THE MISSING CRATERS IN THE LUNAR MARE REGION. W. Liang[1], J. C. Andrews-Hanna[1], A. J. Evans[2], [1]Lunar and Planetary Laboratory, University of Arizona (wl463@lpl.arizona.edu), [2]Department of Earth, Environmental, and Planetary Sciences, Brown University.

Introduction: The nearside lunar mare region represents the most volcanically active, and perhaps tectonically active, region on the Moon. Past studies have constrained the time history of emplacement of the topmost flows [1] and have constrained the depth of certain mare regions to be ~1 km (e.g., [2]). However, the nature and history of the early mare flooding is unknown, as only the top meters of the flooding history are visible.

A gap in the surface crater frequency distributions has long been observed between the farside highlands and the nearside mare, showing the comparatively youthful age of the mare surface. GRAIL Bouguer gravity data led to the discovery of quasi-circular mass anomalies (QCMAs) in the nearside mare, which were hypothesized to be the signal from buried craters [2]. Adding the QCMA population to the exposed crater distribution still fails to completely match the nearside mare and farside highland crater distributions, however, as a dearth of buried craters less than ~90 km in diameter was observed [3]. In contrast, observations of abundant buried craters in both topography data and their tectonic signatures on Mars and Mercury show that buried craters in this size range are preserved on those bodies (e.g., [4]). As such, the dearth of the small buried craters in the maria may be in some way related to the unique details of early mare emplacement.

In this study, we quantify the deficit in crater signal in both power spectral domain and spatial domain, and investigate different candidate processes that may have produced the crater deficit. First, we test whether the attenuation of gravity signal due to the thickness of the mare layer above the buried craters can explain the deficit. Next, we test whether a lower density contrast due to a higher density substrate can explain the signal deficits. Then, we test whether a simple diffusive process, based on physical processes such as impact erosion or thermal erosion, can produce the signal deficit. Finally, we consider a scenario in which the lunar surface was already covered by a mare layer from previous mare flooding at the time of cratering, such that only large impacts penetrate into the lower density crust beneath.

Quantifying Crater Deficiency: We first assume that the farside highlands is a valid approximation of the pre-flooded mare, and simulate a flooding event by adding gravity from topography using the density contrast between substrate and lava (600 kg/m^3), to the Bouguer gravity (corrected at 2500 kg/m^3). We then quantify the crater loss comparing the localized power spectra and map views between the nearside mare and flooded farside. A crater detection algorithm was applied to the modeled Bouguer gravity gradient maps [5] to quantify the recovery of buried craters relative to the observed population [6].

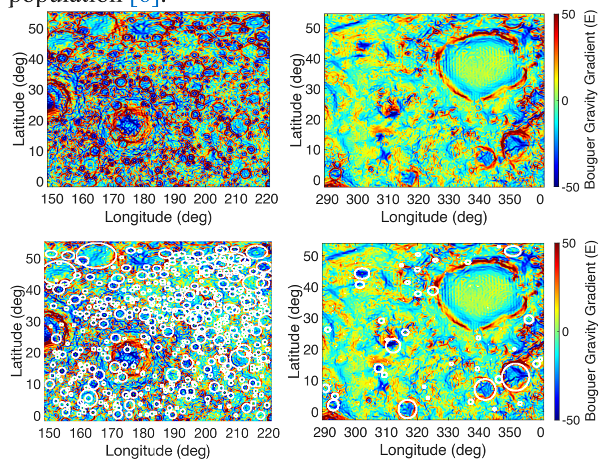

Figure 1. (top) Map view comparisons of a selected area in the nearside mare (right) and flooded farside model (left). (bottom) Craters identified within the selected area in the nearside mare and flooded farside.

Our preliminary map view comparisons between the flooded farside and the nearside mare region (Fig. 1) show a distinct lack of buried craters (rings of positive gravity gradient) in the mare compared to the flooded farside. Preliminary power spectral comparisons between the flooded farside and the nearside mare region (Fig. 3) show that the nearside power dips below the flooded far side at approximately spherical harmonic degree 120.

Methods: The thickness of the mare layer leads to some attenuation of the signal of buried craters. This scenario was approximated by changing the reference radius when calculating the flooded farside gravity to 1 km above the surface. The reduced density contrast scenario was implemented by changing the density contrast in the gravity from topography calculations when generating the simulated flooded farside gravity.

The diffusion model was set up as a 3-D explicit Forward Euler finite difference scheme in spherical coordinates. The diffusion coefficient of interest is highly uncertain and depends on the process. Impact diffusion during the earlier period of heavy bombardment was likely orders of magnitude higher than estimates of current diffusion rates. Diffusion could also represent thermal erosion beneath the mare. The thermal diffusivity is much higher but would operate over shorter timescales. We use the thermal diffusivity of lava (~20 m^2/yr) [7], and the parameter of interest varied was the total time of diffusion.

The pre-mare lava scenario assumes the smaller impactors would not excavate to the plagioclase substrate, and thus would not produce a gravity signal after the subsequent final mare flooding event (Fig. 2), while large craters only partially excavate the substrate. We implement this scenario by creating a density interface representing the base of this lava layer, which is then used to calculate gravity as done in the flooded farside model.

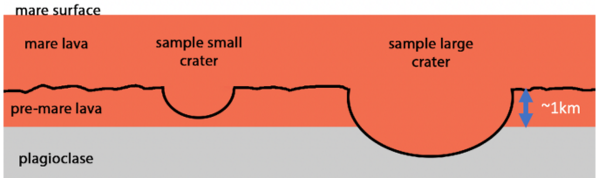

Figure 2. Schematic representation of the pre-mare lava scenario, where only the larger craters excavate to the density interface with lower-density plagioclase.

Results: The signal reduction from the estimated mare depth of 1 km is not enough to produce the observed deficit (Fig. 3), though a much larger and unrealistic thickness (~2.5 km) can provide a match to the power spectrum. A reduced density contrast of ~200 kg/m^3 is able to produce the observed deficit, requiring either a low density mare (2700 kg/m^3) or high density substrate (2900 kg/m^3), neither of which is supported by observations. Diffusive processes are also able to reduce the flooded farside signal to match the nearside spectrum. However, the diffusion spectrum shown was generated after 100 Myr of diffusion (assuming the thermal diffusivity), which is much longer than the expected lifetime of a liquid magma body on the surface. Impact diffusion at lower rates for a longer time would also be insufficient. Diffusion using more reasonable parameters was insufficient to produce the spectral deficits.

The model of impacts into a pre-mare lava layer of 1 kilometer thickness is insufficient to create the observed deficit, with a power spectrum a factor of 2.5× higher than the nearside spectrum. A thickness of 2.5 km is enough to reduce the power to match the nearside. However, this putative pre-mare volcanic layer is several times thicker than estimates of the observed mare thickness.

Conclusions: None of the four tested mechanisms, mare depth effect, alternate lava density, diffusion, and pre-mare mare, was alone sufficient to produce the gravity power deficit between the nearside mare and the synthetic pre-mare surface using parameters supported by observed data. Each of the mechanisms tested can explain a fraction of the deficit in the power spectrum and the crater population, and thus a combination of effects may be the best explanation.

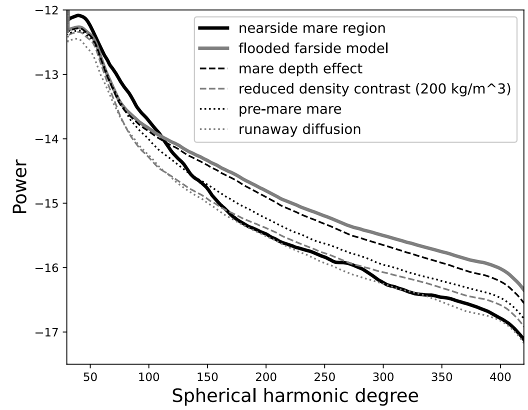

Figure 3. Power spectra comparisons between the modeled spectra of the crater modification mechanisms (dotted, layer depth effect, anomalous density, diffusion, and pre-mare mare) and the observed spectra (bold).

Future work will test additional crater erasure mechanisms, including viscous relaxation, as well as thermal and mechanical erosion during the lava flooding. Viscous relaxation can contribute to significant regional topographic changes due to the high heat flux of the PKT region. Both thermal and mechanical erosion by lavas can preferentially erase sharp edges across the craters and may have contributed to a smoother surface beneath the currently visible mare.

For the realistic parameter choices, the largest effect came from the scenario in which a 1-km thick pre-existing mare layer was present at the time of bombardment. If supported by continuing analyses, this would suggest an early pre-Nectarian phase of voluminous eruptions. The history of the lunar mare region before ~3.5 Ga is hidden by the final mare flooding events. However, the existence of a thick mare layer before that event would not be unusual due to the high heat flow of the region, which may imply either two pulses of mare volcanism or that the nearside mare region has been continuously volcanically active since lunar formation. A better understanding of lunar volcanic history and crater erasure mechanisms may also contribute to the understanding of volcanic flooding history on other Solar System objects, such as the northern plains of Mars as well as the Venusian surface.

References: [1] Hiesinger, H. et al. (2011) USGS *Spec. Paper* 477, 1-51. [2] Evans, A. J. et al. (2018) *GRL* 43, 2445-2555. [3] Evans, A. J. et al. (2018) *JGR Planets*, 123, 1596-1617. [4] Frey, H. V. (2006) *GRL*, 33, L08S02. [5] Andrews-Hanna, J. C. et al. (2013) *Science, 339,* 675-678. [6] Head, J. W. et al. (2010) *Science*, *329*, 1504-1507. [7] Peck, D. L. (1978) *USGS Professional Paper, 935-B*.