EVIDENCE FOR A LATE LUNAR DYNAMO REVISITED R. D. Cottrell[1], K. Lawrence[2], R. K. Bono[1,3], C. L. Johnson[2,4] and J. A. Tarduno[1,5], [1]Dept. of Earth & Environmental Sciences, University of Rochester, Rochester, NY 14627 (rory.cottrell@rochester.edu), [2]Formerly at Planetary Science Institute, Tucson, AZ 85719, [3]Geomagnetism Laboratory, University of Liverpool, Liverpool L69 3GP, UK, [4]Dept. of Earth, Ocean and Atmospheric Sciences, Vancouver, BC Canada V6T 1Z4, [5]Dept. of Physics & Astronomy, University of Rochester, Rochester, NY 14627

Introduction: Apollo samples and satellite magnetic field data indicate magnetization of the lunar crust and suggest that a lunar dynamo may have operated over several 100 Myr between 3.9 and 3.6 billion years ago [1-5]. Estimates of the ancient field strength (paleointensity) at the lunar surface suggest that it was comparable to, or greater than Earth's surface field. The timing and strength of such a magnetic field present extreme challenges to dynamo models [6], and consequently imply profound constraints on the rotational history and thermal evolution of the Moon. These issues have been heightened by the interpretation of magnetization (~5 µT) from a regolith breccia for a late lunar dynamo until at least 2.5 Ga and possible as young as ~1 Ga [7]. Both the satellite and sample records are complex since multiple processes can result in the acquisition and later modification of magnetization. Establishing the earliest record of the field is hindered by the paucity of magnetically pristine samples, and the fact that the lunar magnetic minerals are notorious for their instability with the heating that is required to assess whether they meet robust magnetic recording requirements defined by Thelliers' Laws [8]. But the younger record can be more easily probed, through analyses of lunar basalts. While some samples record an early lunar field most do not, even when measured with modern techniques. Among samples that record a field, paleointensity estimates vary by a factor of 100 or more. Establishing whether these complexities reflect variations in field strength (and even existence) in time, or simply difficulties inherent in studying the whole rock record of the magnetic field is critical to understanding lunar evolution. Here we seek to place bounds on lunar magnetizations through the study of a young Apollo lunar glass sample 64455 [9-10]. This basaltic impact melt is thought to have maintained its orientation over the last ~2 Myr (the [81]Kr exposure age of 64455 is 2.01 Ma [11]) since it landed on the lunar surface. The 5 cm x 3 cm sample is covered by a thick black glass, and has been linked to the South Ray crater. Glass samples were obtained for magnetic and electron microscope studies described below.

Methods: Glass (1-2 mm) samples were mounted within an epoxy stub, polished with 0.5 micron alumina and evaporatively coated in carbon in preparation for scanning electron microscopy characterization. Micrographs were collected at 20 keV with a Zeiss Auriga SEM/FIB equipped with secondary and backscattered electron detectors at the University of Rochester. An EDAX energy-dispersive x-ray spectroscopy (EDS) was used to collect compositional data. For the measurement of magnetic hysteresis, we used the University of Rochester's Alternating Gradient Force Magnetometer and P1-probes. All heatings were conducted using a CO_2 laser (typical heating time of 90 s) [12]. We used an ultra sensitive 3-component DC SQUID magnetometer, housed in the magnetically shielded room of the paleomagnetism laboratories of the University of Rochester (background field less than 200 nT), for remanence measurements. The magnetometer has a 6.3 mm access bore optimized for the measurement of single silicate crystals with low natural remanent magnetizations.

Findings: We found that the 64455 glass contained spherical polycrystalline Fe-Ni-S inclusions.
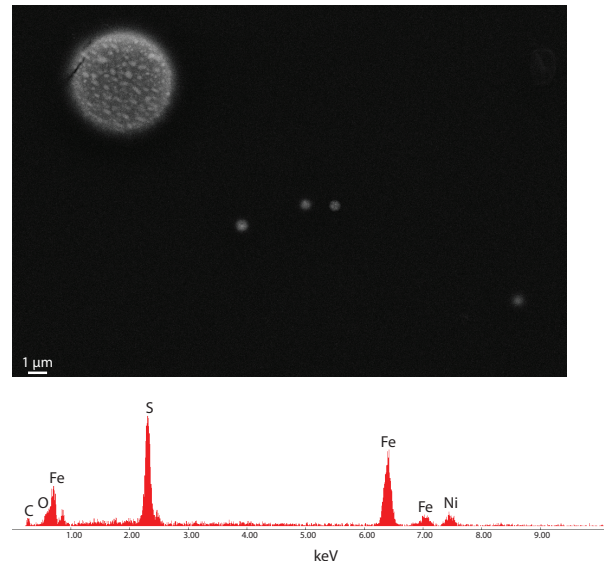

Figure 1. (Top) Secondary electron image of Fe-Ni-S inclusions. The larger sphere contains bright internal features 100-500 nm in length. (Bottom) EDS collected at 20 keV on the larger inclusion.

The inclusions ranged in size from ~5 to <1 microns in diameter in samples examined for SEM, whereas even larger inclusions (~10-20 um) were sometimes observed in light microscope study. The small subdivisions of some inclusions could be stable magnetic recorders, whereas larger divisions are expected to have low stability typical of most lunar samples. To exam-

ine the thermal stability we measured magnetic hysteresis on a sample before heating, and after 2 heating steps (Figure 2).
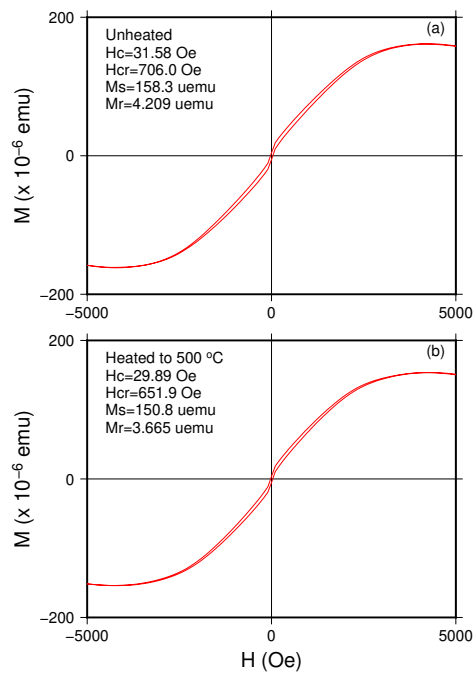

Figure 2. Magnetic hysteresis data (uncorrected for high field slope) on the same sample of 64455 glass before heating (a), and after heating to 500 °C (b). Abbreviations: M_r: saturation remanence; M_s: Saturation magnetization; H_c, coercivity; H_{cr}, coercivity of remanence.

Magnetic hysteresis profiles of unheated samples are "wasp-waisted", indicating a mixture of ultra-fine particles and larger particles, consistent with our SEM observations. Heating appears to have induced neglibible changes in these properties. We conducted total-TRM (thermal remanent magnetization) experiments and Thellier-Coe double heating paleointensity experiments [13] on ~1-2 mm specimens with natural remanent magnetizations >4.4 x 10^{-8} emu and obtained paleointensities ranging from 11.6 - 23.5 μT. We next applied the REM' method [14] of paleointensity estimation which involves a comparison of natural remanent and saturation remanent magnetization (Figure 3) demagnetization. This yielded paleointensities ranging from 29.2 to 38.6 uT.

Discussion: Given the young age of 64455, it is unlikely that the magnetizations record a lunar dynamo. Moreover, the South Ray crater (~680 m in diameter) is far smaller than the large cratering events called upon for impact related magnetic field generation.
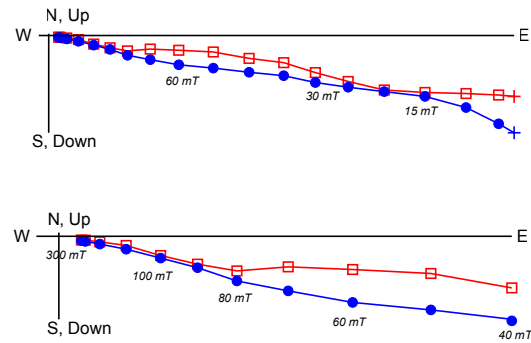

Figure 3. (Top) Alternating field demagnetization of a 3T saturation remanent magnetization. (Bottom) Enlargement of data sequence, emphazing mid-to-high coercivities. Red: relative inclination; Blue: relative declination.

The lack of a dominant soft coercivity component suggests that magnetic contamination from the spacecraft is also unlikely [15]. We suggest that this magnetization is either related to small scale anomalies imprinted by an earlier dynamo, or intrinsic properties of the Fe-Ni magnetic mineral carriers. If either of these hypotheses is correct, then the magnetizations from these relatively young samples may represent a minimum threshold for reliable paleointensity intensity: effectively the "zero" magnetic field values for lunar samples formed during the last ~3 billion years. We note that paleointensity estimates interpreted as a 2.5-1 Ga late dynamo, as well as some from the earlier lunar record, are below this threshold.

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