TESTING WHETHER LUNAR MELT GLASSES PRESERVE RECORDS OF IMPACT-GENERATED MAGNETIC FIELDS. T. Chaffee[1] (thomc@stanford.edu), S. M. Tikoo[1], R. Abubo[1], S. G. Boeschen[1], B. P. Weiss[2], [1]Department of Geophysics, Stanford University, Stanford, CA 94305, [2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

Introduction: Remanent magnetization is found globally in regions of the lunar crust and in samples from the Apollo and Chang'e-5 missions [1,2,3]. Paleointensities of ~1-100 µT have been measured in many lunar samples aged between 4.249 ± 0.012 and 1.47 ± 0.45 Ga. The unshocked (peak pressures <5 GPa) nature and largely undisturbed thermal history of several of these samples indicate that their natural remanent magnetizations (NRMs) were likely acquired during primary cooling in a stable field. These records have been interpreted as evidence for a lunar dynamo that operated at least intermittently over a period of >2.5 Gyr and ultimately ceased by ~1 Ga [4]. Until recently, all modern paleomagnetic studies of lunar samples <1 Ga found no evidence of magnetizing fields [4-7].

The energy budget of the Moon is insufficient to have sustained a continuously operating dynamo powered by purely thermal core convection for billions of years [8]. In contrast, a dynamo powered by thermochemical convection resulting from inner core crystallization may persist for such a duration, but the resulting surface field intensities are likely limited to <~1 µT based on current dynamo scaling laws [9]. However, a range of other mechanisms may have helped power a dynamo within the Moon long after 4 Ga, including impact-driven differential motion of the crust and mantle [10], precession [11,12], or foundering of cold cumulates after the unstable density stratification caused by lunar magma ocean crystallization [13].

A pair of recent studies have challenged the idea of a long-lived lunar dynamo field [14,15]. One of the key new findings of ref. [14] is that a young (2 Ma) lunar basaltic impact melt sample, 64455,24, that formed during the impact that created the South Ray crater [16] was measured to have a high paleointensity value of 10-89 µT. Due to its young age, such a high paleointensity recorded within 64455,24 would necessitate magnetization from a non-dynamo field. Ref. [14] proposed that transient magnetic fields (lasting seconds to minutes, depending on impact scale) caused by charge separation in impact-generated plumes could have magnetized lunar crustal rocks throughout the Moon's history and that the attribution of magnetization within Apollo samples to a dynamo may be erroneous. However, the cooling timescales of the 64455 impact melt glass from (i) its initial molten state down to the 780 °C Curie temperature of iron and (ii) from 780 °C to 0°C both exceed 60 seconds [17]. These timescales are significantly longer than the predicted ~0.5 second duration of a transient field produced by an impact the size (resulting in a 340 m diameter crater) and velocity (14 km/s) [14] of South Ray [18]. In addition, we note that sample 64455 was collected 4.4 km away from South Ray crater [19], meaning that it could only have been exposed to a localized impact-generated field for a portion of its cooling history.

If 64455,24 truly contains a record of an impact-generated magnetic field, it would indeed be a transformative result with implications for the crustal magnetism of rocky bodies across the solar system. To test this claim, we are conducting a paleomagnetic study of several young lunar impact melt glass samples to see if they contain similar remanences.

Samples and Methods: We obtained pristine (i.e., not previously allocated) chips of rapidly cooled impact melt splash coatings from five Apollo samples including the two featured here: 61016,556 and 65315,25. The splash coatings on these samples have been linked to the South Ray impact [16]. Our chips primarily consist of melt glass, although the melt may contain small clasts or residues of anorthosite from the rocks they initially overlaid. From each chip, we prepared multiple mutually oriented subsamples (each ~100 mg) for paleomagnetic investigations. To characterize the NRM of each sample, we subjected at least 2 subsamples per rock to alternating field (AF) demagnetization and anhysteretic remanent magnetization (ARM) paleointensity experiments following the same methods used in other modern paleomagnetic studies [e.g., 4]. Small (<5 mg) fragments from each sample were used for magnetic hysteresis and first-order reversal curve (FORC) measurements, which provide insight into the coercivities and grain sizes of magnetic minerals. We additionally obtained thin sections from each sample for petrographic and electron microprobe analyses.

Results: Our AF demagnetization results revealed that neither 61016,556 nor 65315,25 contain stable high coercivity remanence and that nearly all subsamples are fully demagnetized at AF levels of <20 mT (**Fig. 1**). Paleointensities obtained from fitting data at higher AF levels are <~1 µT and within a 95% confidence interval of zero, assuming a TRM/ARM ratio of 1.3. Our hysteresis experiments suggest that both 61016,556 and 65315,25 are dominated by low coercivity multidomain FeNi grains (M_{rs}/M_s = 0.014 and 0.007, respectively, where M_{rs} is the saturation remanent magnetization and M_s is the saturation magnetization). However, our FORC data have a prominent central ridge, suggesting that a population of higher coercivity single domain grains are likely also present in addition to the multidomain grains.

Discussion and Conclusions: The demagnetization behaviors of 61016,556 and 65315,25 suggest that both impact melt glass samples formed in a very weak to null field. Any low coercivity overprints in these samples likely represent viscous contamination from spacecraft magnetic fields or from five decades of storage in Earth's field at Johnson Space Center. Neither of our pristine chips from South Ray impactites 61016,556 nor 65315,25 show any evidence of having acquired magnetization from a strong (>~10 μT) transient impact-related magnetic field, in contrast to the returned sample 64455,24 which likely formed during the same impact. It is possible that the magnetic record within 64455,24 reflects terrestrial magnetic contamination rather than a record acquired on the lunar surface. This is because 64455,24 was a "returned sample", meaning that it had already been subjected to laboratory analyses or sample handling [20,21] that could potentially have imparted magnetic contamination into the sample prior to its being returned to NASA and re-allocated to the authors of Ref. [14]. Further study of additional material from 64455 is needed to assess the possibility of magnetic contamination in that sample. 61016 and 65315 add to a growing list of young impactites that appear to lack any primary remanent magnetization [4-7]. Altogether, these studies demonstrate that impact-generated fields are far from a ubiquitous source of primary magnetization, even in the impact glasses that are the most likely to record them out of all lunar rocks.

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References: [1] Wieczorek M. A. et al. (in press) in *NVM2*, https://hal.archives-ouvertes.fr/hal-03524536. [2] Cai S. et al. (2022) *Ac. Petrol. Sin.*, 38(6). [3] Weiss B. P. et al., *LPS LIV*, submitted. [4] Mighani S. et al. (2020) *Sci. Adv.*, 6(1). [5] Buz J. et al. (2015) *JGR:Planets*, 120(10). [6] Lima E. A. et al. (2018) *AGU Fall Meeting*, GP21C-0669. [7] Tikoo et al. (2017) *Sci. Adv.* 3(8). [8] Evans A. J. et al. (2017) *Geophys. Res. Lett.*, 44. [9] Scheinberg A. et al. (2015) *Icarus*, 254. [10] Le Bars M. et al. (2011) *Nature*, 479. [11] Dwyer C. A. et al (2011) *Nature*, 479. [12] Stys C. & Dumberry M. (2020) *JGR:Planets*, 125(7). [13] Evans A. J. & Tikoo S. M. (2022) *Nat. Astron.*, *6*. [14] Tarduno J. A. et al. (2021). *Sci. Adv.* 7(32). [15] Zhou T. et al. (2022) *AGU Fall Meeting*, P46A-05. [16] Eugster O. (1999) *Meteorit. Planet. Sci.* 34. [17] Ulrich D. R. (1974). *NASA-CR-134307*. [18] Crawford, D.A. (2020) *Int. J. Impact Eng.* 137 [19] Ryder, G. & Norman, M.D. (1980). *NASA-JSC-16904*. [20] Leich D. A. et al. (1973) *Proc. Lunar Sci. Conf. 4th, Supp. 4, Vol. 2,* pp. 1597-1612. [21] Leich D. A. & Tombrello T. A. (1973) *Nucl. Instrum. Methods*, 108.

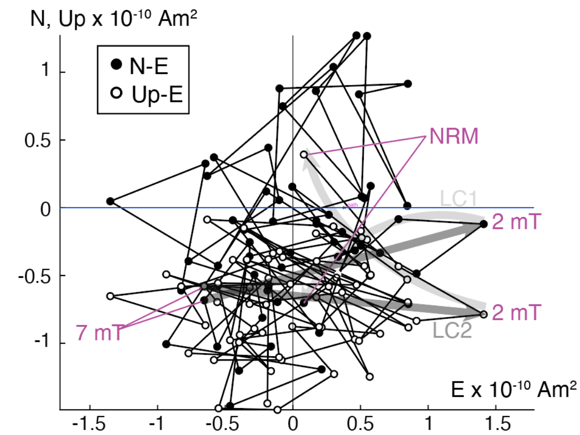

Fig. 1. Vector-endpoint diagram depicting AF demagnetization of sample 65315,25c. Closed and open circles represent projections of the NRM vector onto the horizontal (N-E) and vertical (Up-E) planes in laboratory coordinates, respectively. Light and dark gray arrows indicate low coercivity components. Selected AF levels are labeled.

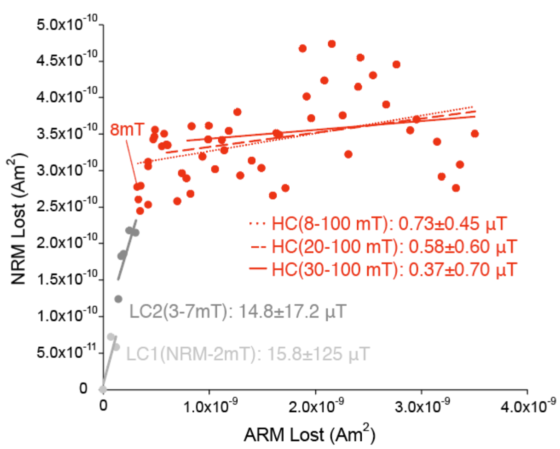

Fig. 2. ARM paleointensity results for subsample 65315,25c (same subsample as shown in Fig. 1). Plotted are values of NRM lost versus ARM lost following each AF demagnetization step calculated using vector subtraction. ARM was applied using an alternating field of 200 mT and a dc bias field of 40 μT. Paleointensities and corresponding AF ranges are labeled for each remanence component (LC1 and LC2) and the unmagnetized high coercivity fraction (HC). HC paleointensities are calculated for 3 different intervals of AF steps that demonstrate the highest coercivity grains (>20 mT) are associated with a paleointensity within error of zero.