PALEODIRECTION OF THE ANCIENT LUNAR MAGNETIC FIELD FROM CAMELOT CRATER BASALTS: EVIDENCE FOR A SELENOCENTRIC AXIAL DIPOLE.

B. L. Getzin[1,2], B. P. Weiss[2], R. A. Wells[3], H. H. Schmitt[4], [1]Smith College, Northampton, MA, USA, (bgetzin@smith.edu), [2]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, [3]Tranquillity Enterprises, s.p., Abingdon, VA, USA [4]University of Wisconsin, Madison, USA.

Introduction: Paleomagnetic studies of Apollo samples and spacecraft magnetometry measurements of the lunar crust indicate that the Moon generated a dynamo magnetic field from at least 4.2 Ga until sometime between 2.5-1.0 Ga [1, 2]. However, because virtually all Apollo samples studied thus far have not been unambiguously oriented with respect to their original formation positions on the lunar surface, they have only yielded measurements of the ancient field's paleointensity rather than its paleodirection. Although two studies used magnetic anisotropy to constrain the orientations of several Apollo samples, these samples were not in-place bedrock and no petrographic evidence supporting the orientations was identified [3, 4].

Paleodirectional field measurements would be invaluable for several reasons. First, they could provide further confirmation for the past existence of a lunar dynamo by demonstrating that the paleofield was on average that of a selenocentric, oriented along the lunar spin axis, and predominantly dipolar [5]. Second, paleodirectional data could establish whether the lunar field experienced reversals and/or secular variation, which would constrain the dynamo generation mechanism and the nature of core flows. Third, paleodirectional measurements could be used constrain lunar Moon tectonism. For example, analyses of crustal magnetic anomalies suggest that the Moon may have experienced true polar wander in which its solid outer shell rotated by tens of degrees with respect to the core [6, 7].

We have recently shown that boulders on the edge of Camelot crater at the Apollo 17 landing site, which were once thought to be ejecta, are more likely either part of an overturned flap produced by the cratering event or approximately in-place subfloor basalts exposed by recent mass wasting [8-10]. Samples 75035, 75055, and 75075, which were acquired from these boulders, have crystallization ages of ~3.8 Ga [9] indicating that they formed when a strong (>10 μT) dynamo is thought to have been active [1].

We have initiated a paleomagnetic and petrographic study of these samples to attempt to obtain paleodirectional constraints on the lunar field. Here we present our initial analyses of the natural remanent magnetization (NRM) of basalt sample 75055 along with a reconstruction of the original orientation in which it formed. From this, we are able to constrain what appears to be a robust measurement of the paleodirection of the ancient lunar magnetic field.

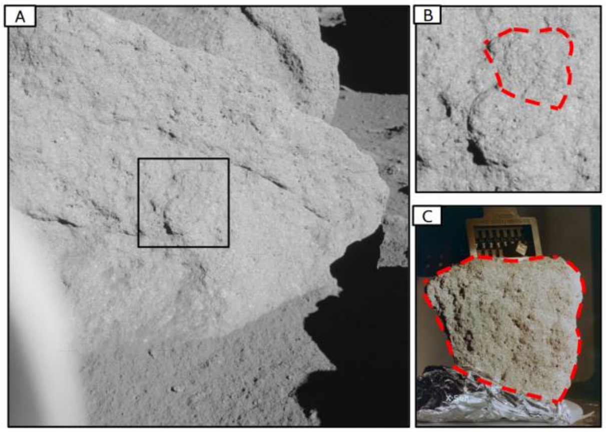

Fig. 1. (A) Astronaut photograph showing the sampled face of 75055 as well as planar features associated with enhanced vesicularity. (B) Zoom in of the boxed area in (A) showing outline of 75055 prior to sampling. (C) JSC photograph of 75055 in reconstructed lunar lighting conditions.

Methods:

Sample: Sample 75055 is a medium-grained ilmenite basalt chipped from a boulder with distinct layering associated with variations in vesicularity, parting planes, and aligned planar facets [12, 13] (Fig. 1). Because 75055's ^{40}Ar/^{39}Ar age of 3.82 ± 0.05 Ga [14] is within error of its Rb-Sr age (3.77 ± 0.06 Ga) [15] and the rock shows no evidence for shock, any stable NRM likely dates to the time of crystallization at 3.8 Ga.

The NRM of a single unoriented chip of 75055 was previously studied, but a stable component of likely lunar origin was not isolated [3]. Hysteresis measurements found that 75055 has a squareness of ~0.003, indicating a dominantly multidomain grain size [16].

Orientation: We chipped 75055,127 from the parent sample at Johnson Space Center (JSC). Using astronaut photos and JSC photos taken under simulated lunar lighting conditions, we oriented our subsamples with respect to the parent boulder on the lunar surface with an estimated uncertainty ±5º [17]. We also used these photos to estimate the orientation of the planar features in the parent boulder. Assuming these features are indicators of paleohorizontal, they can be used in conjunction with paleomagnetic measurements to

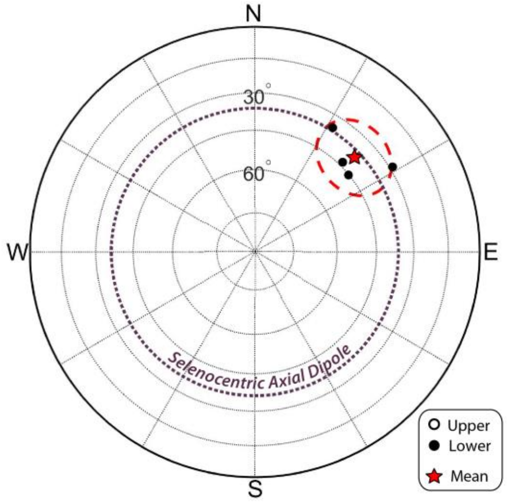

Fig. 2. Evidence for a selenocentric axial dipole on the Moon at 3.8 Ga. Shown is an equal area stereographic projection depicting the directions of the HC components of four subsamples of 75055 (circles) and their mean direction and 95% confidence interval (red star and ellipse). Also shown is the estimated local inclination of a selenocentric axial dipole field at Camelot crater.

recover the paleoinclination of the lunar field. We cannot currently unambiguously recover the paleodeclination of the field due to the possibility that the boulder experienced vertical-axis rotation during tilting.

Paleomagnetism: We studied the paleomagnetism of four mutually oriented subsamples of 75055 in the MIT Paleomagnetism Laboratory. Following our previous analyses of lunar samples (e.g., [2]), we demagnetized the subsamples using stepwise three-axis alternating fields (AF) and measured their NRMs with a 2G Superconducting Rock Magnetometer equipped with an automated sample handling system. Subsamples were demagnetized up to peak fields ranging between 145 and 420 mT. After removal of a low coercivity component blocked up to ~5 mT, each subsample was found to contain a stable, origin-trending, high coercivity (HC) component blocked up to ~80 mT that was unidirectional across the parent sample. Although the multidomain grain size of 75055 means it not an ideal magnetic recorder, the AF stability and unidirectionality of the HC component, combined with the lack of evidence for shock and secondary reheating, indicate it is likely a thermoremanence (TRM) produced during primary cooling on the Moon.

We estimated the paleointensity of the field that produced the HC component by comparing the AF demagnetization of NRM to that of anhysteretic remanent magnetizations (ARM) and isothermal remanent magnetization (IRM) (see [2]). The ARM and IRM average paleointensities are 29.6 ± 4.3 µT (4 samples) and 29.2 ± 3.8 µT (2 subsamples), respectively (uncertainties are 1σ and do not take into the account the factor of ~5 uncertainty associated with the unknown ratios of ARM and IRM to TRM).

To further measure the fidelity of the samples as field recorders, the samples were given ARMs with various bias fields and these ARMs were then subjected to paleointensity experiments. Within each subsample's HC range, we were able to accurately recover the expected field value down to TRM-equivalent fields as weak as 14 µT. We also found that the NRM has similar or higher AF stability as that of an ARM, supporting a TRM origin for the NRM.

Conclusions: Apollo basalt 75055 contains a characteristic NRM component that likely formed during primary cooling on the lunar surface at 3.8 Ga. Tilting this component to restore the sample to its original horizontal orientation during primary cooling, we find that the mean inclination of the local paleomagnetic field was $i = 38.6 \pm 13.5°$ (uncertainties are 95% confidence interval on Fisher mean direction from four subsamples and do not take account ~5-10° uncertainties in orientations of sample on Moon and the boulder parting plane). Surprisingly, this inclination is within error of the predicted $i_\mathrm{d} = \arctan(2 \tan \lambda) = 36.3°$ local field inclination for a selenocentric axial dipole at the latitude of Camelot crater $\lambda = 20.19°$N. This is consistent with the hypothesis that the ancient Moon generated a dynamo field with the orientation of the lunar spin axis at 3.8 Ga being close to that of the present-day. Furthermore, because i was measured from a single basalt flow without averaging any secular variation, its agreement with i_d may indicate that the lunar dynamo was more temporally stable than that of Earth. Our ongoing analyses of other oriented Apollo samples will further test these conclusions.

References: [1] Weiss B. P. and Tikoo S.M. (2014) *Science, 346*, 1246753-1. [2] Tikoo S. M. et al. (2017) *Sci. Adv., 3*, e1700207. [3] Cournède C. et al. (2012) *EPSL, 331-332*, 31-42. [4] Potter (2011) *CASJ, Vol. 57, No. 1*, 1223. [5] Merrill et al. (1998) *2nd ed., Academic Press, San Diego* [6] Arkani-Hamed J. and Boutin D. (2014) *Icarus, 237*, 262-277. [7] Takahashi (2014) *N.Geo., 7*, 409-412. [8] Schmitt H. H. et al. (2017) *Icarus, 298,* 2-33. [9] Schmitt H. H. et al. (2018) *LSC XVIX*, submitted. [10] Wells R. A. et al. *LSC XVIX*, submitted. [11] Mercer C. (2015) *EPSL, 23*, 453-461 [12] Meyer C. (2008) *Lunar Sample Compendium.* [13] Ryder, G. (1993) *Catalog of Apollo 17 Rocks*, NASA Johnson Space Center, Houston. [14] Kirsten T. et al. (1973) *EPSL, 20*, 125-130. [15] Tatsumoto M. et al. (1973), *Eos, 54*, 614-615. [16] Pearce G. W. et al. (1974) *LSC III*, 2815-2826. [17] Wolfe E. W. et al. (1981) *USGS Prof. Pap. 1080.*