

THE MOON WITHOUT MARE. A. Broquet¹ and J. C. Andrews-Hanna¹, ¹Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA (adrienbroquet@arizona.edu).

Introduction: Volcanic products on the Moon are dominantly expressed in the form of dark deposits covering much of the nearside. These mare deposits consist of effusive iron-rich basaltic plains that are thought to be the result of partial melting in the mantle and subsequent upward propagation through dikes due to excess pressure [1]. Crater counting statistics on exposed mare units suggest that the last major mare eruption stage occurred during the late Imbrian period (~ 3.8 – 3.6 Ga, [2]).

Mare materials cover about 20% of the lunar surface [3], making these deposits a substantial component of the upper crust. A plethora of approaches have been used to investigate the structure of the maria, including localized [4] and global [5] gravity and topography inversions, and analyses of partially [6] and fully [7] buried craters. However, these studies arrived at different and sometimes contradictory maps of mare thickness. Knowing the lateral variations in mare thickness is crucial to understand the structure of both large nearside impact basins and the enigmatic Procellarum KREEP Terrane (PKT) region that is thought to have played a prominent role in the thermal evolution of the Moon [8].

Methods: We investigate lateral variations in mare thickness by expanding upon the two-layer global inversion of gravity and topography data [9,10] by [5]. The inversion uses a thin-shell model [11] that partitions the crust into a mare top load, a feldspathic top and bottom load, and constrains lithospheric displacement as a function of the elastic thickness of the lithosphere (T_e).

Our model requires an assumption regarding the shape of one of the interfaces. Given that the lunar crust is thought to be the result of the solidification of a floatation crust following a global magma ocean, its root should have initially been in the isostatic ratio with the surface loads [12]. Crustal modifications later in time may induce significant departure from isostasy with local lithospheric support of geologic loads. Therefore, only the long-wavelength (degree < 90) top and bottom loads in the feldspathic crust are constrained to be in the isostatic ratio, with a second independent top load of basaltic mare material. From degree 90 to 150 the model transitions to full mare compensation (where the bottom crustal load is equal to zero) using a cosine taper. This transition accounts for the flexural strength of a 15 km thick elastic lithosphere, representing the warmer and weaker state of the early crust. The mare models taper to zero between degrees 350 and 500 to prevent ringing.

In some areas, particularly outside the maria, the inversion will make unrealistic predictions including negative mare thicknesses and finding mare where none

exist. Thus, the output mare thickness is thresholded to a minimum value of zero and then clipped to the observed mare distribution [3]. This updated mare thickness is input into a new inversion as a known load, allowing to solve for the independent (no longer isostatic) top and bottom loads in the feldspathic crust required to exactly match the observed gravity and topography. The result is a self-consistent model of mare and crustal thickness matching the expectation for an approximately isostatic pre-mare crust. The analysis is repeated for different choices of mean mare thickness to find the model that best matches the observed mare distribution.

The elastic thickness of the lithosphere. Amongst several unknown parameters, T_e has the largest effect on the inverted mare thickness. This parameter is determined using the tectonic record [13] and constraints on mare thickness based on partially buried craters [6,14].

Several nearside impact basins are surrounded by long (> 250 km) arcuate rilles, which are graben-like features that testify of mare-induced extension. Our loading model outputs lithospheric strains [11], which can be used to infer the location of loading-induced faulting. The distribution of the modeled extensional minimum principal strain is compared to observed rille positions using an RMS (root-mean-square) misfit as a function of elastic thickness. To ensure that loading strains can drive tectonism, the modeled strains are thresholded to a minimum of 5×10^{-4} , which is slightly lower than that recorded by lunar graben [15] and representative of the crust frictional yield strength at 5–15 km depth.

Geologic observations on crater morphology also hold crucial constraints on the mare thickness outside of major impact basins. However, inferred mare thicknesses are typically lower bounds (craters excavating fully through the maria) or upper bounds (craters not excavating through the maria). Mare thickness estimates

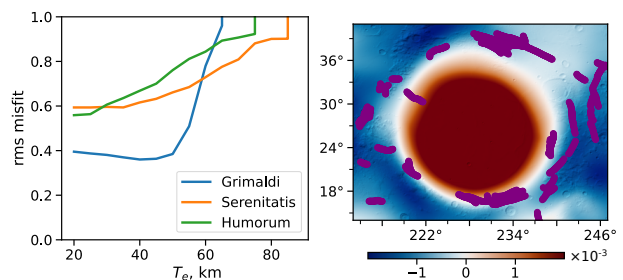


Figure 1: RMS misfit to the tectonic record as a function of elastic thickness (left), and horizontal strain for $T_e = 35$ km at Serenitatis (right). Purple lines show arcuate rilles positions and negative strains indicate extension.

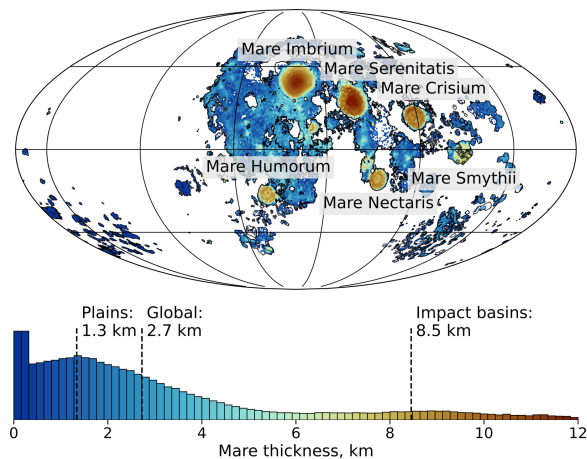


Figure 2: Global mare thickness and associated color-coded histogram annotated with the mean mare thickness for the plains, impact basins, and on a global scale.

from partially buried craters [6,14] are thus used as lower bounds to constrain the mare thickness and T_e .

Results: Our nominal inversion uses a crustal thickness of 40 km and mean mare thickness of 1.5 km, together with mare, feldspathic crust, and mantle densities of 2850, 2550, and 3220 kg m⁻³, respectively [16].

For T_e of 20, 35, and 45 km, respectively for Humorum, Serenitatis, and Grimaldi, our loading model predicts local extension where most arcuate rilles occur (Fig. 1). The fit to the tectonic record generally favors thin elastic lithospheres ($T_e < 50$ km) at the time of mare emplacement. Our second investigation based on partially buried craters, however, favors $T_e \geq 40$ km in order satisfy 90% of the lower bound thickness estimates ($N=181$). Together, these analyses suggest T_e of about 40 km at the time of the bulk of mare emplacement.

For an elastic thickness of 40 km, our inversion obtains mare thicknesses of ~ 8.5 km on average inside large nearside basins, which is significantly higher than in the plains outside (~ 1.3 km, Fig. 2). These basins contain $\sim 40\%$ of all mare materials, though their surface represents only 13% of that covered by mare.

An interesting product of the mare thickness map is the pre-mare topography, which is obtained after having removed the mare deposits and the mare-induced flexure (Fig. 3). The pre-mare topography is about 2 km lower than observed within the PKT region, reinforcing the long-wavelength asymmetric structure of the Moon, and the unique geophysical signature of the PKT region relative to the rest of the nearside. The nearside basins are found to be ~ 6 km deeper than currently observed.

Finally, our inversion also constrains the thickness of the pre-mare feldspathic crust (Fig. 3), which is ~ 6 km thinner within nearside basins than in crustal thickness models not correcting for the mare [16].

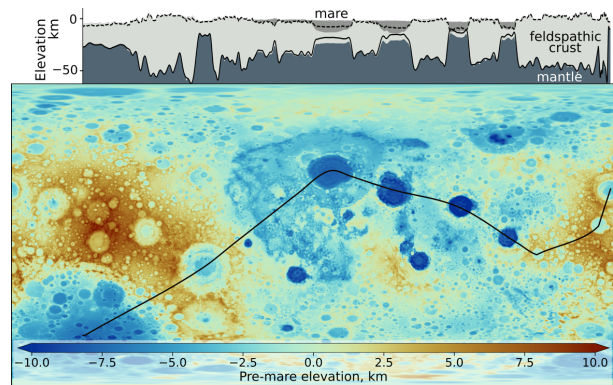


Figure 3: Pre-mare surface elevation and transect for the upper cross-section. Color-coded cross-section of the mare, feldspathic crust, and mantle. Lines indicate the pre-mare elevation (dashed), and crust-mantle interface (solid) for a constant crustal density of 2550 kg m⁻³.

Conclusion: Our fit to the tectonic and cratering record suggest a ~ 40 km elastic thickness at the time of mare emplacement. The associated global mare thickness map shows a strong mare concentration in the nearside basins. Our mean mare thickness is consistent with that of previous work [5,6,14], but we predict a different spatial distribution [4]. The total mare volume is found to be $\sim 2.3 \times 10^7$ km³, two times higher than typically assumed (e.g. [2]). However, our analysis better constrains the large volumes of mare within impact basins.

Our constraints on the lunar surface and crust prior to mare volcanism reinforce the unique geophysical signature of the mare region and the likely influence of the PKT region on the geodynamic evolution of the Moon [8]. These constraints are particularly useful for models that try to reproduce the crustal structure of large impact basins [17].

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