nature portfolio

Peer Review File

Magnetic signatures and origins of ferromagnetic minerals in Chang’e-6 lunar farside soils

Corresponding Author: Professor Jin-Hua Li

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This manuscript is centered on the understanding of lunar magnetism, crucial for our understanding of the Moon's geologic history. The characterization of ferromagnetic minerals within lunar materials as potential recorders of lunar magnetism, the timing of a lunar magnetic field, and other processes that might affect the surface of the Moon (space weathering, meteorite impacts, for example). The authors have been influential in the reporting of Chang'e-6 mission results from the South Pole-Aitken (SPA) basin, and this is the next in a succession of recent manuscripts detailing the results of the mission.

The Chang'e-6 samples are of particular interest because this basin is the largest and deepest impact structure, not sampled by previous lunar Apollo missions, and fills a vital role in the understanding of the lunar geologic and magnetic history. The study aims to provide insight to the evolution of the lunar dynamo, the mechanisms of crustal magnetization and the role of impact events in magnetic anomalies on the lunar surface.

There is a level of detail in the magnetic analyses that is lacking for the community, and this manuscript will provide information towards that end. This manuscript should absolutely be published, but I have some comments on the presentation. I will outline these concerns below. These concerns are more geared towards disclosure of information that the community will want to see.

There is considerable debate about the evolution of the Moon's geodynamo -- which the authors do state and cite many of the published papers on this debate in the first paragraph. This study hopes to address the magnetic carriers through an analysis of the sample returns from SPA Basin, both soil and basalt samples. Primarily, the ferromagnetic minerals are not magnetite as seen on Earth, and therefore do not record magnetic fields in the same way and as commonly compared within the literature. Caveats should be made clear in the manuscript. The magnetic behavior of non-magnetite bearing rocks, and how the fidelity of the magnetic recording. What this manuscript attempts is to elucidate how variations in grain size, nickel content and crystalline structure will affect this recording fidelity.

Line 49: please do not use etc, and list the the variables that affect magnetic recording fidelity as this is meant to be for a more broad audience; they may not recognize what the etc should represent.

Figure 1f,g,h - What Apollo and Luna mission studies are being used for comparison in this figure? It is not clear to me. Is it just the Rochette et al 2010 compilation? Please properly cite the data that is shown in Figure 1 in terms of magnetic properties not collected by the authors.

Lines 247-267: I appreciate that the authors discuss the differing interpretations of paleointensity studies for the evolution of the lunar dynamo, though I find relegating it to 'methodological difficulties associated with laboratory-heating methods' is an over-simplification. A number of studies of lunar paleointensity are based on non-thermal proxy determination via comparison to ARM or IRM or a multitude of comparative strategies that may not represent a thermal remanent magnetization, techniques developed - in large part, though not exclusively - through an examination of how magnetite behaves under these experimental conditions. A thorough review of this is beyond the scope of this manuscript, but as written, this implies the paleointensities in question were determined via thermal techniques, and that is not the case.

Figure 4: this is a schematic summary of some interpretations, not a single-defining interpretation as I view this diagram. I think this needs a bit more context for the source of the underlying crustal structure as a start. Though I do appreciate the many magnetization pathways represented here.

Line 272: pathwyas should be pathways

I feel that these changes and suggestions are minor and can be easily be incorporated into a revision.

Reviewer #2

(Remarks to the Author)
Review of “Magnetic signatures and origins of ferromagnetic minerals in Chang’e-6 lunar farside soils” by Li et al.

This is a well-written research article that presents the first comprehensive magnetic and mineralogical results of lunar soils from the CE-6 mission from the South Pole-Aitken Basin on the Moon’s farside. This manuscript is easy to read and easy to understand. Ferromagnetic minerals in lunar materials are the key to studying the Moon’s ancient dynamo. Li et al. show that the CE-6 soils exhibit stronger rock magnetic properties than the Apollo nearside samples, indicating enhanced magnetic minerals despite the relatively weak crustal magnetism. They used advanced electron microscopy to reveal two primary mineralogical populations: basalt clasts containing rare, nickel-poor iron particles with euhedral shapes; and breccias, agglutinates, and glassy materials dominated by nickel-rich metallic iron and Fe-Ni alloys. These two populations indicate formation by endogenous magmatic processes and recrystallization of meteoritic materials by impacts, respectively. Understanding these ferromagnetic mineral formation pathways is essential to deciphering the lunar dynamo evolution history. This is a significant advance in our understanding of the lunar magnetism, which is supported by solid magnetic and mineralogical data from a precious sample by state-of-the-art experimental procedures. I only have some minor comments, which I have made in the Word file in track-changes mode. I think this manuscript is ready for publication after minor revisions.

Huapei Wang
Paleomagnetism and Planetary Magnetism Laboratory
School of Geophysics and Geomatics
China University of Geosciences (Wuhan)

Reviewer #3

(Remarks to the Author)
Review of Li et al. (2024) Magnetic signatures and origins of ferromagnetic minerlas in Chang’e-6 lunar farside soils, submitted to Nature Commun

This paper reports measurements of the ferromagnetic mineralogy and rock magnetic properties of soil particles collected by the Chang’e-6 mission from the South Pole-Aitken Basin on the lunar far side. This is the first detailed study of these samples, which include a diversity of lithologies including endogenous igneous rocks (mare basalts), impact melts, and agglutinates. This work follows up on studies of the paleomagnetism and rock magnetism of basalt samples in Chang’e-6 by Cai et al. 2025 Nature. It is potentially very important since these samples are ~500 km south of the largest province of magnetic anomalies on the moon, on the northern edge of SPA. The current studies finds that collectively the soil has higher saturation magnetization than the soils returned from any previously sampled landing on the Moon.

This paper focuses on high resolution compositional and mineralogical studies in the context of bulk rock magnetic properties. It provides a fine catalog the wide range of grain sizes, shapes and textures of metallic particles and how they relate to the petrographic origin of their host clasts. This will be useful to future researchers who will seek to study these samples. This a unique sample suite and a unique dataset and it is exciting to see these new measurements.2qw3

My main comment is that it would strengthen the paper if the author could further broaden the discussion of the implications of their study. For example, as they briefly mention at the end, their data likely have implications for (a) determining the nature and origin of the lunar dynamo and (b) the large SPA crustal anomaly north of the Chang’e-6 landing site. Re: (a), do these results help distinguish the origin of lunar paleomagnetism (i.e., from a dynamo or impact-generated field)? Re: (b), is the saturation remanent magnetization in these samples quantitatively sufficient to explain the strong lunar remanent in the SPA crustal anomaly if one assumes a magnetizing field like that inferred from paleomagnetic studies (10-100 microteslas)? Also, does the petrography of these samples enable distinguishing between the various proposed sources of the highly magnetic materials in the SPA anomalies: exogenous impactor material (Wieczorek et al. 2012)), highly magnetic dikes (Purucker et al. 2012), possibly from reduction of ilmenite in dikes (Liang et al. 2024), or some other magnetic material?

Other comments:

The Chang’e6- samples reported here had almost twice the saturation remanence (Mrs) and susceptibility (Xlf) as the values of samples from other landing sites (Fig. 1g), suggesting that this might at least partially explain the SPA magnetic anomalies. However, the nature and source of the data in the data for the Apollo, Lunar and Chang’e-5 samples in Figs. 1f-h and S3 are unclear: does each point represent a single soil sample (if so, which one?) or means of many soil samples? If they represent means, then how does the Mrs and Xlf of Chang’e-6 samples compare to the *distributions* of these values for Apollo, Luna and Chang’e-5: are they statistically distinct, especially given the large differences in samples sizes of the various soil suites? Please also provide references for the source data for the Apollo, Lunar and Chang’e-5 samples.

Fig. 2k. That is a quite a bit of data! How were the grain sizes in this figure determined?

Line 245 and Fig. 4. The authors refer to detrital remanent magnetization (DRM) as a possible source of the lunar magnetic anomalies. But I have never heard this magnetization form mentioned before in the context of the Moon, which has no atmosphere or fluids (the only related concept I am aware of is DRM in the solar nebula as described by Fu and Weiss, 2012 JGR). Could the authors elaborate a little on how they think this would form on the Moon? Wouldn’t a TRM in the hot impact ejecta be a more likely source for the anomalies on the northern rim of SPA?

Lines 263-265: re: investigations targeting impact-generated materials, see, for example, Buz et al. 2015, Tikoo et al. 2017, and Mighani et al. 2022, Tarduno et al. 2021.

Fig. S14: Please show how the images of the FIB slices in (right column) are oriented with respect to the images of the source sample from which they are extracted (middle column).

Version 1:

Reviewer comments:

Reviewer #3

(Remarks to the Author)
The authors have adequately addressed by comments and I have no further comments. I believe it is ready for publication.

Point-to-point response to Reviewers

Reviewer #1 (Remarks to the Author):

This manuscript is centered on the understanding of lunar magnetism, crucial for our understanding of the Moon's geologic history. The characterization of ferromagnetic minerals within lunar materials as potential recorders of lunar magnetism, the timing of a lunar magnetic field, and other processes that might affect the surface of the Moon (space weathering, meteorite impacts, for example). The authors have been influential in the reporting of Chang'e-6 mission results from the South Pole-Aitken (SPA) basin, and this is the next in a succession of recent manuscripts detailing the results of the mission.

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There is a level of detail in the magnetic analyses that is lacking for the community, and this manuscript will provide information towards that end. This manuscript should absolutely be published, but I have some comments on the presentation. I will outline these concerns below. These concerns are more geared towards disclosure of information that the community will want to see.

Response: We sincerely thank Review #1 for recognizing the significance of SPA samples and the value of a comprehensive magnetic characterization. We are encouraged by the recommendation for publication and have revised the manuscript accordingly to address your comments.

There is considerable debate about the evolution of the Moon's geodynamo -- which the authors do state and cite many of the published papers on this debate in the first paragraph. This study hopes to address the magnetic carriers through an analysis of the sample returns from SPA Basin, both soil and basalt samples. Primarily, the ferromagnetic minerals are not magnetite as seen on Earth, and therefore do not record magnetic fields in the same way and as commonly compared within the literature. Caveats should be made clear in the manuscript. The magnetic behavior of non-magnetite bearing rocks, and how the fidelity of the magnetic recording. What this manuscript attempts is to elucidate how variations in grain size, nickel content and crystalline structure will affect this recording fidelity.

Response: We thank the reviewer for insightful suggestions. In the revised manuscript, we have clarified that the magnetic minerals in lunar soils differ markedly from the magnetic oxides and sulfides typically encountered on Earth. These revisions appear in Lines 43-44 of the Introduction and Lines 252-262 of the Discussion.

Line 49: please do not use etc, and list the the variables that affect magnetic recording fidelity as this is meant to be for a more broad audience; they may not recognize what the etc should represent.

Response: Changed. It has been rephrased as “considerable variations in grain size, morphology, nickel content, crystallographic structure, and internal stress state”. Please see Lines 48-49 in the revised manuscript.

Figure 1f,g,h - What Apollo and Luna mission studies are being used for comparison in this figure? It is not clear to me. Is it just the Rochette et al 2010 compilation? Please properly cite the data that is shown in Figure 1 in terms of magnetic properties not collected by the authors.

Response: We appreciate the reviewer’s request for a fuller information about the origin of raw data. Figure 1 f–h plots every published magnetic data point for lunar soils from Apollo, Luna, and Chang’e-5 missions. These data include not only the compilation by Rochette et al. (2010), but also the comprehensive dataset provided by Qian et al. (2024), which integrates original measurements from Nagata et al. (1971, 1972), Gose et al. (1972), Pearce et al. (1973, 1974), Morris (1980). Accordingly, in the revised manuscript, we have updated the caption of Figure 1 to cite the sources of these data (see Lines 107-110). Additionally, we have added Supplementary Table 2, which lists for each data point: mission, landing site, sample number, sample type, measured magnetic properties, corresponding numerical values, and the original literature reference.

Lines 247-267: I appreciate that the authors discuss the differing interpretations of paleointensity studies for the evolution of the lunar dynamo, though I find relegating it to 'methodological difficulties associated with laboratory-heating methods' is an over-simplification. A number of studies of lunar paleointensity are based on non-thermal proxy determination via comparison to ARM or IRM or a multitude of comparative strategies that may not represent a thermal remanent magnetization, techniques developed - in large part, though not exclusively - through an examination of how magnetite behaves under these experimental conditions. A thorough review of this is beyond the scope of this manuscript, but as written, this implies the paleointensities in question were determined via thermal techniques, and that is not the case.

Response: Thank you for highlighting this important point. In the revised Discussion (Lines 288-294), we now note that most paleointensity determinations employ non-heating, alternatingfield remanence methods (e.g., ARM and IRM), which cannot faithfully reproduce thermoremanent magnetization (TRM) acquisition processes. We further discuss that the empirical calibration factors (f' and a) are typically derived from single-mineral standards, yet lunar soils contain a complex, heterogeneous mixture of ferromagnetic phases spanning a broad range of grain sizes, shapes, and compositions. As a result, applying these calibration constants across such diverse assemblages can introduce significant uncertainties into paleointensity.

Figure 4: this is a schematic summary of some interpretations, not a single-defining interpretation as I view this diagram. I think this needs a bit more context for the source of the underlying crustal structure as a start. Though I do appreciate the many magnetization pathways represented here.

Response: We thank Reviewer #1 for noting that the diagram is illustrative rather than prescriptive. Its aim is to highlight the most plausible formation pathways for the ferromagnetic minerals identified in CE6 soils and the types of remanent magnetizations they are likely to acquire. To provide the necessary geological context, we have added a discussion of SPA-soil formation in the Discussion (Lines 212-220) and cited the underlying crustal-structure model (Wieczorek et al. 2013; adopted by Qian et al., 2024) both in the text and in the Figure caption (Lines 319-320).

Line 272: pathwyas should be pathways

Response: Changed. See Line 310.

I feel that these changes and suggestions are minor and can be easily be incorporated into a revision.

Response: Thank you for your constructive suggestions again.

Reviewer #2 (Remarks to the Author):

Review of "Magnetic signatures and origins of ferromagnetic minerals in Chang'e-6 lunar farside soils" by Li et al.

This is a well-written research article that presents the first comprehensive magnetic and mineralogical results of lunar soils from the CE-6 mission from the South Pole-Aitken Basin on the Moon's farside. This manuscript is easy to read and easy to understand. Ferromagnetic minerals in lunar materials are the key to studying the Moon's ancient dynamo. Li et al. show that the CE-6 soils exhibit stronger rock magnetic properties than the Apollo nearside samples, *indicating enhanced magnetic minerals despite the relatively weak crustal magnetism. They used advanced electron microscopy to reveal two primary mineralogical populations: basalt clasts containing rare, nickel-poor iron particles with euhedral shapes; and breccias, agglutinates, and glassy materials dominated by nickel-rich metallic iron and Fe-Ni alloys. These two populations indicate formation by endogenous magmatic processes and recrystallization of meteoritic materials by impacts, respectively. Understanding these ferromagnetic mineral formation pathways is essential to deciphering the lunar dynamo evolution history. This is a significant advance in our understanding of the lunar magnetism, which is supported by solid magnetic and mineralogical data from a precious sample by state-of-the-art experimental procedures. I only have some minor comments, which I have made in the Word file in track-changes mode. I think this manuscript is ready for publication after minor revisions.*

Response: We sincerely thank the reviewer for the thorough and supportive evaluation of our manuscript. We are grateful for your recognition of the novelty and significance of our study, as well as the clarity of our presentation. We appreciate your positive assessment of our magnetic and mineralogical dataset and its implications for understanding lunar dynamo evolution. Your comments greatly encourage us, and we are pleased to hear that only minor revisions are required.

We have carefully addressed all the minor suggestions and corrections provided in the annotated Word file. These changes have been implemented in the revised manuscript and are highlighted accordingly.

Line 86 Make sure if the unmixing analysis is done the IRM curve or the DCD curve

Response: Thank you for the clarification. We've updated the Figure caption to explicitly state that the remanence acquisition analysis is performed on the IRM acquisition curve, ensuring consistency with the reviewer's recommendation. Please see Lines 102-104.

Line 104 need to be more specific. Is it orbital field strength or projected surface field strength?

Response: Thank you for the suggestion. We've revised the Figure caption to clarify that the plotted values represent projected surface field strength. Please see Lines 100-101.

Line 108 *IRM curves can also be shown in Fig. 1c*

Response: Thank you for the suggestion. We have updated Figure 1c to include the IRM acquisition curve as requested. Please see the new Fig. 1c.

Reviewer #3 (Remarks to the Author):

This paper reports measurements of the ferromagnetic mineralogy and rock magnetic properties of soil particles collected by the Chang'e-6 mission from the South Pole-Aitken Basin on the lunar far side. This is the first detailed study of these samples, which include a diversity of lithologies including endogenous igneous rocks (mare basalts), impact melts, and agglutinates. This work follows up on studies of the paleomagnetism and rock magnetism of basalt samples in Chang'e-6 by Cai et al. 2025 Nature. It is potentially very important since these samples are ~500 km south of the largest province of magnetic anomalies on the moon, on the northern edge of SPA. The current studies finds that collectively the soil has higher saturation magnetization than the soils returned from any previously sampled landing on the Moon.

This paper focuses on high resolution compositional and mineralogical studies in the context of bulk rock magnetic properties. It provides a fine catalog the wide range of grain sizes, shapes and textures of metallic particles and how they relate to the petrographic origin of their host clasts. This will be useful to future researchers who will seek to study these samples. This a unique sample suite and a unique dataset and it is exciting to see these new measurements.2qw3

Response: We sincerely thank the reviewer #3 for their thoughtful and constructive comments, and for recognizing the novelty and potential significance of our Chang'e-6 magnetic and mineralogical study. We appreciate your positive remarks regarding the uniqueness of the sample set and the detailed characterization we have provided. We especially value your suggestion to further broaden the discussion of the scientific implications, which we fully agree will enhance the impact of the manuscript.

My main comment is that it would strengthen the paper if the author could further broaden the discussion of the implications of their study. *For example, as they briefly mention at the end, their data likely have implications for (a) determining the nature and origin of the lunar dynamo and (b) the large SPA crustal anomaly north of the Chang'e-6 landing site. Re: (a), do these results help distinguish the origin of lunar paleomagnetism (i.e., from a dynamo or impact-generated field)? Re: (b), is the saturation remanent magnetization in these samples quantitatively sufficient to explain the strong lunar remanent in the SPA crustal anomaly if one assumes a magnetizing field like that inferred from paleomagnetic studies (10-100 microteslas)? Also, does the petrography of these samples enable distinguishing between the various proposed sources of the highly magnetic materials in the SPA anomalies: exogenous impactor material (Wieczorek et al. 2012)), highly magnetic dikes (Purucker et al. 2012), possibly from reduction of ilmenite in dikes (Liang et al. 2024), or some other magnetic material?*

Response: Thank you for your insightful feedback. In the revised manuscript, we have substantially expanded the Discussion (Lines 212-220, 244-262, 271-280, 288-294) to highlight the broader implications of our combined magnetic and microscopic analyses. Below is a concise summary of the key revisions:

(1) Two distinct mineral populations

- **Magmatic grains**: Nickel-poor, euhedral Fe particles hosted in basalt clasts, likely carrying primary thermoremanent magnetization (TRM) upon cooling.
- **Impact-related phases**: Nickel-rich metallic Fe and Fe–Ni alloys within breccias, agglutinates, and glassy materials, exhibiting varied grain sizes and domain states that record chemical (CRM), shock (SRM), depositional-like (DRM), and viscous (VRM) remanences.

(2) Remanence Stability and Mineral Physics

- SD–SV metallic iron and Fe–Ni alloys (including kamacite) possess higher Curie temperatures than magnetite, favoring long-term thermal stability. However, their high saturation magnetization and lower intrinsic coercivity make them susceptible to shock-induced domain-wall pinning and space-weathering defects .
- We discuss recent micromagnetic modeling and experiments showing that nanometer-scale taenite grains can retain stable primary magnetizations (coercivity ~250 mT) over geological timescales.

(3) Implications for the SPA Anomaly

- We reiterate that our bulk-soil M_{rs} measurement for CE6 is the highest among all returned lunar samples, implying an unusually large abundance of high-thermal-susceptibility metallic Fe phases.
- According to Wieczorek et al. (2012), high-susceptibility materials require far less thickness to reproduce the SPA magnetic anomaly. Thus, the enrichment in meteoritic and impact-generated Fe makes it easier to account for the SPA signal with a smaller volume of source material.

We believe these additions clarify how the diverse ferromagnetic mineral assemblage in CE6 soils informs both paleomagnetic stability and the origin of the farside magnetic anomaly. Thank you again for guiding these improvements.

Other comments:

The Chang'e6- samples reported here had almost twice the saturation remanence (Mrs) and susceptibility (Xlf) as the values of samples from other landing sites (Fig. 1g), suggesting that this might at least partially explain the SPA magnetic anomalies. However, the nature and source of the data in the data for the Apollo, Lunar and Chang'e-5 samples in Figs. 1f-h and S3 are *unclear: does each point represent a single soil sample (if so, which one?) or means of many soil samples? If they represent means, then how does the Mrs and Xlf of Chang'e-6 samples compare to the *distributions* of these values for Apollo, Luna and Chang'e-5: are they statistically distinct, especially given the large differences in samples sizes of the various soil suites? Please also provide references for the source data for the Apollo, Lunar and Chang'e-5 samples.*

Response: We appreciate Reviewer #3's emphasis on preserving sample-level variability. In response, we have:

- **Expanded our dataset** to include nearly all published soil measurements from Apollo, Luna, Chang'e-5, and Chang'e-6, with each point in Figures 1f–h and S3 representing a single, unaveraged soil sample.
- **Retained individual values** rather than regional averages, so that genuine sample-to-sample differences—and any compositional or geographic trends—remain visible.
- **Updated all figure captions** to cite the original sources for each dataset.
- **Added Supplementary Table 2**, which details for every plotted sample: mission, landing site, sample number, sample type, measured magnetic parameters (Mrs, χlf, etc.), and the corresponding literature reference.

Fig. 2k. That is a quite a bit of data! How were the grain sizes in this figure determined?

Response: We thank the reviewer for this question. In our study, grain-size distributions of metallic iron particles were quantified using high-resolution backscattered-electron SEM (BSE-SEM) imaging combined with automated image analysis. Specifically:

(1) Image Acquisition:

- Samples were imaged with a Zeiss CrossBeam 550 field-emission SEM (Gemini II column) equipped with an Oxford Ultim Max EDXS detector and a Capella Ga-LMIS FIB column.
- High-resolution BSE-SEM micrographs (pixel size = 1 nm) were captured using Atlas 5 software (v5.3) to document the occurrence and spatial distribution of metallic Fe and Fe–Ni alloy particles within agglutinates, glassy agglutinates, and volcanic glass matrices.

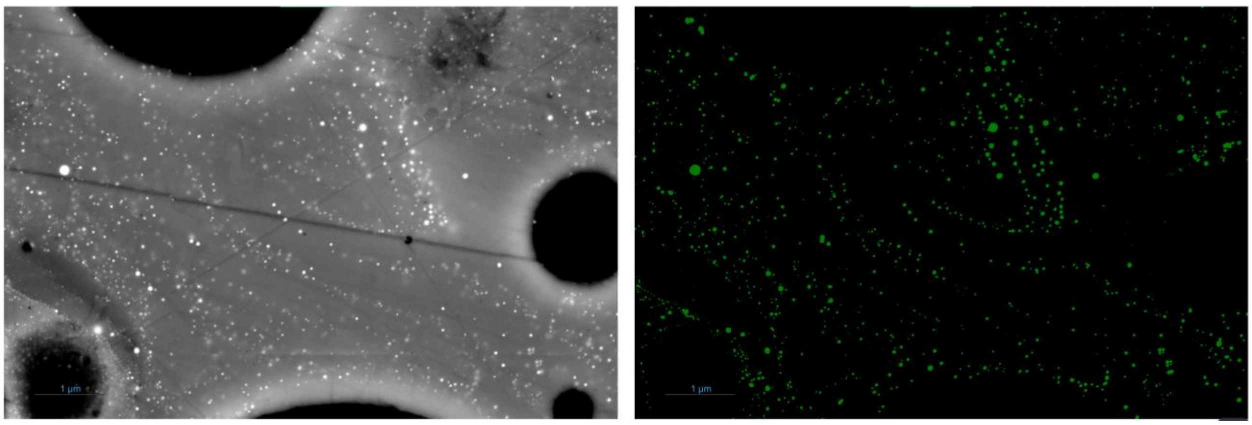
(2) Image Segmentation and Validation:

- All images were processed in ORS Dragonfly Pro (v2024.1).
- Strong compositional contrast between metallic phases and the surrounding silicate matrices enabled initial segmentation via manual thresholding of grayscale histograms.
- Segmentation outputs were visually inspected and, where necessary, manually refined to ensure accurate particle delineation.

(3) Morphometric Analysis:

- Automated "2D Aspect Ratio" measurements extracted major and minor axis lengths for each particle.
- For coarse or highly irregular grains, dimensional parameters were determined through operator-assisted manual measurement to maintain statistical rigor.

This combined approach yields robust, high-precision grain-size datasets that underpin our interpretations of particle formation environments and magnetic domain states. Please see Lines



Line 245 and Fig. 4. The authors refer to detrital remanent magnetization (DRM) as a possible source of the lunar magnetic anomalies. But I have never heard this magnetization form mentioned before in the context of the Moon, which has no atmosphere or fluids (the only related concept I am aware of is DRM in the solar nebula as described by Fu and Weiss, 2012 JGR). Could the authors elaborate a little on how they think this would form on the Moon? Wouldn't a TRM in the hot impact ejecta be a more likely source for the anomalies on the northern rim of SPA?

Response: Thank you for the opportunity to clarify. We have reworded the sentence in Lines 244-251 to make the analogy explicit without implying a true sedimentary process:

"As impact ejecta settle through the exosphere, each clast's primary TRM becomes partially randomized in orientation, producing a net remanence analogous to depositional remanent magnetization (DRM), despite occurring in the Moon's anhydrous environment."

This phrasing should eliminate any confusion about the mechanism while retaining the DRM analogy.

Lines 263-265: re: investigations targeting impact-generated materials, see, for example, Buz et al. 2015, Tikoo et al. 2017, and Mighani et al. 2022, Tarduno et al. 2021.

Response: Excellent! Thank you for adding and citing those references. Including them in the revised manuscript ensures full traceability of our sources and strengthens the robustness of the discussion. Please see Lines 301-303.

Fig. S14: Please show how the images of the FIB slices in (right column) are oriented with respect to the images of the source sample from which they are extracted (middle column).

Response: The new Supplementary Fig. 14 clearly indicates the orientation relationships: schematic arrows and labels now link each FIB slice (right column) back to its parent region in the source-sample image (middle column). This makes it immediately obvious how each cross-section corresponds to the original sample. Let me know if you'd like any further tweaks!