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Peer Review File

Zinc isotopes record lunar magmatic outgassing and surface processes in different Chang'e-5 samples

Corresponding Author: Professor Haolan Tang

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Professor Tang,

Your manuscript titled "Zinc Isotopic Insights into Lunar Magmatic Outgassing and Surface Processing from Chang'e-5" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Pilar Madrigal, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-2089-0560

Joe Aslin
Deputy Editor
Communications Earth & Environment

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• Life sciences
An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript reports Zn isotope compositions of basalts and soils returned by the Chang'e-5 mission. The CE-5 basalts exhibit similar Zn isotope compositions to Apollo basalts, supporting a link to the global evaporation event associated with the Moon's formation. By contrast, the CE-5 soils are distinct from Apollo soils and interpreted to primarily reflect recondensation of isotopically light Zn from volcanic degassing, with only limited effects from space weathering.

Overall, the study is well executed and expands the existing dataset on lunar Zn isotope compositions. I recommend publication after the authors address the minor comments outlined below.

Lines 27-34: missing references for these three statements.

Lines 47-50: this statement is a bit hard to follow and would benefit from rephrasing. Typo in line 48 (potentially difference).

Lines 50-52: again, this needs rephrasing. Typos: exhibits, factor, inspire.

Lines 94-96: needs some rewording.

Source Region inferred from CE-5 Basalts
The first paragraph is confusing as written. Line 127 states that Apollo high-Ti samples have higher delta66Zn than CE-5 samples, while lines 135–136 describe says the delta66Zn of CE-5 basalts as comparable to Apollo mare basalts. As presented, these statements seem at odds, and it is unclear what point the authors are aiming to make. I recommend rephrasing this paragraph for clarity.

Lines 129-131: Ref. 43 only provides the compositions of CE-5 basalts. Please provide refs. for Apollo samples for comparison to support this statement. At least for K, for example.

Line 143: I assume the Zn concentration here corresponds to BSE, not chondrite.

Low maturity of CE-5 soils
While I agree that CE-5 soils are overall distinct, they do overlap substantially with Apollo soils for several of the parameters considered. The current text implies a sharp distinction between them and would benefit from a more nuanced discussion. In addition, as with the CE-5 samples, the full range of values for the Apollo samples should be provided throughout this section, not just the highest value. This applies to delta66Zn (line 180), Is/FeO (line 191), and Ni (line 210).

Lines 190-191: According to the refs. cited here, a number of Apollo soils are also immature, with Is/FeO values as low as 4.6, well below the 20-80 range that is currently cited. If there's a reason why these were excluded from the comparison, that should be clarified.

Lines 195-196: Missing ref. for the Fe0/FeO values. Are they the same for all samples?

Lines 208–210: Several Apollo soils (e.g., 12032, 61221, 73131, 70311, 71041, 15401, 15601…) have Ni values within the range reported for the CE-5 samples. Please provide the full range of Apollo values and clarify the comparison. Missing ref. for CE-5 range.

It is unclear why the sections "Low maturity of CE-5 soils" and "Trivial contribution from micrometeorite impacts on Zn isotopic compositions in CE-5 soils" are separated, as the discussions substantially overlap. I suggest combining them, since both address the role of space weathering on the Zn isotope compositions. That would make it easier for readers to follow, and better tie the discussion back to the conclusions in the abstract.

Lines 218-221: please rephrase.

Lines 295-297: missing ref.

Line 401: the total Zn of the samples is not provided in Table 2.

Line 402: The blank is more than 10% of the total Zn for one of the samples, and a considerable fraction for the others. Please address how this may have influenced the results.

Reviewer #2 (Remarks to the Author):

Review of "Zinc isotopic insights into lunar magmatic outgassing and surface processing from Chang'e-5"

Thankyou for the opportunity to review this work. The new study has analysed the Zn isotope composition of the sample return material from the Chang'e-5 lunar mission; in particular lunar low-Ti basalts and regolith from the rover site. This is of course of high interest, given the uniqueness of the sample set, as well as the previous significant insights from Zn isotope studies of lunar material.

I read the work with interest, and I broadly think this is a great study. The data seem excellent, and the work is neatly presented with broadly useful figures. The basalt data are interpreted within, and agree with, the framework and findings drawn from the Zn isotope studies of Apollo samples – to whit, the Moon's Zn isotope composition was wholesale fractionated during a moon-scale devolatilization event potentially associated with the giant impact. The novelty of the work (apart from, of course, the uniqueness of the samples) comes from the intepretation of the lunar regolith data, which are used to imply transient but potentially important volcanic outgassing which may have effected parts of the lunar landscape (and, I would argue, the outgassing lavas forming on the lunar surface).

I have only a few comments that would be easily addressed in revisions to the text. These are detailed below; most are minor, but I do have questions about how the range of CE5 (and Apollo) Zn isotope compositions could be generated if a single stage devolatilization event pre- or during magma ocean stage is the reason for an isotopically heavy Moon. I further suggest that the proposed degassing that has generated the isotopically light material in the CE5 regolith samples could also be used to explain the range of Zn isotope composition in the basalts.

Thanks again,

Paul Savage

I'm not sure how statistically accurate it is to state that the Apollo low-Ti basalts have a "higher" Zn isotope composition than the CE5 samples; the range from the Apollo samples is a lot wider, but the samples seem to plot in the higher side of the range of both low and high Ti Apollo samples. With n = 3 it's highly possible there could be basalt unsampled by CE5 that shows this range. It would be more accurate to describe the data as plotting near the median of Apollo samples; I think also that it would be worth plotting a histogram of the Apollo and CE5 data to show this in more detail. This could be Figure 1a, for instance, and the current figure 1 could be Fig 1b.

I am somewhat unconvinced that the range of CE5 Zn isotope data in the basalts is demonstrating that they have been ONLY fractionated by wholescale volatile Zn depletion of the bulk silicate Moon, which I think is what the authors are arguing for. The authors state they find no evidence for Zn isotope fractionation via "later-stage magmatic activities and associated degassing…". (this directly contradicts the findings from the regolith samples later on in the work!). My main issue is that there is a relatively large range of Zn isotope compositions defined by the CE5 basalts, ranging over almost 1 per mil. If there is limited Zn isotope fractionation associated with later-stage magmatic activities and associated degassing, this implies that the lunar mantle has an extremely heterogeneous Zn isotope composition. There is no explanation as to how this could be generated – I am here assuming the authors agree that the lunar mantle rocks cooled from a magma ocean which would, you would imagine, be initially homogeneous with respect to Zn isotopes. I do agree that the whole CE5 suite is isotopically heavy compared to Earth, which is canonically interpreted to mean whole Moon degassing at an early stage, but there is additional complexity in the CE5 (and Apollo) data which does not, I think, fit the single stage degassing model, as in my mind this should affect the whole lunar mantle broadly equally. The authors later in the piece point to volcanic outgassing as a way to generate the isotopically light lunar soils in the region of the CE5 basalts. Could this not explain the range of Zn isotope compositions in the basalts?

I enjoyed the discussion about the relative maturity of the Apollo vs CE5 regolith. Could the authors perhaps discuss why one lunar site would experience less gardening than another? Is there a geographic reason for this?

- Line 37: Not all mass dependent stable isotope systems show lunar material to be isotopically heavy relative to Earth – cf. Sossi et al 2018 PNAS for Cr isotopes, and Wang et al 2019 Nature Geoscience for Sn isotopes.
- Line 50: In think "inspire" here is supposed to be "in spite"? In any case, this sentence could do with a revisit.
- Line 64: I'm not sure what is meant by this sentence – how is something buried downwards on the Moon's surface? Is this saying that ongoing meteorite gardening pushes the space weathering front deeper into the regolith?
- Line 138: "lighter", not "lower"
- Line 147: I'm unclear as to what this equation is modelling – could the authors point to a paper which explains its utility and/or include a derivation of it in their supplementary material? I am guessing that Si is Zn vapor saturation but again this isn't clear.
- Line 173: Perhaps refer to Fig 3 in this paragraph.
- Line 221: There is a repetition here of the statement "relatively mild space-weathering modification at the CE-5 site".
- Line 229: I think "effect" would be a better word than "contribution" here, as the latter word implies mixing with, whereas the previous discussion confirms that micrometeorite gardening can lead to enrichment in heavier isotopes by volatile loss of MVE elements.
- Line 231: Is it correct to describe deeper regolith as more "mature"? This is confusing terminology I think as more mature soils tend to be more chemically depleted so are mostly the shallowest. Deeper soils are closer in composition to the bedrock.
- Line 279: Here I would include a statement that the authors will assess the effect of volcanic outgassing on lunar soils in the next section.
- Line 345: Redefine "PKT"

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Version 1:

Decision Letter:

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Dear Professor Tang,

Your manuscript titled "Zinc Isotopic Insights into Lunar Magmatic Outgassing and Surface Processing from Chang’e-5" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within three weeks; please let us know if you need more time.

Best regards,

Pilar Madrigal
Editorial Board Member
Communications Earth & Environment

Joe Aslin
Deputy Editor,
Communications Earth & Environment
Consulting Editor,
Communications Sustainability

https://www.nature.com/commsenv/
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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily addressed the points raised in the previous round of reviews. The revisions have improved the clarity and overall quality of the manuscript. I recommend it for publication without further revision.

Reviewer #2 (Remarks to the Author):

Review of resubmission of “Zinc Isotopic Insights into Lunar Magmatic Outgassing and Surface Processing from Chang’e-5”.

Thankyou for the opportunity to review the new draft of this contribution. I was positive about the paper in my initial review; my main comments focussed on clarifying/extending some of the arguments about how the range of Zn isotope compositions in lunar basalts including the CE5 samples might be generated, and some presentational improvements. The revised submission has been significantly improved, with the authors including some revised/new modelling to explain the range of isotope compositions recorded in their samples; I have a couple of suggestions which I think might clarify some of the new text additions, but otherwise I would be happy to recommend this work for publication. I would also like to thank the authors for providing a conscientious rebuttal document and tracked-changes manuscript.

Congratulations on an excellent piece of science,

Paul Savage
St Andrews, November 2025

Line 26: depletion relative to bulk solar system compositions.

Line 132: “…such differentiation should exert minimal influence on both the Zn concentration and isotope composition, given the small equilibrium fractionation factor and partition coefficients close to unity between minerals and mafic melt during crystalisation”

Line 134: This new sentence starting “Consequently…” could do with a rewrite; perhaps: “Consequently, magmatic differentiation during the formation of the CE-5 basalts should not significantly shift their isotopic composition away from their source, and as such these materials should be comparable to the Apollo mare basalt dataset.”

Line 136: I would rewrite this as follows: “Thus, the observed widescale enrichment in heavy Zn in the CE-5 basalts relative to BSE can, as for the Apollo basalts, be mainly attributed to a lunar-scale, high-temperature evaporation process, likely related to the Moon-forming giant impact.”

Line 139: The term “subsequent global melting” is a little vague here – it could be taken to mean an event subsequent to the initial magma ocean stage of the Moon (i.e. a remelting event).

Line 141: “broadly correlate with Zn concentrations across mare basalts, and the new CE-5 data plot on this trend.” instead of “correlated”.

Line 159: I would say “unlikely to reflect lunar mantle heterogeneity, nor be related to the global scale devolatilization process linked to the giant impact”.

Line 161: Perhaps include “localized processes, overprinting the initially homogeneous isotopically heavy lunar signature, including…”

Line 162: I don’t think this final sentence is necessary – it’s all said above.

Fig 3 caption – should be “Zinc and Ni isotope compositions”

Line 204: Consider putting a colon between “regolith” and “the” instead of a full stop.

Line 230: word missing “of” between immaturity and CE-5

Line 243: Figure 4 shows this correlation – perhaps cite it here.

Line 366: there does seem to be a small but resolvable heavy shift in Zn isotope composition, as well as a drop in [Zn], in the very top layer of the CE-5 regolith profile; even though it is clear that this does not extend deeply in the profile, it might be stated that this might reflect a small degree of gardening/weathering (and subsequent loss of isotopically light Zn), but it of course still implies that the starting material for the regolith was already enriched in light Zn relative to the basalts. This small degree in the very top layer I think adds credibility to the authors’ thesis, as there is still evidence for space weathering in the profile.

Line 375: perhaps add “with their range of Zn isotope compositions generated by localised processes during sample petrogenesis”.

Line 382: suggest adding “which can also explain the range of d66Zn compositions in the CE-5 basalts.” at the end of the sentence.

Line 424: replace “final” with “analysed”

Line 436: “acid intensity” is a weird phrase in this context; consider rewriting to “Each sample and standard was bracketed by analyses of the running acid, and these were used to correct for on-peak acid blanks.”

Response to Reviewers

Note: The line numbers cited in the comments are those in the original submission, while the line numbers cited in the responses are those in the revision. All the changes in the revised manuscript are highlighted in blue.

Reviewer #1 (Remarks to the Author):

The manuscript reports Zn isotope compositions of basalts and soils returned by the Chang'e-5 mission. The CE-5 basalts exhibit similar Zn isotope compositions to Apollo basalts, supporting a link to the global evaporation event associated with the Moon's formation. By contrast, the CE-5 soils are distinct from Apollo soils and interpreted to primarily reflect recondensation of isotopically light Zn from volcanic degassing, with only limited effects from space weathering.

Overall, the study is well executed and expands the existing dataset on lunar Zn isotope compositions. I recommend publication after the authors address the minor comments outlined below.

We sincerely thank Reviewer #1 for the thoughtful and constructive comments that helped us improve the clarity and contextual balance of the manuscript. We have revised the text throughout to better articulate the connection between the Chang'e-5 and Apollo datasets, provide complete value ranges for $\delta^{66}Zn$, I_s/FeO, and Ni, and clarify our interpretation of the CE-5 soils as representing the low-maturity endmember of lunar regolith. We have also corrected typographical issues, added missing references, clarified the section structure by combining overlapping discussions, and expanded Figure 1 to include the new histogram requested by Reviewer #2 for consistency. These changes have improved both the precision and readability of the paper. We greatly appreciate the reviewer's detailed attention, which has strengthened the manuscript.

Lines 27-34: missing references for these three statements.

Reply 1: Thank you for your comment. We have rephrased these three sentences to make them more concise and cited with the appropriate references (Hartmann and Davis, 1975; Wood, 1975; Cameron and Ward, 1976; Canup and Asphaug, 2001; Davis, 2006; Canup, 2012; Ćuk and Stewart, 2012; Tartèse, et al., 2013; Day and Moynier, 2014; Kato, et al., 2015; McCubbin, et al., 2015; Barnes, et al., 2016; Dhaliwal, et al., 2018; Barnes, et al., 2019). (**Line 28-34**)
The added references are listed in both the revised manuscript and this response letter in the end.

Lines 47-50: this statement is a bit hard to follow and would benefit from rephrasing. Typo in line 48 (potentially difference).

Reply 2: Thank you for your comment. Our point was that the lunar magma ocean (LMO) process might lead to varying isotopic fractionation, underscoring the necessity to investigate the MVEs in younger basalts. We have rephrased the sentence as: " Subsequent modeling of lunar magma ocean (LMO) crystallization and degassing has been motivated by the compositional differences between mare and KREEP basalts, which represent chemically distinct LMO cumulates. " (**Line 45-48**).

Lines 50-52: again, this needs rephrasing. Typos: exhibits, factor, inspire.

Reply 3: Thank you for your comment. The sentence has been rephrased as follows (**Lines 48-50**): "However, the nearly uniform MVE isotopic fractionation across mare basalts from diverse mantle sources suggests that the bulk lunar interior was already homogeneously volatile-depleted early in the Moon’s evolution."

Lines 94-96: needs some rewording.

Reply 4: The sentence has been revised as follows (**Lines 93-95**): "However, the shorter exposure age of the CE-5 samples relative to Apollo samples indicates that it has experienced substantially less meteoritic bombardment and solar-wind irradiation."

Source Region inferred from CE-5 Basalts

The first paragraph is confusing as written. Line 127 states that Apollo high-Ti samples have higher δ^{66}Zn than CE-5 samples, while lines 135–136 describe says the δ^{66}Zn of CE-5 basalts as comparable to Apollo mare basalts. As presented, these statements seem at odds, and it is unclear what point the authors are aiming to make. I recommend rephrasing this paragraph for clarity.

Reply 5: Thank you for your comment. We do agree that CE-5 low-Ti basaltic clasts exhibit δ^{66}Zn values ranging from 0.63 ‰ to 1.55 ‰, overlapping with the median of Apollo mare basalts and basaltic lunar meteorites. The sentence is rephrased as follows: "Three CE-5 low-Ti basaltic clasts exhibit δ^{66}Zn values of 0.63 ‰ to 1.55 ‰ (Fig. 1 and Table 2), overlapping with the median of Apollo mare basalts and basaltic lunar meteorites. "(**Line 126-128**)

Lines 129-131: Ref. 43 only provides the compositions of CE-5 basalts. Please provide refs. for Apollo samples for comparison to support this statement. At least for K, for example.

Reply 6: Thank you for your comment. The references for the abundance of Zn and K for Apollo samples have been added (Dai, et al., 2025). (**Line 131**)

Line 143: I assume the Zn concentration here corresponds to BSE, not chondrite.

Reply 7: Yes, the term "chondrite" has been changed to "BSE". (**Line 143**)

Low maturity of CE-5 soils

While I agree that CE-5 soils are overall distinct, they do overlap substantially with Apollo soils for several of the parameters considered. The current text implies a sharp distinction between them and would benefit from a more nuanced discussion. In addition, as with the CE-5 samples, the full range of values for the Apollo samples should be provided throughout this section, not just the highest value. This applies to delta66Zn (line 180), Is/FeO (line 191), and Ni (line 210).

Reply 8: Thank you for this helpful suggestion. Recent analyses of Apollo 17 drive tube 73001/2 samples (Broussard, et al., 2025a; Broussard, et al., 2025b), together with previous studies, show that Apollo soils span a wide maturity spectrum, and the CE-5 soils are more comparable to the less mature endmember rather than being fundamentally distinct. Following your advice, we have added the corresponding Apollo ranges for δ^{66}Zn (δ^{66}Zn = 1.60‰ to 6.39‰, **Line 184-185**), I_s/FeO (4.6 to 106, **Line 198-199**), and Ni content (80~700 μg/g; **Line 218**) to the relevant sections. We also plotted Ni concentrations of the CE-5 soil samples against their calculated I_s/FeO values (Fig. R1). The CE-5 soils fall at the lower end of the Apollo trends, consistent with their overall low maturity. The manuscript has been revised accordingly to reflect this context.

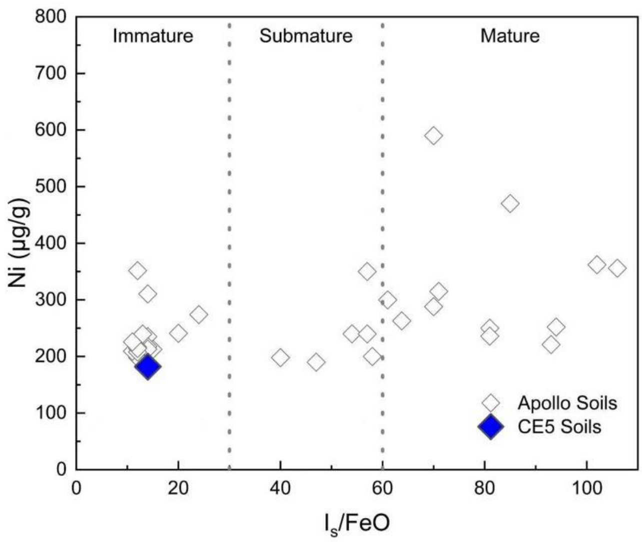

Fig. R1. I_s/FeO values and Ni concentration of Apollo and CE-5 soils. The data of Apollo soils are from (Morris, 1976; Meyer, 2012; Li, et al., 2025; Neuman, et al., 2025; Wang, et al., 2025)

Lines 190-191: According to the refs. cited here, a number of Apollo soils are also immature, with Is/FeO values as low as 4.6, well below the 20-80 range that is currently cited. If there's a reason why these were excluded from the comparison, that should be clarified.

Reply 9: Thank you for your comment. We now include the full range of I_s/FeO values for the Apollo samples (4.6 to 106, **Line 198-199**), and the CE-5 samples plot within the low-maturity portion of this range.

Lines 195-196: Missing ref. for the Fe0/FeO values. Are they the same for all samples?

Reply 10: Thank you for your advice. We now cite (Qian, et al., 2024) for the I_s/FeO estimates of the CE-5 soil samples (**Line 199**). As all CE-5 soils were collected from the same landing site and share similar physical characteristics (e.g., mineralogy, grain size, low Ni concentrations) (Zhao, et al., 2023; Li, et al., 2025), the entire CE-5 soil suite is most appropriately classified as immature.

Lines 208–210: Several Apollo soils (e.g., 12032, 61221, 73131, 70311, 71041, 15401, 15601…) have Ni values within the range reported for the CE-5 samples. Please provide the full range of Apollo values and clarify the comparison. Missing ref. for CE-5 range.

Reply 10: Thank you for your comment. The full ranges of Ni content in Apollo soils as well as CE-5 soils are provided (80~700 μg/g for Apollo soils, **Line 218**; 96~186 μg/g for CE-5 soils, **Line 217**) (Meyer, 2012; Li, et al., 2025; Neuman, et al., 2025). We have revised the discussion in this section and have added a crucial sentence to bridge the concepts of maturity and Ni content: " In Apollo lunar soils, Ni content shows a roughly positive correlation with the I_s/FeO maturity index. Consistent with this relationship, the Ni concentrations of CE-5 soils (96~186 μg/g) lie at the lower end of the range observed for typical Apollo soil (80~700 μg/g), suggesting that the CE-5 regolith has experienced a relatively small cumulative meteoritic flux and fewer micrometeorite impacts." in **Line 215-220**.
The most recent publications related to the maturity of CE-5 and Apollo soils are also cited in the revised manuscript in **Line 208-209** (Chen et al., 2025) and **Line 184** (and updated Fig. 3A) (Broussard et al., 2025)

It is unclear why the sections "Low maturity of CE-5 soils" and "Trivial contribution from micrometeorite impacts on Zn isotopic compositions in CE-5 soils" are separated, as the discussions substantially overlap. I suggest combining them, since both address the role of space weathering on the Zn isotope compositions. That would make it easier for readers to follow, and better tie the discussion back to the conclusions in the abstract.

Reply 11: Thank you for your advice. These two sections are combined as "Trivial contribution from space weathering on Zn isotopic compositions in CE-5 soils".

Lines 218-221: please rephrase.

Reply 12: Thank you for your advice. The sentence has been revised to be clean and direct as follows (**Lines 226-230**): " In contrast, CE-5 soils are characterized by low maturity, and thus limited isotopic modification is expected. Consistent with this, recent measurements show that CE-5 soils have average δ^{30}Si values ~0.1‰ lower than those of Chang'e-6 soils, indicating comparatively mild space-weathering effects at the CE-5 landing site. "

Lines 295-297: missing ref.

Reply 13: Thank you for your advice. We cited (Ma and Liu, 2019a; Ma and Liu, 2019b) here to show the presence of a zinc-rich mineral on the surface of lunar orange glass derived from volcanic vapor condensates on the Moon (**Line 303-304**).

Line 401: the total Zn of the samples is not provided in Table 2.

Reply 14: The total Zn of the samples is now provided in Table 2.

Line 402: The blank is more than 10% of the total Zn for one of the samples, and a considerable fraction for the others. Please address how this may have influenced the results.

Reply 15: Thank you for your comment. The total procedural blank for Zn was 3–5 ng, which would correspond to a shift of approximately 0.01–0.2‰ in $\delta^{66}Zn$ assuming terrestrial composition ($\delta^{66}Zn_{BSE}$=0.28±0.05) (Chen, et al., 2013). This potential shift is significantly smaller than the isotopic difference observed between the CE-5 lunar basalts (~+1.6‰ for CE5-062 with the lowest amount of Zn) and the BSE. Moreover, the Zn abundances in the CE-5 lunar soils (64–392 ng) are substantially higher than the blank contribution, indicating that blank correction has a negligible effect on the final $\delta^{66}Zn$ values for these samples. (**Line 418-425**)

We also clarified in the text that the background intensity from the acid was substracted from the signal intensities to eliminate the influence from the blank. **(Line 435-438)**

Reviewer #2 (Remarks to the Author):

Review of "Zinc isotopic insights into lunar magmatic outgassing and surface processing from Chang'e-5"

Thank you for the opportunity to review this work. The new study has analysed the Zn isotope composition of the sample return material from the Chang'e-5 lunar mission; in particular lunar low-Ti basalts and regolith from the rover site. This is of course of high interest, given the uniqueness of the sample set, as well as the previous significant insights from Zn isotope studies of lunar material.

I read the work with interest, and I broadly think this is a great study. The data seem excellent, and the work is neatly presented with broadly useful figures. The basalt data are interpreted within, and agree with, the framework and findings drawn from the Zn isotope studies of Apollo samples – to whit, the Moon's Zn isotope composition was wholesale fractionated during a moon-scale devolatilization event potentially associated with the giant impact. The novelty of the work (apart from, of course, the uniqueness of the samples) comes from the interpretation of the lunar regolith data, which are used to imply transient but potentially important volcanic outgassing which may have effected parts of the lunar landscape (and, I would argue, the outgassing lavas forming on the lunar surface).

I have only a few comments that would be easily addressed in revisions to the text. These are detailed below; most are minor, but I do have questions about how the range of CE5 (and Apollo) Zn isotope compositions could be generated if a single stage devolatilization event pre- or during magma ocean stage is the reason for an isotopically heavy Moon. I further suggest that the proposed degassing that has generated the isotopically light material in the CE5 regolith samples could also be used to explain the range of Zn isotope composition in the basalts.

Thanks again,

Paul Savage

We are very grateful to Dr. Paul Savage for the encouraging assessment and insightful suggestions that substantially enhanced the manuscript. In response, we clarified the distinction between large-scale lunar volatile loss during the Moon-forming event and later localized processes such as impact-induced or volcanic outgassing, which better explains the observed $\delta^{66}Zn$ range in the CE-5 basalts and soils. We added quantitative modeling showing that small additions of condensed $ZnCl_2$ vapor can reproduce the lighter isotopic compositions, revised Figure 4 accordingly, and expanded discussion of site maturity and regolith gardening. Numerous textual edits (e.g., clarification of equations, figure references, and typographical corrections) were implemented following the reviewer's detailed notes. We sincerely thank the reviewer for these constructive comments and their positive evaluation of our work.

I'm not sure how statistically accurate it is to state that the Apollo low-Ti basalts have a "higher" Zn isotope composition than the CE5 samples; the range from the Apollo samples is a lot wider, but the samples seem to plot in the higher side of the range of both low and high Ti Apollo samples. With n = 3 it's highly possible there could be basalt unsampled by CE5 that shows this range. It would be more accurate to describe the data as plotting near the median of Apollo samples; I think also that it would be worth plotting a histogram of the Apollo and CE5 data to show this in more detail. This could be Figure 1a, for instance, and the current figure 1 could be Fig 1b.

Reply 16: Thank you for your advice. A histogram of the Apollo and CE-5 data is added in Fig. 1B, showing that $\delta^{66}Zn$ values of CE-5 basalts are consistent with the range of $\delta^{66}Zn$ for Apollo mare basalts. We agree that CE-5 low-Ti basaltic clasts exhibit $\delta^{66}Zn$ values of 0.63‰ to 1.55‰ (Fig. 1 and Table 2), overlapping with the median of Apollo mare basalts and basaltic lunar meteorite.

I am somewhat unconvinced that the range of CE5 Zn isotope data in the basalts is demonstrating that they have been ONLY fractionated by wholescale volatile Zn depletion of the bulk silicate Moon, which I think is what the authors are arguing for. The authors state they find no evidence for Zn isotope fractionation via "later-stage magmatic activities and associated degassing…". (this directly contradicts the findings from the regolith samples later on in the work!). My main issue is that there is a relatively large range of Zn isotope compositions defined by the CE5 basalts, ranging over almost 1 per mil. If there is limited Zn isotope fractionation associated with later-stage magmatic activities and associated degassing, this implies that the lunar mantle has an extremely heterogeneous Zn isotope composition. There is no explanation as to how this could be generated – I am here assuming the authors agree that the lunar mantle rocks cooled from a magma ocean which would, you would imagine, be initially homogeneous with respect to Zn isotopes. I do agree that the whole CE5 suite is isotopically heavy compared to Earth, which is canonically interpreted to mean whole Moon degassing at an early stage, but there is additional complexity in the CE5 (and Apollo) data which does not, I think, fit the single stage degassing model, as in my mind this should affect the whole lunar mantle broadly equally. The authors later in the piece point to volcanic outgassing as a way to generate the isotopically light lunar soils in the region of the CE5 basalts. Could this not explain the range of Zn isotope compositions in the basalts?

Reply 17: Thank you for your constructive comment. We agree that the Zn isotope record in the lunar samples reflects contributions from multiple stages of processing. Following your suggestion, we have revised the manuscript to more clearly distinguish the effects of large-scale processes associated with lunar formation from later localized surface processes. We also now quantify the role of Zn-rich vapor in producing the lighter Zn isotopic signatures observed in some CE-5 basalts. Incorporation of approximately 5 ppm condensed $ZnCl_2$ with $\delta^{66}Zn \approx 0‰$ can reproduce the composition of CE5-052, supporting the interpretation that mixing with outgassed Zn-rich vapor can account for the observed range of Zn isotopic values in the CE-5 basalts. The specific revisions are summarized below:

1) We have restructured the sentence "Consequently, magmatic differentiation in the CE-5 basalts causes only minor Zn enrichment and essentially unchanged isotopic variation, comparable to that of Apollo mare basalts. Thus, the observed Zn isotopic fractionation is mainly attributed to a large-scale, high-temperature evaporation process that preferentially removed lower MVE isotopes, likely during the Moon-forming giant impact and subsequent global melting, and remains the most plausible primary cause consistent with Apollo basalt signatures. " in **Lines 134-140**.
2) We have added a new discussion on localized processes: " The ~1‰ range in $\delta^{66}Zn$ among CE-5 basalts, which is also seen in Apollo basalts and lunar meteorites but absent in terrestrial analogues, is therefore unlikely to reflect global volatile loss during the Moon-forming giant impact. Instead, the relatively large spread in Zn isotopic compositions in both CE-5 and Apollo mare basalts likely reflects later, localized processes, including impact-induced evaporation/condensation and late-stage outgassing." in **Line 157-162**.
3) We have added the following in **Lines 162-164** to clarify the limited role of secondary processes: "These secondary modifications, however, only affect sample-scale isotopic signatures and do not substantially alter the overall Zn isotopic composition of lunar mare basalts."
4) In the section of "Mild volcanic outgassing events inferred from Zn isotopic compositions in CE-5 lunar soils", we recalculated the isotopic composition of $ZnCl_2$ vapor to reproduce $\delta^{66}Zn$ in CE-5 soils as well as the CE-5 basalt displaying lighter isotopic signatures (CE5-052, $\delta^{66}Zn$=0.63±0.05‰). As shown in the updated **Fig. 4 and Line 314-324**, the addition of 5 ppm condensed $ZnCl_2$ with $\delta^{66}Zn$~0‰ can explain Zn composition in CE5-052. The estimated range of $\delta^{66}Zn$ in the condensed $ZnCl_2$ vapor is 0‰~ –3‰. To achieving a $ZnCl_2$ vapor with $\delta^{66}Zn$ in the 0‰ to –3‰ from the homogenous mantle reservoir ($\delta^{66}Zn$~+1‰) would require a vapor saturation (*S*) on the order of ~45–85% (**Line 335-338**).
5) Since we do observe the contribution from outgassed Zn vapor in CE-5 regolith, in

Line 367-370, we add the discussion about possibility of overprinting the Zn isotopic composition of the lunar basalts from condensed outgassed vapor: "Furthermore, interaction with condensed outgassed vapor may have overprinted the original Zn isotopic composition of the lunar basalts, contributing to the variation in δ^{66}Zn observed in CE-5 and Apollo basalts, particularly in samples displaying lighter isotopic signatures. "

We agree that outgassed Zn vapor can influence the Zn isotopic composition of basaltic clasts. However, because basaltic clasts have substantially smaller specific surface areas than lunar regolith, the contribution from Zn-rich vapor is expected to be much less effective at overprinting their Zn isotopic compositions, relative to the regolith.

I enjoyed the discussion about the relative maturity of the Apollo vs CE5 regolith. Could the authors perhaps discuss why one lunar site would experience less gardening than another? Is there a geographic reason for this?

Reply 18: Thank you for your advice. Although our study has not undertaken a detailed geological investigation of the Chang'e-5 sampling site, the findings of other scholars regarding its geology indicate that " The immaturity CE-5 soils are most plausibly linked to their relatively young surface exposure ages compared to Apollo sites, which reduced the extent of stratigraphic overturn and regolith gardening" (**Line 230-232**).

• Line 37: Not all mass dependent stable isotope systems show lunar material to be isotopically heavy relative to Earth – cf. Sossi et al 2018 PNAS for Cr isotopes, and Wang et al 2019 Nature Geoscience for Sn isotopes.

Reply 19: Thank you for your advice. We have restructured the sentence "Most MVEs display heavier isotopic compositions relative to Earth, consistent with fractionation during volatile depletion except redox-sensitive elements (e.g., Cr and Sn). All these isotopic trends collectively point to large-scale volatile loss." in **Line 36-39**.

• Line 50: In think "inspire" here is supposed to be "in spite"? In any case, this sentence could do with a revisit.

Reply 20: Thank you for your advice. The sentence has been revised as follows (**Lines 48-50**): "However, the nearly uniform MVE isotopic fractionation across mare basalts from diverse mantle sources suggests that the bulk lunar interior was already homogeneously volatile-depleted early in the Moon's evolution."

• Line 64: I'm not sure what is meant by this sentence – how is something buried downwards on the Moon's surface? Is this saying that ongoing meteorite gardening pushes the space weathering front deeper into the regolith?

Reply 21: Thank you for your advice. This sentence is rewritten in **Lines 61-63** as "Regolith gardening progressively reworked the surface lunar soil through sustained meteorite and micrometeorite bombardment."

• Line 138: "lighter", not "lower"

Reply 21: Thank you for your advice. It has been changed to "lighter" in **Line 138**.

• Line 147: I'm unclear as to what this equation is modelling – could the authors point to a paper which explains its utility and/or include a derivation of it in their supplementary material? I am guessing that Si is Zn vapor saturation but again this isn't clear.

Reply 21: Thank you for your advice. This equation is from (Dauphas, et al., 2015; Nie and Dauphas, 2019). We have cited these references in the text. (**Line 147**)

• Line 173: Perhaps refer to Fig 3 in this paragraph.

Reply 22: Thank you for your advice. We have swapped the panel order in Figure 3. We have introduced the reference to Figure 3 earlier in **Line 183**.

• Line 221: There is a repetition here of the statement "relatively mild space-weathering modification at the CE-5 site".

Reply 23: Thank you for your advice. The sentence has been revised as follows (**Lines 226-230**): "In contrast, CE-5 soils are characterized by low maturity, and thus limited isotopic modification is expected. Consistent with this, recent measurements show that CE-5 soils have average $\delta^{30}Si$ values ~0.1‰ lower than those of Chang'e-6 soils, indicating comparatively mild space-weathering effects at the CE-5 landing site".

• Line 229: I think "effect" would be a better word than "contribution" here, as the latter word implies mixing with, whereas the previous discussion confirms that micrometeorite gardening can lead to enrichment in heavier isotopes by volatile loss of MVE elements.

Reply 23: Thank you for your advice. The sentence has been rewritten as follows: " In Apollo drill cores, progressively lighter isotopic compositions of MVEs are observed with increasing depth, reflecting the decreasing influence of micrometeorite bombardment." (**Line 234-236**)

• Line 231: Is it correct to describe deeper regolith as more "mature"? This is confusing terminology I think as more mature soils tend to be more chemically depleted so are mostly the shallowest. Deeper soils are closer in composition to the bedrock.

Reply 24: Thank you for your comment. This sentence is rewritten as "In Apollo drill cores, progressively lighter isotopic compositions of MVEs are observed with increasing depth, reflecting the decreasing influence of micrometeorite bombardment. A similar trend is present in the CE-5 drill core: both $\delta^{60}Ni$ and soil maturity decrease systematically with depth, indicating that space-weathering processes exert primary control on Ni isotopic variations in the surface regolith." (**Line 234-239**).

• Line 279: Here I would include a statement that the authors will assess the effect of volcanic outgassing on lunar soils in the next section.

Reply 25: Thank you for your advice. This sentence is rewritten as "The combination of isotopically light Zn and elevated Zn abundances requires an additional Zn source capable of producing strongly negative δ^{66}Zn, such as Zn-rich condensates derived from volcanic degassing. The influence of such volcanic contributions is evaluated in the following section." (**Line 283-286**)

• Line 345: Redefine "PKT"

Reply 26: Thank you for your advice. The definition of PKT (Procellarum KREEP Terrane) has been added in **Line 356**.

References Added in the Revised Manuscript

The following references are newly cited in the revised manuscript.

(Hartmann and Davis, 1975; Wood, 1975; Cameron and Ward, 1976; Ringwood and Kesson, 1977; Wolf, et al., 1980; O'Neill, 1991; Jones and Palme, 2000; Canup and Asphaug, 2001; Davis, 2006; Canup, 2012; Ćuk and Stewart, 2012; Tartèse, et al., 2013; Dauphas, et al., 2015; McCubbin, et al., 2015; Barnes, et al., 2016; Dhaliwal, et al., 2018; Sossi, et al., 2018; Barnes, et al., 2019; Gleißner and Becker, 2019; Ma and Liu, 2019a; Ma and Liu, 2019b; Broussard, et al., 2025b; Chen, et al., 2025; Neuman, et al., 2025)

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Response to Reviewers

We sincerely thank the Editor and Reviewer #2 (Dr. Paul Savage) for their continued time, careful evaluation, and constructive feedback on our revised manuscript. We are particularly grateful for the positive assessment of the scientific quality of the work and for the thoughtful and detailed suggestions provided in this second round of review, which have helped further improve the clarity and precision of the manuscript. We have carefully considered each comment and revised the text accordingly. All changes are indicated in the revised manuscript, and detailed point-by-point responses are provided below.

Reviewer #1 (Remarks to the Author):
The authors have satisfactorily addressed the points raised in the previous round of reviews. The revisions have improved the clarity and overall quality of the manuscript. I recommend it for publication without further revision.

Reviewer #2 (Remarks to the Author):
Review of resubmission of "Zinc Isotopic Insights into Lunar Magmatic Outgassing and Surface Processing from Chang'e-5".

Thankyou for the opportunity to review the new draft of this contribution. I was positive about the paper in my initial review; my main comments focussed on clarifying/extending some of the arguments about how the range of Zn isotope compositions in lunar basalts including the CE5 samples might be generated, and some presentational improvements. The revised submission has been significantly improved, with the authors including some revised/new modelling to explain the range of isotope compositions recorded in their samples; I have a couple of suggestions which I think might clarify some of the new text additions, but otherwise I would be happy to recommend this work for publication. I would also like to thank the authors for providing a conscientious rebuttal document and tracked-changes manuscript.

Congratulations on an excellent piece of science,

Paul Savage

St Andrews, November 2025

Line 26: depletion relative to bulk solar system compositions.
Reply 1: Thank you for your comment. We have rephrased the sentence as "The Earth–Moon system exhibits a pronounced depletion in volatile elements relative to bulk solar system compositions, with the Moon containing significantly lower abundances of elements compared to Earth" (Line 26-28)

Line 132: "…such differentiation should exert minimal influence on both the Zn concentration and isotope composition, given the small equilibrium fractionation factor and partition coefficients close to unity between minerals and mafic melt during crystalisation"
Reply 2: The sentence has been revised accordingly. (Line 131-134)

Line 134: This new sentence starting "Consequently…" could do with a rewrite; perhaps: "Consequently, magmatic differentiation during the formation of the CE-5 basalts should not significantly shift their isotopic composition away from their source, and as such these materials should be comparable to the Apollo mare basalt dataset."
Reply 3: The sentence has been revised accordingly. (Line 134-137)

Line 136: I would rewrite this as follows: "Thus, the observed widescale enrichment in heavy Zn in the CE-5 basalts relative to BSE can, as for the Apollo basalts, be mainly attributed to a lunar-scale, high-temperature evaporation process, likely related to the Moon-forming giant impact."
Reply 4: The sentence has been revised accordingly. (Line 137-140)

Line 139: The term "subsequent global melting" is a little vague here – it could be taken to mean an event subsequent to the initial magma ocean stage of the Moon (i.e. a remelting event).
Reply 5: We have revised "subsequent global melting" to "subsequent global magma ocean processes". (Line 141)

Line 141: "broadly correlate with Zn concentrations across mare basalts, and the new CE-5 data plot on this trend." instead of "correlated".
Reply 6: The sentence has been revised accordingly. (Line 142-143)

Line 159: I would say "unlikely to reflect lunar mantle heterogeneity, nor be related to the global scale devolatilization process linked to the giant impact".
Reply 7: The sentence has been revised accordingly. (Line 160-161)

Line 161: Perhaps include "localized processes, overprinting the initially homogeneous isotopically heavy lunar signature, including…"
Reply 8: The sentence has been revised accordingly. (Line 163-164)

Line 162: I don't think this final sentence is necessary – it's all said above.
Reply 9: The sentence has been revised accordingly.

Fig 3 caption – should be "Zinc and Ni isotope compositions"
Reply 10: The sentence has been revised accordingly.

Line 204: Consider putting a colon between "regolith" and "the" instead of a full stop.
Reply 11: A colon has been added between "regolith" and "the". (Line 192)

Line 230: word missing “of” between immaturity and CE-5
Reply 12: We have added “of” accordingly. (Line 218)

Line 243: Figure 4 shows this correlation – perhaps cite it here.
Reply 13: We have cited Fig. 4 at Line 231 accordingly.

Line 366: there does seem to be a small but resolvable heavy shift in Zn isotope composition, as well as a drop in [Zn], in the very top layer of the CE-5 regolith profile; even though it is clear that this does not extend deeply in the profile, it might be stated that this might reflect a small degree of gardening/weathering (and subsequent loss of isotopically light Zn), but it of course still implies that the starting material for the regolith was already enriched in light Zn relative to the basalts. This small degree in the very top layer I think adds credibility to the authors’ thesis, as there is still evidence for space weathering in the profile.
Reply 14: We have added a new discussion as “Notably, the very topmost regolith layer shows a small but resolvable enrichment in heavy Zn isotopes accompanied by a decrease in Zn abundance, consistent with limited surface gardening and preferential loss of isotopically light Zn during space weathering. The confinement of this effect to the uppermost layer indicates that, aside from limited near-surface modification, the underlying CE-5 regolith retains an isotopically light Zn signature relative to the basalts.” (Line 239-244)

Line 375: perhaps add “with their range of Zn isotope compositions generated by localised processes during sample petrogenesis”.
Reply 15: The sentence has been revised accordingly. (Line 359-360)

Line 382: suggest adding “which can also explain the range of d66Zn compositions in the CE-5 basalts.” at the end of the sentence.
Reply 16: The sentence has been revised accordingly. (Line 368-369)

Line 424: replace “final” with “analysed”
Reply 17: The sentence has been revised accordingly. (Line 411)

Line 436: “acid intensity” is a weird phrase in this context; consider rewriting to “Each sample and standard was bracketed by analyses of the running acid, and these were used to correct for on-peak acid blanks.”
Reply 18: The sentence has been revised accordingly. (Line 423-424)