The Contribution of Impact Melt Sheets to Lunar Impact Basin Gravity Anomalies

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Introduction

A variety of density structures contribute to the gravity anomalies observed at lunar impact basins. In the centers of basins, both super-isostatic uplift of the mantle and lithospheric support of surface deposits of mare basalt can provide the super-isostatic dense material needed to explain the positive free-air gravity anomalies observed at lunar mascon basins [1, 2]. At greater distances from the basin center (> 150 km radius at Orientale), both thicker than average highland crust and low density impact-damaged material can provide sub-isostatic material to explain rings of negative free-air gravity anomalies [3, 4].

Another source of dense material near the basin center is the impact melt sheet. Large volumes of impact melt are expected to form from the impacts that produce lunar multi-ring impact basins [5, 6]. This study considers the expected gravitational signature of these melt sheets, focusing on the Orientale and South Pole-Aitken basins as examples.

Orientale Basin

The Orientale impact basin is the youngest large lunar impact basin (diameter 930 km, age 3.68-3.8 Ga [7]). Because of its relatively young age and limited amount of post-impact mare basalt filling, the basin structure is well exposed and has been mapped in detail [7, 8]. The final phase of NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission orbited at elevations of 2 to 11 km over the Orientale basin. The resulting gravity model has a resolution of 3-5 km over Orientale, which is the best resolution data obtained by GRAIL over any part of the Moon [9]. These data sets can be used to test geophysical models for melt sheet distribution.

Hydrocode models for the Orientale impact event [6] predict that essentially all of the pre-existing crust will be ejected by the impact within about 150 km of the basin center. Shock heating of the mantle produces a partially molten mixture of mantle-derived impact melt and solid mantle residuum. Immediately after the impact, the impact melt is distributed within 100-200 km of the basin center and extends to depths of at least 100 km. Accounting for the latent heat of melting, the preferred hydrocode simulations for Orientale produce 1.1-2.4x10^6 km^3 of mantle impact melt [6].

Because the melt is less dense than the residuum, it will tend to rise toward the surface. A two-phase flow calculation [10] shows that the melt and solid separate at a relative velocity of about 80 meters/year. This calculation assumes a melt viscosity of 1 Pa-s, which is appropriate for low silica, high iron lunar magma compositions [11]. This rapid velocity implies that the melt sheet is emplaced as a liquid layer near the surface within a few thousand years after the impact. For a final melt sheet radius of ~175 km that is confined within the inner ring of the Orientale basin [12] and assuming that 5-10% of the melt volume is ejected from the basin's transient cavity, the melt layer will be about 10-22 km thick when it has completely escaped to the surface. We refer to this as the impact melt sheet because of the large aspect ratio of the melt layer.

The timescale for cooling and solidification of the melt sheet depends strongly on the dominant heat transport mechanism. Cooling can occur by thermal conduction of heat to the top surface of the melt sheet. The base of the melt sheet is at the solidus, which limits downward conduction of heat. For the expected range of melt sheet thicknesses, solidification of the melt sheet by conduction takes about 10^6 years. This is longer than the estimate in [12], which used a sill-cooling model that assumes cooling both upward and downward from the melt sheet. If convection occurs in the melt sheet or if radiative cooling via exposed lava skylights in the top surface of the melt sheet are important, the cooling time will be reduced.

For the upper bound melt sheet cooling time of 10^6 years, an elastic lithosphere at the top of the melt sheet will be no more than a few kilometers thick. Such a lithosphere can not provide significant flexural support to a melt sheet that is 350 km in diameter. Thus, when it has solidified, the melt sheet should be close to isostatic equilibrium. The isostatic state of the impact melt sheet is in contrast to the visco-elastic mantle uplift in the basin center, which takes ~30 million years to be completed [2]. The longer time scale for mantle uplift allows development of a thicker elastic lithosphere, which can support the super-isostatic mantle for subsequent lunar history. The sub-isostatic ring of negative gravity anomalies at Orientale is sufficiently far from the basin center that impact heating is negligible. Thus, the elastic lithosphere in that region retains its pre-impact thickness and can support the sub-isostatic load.

Because the melt sheet is denser than the highland crust outside the basin rim, the melt sheet makes a positive contribution to the gravity anomaly observed in the basin center. The various melt sheet evolution scenarios in [12] result in grain densities (averaged over depth) in the melt sheet of 3000-3070 kg m^{-3}. Due to the relatively young age of the Orientale impact, we use the measured porosities in mare basalts, which average about 7% [13], as a guide to the melt sheet's porosity. Assuming that the porosity declines somewhat with depth, we assume an average melt sheet porosity of 5%. This implies that the bulk density of the melt sheet is 2850-2920 kg m^{-3}, which corresponds to a density contrast of 300-370 kg m^{-3} with respect to the mean density of the highland crust [4]. The resulting free-air gravity anomaly is 15-35 mGal, which is 5-10% of the total super-isostatic gravity anomaly observed at the Orientale basin.

Although the Orientale gravity anomaly is dominated by super-isostatic mantle uplift [2], the melt sheet is closer to the surface and the short wavelength components of the melt sheet gravity anomaly are not as strongly attenuated as similar wavelengths in the mantle uplift. Thus, it may be possible to isolate the signature of the melt sheet in the GRAIL gravity model for Orientale [9] despite its small fractional contribution to the overall gravity anomaly.

South Pole-Aitken Basin

The South Pole-Aitken (SP-A) basin is the largest and possibly oldest lunar impact basin (2050 by 2400 km, [14]). Hydrocode models predict a mantle impact melt volume of about 7×10^7 km^3 for SP-A [5], which is likely to solidify to grain densities in excess of 3180 kg m^{-3} [15, 16]. SP-A has a negative free-air gravity anomaly [17, 18], indicating that super-isostatic mantle uplift is not present at this basin. Mare basalt units are thin and cover only a small portion of the SP-A floor [19, 20]. The absence of these competing gravity signatures should facilitate an ongoing search for gravity evidence of the SP-A melt sheet.

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