LONG-WAVELENGTH LUNAR GEOLOGY AND THE FOSSIL BULGE. I. Garrick-Bethell[1] and M. T. Zuber[1], [1] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, iang@mit.edu.

Introduction: Ever since Laplace [1] it has been known that the Moon is not in hydrostatic equilibrium with its present tidal and spin state. Jeffreys considered the problem in 1915 [2], and showed in 1937 [3] that the ratio of the libration parameter α = (C-B)/A to β = (C-A)/B is 0.63, in disagreement with the predicted ratio of 0.25 for a synchronous satellite. Thus the idea that the Moon holds a "fossil bulge" of a past tidal-rotational state was difficult to accept. There are, however, at least several good reasons why the lunar fossil bulge hypothesis has persisted: the Moon's orbit evolved relatively close to Earth as it cooled, statistical noise in the lunar gravity spectrum cannot fully explain the high power of the low-order terms [4,5], the lunar lithosphere was able to support loads [6], and timescales of crystallization of the magma ocean are now slower than previously believed [7]. There are also good reasons to suspect the Moon may not bear a fossil bulge, such as insufficient time available to form a lithosphere thick enough to support the implied loads, and the fact that large-scale density heterogeneities cannot be ruled out.

Here we study the likelihood of a lunar fossil bulge by examining how large-scale geologic features influence the low-order shape and gravity of the Moon. This type of study is particularly relevant for the Moon, where large geologic units may confound our interpretation of low-order parameters such as the flattening and the equatorial ellipticity. Our ultimate goal is to "undo" the effects of these features in order to unveil a more primitive lunar shape. It is possible that collectively undoing multiple geologic events may reveal a gravity and topography field more coincident with a tidally-locked body. Whatever the result, we believe that this methodology should give insight into how large geologic units influence our evaluation of data generally modeled by global-scale physics and dynamics. In our analysis, in place of α and β we use the normalized gravity harmonic coefficients C_{20} = $9.09\text{x}10^{-5}$ and C_{22} = $3.46\text{x}10^{-5}$ [8], whose predicted ratio is ≈ 1 for synchronous rotation. The observed C_{20}/C_{22} ratio is 2.63. To assess the lunar shape, we examine the difference between the equatorial and polar radii, here represented by *a* and *c*.

South Pole-Aitken (SP-A) basin gravity: In an attempt to remove the gravitational effect of the largest impact structure on the Moon, we replaced the SP-A gravity potential with the potential of the northern farside, Fig. 1. The northern highlands is a relatively homogenous mare-free region and is arguably a reasonable estimate for the pre-SP-A region. Using a 60^{th} degree and order expansion, we replaced the potential southward of 30ºS, between 120ºE and 240ºE, with the reflected potential northward of 30ºN, between 120ºE and 240ºE. The boundaries of the southern region were chosen because the topographic effects of SP-A are clearly visible here (see Fig. 2). While this replacement process obviously does not perfectly recreate the pre-SP-A Moon (*e.g.* it ignores effects such as ejecta emplaced in the surrounding area), we feel that it is a good enough approximation for insight into the magnitude of change in the gravity field. Expanding the new gravity field to 60^{th} degree and order, we obtain C_{20} = $8.8\text{x}10^{-5}$ and C_{22} = $3.7\text{x}10^{-5}$, yielding a ratio of 2.4, or approximately 10% closer to the hydrostatic prediction. A modest improvement.

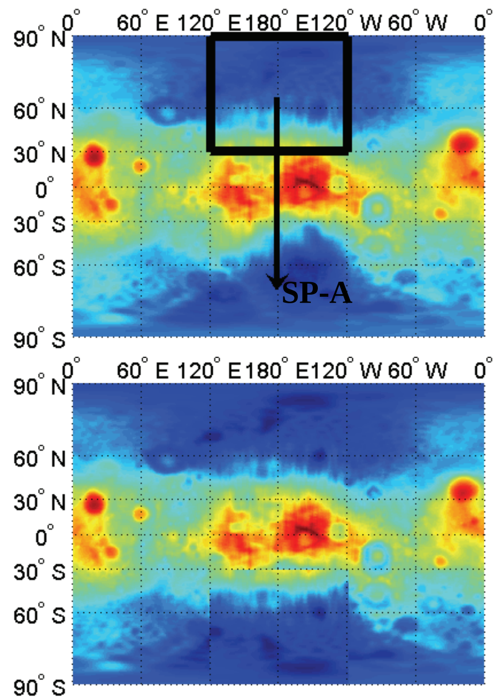

Fig. 1 Reflection of the northern farside gravity potential onto SP-A.

SP-A topography: The observed difference between *a* and *c* is 2.2 ± 0.5 km [9], certainly high enough to suggest a frozen remnant of a synchronous orbit closer than 20 Earth radii [10]. To test if undoing the SP-A topography would affect *a*-*c* significantly, we first approximated the bulk of SP-A as a circular area centered at (55ºS, 190ºE), with a radius of 800 km, Fig. 2. The volume of material required to fill in this area up to a lunar radius of 1738 km is $8.5\text{x}10^{6}$

km^3 using data of [9]. We then assumed that the elevated terrain north of SP-A is largely SP-A ejecta, as speculated elsewhere [6], and drew a border around the highest topography contours, Fig 2. A volume of 8.5x10^6 km^3 was then uniformly removed from the area. The volume of SP-A was then used to derive the required of height of a perfect cylinder of 800-km radius, and this height was added to all data points in the SP-A region. We then calculated the new *a-c* value using averages of points within 1 degree of the equator to obtain a value of 1.7±0.5 km. While this decrease from 2.2 km is substantial, the rapid decay of the flattening with increasing orbital radius makes the change insignificant for changing our assumptions about the fossil bulge; it is still much larger than the current predicted hydrostatic flattening of ~7 m [10]. However, this example shows how impact processes, even though exaggerated here, may have a significant effect on interpreting more sensitive parameters, such as the equatorial ellipticity [9].

Interestingly, when the center-of-mass/center-of-figure (COM/COF) offset is calculated for the new lunar shape, we find that the previous offset has moved the COF 4% closer to the COM in the eastward direction, and 12% closer in the Earth direction.

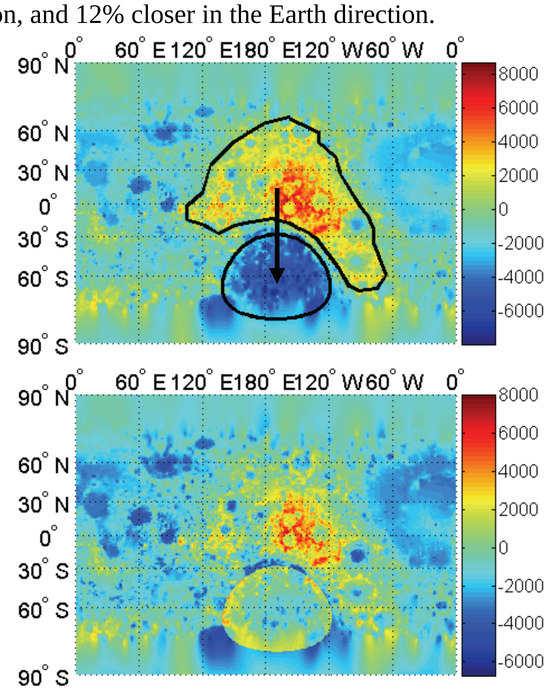

Fig. 2 Top: outline of SP-A and estimated ejecta. Bottom: SP-A volume filled-in. Units in meters.

Effect of nearside maria: We have also examined the effect of the main geologic feature on the nearside of the Moon, the lunar maria. In Fig. 3 we show a box enclosing much of the nearside mare, with notably high potential fields at the mare Imbrium and mare Serenitatis mascons. However, there are relatively high fields in non-mare areas, such as the area enclosed by corners at (0ºN, 0ºE) and (-30ºS, 30ºE), mapped as mostly hilly and furrowed terrain [11]. Rather than disentangle these units, we attempt to nullify the higher valued mare units by setting all potentials within the box that are greater than the mean potential in the box, equal to the mean potential in the box (Fig. 3). Expanding in harmonics yields $C_{20} = 8.4x10^{-5}$ and $C_{22} = 2.4x10^{-5}$, with a ratio of 3.5, a value further from hydrostatic equilibrium.

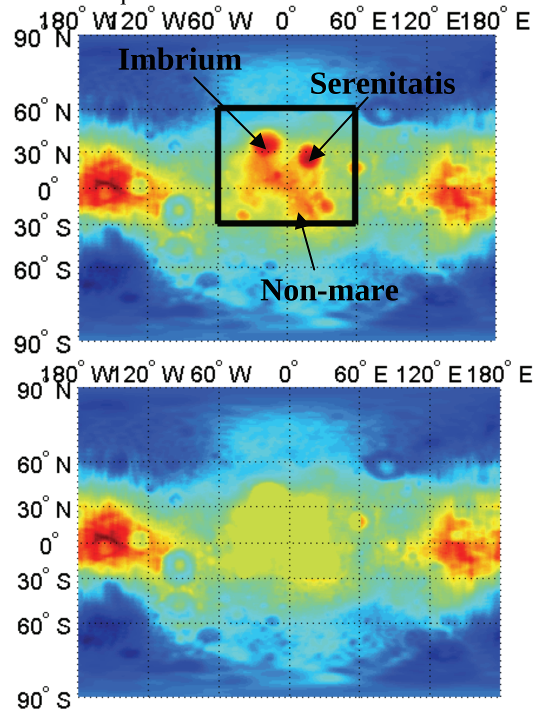

Fig. 3 Subtraction of near-side mare from the gravitational potential.

Conclusions: The lunar fossil bulge hypothesis is robust to long-wavelength influences of lunar geology. However, we cannot yet eliminate the possibility of stochastic internal density anomalies, and the problem of the anomalous C_{20}/C_{22} ratio remains.

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