THE TIDAL-ROTATIONAL SHAPE OF THE MOON AND EVIDENCE FOR POLAR WANDER.

I. Garrick-Bethell[1,2], V. Perera[1], F. Nimmo[1], and M. T. Zuber[3], [1]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064 USA (igarrick@ucsc.edu); [2]School of Space Research, Kyung Hee University, Yongin, South Korea; [3]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

Introduction: The origin of the Moon's large-scale topography is important for understanding lunar geology, orbital evolution, and the Moon's orientation in the sky. Previous hypotheses for its origin have included late accretion events [1], large impacts [2], tidal effects [3], and convection processes. However, testing these hypotheses is complicated by the large basins that have formed since the crust crystallized. Here we use least-squares regressions to estimate the low-order lunar topography and gravity spherical harmonics outside these basins. We find that a portion of the degree-2 topography is consistent with a crust-building process controlled by early tidal-heating throughout the Moon. The remainder of the degree-2 topography is consistent with a frozen tidal-rotational bulge that formed later, at a semi-major axis of ≈32 Earth radii.

Lunar topography and gravity power spectra: It has been argued that the Moon's degree-2 spherical harmonic gravity coefficients, which have traditionally been used as proxies for the degree-2 shape, are especially large when compared to higher degree coefficients. Figure 1 shows a "Kaula's rule" fit to degrees n = 3 to 50 for the Moon's gravity (GRAIL) and topography (LOLA) power. The power at degree-2 is 4.5 times and 2.6 times the power expected from extrapolating the best-fit power law, for gravity and topography, respectively, supporting the idea that the degree-2 coefficients are unique. This strong degree-2 power has been interpreted as a frozen tidal-rotational state inherited from when the Moon was closer to the Earth, known as the fossil bulge hypothesis. An open problem, however, has been that the ratio of the $C_{2,0}$ and $C_{2,2}$ spherical harmonic coefficients is different from the expected value by a factor of 2.6. Garrick-Bethell et al. 2010 [3] proposed that tidal heating [4] could have affected the farside degree-2 shape, but they did not reconcile their results with the fossil bulge hypothesis, and nor did they consider the global shape.

The Moon without large basins: The South Pole-Aitken basin (SP-A) is the largest, deepest, and oldest known lunar basin, and its degree-2 power affects our interpretation of the primordial degree-2 shape. In addition to SP-A, we focus on the 12 largest basins that produce obvious local anomalies in topography, crustal thickness, or gravity (in all, comprising 22% of the surface, Fig. 2a-c). To determine the Moon's degree-2 shape without these basins, we fit spherical harmonics of degrees n = 0 to 5 to data outside their boundaries, and used Monte Carlo methods to estimate uncertainties. Figure 2 shows the Moon's topography and appearance after rotation to the reference frame where the only non-zero degree-2 terms are $C_{2,0}$ and $C_{2,2}$, hereafter the "principal frame." If the Moon's outer figure, as opposed to its internal density distribution, once controlled the lunar moments of inertia, this would be the reference frame that once faced the Earth. This frame's largest principal axis is at (-6 ± 4°, 30 ± 1° E), its polar axis is at (54 ± 5°, 309 ± 6°), and its intermediate axis is at (-35.1 ± 5°, 296.4 ± 4°) (black points in Fig. 2).

Without the largest basins, the Moon's topography power spectrum displays substantially less variance at low degrees. Performing a power-law fit for n = 3 to 50 using the new power at degrees 3, 4 and 5 (Fig. 1, dashed red line), we find the degree-3 and degree-4 power is much closer to the Kaula's rule predictions. However, the degree-2 power remains in excess by a factor of 2.8. The Moon's strong degree-2 power, even without its large basins, implies that purely local explanations are less plausible.

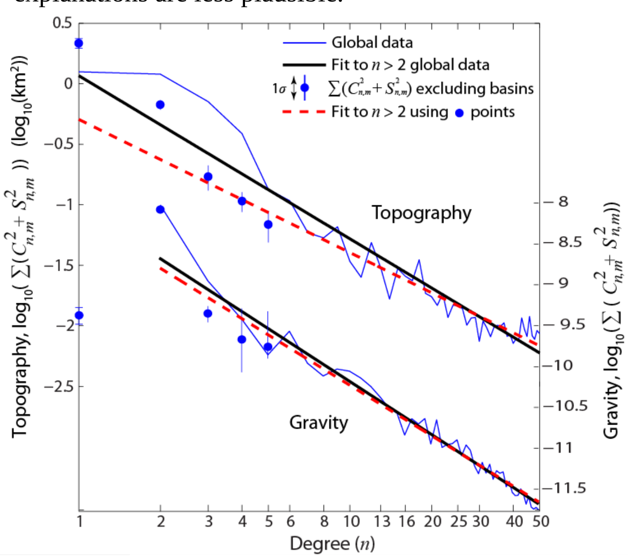

Fig. 1. Topography and gravity power spectra for the Moon, with and without large basins.

To address the origin of the Moon's primordial degree-2 shape, we must also consider the degee-2 gravity potential of the Moon (Fig. 2b). If we again fit degree-2 coefficients outside these basins, we find that gravity's largest principal axis shifts only 5 ± 2°, from (0°, 180° E) to (-5 ± 2°, 182 ± 1° E). In addition, the degree-2 gravity power decreases by a small amount, 12% (Fig. 1, blue dot). The weakness of the basins' effect on the degree-2 gravity potential is partly due to SP-A's nearly-compensated state, as well as its large contribution (45%) to the surface area removed.

Topography and gravity principal frames: The gravity and topography principal frame calculations above reveal a critical problem: the principal topography and gravity reference frames do not align presently (i.e. using global data), and nor do they when using degree-2 harmonics fit outside the largest basins. Using global data, the largest gravity and topography principal axes are separated by 34°, and using data outside large basins, the largest principal axes are separated by 30° ± 5°. Therefore, it is ambiguous which data set represents the primordial frame where any tidal-rotational effects were acquired.

However, a simple argument suggests that topography's principal frame formed first. Degree-2 tidally-produced crustal thickness variations, if they exist, must have developed early when the lithosphere was weak enough to permit significant tidal flexing, and will therefore be isostatically compensated (with a relatively small gravity signature). Furthermore, any uncompensated fossil component of shape, if it exists, must have frozen-in after the lithosphere cooled and degree-2 crustal-thickness growth largely ceased.

We may calculate the combination of compensated (crustal thickness) and uncompensated (fossil bulge) topography that match the observed $C_{2,0}$ and $C_{2,2}$ gravity and topography coefficients, in topography's principal frame (outside of large basins, Table 1) [4]. Table 1 also shows the ratios of $C_{2,0}/C_{2,2}$ for each type of topography. We find that the ratio for uncompensated topography is the same as the value predicted for a fossil bulge (≈ -1.0), and the compensated ratio is within the range expected when tidal heating is important (approximately -1.1 to -1.3). The statistics of the lunar topography and gravity coefficients suggest that the probability of both ratios falling randomly into the ranges expected from each process is less than 1%.

Conclusions: These results suggest that the early shape of the Moon was sculpted by two different tidal processes. Model calculations suggest tidal heating likely became unimportant after the Moon receded beyond 25 Earth radii, while the uncompensated topography harmonics imply a freeze-in location of 32 Earth radii. Eventually, gravity power must have developed in the $C_{2,1}$, $S_{2,1}$, and $S_{2,2}$ terms and reoriented the Moon to the configuration we see today.

References: [1] Jutzi M. and Asphaug E. (2011), *Nature 476*, 69-72. [2] Wilhelms D. E. (1987), USGS Prof. Paper 1348. [3] Garrick-Bethell I. et al. *Science 330*, 949-951 (2010). [4] Ojakangas G. W. and Stevenson D. J. *Icarus 81*, 242-270 (1989).

Table 1. Solution for the combination of compensated and uncompensated topography to match the $C_{2,0}$ and $C_{2,2}$ gravity and topography harmonics shown in Fig. 2d and 2e. The $C_{2,0}$ values do not sum to -0.65 km due to rounding.

	Compensated topography (± 1σ)	Uncompensated topography (± 1σ)
$C_{2,0}$	-0.53 ± 0.07 km	-0.11 ± 0.04 km
$C_{2,2}$	0.40 ± 0.06 km	0.11 ± 0.03 km
$C_{2,0}/C_{2,2}$	-1.3 ± 0.2	-1.0 ± 0.3

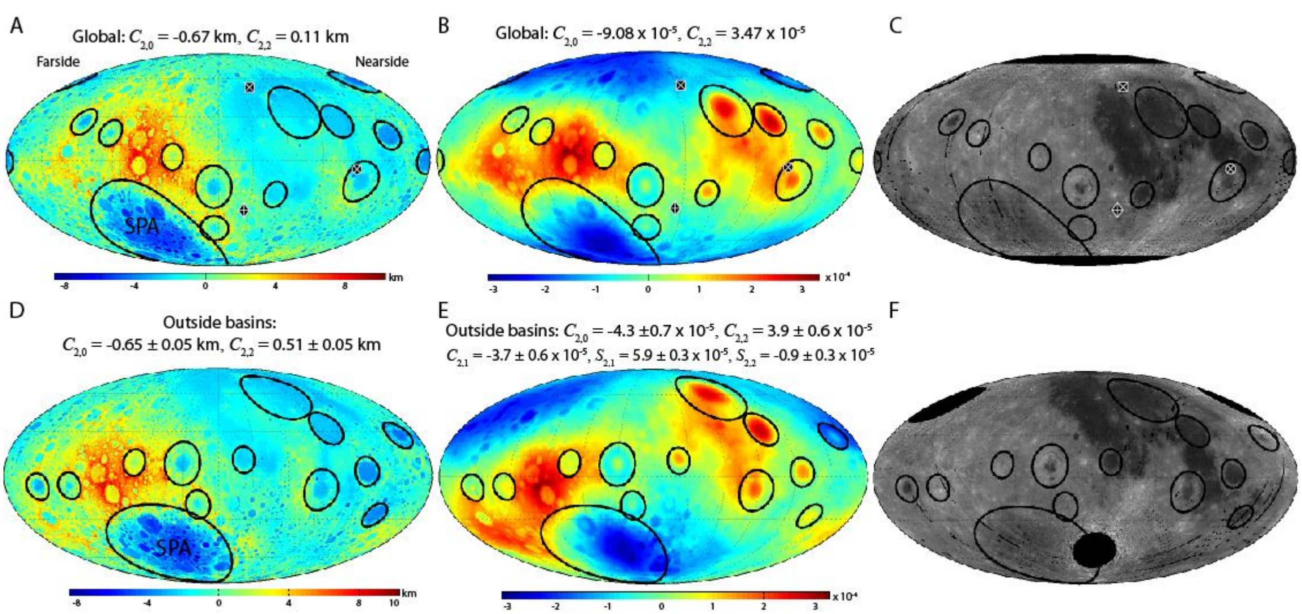

Fig. 2. (**A-C**) Topography, gravity potential, and 750-nm reflectance, respectively, in the present Earth-facing reference frame. (**D-F**) Parts A-C rotated into topography's principal frame, calculated outside of large basins.