Response to Reviewers

Dear Editor,

We believe that we have sufficiently replied to the interactive comments, and we have updated our manuscript files accordingly. Please find our responses to each reviewer comment below. Reviewer comments are copied as black text *and our responses are given in blue italicized text. A complete list of our revisions is given at the end of the document.*

Thank you for your time and consideration.

Respectfully,

Austin M. Weber, on behalf of all authors

Anonymous Referee #1

This manuscript provides a morphological and mineralogical characterization of dust particles found in ice cores collected in the tropical Peruvian Andes and discusses their potential sources. Overall, I found the manuscript well written, and the discussion of potential dust sources is thorough. I only have a few minor comments.

(1) I was wondering whether it would be possible to identify or use accessory minerals that can be specifically linked to the granodiorite, tonalite, and Chicama Formation. These could provide additional constraints for source attribution.

Yes, to some extent it is possible to identify accessory minerals that may be linked to specific source areas. For example, among the 1887 particles that we characterized, we could consider:

Potential Accessory Mineral / Group	**Number Observed**	**Relative Abundance†**	**Mineral Type**	**Possible Source**
Apatite	$n = 1$	0.1 ± 0.1%	Igneous	Cordillera Blanca batholith / African dust
Cordierite	$n = 8$	0.4 ± 0.1%	Metamorphic	Cordillera Blanca batholith
Garnet	$n = 7$	0.4 ± 0.1%	Metamorphic	Cordillera Blanca batholith
Titanite	$n = 5$	0.3 ± 0.1%	Igneous	Cordillera Blanca batholith
Pyrite	$n = 0$	n/a	Metasedimentary	Cordillera Blanca batholith / Chicama Formation (weathered phyllite, shale)

†Uncertainties are reported as Poisson counting errors: 100% × ($\sqrt{n} / N$) where N = 1887.

Atherton and Sanderson (1987) provide a lot of useful information on the types of minerals found in the Cordillera Blanca. The batholith is largely igneous-metamorphic and is dominated by plagioclase-rich *granites which we refer to as granodiorite and tonalite in the manuscript. These rocks contain several accessory minerals including apatite, titanite (sphene), magnetite, pyrite, and zircon. However, apatite is not very diagnostic because it may also be present in African dust (e.g., Bristow et al., 2010; Besl, 2022). It is possible that magnetite (an Fe-oxide mineral) exists in the ice core record, but without x-ray diffraction data we cannot distinguish magnetite from other Fe-oxide minerals such as goethite or hematite. Fe-oxides are also found in trace amounts in Amazonian soils (Irion, 1984), and so, unfortunately, we cannot use Fe-oxides to generally constrain the dust to any one source area. In contrast, titanite was identified in the ice core record (n=5), which may be linked specifically to the granodiorites and tonalites. We did not identify any particles consistent with pyrite or zircon in this study. In the original manuscript we discuss how pyrite may also be characteristic of the Chicama Formation, while its absence in the ice core record may be explained by the difficulty of lofting such a dense mineral to the high altitude of the Huascarán col (Lines 434 – 445).*

(2) Carbonates were not observed in the analyzed particles. Could the absence of carbonates help to exclude or support specific potential dust sources?

This is an astute observation and relevant question. Indeed, we did not observe carbonates in any of our samples. While the absence of carbonates may say something about source attribution, we were cautious to not speculate on this because carbonates are at least partially soluble (e.g., Sala et al., 2008). It is very possible that carbonates exist in situ (i.e., within the ice) but are dissolved when the samples are melted and then lost during filtration. Alternatively, interactions between calcium carbonate and nitric acid during atmospheric transport could convert carbonate minerals into calcium nitrate (Gibson et al., 2006; Preszler Prince et al., 2007), which, according to solubility rules, should dissociate completely in water (LibreTexts [link]). In our revisions we have added the following (Lines 329 – 332): "It is also worth noting that no carbonate minerals were identified in our analysis. While this result may have implications for source attribution, we do not interpret this in detail because carbonates are at least partially soluble (Sala et al., 2008) and therefore the absence of carbonate-like particles in the ice core may be attributed to dissolution when the ice samples were melted for filtration."

(3) Do the particles show any coatings or internal mixing that could support atmospheric processing during long-range transport? Since the manuscript discusses the possibility of a North African contribution, I was wondering whether the particles show any evidence of atmospheric ageing that could provide additional support for their long-range transport.

It is difficult in the context of the data we collected to draw conclusions about whether the particles exhibit evidence of atmospheric ageing. Particle aggregates are present, but it is unclear whether they formed in situ or during atmospheric transport. As mentioned on Lines 173—174 in the original manuscript, we tried to focus our analysis on isolated particles to avoid the generation of mixed x-ray (EDS) signals. Regrettably, we did not collect high spatial-resolution secondary electron (SE) images for each particle, which would have provided us with more information regarding their textural features.

Instead, we primarily collected backscatter electron (BSE) images because the particles appear as bright spots against the relatively dark filter background. † *This makes image processing much easier for determining the shapes and sizes of the particles, but it comes at the expense of losing information about sample topography. Given that our focus is on very fine particulate matter, it becomes very difficult to qualitatively describe whether the BSE images show evidence of coatings. Our analysis is limited to specifically characterizing size, shape, and mineralogy.*

† For clarity, BSE images highlight differences in composition. The contrast between bright pixels and dark pixels is determined by average atomic number---that is, regions containing relatively high atomic number elements (e.g., dust particles) appear brighter than regions with relatively low atomic number elements (e.g., the polycarbonate filters).

(4) In the introduction, the authors mention the role of iron oxides as strong light absorbers, including after deposition on glaciers. However, the iron oxide content is not really highlighted or discussed in the rest of the manuscript. If iron oxides were identified, I think it would be interesting to briefly discuss their abundance and potential implications.

When mentioning iron oxides in the Introduction, our intent was simply to provide an example of why mineralogy is important to consider, particularly with regard to radiative transfer. However, since radiative transfer was not the focus of our analysis, we did not return to the discussion later on in the manuscript.

That said, we were able to identify 11 particles whose EDS spectra are consistent with iron oxides. This amounts to 0.6 ± 0.2% of all characterized particles (see Fig. 5). Such a low quantity is unlikely to have a significant radiative impact on glacial albedo. On Lines 328—329 in the revised manuscript we have added the following statement: "The very low abundance of iron oxide particles (0.6 ± 0.2%, n=11) suggests that their presence is unlikely to have a significant radiative impact."

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Anonymous Referee #2

The manuscript on the evaluation and characterization of particles deposited on the Huascarán Glacier in the Cordillera Blanca, Peru, is well written and detailed. Furthermore, it provides information on the morphology and chemical composition of particulate matter from 1960-2015.

Nevertheless, detailed comments and questions are listed below:

(1) In the first paragraph, it would be beneficial to further improve and expand the list of different effects of particulate matter in the atmosphere as an example: ocean productivity, human health, reduce solar radiation....

Mineral dust does indeed play many important roles that we did not explicitly mention in the introduction. We were trying to keep the background details relevant to how particulate matter influences albedo (Lines 28-30) and its impact on glaciers (Lines 30-33), though we agree there are still merits to highlighting other ways in which dust is significant.

We have appended the following to the first paragraph (Lines 33 – 40): "Mineral dust is also a key player in many other parts of the Earth system (Knippertz and Stuut, 2014 and references therein). For example, particles in the atmosphere serve as cloud condensation nuclei and therefore influence cloud albedo and precipitation dynamics (Nenes et al., 2014). Additionally, the deposition of mineral dust over terrestrial ecosystems can act as a natural fertilizer for chemically depleted soils (e.g., Bristow et al., 2010; Yu et al., 2015; Besl, 2022) while deposition across marine environments affects ocean productivity (Jickells et al., 2014). Particulate matter also has significance for respiratory health in people, as demonstrated by increased mortality rates during dust events in Europe, Asia, and Africa (Morman and Plumlee, 2014; Perez et al., 2008; Lopez-Villarrubia et al., 2010; Chan et al., 2008)."

(2) Line 57: I would highly recommend to change the use of To our knowledge, to In this study,.

We have changed the line to read: "In this study, we report …" (now Line 65).

(3) On the mineral identification: Although the methodology and the references on which the mineral classification is based are cited, the manuscript does not specify the final classification criteria or the used elemental ratios to assign particles to the different mineral groups. Those ratios may be subtle to different interpretations, providing them would improve the transparency of the methodology and facilitate the reader's understanding of the final mineral classification. So, I highly recommend to attach a table in the supplementary material describing and fixing those elemental ratios for each mineral class.

We used a combination of five independent algorithms to identify each mineral, and each algorithm assigns a mineralogy based on a completely different set of EDS net intensity ratios, atomic percentages, *or spectral characteristics. It would be impossible to communicate every classification criterion in a simple table, but we can provide a table that clarifies the metrics used by each algorithm to identify mineralogy. We have added a reference in the main text (Lines 234 – 235) that directs the reader to the updated supplementary materials, which contains the following table:*

Table S1. *Details on the mineral classification algorithms used in the text, including relevant classification criteria, benefits, and individual limitations.*

Algorithm	**Algorithm Type**	**Classification Criteria**	**Benefits**	**Limitations**
Donarummo et al. (2003)	Sorting Scheme	Net intensity	Fast algorithm; designed for, and commonly used in, ice core studies	Restricted to aluminosilicates; many "Unknown" classification nodes
Kandler et al. (2011)	Comparative Criteria	Atom percent relative abundance	44 mineral groups, including quartz, salts (e.g., NaCl), and mixtures	Mostly broad mineral groups, not necessarily specific minerals
Panta et al. (2023)	Comparative Criteria	Atom percent relative abundance	23 mineral classes, including simple minerals such as quartz and calcite	Cannot differentiate plagioclase solid solution or mafic minerals (pyroxene, amphibole, etc)
Severin (2004)	Dichotomous Key	EDS full spectrum	Includes 182 reference mineral spectra; very easy to use	Requires access to information in Severin (2004), usually in the form of a hard copy of the book; qualitative only; can be subjective and cannot be automated
Weber (2025)	Ensemble Machine Learning Classifier	Net intensity	Provides probability table; can recognize palygorskite and can differentiate plagioclase solid solution series and is trained to recognize certain mafic minerals (e.g., pyroxenes)	Restricted primarily to aluminosilicates

All of these algorithms (with the exception of the Severin dichotomous key) were applied to the EDS data using the open source MATLAB functions provided by Weber (2025) at https://github.com/weber1158/eds-classification. The outputs were cross-referenced with one another and with the Severin dichotomous key to determine the most likely mineral for each particle. The limitations presented in the table clarify the importance of relying on more than just one algorithm to determine mineralogy.

(4) To facilitate comparison with previous work done in the topic, it would also be beneficial to complement the results and discussion sections with comparisons to other studies, highlighting similarities and differences in particle size distributions, particle shapes, and mineralogical composition. Such comparisons would strengthen the interpretation of the data and help better constrain the relative contributions of long-range transported North African dust versus locally sourced dust.

Dust studies for the tropical Andes are extremely scarce (Gilardoni et al., 2022), and so we are quite limited in our ability to compare our results with previous work (which highlights the novelty of our study). The only other ice core mineral dust study that explicitly identifies mineral particles is from Lindau et al. (2021), which we mention in Lines 441-444 in the manuscript. They used micro-Raman to identify 630 mineral grains in a firn core from Nevado Illimani (Bolivia) and found that phyllosilicates are sorted by means of wet deposition. There are a few studies that discuss size distributions (e.g., dos Reis et al., 2022), but the size distributions are categorized according to very wide bin sizes (<2 µm, 2-10 µm, 20-60 µm, etc.). Also, until now there have been no studies that discuss particle shapes in the tropical Peruvian Andes.

In contrast, there is a lot of information in the literature about dust from African source regions. Formenti et al. (2011) provides a good overview of what is known. For instance, they cite numerous studies that examined illite/kaolinite ratios across North Africa, all of which report ratios between 0 and 2 (see their Table 2a). Figure 10 in the manuscript shows how our results compare to various African sources according to the work of Caquineau et al. (1998, 2002). Scheuvens and Kandler (2014) provide insights into the median aspect ratio (AR) of particles from North Africa, which ranges from about 1.6 to 1.9, but the way they calculate AR is very different than how we calculate AR using the automated process provided by Fiji-ImageJ (Schindelin et al., 2012). That is, we calculate AR as the length of a particle's major axis divided by the length of its minor axis, while Scheuvens and Kandler (2014) calculate AR as four-times the particle's long axis divided by the product of the two-dimensional area multiplied by pi. Huang et al. (2020) and Panta et al. (2023), however, calculate AR in the same way as we do in our study. Panta et al. (2023) characterized 300,000 freshly emitted dust particles from the Moroccan Sahara using SEM and identified a median AR of 1.46, which is consistent with the median AR of 1.42 that we observed in the ice core record. However, Huang et al. (2020) compared the ARs of African dust particles reported across the literature and found that the median AR of North African dust increases significantly during long-range transport due to the preferential settling of spherical particles, from about 1.60 over the source regions to 1.90 after long-range transport. Thus, the ARs of dust particles in the ice core from Peru are inconsistent with long-range transport from Africa. There is not much information in the literature regarding the circularity of African dust particles, although one study by Varga et al. (2021) measured the circularity of dust transported from Africa to Iceland and found median values between 0.75 and 0.80, which is consistent with what we noted in the ice core record. We have added most of this discussion on AR and circularity in the revised manuscript (Lines 293 – 301).

(5) The manuscript shows a good correlation between the abundance of kaolinite detected in the ice core, and regional deforestation rates. It would also be interesting to investigate whether the relative abundance of specific mineral groups (e.g., montmorillonite, mica, kaolinite, or oligoclase) correlates with the frequency of North African dust events affecting the region during the same period. Such an analysis could provide additional evidence supporting the contribution of long-range transported Saharan dust to the mineral assemblages identified in the ice core.

Such an analysis was attempted in the first author's dissertation: that is, trying to correlate the abundance of individual mineral species with aerosol optical depth (AOD) data for North Africa *collected with the MODIS sensor aboard NASA's Terra satellite (Weber, 2026). Unfortunately, because the mineralogical data were sampled at multiannual resolution (5-yr intervals), and the MODIS data begin in the year 2000, we cannot draw any meaningful statistical conclusions about the relationship. At 5-yr resolution, the temporal overlap is just four data points: 2000-2004, 2005-2009, 2010-2014, and 2015-2018. If the mineralogical data were annual, then we would have 19 data points to compare with the AOD data. A higher temporal-resolution sampling study is needed to test this relationship in detail. It is not possible to "up-sample" the mineralogical data to annual resolution because that would require interpolation, which would be statistically erroneous in this case because the interpolated data points would be completely artificial and not necessarily reflective of reality. In the conclusions section (Lines 697 – 698) we have added a statement regarding the need for higher-resolution sampling to improve our understanding of dust seasonality and its relationships to various climatological and environmental phenomena.*

(6) Finally, I would like to congratulate the authors on this valuable work and the results presented. This study provides important new insights into the characterization of mineral dust transported to the tropical Andes and offers valuable information that will support future studies on dust sources, transport pathways, and environmental change.

We greatly appreciate these kind words. It is our hope that these data will be beneficial to the broader atmospheric science community and not just those interested in ice core records. We thank the reviewer for their constructive feedback and their thoughts.

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Complete List of the Authors' Changes

From the Manuscript

Lines 33 – 40 | We added the following text to the Introduction:

> Mineral dust is also a key player in many other parts of the Earth system (Knipperz and Stuut, 2014 and references therein). For example, particles in the atmosphere serve as cloud condensation nuclei and therefore influence cloud albedo and precipitation dynamics (Nenes et al., 2014). Additionally, the deposition of mineral dust over terrestrial ecosystems can act as a natural fertilizer for chemically depleted soils (e.g., Bristow et al. 2010; Yu et al., 2015; Besl, 2022) while deposition across marine environments affects ocean productivity (Jickells et al., 2014). Particulate matter also has significance for respiratory health in people, as demonstrated by increased mortality rates during dust events in Europe, Asia, and Africa (Morman and Plumlee, 2014; Perez et al., 2007; López-Villarrubia et al., 2010; Chan et al., 2008).

Line 46 | We removed the word "legacy".

Line 65 | We replaced "To our knowledge..." with "In this study, ..."

Line 208 | We replaced "Text S1" with "Text S2" to reflect the updated Supplementary Materials.

Lines 234 – 235 | We added the following line regarding our mineral classification method: "Additional details on the classification algorithms are provided in Table S1 in the Supplementary Materials."

Line 274 | We replaced "Text S1" with "Text S2" to reflect the updated Supplementary Materials.

Lines 293 – 301 | We added the following text on the discussion of particle shapes:

> Information on the circularity of mineral particles in the tropics is very limited, although Varga et al. (2021) examined African dust transported to Iceland and found median circularity values between 0.75 and 0.80, which is consistent with what we note in the ice

> core record. Likewise, Panta et al. (2023) characterized 300,000 freshly emitted dust particles from the Moroccan Sahara and identified a median aspect ratio of 1.46, which is consistent with the ice core record. However, the preferential settling of rounded particles during long range transport is known to increase aspect ratio, as noted by Huang et al. (2020) who compared the aspect ratios of African dust particles reported across the literature. That is, for African dust, median aspect ratios increase from about 1.60 over the particle source regions to 1.90 following long range transport (Huang et al., 2020). From this perspective, the relatively low median aspect ratio of 1.42 measured for the Huascarán ice core is inconsistent with an Africa-to-Peru transport pathway.

Line 316 | We added "100%×" to our quantification of uncertainty to make it clearer to the reader that we express Poisson errors as percentages rather than fractions.

Line 326 | We re-worded "gibbsite, goethite, and rutile" to say "rutile, iron oxides, and aluminum oxides" for clarity and consistency with what is presented in Figure 5.

Lines 328 – 332 | We added the following to the discussion on bulk mineralogy:

> The very low abundance of iron oxide particles (0.6 ± 0.2%, n=11) suggests that their presence is unlikely to have a significant radiative impact. It is also worth noting that no carbonate minerals were identified in our analysis. While this result may have implications for source attribution, we do not interpret this in detail because carbonates are at least partially soluble (Sala et al., 2008) and therefore the absence of carbonate-like particles in the ice core may be attributed to dissolution when the ice samples were melted for filtration.

Line 360 | We replaced "Text S2" with "Text S3" to reflect the updated Supplementary Materials.

Lines 699 – 700 | We added the following to the Conclusions section: "There is also a need for higher-resolution sampling to improve our understanding of dust seasonality and its relationships to various climatological and environmental phenomena."

Line 750 | We fixed the DOI link for the Atherton and Sanderson (1987) citation.

Line 764 | We fixed the DOI link for the Besl (2022) citation.

Lines 812 – 814 | We added a citation for Chan et al. (2008).

Line 839 | We fixed a typo in the author list for Engelbrecht and Derbyshire (2010).

Lines 895 – 897 | We added a citation for Huang et al. (2020).

Lines 901 – 903 | We added a citation for Jickells et al. (2014).

Lines 918 – 919 | We added a citation for Knippertz and Stuut (2014).

Lines 945 – 946 | We added a citation for López-Villarrubia et al. (2010).

Lines 982 – 984 | We added a citation for Morman and Plumlee (2014).

Lines 999 – 1001 | We added a citation for Nenes et al. (2014).

Lines 1024 – 1026 | We added a citation for Perez et al. (2008).

Lines 1084 – 1087 | We added a citation for Sala et al. (2008).

Line 1133 | We updated the archive link to a DOI for Svensson et al. (2000).

Lines 1162 – 1163 | We added a citation for Varga et al. (2021).

Line 1197 | We fixed the DOI link for the Yu et al. (2015) citation.

From the Supplementary Materials

- We added a new Supplementary Text S1 to address the comments of Anonymous Referee #2. This text provides additional details about the mineral classification procedure and includes a descriptive table (Table S1) that organizes the details very clearly for the reader. The new Supplementary Text S1 reads as follows:

Supplementary Text 1 – Mineral Classification

Five independent mineral classification algorithms1 were applied to the EDS data for each particle analyzed in this study (Table S1). All of these algorithms, with the exception of the Severin dichotomous key, were automated using the open-source MATLAB® functions provided by Weber (2025) at https://github.com/weber1158/eds-classification. The outputs were cross-referenced with one another and with the Severin dichotomous key to determine the most likely mineral for each particle. The limitations presented in the table clarify the importance of relying on more than just one algorithm to determine mineralogy.

Table S1. Details on the mineral classification algorithms used in the text, including relevant classification criteria, benefits, and individual functions.

Algorithm	Algorithm Type	Classification Criteria	Benefits	Limitations
Donarummo et al. (2003)	Sorting scheme	EDS net intensity	Fast algorithm; designed for, and commonly used in, ice core studies	Restricted to aluminosilicate minerals; many “Unknown” classification nodes
Kandler et al. (2011)	Comparative criteria	Atom percent relative abundance	44 mineral groups, including quartz, salts (e.g., NaCl), and mixtures	Mostly broad mineral groups, not necessarily specific minerals
Panta et al. (2023)	Comparative criteria	Atom percent relative abundance	23 mineral classes, including simple minerals such as quartz and calcite	Cannot differentiate plagioclase solid solution or mafic minerals (pyroxene, amphibole, etc.)
Severin (2004)	Dichotomous key	EDS full spectrum	Includes 182 reference mineral spectra; very easy to use	Requires access to information in Severin (2004), usually in the form of a hard copy of the book; qualitative only; can be subjective and cannot be automated
Weber (2025)	Ensemble machine learning classifier	EDS net intensity	Provides probability table; can recognize palygorskite and can differentiate plagioclase solid solution series and is trained to recognize certain mafic minerals (e.g., pyroxenes)	Restricted primarily to aluminosilicate minerals

- Supplementary Text S1 from the original submission has been renamed as Supplementary Text S2, while the original Supplementary Text S2 has been renamed as Supplementary Text S3.
- The in-text references to the original Supplementary Table S1 have been changed to Table S2 in accordance with the previous bullet points.