GRAVITATIONAL INFERENCES ON LUNAR IGNEOUS HISTORY BEYOND MARE VOLCANISM.

K. Izquierdo[1] (kig@purdue.edu), M. M. Sori[1], J. M. Soderblom[2], B. C. Johnson[1,3], T. C. Prissel[4], K. Prissel[5]. [1] EAPS Department, Purdue University, West Lafayette, IN., [2]EAPS Department, MIT, Cambridge, MA., [3]Physics Department, Purdue University, West Lafayette, IN., [4]NASA Johnson Space Center, Houston, TX. [5]Jacobs, NASA Johnson Space Center, Houston, TX.

Introduction: The source, distribution, and volume of igneous material on the Moon sheds light into its thermal evolution. Previous work has focused on extrusive mare volcanism, but intrusions and non-mare compositions are equally as important. Constraints on the ratio of magma production to volcanic output (intrusive/extrusive ratio) inform mantle melting rates and the conditions that allowed transport of magma through the crust [1]. Additionally, the lithological diversity of lunar volcanic products sheds light on the timeline of lunar cooling and fracturing of the crust [2].

Here, we provide two new constraints on lunar igneous activity. First, we determine the Moon's intrusive/extrusive (I/E) ratio by finding the upper volume of magmatic intrusions consistent with the observed high correlation between gravity and topography. The I/E ratio for the Moon has been roughly estimated to be <50 based on the volume of dikes that significantly increase crustal density [3]. However, this ratio is highly uncertain, as it is for all planetary bodies [4]. Second, we test for the presence of Mg-suite material buried in the farside highlands. We study an area north of the South Pole-Aitken (SPA) basin, previously proposed to be buried mare basalts (cryptomaria) [5]. The gravity data in this region is consistent with volcanic material, but the region lacks dark halo craters (DHCs), characteristic of excavated and exposed underlying basalts [6]. Instead, Mg-suite exposures have been detected in this region [7].

Magmatism volume from gravity–topography correlation: The free-air gravity of the Moon, sampled by the GRAIL mission [8], has a correlation >0.99 with the gravity produced by its topography, sampled by LRO [9] [10] (Fig. 1). This high correlation means that intrusions contribute little to the free-air gravity. We compute the uppermost volume of magmatic intrusions consistent with the observed gravity/topography correlation.

Methods. We discretize the lunar crust into 10° tesseroids in longitude and latitude (36 ×18 grid) at three different depth ranges: 10–20, 20–30, and 30–40 km. The initial density of all 1944 tesseroids is set to 2550 kg/m^3, representative of the highlands crust [11]. At each iteration we randomly select 100–1000 tesseroids and assign them a density of 3460 kg/m^3 [12] to represent a random distribution of magmatic intrusions (globally or nearside only). We compute the gravity acceleration produced by the model using the algorithm in [13], shown to have an error ≤ 0.1%. The observed lunar gravity from topography, or Bouguer correction (BC), is added to the synthetic gravity field of the modeled intrusions to produce the modeled free-air gravity. This modeled free-air gravity has a resolution up to $l_{max} = 250$, limited by the size of the tesseroid grid. The correlation between the modeled free-air gravity (f) and BC follows $S_{fBC}/\sqrt{S_{ff}S_{BCBC}}$, where S_{fBC} is the cross-power spectrum of the two functions, computed using the software in [14]. Successful intrusion models are defined as those having equal or higher correlation than the observed global correlation, for all degrees between 200–250. We repeat this process for 10,000 iterations to find the upper volume of magmatic intrusions in successful models.

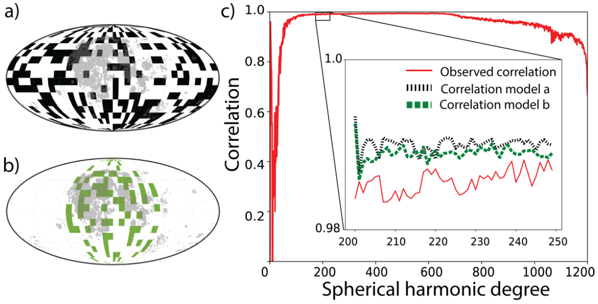

Figure 1. a) Model with a uniform global distribution of intrusions on the Moon (black rectangles). Gray regions show the locations of visible mare. b) Model with intrusions uniformly distributed on the nearside of the Moon (green rectangles). c) Correlation between free-air gravity (observed and modeled) and the gravity from lunar topography.

Results and Future work. Our preliminary upper volume of magmatic intrusions is 1×10^9 km^3. Considering the volume of visible mare (6×10^5–1×10^7 km^3 [15], [16]) as the only extrusive volcanism, the upper limit on I/E is 1666. Adding cryptomare volumes inferred from gravity data (3.6×10^6 km^3 [5]) to the extrusive volcanism, the upper limit of the I/E ratio becomes 238. These values are both higher than the previously proposed upper limit of 50 [3], which shows that the correlation constraint on the intrusions volume, using our current set up, is less rigid than the previously used density constraint. Our current tesseroid grid resolution limits comparison with the data to the spherical harmonic degree range 200–250; degrees 200–600, however, represent the complete degree range available. Current work is focused on obtaining a higher resolution tesseroid grid (smaller intrusions) which may provide tighter volume constraints.

Origin of proposed buried volcanism north of SPA: We use the effective density spectrum (ρ_{eff}) to investigate the subsurface structure north of SPA. $\rho_{eff}\,(l) = S_{fb}(l)/S_{bb}\,(l)$ where S_{fb} is the cross-power spectrum between observed free-air gravity and BC per unit density [11], [17]. ρ_{eff} has been proposed to be an unbiased estimate of the density of the crust with depth [11].

Methods. We compare the ρ_{eff} of four subsurface models in the degree range 200–600 to find the structure that best fits the observed ρ_{eff} in the region of interest: 1) a linear increase in density with depth, representative of highlands rock and no igneous material, 2) a mare layer on top of highlands rock, representative of shallow buried mare, 3) a layer of highland material covering a mare layer, representative of deeply buried mare, and 4) a layer of highland material covering a Mg-suite layer. We consider models of shallow (2) and deeply buried (3 and 4) igneous material because deeper material would be harder to excavate by impacts and could explain the lack of DHCs in this region. We find the parameters that best fit the localized observed ρ_{eff} for each model using a Monte Carlo method [5] and the model ρ_{eff} described in [17], [18]. We use the Bayes factor to assess the degree of significance in favor of one model over other.

Results and Discussion. Fig. 2a shows the locations where models having an added highlands layer on top of the volcanic material (3 and 4) have a significantly better fit to the local ρ_{eff} compared to models with negligible cover (1 and 2). Our results indicate the highlands layer covering at these locations is 1–4 km thick. If so, impact craters several 10's of km in diameter would be required to excavate and expose the buried igneous material [19]. The buried material may represent volcanism overlain by SPA ejecta [20] or intrusions that failed to erupt due to a thicker farside crust [10].

While our study supports the presence of deeply buried igneous products, it cannot distinguish the material composition. Both Mg-suite and mare basalt densities have similar fits to the observed ρ_{eff} data. Fig. 2b shows the thicknesses of the buried material depending on the assumed melt densities. Nevertheless, the presence of candidate Mg-suite exposed in the central peaks of craters ≥35 km in diameter within this region [7] is broadly consistent with our modeled depth of burial and thus supports the existence of buried Mg-suite rocks rather than cryptomaria.

Conclusions: We use gravity and topography data to elucidate part of the igneous history of the Moon. We find an upper volume of magmatic intrusions of 1×10^9 km^3, corresponding to a higher lunar I/E ratio than previously proposed [3]. We find that a previously proposed cryptomare region north of SPA is likely deeply buried (1–4 km). Alternatively, the data is also consistent with the buried material as non-mare volcanism and geologic evidence favors Mg-suite material.

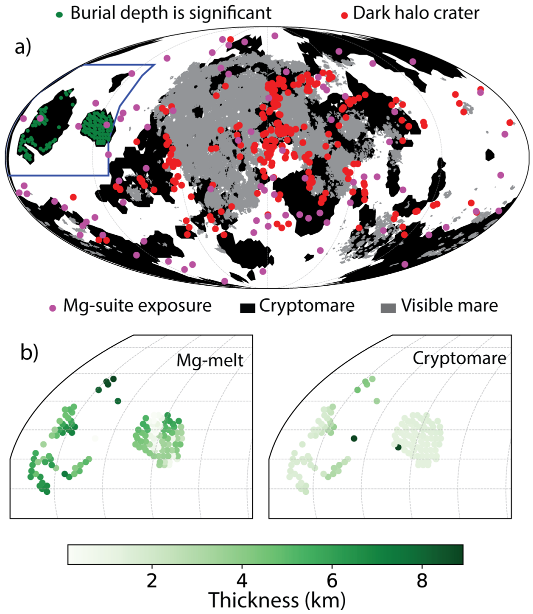

Figure 2. Distribution of lunar volcanic material. a) Black areas show cryptomare regions in [5]. *Red dots show DHCs* [5]. *Pink dots show Mg-suite exposures* [21]. *The blue rectangle shows the region of study, which encloses previous proposed cryptomare in black. Green dots show the locations where the burial depth of volcanism is significant. b) Thickness of the volcanic material within the blue rectangle in a if Mg-melt (2800 kg/m^3) or cryptomare (3460 kg/m^3).*

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