ISOLATING THE GRAVITATIONAL SIGNATURE OF THE LUNAR MANTLE FROM GRAIL.

David E. Smith[1] and Maria T. Zuber[1], [1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts of Technology, Cambridge, MA 02139 USA (smithde@mit.edu; zuber@mit.edu).

Introduction: The development of very accurate gravity models of the Moon from the GRAIL Discovery mission [1] is providing considerable insight into the crust and deep interior of the Moon [2-7]. Although gravity is not unambiguous, it is valuable in combination with other data, particularly topography, in the development of models that describe how the Moon formed and evolved. With high quality data sets for which uncertainties are well-characterized, physical models of the Moon's structure and evolution can be developed that have a high degree of confidence.

High-resolution free air gravity and topography are providing details of the properties of the lunar crust [2-4, 6] but the most accurate part of these fields are the longest wavelengths (lowest spherical harmonic degrees) where GRAIL has improved our knowledge by ~5 orders of magnitude with respect to previous data sets. The longest wavelengths sample the largest features on the Moon and, unlike the short wavelengths, provide information about the deep lunar interior.

Here we explore the possible implications of the long-wavelength gravitational signature measured by GRAIL for the structure of the lunar mantle and the possible presence of deep-seated density anomalies. We investigate the power and wavelength sensitivity of the GRAIL Bouguer gravity field and compare observations to the calculated gravitational signatures of density anomalies of various sizes at various depths and locations within the lunar mantle that might be expected from lunar evolution scenarios [*cf.* 7, 8].

Bouguer Gravity: Fig. 1A shows the lunar Bouguer gravity field to degree and order 120 derived from the GRAIL free air gravity model [9] and topography [10] obtained by the Lunar Orbiter Laser Altimeter (LOLA) [11]. The South Pole-Aitken (SP-A) basin is clearly visible, as are the highlands north of SP-A and the nearside mascons and farside basins, including Orientale in the lower center. Figs. 1B, 1C and 1D show the Bouguer field for 3 different wavelength bands.

Fig. 1B shows only the largest features, SP-A and the highlands. There is no evidence of any large basins or mascons and a possible conclusion would be that these features are not only small in terms of spatial scale in comparison to the smallest resolvable block (~1350 km), but also shallower since they have no detectable long-wavelength signal. In contrast, Fig. 1C for the range of spatial blocksize ~680 to 455 km, shows the major nearside mascons and hints of some farside basins. But there is no evidence of SP-A nor the

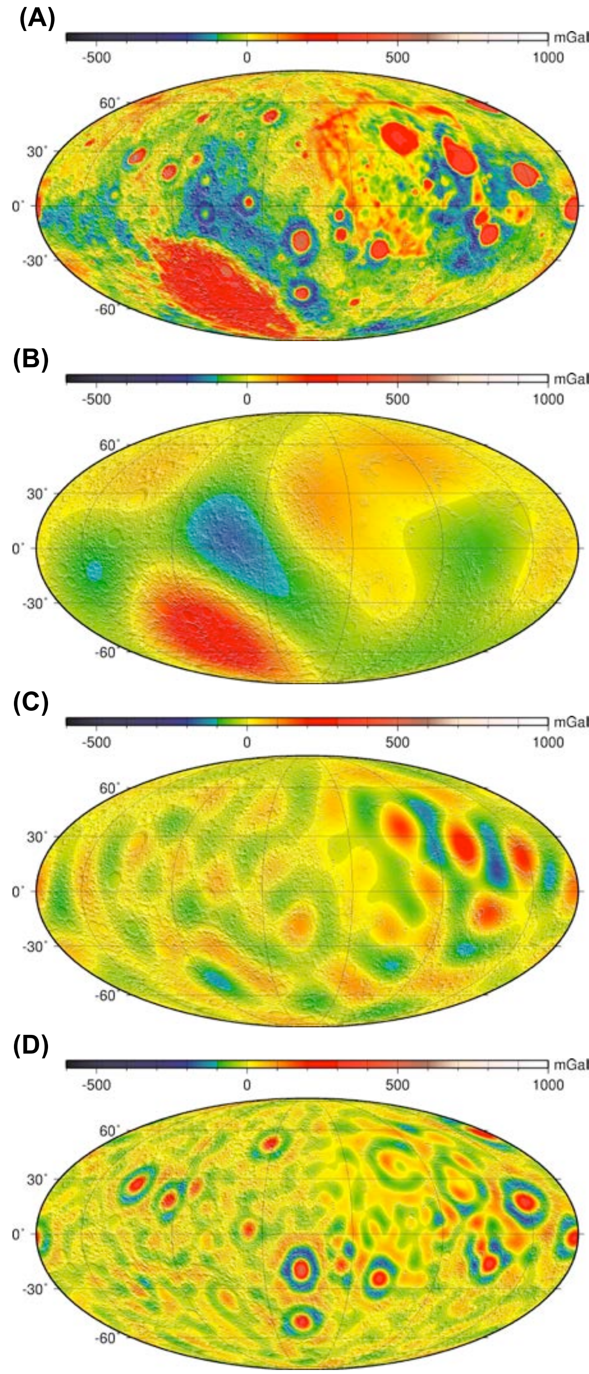

Figure 1. Mollweide projection of GRAIL Bouguer field [9], with the lunar farside on left and the nearside on right. **(A)** degrees 2 through 120; **(B)** degrees 2 through 4; **(C)** degrees 8 through 12; **(D)** degrees 16 through 32. Gravity is plotted over a shaded relief map of topography [10] for context and orientation.

highlands that are observed in Figs. 1A and 1B, suggesting that the mass anomaly that produces the Bouguer signature of SP-A is likely to be a deep-seated feature in which any short-wavelength structure is attenuated before reaching the surface.

Fig. 1D shows the smaller regional anomalies of ~340 to 170 km spatial scale. The nearside and farside basins are now evident and the nearside mascons show distinct differences among themselves. This observation represents additional support for the hypothesis of a significant mantle component to the mascons [12. 13] and illustrates a means of isolating the mantle signature. In Fig. 1D Orientale appears very similar in size and magnitude to the nearside mascons but is barely detectable in Fig. 1C, which suggests that the major contribution to Orientale's mascon anomaly is at shallower depth than the other major nearside mascon basins.

Forward Modeling: In an attempt to provide insight into the Bouguer observations, we next explore the sensitivity of the size and magnitude of buried masses represented by density contrasts of various shapes. For a variety of density contrasts and depths guided by: current knowledge of the Moon's internal structure [*cf.* 7], processes that are believed to have operated over the course of lunar evolution [*cf.* 8], and constraints from geochemical and petrological modeling [*e.g.,* 14, 15], we derive the magnitude and apparent shape of the gravity field on the surface, and its power spectrum for general comparison with individual, spectrally-filtered Bouguer anomalies. Fig. 2 schematically shows simplified models of internal mass anomalies conceivably arising from extensive melting and subsequent geochemical depletion associated with the magma ocean or other large-scale melting processes such as impact heating or plumes, impact-related brecciation and melt sheets, and dikes associated with early lunar expansion [4, 16].

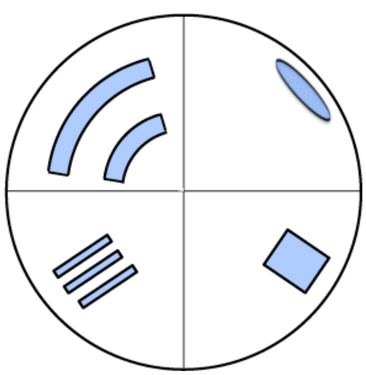

Figure 2. Cross section showing schematic examples of internal density contrasts under consideration.

We are very aware of the non-uniqueness of forward models of the Bouguer anomaly data and that a combination of different density contrasts due to compensation or other effect would change any result. However, the extraordinary quality of the GRAIL and LOLA data sets provides an unprecedented opportunity to restrict the range of possible explanations for mantle signatures in the gravity data based on incorporation of constraints provided by other remote sensing, sample and analog observations.

References: [1] Zuber M. T. et al. (2013) *Space Sci. Rev.,* doi:10.1007/s11214-012-9952-7. [2] Zuber M. T. et al. (2013) *Science 339,* doi: 10.1126/science.1231507. [3] Wieczorek M. A. et al. (2013) *Science 339,* doi: 10.1126/science.1231530. [4] Andrews-Hanna J. C. et al. (2013) *Science 339,* doi: 10.1126/science.1231753. [5] Williams J. G. et al. (2013) *J. Geophys. Res. Planets,* submitted. [6] Besserer J. et al. (2014) *Science,* submitted. [7] Wieczorek M. A. et al. (2006) *New Views of the Moon,* doi: 10.2138/rmg.2006.60.3. [8] Shearer C. K. et al. (2006) *New Views of the Moon,* doi: 10.2138/Rmg.2006.60.4. [9] Lemoine F. G. et al. (2013) *J. Geophys. Res. Planets 118,* doi: 10.1002/jgre.20118. [10] Smith D. E. et al. (2010) *Geophys. Res. Lett. 37,* doi: 10.1029/2010GL043751. [11] Smith D. E. et al. (2010) *Space Sci. Rev. 150,* doi:10.1007/s11214-009-9512-y. [12] Neumann G. A. et al. (1996) *J. Geophys. Res. 101*, 16,841-16,863. [13] Melosh H. J. et al. (2013) *Science 340,* doi: 10.1126/science.1235768. [14] Grove T. L. and Krawczynski M. J. (2009) *Elements 5,* 29-34. [15] Taylor G. J. et al. (2014) in prep. [16] Solomon S. C. (1977) *Phys. Earth Planet. Int. 15,* 135-145.