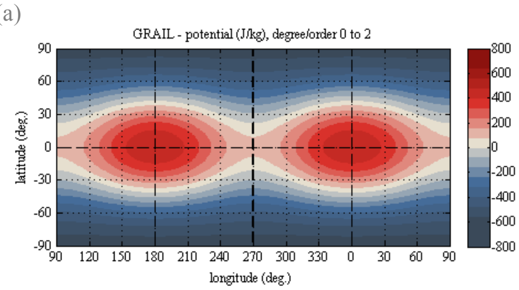
THE CONTRIBUTION OF MASCONS TO LUNAR FIGURE. J. T. Keane[1] and I. Matsuyama[1]; [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA (jkeane@lpl.arizona.edu).

Introduction: The Moon's figure is triaxial, due to the combination of rotational deformation (which acts to create an equatorial bulge), and tidal deformation (which acts to create a tidal bulge along the Earth-Moon vector). However, the observed lunar figure (Fig. 1a) is order of magnitudes larger than what would be predicted from hydrostatic equilibrium and the Moon's current orbital and rotational state (Fig. 1b). This difference has been ascribed to the presence of a fossil figure, preserving a time when the Moon was experiencing larger rotational and tidal potentials [1, 2, 3, 4]. Curiously, to completely explain the observed figure, it is necessary for the Moon to have formed on a high eccentricity orbit [3, 4], which is at odds with our current understanding of the formation and evolution of the Moon.

All previous work to determine the Moon's orbital and rotational state at the time the figure "froze-in" has assumed that the observed figure is due entirely to the fossil figure (or the relaxed remnant of the fossil figure [4]). However, lunar mass concentrations, or "mascons" [5], can have significant contributions to the lunar figure, and may be partially controlling the Moon's current orientation [6]. In this work, we seek to quantify the contribution of mascons to the lunar figure, using the newly available, high-precision, global, GRAIL gravity data [7]. By isolating the contribution of the lunar mascons, we can more accurately determine the Moon's "true" fossil figure, which can provide insight into the Moon's orbital and rotational history.

(a)



(b)

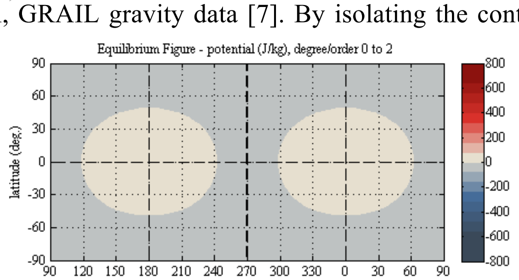


Fig. 1: (a) the observed lunar figure. (b) the lunar figure expected from hydrostatic equilibrium, and the Moon's current orbital and rotational state (with $k_2 = 1.5$) [4].

Modeling the Mascons: Lunar impact basins are characterized by central, large, positive free-air anomaly (the classical "mascon"), surrounded by a negative free-air anomaly ring, and outer positive free-air anomaly annulus. (In this work, we refer to this entire structure as the "mascon.") This gravitational "bullseye" signature is the result of the impact, excavation, collapse, and subsequent isostatic adjustment, and (in some cases) Mare infill [8]. Since the lunar figure (as quantified by its moments of inertia) is only dependent on degree-2 spherical harmonic gravity coefficients [9], it is not crucial to model all of these processes in detail to determine the mascon's contribution to the lunar figure. Instead, we opt for a simpler gravity model with each mascon represented by a linear combination of spherical caps.

Fig. 2 illustrates an example of our mascon fitting procedure for the Orientale basin (Fig. 2a). First, for each mascon we generate an array of spherical caps, spanning from within the central free-air anomaly high, to completely outside the entire "bullseye" structure. We analytically solve for each cap's free-air anomaly, gravitational potential, and corresponding spherical harmonic gravity coefficients. For any individual spherical cap, all three of these quantities scale proportionally with the the single cap surface density. We use weighted, damped least squares to determine the best fitting surface densities for the linear combination of caps in each mascon model. We fit both the free-air anomaly and gravitational potential simultaneously. To prevent directly fitting the fossil figure, we perform the fit from degree-3 and up. Once the best-fit surface density for each cap is found, we can apply that surface density to the cap's degree-2 coefficients to determine its contribution to the lunar figure. Fig. 2b & 2c show the resulting best-fit for the Orientale basin, and the residuals when it is subtracted out.

Results: We used our mascon fitting routine to remove the 31 largest mascons from the lunar figure (Fig. 3). We find that the lunar mascons only contribute a small amount to the overall lunar figure (as evidenced by the similarity of Fig. 1a and Fig 3d). Surprisingly, after subtracting the mascons from the lunar figure, we find that the fossil figure is *more deformed*: J_2 is 10% *larger*, and C_{22} is 2% *larger*. In future work, we will determine the orbital and rotational state that best reproduces this adjusted fossil figure. The residual, mascon-free, fossil figure is also not completely aligned with the current principal axes. This misalignment suggests either: (a) the mascons may have induced global reorientation (true polar wander), or (b) the fossil figure froze in during a period of higher obliquity [10]. Future work will investigate both possibilities.

In our analysis, we have ignored any contribution from South Pole-Aitken (SPA) basin. SPA is significantly larger than any other impact basin, and likely has a significant contribution to the global figure. SPA has been previously suggested as a driver for true polar wander [11, 12]. In future work, we will include SPA in our mascon analysis, and determine if it can provide additional insight into the mysterious lunar figure.

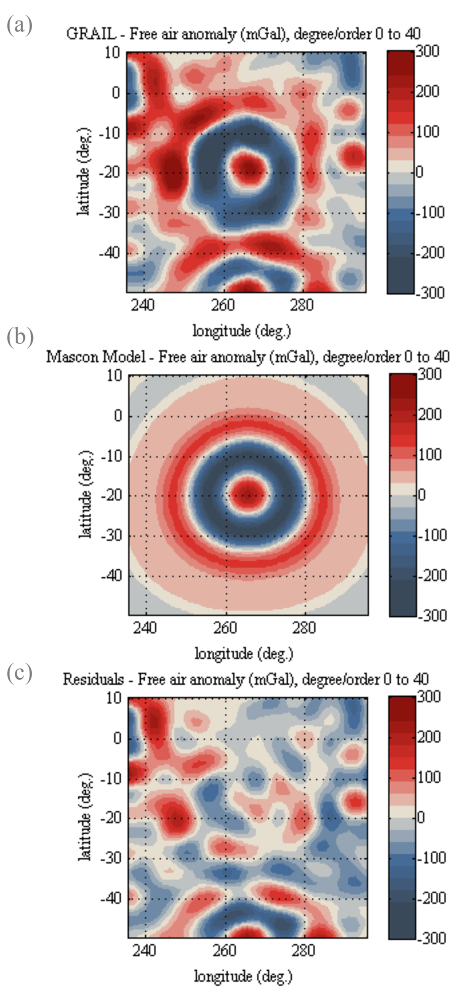


Fig. 2: (a) the observed free-air anomaly for Orientale basin. (b) the best-fit spherical cap model. (c) the residuals, after subtracting Orientale.

References:

[1] Jeffreys, H. (1915) *MNRAS*, 60, 187.
[2] Lambeck, K. and Pullan, S. (1980) *Phys. Earth Planet. Interiors*, 22, 29.
[3] Garrick-Bethell, I. et al. (2006) *Science*, 313, 652.
[4] Matsuyama, I. (2013) *Icarus*, 222, 411.
[5] Muller, P. M. and Sjogren, W. L. (1968) *Science*, 161, 680.
[6] Melosh, H. J. (1975) *Earth & Planet. Sci. Lett.*, 25, 322.
[7] Zuber, M. T. et al. (2013) *Science*, 339, 668.
[8] Melosh, H. J. et al. (2013) *Science*, 340, 1552.
[9] Konopliv, A. S. et al. (1998) *Science*, 281, 1476.
[10] Ward, W. R. (1975) *Science*, 189, 377.
[11] Ong, L. and Melosh, H. J. (2009) *DPS*, 41, 58.02.
[12] Ong, L. and Melosh, H. J. (2010) *LPSC*, 41, 1363.

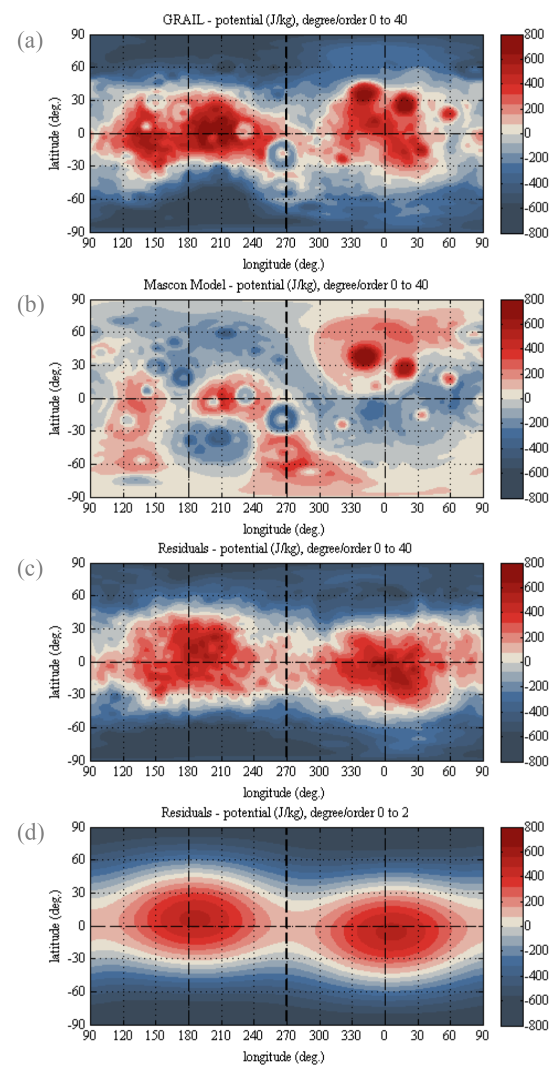


Fig. 3: (a) the observed gravitational potential, from GRAIL. (b) our model for the 31 largest mascons. (c) the residuals, after subtracting all of the mascons. (d) the degree-2 component of the residual, indicating the fossil figure.