THE ORIGIN OF LUNAR MASCON BASINS, PART I. IMPACT AND CRATER COLLAPSE. Brandon C. Johnson[1], David M. Blair[2], Andrew M. Freed[2], H. J. Melosh[2], 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], Maria T. Zuber[6]; [1]Department of Physics, Purdue University, 525 Northwestern Avenue, West Lafayette, IN 47907, USA (johns477@purdue.edu); [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN 47907, USA; [3]Department of Geophysics, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, 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.

Preamble: This is part 1 of a two-part study on the origin of lunar mascon basins that combines a hydrocode calculation of the evolution of a lunar basin during impact and crater collapse (part 1) and a finite element analysis of subsequent cooling and isostatic adjustment (part 2) [1].

Introduction: Positive free-air gravity anomalies associated with large impact basins are the most striking and consistent features of the Moon's large-scale gravity field. In basins partially filled with mare basalt, such as Humorum (Fig. 1), these anomalies have been known since 1968, when lunar mass concentrations or "mascons" were discovered [2]. Previous analyses of lunar gravity and topography data indicate that at least nine of these mare basins possess central positive anomalies exceeding that attributable to mare emplacement alone [3, 4]. Such a configuration indicates an excess of subsurface mass beyond that required for isostatic (mass) balance—a "superisostatic" state. This result has been confirmed by observations by NASA's dual Gravity Recovery and Interior Laboratory (GRAIL) spacecraft over basins that lack mare infill, such as Freundlich-Sharanov (Fig. 1) [5]. GRAIL has provided unprecedented high-resolution measurements of the gravity anomalies associated with lunar impact basins that show mascon basins to generally be part of a broader bulls-eye pattern in which the central positive free-air gravity anomaly is surrounded by a negative anomaly collar, which in turn is surrounded by an outer annulus of positive anomalies (Fig. 1). How bolide impact, a process of mass removal that leaves a topographic low, leads to the formation of basins with subsurface mass excesses, remains one of the oldest puzzles in planetary geophysics.

Here we model the evolution of basin formation from impact to contemporary form by use of a hydrocode to simulate impact and crater collapse (i.e., the first several minutes of basin evolution), and we apply these results as initial conditions of a finite-element model [1] to simulate subsequent cooling and viscoelastic relaxation over the next several hundred million years. Design and testing of these models is guided by lunar gravity data from GRAIL and topography data from the Lunar Orbiter Laser Altimeter (LOLA) [6]. This process enables us to track temperature and density structure as functions of time, and therefore basin topography and gravity anomalies through the entire evolution of basin formation. In this manner we seek to understand how the diameter and velocity of the impactor, along with thermal conditions and crustal thickness at the time of impact, influence the formation of the free-air gravity anomaly bulls-eye pattern of mascon basins observed by GRAIL. Here we describe the hydrocode portion of the calculation with which we seek to find the combination of parameters (i.e., impact diameter and lunar thermal gradient) that leads to a basin excavation diameter and thickened crustal collar in agreement with LOLA and GRAIL data.

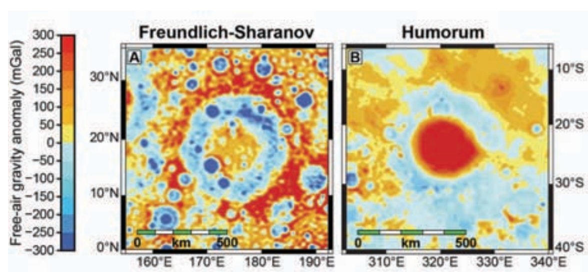

Figure 1. Free-air gravity anomalies over (**A**) the mare-free Freundlich-Sharanov basin (diameter of the center of the free-air gravity low: 425 km) and (**B**) the mare-filled Humorum basin (diameter of the center of the free-air gravity low: 425 km) from GRAIL observations [5].

Hydrocode Modeling Approach: We used the axisymmetric iSALE hydrocode to simulate the process of crater excavation and collapse. Our models treat a typical lunar impact velocity of 15 km/s into a two-layer target simulating a gabbroic lunar crust and a dunite mantle. Our objective is to simulate the cratering process that led to the Freundlich-Sharanov and Humorum basins, which are located in areas where the crustal thickness inferred from GRAIL and LOLA observations is 40 and 25 km, respectively [7]. 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. With the uncertainty 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 prior to the impact, 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.

Hydrocode Modeling Results: 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 is also drawn into the transient crater cavity, deforming downward into a subisostatic configuration. This arrangement is maintained by the frictional strength of the cool (but thoroughly shattered) crust, as well as by 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 difference 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, after crater collapse, the impact into relatively thin crust at Humorum leaves fully exposed mantle material in the central region of the basin (Fig. 2B), whereas the impact into relatively thick crust at Freundlich-Sharanov basin leaves a ~15-km-thick cap of crustal material in the basin's center (Fig. 2A). This crustal cap material is originally warm, weak lower crust that migrates to the basin center during crater collapse. This cap of crustal material is thinner for the 20 K/km thermal gradient and non-existent for the 10 K/km thermal gradient. For the lower thermal gradients this lower crustal material is cooler and stronger, allowing it to resist migration toward the basin center. At the end of the crater collapse process, the basins (defined by their negative topography) were 4–5 km deep out to 150 km from the basin center (in agreement with LOLA data), with shallowing negative topography continuing to a radial distance of 350–400 km, approximately twice the excavation radius. A substantial melt pool, defined as mantle at temperatures above 1500 K, developed in both basins. This melt pool extended out to ~150 km from the basin center and to more than 100 km depth (Fig. 2).

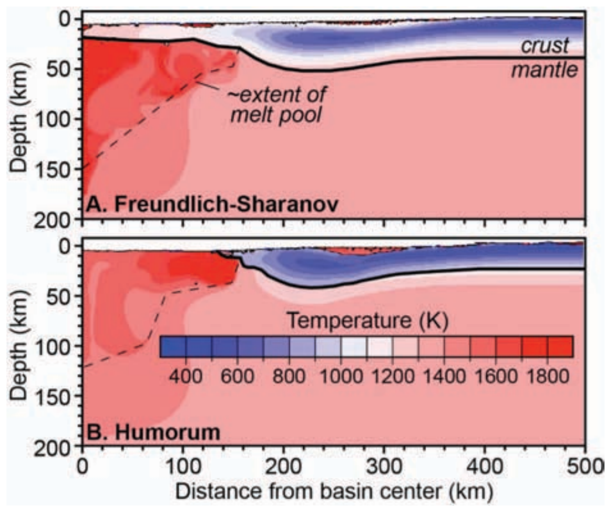

Figure 2. Vertical cross section of crust and mantle geometry and thermal structure after crater collapse (2 hours after impact) for the (**A**) Freundlich-Sharanov basin (40-km-thick original crust) and (**B**) Humorum basin (25-km-thick original crust), according to the hydrocode calculation.

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