A two-billion-year history for the lunar dynamo

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<td><a href="http://dx.doi.org/10.1126/SCiADV.1700207">http://dx.doi.org/10.1126/SCiADV.1700207</a></td>
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<tr>
<td>Publisher</td>
<td>American Association for the Advancement of Science (AAAS)</td>
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<tr>
<td>Version</td>
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<tr>
<td>Accessed</td>
<td>Tue Feb 12 01:48:24 EST 2019</td>
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A two-billion-year history for the lunar dynamo
Sonia M. Tikoo,1,2,3,4* Benjamin P. Weiss,1,2 David L. Shuster,2,3 Clément Suavet,1 Huapei Wang,1 Timothy L. Grove1

Magnetic studies of lunar rocks indicate that the Moon generated a core dynamo with surface field intensities of ~20 to 110 µT between at least 4.25 and 3.56 billion years ago (Ga). The field subsequently declined to <~4 µT by 3.19 Ga, but it has been unclear whether the dynamo had terminated by this time or just greatly weakened in intensity. We present analyses that demonstrate that the melt glass matrix of a young regolith breccia was magnetized in a ~5 ± 2 µT dynamo field at ~1 to ~2.5 Ga. These data extend the known lifetime of the lunar dynamo by at least 1 billion years. Such a protracted history requires an extraordinarily long-lived power source like core crystallization or precession. No single dynamo mechanism proposed thus far can explain the strong fields inferred for the period before 3.56 Ga while also allowing the dynamo to persist in such a weakened state beyond ~2.5 Ga. Therefore, our results suggest that the dynamo was powered by at least two distinct mechanisms operating during early and late lunar history.

INTRODUCTION

The Moon is a unique venue for exploring the longevity of dynamos generated by planetary bodies intermediate in size between planets and asteroids. A central conundrum is that the lunar dynamo was apparently intense and long-lived, with surface fields reaching ~20 to 110 µT between at least 4.25 and 3.56 billion years ago (Ga) (1–6). The field intensity then precipitously declined by at least an order of magnitude (possibly even to zero) by ~3.19 Ga (7–9). It is unknown whether this decrease reflects total cessation of the dynamo or whether the dynamo persisted beyond 3.56 Ga in a markedly weakened state.

The mechanisms that generated such a long-lived dynamo are uncertain but may include thermal convection (10–13) and mechanical stirring produced by differential rotation between the lunar core and mantle driven by impacts (14) or mantle precession (15, 16). Geo-physical evidence for a ~200- to ~280-km-radius solid inner core (17, 18) within a larger ~220- to ~450-km-radius liquid outer core (17–23) also suggests that thermochemical convection resulting from core crystallization—the driving force behind the Earth’s dynamo—may have helped sustain the dynamo (24–26). Without invoking special conditions, such as an early thermal blanket enveloping the lunar core, a hydrous lunar mantle, or a low core adiabatic heat flux, purely thermal convection dynamos are unlikely to persist beyond ~4 Ga (6). Impact-driven dynamos are transient (lasting up to a few thousand years after each large basin-forming impact (14)) and cannot have occurred after the last basin-forming impact at ~3.7 Ga (5). On the other hand, mantle precession or thermochemical convection may be capable of powering a dynamo well beyond 3.5 Ga (6).

Key to distinguishing between these lunar dynamo mechanisms is establishing the lifetime of the dynamo. However, the poor magnetic recording properties (7, 8, 27) and complex thermal and deformational histories of most lunar samples (6, 7) as well as the rarity of young (<3.2 Ga) Apollo igneous samples have thus far hindered efforts to establish when the dynamo ultimately ceased. Although some Apollo-era studies have suggested that lunar samples as young as ~200 million years old (Ma) formed in lunar paleofields of ~1 to ~10 µT (28), most of these values are likely upper limits given the samples’ magnetic recording fidelities (8, 27, 29). Furthermore, it has been proposed that impact-generated plasmas could generate transient magnetic fields [lasting up to ~1 day for large basin-forming impacts (30) or <~1 s for the small impacts after 3.7 Ga (8)] that could magnetize shocked and quickly cooled rocks throughout lunar history (31, 32). Given these complexities, determining when the lunar dynamo actually ceased requires a young rock with exceptionally high-fidelity magnetic recording properties and a well-constrained thermal and shock history.

To address these deficiencies, we conducted a new analysis of such a young lunar sample, glassy regolith breccia 15498.

Apollo 15 sample 15498 was collected on 1 August 1971 as un-oriented float on the southern rim of Dune Crater within eastern Mare Imbrium. The rock consists of a cohesive impact melt glass matrix containing <1-mm- to ~2-cm-diameter mare basalt clasts (Fig. 1) (31, 32). The clasts are petrogenetically related to the Apollo 15 quartz- and olivine-normative mare basalt suites, suggesting that the breccia was melted and assembled in close proximity to the Apollo 15 landing site (35). The rock is partially coated by a variably ~1- to 6-mm-thick spatter of impact melt glass (textural relationships indicate that this rind is younger than the interior breccia, but its precise age is unknown). A network of fissures lined with vesicular glass crosscuts the interior of the rock (see section S1). Although the basalt clasts contain abundant shock deformation features, including maskelynite (33, 34), the lack of microfractures within the glassy matrix (see section S1) indicates that the rock has not been significantly shocked [peak pressures likely <~3 GPa (36)] since lithification.

The petrography and degree of crystallinity of the glassy matrix of 15498 suggest that it formed by viscous sintering of a clast-laden melt (37). During this primary cooling, ferromagnetic metal grains crystallized from the melt portion of the breccia. Consistent with a previous study of metal compositions in 15498 (38), our electron microprobe analyses found that the major ferromagnetic minerals within the resulting glass matrix are kamacite (α-Fe1−xNi, for x < ~0.05) and martensite (α2-Fe1−xNi, for ~0.05 < x < ~0.19). If an ambient magnetic field was present at the time 15498 formed, kamacite and martensite grains with the observed compositions would have acquired mostly thermoremanent magnetization (TRM), with some possible contribution of thermochemical remanent magnetization (TCRM) during primary cooling on the Moon.
Conductive cooling calculations indicate that the glass matrix cooled from above the Curie temperature of kamacite (780°C) to ambient lunar surface temperatures (<100°C) over a period of at least a few hours (see section S1). However, this cooling time scale is long relative to the expected <1-s duration of impact fields when the rock formed. Therefore, impact fields are extremely unlikely to be the source of any TRM or TCRM acquired by the breccia’s glass matrix during primary cooling.

Hysteresis data (see section S4) and our electron microscopy imaging indicate that, in stark contrast to the multidomain grain size of metal in virtually all lunar crystalline rocks, metal within the glass matrix of 15498 is a mixture of predominantly superparamagnetic to pseudosingle domain grains, with only a relatively small contribution from multidomain grains in lithic fragments (Fig. 2). The presence of these fine-grained magnetic carriers indicates that the melt glass portion of 15498 should provide unusually high-fidelity paleomagnetic records. The relatively low Ni content of kamacite and martensite grains present within the rock suggests that the rock should retain any primary TRM and TCRM through laboratory thermal demagnetization experiments up to maximum temperatures between ~600° and 780°C (which correspond to the austenite-start solid-state phase transformation temperature for the observed martensite compositions and the kamacite Curie temperature, respectively (see section S1)). In combination, these rock magnetic properties indicate that 15498 is an excellent target for lunar paleomagnetic studies.

A previous analysis of 15498 found that the glass matrix of the sample contained a stable natural remanent magnetization (NRM) component that persisted during alternating field (AF) demagnetization to at least 40 mT and during thermal demagnetization to at least 650°C. The trapped ⁴⁰Ar measured using this technique must have experienced degassing into the exosphere, and assumptions are required about the efficiency of each of these processes. The method also assumes that solar wind ³⁶Ar at the Moon is constant with geological time, whereas this quantity

**RESULTS**

**Thermochronometry and sample age constraints**

The glass matrix of 15498 should have acquired its original NRM during primary cooling. To establish the timing of this event and constrain the possibility of postformational thermal remagnetization, we conducted ⁴⁰Ar/³⁹Ar and ³⁸Ar/³⁷Ar thermochronometry on a whole-rock aliquot taken from the interior of a ~1-cm-diameter basalt clast from the interior of sample 15498. We obtained a minimum ⁴⁰Ar/³⁹Ar clast crystallization age of 3310 ± 24 Ma [1 SD analytical uncertainty not including uncertainties in the age of the fluence monitor and decay constant (42)]. This value is consistent with the crystallization ages of other studied Apollo 15 mare basalts (43, 44) and is therefore likely close to the true clast crystallization age. Subsequent heating experienced by this clast due to breccia formation and daytime heating on the lunar surface triggered thermally activated diffusive loss of radiogenic ⁴⁰Ar. The apparent spatial distributions of radiogenic ⁴⁰Ar (⁴⁰Ar*) and cosmogenic ³⁸Ar (³⁸Ar) within clast K-rich mesostasis glass and feldspathic glass are consistent with a three-stage thermal history involving (i) clast formation at ~3.3 Ga, (ii) diffusive loss of Ar due to impact heating to peak temperatures of ~500° to ~650°C at the time of breccia lithification (occurring between ~2.5 and 1.0 Ga), and (iii) further Ar loss from daytime heating after the rock was exposed near the lunar surface at ~600 Ma [as indicated by our cosmogenic exposure age measurements (see section S5)] (Fig. 3).

Our inferred lithification age of ~2.5 to 1.0 Ga (with 1.0 Ga being our best estimate) is broadly consistent with other semiquantitative age estimates (~0.9 to 1.8 Ga) obtained from measuring trapped ⁴⁰Ar/³⁶Ar within the melt glass matrix (see section S5) (45). The trapped ⁴⁰Ar/³⁶Ar method aims to obtain breccia lithification model ages by measuring the ratio of lunar atmospheric ⁴⁰Ar to solar wind ³⁶Ar for the implanted component of Ar in the regolith. However, this method is subject to limitations associated with its primary assumptions. First, the trapped ⁴⁰Ar measured using this technique must have experienced a complex history of (i) formation from decay of ⁴⁰K in the Moon, (ii) degassing into the exosphere, and (iii) ionization and reimplantation into the lunar regolith, and assumptions are required about the efficiency of each of these processes. The method also assumes that solar wind ³⁶Ar at the Moon is constant with geological time, whereas this quantity
will actually vary depending on the strength of the lunar magnetic field (that is, its solar wind–shielding capacity) over time. Hence, this method relies on a calibration that accounts for these various factors (each subject to its own uncertainties) to relate the trapped $^{40}\text{Ar} / ^{36}\text{Ar}$ to a lithification age in geologic time [see the studies of Fagan et al. (45) and Joy et al. (46) for further details regarding this method]. The aforementioned uncertainties in the trapped $^{40}\text{Ar} / ^{36}\text{Ar}$ method encourage the use of an alternative chronometer to obtain complementary sample age constraints, and we were able to do so via our $^{40}\text{Ar} / ^{39}\text{Ar}$ thermochronology modeling. In any case, we conclude that the breccia most likely formed between 1.0 and 2.5 Ga.

**Paleomagnetism**

To characterize the NRM in 15498, we studied 20 mutually oriented subsamples of 15498 collected from the glass matrix portions of five mutually oriented parent chips (15498,274, 15498,282, 15498,287, 15498,313, and 15498,314). Twelve subsamples were collected from the interior of 15498, and 8 subsamples were collected from near the edge of the rock (from a distance ≤~3 times the width of the young glass grain coating the sample in the vicinity of each subsample). The proximity of these peripheral subsamples to the young impact melt glass grain enables using thermal demagnetization to conduct a paleomagnetic baked contact test to determine whether the NRM of the interior subsamples predates sampling by the Apollo astronauts (47).

Of the 20 total subsamples, 7 subsamples were subjected to stepwise AF demagnetization (Fig. 4A). The remaining 13 subsamples were stepwise thermally demagnetized (Fig. 4B). Among the interior subsamples, we observed a low-coercivity (LC) and low-temperature (LT) magnetization component in all 12 subsamples that typically unblocked below AF levels of ≤6.5 mT and temperatures of ≤125°C, respectively. We observed a medium-coercivity (MC) and medium-temperature (MT) component in most subsamples that typically unblocked between the end of the LC/LT component and ~50 mT/~200°C (see section S2). The LC/LT and MC/MT components are largely non-unidirectional among mutually oriented subsamples (Fig. 5). The relatively low coercivities and unblocking temperatures associated with the LC/LT and MC/MT components suggest that these magnetizations likely represent viscous remanent magnetization (VRM) contamination from the terrestrial field acquired during storage and multiple stages of subdivision and handling at JSC over ~42 years (see sections S2 and S4).

We also identified a high-coercivity (HC) and high-temperature (HT) component in all 12 interior subsamples that was blocked up to AF levels of at least 290 to 420 mT and temperatures of up to 660° to 750°C (see section S2). The HC/HT component decays linearly toward the origin (Fig. 4), suggesting that it is the characteristic magnetization component. Although there is modest dispersion (up to ~30°) in directions from individual subsamples (Fig. 6), the HC/HT components generally cluster in the northeastern quadrant of the upper hemisphere. A Watson (48, 49) statistical test for dispersion on a sphere demonstrates that the HC/HT component directions are nonrandom to 99% confidence [that is, the length of the resultant vector of our HC/HT component directions ($R = 11.5$) was greater than the critical value ($R_c = 6.55$ for 12 subsamples)] and therefore likely have a common origin. The low ratio of NRM to isothermal remanent magnetization (IRM) (~≤0.1) suggests that this component was not imparted by a strong-field IRM (see section S3). The HC magnetization is unlikely to be a shock remanent magnetization (SRM), given that SRM acquired at pressures of ≤3 GPa is typically acquired by low-coercivity grains (see section S4) (50, 51). Because single-domain kamacite grains (which dominantly carry the remanence in 15498) should not retain a terrestrial VRM after laboratory heating to temperatures above ~125°C (52), the persistence of the HT component to temperatures ≥660°C precludes its origin as a VRM. Crystallization remanent magnetization (CRM) is also excluded because the metal grains are in the form of primary low-Ni kamacite and martensite (and have not recrystallized to plessite or to Widmanstätten taenite and kamacite).
We obtained high-quality Thellier-Thellier paleointensity values of $5 \pm 2 \mu T$ (mean $\pm 1 \sigma$) from the HT components of six of the interior subsamples (Fig. 7). These values are broadly consistent with our anhysteretic remanent magnetization (ARM) and IRM paleointensity measurements on the HC components of four AF-demagnetized subsamples, which yielded values ranging between $\sim 600$ nT and $\sim 2 \mu T$ [within the factor 2 to 5 uncertainties on the latter values (6)]. It is conceivable that the remanence being carried is not purely TRM and that some martensite may have acquired TCRM upon formation. However, if the NRM of 15498 is a TCRM, the paleointensities inferred from our Thellier experiments would likely represent lower limits due to the inefficiency of CRM relative to TRM (53). Regardless, paleointensities derived from TCRM are usually within several tens of percent of the actual value (54). Therefore, we suspect that our paleointensity results are reasonably accurate even if the remanence is not a pure TRM.

In contrast, four of the five thermally demagnetized peripheral subsamples taken from near the young melt glass rind were fully demagnetized by 360°C, and two of the three AF-demagnetized peripheral subsamples were fully demagnetized by ac fields of 20 mT. The only subsample that contained a magnetization component with the same direction as the HC/HT component observed within the interior subsamples was the subsample collected the farthest away (0.7 cm) from the melt glass rind (274v3). Furthermore, the inferred NRM intensities of these subsamples are, on average, $\sim 90\%$ lower than those of the interior subsamples (see Fig. 8 and section S2). The general absence of HC and HT magnetization within peripheral subsamples suggests that they were thermally demagnetized on the Moon when the impact melt glass was emplaced on the surface of the rock. Collectively, these data are consistent with a positive baked contact test for 15498 and indicate that the HC/HT component observed in the interior subsamples is very likely a TRM acquired during primary cooling in the presence of a temporarily stable ambient field on the Moon.

**DISCUSSION**

The $\sim 5$-$\mu T$ paleointensities obtained from the melt glass matrix of 15498 are $\sim 1000$ times stronger than the field measured by astronauts.
Fig. 6. Equal-area stereographic projection of HC and HT magnetization component directions. Shown directions are observed for mutually oriented matrix glass subsamples from the interior of 15498. Symbols and surrounding ellipses represent directions and associated maximum angular deviation values obtained from principal component analysis. AF and thermally demagnetized subsamples are displayed using circles and squares, respectively. Subsamples from parent chips 274, 282, 287, 313, and 314 are shown by light blue, medium blue, dark blue, dark green, and light green symbols, respectively. Open symbols (dashed lines) represent directions in the upper hemisphere, and filled symbols (solid lines) represent directions in the lower hemisphere. The Fisher mean direction and 95% confidence interval (star and surrounding ellipse, respectively) are shown.

Fig. 7. Thellier-Thellier paleointensity experiment for subsample 15498,313e. (A) Arai plot displaying NRM lost during progressive thermal demagnetization (ordinate) versus laboratory pTRM gained (abscissa). Peak temperatures for selected steps are shown. pTRM checks for alteration are shown as triangles. Paleointensities for unblocking temperature ranges of 250° to 540°C and 560° to 680°C are denoted with dark gray and green symbols, respectively. Gray segments link consecutive thermal steps. (B) Vector endpoint diagram showing zero-field thermal demagnetization steps for subsample 313e. LT and HT components are denoted using blue and green symbols, respectively. Paleointensity experiments were conducted following the IZZI protocol (alternating zero-field and in-field measurements).

Our data indicate that the lunar core dynamo persisted until at least ~1.0 to ~2.5 Ga, thereby extending the known lifetime of the dynamo by ~1.0 billion to ~2.5 billion years [from the previous youngest dynamo record observed in 3.56-Ga mare basalts (5)]. Exactly when the lunar dynamo ceased remains unclear. Given the expected geophysical properties of the lunar interior, no current dynamo scenarios powered by large impacts or purely thermal convection predict that the magnetic field could persist this late in lunar history. Thermal evolution models suggest that thermochemical convection produced by core crystallization could generate a ~1-μT dynamo field that persisted (either continuously or in an intermittent “start-stop” regime) beyond ~1.6 Ga (24, 26). However, according to current scaling laws for convective dynamos, thermochemical convection alone may not be able to reproduce the high ~10- to ~100-μT surface fields inferred for Apollo samples aged 4.25 to 3.56 Ga (6). In contrast, a precession dynamo may be capable of generating ~10- to ~100-μT fields for the period before 3.56 Ga (15, 16), but persistence of such a dynamo beyond ~2 Ga would likely require that the Moon’s orbit receded from the Earth at a rate far slower than expected (6, 8). Given these constraints, no single dynamo generation mechanism proposed thus far can readily reproduce the paleointensity record inferred from Apollo samples. One possible solution is that the dynamo may have been powered by at least two distinct mechanisms operating during early and late lunar history. A second possible solution...
reversal curve (FORC) measurements were conducted using a vibrating sample magnetometer at the Institute for Rock Magnetism at the University of Minnesota (see section S4).

**METHODS**

**Paleomagnetic and rock magnetic analyses**

All paleomagnetic measurements were conducted using a 2G Enterprises Superconducting Rock Magnetometer 755 located within a magnetically shielded room (ambient field of <200 nT) in the Massachusetts Institute of Technology (MIT) Paleomagnetism Laboratory. The magnetometer is equipped with automated AF demagnetization, sample handling, and rock magnetic remanence characterization capabilities (57). Purely nondestructive static three-axis AF demagnetization experiments were conducted on 7 of the 20 total subsamples up to peak ac fields of at least 290 mT. Purely thermal demagnetization was conducted on nine subsamples up to maximum temperatures of 660° to 700°C, or until samples were fully demagnetized, in a new controlled oxygen fugacity oven (58). Thermal experiments were conducted in an H2-CO2 atmosphere at 1 log unit below the iron-wüstite buffer. The four remaining subsamples were AF-pretreated up to peak ac fields of 35 mT and then thermally demagnetized. The subsamples were measured in differing orientations, and the demagnetization data were subsequently rotated into a mutually oriented reference frame for analysis. Principal component analysis was used to determine the best-fit directions for all observed magnetization components (59). Thellier-Thellier paleointensity experiments were conducted on six of the thermal demagnetization subsamples following the IZZI (in-field, zero-field, zero-field, in-field) protocol (60), including partial TRM (pTRM) checks for alteration. ARM and/or IRM paleointensities (2, 5, 61) were determined for four subsamples. Full details of the demagnetization and paleointensity experiments are provided in section S3. Remanence-based rock magnetic experiments (for example, ARM and IRM acquisition and demagnetization) were conducted at MIT. Hysteresis and first-order reversal curve (FORC) measurements were conducted using a vibrating sample magnetometer at the Institute for Rock Magnetism at the University of Minnesota (see section S4).

**40Ar/39Ar and 38Ar/37Ar thermochronology**

All 40Ar/39Ar and 38Ar/37Ar thermochronometry experiments were conducted at the Berkeley Geochronology Center. Using the procedures described in previous works (4, 5, 62), we conducted stepwise degassing 40Ar/39Ar and 38Ar/37Ar experiments on one (~2 mg) whole-rock aliquot of a basalt clast (referred to as 282-1 herein) located adjacent to the glass matrix portion of parent chip 15498,282 that we used for paleomagnetic analyses. Additional stepwise degassing experiments conducted on two whole-rock aliquots of matrix glass yielded complex, discordant age spectra from which no plateau age could be inferred due to the presence of excess nonradiogenic (trapped) 40Ar and solar wind 36Ar. This degassing behavior has been observed for many other lunar impact glasses and regoliths (63). Because it was not possible to directly obtain ages for the matrix glass samples, we do not discuss these experiments further. Apparent 40Ar/39Ar ages for each degassing step were calculated relative to the Hb3gr fluence monitor [age, 1081 Ma (42)] using the decay constants of Renne et al. (42) and the isotopic abundances of Steiger and Jäger (64). We also determined apparent cosmogenic 38Ar exposure ages for each degassing step following procedures described in previous works (4, 5, 65). Following Shea et al. (4), we constructed multi-phase, multi-diffusion domain (MP-MDD) model fits to the 40Ar/39Ar age spectrum and the cosmogenic 38Ar age spectrum to quantify the diffusion of radiogenic 40Ar (40Ar*) and cosmogenic 38Ar (38Arcos) in our sample in the context of various possible thermal histories. All modeled thermal histories include (i) the initial formation of the basalt clast, (ii) diffusive loss of Ar due to impact heating at the time of breccia lithification, and (iii) further loss of Ar from daytime heating while the rock was exposed near the lunar surface before its collection. Full details regarding our MP-MDD models are given in section S5.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/8/e1700207/DC1

section S1. Sample 15498
section S2. NRM behavior
section S3. Paleointensity
section S4. Rock magnetic properties
section S5. 40Ar/39Ar and 38Ar/37Ar thermochronology

fig. S1. Apollo 15 landing site and 15498 sampling context.
fig. S2. Sample 15498.
fig. S3. Backscattered scanning electron microscopy images of 15498 matrix showing absence of post-lithification microfracturing.
fig. S4. BSEM images of FeNi grains in 15498.
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fig. 517. 15498 MP-MDD model predictions for diffusion of 40Ar resulting from impact heating at various times in lunar history. (a) to temperatures ranging between 450° and 675°C, followed by daytime heating to an effective mean temperature of 25°C after 600 Ma. Table S1. WDS measurements of metal grains in 15498 thin sections 298 and 299. Table S2A. NRM components identified for interior matrix glass sub-samples of 15498. Table S2B. NRM components identified for peripheral matrix glass sub-samples of 15498. Table S2C. Fisher mean component directions derived from 15498 data in table S2A. Table S3A. Thellier-Thellier paleointensity determinations for 15498 sub-samples. Table S3B. Comparison of pTRM and pTRM check values for 15498 subsamples. Table S4A. ARM paleointensity determinations for 15498 sub-samples. Table S4. Rock magnetic and hysteresis parameters. Table S5. Anisotropy of ARM (85-mt ac field with 0.01-mt dc field). Table S6. Complete 40Ar/39Ar incremental heating results. Table S7. Oxide weight percent compositions of K-bearing phases in basalt clast 15498-282-1. Table S8. Summary of MP-MDD model parameters with cosmogenic 40Ar production rates for 15498. Table S9. Summary of 40Ar/39Ar chronology for 15498. Table S10. Reduced References (data file S2). 15498 Thellier-Thellier paleointensity data sets. 15498 demagnetization data sets. Table S2C. Fisher mean component directions derived from 15498 data in table S2A. Table S3A. Thellier-Thellier paleointensity determinations for 15498 sub-samples. Table S3B. Comparison of pTRM and pTRM check values for 15498 sub-samples. Table S3C. ARM paleointensity determinations for 15498 sub-samples. Table S3D. IRM paleointensity determinations for 15498 sub-samples.


Acknowledgments: We thank M. Fuller for suggesting the study of regolith breccias, J. Gattacceca for sharing pressure remanent magnetization cell, B. Carbone for administrative support, and the Institute for Rock Magnetism at the University of Minnesota for use of their vibrating sample magnetometer. We also thank P. Boehnke and two anonymous reviewers for helpful suggestions. Funding: We thank the NASA Solar System Workings and Planetary Major Equipment Programs (grant #NNX15AL62G), the NASA Solar System Exploration Research Virtual Institute node at Brown-MIT (grant #NNA14AB01A), the MIT International Science and Technology Initiatives Global Seed Fund, the Rutgers University School of Arts and Sciences, and the Miller Institute for Basic Research in Science for financial support. Author contributions: S.M.T., B.P.W., and D.L.S. conceived the study and supervised the research. S.M.T. designed and carried out the experiments. C.S., H.W., and T.L.G. assisted with the experimental work and analysis. S.M.T. led the writing of the paper with contributions from B.P.W. and D.L.S. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors and will be posted in the Magnetics Information Consortium (MagIC) database (www2.earthref.org/MagIC/).

Submitted 6 February 2017
Accepted 11 July 2017
Published 9 August 2017
10.1126/sciadv.1700207

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Sci Adv 3 (8), e1700207.
DOI: 10.1126/sciadv.1700207

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