nature portfolio

Peer Review File

Phasing and climate forcing potential of the ‘Millennium Eruption’ of Mt. Baekdu

Corresponding Author: Professor Jinho Ahn

Attachments originally supplied by the reviewers can be found at the end of this file, in order by reviewer number and revision.

Version 0:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Ahn,

Your manuscript titled "Phasing and climatic impact of the ‘Millennium Eruption’ of Mt. Baekdu" 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.

Important: The response to reviewers must not include any figures, tables or graphs. If you wish to respond to the reviewer reports with additional data in one of these formats, please add them to the main article or Supplementary Information, and refer to them in the rebuttal. Due to current technical limitations, any figures, tables, or graphs embedded in your rebuttal will not be included in the peer review file, if published.

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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** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

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,

Domenico M. Doronzo, PhD

Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-6866-8870

Carolina Ortiz Guerrero, PhD
Associate Editor
Communications Earth & Environment

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- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The main contribution of this paper is the estimation of the time elapsed between the two phases of the Millennium eruption from the Paektu (Changbaishan) volcano. By combining various methods, the authors conclude that the first rhyolitic eruption plume was followed by the trachytic one after one to two months, with a 98% probability that it occurred within 8 weeks. These methods include the analysis of an ice core from Greenland (e.g., tephra chemical analyses, sulfur concentrations, microparticles, etc.) to find any signals recorded from the Millennium eruption (e.g., concentration spikes). Using statistical methods such as a snow accumulation model, they estimated the time between these spikes, and therefore, between the eruption phases of the Millennium eruption. Additionally, with a model of ash distribution and wind trajectories, they inferred that the Millennium ash took 1 to 3 weeks to reach the NGRIP core site.

Another notable contribution of this work is the low climatic impact of the Millennium eruption. The authors conducted several sulfur isotope analyses and corrections to determine that not much SO_2 penetrated the upper layers of the stratosphere, thus limiting its transportation and atmospheric lifetime. However, they should consider more the physical properties of the Millennium eruption, with its two ~30-km high plumes (Costa et al., 2024, commsenv) when interpreting why the Millennium sulfate deposition (~9 kg/km^2) was so low compared to other recent and larger eruptions like Tambora (40 kg/km^2 by a column of 45 km in height). The 15 km difference in column height could explain why Tambora had a much greater climatic impact than the Millennium eruption.

In my opinion, this paper makes a significant contribution to the knowledge of volcanic systems and climatology in general, providing novel insights into the Millennium eruption. The methodologies used to study the Millennium eruption and its impacts are exemplary and can be applied to similar studies (including the statistical analyses, though they could be presented in more detail). However, for better tephra characterization, I suggest the authors conduct trace element analyses in a future study because correlations based solely on major elements are sometimes not robust enough. Having more glass chemical information will provide better constraints (e.g., to confirm if the volcanic sources of T3 and T7 are Mt. Rainier or others). Additionally, it is better to analyze all the major elements with the same method/instrument (in this work one tephra composition was measured by EDS and all the others by WDS; all should be analyzed by EMP-WDS).
The interpretations and conclusions (which should be better summarized in a conclusion chapter between the results and methods chapters) are well-supported. Determining a hiatus of 1-2 months between the two phases of the Millennium eruption is of great interest to the volcanological community and society in general. Understanding that a volcanic eruption could have an extended duration even after a 2-month break will have important implications for risk management, forecasting, and decision-making.

Below, I suggest some minor edits in the text, tables, and figures:

1. The design of Fig. 1 could be improved by using plot symbols and colors with more contrast for better visibility. Moreover, I would add a small inset map in the top-right corner showing the locations of the volcano and the ice core (not as big as the entire Northern Hemisphere as in SM Fig. S1). Additionally, since you provide your original tephra chemical data in ED1, you should also include the Millennium eruption chemical data used to draw the compositional field (references 6, 9, 47, and 48) in a Supplementary Material (SM) table or an Extended Data (ED) table.
2. Suggestion for Fig. 2: instead of showing depth twice in panels a and b, you could add time in years to one of the x-coordinates.
3. The text must be checked to improve readability, including for non-experts. For example: a) when referring to methods throughout the body text, please specify which sub-chapter; b) avoid repetitive words (e.g., "blank" three times in a sentence, line 281) and improve the English in general (vocabulary, grammar, syntax, etc.); c) give more concise methodological descriptions (e.g., in the accumulation model sub-chapter, the word “snow” is not mentioned even once, or in the model of ash distribution and wind trajectories, the authors give the result directly but do not explain very well how they got it); d) ensure you define acronyms before using them; e) smooth the text of the “Tephra geochemistry chapter” when referencing SMs and EDs.
4. The reference list must be checked (some DOI links are not working).
5. ED1 to ED5 could be merged into a single Excel file with 5 different spreadsheets.

I recommend the publication of this paper after the mentioned minor revisions.
Sincerely,
Dr. Ivan Sunyé Puchol

Reviewer #2 (Remarks to the Author):

Review of “Phasing and climatic impact of the ‘Millennium Eruption’ of Mt. Baekdu

Attached also as a PDF.

Overall Impression

This study utilises high-resolution evidence from the NGRIP1 ice core to investigate the phasing and climate-forcing potential of the Millenium Eruption (ME) of Mt Baekdu. A combination of glaciochemical and tephra analysis are employed to good effect to place more robust constraints on the timing of the ME. The authors support a multiphase eruption scenario with an interval of one to two months between the two main eruption phases. Sulfur isotope analysis also reveals the absence of a sulfur mass-independent fractionation (S-MIF) signal for the ME, which is consistent with sulfate aerosol formation below the stratospheric ozone layer. The authors suggest that the lack of stratospheric sulfate may explain why, for such a large eruption, there is limited evidence for global or regional climatic impacts in tree ring or other proxy records.

The article is well-written and has a coherent narrative throughout, making it accessible to the broad readership that will most likely be interested in this study. The use of ultra-high resolution ice core evidence is novel but is also not overstretched by the authors, who do a good job of acknowledging the associated uncertainties in their methods, particularly in deriving their annual accumulation model. This is an exciting advancement in the application of high-resolution ice-core evidence to resolve the timing of a historical CE eruption at such a high temporal resolution. It will be exciting to see where a similar approach may be applied in the future with other CE eruptions. S-MIF analysis also contributes well to the study, resulting in a compelling argument for why the ME did not result in significant climate impacts despite its large magnitude and previous estimates of large sulfur emissions. Overall, I would recommend this article for publication in Communications Earth & Environment after minor revisions of the comments highlighted below.

Specific Comments

Title: Whilst the title does reflect the study's investigation into the phasing of the ME eruption, I wonder if it is a little misleading to say "climate impact". From reading the title, I initially anticipated the paper would include new proxy evidence or a lengthier discussion as to the climate impacts (globally or locally) following the eruption. Given the focus of the study (along with constraining the phasing) is on the sulfur injection height and transport of sulfate aerosol in the atmosphere, using "climate forcing" or "climate forcing potential" instead may more accurately reflect the work done in the paper.

Line 19: It would flow more easily here to say "resulted from one eruption episode or two separated by several months".

Line 56: Should be "estimations".

Line 59: Do either of the chronicles from Japan make reference to localised climatic impacts?

Figure 1: The pink-blue colour scheme is a little difficult to distinguish – particularly given T3 and T4 have similar marker shapes. Could a wider colour palette be used? I.e green square for T4.

On Figure 1a a vertical line next to T4-T5 could also be added to highlight the relevant depths for the ME.

There is also no reference to the context of the tephra shards in T3 and T7 in the figure caption or main body of Figure 1. Although they are not the focus of this study, it would still be helpful to clarify that they correspond to different eruptions and that you have attempted to identify credible source regions (as outlined in the supplementary).

Figure 2: The spikes are currently quite squished together on the figure which makes them difficult to distinguish, does T10 need to be included or could that be removed to space the spikes further apart?

Line 117: Assuming a similar accumulation trend between 946 AD and the 1990s seems to be one of the most significant uncertainties/assumptions made in deriving the seasonal accumulation model. Is there any indication that modern climate warming may have affected the accumulation rate in the 1990's? Andersen et al., 2006 highlight the influence on accumulation rates of changing climatic conditions during the little ice age for example.

Line 121: It would be helpful here to be more specific about the uncertainties you have accounted for. Saying "We have taken into account all uncertainties" without (even briefly) acknowledging what those uncertainties are is perplexing and feels somewhat awkward.

Line 160: UT/LS seems somewhat inconsistent with the other plume heights estimated based on tephra thickness and fall deposits (25-40 km). Whilst sulfur injection height may well be lower than these maximum ash heights, a discrepancy of 15-20 km between them seems quite high. Can these estimates be reconciled? It would be helpful to explicitly address this discrepancy given you mention these higher plume height estimates earlier in the paper.

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L Wainman, University of Leeds, June 2024.

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Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Professor Ahn,

Your revised manuscript titled "Phasing and climate forcing potential of the ‘Millennium Eruption’ of Mt. Baekdu" has now been seen by our two original 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 two weeks; please let us know if you need more time.

Best regards,

Carolina Ortiz Guerrero, Ph.D.
Associate Editor
Communications Earth & Environment

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I'm satisfied with the authors' response and strongly recommend this paper for publication.
Kind regards,
Ivan

Reviewer #2 (Remarks to the Author):

The authors have comprehensively responded to my suggestions and I am happy to recommend the paper for publication.

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Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

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Review of “Phasing and climatic impact of the ‘Millennium Eruption’ of Mt. Baekdu

Overall Impression

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L Wainman, University of Leeds, June 2024.

Dear reviewer #1 and #2,

We sincerely thank you for the helpful comments and for thoroughly reviewing the manuscript. The comments were very valuable and helpful for improving the manuscript and for making it clearer. We have included all the comments and responded to them in red and blue colors. The line numbers are from the tracked-changes version of the manuscript.

Response to reviewer #1

The main contribution of this paper is the estimation of the time elapsed between the two phases of the Millennium eruption from the Paektu (Changbaishan) volcano. By combining various methods, the authors conclude that the first rhyolitic eruption plume was followed by the trachytic one after one to two months, with a 98% probability that it occurred within 8 weeks. These methods include the analysis of an ice core from Greenland (e.g., tephra chemical analyses, sulfur concentrations, microparticles, etc.) to find any signals recorded from the Millennium eruption (e.g., concentration spikes). Using statistical methods such as a snow accumulation model, they estimated the time between these spikes, and therefore, between the eruption phases of the Millennium eruption. Additionally, with a model of ash distribution and wind trajectories, they inferred that the Millennium ash took 1 to 3 weeks to reach the NGRIP core site.

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- Line 189: We changed "This is much lower than that from the 1815 Tambora eruption (40 kg km^{-2})[5]". to "This is much lower than the 1815 CE Tambora eruption (40 kg km^{-2})[5], reflecting lower sulfur yield and lower sulfur injection height of the ME[20] compared with the Tambora eruption[34].".

In my opinion, this paper makes a significant contribution to the knowledge of volcanic systems and climatology in general, providing novel insights into the Millennium eruption. The methodologies used to study the

Millennium eruption and its impacts are exemplary and can be applied to similar studies (including the statistical analyses, though they could be presented in more detail). However, for better tephra characterization, I suggest the authors conduct trace element analyses in a future study because correlations based solely on major elements are sometimes not robust enough. Having more glass chemical information will provide better constraints (e.g., to confirm if the volcanic sources of T3 and T7 are Mt. Rainier or others). Additionally, it is better to analyze all the major elements with the same method/instrument (in this work one tephra composition was measured by EDS and all the others by WDS; all should be analyzed by EMP-WDS).

- We agree that trace element analyses and WDS measurements are needed. We will consider this in a future study. Thank you for pointing it out.

The interpretations and conclusions (which should be better summarized in a conclusion chapter between the results and methods chapters) are well-supported. Determining a hiatus of 1-2 months between the two phases of the Millennium eruption is of great interest to the volcanological community and society in general. Understanding that a volcanic eruption could have an extended duration even after a 2-month break will have important implications for risk management, forecasting, and decision-making.

- We added a conclusion chapter between the results and methods chapters. Thank you for the catch.

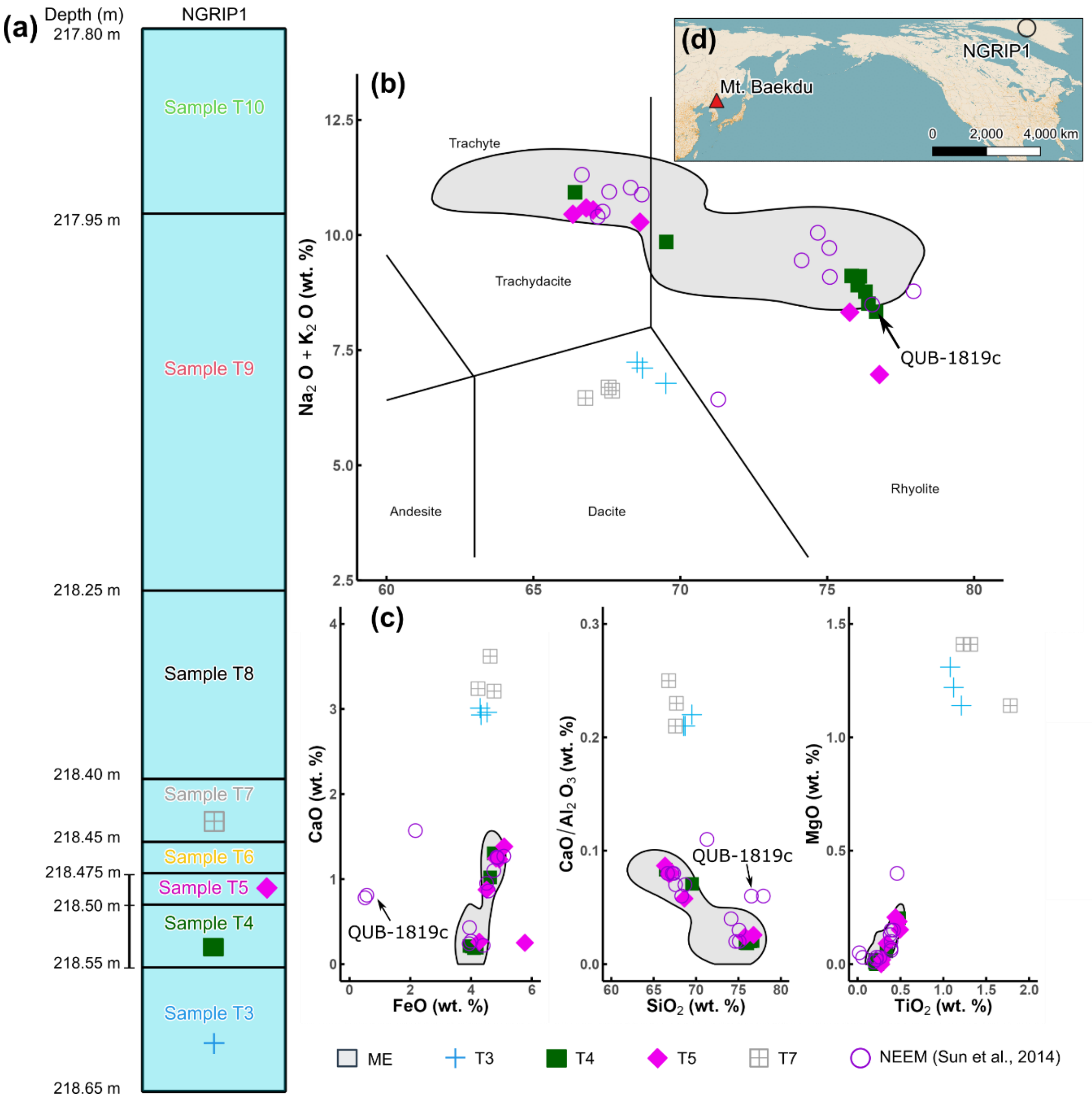
Line 212: We conducted high-resolution analyses of cryptotephras, glaciochemical records (e.g. water-soluble ion concentrations, conductivity, multiple sulfur isotopes), and insoluble particles within the NGRIP1 core from Greenland. We identified a transition from rhyolitic to trachytic tephra, associated with the ME, which was accompanied by discrete spikes in insoluble particle concentrations. Based on a simple annual snow accumulation model for northern Greenland, we estimated the interval between the insoluble particle spikes to be equivalent to one to two months. This suggests a hiatus between the rhyolitic and trachytic phases of the ME. However, our accumulation model is based on a relatively short data set and more accurate reconstructions of monthly accumulation in Greenland could lead to improvements. Our findings also revealed negligible sulfur mass-independent fractionation, near-synchronous deposition of insoluble particles and sulfate, and peak sulfur deposition occurring in winter. Based on these observations, it is likely that the limited climate forcing of the ME reflects short atmospheric lifetime of the volcanic sulfate aerosol veil. This refined picture of the timeline of the ME and sulfur injection heights can inform risk assessment at restless calderas worldwide.

Below, I suggest some minor edits in the text, tables, and figures:

1. The design of Fig. 1 could be improved by using plot symbols and colors with more contrast for better visibility. Moreover, I would add a small inset map in the top-right corner showing the locations of the volcano and the ice core (not as big as the entire Northern Hemisphere as in SM Fig. S1). Additionally, since you provide your original tephra chemical data in ED1, you should also include the Millennium eruption chemical data used to draw the compositional field (references 6, 9, 47, and 48) in a Supplementary Material (SM) table or an Extended Data (ED) table.

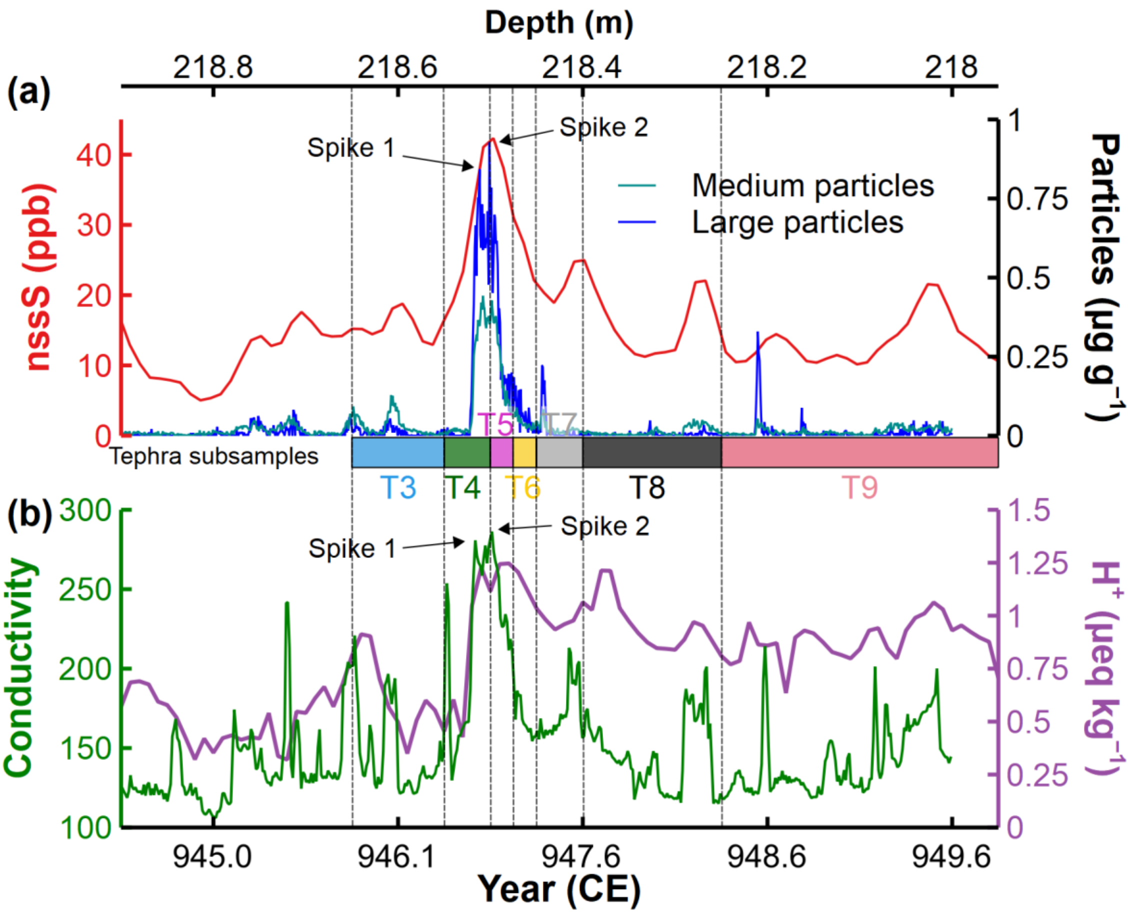
➢ We improved Fig. 1 as suggested.

➢ We added the Millennium eruption chemical data used to draw the compositional field in Extended Data 1.



2. Suggestion for Fig. 2: instead of showing depth twice in panels a and b, you could add time in years to one of the x-coordinates.

➢ We added time in years to the bottom x-coordinate.



3. The text must be checked to improve readability, including for non-experts. For example: a) when referring to methods throughout the body text, please specify which sub-chapter; b) avoid repetitive words (e.g., "blank" three times in a sentence, line 281) and improve the English in general (vocabulary, grammar, syntax, etc.); c) give more concise methodological descriptions (e.g., in the accumulation model sub-chapter, the word “snow” is not mentioned even once, or in the model of ash distribution and wind trajectories, the authors give the result directly but do not explain very well how they got it); d) ensure you define acronyms before using them; e) smooth the text of the “Tephra geochemistry chapter” when referencing SMs and EDs.

A)

- We specified the sub-chapter when referring to the methods as suggested.

B)

- We changed some of “ice core” to “ice-core”.
- Line 26: We changed “all are” to “are all”.
- Line 31: We changed “…is one of the largest eruptions of the Common Era (CE) with a Volcanic Explosivity Index (VEI) of 6 or 7, and is dated to late 946 CE[2–5].” to “…is dated to late 946 CE[2–5] and is one of the largest eruptions of the Common Era (CE) with a Volcanic Explosivity Index (VEI) of 6 or 7.”.
- Line 38: We changed “thunder like sounds” to “thunderous sounds”.
- Line 38: We changed “Both records may represent observations of the ME. Understanding whether such a hiatus exists and its duration if it did, is important for understanding of volcanic hazards at large caldera complexes and how volcanologists determine whether or not an eruption is ‘over’.” to “The first observation very likely represents the ME, while the second conceivably reflects the detonations of a subsequent phase. Resolving whether or not there was a hiatus, and estimating its duration if there was one, has significant implications for understanding of volcanic hazards at large caldera complexes, notably concerning the question of when to conclude that an eruption is ‘over’.”.
- Line 50: We changed “…migration, and therefore the total ME sulfur release would have been between 2 to 7 Tg, depending on the eruption magnitude[17]. These wide-ranging estimates of sulfur loading propagate

uncertainty into evaluations of the climate forcing potential of the ME." to "…migration, suggesting a total ME sulfur release of 2 to 7 Tg (allowing for uncertainty in the eruption magnitude)[17]. These wide-ranging estimates of sulfur loading propagate uncertainty into evaluations of any climate forcing arising from the ME.".

- Line 54: We changed "Any climate forcing associated with ME sulfur emissions would also be sensitive to plume height. However, estimations of plume height vary considerably." to "Another factor influencing climate forcing is plume height. In the case of the ME, estimations of this vary considerably.".

- Line 58: We changed "Nevertheless, the sulfur injection height could be much lower than the plume height depending on its mass eruption rate[21]. Ultimately, stratospheric sulfate is crucial for global climate impacts, and therefore new estimations of the sulfur injection height are critical to understanding the climatic implications of the ME." to "However, it is well established that the sulfur injection height can be much lower than the tephra (isopleth) derived plume height[21]. Resolving the altitude at which the ME sulfate aerosol dispersed is therefore also critical to understanding the climatic impacts of the ME.".

- Line 68: We changed "a section of the North Greenland Ice Core Project 1 (NGRIP1) core" to "a section of the NGRIP1 core of the North Greenland Ice Core Project".

- Line 124: We changed "Spikes 1 and 2 thus represent the two compositional phases of the ME." to "Accordingly, we conclude that Spikes 1 and 2 represent the two compositional phases of the ME.".

- Line 127: We changed "…snowfall through the year of 1991 to…" to "…snowfall recorded from 1991 to…".

- Line 142: We changed "…spike was then dated to…" to "…spike then dates to…".

- Line 143: We changed "…spikes was 31 ± 25 days…" to "…spikes is 31 ± 25 days…".

- Line 144: We changed "We estimated…" to "We estimate…".

- Line 150: We changed "Transport timescales for the two phases likely differed, reflecting disparate injection heights and meteorology but our analysis nevertheless supports the hiatus hypothesis rather than a single eruptive episode, given atmospheric residence times of one to two months for tephra shards are unlikely[33]. However, we note that the accumulation model was based on a relatively short data set and accumulation during the 940s would not be exactly the same as the 1990s. Hence, the estimated timings would be improved by more accurate constraints on the monthly accumulation history in northern Greenland." to "Transport timescales for the two phases may well have differed, reflecting different injection heights and meteorology but atmospheric residence times for tephra shards exceeding one to two months are unlikely[33]. Accordingly, our analysis does support the hiatus hypothesis rather than a single eruptive episode. More accurate constraints on the monthly accumulation history in northern Greenland could improve estimation of the time between microparticle peaks.".

- Line 166: We changed "exhibited" to "has".
- Line 166: We changed "Ice-core sulfate" to "On the other hand, ice-core sulfate".
- Line 168: We changed "lacked" to "lacks".
- Line 169: We changed "lacked" to "lack".
- Line 169: We changed "was" to "is".
- Line 173: We changed "This difference in residence time explains the delayed deposition of sulfate against microparticles in the polar regions of past stratospheric eruptions as recognized in high-resolution ice-core records (Supplementary Fig. 9)[23,27,34,40]." to "This difference in residence time explains the delayed deposition of sulfate against microparticles in the polar regions following past explosive eruptions that generated stratospheric aerosol veils, as recognized in high-resolution ice-core records (Supplementary Fig. 9)[23,27,34,40].".
- Line 178: We changed "exhibited" to "reveals".
- Line 182: We changed "lack of an S-MIF signal" to "the lack a S-MIF signal".
- Line 191: We changed "Furthermore, based on our accumulation model, sulfate deposition on the ice spanned 232 ± 42 days (2 σ) since 1 November (see 'Processes of time interval estimation' in Methods), indicating that the ME sulfate aerosols persisted largely in the boreal winter and spring." to "Furthermore, our accumulation model suggests sulfate deposition on the ice spanned 232 ± 42 days (2σ), and based on a 1 November start date (see 'Processes of time interval estimation' in Methods) this implies the ME sulfate aerosols persisted mainly in the boreal winter and spring.".
- Line 194: We changed "leading to limited climate forcing." to "a further factor limiting any climate forcing.".
- Line 196: We changed "large" to "high".

- Line 197: We changed "Reasons for the limited sulfur injection may be the loss of pre-eruptive sulfur and/or the low altitude of the sulfate aerosol veil and its hastened scavenging." to "Reasons for this may include the loss of pre-eruptive sulfur and/or the low altitude of the sulfate aerosol veil and its accelerated scavenging.".
- Line 199: We changed "Our high-resolution glaciochemical records and cryptotephra results also demonstrate that the ME was a multi-phases eruption rather than a single large magnitude eruptive event." to "Our high-resolution glaciochemical records and cryptotephra results also add weight to the hypothesis of a hiatus between the rhyolitic and trachytic phases of the ME.".
- Line 204: We changed "This reinforces the tree-ring data which shows limited cooling over this period and shows the importance of evaluating the role of volcanism in climate variability and human history on a case-by-case basis." to "This reinforces the evidence from tree-ring data which show insignificant cooling over this period, and highlights the importance of evaluating the role of volcanism in climate variability and human history on a case-by-case basis.".
- Line 225: We changed "Two longitudinal samples with approximately 10 cm^2 cross-sections were cut from the archived core, but not concurrently." to "Two longitudinal samples with approximately 10 cm^2 cross-sections were cut from the archived core.".
- Line 234: We changed "Continuous flow aerosol analyses" to "Continuous-flow aerosol analyses".
- Line 236: We changed "continuous flow" to "continuous-flow".
- Line 251: We changed "the supernatant was pipetted off" to "the supernatant pipetted off".
- Line 345. We changed "Sulfate in the in-house secondary standards Switzer Falls and seawater samples were also purified for checking accuracy and reproducibility and a blank sample was processed to monitor blank (sulfur blank was 0.04 nmol and had a $\delta^{34}S$ = 4.53 ‰) and enable a blank correction." to "Sulfate in the in-house secondary standards Switzer Falls and seawater samples were also purified for checking accuracy and reproducibility. A blank sample was also processed (sulfur blank was 0.04 nmol and had a $\delta^{34}S$ = 4.53 ‰)."
- Some vocabulary and grammar errors were pointed out by reviewer #2 and now corrected.

C)

- We revised the "Annual net accumulation model" chapter as follows:

We developed an annual net snow accumulation model based on the seasonal variation of net snow accumulation in north central Greenland from 1991 to 1995[31]. First, we digitized figure 6a from Shuman et al.[31] to obtain monthly net accumulation values (mm in water equivalent (w.e.)) for four sites. These values were averaged by month for each site, and then across all sites to produce the overall monthly average net accumulation (Supplementary Fig. 10). Error bars shown in Supplementary Fig. 10 represent standard deviations for each month. However, we argue that this is not an appropriate average and error estimate, since it is based on a relatively short data set which is not normally distributed. In addition, the accumulation for January has only one data point available, which makes the standard deviation meaningless (Supplementary Fig. 10). To overcome this problem, we generated 1,000 random values from the monthly net accumulation range, assuming a uniform distribution. The minimum and maximum value for net accumulation of January, where only one data point available, was assumed to be the same as the average of the minimum and maximum net accumulation of November, December, February, and March. The resulting annual net accumulation distribution (sum of the monthly net accumulation) was near-normal, estimated at 191 ± 22 mm w.e. (2σ). The averages and standard deviations of these 1,000 monthly net accumulation simulations are provided in Supplementary Table 2. In order to establish the annual net accumulation model (Fig. 3), the monthly net accumulations were divided by the annual net accumulation in each random generation to determine the monthly fractions (averages and standard deviations are reported in Supplementary Table 2).

- We revised the "Processes of time interval estimation" chapter as follows:

- In order to estimate the time interval between the two spikes from the observed depth difference, we used the accumulation model to derive the time elapsed since the assumed eruption date of 1 November 946. According to the 240-hour forward air trajectory, the ash from the ME could have reached Greenland within a few days to weeks after the eruption started (Supplementary Fig. 7). In this study, we assumed that the ash would have taken 14 ± 7 days to reach the NGRIP site in Greenland after 1 November (see the next 'Forward air trajectory analysis' section). We assumed a normal distribution for the estimated accumulation and ash travel timing. Using the developed annual net accumulation model, we assigned a 'fraction of annual net accumulation' value (i.e. y-axis value) to the ash travel timing, which was 14 ± 7 days from 1 November (i.e. x-axis value). This process was repeated 1,000 times. As a result, the duration of 14 ± 7 days corresponds to a 'fraction of annual net accumulation' of 0.0258 ± 0.0245. This value is converted to 0.005 ± 0.005 m by multiplying it with the NGRIP average annual layer ice thickness between 940 and 949 CE (0.183 ± 0.023

m)[58]. Afterwards, we determined the depth that corresponds to 1 November 946 within the NGRIP1 core. The large insoluble particles associated with the ME start at a depth of 218.5225 m in the NGRIP1 core (Extended Data 3). To calculate the depth for 1 November 946, we added 0.005 ± 0.005 to 218.5225, resulting in a depth of 218.527 ± 0.005 m. The depth differences between 1 November 946 and the double spikes of the large particle concentrations are calculated as 0.016 ± 0.005 m for Spike 1 and 0.026 ± 0.005 m for Spike 2 (Extended Data 3). These values were then divided by the NGRIP average annual layer ice thickness of 940–949 CE (0.183 ± 0.023 m) to derive the 'fraction of annual net accumulation'; 0.085 ± 0.031 for Spike 1 and 0.143 ± 0.035 for Spike 2. Finally, we assigned the days after 1 November (i.e. x-axis value) for the double spikes using the annual net accumulation model (Fig. 3) and estimated the time interval between the double spikes. The first microparticle spike was deposited 46 ± 21 days after 1 November and the second to 77 ± 23 days after. Accordingly, the time interval between spikes was 31 ± 25 days. The uncertainties are quoted to 2σ and were achieved by 1,000 Monte Carlo simulations under normal distribution.

For estimating the scavenging of the ME sulfate aerosols in the atmosphere, we determined the sulfur in the NGRIP1 core associated to the ME ends at a depth of 218.431 m (Extended Data 4). The 'fraction of annual net accumulation' (y-axis value) for the end of sulfur associated to the ME was 0.525 ± 0.130 (2σ), by following the same procedure described above. Finally, the days after 1 November of 232 ± 42 days (2σ) was assigned using the annual net accumulation model (x-axis value). The uncertainties were achieved by 1,000 Monte Carlo simulations under normal distribution.

- We revised the "Forward air trajectory analysis" chapter as follows:

Line 321: We added "in the READY (Real-time Environmental Applications and Display System) website".

D)

- Line 98: We defined "NEEM" as "North Greenland Eemian Ice Drilling".
- Line 101: We defined "QUB" as "Queen's University Belfast".
- Line 165: We defined "BCE" as "Before Common Era".
- Line 256: We defined "JEOL" as "Japan Electron Optics Laboratory".

E)

- We revised the "Tephra geochemistry, glaciochemical and insoluble microparticle records" chapter as follows:

- Discrete sections of ice from the NGRIP1 core, T3 (deepest/oldest) through T10 (shallowest/youngest), were sampled for tephra extraction (see 'Sample collection' in Methods and Fig. 1). Shard sizes ranged from 4 to 38 µm (Supplementary Fig. 2 and 3), and many diverse types were identified in the discrete samples (Extended Data 1, discussed in Supplementary Note 1). The shards in samples T4 and T5 included both trachyte and rhyolite compositions that mostly match those of the ME (Fig. 1 and Extended Data 1). Specifically, sample T4 yielded eight rhyolite shards and one trachyte shard, while the overlying T5 sample yielded two rhyolite and four trachyte shards. One rhyolite in T4 plots near the rhyolite/trachyte border, and one rhyolite shard in T5 does not correspond to the ME (Fig. 1). This transition from rhyolite to trachyte shards in the ice mirrors the temporal progression evident in the proximal stratigraphic record. The preservation of this stratigraphic order in the Greenland ice suggests minimal reworking of snow at the NGRIP site, consistent with the high snow accumulation rates and relatively low wind speeds experienced at the topographic divide where the ice core was drilled, in contrast to more coastal sites in Greenland[29].

  A range of elements, high-resolution liquid conductivity, and size-resolved insoluble particle counts were measured on separate longitudinal samples of the NGRIP1 core using the continuous ice-core analytical system at the Desert Research Institute (DRI) (see 'Continuous-flow aerosol analyses' in Methods)[23]. Sulfur concentrations from discrete and continuous measurements were consistent (Supplementary Fig. 4). Additionally, liquid conductivity, which reflects acidity and is dominated by changes in sulfate concentration in Greenland ice, was used as a high-resolution proxy for volcanic sulfate deposition (Extended Data 2). Insoluble particle concentrations increased abruptly at approximately 218.52 m depth and fell abruptly at 218.49 m, spanning ice samples T4 and T5 (Fig. 2 and Extended Data 3), thereby confirming the microparticle peak's association with the ME. This microparticle peak coincided with seasonal peaks in concentrations of Na (a sea salt proxy) and Ca (a terrestrial dust proxy; Supplementary Fig. 5 and Extended Data 4), consistent with the late 946 CE timing of the ME suggested by studies of tree-rings and the NEEM-2011-S1 core from the North Greenland Eemian Ice Drilling (NEEM) site in Greenland[2,30].

4. The reference list must be checked (some DOI links are not working).

- Thank you for checking the DOI links. We corrected the DOI links that were not working.

5. ED1 to ED5 could be merged into a single Excel file with 5 different spreadsheets.

➢ We merged Extended Data 1 to 5 to a single Excel file.

Response to reviewer #2

This study utilises high-resolution evidence from the NGRIP1 ice core to investigate the phasing and climate-forcing potential of the Millenium Eruption (ME) of Mt Baekdu. A combination of glaciochemical and tephra analysis are employed to good effect to place more robust constraints on the timing of the ME. The authors support a multiphase eruption scenario with an interval of one to two months between the two main eruption phases. Sulfur isotope analysis also reveals the absence of a sulfur mass-independent fractionation (S-MIF) signal for the ME, which is consistent with sulfate aerosol formation below the stratospheric ozone layer. The authors suggest that the lack of stratospheric sulfate may explain why, for such a large eruption, there is limited evidence for global or regional climatic impacts in tree ring or other proxy records.

The article is well-written and has a coherent narrative throughout, making it accessible to the broad readership that will most likely be interested in this study. The use of ultra-high resolution ice core evidence is novel but is also not overstretched by the authors, who do a good job of acknowledging the associated uncertainties in their methods, particularly in deriving their annual accumulation model. This is an exciting advancement in the application of high-resolution ice-core evidence to resolve the timing of a historical CE eruption at such a high temporal resolution. It will be exciting to see where a similar approach may be applied in the future with other CE eruptions. S-MIF analysis also contributes well to the study, resulting in a compelling argument for why the ME did not result in significant climate impacts despite its large magnitude and previous estimates of large sulfur emissions. Overall, I would recommend this article for publication in Communications Earth & Environment after minor revisions of the comments highlighted below.

Specific Comments

Title: Whilst the title does reflect the study's investigation into the phasing of the ME eruption, I wonder if it is a little misleading to say "climate impact". From reading the title, I initially anticipated the paper would include new proxy evidence or a lengthier discussion as to the climate impacts (globally or locally) following the eruption. Given the focus of the study (along with constraining the phasing) is on the sulfur injection height and transport of sulfate aerosol in the atmosphere, using "climate forcing" or "climate forcing potential" instead may more accurately reflect the work done in the paper.

- We changed the title from "Phasing and climatic impact of the 'Millennium Eruption' of Mt. Baekdu" to "Phasing and climate forcing potential of the 'Millennium Eruption' of Mt. Baekdu".

Line 19: It would flow more easily here to say "resulted from one eruption episode or two separated by several months".

- Line 19: We changed it as suggested.

Line 56: Should be "estimations".

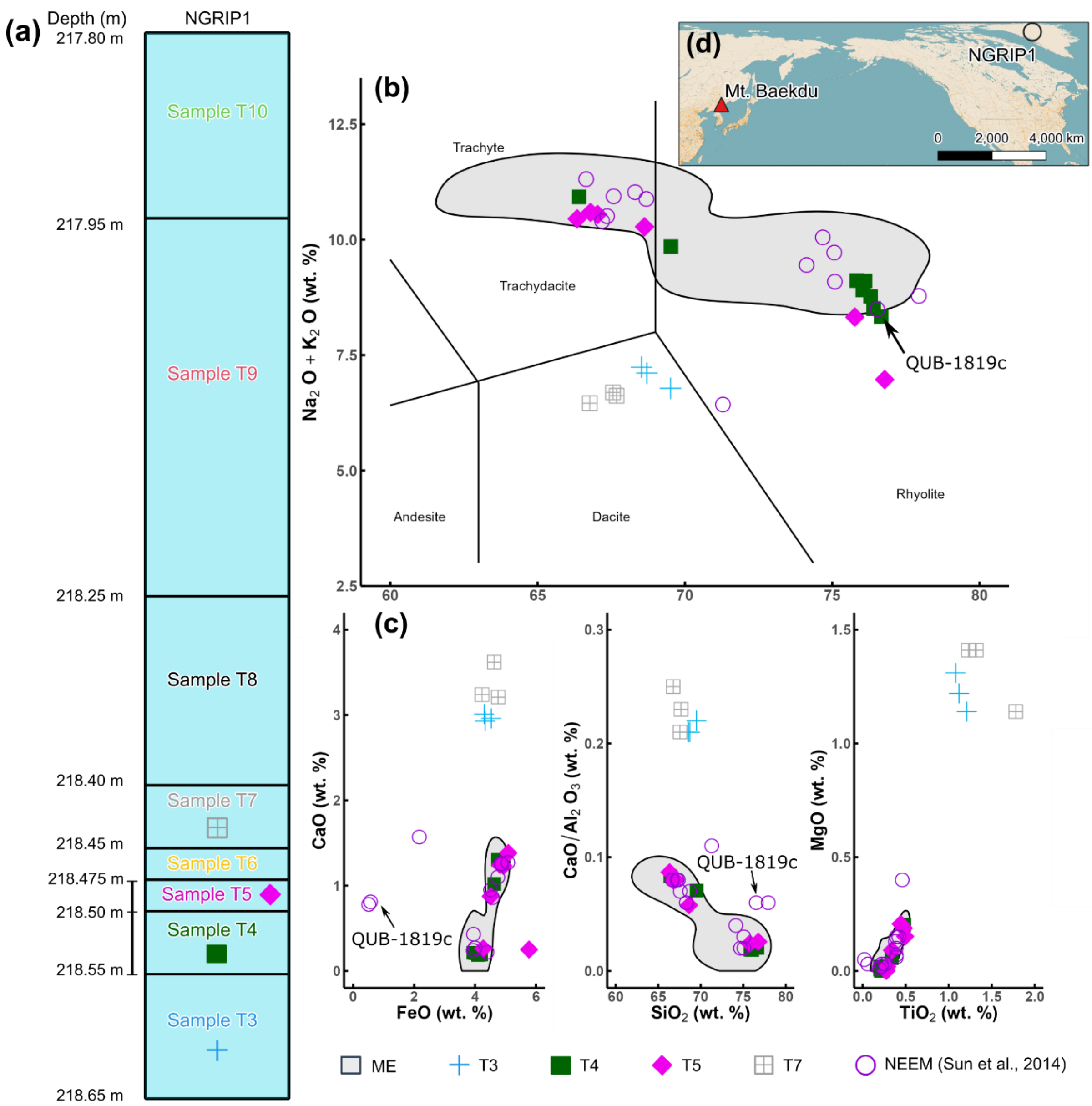
- Line 57: We changed it as suggested.

Line 59: Do either of the chronicles from Japan make reference to localised climatic impacts?

- Line 63: We changed "While explosive extra-tropical northern hemisphere (NH) winter-time eruptions can have a significant climatic impact[22–24], there is no evidence for significant NH summer cooling following the ME in tree-ring temperature reconstructions[2]." to "While extra-tropical northern hemisphere (NH) winter-time explosive eruptions can have a significant climatic impact[22–24], evidence for significant NH summer cooling following the ME is lacking in tree-ring temperature reconstructions[2] and has not been identified in historical records[4].".

Figure 1: The pink-blue colour scheme is a little difficult to distinguish – particularly given T3 and T4 have similar marker shapes. Could a wider colour palette be used? i.e green square for T4. On Figure 1a a vertical line next to T4-T5 could also be added to highlight the relevant depths for the ME.

➢ We improved figure 1 as suggested.



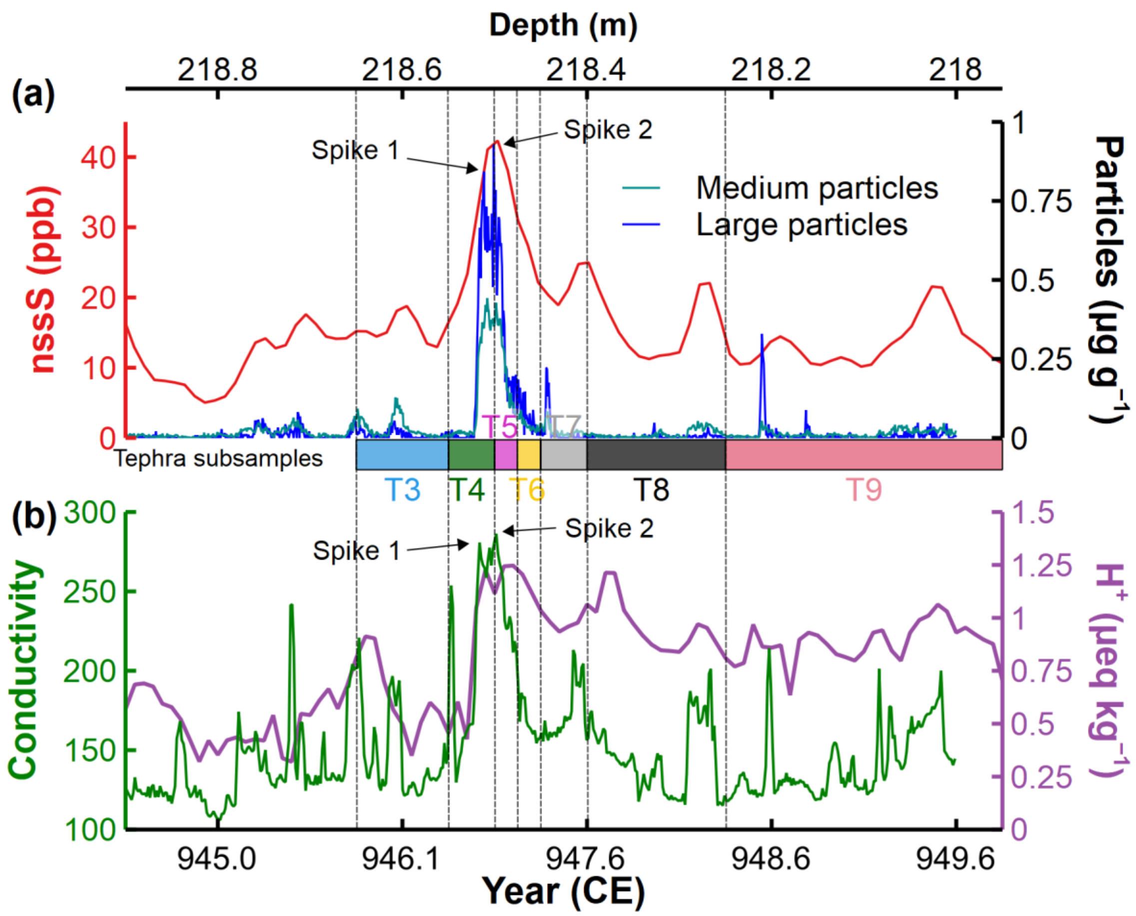
There is also no reference to the context of the tephra shards in T3 and T7 in the figure caption or main body of Figure 1. Although they are not the focus of this study, it would still be helpful to clarify that they correspond to different eruptions and that you have attempted to identify credible source regions (as outlined in the supplementary).

- Line 106: We added "Tephra populations in T3 and T7 may correspond to fallout from Mt. Rainier eruptions (Supplementary Note 1)." in the figure caption.

Figure 2: The spikes are currently quite squished together on the figure which makes them difficult to distinguish, does T10 need to be included or could that be removed to space the spikes further apart?

- We removed T10 in figure 2.

- Line 111: We changed "T10" to "T9".



Line 117: Assuming a similar accumulation trend between 946 AD and the 1990s seems to be one of the most significant uncertainties/assumptions made in deriving the seasonal accumulation model. Is there any indication that modern climate warming may have affected the accumulation rate in the 1990's? Andersen et al., 2006 highlight the influence on accumulation rates of changing climatic conditions during the little ice age for example.

- Thank you for the very constructive comment!

  Annual accumulation rate in NGRIP site during the 1990s does not seem exceptional compared to the last 2000 years in Andersen et al. (2006). Therefore, we assume the 'fraction' of accumulation rate in the 1990s is not significantly affected by climate warming. We would add this explanation in the text.

  Line 130: We changed "However, as this was the only time available for the net accumulation in northern Greenland, we assumed that the accumulation trend of 946–947 CE would be comparable to that of the 1990s. We believe the seasonal trend would not be significantly different since the average annual accumulation rate in NGRIP site is relatively constant throughout the last 2,000 years[32]." to "We assume that the seasonal accumulation trend (i.e. monthly fraction of the annual accumulation rate) of 946–947 CE was comparable to that of the 1990s, which seems reasonable given that the annual accumulation rate at the NGRIP site during the 1990s is not exceptional in the context of the last 2,000 years[32]. We acknowledge that seasonality of snow accumulation at the NGRIP site is highly variable from year to year, but the 1991–1995 data set is to our knowledge the only observed record of sub-seasonal accumulation from northern Greenland.".

  The decreasing trend on accumulation rates during the little ice age mentioned in Andersen et al. (2006) seems mostly affected only in the southern Greenland (DYE-3 core).

Line 121: It would be helpful here to be more specific about the uncertainties you have accounted for. Saying "We have taken into account all uncertainties" without (even briefly) acknowledging what those uncertainties are is perplexing and feels somewhat awkward.

- Line 135: We changed "Therefore, we have taken into account all uncertainties to ensure a cautious interpretation (see Methods)." to "Our accumulation model incorporated both spatial and temporal variability to ensure a conservative interpretation (see 'Annual net accumulation model' in Methods).".

Line 160: UT/LS seems somewhat inconsistent with the other plume heights estimated based on tephra thickness and fall deposits (25-40 km). Whilst sulfur injection height may well be lower than these maximum ash heights, a discrepancy of 15-20 km between them seems quite high. Can these estimates be reconciled? It would be helpful to explicitly address this discrepancy given you mention these higher plume height estimates earlier in the paper.

➢ According to Aubry et al. (2023), when the mass flow rate exceeds 10^8 kg/s, there can be a discrepancy of >15 km between the maximum plume height and the sulfur injection height. Given Costa et al. (2024)'s estimate of ~4×10^8 kg/s for the ME's eruption rate, the difference between the maximum plume height of 30–40 km and the sulfur injection height in the upper troposphere/lower stratosphere (UT/LS) falls within the discrepancy range of Aubry et al. (2023).

Line 180: We changed "The near-synchronous fallout of insoluble particles and sulfur associated with the ME evident in the NGRIP1 core (Fig. 2a) is consistent with UT/LS transport and lack of an S-MIF signal." to "The near-synchronous fallout of insoluble particles and sulfur associated with the ME evident in the NGRIP1 core (Fig. 2a) is consistent with UT/LS sulfate transport and the lack of a S-MIF signal. The discrepancy between the maximum plume height of 30–40 km[20] and the sulfur injection height of UT/LS might be attributed to the estimated high mass eruption rate[20] of approximately 4×10^8 kg s^{-1}. This inference is based on a previous study that compiled data on mass eruption rates, maximum plume heights and sulfur injection heights for past eruptions[21]. According to the study, there can be a significant difference of >15 km between the maximum plume height and the sulfur injection height for eruptions with a mass eruption rate of >10^8 kg s^{-1}.".

Line 171: This seems to be a critical point to draw out. Even for total stratospheric sulfur injection (SSI) of ~ 2 Tg, if this is split between two eruption phases then the effective forcing may be lower than for a single phase 2 Tg eruption. Is there any estimation, or the possibility of estimating, the relative contribution of each phase of the eruption to the overall SSI (i.e did one phase release much more SO2)?

➢ There is no estimation of SO_2 emission of each phase. However, our high-resolution conductivity record (Fig. 2b) might differentiate the SO_2 emission of each phase. The conductivity height and width of Spike 2 seems a bit greater than those of Spike 1. This may indicate that more SO_2 was released during Phase 2 of the Millennium eruption, which aligns with an estimate of larger 'total erupted volume' and a longer duration during Phase 2 compared to that of Phase 1 (Costa et al., 2024).

Line 201: We added "The conductivity peak and width of Spike 2 appear to be greater than those of Spike 1 (Fig. 2b). This suggests that more SO_2 was released during Phase 2 of the ME, which is consistent with estimates indicating a larger total erupted volume and a longer duration of the second phase compared with the first[20].".

Additional changes not suggested by reviewers #1 and #2.

- We changed all "2 σ" to "2σ".
- Line 48: We added "Common Era".
- Line 67: We added "new".
- Line 73: We added "Results and discussion".
- Line 75: We changed "Discrete sections of ice from the NGRIP1 core – T3 (deepest/oldest) through T10 (shallowest/youngest) – were sampled for tephra extraction (see 'Sample collection' in Methods and Fig. 1)." to "Discrete sections of ice from the NGRIP1 core, T3 (deepest/oldest) through T10 (shallowest/youngest), were sampled for tephra extraction (see 'Sample collection' in Methods and Fig. 1).".
- Line 115: We changed "The microparticle peak" to "On close inspection, the microparticle peak".
- Line 146: We changed "This timescale does not preclude the possibility that the sounds heard in Japan on 7 February 947 CE were related to a second phase of the ME, resulting in approximately 14 weeks of time interval, but such an interpretation is not compelling." to "Even allowing for the vagaries of aerosol transport times from source to Greenland, this timescale likely precludes the possibility that the thunderous sounds heard in Japan on 7 February 947 CE (i.e., 14 weeks after 1 November 946 CE) were related to a second phase of the ME (Fig. 3).".
- Line 166: We added "CE"
- Line 168: We added "CE"
- Line 178: We added "CE"
- Line 179: We added "CE"
- Line 228: We added "in the year 2022".

- Line 231: We added "in 2013".
- Line 231: We added "The NGRIP1 core has been stored at −24 °C in a freezer facility in Copenhagen since it was drilled in 1996, and subsequently, at −30 °C since 2019.".
- Line 244: We added "The outer 70% was discarded due to potential contamination.".
- Line 266: We changed "were within 2 σ uncertainty" to "were generally within 2σ uncertainty".
- Line 520: We added "The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (https://www.ready.noaa.gov) used in this publication.".
- Line 527: We added "the European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement no. 820047).".
- Changed the color of T4 from light blue to dark green in Fig. S6 as same as the Figure 1 and 2.
- Changed the symbol of T7 in Figure S6, S11, S12, and S13.
- Supplementary Information Line 13: We changed "In Supplementary Figure 13, we present the major element chemistry data for a particular eruption of Mt. Rainer. This eruption has been dated to approximately 1,040 ± 410 cal years BP[1], which corresponds to the time period of 910 ± 410 CE (cal year refers to radiocarbon ages calibrated to calendar year; BP, before the present)." to "In Supplementary Figure 13, we present the major element chemistry data of an eruption of Mt. Rainer that has been dated to approximately 1,040 ± 410 cal years BP[1] (cal year refers to radiocarbon ages calibrated to calendar year; BP, before the present). This corresponds to the time period of 910 ± 410 CE and overlaps our precise ice core age of 946–947 CE.".
- Supplementary Information: We deleted the paragraph of "Mt. Rainier may have erupted around ten to 12 times during the last 2,600 years[1]. Most of the eruption magnitudes of Rainier have been estimated as a VEI 2–3 eruption[1], and eruptions this size would be unlikely to produce far-traveled ash deposits[2,3]. However, considering that potential Rainier shards were identified in Svartkälsjärn, Sweden, the VEI of Rainier eruptions might have been underestimated due to distraction of local tephra deposit by concurrent and subsequent mudflows[2]. In addition, the VEI estimates of Mt. Rainier were derived from limited thickness measurements rather than detailed isopach mapping[1], which could potentially result a significant level of uncertainty. Conducting trace element analysis on proximal fallouts from Mt. Rainier and the tephra shards

identified in NGRIP1 is essential to confirm whether the tephra shards originated from Mt. Rainier. However, caution is warranted when attributing a specific volcano to the identified tephra due to the under-recording of volcanic eruptions in the past millennium[4].” due to high speculation.

- Supplementary Information Line 19: We added “because there are only one or two shards, chemistries were not consistent between shards, and Na was too low for fresh glass”.
- Extended Data 1. We provided the beam size, beam current, and date of analyses for all data points of the WDS measurements.
- Extended Data 5. We provided the beam size, beam current, and date of analyses. In addition, we grouped the results by session.

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I'm satisfied with the authors' response and strongly recommend this paper for publication.

Kind regards,

Ivan

Reviewer #2 (Remarks to the Author):

The authors have comprehensively responded to my suggestions and I am happy to recommend the paper for publication.

Dear reviewers,

We are pleased to receive your recommendation for publishing our work. Thank you for your constructive comments, which have improved the manuscript than before!

We have made additional changes to the manuscript.

- Line 17: We revised the abstract as follows.

The Millennium Eruption of Mt. Baekdu, one of the largest volcanic eruptions in the Common Era, initiated in late 946. It remains uncertain whether its two main compositional phases, rhyolite and trachyte, were expelled in a single eruption or in two. Investigations based on proximal and medial ash have not resolved this question, prompting us to turn to high-resolution ice-core evidence. Here, we report a suite of glaciochemical and tephra analyses of a Greenlandic ice core, identifying the transition from rhyolitic to trachytic tephra with corresponding spikes in insoluble particle fallout. By modeling annual snow accumulation, we estimate an interval of one to two months between these spikes, which approximates the hiatus between two eruptive phases. Additionally, negligible sulfur mass-independent fractionation, near-synchroneity between particle and sulfate deposition, and peak sulfur fallout in winter all indicate an ephemeral aerosol veil. These factors limited the climate forcing potential of the Millennium Eruption.

- Line 34: We deleted 'also'.
- Line 41: We changed 'significant' to 'important'.

- Line 47: We rephrased sentences to '…(including 3 Tg of syn-eruptive sulfur), surpassing estimated emissions for all Common Era eruptions bar Samalas (circa 1257 CE)[14]. However, more recent work suggests a total ME sulfur release of 2 to 7 Tg, with most of the pre-eruptive sulfur lost prior to eruption through crystal fractionation processes and bubble migration[17].'.
- Line 54: We added the sentence to 'from volcanic eruptions.'.
- Line 54: We rephrased the sentence to 'In this regard also, estimates vary considerably for the ME.'.
- Line 55: We added 'have'.
- Line 57: We changed 'The most' to 'More'.
- Line 61: We changed 'significant' to 'substantial'.
- Line 62: We changed 'significant' to 'transient'.
- Line 65: We changed '…conducted new continuous…' to '…conducted continuous…'.
- Line 66: We changed '1' to 'i'.
- Line 67: We changed '2' to 'ii'.
- Line 69: We changed '3' to 'iii'.
- Line 75: We rephrased the sentence to '… and their morphologies are diverse (Supplementary Data 1, discussed in Supplementary Note 1).'.
- Line 80: We rephrased the sentence to '… record of the ME, suggesting minimal reworking of snow at the NGRIP site, and consistent…'.
- Line 87: We deleted 'Additionally,'.
- Line 88: We changed 'was used as a' to 'provides an additional'.
- Line 89: We changed 'increased' to 'increase'.
- Line 91: We changed 'coincided' to 'coincides'.
- Line 114: We deleted 'approximately'.
- Line 124: We rephrased the sentence to 'Given that the annual accumulation rate at the NGRIP site during the 1990s is unexceptional in the context of the last 2,000 years[32], we assume that the seasonal accumulation trend (i.e. monthly fraction of the annual accumulation rate) of 946–947 CE was comparable to that of the 1990s.'.
- Line 130: We changed 'incorporated' to 'incorporates'.
- Line 135: We added 'maximum in the'.
- Line 155: We deleted 'from'.

- Line 156: We changed ‘eruption of’ to ‘aerosol from’.
- Line 162: We changed ‘significantly longer’ to ‘longer’.
- Line 174: We changed ‘significant difference’ to ‘difference’.
- Line 175: We changed ‘of >’ to ‘exceeding’.
- Line 177: We deleted ‘and’.
- Line 178: We changed ‘by’ to ‘based on’.
- Line 180: We changed ‘on’ to ‘to’.
- Line 184: We deleted ‘and previous estimates of very high sulfur emissions’.
- Line 186: We deleted ‘[17]’.
- Line 188: We rephrased the sentence to ‘This may suggest that more SO_2 was released during Phase 2 of the ME, which may help in understanding the sulfur budgets of the two magma compositions in respect of eruptive volumes and degassing histories[17,20]. Taken together with understanding of the radiative and dynamical impacts of boreal winter, extra-tropical northern hemisphere (NH) eruptions[23,43–45], our findings reinforce the evidence from tree-ring summer temperature reconstructions[2] for negligible cooling after the ME, and highlight the importance of evaluating the role of volcanism in climate variability and human history on a case-by-case basis’.
- Line 204: We changed ‘which was accompanied by’ to ‘corresponding with’.
- Line 206: We rephrased the sentence to ‘…the insoluble particle spikes suggests a hiatus between the rhyolitic and trachytic phases of the ME of order one month.’.
- Line 209: We added ‘and reductions in uncertainty.’.
- Line 211: We rephrased the sentence to ‘Based on these observations, the muted climate forcing arising from the ME likely reflects a short atmospheric lifetime of the volcanic sulfate aerosol veil, along with boreal winter timing of aerosol formation and modest sulfur yield.’.
- Line 360: We provided access information in the Data Availability Statement as follows.

The data used for manuscript figures are available on Figshare, with the Supplementary Data under identifier https://doi.org/10.6084/m9.figshare.26549344.v1 and the Supplementary Tables under identifier https://doi.org/10.6084/m9.figshare.26550304.v1. Supplementary Tables are also available in the Supplementary Information.

- Line 526: We added ‘a Philip Leverhulme prize in Earth Sciences (PLP-2021-167);’.

- Line 540: We grouped Figure captions at the end of the manuscript as follows.

Figure 1. Stratigraphy and geochemistry of shards found in NGRIP1 and NEEM-2011-S1[6] cores. QUB-1819c is a shard potentially corresponding to a Japanese volcano (see Supplementary Note 1) (QUB stands for Queen's University Belfast). **(a)** Schematic diagram of the NGRIP1 ice core. **(b)** Total alkali versus silica (TAS) diagram[60]. **(c)** Additional major oxide bi-plots for glass shards. Only samples for which analytical totals exceeded 90 % and those that might represent a tephra population are shown. Shards in sample T7 were measured by scanning electron microscope energy dispersive spectroscopy (SEM-EDS); all other shards were measured by wavelength dispersive spectroscopy (WDS). Grey shading characterizes the previously reported range of ME glass geochemistry for both proximal and distal deposits[6,9,61,62]. Tephra populations in T3 and T7 may correspond to fallout from Mt. Rainier eruptions (Supplementary Note 1). **(d)** Location of Mt. Baekdu and NGRIP1 core.

Figure 2. Glaciochemistry and microparticle records from the NGRIP1 ice core. **(a)** Non-sea-salt sulfur (nssS) and insoluble particle (large: 4.5–9.5 µm; medium: 2.5–4.5 µm) concentrations from Continuous Flow Analysis (CFA) at the Desert Research Institute (DRI). T3 to T9 represent consecutive ice samples for tephra shard analysis, with corresponding depths shown at the bottom of the panel. **(b)** High-resolution liquid conductivity (dimensionless) analyzed at the DRI, and previously published 1-cm resolution H^+ measurements based on the electrical conductivity method (ECM)[63].

Figure 3. Annual net accumulation model for north central Greenland between 1991 and 1995[31]. Error bars indicate 1 σ uncertainty. Histograms are for the timing of microparticle deposition (onset and Spikes 1 and 2) and represent probability density distributions based on 1,000 Monte Carlo simulations in each case. See 'Processes of time interval estimation' in Methods for details.

Figure 4. Measured $\delta^{34}S$ and $\Delta^{33}S$, and estimated volcanic (background corrected) $\delta^{34}S$ and $\Delta^{33}S$ with continuous nssS concentrations. Background correction is applied when volcanic sulfate accounts for over 60 % (f_{volc} >0.60). Solid line at $\Delta^{33}S$ = 0 ‰. Dashed lines indicate $\Delta^{33}S$ ± 0.09 bracketing range of S-MIF signals. Error bars represent 2σ uncertainty.

- We changed all 'Extended Data' to 'Supplementary Data'.
- We re-numbered the reference list in sequential order in the following sections of the manuscript: Main text, Methods, Data Availability Statement, Tables, Figures/Schemes.