EVIDENCE FOR TEMPORAL VARIABILITY OF THE LUNAR DYNAMO.

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Introduction: Paleomagnetic measurements of Apollo samples suggest that the Moon once had a global magnetic field generated by a core dynamo with field intensities apparently reaching tens of µT during the period 4.2 to 3.5 Ga (billion years) ago [1]. However, if the field was continuously this strong during this 700 Ma period, scaling laws suggest it would be incompatible by an order of magnitude with the Moon's available energy budget for a thermochemical convection core dynamo [2]. Several proposals have been put forward to explain this discrepancy. These include alternative dynamo mechanisms [3], a core dynamo that was fluctuating in intensity [4], and inaccuracies associated with the measured paleointensities (i.e., for samples older than 1.5 Ga, whose paleointensities have thus far been derived by non-thermal techniques). To help distinguish between these hypotheses, we conducted controlled-oxygen fugacity thermal paleointensity analyses [5] on three lunar regolith breccias of different ages. While thermal paleointensity analyses are routinely conducted on terrestrial samples [6], they are challenging to perform on extraterrestrial material because of the risk of alteration due to the different oxygen fugacity of Earth's atmosphere and that of their parent body. Heating the samples in a controlled atmosphere mitigates the risk of alteration.

Samples: We analyzed Apollo 16 lunar regolith breccias 60255, 60019, and 61195. ^{40}Ar/^{36}Ar isotopic measurements data suggest they have an assembly age of 1.70 ± 0.43 Ga, 3.35 ± 0.43 Ga, and 3.41 ± 0.43 Ga, respectively [7]. Our hysteresis measurements show that matrix-rich specimens of 60255 have a mean single-vortex (SV) to superparamagnetic (SP) grain size (H_{cr}/H_c=15, M_{rs}/M_s=0.035, with H_{cr} the coercivity of remanence, H_c the coercivity, M_{rs} the saturation remanent magnetization, and M_s the saturation magnetization), while matrix glass specimens of 60019 and 61195 have a multidomain (MD) grain size, with 60019 lying at the SV-MD boundary (H_{cr}/H_c=20, M_{rs}/M_s=0.015).

Paleomagnetic measurements:

Methodology. We divided the samples into mutually oriented specimens and determined their natural remanent magnetization (NRM) components and paleointensities by means of double-heating experiments. These were conducted in a CO_2-H_2 gas-mixing controlled-atmosphere oven at an oxygen fugacity of 1 log unit below the iron-wüstite buffer [5]. We also conducted alternating field and anhysteretic remanent magnetization paleointensity experiments.

Results. Matrix glass specimens in 60019, 60255 and 61195 have a low-temperature (LT) component that unblocks by 300-400˚C, 150-390˚C and 300-390˚C, depending on the specimen, respectively (Fig. 1). The respective average LT paleointensities are 6.5 ± 6.4 µT (1-sd), 4.9 ± 1.6 µT and 8.55 ± 15.5 µT. Matrix glass specimens in 60019 and 60255 do not have origin-trending, high-temperature (HT) components blocked above 400˚C (Fig. 1). Nevertheless, these two samples can acquire laboratory thermoremanent magnetization, which results in average HT paleointensities within error of zero (1.1 ± 2.3 µT for 60019, and 0.3 ± 0.5 µT for 60255). Our partial thermoremanent magnetization (pTRM) alteration checks are consistent with a lack of significant thermochemical alteration during the experiments [difference ratio sum (DRATS) alteration parameters for the HT range as low as 17.2% for 60019 and 16.1% for 60255].

The results from 61195 are different. Three out of the seven specimens of 61195 had origin-trending, HT components (over the temperature range of 300-450 ˚C for 61195-QAm, 390-680 ˚C for 61195-QBb3h, and 620-770 ˚C for 61195-QCbm) oriented along similar directions (Fig. 1). The respective paleointensities are 4.3 ± 2.8 µT, 5.8 ± 2.5, and 4.5 ± 2.4 µT. Our pTRM alteration checks are consistent with a lack of significant thermochemical alteration during the experiment for two of these specimens (DRATS = 3.5% and 19%, for QAm and QBb3h, respectively) but point to a certain degree of thermochemical alteration for QCbm (DRATS=77%). Specimen 61195-QCdh had a HT component along a similar direction but is not clearly origin-trending. The remaining three specimens did not have a stable primary component.

X-ray Computed Tomography (CT): To investigate the origin of the observed variation in magnetic recording properties among the various specimens of 61195, we performed CT scanning to three-dimensionally quantify the sizes of their metal grains.

Methodology. X-ray CT scanning was performed at the Astromaterials X-ray CT Lab at NASA JSC. Resolution of the reconstructed 3D datasets varied from 3.36 µm/voxel edge to 4.93 µm/voxel edge. Data were visualized and whole-rock volumes measured using Dragonfly™ software (ORS). Volume and caliper dimensions of individual bright phases, interpreted to be Fe metal, were quantified using Blob3D [8].

Results. We found that specimens 61195-QAm and 61195-QBb3h have the lowest abundances of detectable (>~10 µm long axis) metal grains (0.03 vol. % for both) and are the specimens whose largest metal grains are the smallest (maximum long axis of 0.306 mm and 0.300 mm, respectively). Specimen 61195-QBb3l, which was found to have the 3rd lowest abundance in metal grains (0.06 vol. %), has the largest metal grain (maximum long axis of 0.556 mm). This specimen did not give an origin-trending HT component.

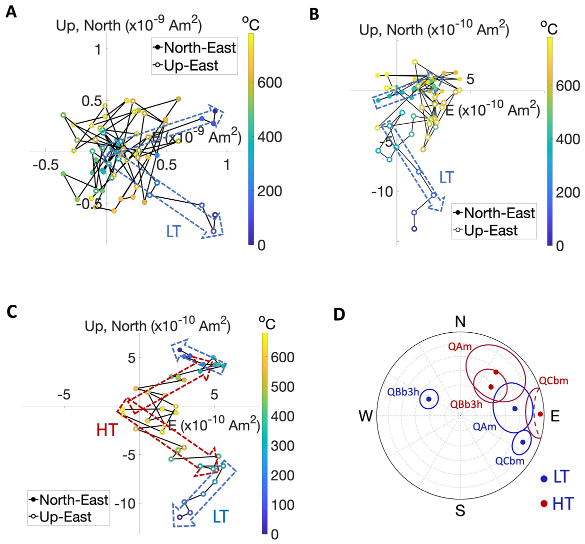

Fig. 1: Paleomagnetism of the 3 regolith breccias of this study. (A) Orthographic projection showing endpoints of NRM during controlled oxygen fugacity thermal demagnetization of specimen 60019-263Y. (B) Same as (A) for specimen 60255-126V. (C) Same as (A) for specimen 61195-QBb3h. (D) Equal area stereonet showing directions of LT and HT components for the three 61195 specimens that gave a HT component.

61195-QCam and 61195-QD2u have the highest abundance (0.13 vol. % and 0.10 vol. %, respectively) and also large grains, and did not give origin-trending HT components either. 61195-QCbm and 61195-QCdh gave similar CT scan results, with 61195-QCdh showing a slightly higher abundance in metal grains than 61195-QCbm (0.08 vol. % vs 0.07 vol. %). These results suggest that CT scanning can be used as a non-destructive method to detect, and therefore avoid, rock specimens with MD grains.

Discussion: By means of controlled-atmosphere, double-heating experiments, we found that regolith breccias 60255 and 60019, with estimated assembly ages of 1.70 ± 0.43 Ga and 3.35 ± 0.43 Ga, respectively, have paleointensities within error of zero (0.3 ± 0.5 µT and 1.1 ± 2.3 µT, respectively). We found that regolith breccia 61195, with an estimated assembly age of 3.41 ± 0.43 Ga, has a non-zero paleointensity of 4.9 ± 2.5 µT, with the caveat that it is MD and has experienced some degree of thermochemical alteration during our experiments. Non-zero paleointensities have been found using controlled-atmosphere, double-heating experiments for two other glassy lunar regolith breccias younger than 3 Ga [9, 10] (Fig. 2).

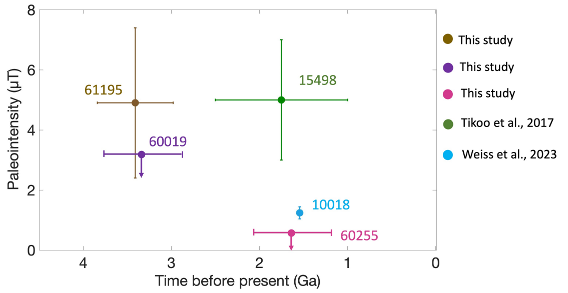

Fig. 2: Paleointensities obtained for lunar regolith breccias by means of double-heating experiments. Arrows signify upper limits of paleointensities within error of zero.

Collectively, these results suggest that the lunar dynamo has been fluctuating in intensity up to an order of magnitude since 3.5 Ga (Fig. 2). All of the inferred paleointensity values are less than several µT such that they are compatible with theoretical expectations for a thermochemical convection core dynamo. Because none of these rocks were magnetized at >3.5 Ga, when nonthermal paleointensity data suggest a field of tens of µT, they cannot directly address the energy budget conundrum during that time period. Nevertheless, their demonstration that the lunar dynamo has exhibited order of magnitude fluctuations in intensity after 3.5 Ga ago hints at the possibility that even larger field fluctuations could have occurred earlier, potentially providing a solution to the energy budget conundrum.

References: [1] Wieczorek M. A. et al. (in press), https://hal.archives-ouvertes.fr/hal-03524536. [2] Evans, A.J. et al. (2018) *Geophysical Research Letters*, *45*, 98-107. [3] Dwyer C. A. et al. (2011) *Nature*, *479*, 212-214. [4] Evans A.J . & Tikoo, S. M. (2022) *Nature Astronomy*, *6*, 325-330. [5] Suavet C. et al. (2014) *Geochemistry, Geophysics, Geosystems*, *15*, 2733-2743. [6] Tauxe L. & Love J. J. (2003) *Geochemistry, Geophysics, Geosystems*, *4*(2). [7] Fagan A.L. et al. (2014) *Earth, Moon, and Planets*, *112*, 59-71. [8] Ketcham R. A. (2005) *Geosphere*, *1*, 32-41. [9] Tikoo S. M. et al. (2017) *Science Advances*, *3*, p.e1700207. [10] Weiss B. P. et al. (2023) *LPSC LIV*, submitted.