Lunar Paleointensity Measurements Using Both Thermal and Microwave Methods. 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: Measurements of paleointensity of Apollo samples have led to the suggestion of a lunar dynamo from 3.9 to 3.6 Ga, that resulted in surface fields of ~100μT [1]. We have conducted a reevaluation of published lunar paleointensity data [2] and shown that no measurements pass all modern criteria [3] necessary for verifiable interpretation of primary thermal remanent magnetization (TRM). Furthermore, only four prior measurements pass a less stringent set of criteria for possible primary TRM [2]. Modern laboratory studies provide both greater accuracy and tools to demonstrate that a measured intensity is or is not a primary remanence. Here, we present results from new thermal and microwave paleointensity experiments on five lunar samples, spanning the time interval 3.3 – 3.9 Ga.

Paleointensity Methods: This study uses the IZZI variant [4,5] of the Koenigsberger-Thellier-Thellier (KTT) paleointensity experiments. The KTT method is a double heating technique during which the sample is heated in a stepwise manner, progressively replacing the original natural remanent magnetization (NRM) with a laboratory-controlled partial TRM (pTRM). The ratio of NRM remaining to pTRM gained yields an estimate of ancient field strength. Successful experiments should include procedures to verify that 1) the intensity is a primary remanence, 2) no alteration occurred during the experiment, and 3) the sample magnetized in a linear fashion. The particular stepwise pattern of the IZZI variant is uniquely devised to evaluate all three criteria.

Thermal KTT. IZZI-modified KTT paleointensity experiments on specimens from four lunar samples (60015, 62235, 72215, 76535) were conducted in 50°C temperature steps from 150°C to 500°C, followed by smaller temperature increments until > 95% of the NRM was lost. Demagnetization and field acquisition in a 15μT field were performed with custom-built ovens at the Scripps Paleomagnetic Laboratory. In an effort to reduce oxidation and subsequent alteration during the experiment, samples were sealed in an evacuated quartz tube (~10^{-4} Torr). Details of these experiments and results can be found in [2].

Microwave KTT. Microwave paleointensity experiments were conducted on specimens from three samples (60015, 62235, 73235). The microwave technique is equivalent to the thermal technique [6], but it uses high frequency microwaves (14.4 GHz) to (de)remagnetize magnetic grains rather than thermal energy (heat) [7]. Microwave energy directly excites the magnetic spin system of a mineral such that the magnetic carriers may realign with an applied field direction. Because the bulk sample is not heated, the microwave technique reduces the likelihood of thermo-chemical alteration.

All microwave paleointensity experiments were performed at the Liverpool University Paleomagnetics Laboratory using the same protocol as the thermal experiment. Each sample was exposed to increasingly strong power (2 to 80 Watts) for 3-6 seconds until the sample was 95% demagnetized or the remaining magnetization was too small to measure. It is difficult to impart a prescribed amount of microwave energy to a sample because the absorbed energy is not only dependent upon the power and duration, but also the resonance characteristics of apparatus, which change with each specimen, and can change if alteration occurs. Therefore, we calculated the cumulative absorbed energy *in situ* from the difference between the applied and reflected energies during each microwave step [7]. If the reflected (or absorbed) energy significantly changed between steps of the experiment, alteration was suspected.

Results: *Thermal KTT.* Samples 60015 (anorthosite) and 76535 (troctolite) failed during absolute paleointensity experiments, while samples 72215 and 62235 (impact breccias) yielded ambiguous results regarding the origin of observed paleointensities. Samples 72215 and 62235 recorded a complicated, multi-component magnetic history that includes a low temperature (< 500°C) component associated with a high intensity (~90 μT) and a high temperature (> 500°C) component associated with a low intensity (~2 μT). These two samples were also subjected to an sIRM (saturation isothermal remanent magnetization) experiment, from which neither sample provided unambiguous evidence for a thermal origin of the recorded remanent magnetization.

Microwave KTT. Sample 73235 (impact breccia) does not produce an interpretable paleointensity as it failed all pTRM checks during the experiment. This experiment ended before the sample completely demagnetized due to limited magnetometer sensitivity.

Similar to the thermal KTT results, 62235 (impact breccia, Figure 1) recorded high paleointensity (~1mT) at low-energy steps, then altered (observed by a change in energy absorption, a failed pTRM check, and visual verification) at a mid-energy step resulting in a low intensity component at higher energy steps., The high-intensity component does not decay to the origin, indicating a non-primary remanence.

We performed a microwave T-T experiment on a glassy portion of 60015 (separated with a diamond saw blade) compared to the anorthosite specimen used in the thermal KTT experiment. Unlike the other microwave paleointensity experiments, this sample gained a measurable pTRM (20% of the NRM, Figure 2) before the experiment ended. Unfortunately, this is an incomplete experiment due to experimental complications, which caused the sample to move during energy steps. While this experiment yields no evidence of two magnetization components, the incomplete (60% demagnetization) nature of this experiment cannot verify a single component of magnetization. The direction is stable but does not trend to the origin, so the corresponding 51μT interpretation of the low energy steps may be associated with an overprint.

Discussion/Conclusions: In summary, there is not a single lunar paleointensity result (in this study or in the published literature) that passes the criteria of a robust paleointensity experiment as applied to terrestrial samples [2]. Of the five samples measured here, two (76535 and 73235) experiments failed due to alteration; another (72215) likely has a magnetic remanence from shock or IRM contamination [2]. The anorthosite portion of 60015 did not record a measurable paleointensity while the glassy coating of the same sample yielded a non-primary remanence of 51μT. The complicated results from both thermal and microwave experiments for 62235 cannot be unambiguously interpreted as a thermal remanent magnetization. More importantly, there is no conclusive evidence that any measured paleointensities are original thermal remanent magnetizations for lunar samples regardless of method. Hence, all future lunar paleointensity studies need to demonstrate original thermal remanent magnetization prior to interpreting paleointensity as record of an early lunar dynamo.

Clearly impacts, and therefore shock, have played a significant role in the formation of the lunar surface. All samples that have paleointensity measurements passing the reliability criteria set forth in this study have been extensively modified by shock-related events. [8] and [9] argue that SRM (shock remanent magnetization) is the likely source of NRM in certain regolith breccias and that shock may modify the primary remanence of many other samples. Furthermore, The effects of SRM cannot be disregarded; analyses of LP-ER [10] and LP-MAG [11] data suggest correlations of some crustal magnetic anomalies with antipodal concentrations of basin ejecta. Problematically, both previous and modern paleomagnetic methods cannot differentiate between SRM and TRM. In particular, further work is needed to understand the acquisition of SRM in the lunar environment, and to understand the relative contributions of SRM and TRM to the satellite, surface, and Apollo sample magnetic observations.

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Figure 1. Sample 62235

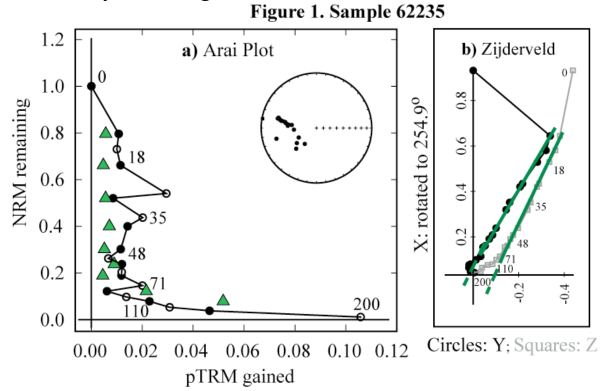

Figure 2. Sample 60015

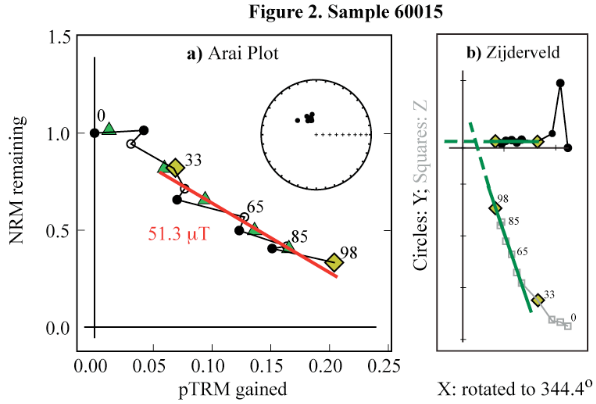

Figure 1. a) Arai plot of NRM remaining vs pTRM gained where NRM is normalized to 1.43e-08Am^2. Demagnetization steps are labeled in energy (W·s). Triangles are the pTRM checks. Inset is the equal area projection of direction **b)** Zijderveld diagram of direction during demagnetization where circles (squares) are the horizontal (vertical) plane. Green line is best-fit direction. **Figure 2.** Same as Figure 1 for sample 60015 where NRM is normalized to 1.21e-08 Am^2 and the red line is inferred paleointensity. Note the different pTRM gained scales.