THE COLLAPSE OF SUPER-ISOSTASY: THE THERMAL EVOLUTION OF LARGE LUNAR IMPACT BASINS AND A VOLCANIC INTRUSION MODEL FOR LUNAR MASCON GRAVITY ANOMALIES

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Introduction

Gravity observations of the Moon have long been known to have large positive free-air gravity anomalies over impact basins such as Imbrium, Crisium, and Orientale [1-4]. It is not generally expected to find large gravity highs over topographically low basins, and these results require the presence of high density material somewhere in the crustal column beneath the impact basin. Two primary alternative models have been developed, involving either flexurally supported extrusions of dense mare basalts [5] or super-isostatic uplift of the crust-mantle interface [6]. Although extrusive basalt flows are present at many but not all mascon basins, the available constraints on basalt flow thicknesses [7-9] 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 [10-13].

If super-isostatic uplift of the mantle is present, it imposes a load on the lithosphere that will drive visco-elastic flow, which acts in the direction of relaxing the uplift towards an isostatic state. The rate at which basins relax depends strongly on the temperature and viscosity of the crust and mantle. A number of visco-elastic [14-16] or flexural [17] evolution models for lunar basin structure have been presented in recent years. However, these models have not considered the strong influence of impact heating of the lithosphere by the basin-forming impact. We show here that this heating allows very rapid relaxation of the basin structure and precludes the long-term preservation of super-isostatic mantle uplift.

As an alternative model of mascon gravity anomalies, we propose the existence of a thick layer of intrusive volcanic material filling the pervasively fractured pore space in the crust below the impact zone [18]. Such volcanism can occur long after the basin-forming impact, allowing time for the lithosphere to cool and thicken after the impact. This model is both an important modification to our understanding of large impact basin formation and a significant enhancement to the inferred volume of lunar volcanism.

Post-impact Thermal Structure

The impact energy associated with the formation of a large lunar impact basin will significantly heat the lunar mantle beneath the impact zone. Several research groups have explored this using the iSALE and CTH impact hydrocodes [19-22]. For an impact appropriate for large lunar basins (impact diameter ~60 km, impact velocity 15-18 km/sec), the mantle beneath the impact is partially molten to a depth of several hundred km and to a distance of about half the basin radius out from the basin center. This partially molten material has no long term strength, which has important implications for the post-impact evolution of basin structure. Because the impact heating decays with distance from the impact, the heating at the rim of the basin is small.

Long-term Thermal Evolution

The focus of this study is understanding how this impact heating affects the lithospheric structure of the Moon and thus the visco-elastic evolution and compensation state of impact basin structures such as mascons and basin rims. The initial thermal state in our models is based on the output of hydrocode simulations of the formation of an Orientale-size impact basin [20,21]. We assume that convection in the partially molten zone will rapidly cool the melt to the solidus and thus begin our modeling with the maximum temperature set to the pressure-dependent solidus temperature. Because of the approximate circular symmetry of many large lunar impact basins, we model the thermal evolution in spherical axisymmetric geometry. We use the spherical axisymmetric version of the well known convection code CONMAN, which has been previously used to study mantle plume volcanism on Mars [23, 24]. The basic conceptual approach of the thermal model is similar to other recent studies [25, 26]. Our models include radioactive heating at a magnitude appropriate for early lunar history [27, 28].

The time evolution of the elastic lithosphere thickness is calculated using a standard strength envelope approach [24]. The upper crust, lower crust, and mantle are represented by dry anorthite, dry diabase (as a proxy for norite), and dry olivine respectively. Brittle portions of the strength envelope are modeled using Byerlee's law. The initial lithosphere thickness at the center of the basin is at most a few kilometers and is controlled by the impact heating, independent of the pre-impact thermal state. As the lithosphere cools, its thickness increases to more than 20 km at the basin center 100 million years after the impact (Figure 1).

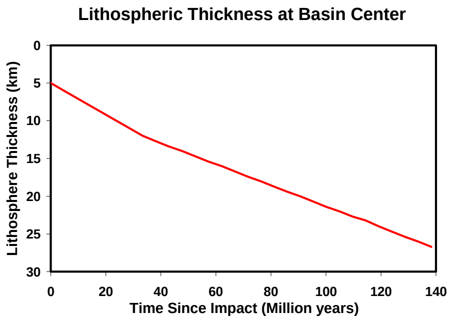

Figure 1. Elastic lithosphere thickening at basin center due to post-impact cooling of the lithosphere.

Visco-elastic Flow and the Collapse of Super-isostasy

We calculate the visco-elastic flow associated with super-isostatic uplift of the crust-mantle interface in an Orientale-size basin using the finite element code TEKTON [29]. In Figure 2, a degree of compensation of 1.0 corresponds to Airy isostasy and a degree of compensation of 1.5 corresponds to a large amount of initial super-isostatic uplift. The hydrocode post-impact thermal field corresponds to an effective near-surface thermal gradient of 20-25 K/km or more. For those thermal gradients, Figure 2 shows that any initial superisostatic uplift is largely relaxed in 100,000 to 10 million years. Thus, the large amount of super-isostatic uplift required by standard mascon models does not survive for geologically long times after the impact. On the other hand, impact heating does not alter the pre-existing thermal gradient at the basin rim. This is ~10-15 K/km at the time of the Orientale impact. Figure 2 shows that for such gradients, the relaxation time is very long, consistent with the long term preservation of the basin rim topography.

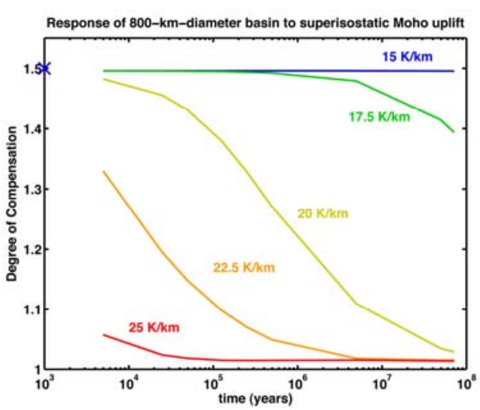

Figure 2: Visco-elastic relaxation time of an Orientale-size basin as a function of initial thermal gradient.

Volcanic Intrusion Mascon Model

Collectively, Figures 1 and 2 imply that any flexurally supported structure that contributes to the mascon gravity must be created at least 50-100 million years after the basin impact in order to allow the lithosphere to cool and thicken enough to provide at least partial flexural support for the load. At Orientale, the peak rate of volcanic filling was about 200 million years after the impact [9]. The crust below the impact zone must be pervasively fractured, forming a major reservoir for magma ponding within the crust. Calculations using the DISKGRAV modeling software [30] show that for plausible choices of basalt density, crustal porosity, and the rate of pore closure with depth, the volcanic intrusion model can explain the Orientale gravity anomaly [18]. Filling the pore space may be necessary to permit buoyant eruption of magma at the surface. Variations in the relative contributions of intrusive magmatism and surface lava flows may explain the different types of mascon documented by the Kaguya mission [13].

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