The Density and Porosity of Lunar Impact Breccias and Impact Melt Rocks and Implications for GRAIL Gravity Modeling of the Orientale Impact Basin Structure

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Introduction

NASA's GRAIL mission has provided a highly detailed map of the Moon's gravity field, resulting in fundamental new insights into lunar crustal structure. One important aspect of study involves lunar impact basins. GRAIL data has been used to infer the thickness of the crust in the center of impact basins and the presence of a low bulk density, high porosity collar of ejecta surrounding large basins [1]. Results from the GRAIL "Endgame" gravity mapping of the Orientale basin provide an especially high resolution view of the structure of this archetypal basin [2].

Our previous measurements of lunar density and porosity [3] have been an important contribution to studies of lunar gravity data [1, 4, 5]. This abstract focuses on the density and porosity of Apollo impact breccias and impact melt rocks, which can be applied as input to gravity models of lunar impact basins. For example, the density of the impact melt sheet in the basin center is a key parameter in estimating the thickness of the crust within the basin, which in turn affects estimates of impactor energy and of post-impact mascon uplift.

Methods

We measured both the bulk density, ρ_{bulk}, and the grain density, ρ_{grain}, using non-containinating and non-destructive methods. The bulk density is based on the entire volume of the sample, including any pore space. The grain density is based solely on the solid material, excluding the pore space. Bulk density is important for calculation of gravity anomalies, and grain density is used for studying systematic trends in density as a function of rock composition. Porosity is calculated as $P=1-(\rho_{bulk}/\rho_{grain})$. Grain volume was measured by ideal gas pycnometry [6, 7]. Bulk volume was measured either by laser scanning (15 samples) or by immersion in glass beads (3 samples) [8, 9]. Errors determined by repeated sample measurements are typically $< 0.6\%$ for grain density and $< 0.4\%$ for laser scanned bulk densities.

Samples

We report measurements of the density and porosity of 20 rocks from the Apollo 14, 15, 16, and 17 landing sites that are impact breccias and impact melt rocks formed in large basin-forming impacts. Crystalline matrix breccias and an impact melt rock from Apollo 14 [10, 11] are samples of the Fra Mauro Formation, which is Imbrium basin ejecta. We have measured crystalline matrix breccias collected at a range of distances from the rim of Cone Crater, corresponding to a vertical sample through about 70 meters of the Fra Mauro Formation's stratigraphy. Apollo 15 impact melt rocks with norite clasts represent the melt sheet at the rim of the Imbrium basin [12]. Apollo 16 samples include material from both the Cayley Formation and the Descartes Formation and likely represent ejecta from both the Nectaris and Imbrium basins [13-15]. Excavation of material by both the North Ray and South Ray Craters provides sampling through about 200 meters of the local stratigraphy. Apollo 17 samples include both aphanitic and micropoikilitic impact melt rocks from the North and South Massifs [16, 17]. Chemical and petrological differences among the Apollo 17 sample suite have been interpreted as requiring the presence of material from multiple impact events [18], although the abundances of highly siderophile elements in these samples permit a single impactor [19]. Possible basin sources include Serenitatis, Imbrium [20], and possibly Crisium.

Approximately two-thirds of these samples have Al_2O_3 concentrations in the range 15-20 weight % [21]. This suggests derivation from a roughly 50:50 mix of mantle and crustal sources (the lunar crust has a maximum of 36.6 wt % Al_2O_3 (pure anorthite), while the lunar mantle is estimated to have 1.5-3 wt% Al_2O_3 in the mare basalt source region [22]). The remaining samples in our data set have Al_2O_3 of up to 30 wt %, indicating a preponderance of crustal material.

When using these density results to develop geophysical models of basins that are not included in the sample suite, one should be cautious about possible regional variations in composition across the Moon, which may influence the rock densities. The samples measured here mostly have FeO concentrations in the range 5-9 wt %. In contrast, remote sensing studies of the Maunder Formation (the Orientale basin's melt sheet) have measured a mean FeO concentration of 4.4±2.0 wt % [23]. Because our sample suite includes a range of compositions, we can apply a multi-variate analysis to estimate how grain density varies with composition (similar to the analysis for mare basalt densities in [3]). Such an analysis for the impact breccia density data set is presently being developed. Once completed, this analysis will allow us to estimate how the density of the Orientale melt sheet differs from the Apollo impact melt breccias.

Results

Figure 1 shows the bulk densities for these samples and Figure 2 shows the porosities. Half of the samples occur in a narrow peak at low density (mean 2490 kg m^{-3}, range 2440 to 2520 kg m^{-3}). Many of these samples are clast rich, and the samples with impact melt are highly vesicular. These samples have high porosities (mean 16.5%, range 11.5-21.1%). This is similar to the range of bulk densities and porosities observed around basins such as Orientale and Moscoviense [1]. There is also a more dispersed distribution of higher bulk densities (mean 2720 kg m^{-3}, range 2590-2830 kg m^{-3}). The high bulk density samples have lower porosity (mean 8.8%, range 5.5-15.8%). These samples are dominated by impact melt and the variation in density depends at least in part on the degree of sample vesicularity.

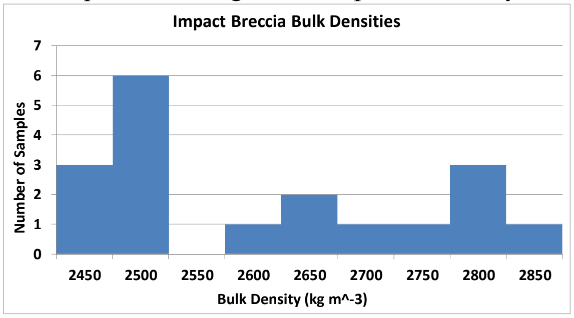

Figure 1: Histogram of impact breccia and melt rock bulk densities. Each bin is 50 kg m^{-3} wide, e.g., the 2500 kg m^{-3} bin includes values from 2475 to 2525 kg m^{-3}.

Estimates of the Moon's crustal thickness using GRAIL data depend on the assumed density difference between the crust and mantle. Initial GRAIL results used a crustal density of 2550 kg m^{-3} [1], which is appropriate for most of the feldspathic highlands but may not be correct for basin melt sheets. However, if instead one uses an average bulk density of 2720 kg m^{-3} for the central melt sheet, the inferred crustal thickness increases by ~25%. If vesicularity decreases with depth (pressure), then the higher average bulk density would further increase the inferred melt sheet thickness. The impact melt volume is one of the major predictions of hydrocode models of impact basin formation [e.g., 24]. The impact melt pool initially extends to a depth of 100 km or more, but the melt migrates rapidly to the surface by Darcy flow to form a melt sheet of ~10-20 km thickness [25]. The GRAIL gravity results can measure the thickness of this melt sheet and thus can provide an important new constraint on impact basin formation models and impactor energy. Specific results for Orientale are discussed by Zuber et al. [2].

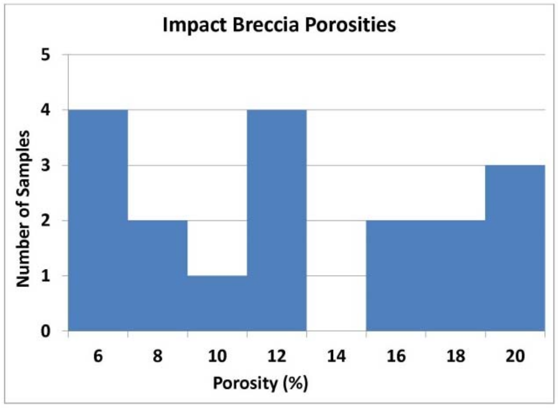

Figure 2: Histogram of impact breccia and melt rock porosities. Each bin is 2% wide, e.g., the 6% bin includes values between 5 and 7% porosity.

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