DENSITY AND POROSITY OF APOLLO LUNAR BASALTS AND BRECCIAS. R. J. Macke[1,2], W. S. Kiefer[3], D. T. Britt[1], A. J. Irving[4], and G. J. Consolmagno[5]; [1]University of Central Florida Department of Physics, P.O. Box 162385, Orlando FL 32816-2385, macke@alum.mit.edu, britt@physics.ucf.edu; [2]Boston College, Chestnut Hill MA; [3]Lunar and Planetary Institute, Houston TX 77058, kiefer@lpi.usra.edu; [4]University of Washington Department of Earth and Space Sciences, Seattle WA 98195, irving@ess.washington.edu; [5]Vatican Observatory, V-00120 Vatican City State, gjc@specola.va.

Introduction: Data on the Moon's gravity and topography, as provided by missions such as Lunar Prospector, Kaguya, Lunar Reconnaissance Orbiter, and the current Grail mission, can constrain our understanding of the Moon's internal structure. In order to take advantage of this flood of data to understand the Moon's interior, we have been developing a comprehensive database of lunar rock densities and porosities. Prior to our work, few measurements of lunar rock porosity or hydrostatic density measurements could be found in the literature.

In developing such a database, it is important to include contributions from both lunar meteorites and samples collected directly from the lunar surface. Meteorites may sample a broader diversity of geologic types and a larger portion of the lunar surface, but specimens collected during the Apollo missions provide invaluable information about the geologic context where the rocks originated. This in turn aids the interpretation of density and porosity data as it pertains to the total lunar surface.

We have in the past reported preliminary findings on our results for five Apollo lunar samples and numerous lunar meteorites [1,2]. Recently we were granted access to an additional seventeen Apollo samples, which expands our database considerably. Included among the new samples are two high-Ti basalts (10017 and 70215), which had previously been unrepresented in our database. Samples from all six successful missions are now included. We report here the preliminary findings of these 22 Apollo lunar samples; for their application to lunar surface density models, we refer the interested reader to [3].

Measurement: Our methods, which are fast, non-destructive and non-contaminating, are detailed in [4].

Grain density is measured by helium ideal-gas pycnometry. The small atomic radius of helium allows it to diffuse rapidly along microfractures and grain boundaries, thus providing the best possible determination of grain density and subsequently porosity. In contrast, prior measurements of porosity in lunar samples (e.g. [5]) typically required immersion of samples in toluene, which might not fully penetrate pore space and thus would underestimate porosity (as well as risk sample contamination).

Bulk density is measured by the glass bead method developed by [6]. We used beads of average diameter 750 µm, large enough to be easily seen by the unaided eye and removed from the sample after completion of measurement. Porosity is calculated directly from bulk and grain densities: $P = 1 - \left(\rho_{\text{bulk}} / \rho_{\text{grain}} \right)$

We also measured magnetic susceptibility with a handheld SM-30 magnetic susceptibility meter, correcting for sample geometry according to the calibration by [7].

The original five Apollo samples were provided on loan from CAPTEM and were measured in our laboratory at the University of Central Florida. The 17 new samples were measured on-site at Johnson Space Center and were handled only by the curatorial staff. Grain density and magnetic susceptibility were measured for all rocks, but five samples were considered either too small or too friable for bulk density measurements.

Basalts: In addition to the two high-Ti basalts (10017 and 70215) are five low-Ti basalts (12002, 12051, 12052, 15555, and 15556). Both of the high-Ti basalts had somewhat higher grain densities (3.42 and 3.46 g cm^{-3}) than the low-Ti basalts (ranging 3.31 to 3.39 g cm^{-3}). Among the low-Ti basalts, the grain densities are correlated with the abundance of Al_2O_3 and of MgO in a manner similar to that observed among lunar meteorite basalts [3]. Porosities (see Fig. 1) for all basalts were less than ~10%, with the exception of the highly vesicular 15556. In the bulk density measurement, beads penetrated some but not all of the vesicles, so the unusually high porosity of 26% for that sample includes the contribution of these interior vesicles. Because 15556 includes many vesicles that are open to the surface of the measured sample, the true vesicularity is actually considerably larger than the measured 26%. Lunar basaltic meteorites measured so far are all consistent in density, porosity and magnetic susceptibility with the Apollo low-Ti basalts.

Impact-Melt Breccias: Our database includes five samples from impact-melt breccias (14310, 61016, 64435, 66095, and 73255). Most have grain densities in the range 2.85-2.99 g cm^{-3}, which are slightly higher than average for the meteoritic impact-melt breccias, which tend to be closer to 2.82-2.85 g cm^{-3}. Porosities of impact-melt breccias ranged from very low to over

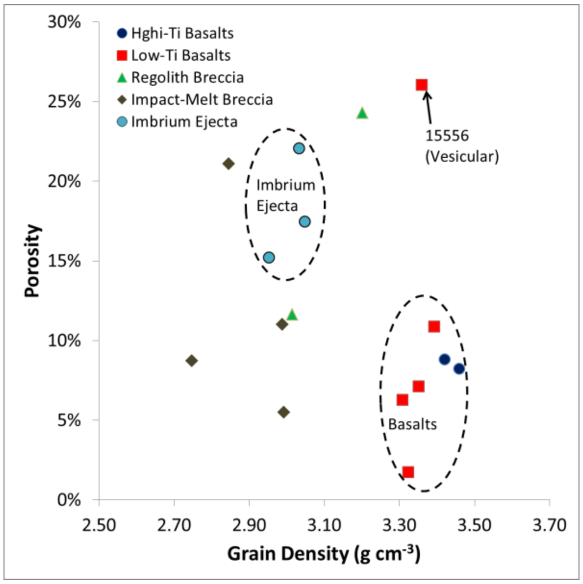

Figure 1: Porosity vs. Grain Density for Apollo samples in this study.

20% and may be influenced strongly by the circumstances of the various impacts. Sample 61016,484 visually appears to be a clast of monomineralic plagioclase, consistent with its grain density (2.75 g cm^{-3}).

Imbrium Basin Ejecta: We have measured four pieces from three rocks retrieved during Apollo 14 from the ejecta blanket of the Imbrium basin. These samples (14303, 14311 and 14321) are all crystalline matrix breccias from the Fra Mauro formation, which are interpreted to represent primary ejecta from the Imbrium basin [8]. The samples were all collected in the ejecta blanket of Cone Crater at various distances from the crater rim and thus sample about 100 meters of stratigraphic height through the Imbrium ejecta. Nevertheless, they do not vary much in grain density. Three of the four samples have grain densities between 3.03 and 3.10 gm cm^{-3}. The remaining sample has the smallest sample mass, 5.5 gm, and may not provide a good sampling of the small-scale heterogeneity in the breccia. They also are higher in porosity than most of the other Apollo samples, with each one greater than 15% porous. Imbrium ejecta is a wide spread unit on the front side of the Moon, and our samples indicate that a typical bulk density of ~2.4 gm cm^{-3} is appropriate for gravity models of this unit.

Regolith Breccias: We measured four ordinary regolith breccias, one from Apollo 11 (10048) and three from Apollo 15 (15015, 15459, 15565). The Apollo 15 breccias ranged in grain density from 3.01 to 3.10 g cm^{-3}, but the Apollo 11 sample was notably more dense at 3.20 g cm^{-3}. This likely reflects differences in the local composition of the regolith at the two landing sites – basalts at Apollo 11 are typically higher in titanium and thus ilmenite than basalts at Apollo 15. The two breccias with measured porosities were about 11% and 24% porous.

Highland Crust Rocks: 60025 is a ferroan anorthosite whose grain density of 2.76 gm cm^{-3} is consistent with a composition of nearly pure plagioclase. The absence of a detectable magnetic susceptibility in this sample is consistent with a complete absence of iron-bearing minerals. Apollo 15 sample 15418 is a brecciated gabbroic anorthosite whose higher grain density of 2.90 g cm^{-3} reflects a greater abundance of mafic minerals than found in 60025.

Conclusion: Our growing database of the density and porosity of lunar materials from both Apollo rocks and meteorites is providing an unprecedented source of information to aid models for interpreting lunar gravimetric data. We present here data for a diverse typology of lunar samples, including regolith breccias, impact-melt breccias, basalts, and others. The different geologies not only exhibit differences in densities (expected simply from different mineralogies) but also differences in porosities, with breccias tending to higher porosities than basalts.

While there is intra-type consistency—for instance, basalts group tightly in grain density—we also see considerable variability, especially in porosities. This emphasizes the need to expand the dataset in order to capture the range and degree of variability of each class of lunar material. Data from lunar meteorites provide a vital supplement to our research, though these materials lack geologic context and are no longer pristine due to exposure to terrestrial environments.

The fact that we are studying both Apollo samples and lunar meteorites also provides a unique opportunity to study the differences between these two populations, which may yield insights into the circumstances of meteorite formation.

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