MAGNETIC CHARACTERIZATION OF LUNAR SAMPLES: **BACK TO BASICS:** Kristin P. Lawrence[1] and Catherine L. Johnson[2], [1]Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093, klawrence@ucsd.edu, [2]Dept. of Earth and Ocean Sciences, University of British Columbia, Vancouver, CANADA.

Introduction: Over the past few decades paleomagnetic analyses of Apollo lunar samples have investigated the microstructure of Fe/Fe-Ni magnetic carriers [e.g. 1], categorized magnetic parameters [e.g. 2, 3, 4], and measured a suite of relative and absolute paleointensities [e.g. 5, 6, 7]. A recent re-evaluation of published lunar paleointensity data and new measurements from improved techniques has shown that paleointensities recorded by lunar samples, even within a single sample, are complex, and the correct interpretation of these data is currently unresolved [7]. However, the observation that selected samples exhibit increased values of normalized natural remanent magnetization (or relative paleointensity) between approximately 3.6 and 3.9 Ga still exists [6]. Unfortunately, it is unclear what this peak indicates: possible interpretations include one or more of (1) a lunar-dynamo-generated field, (2) shock effects, (3) unidentified magnetic contamination Also of key importance in understanding lunar magnetic evolution is the spatially heterogeneous magnetic anomalies observed by lunar satellite magnetometer measurements [e.g. 8]. Addressing all of these issues requires a more thorough understanding of the magnetic remanence within lunar samples. For example, "systematic and detailed descriptions of the occurrence and paragenesis of the various magnetic phases in lunar rocks have not been made and are still badly needed" [4]. Here, we present preliminary results of low and high temperature hysteresis, low and high temperature magnetic susceptibility, and Curie temperature analyses of multiple lunar samples.

Magnetic Hysteresis: We have measured room temperature magnetic hysteresis – magnetization as a function of applied field - of 4 samples (76535, 60015 (glass and anorthosite portions), 73235, 62235). Hysteresis loops were measured on an Alternating Gradient Force Magnetometer with a maximum applied field of 1 T, an example of sample 62235 is shown in Figure 1. Plotting the ratios of remanent (M_{rs}) to saturation (M_s) magnetization and remanent coercive (B_{cr}) to coercive force (B_c) can differentiate between single domain, pseudo-single domain and multidomain magnetic carriers. Figure 2 shows the results for both our new measurements and preexisting sample data compiled by [4]. Lunar samples have multi-domain carriers and therefore are not appropriate for standard Thellier-Thellier experiments. The addition of low-temperature hysteresis will help differentiate the multidomain component from the superparamagnetic contributions in lunar samples.

Shock and Magnetic Parameters: A simple evaluation of magnetic parameters such as susceptibility and saturation remanence is insufficient to determine which samples may be appropriate for investigations of an early internal magnetic field. The relationship between magnetic characteristics and amount of shock pressure a sample experienced is not yet resolved. There are several studies [9, 10, 11, 12, 13] that indicate the magnetic properties and even microstructures of iron grains are significantly altered by shock pressures as low as a few GPa. It has been documented that magnetic hysteresis parameters (e.g. B_c, B_{cr}, M_s) and magnetic susceptibility change with applied stress for many mineralogies including the Fe/Fe-Ni system. In particular, for multi-domain iron particles coercivity increases with shock, and shock hardening increases saturation remanence [10]. For metallic iron grains, the amount of magnetic anisotropy increases with the amount of shock [10] even for shock pressures less than 5 GPa (a pressure that will not result in significant mechanical deformation of the crystal). These property changes can be cumulative, where repeated shocks occurring in the same ambient magnetic field result in larger and larger remanence from SRM (Shock Remanent Magnetization) [11].

Discussion: Ideally we would like to use the magnetic remanence of lunar samples to determine the strength and orientation of the ambient magnetic field at the time of emplacement. Alternatively, we would like to use the differences in remanence among multiple samples to understand the origin and distribution of the lunar surface anomalies. In light of the complexities discussed above, it is important to identify a comprehensive set of magnetic measurements, needed to interpret lunar samples. Broadly, these requirements include:

1. *Type of magnetic remanence* (e.g. thermal, shock, isothermal remanent magnetizations, and single or multiple component magnetizations) – This is crucial for paleointensity measurements that use existing absolute or relative techniques. Absolute techniques have internal tests to differentiate among some types of remanence but not all (e.g. thermal cannot be differentiated from shock remanence).

2. *Magnetic carrier: type and state* (e.g. single domain, multidomain, metallic iron, kamacite or taenite) – Not only is shock a contributing factor in changing magnetic properties, the remanence intensity and stability depend on nickel content, which affects coercivity [9] and domain state. In particular, pressure demagnetization is directly related to the mineralogy of

the sample. For example, kamacite (nickel bearing metallic iron crystals), which is prevalent in lunar materials, demagnetizes with much greater efficiency than taenite or titanomagnetite [13] due to shock pressure.

3. *Magnetic anisotropy* – Understanding this parameter may become very important for samples such as 76535, which has very little evidence of shock via petroglocial observations [14] but shows significant magnetic anisotropy [15]. [13] suggested that the pressure wave during impact creates a magnetic texture defined by the uniaxial strain that orients magnetic remanence. This preferred orientation has been measured through magnetic anisotropy for shock pressures as low as 1.5 GPa [10]. Reciprocally, [10] suggests that coercive force measurements could be used as a shock level indicator.

4. *Shock history* Shock, even at pressures not resulting in melt, can significantly alter the magnetic remanence and/or microstructure of magnetic grains [1, 9]. If we are to unravel properties of the ambient magnetic field during a shock event, it will be necessary to understand how repeated events affect magnetic remanence.

Conclusions: In contrast to terrestrial samples, which have well-understood theoretical underpinnings for magnetic remanence behavior, the magnetic remanence of lunar samples is complicated and only modestly understood. This is due to a suite of processes (e.g. shock, anoxic cooling environments, meteoritic contamination) evident in lunar samples that are uncommon or avoidable for terrestrial samples. To move forward with lunar paleomagnetic studies, we must, at minimum, resolve the following three issues.

1. We must determine relationships between magnetic parameters in the metallic Fe/Fe-Ni mineralogic system under a suite of modification processes (e.g. thermal and alternating field demagnetization, shock, isothermal exposure). [14] and [17] are currently investigating parts of this problem.

2. We need more thorough and detailed magnetic characterization (including low- & high-temperature susceptibility and magnetic hysteresis, Curie temperature curve analysis, magnetic anisotropy, and detailed, complete AF demagnetization curves) for various lunar sample types. We will present results for many of these experiments on selected lunar samples.

3. We need to evaluate the shock pressures that each sample experienced using indicators such as mechanical deformation of grains within a sample and the amount of melt contained within the matrix [18].

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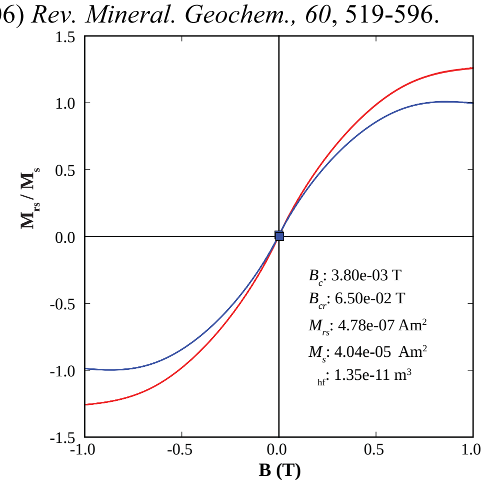

Figure 1. Hysteresis curve for lunar sample 62235.119. The blue (red) line has (not) been corrected for the superparamagnetic component of the sample. The loop is collapsed to a line indicating multidomain behavior.

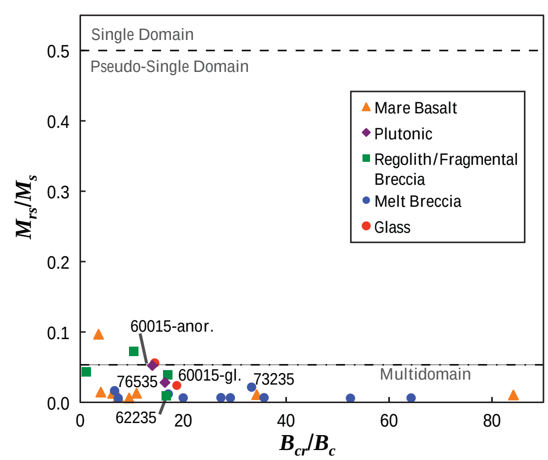

Figure 2. Plot of magnetic hysteresis parameter ratios of lunar samples. Lunar rock type differentiated into broad groups. Samples measured in this study are labeled.