Response to Reviewers

First and foremost, we would like to thank the reviewers for their time and feedback. Please find our responses below to each major/minor comment.

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 (Section 4.3 – Bulk Mineralogy; Lines 309—312) we intend to add the following: "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 308—309 in the revised manuscript we intend to add 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."

References

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