ASSESSING THE EFFECTS OF MAGNETIC CONTAMINATION ON LUNAR SAMPLES AND IMPLICATIONS FOR PALEOMAGNETISM.

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Introduction: Intense magnetic anomalies are located within the slowly cooled (>10 kyr) central melt sheets of numerous lunar basins. In addition, stable and high coercivity remanent magnetizations have been identified within igneous Apollo and Chang'e-5 samples. These remanences have collectively been interpreted by many studies as evidence that the ancient Moon at least intermittently generated a dynamo field over a period spanning at least ~4.25-1.5 (Ga) [1,2,3]. However, numerous studies have also identified samples that do not contain stable remanence, potentially suggesting a dynamo was absent when those rocks formed [4,5,6].

If lunar rocks did not initially form and acquire their natural remanent magnetization (NRM) in the presence of a dynamo field, there are two possibilities for how they could have become magnetized. First, it is possible that some rocks could have acquired shock remanent magnetization (SRM) or thermal remanent magnetization (TRM) during exposure to shock pressures or heating associated with meteorite impacts in the presence of a transient impact-generated field [6,7]. However, we note that several studies have utilized pressure remagnetization experiments and thermochronology modeling to argue against impact-related remanences in specific samples [e.g., 8,9].

Second, it is conceivable that lunar rocks acquired magnetic contamination during sample collection, transport, and handling. Apollo samples were exposed to magnetic fields up to 3-5 mT in intensity while on the return spacecraft [10]. Such fields could have instantaneously imparted lunar rocks with isothermal remanent magnetization (IRM). If the field persisted for an extended duration of time, samples could also acquire a viscous remanent magnetization (VRM). We conduct a detailed exploration of this possibility by exposing lunar rocks to 5-10 mT fields for different durations of time and assessing (*i*) how difficult it is to remove such overprints from samples using alternating field (AF) demagnetization methods and (*ii*) how the presence and removal of such overprints may affect lunar paleointensity determinations.

Samples: We studied specimens from six mare basalt samples (Apollo 10020, 12008, 12009, 12017, 12022, and 15597) and one impact melt splash coating (from sample 65315). Each specimen was ~100 mg in mass. The magnetic hysteresis properties of these samples indicate that they dominantly contain FeNi grains in the multidomain size range, though populations of finer (more single-domain-like) grains may also be present in some samples.

Methods: To assess the response of Apollo samples to magnetic contamination, we conducted two sets of experiments:

Experiment 1. We subjected previously demagnetized specimens to a 5 mT magnetic field by placing them near a neodymium magnet for a duration of 2 days. We hereafter refer to this magnetization as a long-term IRM. Upon removing the sample from the field, we repeatedly measured the NRM of the sample over a period of ~3000 seconds to observe the viscous decay of the acquired remanence. After this period, we conducted stepwise alternating field (AF) demagnetization and paleointensity determinations (for the remaining remanence) using the anhysteretic remanent magnetization (ARM) method [e.g., 8,9,10].

Experiment 2. We imparted previously demagnetized specimens with an initial laboratory ARM as an analog for a primary TRM and then applied a 10 mT IRM overprint (hereafter referred to as an instantaneous IRM) perpendicular to the ARM. Immediately following IRM application, samples were subjected to stepwise AF demagnetization, followed by ARM paleointensity experiments as in *Experiment 1*.

Results:

Experiment 1. Over a period of ~1 hour, between 0 and 3% of the originally imparted long-term IRM was removed via viscous decay from our mare basalt samples. However, ~27% of the long-term IRM was removed from impact melt 65315. During AF demagnetization, the remaining long-term IRM was generally cleaned from our mare basalt samples by 10-40 mT (**Fig. 1**), depending on the sample, resulting in null ARM paleointensities from higher AF levels (**Fig. 2**). In contrast, the residual long-term IRM was not entirely cleaned from 65315 even after AF demagnetization to >50-100 mT. However, viscous decay extrapolation calculations indicate that >90% of the long-term IRM would have been removed from 65315 if the sample had been allowed to reside in a zero-field environment for several years prior to commencing AF demagnetization experiments (**Fig. 1**).

Experiment 2. We found that the instantaneous 10 mT IRM overprints were entirely removed from all samples (irrespective of lithology) by AF demagnetization to 10-20 mT, enabling accurate ARM paleointensity determinations for higher coercivity (>20 mT) remanence (**Fig. 3**).

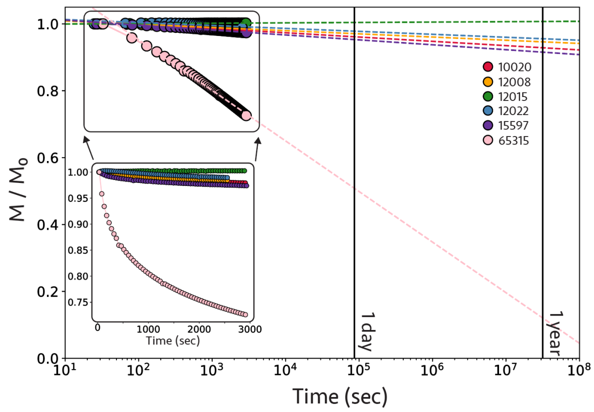

Fig. 1. Viscous decay of an initial laboratory remanence imparted by exposing lunar samples to a 5 mT field for 2 days in Experiment 1 (long-term IRM). Shown is magnetic moment (normalized by initial moment) versus time using a logarithmic time scale. The inset shows the same data in linear time. Color dashed lines represent linear fit (as a function of log (time)) extrapolations to predict the extent of viscous decay at longer time scales. Solid black vertical lines indicate durations of 1 day and 1 year.

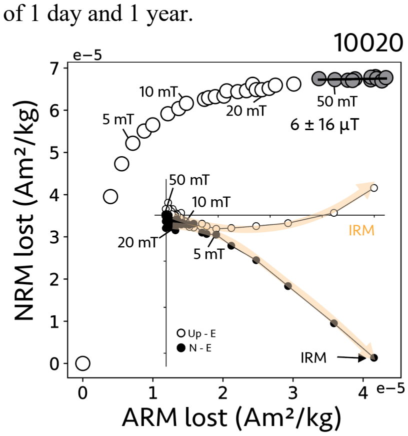

Fig. 2. (main) ARM paleointensity results for mare basalt sample 10020, where the NRM reflects long-term 5 mT IRM exposure (*Experiment 1*). Shown is NRM lost versus ARM lost after each AF demagnetization step calculated using vector subtraction. For this paleointensity experiment, ARM was applied using an AF of 170 mT and a bias field of 200 µT. (inset) Zijderveld diagram showing AF demagnetization of the long-term IRM. The IRM overprint is largely removed by AF 30 mT and a null (i.e., within error of zero) paleointensity is obtained from fitting high coercivity (>50 mT) data.

Discussion and Conclusions: Exposure to moderate (<5-10 mT) fields, whether from spacecraft or sample handling, for varying lengths of time can impart lunar rocks with magnetic overprints. However, we find these overprints are confidently erased from mare basalts using AF demagnetization to 10-40 mT. We recommend that lunar paleomagnetism studies using AF-based methods calculate paleointensities from high coercivity (>40 mT) remanence fractions to ensure reliable results. Because the NRMs of mare basalts studied in previous works persisted to AF levels >100 mT, these remanences are almost certainly lunar in origin [e.g, 8,9]. Impact melt glass samples containing small FeNi grains in the superparamagnetic to single-domain size range (<10-30 nm [11]) are particularly susceptible to viscous remagnetization via long-term field exposure. As such, melt glass samples may require an extended time to viscously decay (or perhaps a thermal pre-treatment to <~125°C [12]) in a zero field prior to commencing demagnetization experiments following field exposures. In addition, because Apollo-era paleomagnetic studies (i) were conducted shortly after samples were returned to Earth and (ii) computed paleointensities from partial AF demagnetization to only 20 mT, it is possible that many of the earliest paleointensity determinations are overestimated. We recommend that steps be taken to mitigate exposure to strong magnetic fields in future lunar sample return missions (such as Artemis) and that samples be stored in a near-zero field environment upon return to Earth.

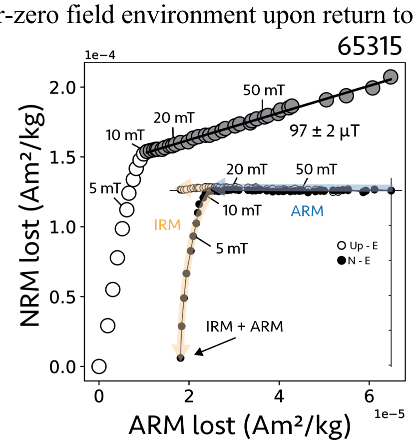

Fig. 3. (main) ARM paleointensity results for impact melt glass sample 65315, where the NRM reflects a laboratory ARM overprinted by an instantaneous 10 mT IRM (*Experiment 2*). For this paleointensity experiment, ARM was applied using an alternating field of 200 mT and a bias field of 100 µT. (inset) Zijderveld diagram showing AF demagnetization of the combined ARM+IRM. The IRM overprint is largely removed by AF 10 mT and an accurate (97±2 µT versus 100 µT) paleointensity is retrieved from fitting high coercivity (>10 mT) data.

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