INFERRING LUNAR MARE BASALT MATERIAL PROPERTIES FROM SURFACE ROCK ABUNDANCE. C. M. Elder[1], J. Haber[2], P. O. Hayne[3], R. R. Ghent[4], J.-P. Williams[5], M. A. Siegler[4,6], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]Purdue University, [3]University of Colorado Boulder, [4]Planetary Science Institute, [5]University of California, Los Angeles, [6]Southern Methodist University.

Introduction: Regolith is a layer of fragmental debris that thickens over time due to a large number of individual impacts that brecciate the surface and subsurface [1]. The canonical model of regolith formation begins with a coherent substrate that develops a regolith layer, growing as a function of total bombardment history such that an older surface will have developed a thicker layer of regolith [2]. Recent work [3] has suggested that regolith growth may also be highly sensitive to initial conditions where, for example, a lava flow with high vesicularity might evolve differently from a denser rock layer. Here, we treat surface rock abundance as a proxy for subsurface rock abundance and/or regolith thickness. We compare the rock abundance derived from multispectral infrared observations by the Diviner Lunar Radiometer Experiment (Diviner) on the Lunar Reconnaissance Orbiter (LRO) [4] to the surface ages of units in the maria derived from crater-size frequency measurements [5]. This builds on work by [6] and interprets the results in light of the recent work by [3].

Methods: We investigate the relationship between surface rock abundance and unit age by calculating the median Diviner rock abundance value [4] in each unit defined by [5], who mapped units using a Clementine color ratio composite and assumed that each unit with a uniform surface composition represents a single eruptive event. They determined unit age from crater size-frequency distribution measurements in one or more count areas within each unit [5]. Nearly all of these units are covered by $>10^4$ Diviner pixels and our conclusions are the same whether we use the median rock abundance of the units or the count areas. Diviner rock abundance represents the fraction of a pixel covered by rocks larger than ~1 m in diameter [4]. Due to the stochastic nature of impact cratering, a generally less rocky unit (assumed to correspond to thicker regolith) may happen to have recently experienced a large impact capable of excavating rocks from greater depth and locally elevating the rock abundance. This is a source of uncertainty in our work but, for large areas, should have a relatively minor effect on the overall median rock abundance.

Results: We find that median Diviner rock abundance is negatively correlated with unit age, as expected (Figure 1). This confirms that regolith thickens with time resulting in fewer impacts capable of excavating rocks on an older surface. We find that the

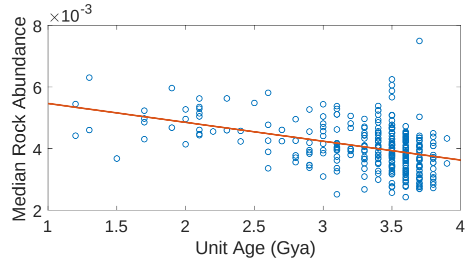

Figure 1: Median value of Diviner rock abundance [4] for each unit defined by [5] versus the age of that unit [5]. The red line is the best fit linear relationship between the two (equation 1).

best-fit linear relationship between rock abundance, RA, and surface age is

$$RA = -0.000613(age) + 0.00608 \qquad (1)$$

However, the residual errors in this fit are large, with an R^2 value of only 0.18. We argue that the scatter is, at least in part, caused by variability in initial conditions and can be used to infer differences in the material properties of different mare basalt units. Figure 2 shows the difference between model rock abundance calculated using equation 1 with ages from [5] and the measured median Diviner rock abundance where negative values indicate units that are rockier than expected for their age.

Discussion: There are several factors that could explain why there is significant scatter in the relationship between surface rock abundance and unit age. First, surface rock abundance is not a direct measure of regolith thickness or the volume fraction of rocks mixed in with the regolith. The stochastic nature of impact bombardment means that for two identical regions, one may happen to have experienced more recent impacts. Blocks break down rapidly on the lunar surface [7, 8], so craters that formed within the last ~100 Myr will be significantly rockier than older craters formed in similar targets. However, in a large region, one anomalous crater is unlikely to have a significant effect on the median rock abundance of the region. There is also inherent uncertainty in crater counting and defining the boundaries of individual lava flows, both of which likely also cause some scatter in the relationship between surface rock abundance and unit age. However, figure 1 shows some regional trends (e.g. most units in Mare Tranquillitatis are rockier than units in Mare Imbrium), which suggest that scatter in the RA-age relationship is not purely stochastic or related to crater counting uncertainties. We argue that these regional differences may be evidence supporting the more complex model of regolith development recently proposed by [3] in which the initial conditions of a volcanic surface have a significant impact on the rate of regolith development. Some especially strong surfaces may require higher energy impacts before they break down. Flows with significant void space, such as lava tubes, might gradually swallow regolith as it develops. Eruptions with a significant explosive component might start with a higher fraction of fines which have since been mixed in with fines formed by brecciation of coherent rock. It is also possible that some areas had earlier layers of regolith, or paleoregolith, develop before the final eruption, and that paleoregolith might have been gradually mixed in with the newly forming regolith.

We find that Mare Humorum and some southern parts of Oceanus Procellarum are anomalously rocky. These regions are adjacent to the Orientale basin. Although the Orientale basin forming impact predated most mare formation, it has been suggested that it may have contributed to mixing of highland and mare material [e.g. 9]. Therefore, the anomalous rock abundance in these regions may be, in part, related to the Orientale basin.

Finally, the Diviner rock abundance map was derived assuming a single thermal inertia for all rocks, but in reality, the thermal inertia of rocks could vary [10], with void space (vesicles and/or small cracks) being the most likely cause of variability. Thus, regions that appear anomalously rocky for their age could actually be regions where rocks have an anomalously high thermal inertia, causing [4] to overestimate the rock abundance. However, this leads to the same conclusion: anomalously rocky regions started as stronger rock. Low-thermal inertia rocks are associated with high porosity and low tensile strength [11], so surfaces currently covered with lower-thermal inertia rocks would imply a weaker initial substrate.

Conclusion: We find that Mare Humorum and some parts of Oceanus Procellarum are anomalously rocky, which we suggest may be evidence that the initial flows in those regions were comprised of rock that breaks down more slowly. Some parts of Mare Imbrium and most of Mare Australe are less rocky than expected for their age. This could imply that the initial flows in those regions were easier to break down. They could have also had a larger pyroclastic component meaning that they were less rocky than "typical" mare units at their formation. Radar and/or microwave observations may provide additional insight into how the abundance of rocks of different sizes and at different depths evolves with time.

References: [1] McKay, D. S. et al. (1991) In *Lunar Sourcebook* (pp. 475-594). [2] Horz. F. (1977) *Phys. Chem. Earth*, *10*, 3-15. [3] Head & Wilson (2020), *GRL*, *47(20)* e2020GL088334. [4] Bandfield J. L. et al. (2011) *JGR Planets*, 116(E12). [5] Hiesinger, H. (2011) *GSA Special Papers 477*, 1-51. [6] Haber et al. (2018) *LPSC 49*, Abstract #2463. [7] Basilevsky, A. et al. (2013) *Planetary and Space Science*, *89*, 118–126. [8] Ghent, R.R. et al. (2014) *Geology*, *42*, 1059-1062. [9] Williams, J.-P. et al. (2017) *Icarus 283*, 300-325. [10] Martinez-Camacho, J. M. et al. (2018) *LPSC 49*, Abstract #2556. [11] Grott, M. et al. (2019) *Nature Astronomy*, *3(11)*, 971-976.

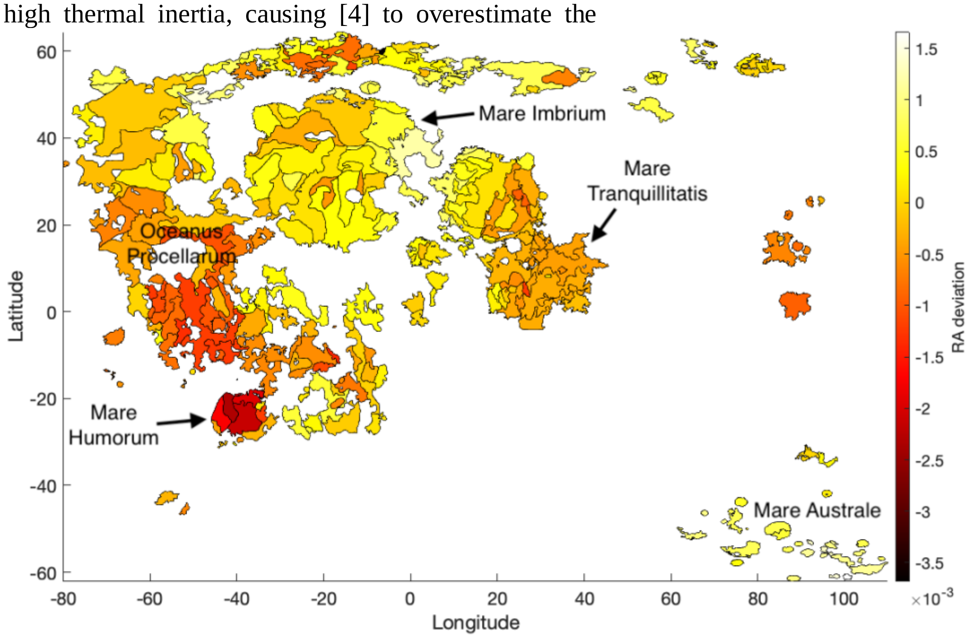

Figure 2: The difference in predicted and observed median rock abundance in each unit defined by [5]. Negative values indicate units that are rockier than expected for their age.