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

Walter S. Kiefer[1], Robert J. Macke[2], Daniel T. Britt[3], Anthony J. Irving[4], and Guy J. Consolmagno[2], [1]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, kiefer@lpi.usra.edu , [2]Vatican Observatory, V-00120 Vatican City State, [3]Dept. of Physics, University of Central Florida, Orlando FL, [4]Dept. of Earth and Space Sciences, University of Washington, Seattle WA.

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, 2].

Our previous measurements of lunar density and porosity [3] have been an important contribution to studies of lunar gravity data [1, 4, 5] and are essential for interpreting the gravity structure 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. Our results also have implications for hydrocode models of large impacts. These results for impact breccias include our first measurements of bulk volume by laser scanning.

Methods

We measured both the bulk density, ρ_{bulk}, and the grain density, ρ_{grain}, using non-containminating 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]. Errors are determined by repeated measurements of each sample and are typically 10-20 kg m^{-3} (< 0.6%) for grain density provided that the sample mass exceeds 10 gm. Bulk volume was measured either by laser scanning (15 samples) or by immersion in glass beads (3 samples) [8]. Laser scanning produces results with smaller uncertaintites and less fear of contamination than for bead immersion. Scanning also permits measurements of samples that are too friable or too large to measure by bead immersion.

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 [9, 10] 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 [11]. 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 [12-14]. 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 [15, 16]. Chemical and petrological differences among the Apollo 17 sample suite have been interpreted as requiring the presence of material from multiple impact events [17], although the abundances of highly siderophile elements in these samples permit a single impactor [18]. Possible basin sources include Serenitatis, Imbrium [19], and possibly Crisium.

We have also made measurements of many lunar meteorites. Some of these, such as Northwest Africa 482 [20] and Sayh al Uhaymir 300 [21] are impact melt breccias that are likely the product of large impact events. Because of the lack of field context for the origin of these samples, we have not incorporated them into the current study, but those measurements do not alter any of the conclusions described here.

Results: Bulk Densities and Porosities

Figure 1 shows the bulk densities for these samples. 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.

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. In turn, this would increase the impact energy required to produce the necessary melt volume.

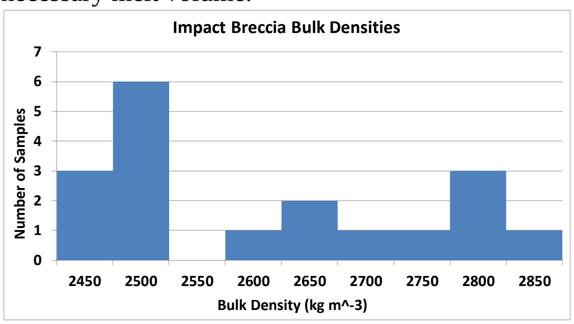

Figure 1: Histogram of impact breccia and melt rock bulk densities. Each bin is 50 kg m^{-3} wide, e.g., the 2500 kg m^{-3} bin includes values from 2475 to 2525 kg m^{-3}.

Results: Melt Sheet Grain Densities

Two competing models for basin melt sheet composition exist. Hydrocode simulations find that most or all of the crust is ejected from the basin (depending on the pre-impact crustal thickness) and that the impact melt pool is composed primarily of mantle material [22, 23]. Alternatively, petrological models of impact melt sheet differentiation assume that about half of the material incorporated into the melt sheet is from the crust [24, 25].

Our results for the grain densities of basin impact breccias and melt rocks show a strong peak between 2990 and 3100 kg m^{-3} (Figure 2). This peak includes material from the Imbrium and Serenitatis rims as well as distal basin ejecta from Apollos 14 and 16. This range of grain densities is consistent with the depth-averaged range of densities predicted by the melt sheet differentiation models [24, 25]. Grain densities between 2800 and 2900 kg m^{-3} in Figure 2 may represent samples from the upper part of a differentiated melt sheet. None of our samples show grain densities of ~3300 kg m^{-3} that would be indicative of a purely mantle origin. This is consistent with the composition of these samples, with Al_2O_3 > 16 weight %, which requires a significant crustal component in the melt. A speculative interpretation is that the observed impact melt grain densities and compositions are due to some form of turbulent mixing between crust and mantle during the initial impact phase that can not be captured in current hydrocode models because of grid resolution and uncertainties in the high stress rheology of shock melts.

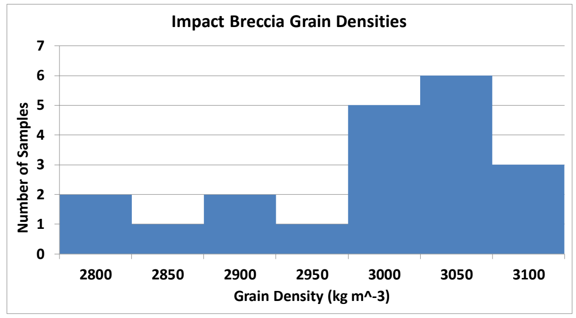

Figure 2: Histogram of impact breccia and melt rock grain densities.

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