixing Process Across Mare and Highland Contacts

Ya-Huei Huang¹, Toshi Hirabayashi¹, David Minton¹, Jacob Elliott¹, Andy Freed¹, Caleb Fassett², Jim Richardson³
¹Department of Earth, Atmospheric, 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.

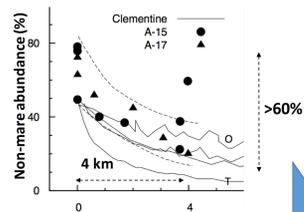
Lateral transport dominated process like crater rays?

The Mystery of Impact Mixing on the Moon: Why do two different data sets appear to contradict each other?

Vertical transport dominated process like crater cavity?



Figure 2: An example of Jackson crater in ~35 km of radius with bright rays around from LROC WAC camera. The white contour along bright rays are mapped by Elliott et al. in prep (See Elliott's Tuesday poster #160). The crater rays are an evidence of dominant lateral transport process on the Moon.



Lateral mixing process must dominate at the lunar surface to explain the sharp drop of non-mare abundance within 4-5 km.

Mare and highland contacts are perfect places to study impact transport on the Moon. Different data sets appear contradictory. Spacecraft data and hand-picked samples directly from mare and highland contacts show that the non-mare component drops rapidly within the distance of 4-5 km from contacts, while many mare soil samples have an average non-mare abundance regardless of distance from contacts [1,2].

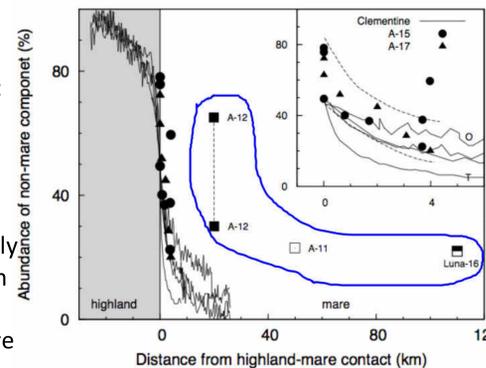


Figure 1: The average non-mare abundance with varying distance from highland (left hand side) and mare (right hand side) contact. Apollo 11, 12, and Luna 16 mare soil samples with varying sampling distance up to 100 km are marked in blue color. Apollo 15 and 17 mare soil samples are shown in black circle and triangle, and Clementine data are black lines [1].

Vertical mixing was believed to be an insignificant process. Crater excavation is vertical mixing or vertical transport. They move debris out of a cavity vertically. The debris is mixed and deposits around a crater's rim highlight in yellow color Figure 3.

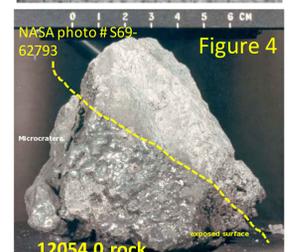
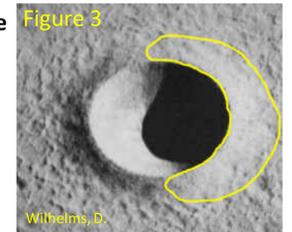


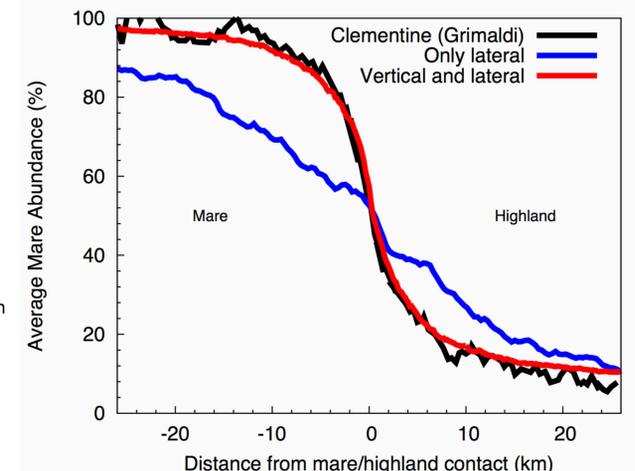
Figure 4: Apollo 12054 rock. Exposed part suffers micrometeoroid impacts, while buried part (upper of yellow dashed line) is free of micro-craters.

Can we neglect vertical mixing process across mare and highland contacts? Especially, any exposed rock or debris at the lunar surface is subject to micrometeoroid impacts (Figure 4).

Our simulation suggests that vertical mixing is as important as lateral transport on the Moon.

Li and Mustard [2000] neglected vertical transport and allowed an ejecta to go infinitely, leading a good match with Clementine data. As a result, they suggested that the vertical mixing process is insignificant. Yet, in our simulation, without vertical mixing, we cannot match with observation data (Figure 9).

Figure 9: The average mare abundance with varying distance from the mare and highland contact. Grimaldi crater is chosen for Clementine data and our final result. The black line is taken from Clementine UV/VIS reflectance data [1], and the lines with blue and red colors are from our study. The blue line is the simulation with only resolvable craters' ejecta and no sub-pixel vertical mixing model, and the red line is the result including both.



Can we explain an elevated non-mare abundance at large distance? Our hypothesis is that this may be a result of heterogeneity caused by rays.

Simulation Method

CTEM, Cratered Terrain Evolution Model, is a Monte Carlo code simulating the evolution of planetary surface subject to an impact flux [3,4]. Yes, CTEM can model cratering very well (Figure 6, see Minton's Thursday poster #97), but it has a resolution limit. That is, craters under 1 pixel cannot be produced.

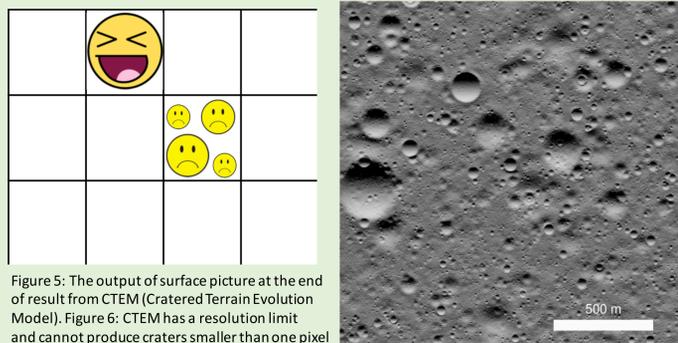
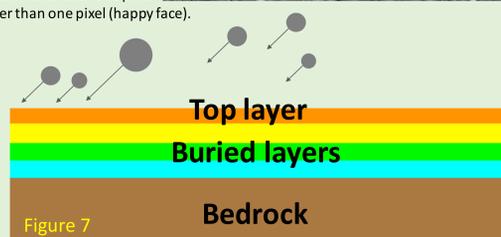


Figure 5: The output of surface picture at the end of result from CTEM (Cratered Terrain Evolution Model). Figure 6: CTEM has a resolution limit and cannot produce craters smaller than one pixel (sad face), but craters larger than one pixel (happy face).

Those sub-pixel craters associate with that how they handle surface deposits that are delivered by either local vertical transport by resolvable craters or lateral transport. Figure 7 shows that how small impacts may bring up buried material that might be exotic to local material.



A mathematical model for the sub-pixel vertical mixing process!

History of vertical mixing: Gault [1974] defined a turnover timescale for a flat, square surface [5]. As a crater forms on a surface, the region occupied by this crater can turnover and, as result, is mixed. For the whole surface to be mixed, one needs to calculate the total number of craters 100% cover the surface. He assumed the same sized crater. The fraction of a surface as function of number of craters takes the form of exponential of total area of number of craters. Instead of same sized craters, Hirabayashi et al. [in prep] [6] asked how long multiple sized craters fill up the surface. As each cratering event with a different size occurs independently, the probability of multiple sized craters takes a similar form as single sized craters.

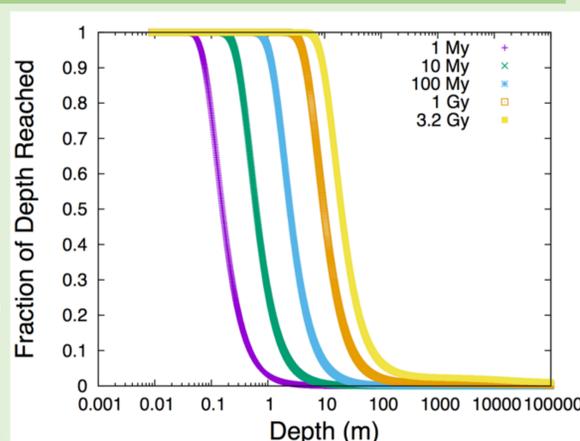


Figure 8: A fraction of a surface that reaches to a depth as function of depth for different times (1, 10, 100, 1000, 3200 My) (See Hirabayashi's Thursday poster #487).

Reference: [1] Li, L and Mustard, J. F. (2000) *JGR*, 105, 20431-20450. [2] Rhodes, J. M. (1977) *Phil. Trans. R. Soc. Lond. A*, 285, 293-301. [3] Richardson, J. E. (2009) *Icarus*, 204, 697-715. [4] Minton, D. A. et al. (2015) *Icarus*, 247, 172-190. [5] Gault, D. E. (1974) *GCA*, 3, 2365-2386. [6] Hirabayashi et al. [in prep]

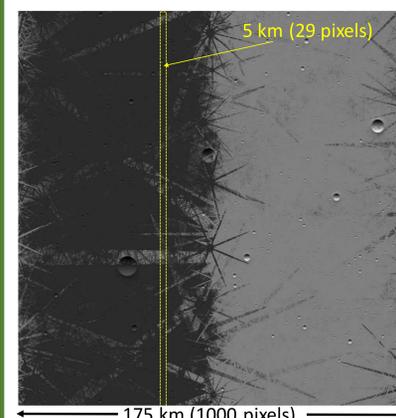


Figure 10: The output of composition map from a simulation including lateral and vertical transport. Left side (dark) is mare, and right side (gray) is highland. The size of simulated mare is about the size of Mare Grimaldi. The strip marked as yellow dashed line is 5 km wide and 175 km long. The location is at ~20 km, about Apollo 12 landing site.

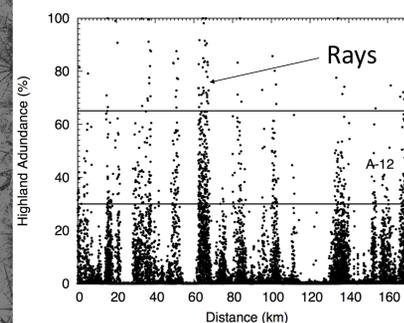


Figure 11: The distribution of highland abundance inside the yellow box in Figure 10, which is similar to the distance at Apollo 12 landing site. The high concentration of highland abundance is responsible for ray deposit. The two black horizontal lines are the range of non-mare abundance at Apollo 12 landing site. It is also evident that Apollo 12 landing site is superposed by rays coming from Copernicus crater.

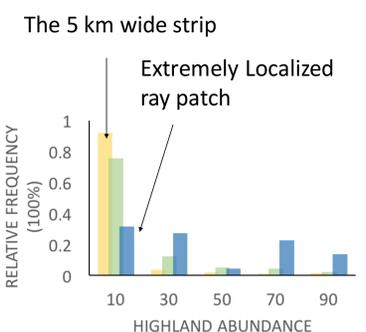


Figure 12: The histogram of highland abundance normalized by the total number of pixels inside counting area, in which yellow color represents the strip in Figure 10 (5 km x 175 km), green color represents about 325 pixels inside the strip, and blue color represents only 22 pixels, describing extremely localized ray deposit inside ray patch.

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