AN INTRUSIVE ORIGIN FOR LUNAR MASCONS: MAGMA ASCENT THEORY, GRAVITATIONAL SIGNATURES, AND TESTS FOR GRAIL.

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Introduction: The origin of the large gravity anomalies associated with lunar impact basins, or "mascons", has been a matter of debate since their discovery at the dawn of the age of lunar exploration. More recently, studies of basin structure have led to a prevailing model for producing the anomalies: super-isostatic uplift of the crust-mantle boundary, frozen in at the time of the basin impact [e.g., 1]. However, recent studies show that the immense amount of heat delivered to the surface of the Moon by basin-forming impacts [e.g., 2] makes it difficult to support superisostatic topography in the immediate post-impact era [3]. Thus, it is more likely that the super-isostatic load was emplaced after the central basin lithosphere had thickened (cooled) enough to support it [3].

Insights from intrusion theory: Studies of intrusive volcanism suggest a role for intrusive bodies as the hidden component of the broader volcanic system that is expressed at the surface as mare volcanism. For example, a compilation of magma emplacement and volcanic output gives ratios of intrusive to extrusive volumes in the ranges 5:1 for oceanic settings and 10:1 for continental ones [4]. While caution should be used in applying a rule of thumb derived from conventional terrestrial situations to the quite different tectonic (both small- and large-scale) and magmatic environment of the Moon, the existence of at least comparable volumes of magma at depth beneath basin-filling mare is quite plausible through this finding. Further, the emplacement of mare at the surface creates a flexural stress trap for magma in the mid-lithosphere [e.g., 5].

Tests for intrusive mascon formation from GRAIL:

Test 1: annular mascon signals. Mid-lithosphere intrusions can contribute to gravity anomalies via its own gravity signal and that of the surface. Caculations of the topographic effects of a sub-surface sill-like intrusion with diameter comparable to the mascon gravity signal (Fig. 1) show a central uplift with a flanking trough. If the basin fills with basalts to a more or less flat surface, the trough creates a basis for an annular signal. Strictly speaking, if the surface deformation were the same as the sill dimensions, there would be a nearly disk-like signal, but stiffness of material above acts as a plate that filters the response, so instead a strongly annular signal may be generated. Such a signal would not be expected from super-isostatic uplift, providing a way to distinguish these mascon models.

Test 2: rough mascon margins. Given the complex geometry and margin structure of intrusive complexes observed on Earth [e.g., 6], one might expect an hypothesized sill complex beneath basins, emplaced over a potentially broad timescale and subject to local and regional stress and structural inhomogeneities, to have a rougher margin structure than a super-isostatic crust-mantle boundary [1] formed nearly instantaneously during the impact process when the material was acting essentially as a fluid. If so, what could GRAIL tell us to distinguish between such origins? Figs. 2-4 show gravity calculated from a disk-shaped high-density body (reflecting either an intrusion or the upper part of a super-isostatic crust-mantle boundary uplift) with horizontal protrusions of scales from 90 km by 90 km, 60 km by 60 km , and down to the nominal GRAIL resolution of 30 km x 30 km. Fig. 1 At Kaguya altitudes (upper plane in Fig. 2), it is not possible to distinguish the protrusions from the main disk: at best, an elongation of the anomaly along the x-axis (nearest the two biggest protrusions) is the only evidence. However, at nominal GRAIL altitude of 50 km (lower plane in Fig. 2), anomalies at the 90 km and 60 km sizes can be identified (middle center and lower center of Fig. 3). The 30 km block leaves a signature too small to be discerned against background signals and noise at 50 km height. However, altitudes of 25 km or lower may be achieved in a GRAIL Extended Mission; at such altitudes, the 30 km by 30 km block becomes detectable.

Detections of subsurface gravity anomaly variations on the scales shown in Figs. 2-4 at mascon margins could be interpreted as evidence in favor of mascon intrusive complexes, although integrated studies of the volcanic and tectonic histories would be needed to fully evaluate this possibility. Future models of lithospheric loading with the COMSOL Multiphysics finite element modeling software will be performed to implement a quantitative study along these lines: the anomalous mass in Fig. 2 can also be a lithospheric load in models like that of Fig. 1, and multidisciplinary characterization and mapping of impact basins [e.g., 7, 8] can provide the context and evolutionary constraints to create a robust scenario(s?) for the basin and its volcanic and crustal structure. This coupled approach has been successful in modeling the emplacement of intrusive bodies at Etna volcano [9].

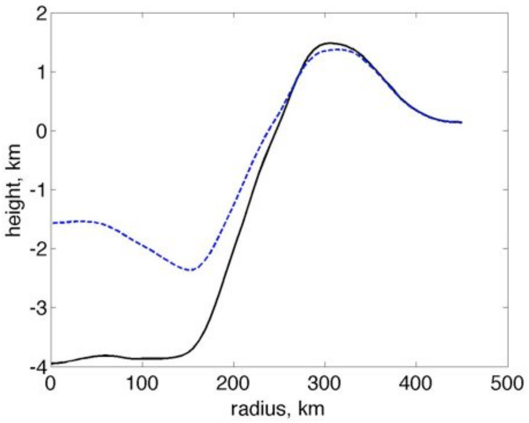

Figure 1: Effects of inflation of sill-like magma chamber under an impact basin, using a penny-shaped crack model [10] with a crack of diameter of 600 km and depth 20 km, overpressured to several percent over lithostatic. The black solid line is pre-impact topography of a 300 km diameter lunar basin, scaled from the Copernicus impact using a lunar basin depth-diameter relation [11]; the dashed blue line is post-inflation topography. Note that this topography is an upper bound due to subsequent subsidence (not modeled here) from the flexural response to the dense sill load.

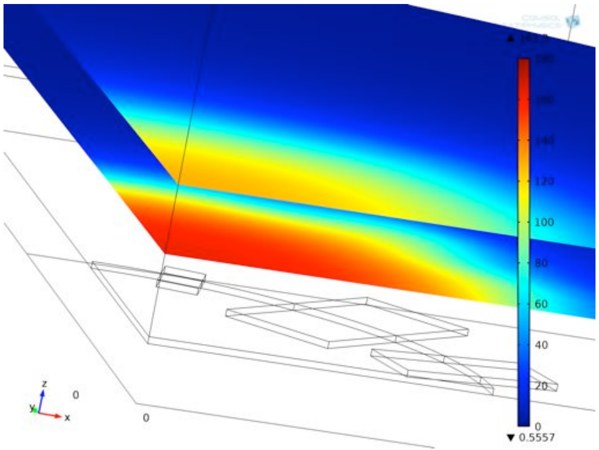

Figure 2: Perspective view of gravity anomaly sources and color slices of gravity anomalies (in mGal) at elevations above lunar surface corresponding to Kaguya (~100 km) and LRO and GRAIL (~50 km) nominal orbital heights above surface, calculated from COMSOL Multiphysics solutions to Poisson's equation for gravitational potential in 3-D geometry. X-y, y-z, and x-z planes are symmetry planes, facilitating calculation of the solution. Base source is disk with radius 250 km, half-thickness 5 km, and depth below lunar surface 15 km, corresponding to the shallow part of the Serenitatis mascon [e.g., 12]. Anomalous masses with characteristic trans-disk dimensions 60, 90, and 30 km, counter-clockwise from lower right, protrude outward from the central disk. Density anomaly for both disk and protrusions is 500 kg/m^3.

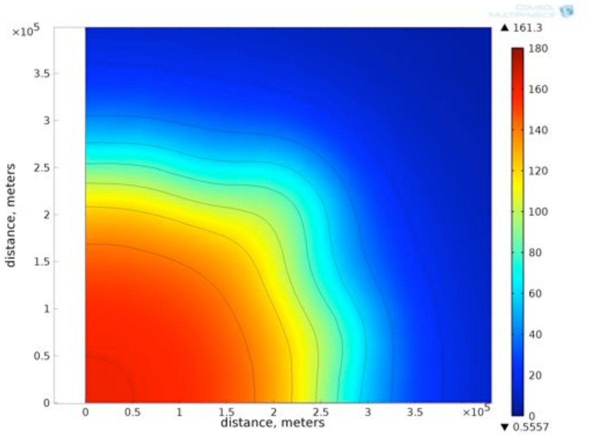

Figure 3: Color image of gravity anomaly (mGal) from sources in Fig. 1 at 50 km altitude (nominal LRO and GRAIL), with superposed contours.

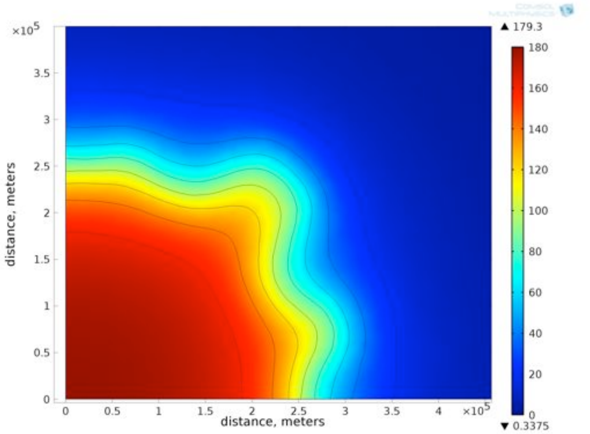

Figure 4: As in Figure 3, for 25 km altitude (potential GRAIL extended mission).

References:

[1] Neumann G. A. et al. (1996) *JGR 101*, 16,841. [2] Potter R. et al. (2011) *LPSC XLII*, abstract 1452. [3] Kiefer W. S. et al. (2011) *AGU Fall Meeting,* abstract *P33G-02.* [4] Crisp, J. A. (1984) *JVGR, 20*, 177. [5] McGovern P. J. and Litherland M. M. (2011) *LPSC XLII*, abstract 2587. [6] Thomson K. (2004) *Geol. Soc. Lond. Spec. Pub. 234*, 229. [7] Whitten et al. (2011) *J. Geophys. Res. 116*, doi:10.1029/2010JE003736. [8] Powell, K. E. et al. (2012) *LPSC XLIII* (this volume). [9] Currenti G. et al. (2007) *GJI 169*, 775. [10] Fialko Y. et al (2001) *GJI 146*, 181. [11] Williams K. K. and Zuber M. T. (1998) *Icarus 131*, 107. [12] Hikida W. and Wieczorek M. A. (2008) *Icarus 192*, 150.