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Research Article

Keywords: lunar magnetic field, paleomagnetic studies, Apollo 17 basalt

Posted Date: March 16th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-311626/v1>

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Version of Record: A version of this preprint was published at Nature Astronomy on September 27th, 2021. See the published version at <https://doi.org/10.1038/s41550-021-01469-y>.

The Paleoinclination of the Ancient Lunar Magnetic Field from an Apollo 17 Basalt

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Paleomagnetic studies of Apollo samples indicate that the Moon generated a core
dynamo lasting for at least 2 billion years^{1,2,3}. However, the geometry of the lunar
magnetic field is still largely unknown because the original orientations of essentially all
Apollo samples have not been well-constrained. Determining the direction of the lunar
magnetic field over time could elucidate the mechanism by which the lunar dynamo
was powered and whether the Moon experienced true polar wander. Here we present
measurements of the lunar magnetic field 3.7 billion years (Ga) ago as recorded by Apollo
17 mare basalts 75035 and 75055. These samples formed as part of basalt flows in the
Taurus-Littrow valley that make up wall-rock within Camelot crater, now exposed at the
rim of the crater⁴. Using apparent layering in the parent boulder for 75055, we inferred

its original paleohorizontal orientation on the lunar surface at the time of magnetization. We find that 75035 and 75055 record a mean paleointensity of $\sim 50 \mu\text{T}$. Furthermore, 75055 records a paleoinclination of $34 \pm 11^\circ$. This inclination is consistent with, but does not require, a selenocentric axial dipole field geometry (i.e., a dipole in the center of the Moon and aligned along the spin axis). Additionally, although true polar wander is also not required by our data, true polar wander paths inferred from some independent studies of lunar hydrogen deposits and crustal magnetic anomalies^{5,6,7} are consistent with our measured paleoinclination.

Measurements of the paleodirection of the Earth’s field have played a fundamental role in our understanding of the geodynamo and the history of global tectonics⁸. These studies have shown that the time-averaged surface magnetic field [over at least several million years (Ma)] of the Earth is largely indistinguishable from that of a geocentric axial dipole. The relationship between magnetic inclination, I , and latitude, λ , of an axial dipolar magnetic field is given by

$$\tan I = 2 \tan \lambda \quad (1)$$

For any given latitude, Equation (1) predicts the expected mean paleoinclination of an Earth-like, dynamo field. Applications of this relationship to constrain the paleolatitude of rocks laid the foundation for the discovery of plate tectonics. Likewise, lunar paleodirectional data would enable a test of whether the Moon’s dynamo was described by an equivalent selenocentric axial dipole relationship and to assess the implications for the dynamo mechanism and the possibility of true polar wander.

However, unambiguous constraints on lunar paleomagnetism have almost exclusively been limited to paleointensity data. These measurements indicate that the early lunar dynamo generated surface fields possibly reaching $\sim 70 \mu\text{T}$ or more from 4.25 – 3.56 Ga ago. The lunar dynamo field subsequently declined to $5 \pm 2 \mu\text{T}$ before apparently ceasing sometime between 1.92 and 0.80 Ga ago^{2,3}. By comparison, only two studies of Apollo samples have attempted to constrain the absolute paleodirection of the lunar magnetic field^{5,9}. One study of mare basalts tentatively suggested that the lunar dynamo 3.3 – 3.8 Ga ago was dipolar and aligned along the present-day spin axis⁵. The other study⁹ was conducted on regolith breccia 15015, but the stable magnetization in this sample has subsequently been shown to have been produced during saw cutting at the Johnson Space Center (JSC)³. Both studies attempted

to infer the field’s paleoinclination using magnetic anisotropy measurements, but the uncertainties on the paleohorizontal orientation of the samples from data are difficult to quantify. In particular, our analyses of mare basalts find magnetic anisotropy to be a poor indicator of paleohorizontality (see Supplementary Text S2 and Figure S15).

Numerous studies have attempted to constrain the geometry of the ancient magnetic field using spacecraft measurements of the crustal magnetic field. Although some such studies found support for the presence of a selenocentric axial dipole geometry from the clustering of some paleopoles, the paleopoles as a whole are spread over the entire surface of the Moon^{6,10}. The large scatter of the paleopoles is likely in part a consequence of the fact that, even for a uniformly magnetized source with a single component of magnetization, inverted paleopoles depend on assumptions about the source, depth and susceptibility of magnetization, resulting in nonunique magnetization solutions^{11,12}. Furthermore, if the crust has multiple components of magnetization acquired at different times throughout lunar history, then even if a paleopole could be uniquely recovered from the net magnetization, it would not correspond to the paleopoles associated with any of the composite magnetization events. Finally, it is difficult to determine the age of paleopoles inferred from orbital data given the uncertainty of using crater counting ages to date deep crustal magnetization sources and the lack of direct radiometric constraints. Therefore, measuring the paleomagnetic directions recorded by lunar samples whose original orientations can be reconstructed, and which can be dated with radiometric techniques, is likely the most unambiguous way to reconstruct lunar paleopoles.

The relative contributions of an axial dipole and multipolar terms to a dynamo field are thought to be influenced by the local Rossby number, Ro_l , which quantifies the ratio of inertial to Coriolis forces for characteristic flow scales within the core^{13,14}. Most bodies with active dynamos in the solar system today are estimated to have Ro_l below a critical value of ~ 0.12 . Furthermore all bodies other than the ice giants have dipole-dominated instantaneous fields with dipole tilts $< 10^\circ$, consistent with Coriolis forces strongly influencing their geometries^{14,15}. For the Earth’s time-averaged field, this is manifested by behavior described by Equation (1).

Synchronous rotation of the Moon was likely established early in lunar history, such that by 3.7 Ga ago the rotation rate was sufficiently slow ($\sim 5 \times 10^{-6} \text{ rad s}^{-1}$) that its Ro_l would have reached a value of ~ 2 , suggesting that the field in the core was dominantly nondipolar¹⁴. In particular, simulations of dynamos with Ro_l exceeding a critical value of ~ 0.1 have found that such dynamos have a dipolarity,

$f_{dip} = \frac{B_d}{B_{nd}} = 0.001 - 0.1$, where B_d and B_{nd} are the intensities of the dipole (e.g., spherical harmonic degree $l = 1$) and non-dipole (e.g., $l > 1$) components of the field, respectively. On the other hand, the small size of the lunar core ($\sim \frac{1}{7}$ of the body's radius¹⁶) should lead to significant attenuation of the higher order multipolar terms at the lunar surface. Conservatively assuming that at the top of the lunar core the multipolar field was dominated by the quadrupolar term, such that $B_d = 0.001 - 0.1$ and the quadrupolar part of the field was $B_q = 0.9 - 0.999$, then given that dipole (e.g., degree $l = 1$) and quadrupole terms ($l = 2$) fall off as $r^{-(l+2)}$ for distance from the top of the core, r , the predicted field at the surface would still be significantly multipolar ($f_{dip} \sim 0.007 - 0.44$). Therefore, we do not expect that the lunar dynamo must have followed Equation (1).

Even so, a high Ro_l does not by itself preclude a dipolar surface magnetic field geometry. The multipolar state implied by the high Ro_l only applies to the field-generating region in the core, whereas paleomagnetic observations only constrain the surface field. For example, as has been proposed for Mercury which has a dominantly dipolar field in spite of its high estimated Ro_l ^{17,18,19}, a subadiabatic, stably stratified layer may have existed at the top of the lunar core (e.g. ref. 16) that suppressed multipolar field components due to their higher time variability relative to that of the low-degree field. In addition, if the core is stratified, then the thermal and compositional buoyancy forces must be considered separately to account for double-diffusive convection. However, previous estimates of the lunar Ro_l were calculated using a co-density approach, which may only be applicable to turbulent, well-mixed cores¹⁴. It has been demonstrated that using a double-diffusion approach instead can drastically change the predicted surface magnetic fields²⁰. Additionally, previous estimates of the lunar Ro_l assumed that dynamo action is convection-driven¹⁴ but this assumption may not apply for a different mechanism of dynamo generation, such as precession^{21,22}.

Although there is strong evidence for the existence of a past lunar dynamo, its physical mechanism and power source are highly uncertain. The small size of the lunar core means that the apparent surface field paleointensities before 3.5 Ga ago imply a very strong core dynamo field (> 24 mT) even in the limiting case of a purely dipolar field. As a result, convective core dynamo scaling laws fail by more than an order of magnitude to generate surface intensities $> 50 \mu\text{T}$ over time periods lasting > 30 Ma²³. Precession-driven dynamos, although potentially able to achieve higher paleointensities²¹, struggle to generate magnetic fields in spherical cores for realistic viscosities²⁴ although the dissipative heat from precession might instead serve as a heat source for a convective dynamo²². Impact-driven

dynamoes that initiate mantle stirring of the core may be able to generate the observed paleointensities, but can only be sustained for thousands of years²⁵ and require basin-forming impacts which ceased before 3.7 Ga ago²⁶. It has also been proposed that a basal magma ocean could generate the observed intensity and longevity of the lunar dynamo, but this requires the magma ocean to have an exceptionally high electrical conductivity²⁷.

Measurements of the geometry of the ancient lunar magnetic field would provide invaluable constraints for distinguishing between these potential dynamo mechanisms (Figure 1). As discussed above, convective core dynamoes in fast rotating bodies ($Ro_l < 0.12$) are expected to be predominantly dipolar (Figure 1a), whereas the lunar dynamo is expected to be multipolar (Figure 1b). If the magnetic field was generated by a highly conductive silicate basal mantle magma ocean²⁷, even higher degrees of multipolarity may be observable given the shallower source region (Figure 1c,d).

The above theoretical challenges with generating a lunar field by the dynamo process has long motivated a diversity of other proposed non-dynamo mechanisms. Although these alternative mechanisms are unlikely to explain the bulk of the observed paleomagnetic record and in many cases are inconsistent with other lunar data, highly speculative, and/or not well-developed theoretically, they may conceivably have accounted for some lunar paleomagnetism. As such, some of these non-dynamo models make first-order predictions for the lunar paleofield geometry that could be assessed with paleodirectional measurements under the assumption of no subsequent true polar wander.

If the lunar surface was magnetized by Earth's time-averaged geocentric axial dipole²⁸ a uniform inclination equal to the lunar latitude would be observed (Figure 1e). Another possibility is that the lunar surface was magnetized by the interplanetary magnetic field (IMF), which is expected, on average, to have been instantaneously aligned along the plane of the lunar equator (Figure 1f)²⁹. Magnetic fields amplified by basin-forming impacts in the solar wind, although recently shown to be unable to explain lunar paleointensities³⁰, were predicted to have inclinations close to horizontal (0°) over much of the lunar surface and close to vertical (90°) at the basin antipodes (Figure 1g)³¹. Magnetic fields generated locally by smaller impacts would likely have scattered inclinations that cluster around 0° for near-vertical impacts in near-zero ambient fields (Figures 1h)^{32,33,34,35}. Near-horizontal inclinations might be expected for a thermoelectric dynamo generated by adjacent lava basins³⁶, while near-vertical inclinations might be expected for a unipolar dynamo in an isolated lava basin²⁸ (Figure 1i,j). Cometary impacts perhaps generated predominantly horizontal inclinations across the lunar

145 surface (Figure 1k)^{28,37,38}.

146 To constrain the geometry and intensity of the ancient lunar dynamo, we studied two mare basalt
147 samples collected during the Apollo 17 mission: 75035 and 75055. These two samples have indistin-
148 guishable ages of 3753 ± 9 Ma and 3752 ± 9 Ma, respectively³⁹. They were collected from within
149 ~ 10 m of the rim of the 610-m-diameter, $\sim 500 \pm 200$ Ma old Camelot crater⁴, located at 20.2°N ,
150 37.3°E ⁴⁰. The Camelot crater event is thought to have exposed > 120 m of mare basalt flow stratig-
151 raphy. The significance of 75035 and 75055 for paleomagnetic studies only recently came to light
152 following reassessment of the geology of the Taurus-Littrow valley⁴. Although they were originally
153 interpreted as ejecta blocks, the parent boulders of these samples are now thought to represent near
154 in-situ wall rock exposed during mass wasting of Camelot Crater. It is unlikely that these samples
155 have moved more than ~ 10 m from their original location, although they may have been differentially
156 tilted or rotated with respect to the underlying bedrock⁴. A similar mass wasting process was observed
157 at the Apollo 15 site Hadley Rille whose eastern rim is composed of a mixture of fractured bed rock
158 and associated locally-derived boulders⁴¹.

159 The parent boulder for 75055, as well as surrounding blocks, exhibit clear layering and planar fea-
160 tures that can be used to infer paleohorizontality (see Methods 1.1 and Figure S3). 75055 is therefore
161 one of very few known Apollo samples whose original orientation can be unambiguously constrained.
162 We have used this sample to measure the paleoinclination (along with the paleointensity) of the lunar
163 field 3.7 Ga ago. Sample 75035 was also acquired from a parent boulder with possible layering fea-
164 tures, but the small number of astronaut photographs and their limited range of perspectives means
165 that we cannot unambiguously reconstruct paleohorizontal for this sample. We therefore report only
166 paleointensity data for 75035.

167 Electron microscopy data indicate samples 75035 and 75055 contain essentially pure-Fe kamacite
168 (α -Fe) with a dominantly multidomain grain size (Supplementary Text S1 and S2). However, isother-
169 mal remanent magnetization (IRM) acquisition data indicate 75035 and 75055 contain grains with
170 coercivities > 1000 mT and > 400 mT, respectively, indicating the presence of a population of pseudo-
171 single domain (e.g., single vortex) grains (Supplementary Text S1 and S2). Both 75035 and 75055
172 have cooling rates $< 3^\circ\text{C hr}^{-1}$ constrained by their petrographic textures^{42,43}, and therefore cooled
173 too slowly to have recorded putative plasma fields or impact fields, which would have had a maxi-
174 mum duration of < 1 day. Additionally, neither sample exhibits evidence for shock metamorphism

(see Supplementary Text S3.3), indicating they never experienced a pressure wave with an amplitude greater than ~ 5 GPa (the Hugoniot elastic limit for lunar rocks^{44,45}), suggesting they are unlikely to have acquired a shock remanent magnetization. The samples should therefore primarily contain a thermoremanent magnetization (TRM) acquired during primary cooling on the Moon after their emplacement.

Our alternating field (AF) demagnetization of specimens of 75035 (taken > 2.5 mm from a JSC bandsawn surface) and 75055 (which has never been cut by JSC bandsaw) revealed a non-origin-trending low coercivity (LC) component of natural remanent magnetization (NRM) that was removed by 0 – 11 mT (Figure 2 and Table S10). The LC components are highly scattered within each parent sample (Figure 3). Once the LC overprints were removed, we found that six non-bandsawn specimens of 75035 and five specimens of 75055 each contained a final origin-trending high coercivity (HC) component that was blocked up to 40 – 60 mT and essentially unidirectional within each parent sample (Figure 2 and Table S10). The Fisher mean anisotropy-corrected HC direction for these six specimens of 75035 is $030^\circ/11^\circ$ in present-day lunar coordinates (see Methods Table 1 for definitions and descriptions of coordinate systems) with a 95% confidence interval $\alpha_{95} = 16^\circ$. The Fisher mean anisotropy-corrected HC direction for five specimens of 75055 in present-day lunar coordinates is $334^\circ/02^\circ$ with $\alpha_{95} = 11^\circ$. In lunar paleohorizontal coordinates, the HC component of 75055 has a paleoinclination of $I_{LPH} = 34^\circ$, $\alpha_{95} = 11^\circ$, and an estimated Fisher precision parameter $\kappa = 46.0$, where the uncertainty is estimated from the scatter in the HC directions among individual specimens.

We measured mean HC paleointensities of $50.7 \pm 13.5 \mu\text{T}$ and $57.0 \pm 17.3 \mu\text{T}$ (1σ standard error of 4 and 8 subsamples) for 75035 and 75055, respectively, using the anhysteretic remanent magnetization (ARM) method (Figure S19 and Table S9). The calculated confidence intervals for individual specimens reported in Table S9 are based on 95% confidence intervals from the least-squares fits of NRM lost versus ARM lost during AF demagnetization and do not take into account systematic uncertainties due to the poorly known ratio of ARM to TRM. The latter 2σ uncertainties are estimated to be a factor of $\sim 5^1$, such the true range of paleointensities is 10 – 250 μT and 11 – 285 μT for 75035 and 75055, respectively. Therefore, the paleointensity estimates for 75035 and 75055 are both within error of the mean value of 77 μT measured from six samples of age 3.5 – 4.2 Ga^{5,26,46,47}. They thereby provide additional evidence that > 3.5 Ga ago, the Moon had an active dynamo generating a strong magnetic field. Even the lower limit on our recovered paleointensity ($\sim 10 \mu\text{T}$) exceeds the field strength predicted

205 by convective dynamo scaling laws and is barely compatible with a dynamo intermittently reaching
206 this strength over an integrated time of just 30 Ma²³. Furthermore, this minimum paleointensity is
207 still a factor of 2 stronger than the weak paleointensities measured between $\sim 3.5 - 1$ Ga ago, and at
208 least an order of magnitude stronger than the weakest fields that can be reasonably attributed to an
209 active dynamo^{2,3,48}.

210 We consider the implications of our paleoinclination results based on two alternative assumptions
211 about 75055's paleoinclination record; first, that it reflects only the instantaneous lunar magnetic
212 field and, second, that it is representative of the time-averaged (over $\sim 0.1 - 10$ Ma) lunar field
213 (i.e., that secular variation on these timescales is negligible). Considering the instantaneous magnetic
214 field, we calculated the location of the virtual magnetic pole under the assumption of a selenocentric
215 axial dipole. Since declination and the sign of the inclination are unconstrained, the possible virtual
216 magnetic pole locations define two small circles (Figure 4c). For our recovered paleoinclination, the
217 implied dipole tilt includes $0 - 10^\circ$, consistent with an axially-aligned instantaneous magnetic field
218 that is dipole-dominated like those of other inner solar system bodies^{15,49,50}.

219 We next consider our paleoinclination results assuming the instantaneous and time-averaged lunar
220 magnetic fields were similar. In this case, the recorded inclination would reflect a durable feature of
221 the lunar field geometry rather than a localized, transient state like those associated with core waves or
222 short-lived convection rolls. First, we use our paleoinclination results to assess the different magnetic
223 field sources that could have magnetized the lunar surface (further details are provided in Supple-
224 mentary Text S3). Second, we consider a multipolar core dynamo field, and, finally, we consider the
225 implications for true polar wander. To assess different magnetic field sources, we assume that Camelot
226 crater was at its present latitude at the time of NRM acquisition. Using Equation 1 and assuming
227 no subsequent true polar wander, the magnetic inclination of a selenocentric axial dipole at Camelot
228 crater would be $\sim 36^\circ$, which is indistinguishable from our paleoinclination estimates (Figure 4a). Ex-
229 ternal field sources from either Earth's ancient dynamo or the IMF are expected to produce inclinations
230 that are too low or high at the latitude of Camelot crater, respectively, under the assumption that
231 their orientations were similar to those observed today (Figure 4a). Other sources of magnetization
232 such as impacts and thermoelectric dynamos (Figure 1g-k) are also apparently inconsistent with our
233 paleoinclination results.

234 Although our recovered paleoinclination is consistent with a selenocentric axial dipole generated

by a core dynamo, we show next that the results do not require such a geometry. In particular, we consider non-axial dipolar and multipolar fields (see Supplementary Text S3.1 for details). As a limiting case, we investigated how the addition of zonal quadrupolar and octupolar components to an axial dipole will effect the predicted magnetic field inclination at the latitude of Camelot crater (Figure 4b). Even just considering these low order, purely zonal terms, our paleoinclination cannot exclude a high degree of multipolarity. A multipolar magnetic field is consistent with the low lunar rotation rate, and would also be favored by dynamo sources closer to the surface (e.g., a basal magma ocean²⁷) given the $r^{-(l+2)}$ dependence of multipolar fields. Clustering of paleopoles near the poles and the equator has been observed by numerous crustal magnetic studies^{10,51} and would be consistent with a predominantly quadrupolar dynamo or else a persistent non-axial dipole field⁵².

Finally, we consider the implications of our paleoinclination for true polar wander, assuming that our measured paleoinclination corresponds to a selenocentric axial dipole. The topography and gravity of the Moon suggest that the rotation axis may have reoriented by $36 \pm 4^\circ$ from an ancient paleopole location of $54 \pm 5^\circ\text{N}$, $309 \pm 6^\circ\text{E}$ since the Cassini state transition⁴⁶. True polar wander has also been suggested to explain variability in the directions of crustal magnetization^{10,53}. Lunar hydrogen deposits, which may represent ancient polar ice deposits, are observed in two distinct, antipodal locations offset from the current spin poles, suggesting that the Moon may have experienced a significant degree of true polar wander⁷. Assuming a selenocentric axial dipole that may have reversed, our paleoinclination measurement predicts paleopole locations offset from the spin axis that are indistinguishable from several independent studies at ~ 3.7 Ga ago^{5,6,7,52} (Figure 4c). However, no subsequent true polar wander is also indistinguishable from our measured paleoinclination.

The novelty of this study is that we were able to reconstruct the paleohorizontal orientation of the parent block for 75055 from planar features documented in astronaut photographs. This has enabled an accurate measurement of the absolute paleoinclination of a lunar sample relative to a known latitude on the lunar surface. The recovered paleoinclination of $34 \pm 11^\circ$ at a latitude of 20.2°N is consistent with, but does not require, a selenocentric axial dipole. In addition, our paleointensity measurements have shown that both 75035 and 75055 cooled in the presence of a strong field ($> 40 \mu\text{T}$), consistent with previous evidence for an epoch of intense magnetic fields $\sim 3.5 - 4.2$ Ga ago¹.

Our data do not exclude the possibility of a significantly multipolar lunar magnetic field (Figure 4b). Nevertheless, under the assumption of a selenocentric axial dipole, we find that allowed 3.7 Ga true

polar wander paths are consistent with those of independent crustal magnetic and hydrogen deposit studies^{5,6,7} (Figure 4c). A dipolar magnetic field is at odds with the high Ro_l of the Moon, which could indicate stratification of the lunar core^{16,18,19} or a lunar dynamo operating in a non-convective regime, such as precession^{21,22}.

We have provided a framework in which other potentially orientable Apollo samples can be included to improve our understanding of how the lunar magnetic field varied with latitude and its implications for the lunar dynamo. Co-temporal measurements of the ancient lunar field from samples at different latitudes on the Moon will enable the magnetic field geometry to be unambiguously determined. Paleoinclination measurements from samples of different ages would also allow the rate and extent of true polar wander to be better defined, as well as allowing lunar secular variation to be quantified. Future sample return missions to the Moon should collect oriented samples from confirmed bedrock from a range of latitudes and formation ages, which will greatly enhance our understanding of the geometry and temporal variability of the ancient lunar magnetic field and the mechanism of dynamo generation.

Figure 1 | Predictions of various hypothesized lunar magnetic field sources for the paleoinclination of the lunar field. The top and bottom of each panel show a schematic of the approximate field direction with respect to the Moon and the inclination as a function of latitude, respectively. The black region represents the lunar core and dark red regions represent molten silicate. In all cases, red lines depict the magnetic field, blue lines depict any currents generated, and the yellow region around the Moon represents the solar wind when this is specifically required to generate the proposed magnetic field. **a**, A selenocentric axial dipolar magnetic field generated by a core dynamo with a rapid planetary rotation rate ($Ro_l < 0.12$). **b**, A multipolar, non-axisymmetric magnetic field generated by a core dynamo with a slow planetary rotation rate ($Ro_l > 0.12$). **c**, An axially-aligned quadrupolar dynamo generated by a deep-sourced magma ocean dynamo²⁷. **d**, An axially-aligned octupolar dynamo generated by a shallow-sourced magma ocean dynamo²⁷. **e**, The Earth's mean axial dipole field at the location of the Moon. **f**, The IMF. **g**, Antipodal field amplified by basin forming impacts⁵⁴. **h**, Fields generated by impact plasmas²⁸. The predicted inclination is for rocks directly below the crater. **i**, Magnetic fields generated by the thermoelectric effect in lava basins that are electrically connected to subsurface magma and the solar wind^{28,36}. **j**, Magnetic fields generated by a unipolar dynamo in lava basins²⁸. The predicted inclination is for a rock at the surface close to the lava pool. **k**, Compression of the IMF around the Moon by a cometary coma²⁸.

Figure 2 | Demagnetization of NRM in 75035 and 75055. Orthographic projections in laboratory coordinates show the NRM vector during AF demagnetization projected along the North-East (closed squares) and Up-East (open symbols) directions. Stable components are shown by blue (LC), purple (medium coercivity, MC) and red (HC) arrows, respectively. Data shown here are not corrected for remanence anisotropy. The peak AF is shown by the colour bar. **a**, Specimen 75035-242Ae. **b**, Specimen 75055-127Aa. **c**, Specimen 75035-242Bg. **d**, Specimen 75055-127Ae.

Figure 3 | NRM components in 75035 and 75055 and associated paleoinclinations. The LC (grey) and HC (pale blue for 75035, pale red for 75055) components are shown in present-day lunar coordinates for individual specimens. Remanence-anisotropy-corrected HC components are shown in bright blue and red for 75035 and 75055, respectively. The mean (stars) and 95% confidence interval (ellipses) were calculated for the anisotropy-corrected HC components. **a**, Equal area stereonet projections of mutually oriented specimen components for 75035 in lunar coordinates. **b**, Equal area stereonet projections of mutually oriented specimen components for 75055 in lunar coordinates. **c**, Paleoinclinations in lunar paleohorizontal coordinates for the HC components in 75055. The mean (horizontal red line) and one standard deviation (red shaded region) are shown for anisotropy-corrected components.

Figure 4 | Predictions for the paleoinclination of the lunar field, and implications for multipolarity and true polar wander. **a**, Paleoinclination results are shown at the present latitude of Camelot crater by the black symbol with 95% confidence error bars. Red dots are the measured paleoinclinations from each specimen of 75055. Predicted inclination versus latitude curves (see Figure 1) are shown for impact fields, a unipolar dynamo and a thermoelectric dynamo (red lines), Earth's magnetic field (purple line), the IMF (yellow line), and a selenocentric axial dipole (green line). **b**, The predicted magnetic inclination at Camelot crater for a magnetic field with zonal dipolar, quadrupolar and octupolar components, where $G2$ and $G3$ are the quadrupolar to dipolar and octupolar to dipolar field ratios, respectively. The thick black line is the mean paleoinclination and the regions bounded by thin black lines represent the 95% confidence interval. Both low and high degrees of multipolarity are permitted by our measured paleoinclination. **c**, Equal area stereographic projection showing the possible paleopole locations 3.7 Ga ago in present-day lunar geographic coordinates. Open symbols/dashed lines and closed symbols/solid lines are in the northern and southern hemisphere, respectively. The star is the current location of Camelot crater where the samples were collected. The thick black lines are the permitted locations of the north pole calculated from our mean recovered paleoinclination. Thin black lines are the 95% confidence interval on our measurement. The grey shaded region represents $< 10^\circ$ dipole tilt. North 3.7 Ga paleopole locations from independent studies are shown in purple⁵, pink⁷, red⁵², orange⁶, green⁵¹ and blue⁵⁵.

1 Methods

1.1 Reconstructing sample orientation relative to the lunar surface

In this study, we analyzed subsamples 75035,242 and 75055,127, which B.P. Weiss and H.H. Schmitt selected and oriented at JSC in 2016. Our subsamples are oriented with respect to their parent samples in JSC coordinates (see Table 1 for details of coordinate systems). We reconstructed the orientations of parent samples of 75035 and 75055 relative to their sampling positions on the lunar surface using JSC and astronaut photographs and transcripts recorded by astronaut H.H. Schmitt and astronaut E.A. Cernan during sample collection. Both 75035 and 75055 were hammered directly off blocks with visible planar features at the edge of Camelot crater by astronaut H.H. Schmitt in December 1972 (Figure S2). The blocks were photographed before and after sampling by astronauts H.H. Schmitt and E.A. Cernan. The present-day orientations of 75035 and 75055 relative to each block on the lunar surface were reconstructed using photographs taken in lunar-lighting conditions at the Lunar Receiving Laboratory⁵⁶. The astronaut photographs indicate that the blocks were likely not undisturbed bedrock when samples 75035 and 75055 were collected but rather had undergone subsequent tilting and rotation since their formation (Figure S3). As a result, outcrop textural features allow the paleohorizontal to be determined, but cannot account for the paleoazimuthal direction. We therefore only attempt to constrain paleohorizontal and determine the ancient field’s paleoinclination and not paleodeclination.

Planar features are observed on the parent boulders of 75035 and 75055 and on other blocks around Camelot crater (Figure S3). The astronauts noted that these planar features were largely defined by variations in vesicle distribution⁵⁷ and may represent the tops of lunar lava flows. A terrestrial analogue to these lava flows are the extensively studied Hawaiian basalts, with the low viscosity lava flows on the lunar surface having an emplacement mechanism comparable to that of pāhoehoe flows^{42,58,59}. Pāhoehoe flows grow via inflation due to injection of fresh magma beneath a solid crust. This results in a distinct distribution of vesicles, with the bottom and top of the lava flow containing horizontally-aligned ‘vesicular zones’ which can be tens of centimetres to metres in thickness, while horizontal ‘vesicle sheets’ (~ 10 cm thickness) form near the centre of the flow. 75035 and 75055 are thought to have formed in the central part of a pāhoehoe-like flow given the coarse (> 1 mm) crystalline nature of ilmenite within the samples^{42,60} such that the planar features observed on the parent boulder of 75055 likely correspond to vesicle sheets. The spatial distribution of features is consistent with a lava flow

307 thickness of < 10 m. Lunar lava flows have a lower viscosity than that of any known terrestrial flow⁶¹
 308 and formed thin (< 10 m) and laterally extensive flows⁶². It should also be noted that horizontal
 309 vesicular layers can be produced without the injection of fresh melt into the system⁶³. In terrestrial
 310 basalts exhibiting vesicular layers, such as the Columbia River flood basalt flows, vesicles have been
 311 observed to form approximately every 1 m, consistent with theoretical calculations⁶³. However, given
 312 the lower viscosity of lunar basalts and lunar gravity, these layers are likely to be closer together on
 313 the Moon due to faster rise times and are therefore a plausible explanation for the ~ 30 cm spacing
 314 between vesicle layers observed on the blocks at Camelot crater (Figure S3). We therefore assumed that
 315 the planar features defined by vesicles within 75055's parent block represent the paleohorizontal at the
 316 time of eruption. Using this assumption, we reconstructed the paleohorizontal orientation of the block.
 317 Note also that the similar compositions of the blocks at the crater edge and their spatial distribution
 318 indicate that they are close to their formation localities such that the measured paleointensities can
 319 be interpreted in the context of the latitude of Camelot crater.

320 We used photographs of sample 75055 (in JSC coordinates) to reconstruct its original orientation in
 321 lunar geographic coordinates (Figure S6). The attitude of the visible foliations on the parent boulder
 322 of 75055 were reconstructed by measuring the apparent trend and plunge of planar features observable
 323 in a series of photographs taken from different locations (Table S2 and Figure S7). A great circle was
 324 fitted to the trend and plunge measurements to define the plane. The planar features have a strike
 325 and dip of $243^\circ/36^\circ$ ($\alpha_{95} = 5^\circ$) in lunar coordinates. The orientation of the plane was used to tilt
 326 the boulder back to its original paleohorizontal position. Once the paleohorizontal orientation of the
 327 parent boulder of 75055 was established, the magnetic paleoinclination was recovered. Because the
 328 lunar magnetic field may have undergone reversals, it is only meaningful to recover the magnitude of
 329 the paleoinclination and not its sign.

Coordinate System	Abbreviation	Description	Samples
Magnetometer	mag	The coordinate system of the superconducting rock magnetometer for AARM measurements at the Fort Hoofddijk Paleomagnetic Laboratory.	
Laboratory	lab	Orientation used in the MIT Paleomagnetism Laboratory.	75035
JSC	JSC	Orientation used at the JSC to document Apollo samples.	75035,75055
Present-day lunar	L	Orientation on the lunar surface, where Top is outward normal from the lunar surface and North is horizontal and toward the present-day spin axis.	75035,75055
Lunar paleohorizontal	LPH	Using planar features on blocks, lunar coordinates are tilt corrected to the paleohorizontal. Only inclination is considered in this coordinate system.	75055

Table 1 | Definitions and descriptions of the coordinate systems used throughout this study. The order in which coordinate systems are listed is the order in which corrections were made to sample orientations throughout the study.

1.2 Paleomagnetic analysis

All demagnetization experiments were conducted on a 2G Enterprises Superconducting Rock Magnetometer 755 in the MIT Paleomagnetism Laboratory. The magnetometer has a sensitivity of $< 1 \times 10^{-12} \text{ Am}^2$ (ref. 64). 15 specimens of 75035 and 9 specimens of 75055 were demagnetized using AF because thermal demagnetization may cause sample alteration (Figure S12)^{65,66}. The NRM was removed by three axis AF demagnetization in steps of 0.5 mT up to 25 mT, steps of 1 mT up to 95 mT, and then steps of 1.5 mT up to 145 mT. The magnetic moment was measured after each AF step and the three orthogonal measurements were then averaged to correct for gyroscopic remanent magnetization (GRM) following the Zijderveld-Dunlop method^{65,67}. A subset of specimens (75055-127Aa, 75055-127Ab, 75055-127Ac, 75055-127Ae and 75055-127b) were demagnetized up to 420 mT in steps of 7.5 mT to ensure HC components were entirely removed.

NRM components were characterized using principal component analysis. Origin-trending components were identified when the maximum angular deviation (MAD) exceeds angular deviation (DANG). The final fits for such origin-trending components were anchored to the origin^{68,69}. These fits were used to calculate a Fisher mean direction and associated 95% confidence interval (α_{95}) for each specimen in PMagPy⁷⁰. Ten specimens of 75035 exhibited resolvable origin-trending HC components, but two of these were disregarded (75035Ad and 75035Ah) since they were partially overprinted by band-sawing at JSC (Figures S1 and S4). Five specimens of 75055 exhibited resolvable origin-trending HC components. Component directions were plotted in Stereonet^{71,72}, rotated to present-day lunar coordinates and, for 75055, tilt-corrected using the paleohorizontal estimates from Section 1.1. Recovered

component directions were also corrected for anisotropy of ARM (AARM) (see Section 1.3).

Paleointensity estimates were calculated using the ARM paleointensity method^{48,67,73}. NRM demagnetization curves were compared to AF demagnetization of an ARM with a 100 μ T DC bias field applied with a 260 mT AF. The TRM-equivalent paleointensity recorded by the samples is given by

$$P_{ARM} = \frac{\Delta NRM}{\Delta ARM} \frac{b}{f'} \quad (2)$$

where b is the DC bias field and $f' = 1.34$ is the TRM/ARM calibration factor experimentally determined using lunar basalts⁷⁴. There are two main uncertainties associated with these paleointensity estimates. First, the least squares slope obtained from $\frac{\Delta NRM}{\Delta ARM}$ has an uncertainty associated with scatter in the data around the best-fit line. Second, the calibration factor f' is estimated to have a 2σ uncertainty of a factor of 5¹. The uncertainty in f' originates from its dependence on ferromagnetic mineralogy including grain size, grain morphology and grain distribution. Cooling-rate corrections are not applied because the heating time (~ 1 hour) for ARM/TRM calibration experiments is similar to the several-day cooling timescales of 75035 and 75055^{75,76}.

1.3 Rock magnetic analysis

We used several rock magnetic techniques to assess the fidelity and magnetic recording properties of samples 75035 and 75055. We conducted paleointensity fidelity tests, IRM acquisition, Curie balance analysis and quantified the degree of AARM.

To assess the magnetic recording fidelity of samples 75035 and 75055, we gave the samples an ARM in a DC bias field ranging from 5 – 100 μ T and quantified how accurately we could recover the paleointensity of this field using the ARM paleointensity method. The ARMs were applied at an AF of 260 mT and were AF demagnetized following the same protocol that was used to demagnetize the NRM. The demagnetization curves were compared to the demagnetization curve of the 100 μ T ARM. For each applied ARM, the difference, $D' = \frac{L-I}{L}$, between the recovered paleointensity (I) and the predicted equivalent TRM (L) and the error, $E = \frac{W}{L}$ based on the 95% confidence on the retrieved paleointensity (W) were calculated^{65,77}. Acceptance criteria for a reliable paleomagnetic recorder are defined by $-50\% < D' < 100\%$ and $E < 100\%$.

We conducted IRM acquisition to assess the coercivity spectrum of magnetic carriers in each sample.

376 Specimens were given a saturation IRM of 400 mT and then AF demagnetized. The derivative of the
377 demagnetization curve, $\delta\text{IRM}/\delta B$, was calculated to infer the coercivity distribution.

378 The magnetic mineralogy and susceptibility to thermal alteration were assessed using a Curie
379 balance at the Fort Hoofddijk Paleomagnetic Laboratory. A small (3.52 mg) fragment of specimen
380 75055Ac was exposed to fields of 100 – 300 mT during a heating cycle from room temperature to
381 800 °C and then back to room temperature in air. The magnetization was measured every second over
382 the course of the experiment, which took ~ 12 hours. Raw data were smoothed using a Savitzky-Golay
383 filter⁷⁸.

384 The AARM of seven specimens of 75035 and six specimens of 75055 was measured at the Fort
385 Hoofddijk Paleomagnetic Laboratory using a 2G Enterprises Superconducting Rock Magnetometer.
386 Specimens were given an ARM of 50 μT in an AF of 150 mT. Samples were given an ARM in 9
387 distinct orientations: E_{mag} , N_{mag} , T_{mag} , NE_{mag} , NW_{mag} , TE_{mag} , TW_{mag} , TN_{mag} and TS_{mag} , with
388 each specimen mounted in a different orientation in laboratory coordinates to remove any directional
389 measurement bias (Table S5). After measuring the magnitude and orientation of the acquired ARM,
390 specimens were AF demagnetized up to 150 mT in three orthogonal directions. The order of ARM
391 and demagnetization steps is shown in Table S6. Specimens were mounted in custom-made glass cubes
392 with three-dimensional-printed sample holders (holder moment $< 7 \times 10^{-11} \text{ Am}^2$) to maintain exact
393 orientations throughout. This enabled the estimation of the three principal axes defining the anisotropy
394 ellipsoid, where p_1 is the maximum, p_2 is the intermediate and p_3 is the minimum principal axis of
395 anisotropy⁷⁹. After defining the axes, we calculated the degree of foliation $F = \frac{p_2}{p_3}$, lineation $L = \frac{p_1}{p_2}$
396 and anisotropy $P = \frac{p_1}{p_3}$ for individual specimens⁸⁰. Anisotropy corrections improved the clustering of
397 directions for 75035, with the Fisher precision parameter, κ , increasing from 11.9 to 19.1, while for
398 75055 κ decreased slightly from 49.2 to 42.9 (Figure 3).

399 Acknowledgements

400 The NASA Solar System Workings Program (grant NNX15AL62G) and the NASA Solar System
401 Exploration Virtual Institute (grant #NNA14AB01A) for support. C.I.O.N. acknowledges funding
402 support from the Simons Foundation. We thank CAPTEM for the loan of samples. We thank Lennart
403 de Groot, Bertwyn de Groot and the Utrecht University glass workshop for assistance with building a

404 customized sample-handling system for anisotropy measurements. We thank Sabine Stanley for helpful
405 discussions on dynamo theory.

406 **Author Contributions**

407 C.I.O.N. and B.P.W wrote the paper. B.P.W. and H.H.S. conceived the study. C.I.O.N., B.L.G.,
408 A.B. and J.S. collected the paleomagnetic data. C.I.O.N., B.P.W. and B.L.G. analysed the data and
409 reconstructed paleogeographic sample orientations. A.S.P.R. conducted the impact simulations.

Supplementary Material

S1 Samples and Methods

S1.1 Sample characterisation and preparation

Samples 75035 and 75055 are coarse-grained subophitic, high-Ti ilmenite basalts of chemical type A and textural type 1B⁵⁷, suggesting they formed as a result of a higher degree of chemical and mineralogical fractionation relative to other Apollo 17 basalts^{42,60}. Sample 75035 has an integrated $^{40}\text{Ar}/^{39}\text{Ar}$ age of 3720 ± 40 Ma and a Rb-Sr age of 3750 ± 120 Ma^{81,82}, while sample 75055 has an integrated $^{40}\text{Ar}/^{39}\text{Ar}$ of 3760 ± 50 Ma and a Rb-Sr age of 3690 ± 70 Ma (indistinguishable from those of 75035)^{81,83}. Recently, more precise Pb-Pb ages for 75035 and 75055 have yielded still-indistinguishable ages of 3753 ± 9 Ma and 3752 ± 9 Ma, respectively³⁹.

We analysed subsamples 75035,242 and 75055,127, which B.P. Weiss and H.H. Schmitt acquired from the JSC in 2016 (Figures S8 and S9). Sample 75035,242 was chipped from a slab that had previously been prepared using a bandsaw in 1973. Specimens 75035-242Ad and 75035-242Ah were immediately adjacent to the bandsaw cut and have been partially overprinted to coercivities > 15 mT (Figure S1). However, all other specimens were taken > 2.5 mm from the bandsaw cut and the overprint appears to have had no effect, which is consistent with the findings of ref. 3. Progressive AF applications revealed curved demagnetization trends for specimens 75035-242Ad and 75035-242Ah that we characterized by fitting approximate LC, medium coercivity (MC) and HC components. The residual NRM direction progressively moved toward the HC component defined by pristine specimens, suggesting the bandsaw has only partially overprinted these specimens (Table S1 and Figure S1). This partial overprinting is consistent with previous paleomagnetic studies^{2,3,48}. Sample 75055,127 was acquired by chipping a slab (,1) which has never been bandsawn.

Figure S1 | The influence of bandsaw cutting on the magnetization of specimens of 75035. Orientation cube is 1 cm across. (a) A diagram showing from where each of our specimens was taken relative to the bandsaw cut. (b) Orthographic projections in laboratory coordinates showing the NRM vector during AF demagnetization for 75035-242Ad and 75035-242Ah in three components projected along the North-East (closed squares) and Up-East (open symbols) directions. Stable components are shown by grey (LC), light blue (medium coercivity, MC) and bright blue (HC) arrows, respectively. (c) Equal area stereographic projection showing the approximate LC, MC and HC components for each specimen of 75035 in lunar coordinates. The two specimens that were immediately adjacent to the bandsaw cut (75035-242Ad and 75035-242Ah) were partially overprinted by the bandsaw, as demonstrated by the fact that during AF demagnetization the NRM progressively moves towards the HC direction defined by the other specimens. All other specimens were acquired > 2.5 mm from the bandsaw cut and retain their primary magnetization.

Sample	LC			MC			HC		
	AF (mT)	Dec ($^{\circ}$)	Inc ($^{\circ}$)	AF (mT)	Dec ($^{\circ}$)	Inc ($^{\circ}$)	AF (mT)	Dec ($^{\circ}$)	Inc ($^{\circ}$)
75035-242Ad	0 – 7	245	42	7 – 17	298	71	17 – 28	324	78
75035-242Ah	0 – 7	222	32	7 – 15	213	66	15 – 50	185	83

Table S1 | LC, MC and HC components of magnetization for bandsaw-overprinted samples 75035-242Ad and 75035-242Ah in laboratory coordinates. The first column lists the sample name, the second, third and fourth columns list the AF range, declination and inclination of the LC component. The fifth, sixth and seventh columns list the AF range, declination and inclination of the MC component. The eight, ninth and tenth columns list the AF range, declination and inclination of the HC component.

Further subsampling was then conducted in the MIT Paleomagnetism Laboratory using a diamond wire saw in a magnetically shielded clean room (DC field < 200 nT) to generate specimens for paleomagnetic analysis. Consistent orientations were maintained between all specimens using an orientation cube in laboratory coordinates. For 75035, this orientation system is distinct from JSC coordinates, whereas for 75055, laboratory and JSC coordinates are the same (Table 1). For both samples, the JSC orientation system is distinct from that of present-day lunar geographic coordinates (Table 1). Each specimen was mounted on a 2.5-cm-diameter quartz disc with a magnetic moment < 2×10^{-12} Am² using a small quantity of cyanoacrylate cement. Specimens were mounted in different orientations relative to one another to ensure there is no directional bias induced by the measurement procedure.

In addition to our measurements, previously-measured hysteresis properties of both 75035 and 75055 indicate a dominantly multidomain state⁸⁴. Previous paleomagnetic studies have reported stable (up to a 1 hour unblocking temperature of ~ 200 °C⁸⁵ and a peak AF ~ 11 mT⁵) natural remanent magnetization (NRM) in both samples. An NRM component was identified in 75035⁸⁵, but it was unclear whether this was a primary TRM or a secondary overprint⁸⁶. A previous study of 75055 yielded a paleointensity of ~ 84 μ T using ARM paleointensity methods⁵.

Figure S2 | Geographic context of Station 5 where samples 75035 and 75055 were collected. Figure adapted from ref. 56. (a) Panorama 19 from ref. 56 using astronaut photographs AS17-145-22181, 22183, 22159 and 22160. The panorama shows a north-east view of the Taurus-Littrow valley. (b) Sketch corresponding to the panoramic photograph in (a). The locations of 75035 and 75055 are shown. (c) Map showing the location from which the panorama was taken and the position of 75035 and 75055 relative to Camelot crater.

Figure S3 | Panorama using astronaut photographs AS17-133-20330 to AS17-133-20335 showing an example of the planar features in large blocks around Camelot Crater that we used to infer paleohorizontal. Astronaut E.A. Cernan is standing next to the block from which 75055 was sampled.

In order to translate samples from one coordinate system to another, a series of rotations are made which can also be described by a single 3×3 matrix. The rotations and associated translation matrices are shown in Figures S4, S5 and S6. The translation matrices $\mathbf{A}_{\text{JSC}}$ and $\mathbf{A}_{\text{L}}$ are used to translate from laboratory to JSC and JSC to present-day lunar coordinates, respectively:

$$\begin{pmatrix} N \\ E \\ T \end{pmatrix}_{\text{JSC}} = \mathbf{A}_{\text{JSC}} \times \begin{pmatrix} N \\ E \\ T \end{pmatrix}_{\text{lab}} \quad (3)$$

$$\begin{pmatrix} N \\ E \\ T \end{pmatrix}_{\text{L}} = \mathbf{A}_{\text{L}} \times \begin{pmatrix} N \\ E \\ T \end{pmatrix}_{\text{JSC}} \quad (4)$$

Figure S4 | The four steps to rotate subsample 75035,242 from its orientation in the MIT Paleomagnetism Laboratory to JSC coordinates. Rotations are referenced to the JSC coordinate reference frame. (a) The orientation of the subsample in the MIT Paleomagnetism Laboratory. (b) The orientation of the subsample photographed at the JSC. Note JSC bandsaw surface on the southeast face of the sample. (c) The steps required to rotate from laboratory to JSC coordinates. Laboratory orientation is shown by the black cube and JSC orientation by the red cube throughout. The rotation matrix is shown for each step. The rotation matrix to transform directly from laboratory to JSC coordinates is shown in bold.

Figure S5 | The steps to rotate sample 75035 from JSC to lunar coordinates. Rotations are made in the lunar coordinate reference frame. (a) JSC photograph S73-19593 showing the orientation of 75035 in JSC coordinates. The sample was illuminated under the same light conditions as those when it was sampled on the Moon. (b) Astronaut photograph AS17-145-22138 showing the orientation of 75035 in lunar coordinates. The direction of North is taken from ref. 56. (c) The steps required to rotate from JSC to lunar coordinates. JSC orientation is shown by the red cube and lunar orientation by the white cube throughout. The rotation matrix is shown for each step. The rotation matrix to transform directly from JSC to lunar coordinates is shown in bold.

Figure S6 | The steps to rotate sample 75055 from JSC to lunar coordinates. Rotations are made in the lunar coordinate reference frame. (a) JSC photograph S73-17796 showing the orientation of 75055 in JSC coordinates. (b) Astronaut photograph AS17-145-22149 showing the orientation of 75055 in lunar coordinates. The direction of the photograph was determined from the change in trend from Astronaut photograph AS17-145-22141 (see Figures S7 and S2). (c) The steps required to rotate from JSC to lunar coordinates. JSC orientation is shown by the red cube and lunar orientation by the white cube throughout. The rotation matrix is shown for each step. The rotation matrix to transform directly from JSC to lunar coordinates is shown in bold.

Figure S7 | Estimating the orientation of planar lava flow features on the 75055 parent boulder. Measurements are summarized in Table S2. (a) Astronaut photograph AS17-145-22183. (b) - (l) are astronaut photographs AS17-145-22141 to AS17-145-22151 taken from a variety of orientations around the block. The trends and plunges of the planar features were measured as shown by the marked reference features. The colour of the trend arrow corresponds to the face on which the linear features were measured. (m) Equal area stereographic projection showing the orientation of the planar features with a strike and dip of $243^{\circ}/36^{\circ}$. The plane of best fit was calculated from the measured trends and plunges of linear features identified on three faces of the boulder, coloured green, yellow and pink. (n) Annotated copies of (a) and (g) show the three faces identified on the boulder identified by the green, yellow and pink colours.

Figure	Photograph	Direction of Facing (°)	Change in Trend (°)	Plunge (°)	Trend (°)
S7a	22183	45	0	42	315
S7a	22183	45	0	28	315
S7a	22183	45	0	29	315
S7a	22183	45	0	17	45
S7a	22183	45	0	26	45
S7b	22141	30	15	9	46
S7b	22141	30	15	33	307
S7b	22141	30	15	27	307
S7b	22141	30	15	25	307
S7b	22141	30	15	3	46
S7c	22142	22	23	9	42
S7c	22142	22	23	27	294
S7c	22142	22	23	23	294
S7c	22142	22	23	0	42
S7d	22143	10	43	9	46
S7d	22143	10	43	0	46
S7d	22143	10	43	22	284
S7d	22143	10	43	17	284
S7e	22144	356	49	5	41
S7e	22144	356	49	22	263
S7e	22144	356	49	7	41
S7f	22145	345	60	12	45
S7f	22145	345	60	8	45
S7f	22145	345	60	51	357
S7g	22146	337	68	11	43
S7g	22146	337	68	11	43
S7g	22146	337	68	41	1
S7h	22147	329	76	12	47
S7h	22147	329	76	12	47
S7h	22147	329	76	32	18
S7i	22148	326	79	15	44
S7i	22148	326	79	16	44
S7i	22148	326	79	35	20
S7j	22149	317	88	18	47
S7j	22149	317	88	28	20
S7k	22150	315	90	24	45
S7k	22150	315	90	32	18
S7l	22151	314	91	17	44
S7l	22151	314	91	32	25
S7l	22151	314	91	11	25

Table S2 | Measurements corresponding to Figure S7 for determining the strike and dip of planar features observed on the 75055 parent boulder. The first column lists the part of the figure to which the measurements correspond. The second column lists the astronaut photograph number (each preceded by AS17-254-). The third column lists the facing direction, (i.e., the direction toward which the astronaut took the photograph). The fourth column lists the change in orientation between the photograph and photograph 22183, determined using linear features. The fifth column lists the plunge, which is the angle between horizontal and the linear features from the perspective of each photograph. The sixth column lists the apparent trend of the linear features from the perspective of the facing direction.

Figure S8 | The location of sample 75035 on the lunar surface and subsequent orientation and sampling at the JSC. (a) Astronaut photograph AS17-145-22139 showing the location of 75035 prior to sampling from the boulder on the lunar surface. 61-cm-long hammer for scale. (b) Astronaut photograph AS17-145-22138 showing the side of the boulder and location of 75035 prior to sampling. (c) JSC photograph S73-19593 showing 75035 in JSC coordinates photographed in the same orientation and lighting conditions as when sampled on the Moon. (d) JSC photograph S73-24259 of the north face of 75035 (in JSC coordinates prior to cutting or chipping). The sample cube is 1 cm across. (e) Photograph S73-31658 showing slabbing of 75035 into three slabs 75035,0, 75035,1 and 75035,2. Slabbing was carried out using the JSC bandsaw. Subsample 75035,242 is part of 75035,1. The orientation cube is 2.5 cm across. (f) Photograph taken during sampling by B.P. Weiss and H.H. Schmitt in 2016 at JSC. Location of sample 75035,242 from cut face (east relative to 2.5 cm orientation cube). (g) Photograph taken during sampling by B.P. Weiss and H.H. Schmitt in 2016 at JSC. Location of sample 75035,242 from the top (south relative to 2.5 cm orientation cube).

Figure S9 | The location of sample 75055 on the lunar surface and subsequent orientation and sampling of subsample 75055,127 at the JSC. (a) Astronaut photograph AS17-145-22149 showing the location of 75055 prior to sampling from the boulder on the lunar surface. (b) JSC photograph S-73-17796. (c) JSC photograph S73-17796 showing the top face of 75055 (in JSC coordinates) prior to chipping. The sample is photographed in the same orientation and lighting conditions as when sampled on the Moon. The sample cube is 1 cm across. (d) Photograph taken during sampling by B.P. Weiss and H.H. Schmitt in 2016 at JSC. Sample 75055 was chipped into smaller fragments. Subsample 75055,127 is in the upper left of the photo. The orientation cube is 2.5 cm across. (e) Photograph taken during sampling by B. Weiss and H. Schmitt in 2016 at JSC. The relative orientation of subsample 75055,127 to 75055,128 and the orientation cube (2.5 cm across).

S1.3 Petrographic analysis

Plagioclase crystals typically define lineations corresponding to flow directions within bodies of magma; the average lineation typically lies approximately in the paleohorizontal plane^{87,88}. In an attempt to identify such lineation in our samples as an independent indicator of paleohorizontality, we analysed 30- μm thin sections 75035,84 and 75055,46 in plane-polarized and cross-polarized transmitted light. Plagioclase crystals were used to assess the degree of flow alignment, since they have the most elongate morphology and their orientation can easily be constrained parallel to the direction of twinning. A histogram of directions was calculated to determine the degree of alignment of plagioclase crystals using the directionality package in the imaging software Fiji (ImageJ)^{89,90}. Crystal orientations were grouped in 10° bins.

We analysed the same thin sections using backscattered electron microscopy (BSEM). Samples were carbon coated and imaged at the MIT Electron Microprobe Facility using a JEOL-JXA-8200 electron microprobe. Mineral compositions were assessed using wavelength dispersive spectroscopy (WDS) for Fe, Ni and S (Table S3).

Figure S10 | BSEM images of 75035. Red (kamacite) and blue (troilite) circles/numbers show locations of WDS probe measurements (Table S3). (a) Pure Fe kamacite blebs within troilite. (b) Pure Fe kamacite bleb within a crystal of plagioclase. plag = plagioclase, qz = quartz, ilm = ilmenite.

Figure S11 | BSEM images of 75055. Red (kamacite) and blue (troilite) circles/numbers show the locations of WDS probe measurements (Table S3). (a) Pure Fe kamacite blebs within troilite. (b) Pure Fe kamacite bleb within a crystal of feldspar. ilm = ilmenite, cpx = clinopyroxene, K-fsp = feldspar.

75035						75055					
Figure	Point	Fe (wt%)	Ni (wt%)	S (wt%)	Mineral	Figure	Point	Fe (wt%)	Ni (wt%)	S (wt%)	Mineral
S10a	1	100.00	0.00	0.00	kamacite	S11a	1	100.00	0.00	0.00	kamacite
S10a	2	100.00	0.00	0.00	kamacite	S11a	2	100.00	0.00	0.00	kamacite
S10a	3	100.00	0.00	0.00	kamacite	S11a	3	100.00	0.00	0.00	kamacite
S10a	4	100.00	0.00	0.00	kamacite	S11a	4	100.00	0.00	0.00	kamacite
S10a	5	100.00	0.00	0.00	kamacite	S11a	5	100.00	0.00	0.00	kamacite
S10a	6	99.99	0.01	0.00	kamacite	S11a	6	100.00	0.00	0.00	kamacite
S10a	7	100.00	0.00	0.00	kamacite	S11a	7	100.00	0.00	0.00	kamacite
S10a	8	100.00	0.00	0.00	kamacite	S11a	8	100.00	0.00	0.00	kamacite
S10a	9	100.00	0.00	0.00	kamacite	S11a	9	100.00	0.00	0.00	kamacite
S10a	10	99.99	0.01	0.00	kamacite	S11a	10	100.00	0.00	0.00	kamacite
S10a	11	62.38	0.00	37.62	troilite	S11a	11	62.50	0.00	37.50	troilite
S10b	1	100.00	0.00	0.00	kamacite	S11b	1a	100.00	0.00	0.00	kamacite
						S11b	1b	100.00	0.00	0.00	kamacite
						S11b	1c	100.00	0.00	0.00	kamacite

Table S3 | WDS data for analyses of BSEM images shown in figures S10 and S11. The first and seventh columns correspond to the figure showing the location of each probe measurement for 75035 and 75055, respectively. The second and eighth columns correspond to the specific probe point. The third and ninth columns list the Fe content, the fourth and tenth columns list the Ni content and the fifth and eleventh columns list the S content measured using WDS for 75035 and 75055 respectively. The sixth and twelfth columns list the mineral.

S2 Results

S2.1 Magnetic Carriers

The ferromagnetic carriers in 75035 and 75055 are kamacite inclusions located in troilite and silicate minerals (e.g., plagioclase and feldspar) (Figures S10 and S11). WDS measurements of the inclusions show that the kamacite is 100 wt. % Fe. BSEM images show that the largest inclusions are $\sim 1 - 10 \mu\text{m}$ in diameter and have an equant morphology, suggesting they are multidomain⁹¹. Curie balance analysis showed that during heating of specimen 75055-127Ac the magnetization decayed as it approached 700 °C, consistent with kamacite as the primary magnetic carrier. IRM acquisition suggest grains have coercivities extending to $> 1000 \text{ mT}$, indicative of a population of smaller, single to pseudo-single domain (e.g., vortex state) kamacite grains (Figure S14).

S2.2 The paleomagnetic recording fidelity of samples 75035 and 75055

Specimens were AF demagnetized due to the likelihood of alteration during thermal demagnetization as indicated by our Curie balance analysis on specimen 75055-127Ac (Figure S12). Upon cooling, the magnetization of specimen 75055-127Ac increases by a factor of 3 at room temperature relative to the magnetization prior to heating. Magnetization begins to increase below $\sim 580 \text{ °C}$ suggesting the formation of magnetite by thermal alteration. The overall increase in magnetization may be due to troilite alteration; since troilite is essentially non-magnetic, alteration to magnetite or iron will cause an increase in magnetic moment.

Figure S12 | Curie balance data for specimen 75055-127Ac. During heating in air to 800 °C the sample loses magnetization at > 700 °C, consistent with the presence of kamacite. During cooling, the sample gains significantly more magnetization than it had prior to heating, particularly at ~ 580 °C, suggesting magnetite has formed during thermal alteration.

To assess the paleomagnetic fidelity of the samples, we used two metrics: difference D' and error E . A permissive threshold for reasonable paleomagnetic recording fidelity⁷⁷ is $-50\% < D' < 100\%$ and $E < 50\%$. The metrics for our specimens are summarized in Table S4. As expected, the ability of specimens to reliably record a paleointensity diminishes with decreasing ARM strength. We found that we were able to consistently recover paleointensities of $< 7.5 \mu\text{T}$ from specimens of 75035 and $< 37.3 \mu\text{T}$ from specimens of 75055.

Sample	ARM DC field (μT)	TRM Equivalent (μT)	Field Range (mT)	Retrieved Paleointensity (μT)	E (%)	D' (%)	Accepted
75035-242Aa	50	37.3	6.5 – 137.0	27.85 ± 4.19	11	-25	✓
75035-242Af	50	37.3	10.0 – 39.0	41.24 ± 3.43	9	11	✓
	20	14.9	10.0 – 39.0	14.4 ± 2.6	17	-4	✓
	10	7.5	10.0 – 39.0	15.8 ± 2.3	31	112	×
75035-242Bc	50	37.3	8.0 – 45.0	48.8 ± 3.4	9	31	✓
	30	22.4	8.0 – 45.0	27.3 ± 3.0	13	22	✓
	20	14.9	8.0 – 45.0	12.3 ± 3.2	21	-18	✓
	10	7.5	8.0 – 45.0	13.9 ± 2.1	28	86	✓
75055-127a	20	14.9	3.0 – 53.0	32.2 ± 5.6	38	116	×
75055-127b	50	37.3	4.0 – 24.5	22.9 ± 5.3	14	-39	✓
	34	25.4	7.0 – 24.5	8.5 ± 4.9	19	-67	×
	10	7.5	7.5 – 24.5	3.8 ± 5.4	72	-49	✓
	5	3.7	4.0 – 24.5	1.0 ± 4.9	131	-73	×
75055-127c1	50	37.3	0.0 – 50.0	39.9 ± 2.1	6	7	✓
75055-127c2	50	37.3	3.5 – 15.5	24.5 ± 3.1	8	-34	✓
75055-127Aa	50	37.3	9.0 – 34.0	34.3 ± 3.9	10	-8	✓
75055-127Ab	50	37.3	4.5 – 20.0	33.8 ± 4.5	12	-9	✓
75055-127Ae	50	37.3	7.5 – 28.0	46.1 ± 5.7	15	24	✓

Table S4 | Paleointensity fidelity tests for 75035 and 75055. The first column lists the specimens. The second column lists the DC bias field used to impart an ARM. The third column lists the TRM-equivalent field using $f = 1.34$. The fourth column lists the field range over which the paleointensity estimate was calculated. The fifth column lists the paleointensity calculated using the ARM paleointensity method. The sixth column lists the ratio error metric, E . The seventh column lists the difference metric, D' . The eighth column lists whether the specimen passes the acceptance criteria defined by ref. 77.

Figure S13 | IRM acquisition curves. (a) Specimen 75035-242Bc contains magnetic carriers with a peak coercivity of ~ 20 mT and a range of coercivities extending up to > 1000 mT. (b) Specimen 75055-127b contains magnetic carriers with a peak coercivity of ~ 10 mT and a range of coercivities extending up to > 400 mT.

Figure S14 | Paleointensity recording fidelity of 75035 and 75055. Results are also summarized in Table S4. (a) Difference metric, D' , for 75035. The grey region $-50\% > D' > 100\%$ indicates samples with adequate paleomagnetic fidelity. (b) Error metric, E' , for 75035. The grey region $E < 50\%$ indicates samples with adequate paleomagnetic fidelity. (c) D' for 75055. (d) E for 75055.

S2.3 Anisotropy of remanence and petrographic fabric analysis

Remanence anisotropy measurements were made for two reasons: to correct the recovered paleoinclinations for anisotropy effects within each specimen and to investigate any evidence for a flow fabric in the sample defined by mutual orientation of the anisotropy axes between specimens. However, a flow fabric is not necessarily anticipated, given the predicted turbulent nature of low-viscosity lunar basaltic flows^{92,93}. The remanence anisotropy of 7 specimens of 75035 and 6 specimens of 75055 were measured, all of which exhibited origin-trending HC components.

The degree of lineation L , foliation F and anisotropy P is reported for individual specimens (Tables S7 and S8). The recovered anisotropy ellipses were used to correct the NRM directions. We found that the degree of anisotropy is dependent on sample mass with smaller specimens tending to show a higher degree of anisotropy, consistent with previous mare basalt studies^{5,65} (Figure S16). The degree of anisotropy in our individual specimens ($P = 1.0 - 1.5$) is similar to that measured for terrestrial basalts ($P = 1.1 - 1.8$)^{94,95}. In both 75035 and 75055, there is no obvious fabric defined by the anisotropy axes of multiple specimens as indicated by the fact that Fisher dispersion factors $\kappa < 4$ for each axis (Figure S15).

Specimen	Direction of applied ARM								
	1	2	3	4	5	6	7	8	9
75035-242Aa	T _{lab}	S _{lab}	E _{lab}	T _{lab} -S _{lab}	B _{lab} -S _{lab}	T _{lab} -E _{lab}	B _{lab} -E _{lab}	S _{lab} -E _{lab}	N _{lab} -E _{lab}
75035-242Ba	N _{lab}	W _{lab}	T _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}	T _{lab} -W _{lab}	T _{lab} -E _{lab}
75035-242Bb	E _{lab}	N _{lab}	T _{lab}	N _{lab} -E _{lab}	N _{lab} -W _{lab}	T _{lab} -E _{lab}	T _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}
75035-242Bd	N _{lab}	W _{lab}	T _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}	T _{lab} -W _{lab}	T _{lab} -E _{lab}
75035-242Be	E _{lab}	S _{lab}	B _{lab}	S _{lab} -E _{lab}	S _{lab} -W _{lab}	B _{lab} -E _{lab}	B _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}
75035-242Bf	E _{lab}	N _{lab}	T _{lab}	N _{lab} -E _{lab}	N _{lab} -W _{lab}	T _{lab} -E _{lab}	T _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}
75035-242Bg	N _{lab}	W _{lab}	T _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}	T _{lab} -W _{lab}	T _{lab} -E _{lab}
75055-127Aa	T _{lab}	S _{lab}	E _{lab}	T _{lab} -S _{lab}	B _{lab} -S _{lab}	T _{lab} -E _{lab}	B _{lab} -E _{lab}	S _{lab} -E _{lab}	N _{lab} -E _{lab}
75055-127Ab	T _{lab}	S _{lab}	E _{lab}	T _{lab} -S _{lab}	B _{lab} -S _{lab}	T _{lab} -E _{lab}	B _{lab} -E _{lab}	S _{lab} -E _{lab}	N _{lab} -E _{lab}
75055-127Ac	T _{lab}	E _{lab}	N _{lab}	T _{lab} -E _{lab}	B _{lab} -E _{lab}	T _{lab} -N _{lab}	B _{lab} -N _{lab}	N _{lab} -E _{lab}	N _{lab} -W _{lab}
75055-127Ae	N _{lab}	W _{lab}	T _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}	T _{lab} -N _{lab}	T _{lab} -S _{lab}	T _{lab} -W _{lab}	T _{lab} -E _{lab}
75055-127a	T _{lab}	N _{lab}	W _{lab}	T _{lab} -N _{lab}	B _{lab} -N _{lab}	T _{lab} -W _{lab}	B _{lab} -W _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}
75055-127b	T _{lab}	N _{lab}	W _{lab}	T _{lab} -N _{lab}	B _{lab} -N _{lab}	T _{lab} -W _{lab}	B _{lab} -W _{lab}	N _{lab} -W _{lab}	S _{lab} -W _{lab}

Table S5 | For AARM measurements, ARMs were applied in nine directions (shown by columns 1 – 9) corresponding to the anisotropy matrix. Specimens were mounted in different orientations with respect to laboratory coordinates and reconstructed to a mutual orientation in JSC coordinates after measuring. The demagnetization procedure between each ARM step is shown in Table S6.

ARM direction	Demagnetization direction 1	Demagnetization direction 2	Demagnetization direction 3
E _{mag}	N _{mag}	T _{mag}	E _{mag}
N _{mag}	E _{mag}	T _{mag}	N _{mag}
T _{mag}	N _{mag}	E _{mag}	T _{mag}
NE _{mag}	T _{mag}	NW _{mag}	NE _{mag}
NW _{mag}	NE _{mag}	T _{mag}	NW _{mag}
TE _{mag}	N _{mag}	TW _{mag}	TE _{mag}
TW _{mag}	TE _{mag}	N _{mag}	TW _{mag}
TN _{mag}	E _{mag}	TS _{mag}	TN _{mag}
TS _{mag}	TN _{mag}	E _{mag}	TS _{mag}

Table S6 | The orientation of the applied ARM and the three subsequent demagnetization steps used for AARM experiments. The first column shows the direction in which the ARM was applied. Samples were then demagnetized in the three orientations listed in the second, third and fourth columns, respectively.

	75035-242Aa	75035-242Ba	75035-242Bb	75035-242Bd	75035-242Be	75035-242Bf	75035-242Bg
p_1	658	998	1169	310	1404	1096	1117
dec (°)	107	075	080	099	065	232	278
inc (°)	-23	-37	-46	-23	-05	-42	-03
p_2	502	940	1140	252	1183	1066	838
dec (°)	040	075	329	033	147	319	024
inc (°)	42	53	-20	43	60	04	-78
p_3	471	783	1038	229	1125	1054	731
dec (°)	358	345	043	349	338	045	008
inc (°)	-40	00	38	-39	31	-47	12
L	1.309	1.062	1.025	1.227	1.187	1.028	1.333
F	1.067	1.200	1.098	1.102	1.051	1.011	1.146
P	1.397	1.275	1.125	1.353	1.248	1.040	1.528
Mass (mg)	59.8	64.8	101.9	16.1	132.1	95.6	74.2

Table S7 | AARM results for specimens of 75035. The first, second and third rows are the magnitude, declination and inclination (in JSC coordinates) of the maximum principal anisotropy axis p_1 . The fourth, fifth and sixth rows are the magnitude, declination and inclination of the intermediate principal anisotropy axis, p_2 . The seventh, eighth and ninth rows are the magnitude, declination and inclination of the minimum principal anisotropy axis, p_3 . The directions of the principal axes for each specimen are plotted in Figure S15a. The tenth row is L , is the degree of lineation, the eleventh row is F , the degree of foliation and the twelfth row is P , the degree of anisotropy. The thirteenth row is the mass of the specimen.

	75055-127Aa	75055-127Ab	75055-127Ac	75055-127Ae	75055-127a	75055-127b
p_1	1197	710	587	539	2705	4931
dec ($^{\circ}$)	221	325	305	224	032	321
inc ($^{\circ}$)	-11	-19	-16	-24	04	18
p_2	1160	641	586	537	2374	4830
dec ($^{\circ}$)	315	051	021	240	282	074
inc ($^{\circ}$)	-17	11	38	64	77	49
p_3	1017	512	499	514	2364	4656
dec ($^{\circ}$)	281	291	233	316	123	038
inc ($^{\circ}$)	68	66	47	-06	12	-34
L	1.031	1.107	1.001	1.004	1.139	1.020
F	1.140	1.251	1.173	1.043	1.004	1.037
P	1.176	1.386	1.175	1.048	1.144	1.059
Mass (mg)	102.5	62.6	58.3	54.9	271.0	641.0

Table S8 | Anisotropy of ARM results for specimens of 75055. The first, second and third rows are the magnitude, declination and inclination (in JSC coordinates) of the maximum principal anisotropy axis p_1 . The fourth, fifth and sixth rows are the magnitude, declination and inclination of the intermediate principal anisotropy axis, p_2 . The seventh, eighth and ninth rows are the magnitude, declination and inclination of the minimum principal anisotropy axis, p_3 . The directions of the principal axes for each specimen are plotted in Figure S15b. The tenth row is L , is the degree of lineation, the eleventh row is F , the degree of foliation and the twelfth row is P , the degree of anisotropy. The thirteenth row is the mass of the specimen.

Figure S15 | Equal area polar stereonet projections showing the minimum p_3 (triangles), intermediate p_2 (squares) and maximum p_1 (circles) principal anisotropy axes for specimens of (a) 75035 and (b) 75055 in JSC coordinates. Solid symbols are in the lower hemisphere, open symbols are in the upper hemisphere. There is no macro clear fabric defined by the anisotropy axes, Fisher precision parameters are < 4 for all axes.

Figure S16 | The degree of anisotropy, P , recovered for AARM measurements as a function of sample mass. Our results are consistent with previous studies of lunar basalts conducted by ref. 5 and ref. 65.

Hand samples and thin sections were also examined for evidence of any flow fabrics. Rose diagrams of plagioclase crystal orientations were found to have a circular variance of 0.73 and 0.98 for 75035 and 75055, respectively, where the circular variance is 0 for perfect alignment in one direction and 1 for an entirely uniform distribution (Figure S17). The lack of fabric defined within the mineralogy of the samples is consistent with the fact that well-aligned fabrics only develop in laminar flows, whereas the flow of lunar basalts is expected to be turbulent^{92,93}.

Figure S17 | Analysis of the orientation of plagioclase crystals assessed from photomicrographs of thin sections 75035,84 and 75055,46. (a) Equal area rose diagram of plagioclase orientation distributions for 75035. The circular variance of the distribution is 0.73. (b) Cross-polarized transmitted light image of thin section 75035. (c) Magnified region of thin section 75035. Red lines show the identified plagioclase orientations used for orientation analysis. (d) Equal area rose diagram of plagioclase orientation distributions for 75055. The circular variance of the distribution is 0.98. (e) and (f) are the same as (b) and (c) for 75055.

Specimen	Experiment	Paleointensity (μT)
75035-242Aa	100 μT ARM	33.1 ± 5.5
75035-242Ae	100 μT ARM	101.3 ± 7.9
75035-242Af	100 μT ARM	23.7 ± 2.4
75035-242Bc	100 μT ARM	47.7 ± 4.7
	Mean $\pm 1\sigma$	50.7 ± 13.5
75055-127a	50 μT ARM	18.2 ± 5.7
75055-127b	100 μT ARM	50.0 ± 10.6
75055-127c1	200 μT ARM	50.4 ± 5.2
75055-127c2	200 μT ARM	84.3 ± 11.9
75055-127Aa	100 μT ARM	33.3 ± 2.6
75055-127Ab	100 μT ARM	12.2 ± 8.3
75055-127Ac	100 μT ARM	34.4 ± 4.2
75055-127Ae	100 μT ARM	173.1 ± 14.3
	Mean $\pm 1\sigma$	57.0 ± 17.3

Table S9 | Paleointensity estimates for HC components for samples 75035 and 75055. The first column is the measured specimen. The second column shows the strength of the applied ARM used for the paleointensity estimate. The third column shows the estimated paleointensity and 2σ uncertainty calculated from a two-tailed Student's t test but does not take into account the factor of 5 uncertainty associated with the calibration factor f'^1 . Paleointensities were calculated over the HC field range shown in Table S10.

Specimen	Mass (mg)	Magnetization ($\times 10^{-6} \text{ Am}^2 \text{ kg}^{-1}$)	HC component							LC component				
			Dec (°)	Inc (°)	MAD (°)	DANG (°)	AF (mT)	O-trending?	Anchored?	Dec (°)	Inc (°)	MAD (°)	DANG (°)	AF (mT)
75035-242Aa	59.8	2.78	354	-66	23	155	0 – 5							
75035-242Ab	203.1	0.64												
75035-242Ac	232.8	2.17								358	77	28	72	0 – 6.5
75035-242Ad*	322.3	7.45	324	78	5	0	17 – 28	✓	✓	245	42	6	37	0 – 7
75035-242Ae	46.6	17.30	93	45	7	0	11.5 – 47	✓	✓	69	31	11	14	0 – 11
75035-242Ai	188	1.99	82	44	26	0	10 – 60	✓	✓	191	16	29	96	0 – 10
75035-242Ag	169.3	1.46								205	58	17	24	0 – 3.5
75035-242Ah*	277.8	9.83	185	83	8	0	15 – 50	✓	✓	222	32	6	38	0 – 7
75035-242Ba	64.9	8.03	85	58	8	0	11 – 33	✓	✓	86	-49	11	93	0 – 5
75035-242Bb	102	4.48								102	70	15	14	0 – 14
75035-242Bc	65.3	6.34	107	54	11	0	10.5 – 40	✓	✓	345	-32	37	137	0 – 7
75035-242Bd	16.1	12.00	94	59	44	47	10 – 40	×	×	105	42	27	27	0 – 7.5
75035-242Be	132.1	4.44	52	16	16	0	10 – 40	✓	✓	58	41	14	9	0 – 6
75035-242Bf	95.6	6.54	94	24	7	0	15 – 50	✓	✓	178	-53	20	110	0 – 3.5
75035-242Bg	74.2	6.31	94	40	14	0	16 – 45	✓	✓	39	62	19	33	0 – 11
75055-127a	271	4.03	210	25	20	27	2.5 – 24	×	×	353	48	10	103	0 – 2
75055-127b	641	3.95	214	8	10	0	27 – 49	✓	✓	37	49	5	126	0 – 1.5
75055-127c1	156	4.03	221	14	8	0	4 – 35	✓	✓	294	39	30	70	0 – 1.5
75055-127c2	166	7.29	215	1	6	0	10 – 35	✓	✓	341	-20	34	131	0 – 9.5
75055-127Aa	102.5	14.60	225	26	9	0	2.5 – 45	✓	✓	183	2	4	44	0 – 2
75055-127Ab	62.6	4.15												
75055-127Ac	54.9	6.19	205	13	13	0	4.5 – 39	✓	✓	89	-48	20	124	0 – 4
75055-127Ad	8.3	3.25												
75055-127Ae	58.3	20.60	219	8	7	14	7.5 – 55	×	×	92	-66	27	101	0 – 6.5

*samples with bandsaw overprint

Table S10 | LC and HC components identified during AF demagnetization of specimens of 75035 and 75055. Declinations and inclinations are in laboratory coordinates. In the case where no reasonable fit could be made, the row is left blank. The first column lists the specimen. The second column lists the mass of the specimen and the third lists the specific magnetization of the NRM. Then for each component the columns are as follows: the first and second columns are declination and inclination, respectively; the third column lists the MAD (after anchoring to the origin for HC components found to be origin-trending); the fourth column lists the deviation angle; the fifth column lists the AF range over which the component was fitted. For the HC component, the sixth column lists whether the component was statistically origin-trending (MAD > DANG) and the seventh column lists whether the fit was anchored to the origin. Italicized subsamples were used to calculate mean HC directions and paleointensities.

Figure S18 | Examples of ARM paleointensity estimates for 75035 and 75055. NRM lost versus 100 μ T ARM lost is plotted for progressive AF demagnetization. (a) ARM paleointensity plot for specimen 75035-242Bc. (b) ARM paleointensity plot for specimen 75055-127b.

Figure S19 | Summary of the paleointensity measurements on Apollo samples colour coded by study from refs. 2, 3, 5, 26, 46, 47, 48, 65, 86, 96, 97. The blue region is the strength of Earth's present day magnetic field. The dashed black line is the weakest field that could be driven by a lunar dynamo (see ref. 3). Paleointensities calculated for 75035 and 75055 are shown by red stars.

Figure S20 | A summary of north paleopole locations summarized from the literature. (a) Paleopole locations for < 3.5 Ga are generally found to be aligned along the present day spin axis^{51,55,98,99}. (b) Paleopole locations 3.5 – 4 Ga^{5,6,7,10,51,52,55,98,100} which have ages broadly similar to our samples (the permitted North pole locations from our paleoinclination are shown by the two small circles with 95% confidence bounds). (c) Paleopole locations > 4 Ga^{46,55,101}.

Figure S21 | Schematic diagrams show the plausible true polar wander paths permitted by our measured paleoinclination for 75055. The blue and red small circles show the permitted locations of the north and south magnetic poles, respectively. We assume a selenocentric axial dipole such that the paleopole location represents the position of the ancient spin axis. (a) If the measured magnetic inclination at Camelot crater is negative, Camelot was in the northern hemisphere 3.7 Ga ago and was located closest the north magnetic pole. (b) If the measured magnetic inclination at Camelot crater is positive, Camelot was in the southern hemisphere 3.7 Ga ago and was located closest to the south magnetic pole. (c) Considering Camelot crater at its present day location, the small circles are shown for the allowed north pole locations for Camelot crater in either the northern or southern hemisphere 3.7 Ga ago.

S3 Distinguishing between sources of the lunar magnetic field in light of new paleoinclination results

Given the difficulties associated with generating the observed strong lunar magnetic field with a thermal or thermochemical core dynamo, a diversity of other dynamo as well as non-dynamo mechanisms have been proposed to have magnetized the lunar surface. We consider these mechanisms here for completeness, but acknowledge that they are less likely given our current understanding of the lunar interior.

S3.1 Multipolar magnetic fields

The high value of Ro_l for the lunar core resulting from its slow rotation rate suggests the dynamo should be multipolar, at least in the dynamo-generating region (main text Figure 1b)¹⁴. Alternatively, it has been suggested that rather than originating in the core, the lunar magnetic field may have been generated by a basal magma ocean dynamo (main text Figure 1c,d), which would be closer to the lunar surface which would favour a higher degree of multipolarity at the surface relative to that of a deeper-seated core dynamo. As such, the measured paleoinclination may not constrain the axial dipole field component. The inclination of the magnetic field at Camelot crater depends on the zonal dipolar, quadrupolar and octupolar contributions to the magnetic field⁸ as:

$$\tan I = \frac{2 \cos \theta + G2(4.5 \cos^2 \theta - 1.5) + G3(10 \cos^3 \theta - 6 \cos \theta)}{\sin \theta + G2(3 \cos \theta \sin \theta) + G3(7.5 \cos^2 \theta \sin \theta - 1.5 \sin \theta)} \quad (5)$$

where I is the inclination and θ is the colatitude which we take to be 69.8° (the current colatitude of Camelot crater, assuming no true polar wander since remanence acquisition), $G2$ is the zonal quadrupole to zonal dipole field ratio, and $G3$ is the zonal octupole to zonal dipole field ratio. Both low ($G2 < 0.2$ and $G3 < 0.2$) and high ($0 < G2 < 1$ and $0.3 < G3 < 0.75$) contributions from the quadrupolar and octupolar components give results consistent with our measured inclinations. Therefore, even when considering just the first two nondipolar zonal terms to the multipole field expansion, the lunar dynamo is permitted to be highly multipolar based on our measured paleoinclination, consistent with either a dynamo originating in the core or a basal magma ocean.

S3.2 External magnetic field sources

We consider whether the lunar surface could plausibly have been magnetized by Earth’s magnetic field. We assume the Earth had an active magnetic field ~ 3.7 Ga ago, although there is currently no robust record beyond 3.5 Ga ago^{102,103,104,105}. Under the assumption that the mean field represented an axial dipole, and given that the Earth and Moon were likely already tidally locked by this time¹⁰⁶, such a field would have uniformly magnetized the lunar surface, with $I = \lambda$ (main text Figure 1e). In this case, the inclination of the magnetic field at Camelot crater would be much lower than the observed paleoinclinations, confirming the Earth’s magnetic field is an unlikely source of lunar magnetization. In addition, given the distance between the Earth and the Moon, the Earth would impart negligible paleointensities ($\sim 1 \mu\text{T}$ assuming the Earth’s magnetic field is similar to today, and the Moon was at the Roche limit) on the lunar surface.

We also consider the influence of the IMF and its ability to magnetize the lunar surface. The IMF constantly changes direction, but the time-averaged field is predominantly aligned in the lunar equatorial plane²⁹, where $I = 90 - \lambda$ (main text Figure 1f). Assuming a similar geometry at 3.7 Ga, the IMF would therefore have generated a much higher inclination than that observed at Camelot crater, ruling out this source of magnetization. In addition, because the Moon rotates 360° with respect to the IMF every orbit around the Earth, the mean field at Camelot should average out to a null field.

S3.3 Impact-generated magnetic fields

It has been suggested that the lunar surface may have been magnetized by impact events¹⁰⁷. In particular, it was proposed that basin-forming impacts could generate a plasma field which expands around the Moon, focusing the magnetic field at the antipodal point to the impact³¹. Although recent magnetohydrodynamic simulations indicate that such a mechanism likely cannot explain the high paleointensities recorded by lunar samples³⁰, we still compare its predictions with our measurements as an experimental test of this hypothesis. Independent of latitude, crustal magnetization generated by impact events would lead to near-vertical paleoinclinations (here we assume they are perfectly vertical) (main text Figure 1g,h). Our recovered paleoinclination at Camelot crater is $\sim 50^\circ$ shallower, suggesting this is an unlikely source of magnetization.

We also consider whether the magnetizations of 75035 and 75055 are compatible with having been acquired during the Camelot crater formation event at 500 Ma ago. Because the dynamo had likely

567 ceased by this time³, the only plausible field source would be the local crustal field. We assume that
 568 the local crustal field was the same as that today and was not modified by the cratering event. We test
 569 this hypothesis in two ways: first, we compare the measured paleoinclination to that of the crustal field
 570 and second, we estimate whether the samples could have been sufficiently heated or shocked by the
 571 impact to acquire a stable NRM. The crustal magnetic field at an altitude of 30 km above the lunar
 572 surface has been measured by the Lunar Prospector fluxgate magnetometer¹⁰⁸. Using both sequential
 573 and correlative field models we found that the inclination of the crustal magnetic field at Camelot
 574 crater is $\sim 47^\circ$ which differs by more than 2σ from our measured paleoinclination from 75055.

575 We now consider whether the samples would likely have been remagnetized by the impact. We con-
 576 ducted impact simulations using the iSALE-2D shock physics code^{109,110,111} to evaluate the potential
 577 for shock metamorphism and heating from the formation of Camelot crater. The impact simulations
 578 were run to match the dimensions of Camelot crater, with a final rim-to-rim diameter of ~ 600 m
 579 and original depth of ~ 120 m⁴. To achieve these dimensions, a 20 m diameter, spherical impactor
 580 travelling at 15 km s^{-1} (a typical lunar impact velocity^{112,113}) perpendicular to the target was used.
 581 Both the impactor and target were assumed to have zero porosity and were simulated using an ANEOS
 582 equation of state for basalt¹¹⁴. Simulations were run with a spatial resolution of 2 m.

583 Our simulations suggest low peak pressures (< 1 GPa) and post-shock temperatures (< 280 K)
 584 associated with the Camelot crater-forming impact event at the inferred formation locations of 75035
 585 and 75055. Results are shown for crater formation at the transient cavity stage (Figure S22). Only
 586 a small volume of material, proximal to the point of impact experiences significant shock pressures
 587 or post-shock temperature increases. However, attenuation would be much greater in a porous target
 588 (e.g., one or more thick layers of intra-basalt regolith layers) so an even smaller volume may experience
 589 temperatures > 100 °C greater than normal¹¹⁵. Temperatures are therefore unlikely to exceed the
 590 Curie temperature given the relatively low porosity of mare basalts¹¹⁶. The peak shock pressure is
 591 also too low to influence the NRM of the samples. Paleomagnetic signals preserved in samples prior
 592 to cratering at this locality are therefore likely to be unperturbed.

Figure S22 | Impact simulations for a 20 m diameter, spherical impactor with a velocity of 15 km s^{-1} . Simulations show the peak pressure and temperature 5 seconds after the impact event. Both the target and impactor are basaltic in composition. The red dot indicates the approximate position of 75035 and 75055 at Station 5. (a) The bulk of the target material is only very weakly shocked, with peak pressures predominantly < 2 GPa. (b) Only the edge of the impact basin experiences significant heating, while the bulk of the target material does not exceed temperatures of 280 K.

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Figures

Figure 1

Predictions of various hypothesized lunar magnetic field sources for the paleoinclination of the lunar field. The top and bottom of each panel show a schematic of the approximate field direction with respect to the Moon and the inclination as a function of latitude, respectively. The black region represents the

lunar core and dark red regions represent molten silicate. In all cases, red lines depict the magnetic field, blue lines depict any currents generated, and the yellow region around the Moon represents the solar wind when this is specifically required to generate the proposed magnetic field. a, A selenocentric axial dipolar magnetic field generated by a core dynamo with a rapid planetary rotation rate ($\text{RoI} < 0.12$). b, A multipolar, non-axisymmetric magnetic field generated by a core dynamo with a slow planetary rotation rate ($\text{RoI} > 0.12$). c, An axially-aligned quadrupolar dynamo generated by a deep-sourced magma ocean dynamo²⁷. d, An axially-aligned octupolar dynamo generated by a shallow-sourced magma ocean dynamo²⁷. e, The Earth's mean axial dipole field at the location of the Moon. f, The IMF. g, Antipodal field amplified by basin forming impacts⁵⁴. h, Fields generated by impact plasmas²⁸. The predicted inclination is for rocks directly below the crater. i, Magnetic fields generated by the thermoelectric effect in lava basins that are electrically connected to subsurface magma and the solar wind^{28,36}. j, Magnetic fields generated by a unipolar dynamo in lava basins²⁸. The predicted inclination is for a rock at the surface close to the lava pool. k, Compression of the IMF around the Moon by a cometary coma²⁸.

Figure 2

Demagnetization of NRM in 75035 and 75055. Orthographic projections in laboratory coordinates show the NRM vector during AF demagnetization projected along the North-East (closed squares) and Up-East (open symbols) directions. Stable components are shown by blue (LC), purple (medium coercivity, MC) and red (HC) arrows, respectively. Data shown here are not corrected for remanence anisotropy. The peak AF is shown by the colour bar. a, Specimen 75035-242Ae. b, Specimen 75055-127Aa. c, Specimen 75035-242Bg. d, Specimen 75055-127Ae.

Figure 3

NRM components in 75035 and 75055 and associated paleoinclinations. The LC (grey) and HC (pale blue for 75035, pale red for 75055) components are shown in present-day lunar coordinates for individual specimens. Remanence-anisotropy-corrected HC components are shown in bright blue and red for 75035 and 75055, respectively. The mean (stars) and 95% confidence interval (ellipses) were calculated for the anisotropy-corrected HC components. a, Equal area stereonet projections of mutually oriented specimen

components for 75035 in lunar coordinates. b, Equal area stereonet projections of mutually oriented specimen components for 75055 in lunar coordinates. c, Paleoinclinations in lunar paleohorizontal coordinates for the HC components in 75055. The mean (horizontal red line) and one standard deviation (red shaded region) are shown for anisotropy-corrected components.

Figure 4

Predictions for the paleoinclination of the lunar field, and implications for multipolarity and true polar wander. a, Paleoinclination results are shown at the present latitude of Camelot crater by the black symbol with 95% confidence error bars. Red dots are the measured paleoinclinations from each specimen of 75055. Predicted inclination versus latitude curves (see Figure 1) are shown for impact fields, a unipolar dynamo and a thermoelectric dynamo (red lines), Earth's magnetic field (purple line), the IMF

(yellow line), and a selenocentric axial dipole (green line). b, The predicted magnetic inclination at Camelot crater for a magnetic field with zonal dipolar, quadrupolar and octupolar components, where G2 and G3 are the quadrupolar to dipolar and octupolar to dipolar field ratios, respectively. The thick black line is the mean paleoinclination and the regions bounded by thin black lines represent the 95% confidence interval. Both low and high degrees of multipolarity are permitted by our measured paleoinclination. c, Equal area stereographic projection showing the possible paleopole locations 3.7 Ga ago in present-day lunar geographic coordinates. Open symbols/dashed lines and closed symbols/solid lines are in the northern and southern hemisphere, respectively. The star is the current location of Camelot crater where the samples were collected. The thick black lines are the permitted locations of the north pole calculated from our mean recovered paleoinclination. Thin black lines are the 95% confidence interval on our measurement. The grey shaded region represents < 10 dipole tilt. North 3.7 Ga paleopole locations from independent studies are shown in purple⁵, pink⁷, red⁵², orange⁶, green⁵¹ and blue⁵⁵.