Thermal Evolution of Lunar Impact Basins and Implications for Mascon Formation

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The gravity field of the Moon has long been known to have large positive free-air gravity anomalies over impact basins such as Imbrium and Orientale [1-3]. Large gravity highs over topographically low basins are not generally expected, and these observations require the presence of high density material somewhere in the crustal column beneath the impact basin. Although extrusive basalt flows are present at many but not all mascon basins, the available constraints on basalt flow thicknesses [4,5] are such that surface basalts by themselves can not account for the observed gravity anomalies. Thus, the consensus has been that some degree of super-isostatic mantle uplift beneath large impact basins is necessary [6-9]. Several recent studies have explored ways in which visco-elastic relaxation of the initial impact basin structure may create the required super-isostatic uplift of the mantle, either due to solidification of the impact melt pool beneath the basin center or by flow driven by an outer annulus of sub-isostatic material [10-13].

Post-impact Thermal Evolution

The impact energy associated with the formation of a large lunar impact basin significantly heats the lunar mantle beneath the impact zone. For an impact appropriate for the Orientale basin, hydrocode simulations using iSALE show that the resulting volume of partially molten mantle is roughly 150 km in radius and extends to a depth of about 200 km, with a total melt volume of $\sim 1\text{-}2\cdot 10^6$ km^3 [14]. This material has a density deficit of -30 to -60 kg m^{-3} relative to the ambient mantle and thus is a major contributor to the density structure that drives visco-elastic flow.

Existing visco-elastic flow models consider only conductive cooling of the melt pool. Due to the size of the melt pool, the conductive cooling time exceeds 10^8 years and is longer than the visco-elastic evolution timescale. However, due to the melt pool buoyancy, convective flow of the mantle plus melt system will also be important, resulting both in a much smaller cooling timescale and in advective redistribution of molten material. The buoyant melt will tend to rise up and flow laterally outward from the basin center, and the resulting thinner melt layer will cool more rapidly. Approximating this flow as a gravity current [15, 16], the melt pool may thin to one third of its original thickness in just a few million years. Porous flow in the partially molten melt pool may also be important. These changes in the buoyancy field are likely to significantly modify the post-impact visco-elastic flow beneath the basin and thus may degrade the fit to the gravity data. Finite element mantle convection models with strongly temperature-dependent rheology are being performed to further quantify this evolution.

Volcanic Intrusion Mascon Model

The crust below the impact zone is pervasively fractured (porosity 15-20% [17]), forming a reservoir for magma ponding within the crust. As an alternative model of mascon gravity anomalies, we proposed a layer of intrusive sills and dikes that thermally anneal the pore space and increase the density of the crust [18, 19]. At Orientale, the peak rate of volcanic extrusion was about 200 million years after the impact [5], allowing time for the lithosphere to cool and thicken after the impact and support a super-isostatic volcanic load. For likely densities and porosities of the feldspathic crust and intrusive basalt [20], the observed gravity anomaly [2] can be explained with an intrusive basalt layer with an effective thickness of 1.8 km. Extrusive volcanism is typically only about 0.2 km thick on the Orientale floor [5], so in this model the intrusive magmatism is about 90% of the total magmatism. This is consistent with typical intrusive/extrusive magmatism ratios observed on Earth. If applied to all lunar mascons, this model would be a significant enhancement to the inferred volume of lunar volcanism. An intermediate model, with mascon contributions from both visco-elastic evolution and intrusive volcanism, is also possible.

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