How Much Does the Lunar Fossil Bulge Contribute to the Moon's Degree-2 Gravity and Topography Anomalies? Shijie Zhong[1], Roger J. Phillips[2], and Chuan Qin[1,3], [1]Dept. of Physics, Univ. of Colorado at Boulder, Boulder, CO 80309, USA, szhong@colorado.edu. [2]Dept. of Earth and Planetary Sciences, Washington University, St Louis, MO 63130, USA. [3]Now at Dept. of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA.

Introduction: The lunar degree-2 gravitational anomalies are about one order magnitude larger than predicted from hydrostatic theory for the Moon's present-day rotational and orbital states [1, 2, 3]. A common hypothesis for the Moon's excess degree-2 gravity anomalies is that it is a remnant feature, "frozen-in" from an early Moon that had a larger bulge because the Moon was closer to the Earth, spun faster and experienced larger rotational and tidal forces [4, 5]. As the Moon moved away from the Earth, it cooled and solidified from an early magma ocean, and the early bulge may have been kept or only partially relaxed [5]. However, other processes or sources including impact basins, crustal compensation, and mantle density anomalies may also generate degree-2 gravity anomalies. Two recent studies [2, 3], using different techniques, determined possible contributions from lunar basins to the gravity anomalies. The basin-corrected degree-2 gravity anomalies (i.e., l=2, m=0 and l=2, m=2) are about a factor of 17 larger than predicted from hydrostatic theory, and also show a ratio of C_{20}/C_{22} that further supports a fossil bulge origin [3]. The basin-corrected degree-2 topography displays a different sets of principle axes from the gravity [2], indicating that degree-2 gravity and topography may not be perfectly correlated.

Taking the basin-corrected gravity from [3] as entirely due to the fossil bulge, a recent study of ours [6] modeled this bulge formation process by considering a time-evolving tidal-rotational potential due to the lunar orbital recession and a lithospheric thickness increasing with time as the Moon cooled. Using the elastic plate thickness determined from mare basin studies as a proxy for lithospheric thickening with time, this study identified Earth's tidal dissipation Q-value as the key parameter for lunar bulge formation [6]. This study provided a satisfactory explanation of the degree-2 gravity anomalies of the Moon, namely that can be attributed to a fossil bulge. Based on the preferred Q-value, this study also proposed that the hydrosphere of the early Earth before 4 Ga may have been in a deep frozen "snowball" state, suggesting that the lunar degree-2 gravity anomalies or the fossil bulge may record important information about the early Earth.

However, it remains unclear whether or how much other processes contribute to the observed degree-2 gravity anomalies. For example, the large amplitude of the basin-corrected degree-2 topography from [2] has a significant power that may require that some fraction of it is supported by isostatic compensation, as might be expected from crust originating in early tidal heating [2]. This obviously would have an effect on the degree-2 gravity anomalies. The goal of this study is to seek to place constraints on how much the basin-corrected gravity and topography at degree-2 can be attributed to a fossil bulge formation process or other processes.

Degree-2 basin-corrected gravity and topography: Topography and gravity anomalies at long-wavelengths are often uncorrelated, because they are controlled by different processes. Hence, the basin-corrected gravity in [3] and topography [2] fields have different principle axes (i.e., the axes of a coordinate system in which C_{21}, S_{21}, and C_{22} coefficients disappear). We found the spectral power of degree-2 basin-corrected gravitational potential anomalies in the coordinate system of gravity principle axes (Fig. 1) to be 8.48×10^{-9} [3, 6]. In [2], degree-2 basin-corrected gravity and topography are given in the topography principle axes system. Although the gravitational coefficients in the topography principle axes system cannot be directly compared with those in [3], their powers, independent of coordinate systems (Fig. 1), can be compared. We found that the degree-2 power of basin-corrected gravitational potential from [2] is 8.30×10^{-9} [3, 6], nearly the same as that computed from [3]. This suggests that these two studies, while using different basin correction techniques [2, 3], basically arrived at the same results for the powers of basin-corrected gravity.

The normalized coefficients (indicated by overbars) of degree-2 basin-corrected topography are $\bar{C}_{20}$=-650 m and $\bar{C}_{22}$=-510 m [2]. We may estimate gravity anomalies produced by the topography anomalies, if they are completely compensated at the Moho. We found that the resulting gravity anomalies only account for 21% of degree-2 basin corrected gravity, which should be viewed as the upper bound of possible contribution from the crustal compensation on the gravity anomalies.

Degree-2 gravity and topography expected from a tidal-rotational fossil bulge: The fossil bulge topography can be estimated by scaling up its present-day hydrostatic value. The present-day hydrostatic bulge topography (zonal) is given by [6] as $\bar{C}_{20,h\_hd} =$

$-\frac{\sqrt{5}}{6g}\Omega^2 R_0^2 h_2$, where Ω is the present-day's lunar spin rate, h_2=2.5 as radial displacement fluid Love number, and g=1.63 m/s^2. Our results [6] is $\bar{C}_{20,h\_hd}$~10 m. Taking the fossil bulge to be 15-20 times of the present-day hydrostatic value as suggested by the gravity anomalies [3, 6], the bulge topography at l=2 and m=0 may range from -150 to -200 meters, which is 23-30% of the basin corrected topography at this harmonic [2]. This suggests that 70-77% of the degree-2 corrected topography from [2] may be compensated at the Moho. Considering that the crustal compensation would only account for ~21% of the gravity for completely crustal compensation, we suggest that ~15% of the basin corrected gravitational potential anomalies may be due to the crustal compensation, while the rest may result from the fossil bulge.

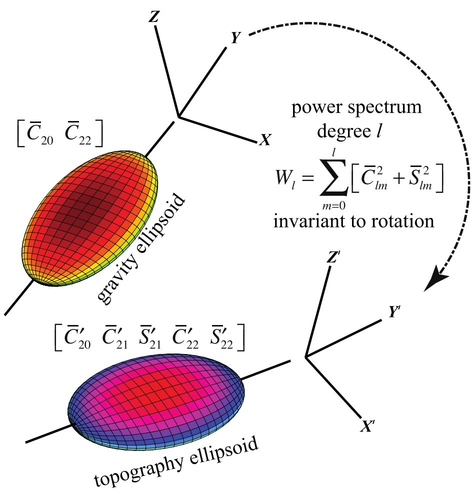

Figure 1. The 2nd degree (l = 2) and order (m) lunar gravity field can be represented by an ellipsoid whose axes coincide with the principal axes of inertia. The field is completely described by a polar oblateness coefficient (l = 2, m =0) and an equatorial ellipticity coefficient (l = 2, m =2). If the coordinate system is rotated out of the principal axis directions, e.g., to the principal axes of topography, then these terms change and the other three 2nd degree terms are no longer zero. If the coefficients are normalized (indicated by overbar), then the power spectrum of the gravity field is not affected by the rotation.

Compensation of crustal and mantle buoyancy with a lithosphere: However, the crustal compensation may be a more complicated process, depending on whether the loading is a surface or internal loading process and depending on elastic thickness at the time of loading. This has been discussed extensively for Mars in terms of the Tharsis gravity and topography anomalies [e.g., 7, 8]. The elastic thickness effect is particularly relevant here, given the relatively small planetary radius for the Moon [9]. The fossil bulge formation process as considered in [6] can be essentially viewed as a surface loading process with time-varying loads on a thickening elastic shell. Based on [8] that considered both surface and internal loading processes for a planetary mantle with an elastic shell, we may further constrain the relative contribution of crustal compensation. If the basin-corrected topography excess to a fossil bulge as given above is caused by internal loading such as crustal thickening (e.g., due to tidal heating [2]) with new crust added at the Moho, then the elastic shell may reduce the compensated topography at the surface, leading to negative contribution to the gravity anomalies from the crustal compensation. Therefore, to explain the basin-corrected gravity, the tidal-rotational fossil bulge effect may be required to be larger than that in [2, 6].

Conclusion: We found that the basin-corrected gravity anomalies by two recent studies [2, 3] have nearly identical power at degree-1, suggesting consistency of these studies. We determined that crustal compensation, while necessary to account for the degree-2 basin-corrected topography, may only account for <15% of the basin-corrected gravity. If the crustal compensation is due to response to internal loads such as tidal heating, an elastic shell may further reduce the contribution of crustal compensation to the gravity anomalies. This suggests that the lunar degree-2 gravity anomalies are largely caused by a fossil bulge formation process. Future studies may seek to place tighter constraints on contributions to the observed gravity anomalies from a fossil bulge and crustal compensation.

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