The Origin of Lunar Mascon Basins

H. J. Melosh[1,2*], Andrew M. Freed[1], Brandon C. Johnson[2], David M. Blair[1],
Jeffrey C. Andrews-Hanna[3], Gregory A. Neumann[4], Roger J. Phillips[5],
David E. Smith[6], Sean C. Solomon[7,8], Mark A. Wieczorek[9] and Maria T. Zuber[6]

[1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA.

[2]Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA.

[3]Department of Geophysics, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401-1887, USA.

[4]Solar System Exploration Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

[5]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA.

[6]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA.

[7]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA.

[8]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.

[9]Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Univ Paris Diderot, 75205 Paris Cedex 13, France

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To whom correspondence should be addressed; E-mail: jmelosh@purdue.edu

High-resolution gravity data from the GRAIL spacecraft have enabled definitive understanding of the origin of lunar mascons. Gravity over lunar impact basins displays bulls-eye patterns of the free-air gravity anomaly consisting of a central positive (mascon) anomaly, a surrounding negative

anomaly collar, and an outer annulus of positive anomaly. We show that this pattern results from impact crater excavation and collapse followed by isostatic adjustment and flexure during cooling and contraction of a voluminous melt pool. We employed a hydrocode to simulate the impact phase and a self-consistent finite-element model to simulate the subsequent viscoelastic relaxation and cooling. The primary parameters controlling the modeled gravity signatures of mascon basins are the impactor diameter and velocity, the lunar thermal gradient at the time of impact, the crustal thickness, and the extent of volcanic fill.

High-resolution gravity data obtained from NASA's dual Gravity Recovery and Interior Laboratory (GRAIL) spacecraft have provided unprecedented high-resolution measurements of the gravity anomalies associated with lunar impact basins (1). These gravity anomalies are the most striking and consistent features of the Moon's large-scale gravity field. Positive gravity anomalies in basins partially filled with mare basalt such as Humorum (Fig. 1B) have been known since 1968, when lunar mass concentrations or "mascons" were first discovered (2). Mascons have subsequently been identified in association with impact basins on Mars (3) and Mercury (4). Previous analysis of lunar gravity and topography data indicates that at least nine such mare basins possess central positive anomalies exceeding that attributable to lava emplacement alone (5). This result is confirmed by GRAIL observations over basins that lack basaltic infilling, such as Freundlich-Sharanov (Fig. 1A), which are also characterized by a central positive free-air gravity anomaly surrounded by a concentric gravity low. These positive anomalies indicate an excess of subsurface mass beyond that required for isostatic (mass) balance—a "superisostatic" state. Mascon formation seems ubiquitous in lunar basins, whether mare-filled or not, despite their formation by impacts (a process of mass removal leaving a topographic low), making mascons one of the oldest puzzles of lunar geophysics, and their elucidation is one of the goals of the GRAIL mission.

The gravity anomaly structure of lunar mascon basins was previously attributed to mantle rebound during crater collapse (5, 6). This process requires a lithosphere beneath the basin capable of supporting a superisostatic load immediately after impact, a proposal that conflicts with the expectation that post-impact temperatures were sufficiently high to melt both crustal and mantle rocks (7). Alternatively, Andrews-Hanna (8) proposed that mascons are created by flexural uplift of a thickened annulus of subisostatic (a deficiency of the subsurface mass required for isostasy) crust surrounding the basin, concomitantly lifting the basin interior as it cooled and became stronger. This alternative model emphasizes the annulus of anomalously low gravitational acceleration surrounding all mascons (Fig. 1) (1, 9, 10), a feature previously attributed to thickened crust or brecciation of the crust during impact (5, 6). Many mascons also exhibit an annulus of positive gravitational acceleration outboard of the annulus of negative gravity anomaly, so the gravity structure of most lunar basins resembles a bulls-eye target (Fig. 1).

The role of uplift in the formation of mascon basins has been difficult to test because little is known about the mechanical state of basins immediately after crater collapse. Here we couple GRAIL gravity and lunar topography data from the Lunar Orbiter Laser Altimeter (LOLA) (11) with numerical modeling to show that the gravity anomaly pattern of a mascon is the natural consequence of impact crater excavation in the warm Moon, followed by post-impact isostatic adjustment (12) during cooling and contraction (13) of a voluminous melt pool. In mare-filled basins this stage in basin evolution was followed by emplacement of mare-basalt lavas and associated subsidence and lithospheric flexure. We have modeled the physics of these processes in a self-consistent manner that tracks the evolution of the temperature, density, and topography of materials within a basin as a function of time from impact to steady state. We employed a hydrocode to simulate the cratering process and then used the results as initial conditions for a thermomechanical viscoelastic finite-element model. These models track the evolution of free-air gravity anomalies, with the final steady-state anomaly compared with GRAIL data. We focus our study on two similar-sized end-member basins, one free of mare deposits (Freundlich-Sharanov) and one partially filled with mare basalt (Humorum).

We used the axisymmetric iSALE hydrocode (14-16) to simulate the process of crater excavation and collapse. Our models treat a typical lunar impact velocity of 15 km/s (17) into a two-layer target simulating a gabbroic lunar crust (density = 2550 kg/m^3; 18) and a dunite mantle (3200 kg/m^3). Our objective is to simulate the cratering process that led to the Freundlich-Sharanov and Humorum basins, which are located in areas where crustal thickness inferred from GRAIL and LOLA observations is 40 and 25 km, respectively (18). Ideally we would have studied two similar-sized, filled and unfilled basins within regions of similar crustal thickness, but most mare-filled basins tend to lie on the near side (thin crust), and most unfilled basins lie on the far side (thick crust). We sought a combination of impactor diameter and lunar thermal gradient that yielded an annulus of thickened crust at a radius of ~200 km, consistent with the annulus of negative free-air gravity anomaly around those basins.

The dependence of material strength on temperature and pressure has the most marked effect on the formation of large impact basins (19). With little certainty regarding the temperature-depth profile of the early Moon or the diameter of the impactor, we considered impactor diameters ranging from 30 to 80 km and three possible shallow thermal gradients, 10, 20, and 30 K/km, from a 300 K surface. To avoid melted material in the mantle, the thermal profile was assumed to follow that for a subsolidus convective regime (0.05 K/km adiabat) at temperatures above 1300 K. We found that impact at vertical incidence of a 50-km-diameter impactor in conjunction with a 30 K/km initial thermal gradient best matched the extent of the annular gravity low and led to an increase in crustal thickness of 10–15 km at a radial distance of 200–260 km from both basin centers (Fig. 2), despite the differences in initial crustal thickness. A more detailed description of this modeling procedure is found in the Supplementary Online Material (SOM).

A crucial aspect of the model is the formation of the subisostatic collar of thickened crust surrounding the deep central pool of melted mantle rock. The crust is thickened as the impact ejects crustal material onto the cool, strong preexisting crust. The ejecta forms a wedge approximately 15 km thick at its inner edge that thins with increasing distance from the center. As the preexisting crust is loaded by ejecta, it also subsides into the transient crater cavity, deforming downward plastically into a configuration that is maintained by the frictional strength of the cool (but thoroughly shattered) crust, as well as the viscoelastically weak mantle that requires time to relax; it is the subsequent relaxation of the mantle that leads to a later isostatic adjustment. The result is a thick, low-density crustal collar around the central hot melt pool that is initially prevented from mechanically rebounding from its disequilibrium state. The higher thermal gradient of 30 K/km, somewhat counter-intuitively, yields a thicker subisostatic crustal collar than the thermal gradients of 10 and 20 K/km. This occurs because the weaker mantle associated with a higher thermal gradient flows more readily during the collapse of the transient crater, exerting less inward drag on the crustal collar, which consequently experiences less stretching and thinning.

Calculations suggest that the impact into relatively thin crust at Humorum basin fully exposed mantle material in the central region of the basin (Fig. 2B), whereas a ~15-km-thick cap of shock-heated crustal material flowed over the central region of the Freundlich-Sharanov impact into thicker crust (Fig. 2A). This thicker crust is not melted, as it originates from cooler outer basin crust (much of it ejecta material) that migrates to the basin center during crater collapse. A time-sequence of this process is shown in the SOM. At the end of the crater collapse process, the basins (defined by their negative topography) are 4-5 km deep out to 150 km from the basin center, with shallowing negative topography continuing to a radial distance of 350-400 km, approximately twice the excavation radius. In both basins a substantial melt pool develops, defined as mantle at temperatures above 1500 K. This melt pool extends out to ~150 km from the basin center and to more than 100 km depth (Fig. 2).

To model the subsequent evolution of the basins, we used the finite element code Abaqus, which has been successfully employed to simulate a variety of post-impact processes (20, 21). We developed axisymmetric models of the

Humorum and Freundlich-Sharanov basins from the hydrocode output, adjusting the thermal structure of the melt to account for rapid post-impact convection and thermal homogenization of the melt pool. The density of solid and liquid silicate material was calculated from the bulk composition of the silicate Moon (22); details of these computations can be found in the SOM.

The gravitational anomalies predicted by the finite-element models at post-crater collapse conditions are shown as black lines in Figs. 1C and 1D for the Freundlich-Sharanov and Humorum basins, respectively; a description of our method for calculating gravity appears in the SOM. Our models show that basin excavation and the lower density of heated material combine to create a substantial negative free-air gravity anomaly at the basin centers. The initial anomaly in the center of Humorum is more negative than in Freundlich-Sharanov because thinner nearside crust led to the complete removal of crust after crater-collapse (see Fig. 2). Free-air anomalies become more negative with greater distance from the basin center (to > 200 km distance), due to thickening of the down-warped crust in the collar, then return to zero outside of the basin. The overall shape of the post-impact free-air gravity anomaly is similar to that observed, but is much more negative, suggesting that the general pattern of the observed gravity anomaly is the result of the impact, but that subsequent evolution of the basin drives the central anomalies positive.

As the impact-heated mantle beneath the basin cools, the pressure gradient from its exterior to its interior drives viscoelastic flow toward the basin center, uplifting the collar of thickened crust and the basin floor. The magnitude of this isostatic adjustment towards mass balance depends on the strength of the lithosphere. The models shown are for a dry gabbro crust and a dunite mantle with temperature-dependent viscosity similar to that of terrestrial oceanic mantle. The hot mantle beneath the basin center is initially viscous, but as it cools below the elastic-viscous transition (~1000 K) it becomes capable of supporting long-term loads. In the case of Freundlich-Sharanov, the 15-km-thick layer of cool crust possesses frictional strength from the beginning, whereas in Humorum the melted mantle strengthens only as it cools. Cooling increases the density of the melt through contraction, which drives inward flow of the surrounding mantle, but also causes the surface to subside modestly. The net effect is that cooling and contraction does not markedly influence the free-air gravity anomaly compared with isostatic uplift.

Isostatic uplift and cooling and contraction raise the surface topography of the Freundlich-Sharanov basin by ~1 km at the center of the basin and ~2 km in the region of the thickened crust relative to post-impact basin geometry (Fig. 3A). These effects place the final basin depth at ~3 km and the outer basin close to pre-impact elevations, consistent with LOLA elevation measurements (11). For the Humorum basin, the inner basin was calculated to rise ~0.5 km and the collar of thickened crust ~3 km. This uplift distribution would have left the Humorum basin ~4.5 km deep prior to mare fill, with the outer basin at or above pre-impact surface levels. Thus, though we can recognize the excavation radius of these basins based on current gravity and topography (6), our results suggest that depressed topography associated with crater collapse originally extended to about twice this distance.

The free-air gravity anomalies of both basins increased markedly after crater collapse as a result of isostatic uplift. The free-air anomaly of the Freundlich-Sharanov basin is predicted to have risen to a positive 70 mGal in the inner basin and -100 mGal in the outer basin above the thickened crust, in excellent agreement with GRAIL observations (1) (red line in Fig. 1C). Furthermore, the model predicts an outer annulus of positive anomalies, also in agreement with observations, though the predicted magnitude of this anomaly is too low. This underprediction is due to a jump in the observed elevation of ~3 km over a short radial distance, likely indicative of a circumferential fault scarp that is not treated in the model. This exception not withstanding, our results can fully match the bulls-eye target pattern of gravity anomalies observed around most unfilled lunar basins (1).

A similar increase in the free-air anomaly is observed in our model of Humorum basin (red line in Fig. 1D), although this gravity anomaly cannot be verified because the Humorum basin cavity was subsequently partly filled with mare basalt. Our results support the inference that lunar basins possess a positive gravity anomaly in excess of the mare load (5). As a final step in our analysis, we emplaced a mare unit 5-km thick, 150 km in radius (tapered to zero thickness over the last 50 km in radial distance), and with a density of 3200 kg/m^3 within the Humorum basin. This load causes the basin to subside 1 km from its post-impact 5 km depth (Fig. 3B), leading to a present-day 1-km-deep mare basin. The addition of the mare increases the mascon at the center of the Humorum basin to 320 mGal (blue line in Fig, 1D), matching GRAIL measurements (1), while modestly increasing the negative gravity anomaly in the region of the thickened crustal collar due to flexural uplift. This model somewhat underpredicts the magnitude of the negative anomaly in the outer basin, though it correctly predicts the outer annulus of positive gravity anomaly. Thus, the Humorum model can also account for the bulls-eye gravity anomaly pattern of mare basins.

This basin evolution scenario depends primarily on the diameter of the impactor, the thermal gradient of the Moon at the time of the impact, and the presence of a strong, low-density crust overlying a warm mantle. A high thermal gradient enables weaker mantle to flow more readily during the collapse of the transient crater, resulting in less inward motion and thinning of the crust. In contrast to hydrocode parameters that control crater excavation and collapse, such as the diameter of the impactor and the initial thermal gradient, the close match of our predicted free-air gravity anomalies with those observed by GRAIL is not a product of finding a special combination of finite-element model parameters associated with isostatic uplift and cooling. These processes are controlled by the evolution of the density and viscosity structure in the model, which follow from the mineralogy of the lunar crust and mantle and the evolution of temperature as the region conductively cools. In summary, GRAIL gravity and LOLA topography now provide collectively the resolution and data quality required to demonstrate how the observed gravitational signatures of mascon basins reflect the crust/mantle density distribution that arises in response to dynamical factors associated with the impact and modification stage of lunar basins.

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Figure Captions

Fig. 1. Free-air gravity anomalies over (**A**) the mare-free Freundlich-Sharanov basin (diameter to the center of the free-air gravity low: 425 km) and (**B**) the mare-filled Humorum basin (diameter to the center of the free-air gravity low: 425 km) from GRAIL observations (1). (**C**, **D**) Comparison of observed and calculated free-air gravity anomalies for the Freundlich-Sharanov and Humorum basins, respectively. The observed anomalies and associated one-standard-deviation uncertainties are derived from averages of the data within concentric rings at different radial distances. The black lines represent the predicted gravity anomaly just after impact and crater collapse, from the hydrocode calculation. The red lines represent the predicted anomaly after uplift following isostatic response and cooling, appropriate for comparison to the Freundlich-Sharanov data. The blue line in (D) represents the predicted gravity anomaly after mare emplacement in the Humorum basin and is appropriate for comparison to data for that basin.

Fig. 2. Cross section of crust and mantle geometry and thermal structure after crater collapse (2 hours after impact) for the (**A**) Freundlich-Sharanov basin (40-km-thick original crust) and (**B**) Mare Humorum basin (25-km-thick original crust), according to the hydrocode calculation.

Fig. 3. Finite element model calculated vertical displacement relative to the initial post-crater collapse configuration predicted by the hydrocode for (**A**) the

unfilled Freundlich-Sharanov basin, (**B**) the partially-filled Humorum basin. The red/white dashed line in (B) outlines the modeled 5-km-thick mare fill. The deformation is exaggerated by a factor of 5.