THE ORIGIN OF LUNAR MASCON BASINS, PART II. COOLING AND ISOSTATIC ADJUSTMENT.

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Preamble: This is part 2 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) [1] and a finite element model (FEM) of subsequent cooling and isostatic adjustment (part 2).

Introduction: Previous analyses of gravity and topography observations of lunar mascon basins indicate an excess of subsurface mass beyond that required for isostatic balance—a "superisostatic" state [2, 3]. Gravity data obtained from NASA's dual Gravity Recovery and Interior Laboratory (GRAIL) spacecraft 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 a positive anomaly outer annulus [4] (Fig. 1). How bolide impact, a process of mass removal leaving a topographic low, leads to the formation of basins with excess subsurface mass, remains one of the oldest puzzles in lunar geophysics.

We modeled the evolution of basin formation from impact to contemporary form with a hydrocode to simulate impact and crater collapse, and we then applied these results as initial conditions for a finite-element model to simulate subsequent cooling, viscoelastic relaxation, and mare infilling (if applicable). We focused our study on two mascon basins that are of similar size, Humorum and Freundlich-Sharanov (Fig. 1), but differ in the thickness of the surrounding regional crust (25 and 40 km, respectively). Humorum is partially filled with mare basalt whereas Freundlich-Sharanov is unfilled. Crucial aspects of the hydrocode results were the formation of a subisostatic collar of thickened crust surrounding the excavation cavity and a deep melt pool. Here we discuss the finite element modeling with which we simulated the effects of subsequent cooling and isostatic adjustment, and how this outcome relates to the free-air gravity anomaly bulls-eye pattern of mascon basins observed by GRAIL.

Finite Element Modeling Results: To understand the evolution of the Humorum and Freundlich-Sharanov basins following crater collapse, we transferred the geometry, thermal, and density structures at the end of crater collapse from the hydrocode models to an axisymmetric Abaqus finite element model. The free-air gravity anomaly predicted by the FEMs at these post-crater-collapse conditions are shown as black lines in Figs. 1C and 1D for the Freundlich-Sharanov and Humorum basins, respectively. Our models show that basin excavation and the lower density of heated material combined to create a substantial negative free-air gravity anomaly throughout the basin region. The post-impact free-air anomaly is more negative with

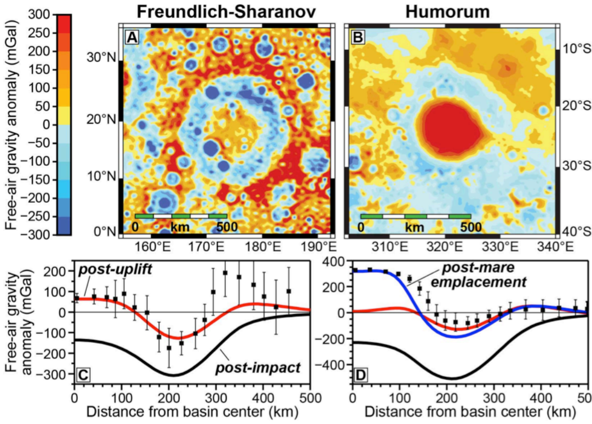

Figure 1. Free-air gravity anomalies over (**A**) the mare-free Freundlich-Sharanov basin (diameter of the center of the free-air gravity low: 425 km) and (**B**) the mare-filled Humorum basin (diameter of the center of the free-air gravity low: 425 km) from GRAIL observations [4]. (**C**, **D**) Comparison 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 transient cavity 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.

greater distance from the basin center (to > 200 km distance), due to thickening of the down-warped crust in the collar, and then returns to zero outside of the basin. The overall shape of the modeled 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 drove the central anomalies positive.

FEM calculations suggest that following crater excavation, higher overburden pressure outside the basin drove viscoelastic flow toward the subisostatic thickened crustal collar, causing the collar to be uplifted. A previous study of isostatic adjustment following crater collapse suggested that isostatic uplift of the thickened crustal collar concomitantly lifted the inner basin as well [5]. In that scenario, the basin center was assumed to be in isostatic equilibrium following crater collapse, then was uplifted due to a strong lithospheric connection to the uplifting crustal collar, leading to a positive free-air anomaly (mascon) at the inner basin.

Our calculations suggest a different scenario. Initially the lithosphere above the melt pool is too weak to cause the inner basin to be uplifted because of mechanical continuity with the lithosphere above the uplifting crustal collar. The inner basin does initially rise following crater collapse, but it does so because it is also in a subisostatic state following crater collapse, though not as far from isostatic equilibrium as the thickened crustal collar. Uplift of the inner basin causes it to reach isostatic equilibrium relatively quickly compared with the crustal collar, causing a mascon to form. However, as the crustal collar continues to rise, it draws in mantle from the surrounding regions, including the inner basin. This flow causes the surface of the inner basin to subside, reversing the development of a positive free-air anomaly and potentially removing the mascon.

Our calculations show that the final topography of the inner basin, and the associated gravity signal, depends on how quickly a strong lithosphere develops over the cooling melt pool. If a strong lithosphere develops by the time isostatic adjustment of the basin center is complete, the lithosphere will be able to resist subsequent subsidence, enabling a mascon to be maintained. The time to develop a thick lithosphere depends primarily on the thermal conductivity, whereas the timescale for isostatic adjustment depends on the viscosity structure.

If we assume a typical thermal conductivity for lunar mantle rocks (2.5 W/mK) and a temperature-dependent viscosity similar to that of terrestrial oceanic mantle with an elastic–viscous transition at ~1000 K, our models suggest that the lithosphere grows fast enough during cooling to prevent subsidence of the inner basin from fully removing the mascon.

The free-air anomaly of the Freundlich-Sharanov basin is predicted to have risen to a net positive 70 mGal in the inner basin, in excellent agreement with GRAIL observations [4] (red line in Fig. 1C). The negative free-air anomaly associated with the thickened crustal collar is also evident—isostatic forces reduced the magnitude of this negative anomaly from the post-impact configuration but did not remove it. Furthermore, the model predicts that an outer annulus of positive anomalies forms as crust outside the collar is uplifted as a result of a strong lithospheric attachment to the uplifting crustal collar. The magnitude of this outer anomaly is lower than observed, due to a fault scarp that is not treated in the model. This exception notwithstanding, our results fully match the bulls-eye pattern of gravity anomalies observed around most unfilled lunar basins [4].

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 was subsequently partially filled with mare basalt. Our results support the inference that lunar basins possess a positive gravity anomaly in excess of the mare load. The Humorum free-air anomaly is smaller than that of Freundlich-Sharanov. This difference is because impact into the thicker farside crust around Freundlich-Sharanov led to crustal cover over the melt pool that was not generated following impact into the thinned nearside crust where Humorum is located. Crustal cover provided a jump start to lithospheric growth over the Freundlich-Sharanov basin. Mare fill not withstanding, our models predict higher-amplitude mascons to form on the lunar farside due to its thicker crust.

As a final step in our analysis of the Humorum basin, we emplaced a 5-km thick mare unit within the excavation cavity of the basin and calculated the effects of the resulting subsidence on the gravity signature. 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 [3].

Summary: We can match the bulls-eye pattern of free-air gravity anomaly around lunar mascon basins as observed by GRAIL as the result of a two-stage process, the development of a subisostatic basin following crater collapse and subsequent cooling and isostatic adjustment. The primary parameters controlling the gravity signature are the impactor diameter and velocity, the crustal thickness and lunar thermal gradient at the time of impact, and the extent of volcanic fill.

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