NEW LUNAR SAMPLE DENSITY AND MAGNETIC SUSCEPTIBILITY MEASUREMENTS. R. J. Macke[1], W. S. Kiefer[2], D. T. Britt[3], G. J Consolmagno[1], and A. J. Irving[4], [1]Vatican Observatory, V-00120 Vatican City State, macke@alum.mit.edu, [2]Lunar and Planetary Institute, Houston, TX, [3]Dept. of Physics, University of Central Florida, Orlando, FL, [4]Dept. of Earth and Space Sciences, University of Washington, Seattle, WA.

Introduction: In order to make use of the flood of data on the Moon's gravity and topography provided by missions such as Lunar Reconnaissance Orbiter and GRAIL [1] to constrain our understanding of the Moon's internal structure, we have been developing a comprehensive database of lunar rock densities and porosities [2]. This database includes 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.

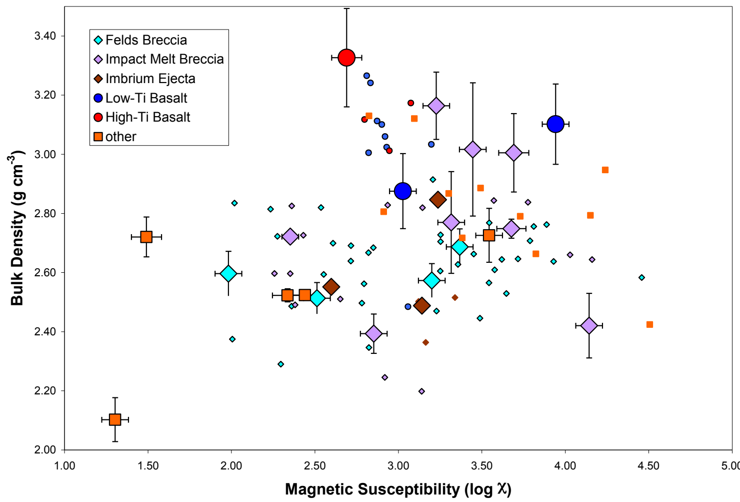

Figure 1: Bulk density vs magnetic susceptibility for lunar samples in this survey. Large symbols are stones reported here, while small symbols represent previous measurements.

In October 2013 we visited both the Apollo lunar receiving laboratory and the antarctic meteorite collection at NASA Johnson Space Center. During this visit, we conducted bulk density and magnetic susceptibility measurements on 19 Apollo samples and three lunar Antarctic meteorites. These samples exhibit a range of lithologies including anorthosites, high- and low-Ti basalts, and impact melt breccias. Among the Apollo samples, each mission except Apollo 11 is represented. These data mark a significant addition to our existing database of 97 lunar samples and meteorites.

Measurement: Our techniques are described in detail in [3] and [4]. All of our techniques are non-destructive and non-contaminating, and were performed on-site at NASA Johnson Space Center. We measure grain density by helium ideal-gas pycnometry, and bulk density by the archimedean glass-bead method. Magnetic susceptibility is measured with a ZH-instruments SM-30 meter, with a volumetric correction consistent with [5], and are reported as logarithmic units. Due to equipment problems, we were unable to measure grain densities during the trip in October 2013. We plan helium pycnometer measurements and possibly also 3D laser scanner measurements during a follow-up visit in early 2014. Both grain and bulk densities are necessary for determining sample porosity.

For the Apollo samples, instead of our usual 700-800 µm-diameter glass beads, CAPTEM requested that we use high-purity alumina (greater than 99.99% pure Al_2O_3) beads to eliminate any possibility of trace element (particularly Na) contamination. These beads were ~500 µm in diameter.

Caveats: The small diameter of the alumina beads, and hence greater surface area to volume, coupled with the low humidity of the facility created a pronounced static electricity effect on them. Beads at the top of the container were literally jumping out, making it difficult to level the surface consistently. As a consequence, measurements of the bead-filled cup mass exhibited much greater variation than similar measurements with our usual glass beads, as exemplified by measurements on the Antarctic meteorites. This led to greater uncertainties in bulk densities.

All of the Apollo samples discussed here are non-pristine specimens that were previously used in other studies. In many cases the available specimens allocated for measurement were less than the 10g minimum mass that we prefer to measure. Volumetric uncertainty is largely independent of the sample volume, and so for a small sample the error is proportionally much higher than for a large sample. This prevents us from reaching our stated goal of ±0.01 error in porosity for those samples. In a few high-priority cases, it may be necessary to measure larger fragments from the pristine sample collection to achieve uncertainties which are small enough to be useful in geophysical modeling.

Another consideration associated with small sizes of samples is whether or not they are representative of their geologic types. The inclusion or exclusion of a large clast, for example, could have significant effect on physical properties. This difficulty is not insurmountable; it simply requires a large cumulative database of samples of similar types. Nevertheless, no single sample should be considered representative of its class, particularly if it is smaller than ~15-20 g.

Samples: (See Fig.1.) We measured two anorthosites: Apollo 65315,32 and 60015(,33 and ,29). 65315,32 is a plagioclase clast with very low magnetic susceptibility and the lowest bulk density (~2.1 g/cm^3) of any lunar sample we have yet measured. 60015,33 had a significant glassy exterior layer, while 60015,29 was from the interior of the stone. 60015,33 had a metallic remnant from a previous study embedded in it, which the curation staff cut away. The piece from the interior (<9 g) had higher bulk density, consistent with nonporous anorthosite, but lower magnetic susceptibility, than 60015,33.

We also measured four feldspathic breccias, including the three Antarctic meteorites in this study (MacAlpine Hills [MAC] 88104, Miller Range [MIL] 090070, and MIL 090036) The one Apollo sample of this type was the polymict breccia 67915,43. All of these had bulk densities ranging from 2.5-2.7 g/cm^3, but had magnetic susceptibilities ranging from log χ = 2.0 to 3.4.

Impact melt breccias included Apollos 60315,34; 61016,35; 64435 (,95 and ,335 together); 65015,6; 73235,17; 76215,79; and 76315,27. Many of these were among the smallest samples, including four pieces <6 g each. These included a variety of types of impact melts. The average bulk density of the group was 2.7 g/cm^3, and magnetic susceptibility was log χ = 3.3.

Sample 15455 is a breccia containing shocked norite, thought to represent ejecta from the Imbrium basin [6]. We measured three pieces (15455,245; 15455,38; and 15455,179) ranging from 12.6 g to 16.5 g, as well as all three together. The average bulk density is in the range 2.55 – 2.60 g/cm^3. Sample 68815,8 is from a glassy polymict breccia, dominated by plagioclase-rich inclusions [7]. Its density of about 2.7 g/cm^3 is consistent with this mineralogy.

Among the basalts are two high-Ti ilmenite basalts (75035,15 and 75055,56) and two low-Ti basalts (12038,75 and 14053,31 and 14053,46), shown in Fig. 2. 12038 and 14053 are notably also Al-rich basalts. All of the basalts in this study were unfortunately <10 g, resulting in relatively large bulk density errors of about 5%. The measured bulk density for 75055,56 exceeded 4 g cm^{-3}, which is much higher than expected for its composition and is most likely the result of static electricity effects on the alumina beads. In general, high-Ti basalts in this study exhibited higher bulk density but lower magnetic susceptibility than low-Ti basalts. In samples measured previously, there is no significant difference in magnetic susceptibility between the two groups overall, though the ilmenite-bearing high-Ti basalts had 0.1 g cm^{-3} higher grain density than the low-Ti basalts. The magnetic susceptibility of 14053 (,31+,46 measured together) is a full order of magnitude greater than all other high-Al, low-Ti basalts that we have measured (12038, Northwest Africa 4898, and Kalahari 009). 14053 has been described as the most reduced lunar basalt ever measured and contains a small amount of metallic Fe [8], which would explain its unusually high magnetic susceptibility.

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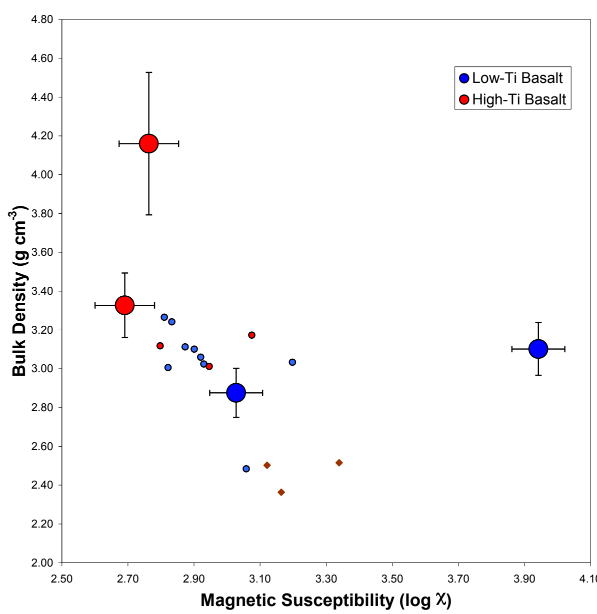

Figure 2: Bulk density vs magnetic susceptibility for basalts in this study. *NB The bulk density of 75055,56, in the upper left of the plot, is unreliable. 14053,31+46 (on the far right of the plot) has has higher magnetic susceptibility than any other basalt we have measured; it is known to contain metallic Fe.*