Response to Anonymous Reviewer 2

This paper presents a shear wave velocity model of the firn at Dome A, using established methods previously applied in other parts of the cryosphere. The results—particularly the identification of a relationship between firn compaction and radial anisotropy—are consistent with findings from studies conducted in other regions (e.g., Pearce et al., 2024; Diez et al., 2016). The value of this work lies in demonstrating that these results can be reproduced at Dome A, thereby contributing to our understanding of the consistency and geographic variability of firn anisotropy.

However, I find that the manuscript does not sufficiently establish the glaciological significance of these findings. The broader comparisons made between East and West Antarctica oversimplify the complex and highly localised nature of firn properties. Firn structure and compaction vary significantly across sites, and the paper's attempt to draw sweeping conclusions at the continental scale lacks the nuance required to be scientifically robust.

Moreover, the discussion does not adequately engage with existing literature on firn modelling and radial anisotropy. Key issues, such as intrinsic versus extrinsic causes of anisotropy, have been addressed more thoroughly in other studies yet are largely overlooked here. This gives the impression that the authors have not fully considered or integrated the existing body of research, weakening the paper's scientific foundation. The authors should narrow their focus to the specific implications of their results for Dome A. Any comparisons should be limited and carefully contextualized. A more detailed engagement with existing firn literature and a clearer articulation of the glaciological relevance of their findings would significantly improve the manuscript.

As it stands, I believe the paper would benefit from Major Reviews. While the Dome A data, and the proof that anthropogenic noise can be used to produce a model of firn, is a valuable contribution to the glaciological community, the current framing, discussion, and treatment of the literature do present itself in an appropriate way.

Dear Anonymous Reviewer 2,

Thank you very much for your constructive comments and suggestions! We have carefully revised our manuscript accordingly. We have focused the implications of our study on Dome A and highlighted the scientific glaciological significance of our finding about firn structure in the revised manuscript. Please find our point-to-point responses below.

The line numbers used in this response letter refers to the manuscript with marks.

Introduction:

1.The introduction would benefit from a clearer and more cohesive structure that better aligns with the specific focus of the study—imaging firn at Dome A. Currently, it opens with a broad discussion on Antarctica's vulnerability to climate change but does not make a direct connection to the relevance of firn studies within that context. For a journal like The Cryosphere, such general framing may not be necessary and could be replaced with a more targeted explanation of why firn structure and compaction at Dome A are scientifically important.

We followed your suggestion and reduced the general background description of Antarctica (Lines 33-39). We added information on the scientific significance of firn research, thereby making the introduction more focused on the shallow firn structure targeted in this study:

"Firn, formed through snow accumulation and subsequent compaction, represents the transitional layer between snow and glacial ice. It is an essential component of the ice sheet and plays a crucial role in material transport (MacAyeal, 2018). Its structure and evolution are influenced by processes such as densification, settling, and refreezing, which are highly sensitive to temperature variation, surface accumulation, and wind patterns (Ligtenberg et al., 2011; Wilkinson, 1988). Understanding firn dynamics is essential for accurately assessing surface mass balance, especially in Antarctica and Greenland (Gardner et al., 2018; Kowalewski et al., 2021; Velicogna et al., 2020). Moreover, firn modulates the depth at which atmospheric gases are sealed into the ice, directly impacting the interpretation of ice core records and paleoclimate reconstructions (Schwander et al., 1997). Variations in firn density and related physical properties affect the retrieval and interpretation of ice sheet elevation changes (Medley et al., 2022; Smith et al., 2023). Firn layers can store meltwater seasonally in the form of firn aquifers, influencing subglacial hydrology and potentially enhancing basal sliding (Forster et al., 2014; Miller et al., 2018). These multifaceted roles establish firn as a critical component in both observational and modeling efforts aimed at improving our understanding of polar ice sheet evolution and mass changes." (Lines 39-51 in the revised manuscript)

Dome A is the highest point of the East Antarctic Ice Sheet and differs significantly from West Antarctica and other coastal regions. It allows for longer preservation times of ice layers and more intact ancient ice records. Moreover, it offers a unique setting where characterizing the subsurface firn structure provides valuable insights into ice dynamics across the East Antarctic Plateau. In the revised manuscript, we have further added descriptions to highlight the significance of studying firn structure at Dome A:

"Although the shallow firn layer is known to be important, detailed investigations on the East Antarctic Plateau are still limited. Prior studies have demonstrated that the mechanical properties of firn can be influenced by ice crystal anisotropy at depths down to 100 m (Schlegel et al., 2019; Gerber et al., 2023; Pearce et al., 2024). Thus, applying seismic ambient-noise studies at Dome A can provide new insights into firn structure across high-elevation regions of the East Antarctic Plateau." (Lines 75-79 in the revised manuscript)

2. Additionally, the paragraph on seismic methods in Antarctica includes discussion of active-source techniques, which are not directly relevant to a study using ambient noise. A more focused discussion on ambient noise methods would strengthen the context. It would also be helpful to reference relevant studies using ambient noise to investigate firn structure, even if conducted outside Antarctica, since the methodology and findings are directly comparable to the present study.

We have added relevant studies using ambient-noise methods to investigate firn/ice structures in the revised manuscript:

"Similar ambient-noise studies have also been performed in Greenland, Glacier d'Argentière (France), Gornergletscher (Switzerland), Aletschgletscher (Switzerland) and de la Plaine Morte (Switzerland) (e.g., Pearce et al., 2024; Sergeant et al., 2020; Preiswerk and Walter, 2018; van Ginkel et al., 2025) to investigate glacier structures. These studies provided important insights into the subsurface structure of firn and ice." (Lines 63-66 in the revised manuscript)

We followed your suggestion and reduced the description of active-source methods, grouping them with radar, gravity, and other techniques (Lines 61-63 in the revised manuscript).

Data & Methods:

3.This section could be improved by restructuring for clarity and cohesion. At present, it reads somewhat like a list of loosely connected points. For example, Line 95 begins with a description of data processing, followed immediately by a sentence about station A's location—two pieces of information that could be better integrated into a more logically flowing narrative.

We have revised the section to improve its clarity and logical coherence, including minor wording and phrasing adjustments in several sentences (Lines 95-123):

"Dome A is located approximately at the central point of Line 1." (sentence moved from Line 115 to Line 95 in the revised manuscript)

"We first cut the ambient-noise data into 10-minute segments. Then, we applied both running absolute mean normalization and spectral whitening to the data. Subsequently, we used cross-correlation and phase-weighted stacking (Schimmel and Paulssen, 1997) to recover empirical Green's functions." (Lines 117-119 in the revised manuscript)

4.Please clarify the process used to forward model the dispersion curves, specifically how different modes were identified and associated. Additionally, it is stated that density is derived from Vs, although V_{SH} is used—this should be corrected or clarified.

(1) The forward problem is formulated as solving a nonlinear implicit function:

$$F(Vr, f; Vs, Vp, \rho, h) = 0,$$

where Vr is the phase velocity to be solved, f is frequency, and Vs, Vp (no need for Love wave), density ρ and layer thickness h are from our layered model. We apply a bisection algorithm to numerically search for the roots at each frequency. Multiple modes are identified by incrementally tracking zero-crossings corresponding to higher-mode solutions.

We clarify this process in the revised manuscript (Lines 142-144):

"The forward simulation of dispersion curves is solved with a Knopoff's method (Knopoff, 1964). For each frequency, we can obtain a set of solutions that correspond to fundamental and higher modes sequentially."

(2) We have corrected V_S with V_{SH} in the revised manuscript. (Line 153)

5. Several statements such as "fairly well" appear throughout the manuscript; these should be quantified where possible to improve scientific rigor. For instance, when discussing the fit between the derived density profile and core data, numerical metrics or visual comparisons would be helpful.

We quantified the misfit by using the root-mean-square error (RMSE) and added these values in the revised manuscript (Table A1 and Table A2 in Appendix A).

We calculated the density results under different empirical relationships (SV velocity-density from Yang et al. (2024) and SH velocity-density from Diez et al. (2014)) and ice density values (900 and

920 kg m^{-3}), and the corresponding RMSEs are summarized in Table A1. We also calculated the RMSEs of the multi-modal dispersion curves fitting (Table A2). The low RMSEs quantitatively support the reliability of the fitting results:

"The RMSEs between the density (mean and knee point results) and ice core data are less than 44 kg m^{-3} (Table A1 in Appendix A)." (Line 174 in the revised manuscript)

"The RMSEs between the synthetic and observed dispersion curves are less than 34 m s^{-1} (Table A2 in Appendix A)." (Line 180 in the revised manuscript)

Table A1. Root-mean-square errors (RMSE) between estimated density results (mean and knee point results) and ice core (DA2005) density.

Empirical Relationships	ρ_{ice} (kg m^{-3})	Mean RMSE (kg m^{-3})	Knee point RMSE (kg m^{-3})
Diez et al., 2014 (SH velocity-density)	900	43.8465*	43.5244*
Diez et al., 2014 (SH velocity-density)	920	46.2571	44.8456
Yang et al., 2024 (SV velocity-density)	920	47.0541	42.3032

* indicates the empirical relationship and ice density value used in the main text.

Table A2. Root-mean-square errors (RMSE) of multi-mode dispersion curve fitting.

Dispersion Modes	Love Wave		Rayleigh Wave	
	Mean RMSE (m s^{-1})	Knee point RMSE (m s^{-1})	Mean RMSE (m s^{-1})	Knee point RMSE (m s^{-1})
Mode 0	22.3250	17.0714	33.9394	25.7128
Mode 1	28.0159	28.1090	22.5358	29.8653
Mode 2	11.9490	8.3569	18.2726	19.9725
Mode 3	14.0678*	15.2696*	14.5797*	14.3996*
Mode 4	—	—	21.4708*	28.0765*

* indicates the mode not involved in the dispersion curve inversion.

6. On Line 165, the interpretation that faster V_{SV} than V_{SH} in the shallow firn is due to vertically aligned snow grains needs further explanation. Please elaborate on the physical mechanism behind this interpretation, and consider whether snow grain settling alone can produce this effect. It would also be beneficial to include a sensitivity analysis to demonstrate which depth ranges are constrained by the frequencies used in the inversion. Providing separate plots of V_{SH} and V_{SV}, in addition to their ratio, in the supplementary material would also help readers interpret the results more fully.

(1) We thank the reviewer for the valuable suggestion. We have removed the interpretation of shallow weak anisotropy (< 5 %) in the revised manuscript (Line 192). Because our observations lack data at shorter wavelength ranges (< 40 m), and the anisotropy results in the shallow layer (< 20 m) exhibit high uncertainty (Fig. 4a).

We have added explanations of the anisotropy in the revised manuscript (Lines 212-232):

"Previous studies (e.g., Pearce et al., 2024; Chaput et al., 2023; Diez et al.,2016; Picotti et al., 2015; Schlegel et al., 2019) show that firn anisotropy may be caused by three primary mechanisms: (1) effective anisotropy, related to very thin layers formed during firn densification; (2) structural anisotropy, related to fractures or microcracks caused by non-isotropic stress; and (3) intrinsic anisotropy, associated with preferred crystal orientation.

In the shallow layer (< 20 m), some lateral variation may exist along Line 1 (~10 km). Our observations lack data at shorter wavelength ranges (< 40 m), and the weak anisotropy results (< 5 %) in the shallow layer exhibit high uncertainty (Fig. 4a). Therefore, we refrain from further interpretation of the anisotropy within the upper 20 m.

The mean accumulation rate in the Dome A region is about 2.3 cm water equivalent per year (Jiang et al., 2012) and, therefore, firn densification can produce millimeter-scale layers whose thicknesses are much smaller than the seismic wavelengths observed in our study. These thin layers lead to different elastic properties in the vertical and horizontal directions (Diez et al.,2016; Schlegel et al., 2019). It makes the SH waves travel relatively faster than SV waves along the horizontal direction, which is consistent with our observation.

The average strain rate in the Dome A region (~1.6×10^{-12} s^{-1}) (Yang et al., 2014) is much lower than the typical ductile to brittle transition values for firn (~10^{-4} to 10^{-2} s^{-1}) (Narita, 1984; Kirchner et al., 2001), suggesting that tensile stresses are unlikely to cause brittle crevasse in our study area. Therefore, the structural anisotropy caused by crevasse is not considered the main reason for anisotropy in the Dome A region.

Regarding intrinsic anisotropy, the preferred orientation direction of ice crystals is related to gravitational compaction and ice flow. For the firn layer after reaching the first critical depth (28.1 m), slow ice flow (~11.1 cm a^{-1}) that is perpendicular to the Line 1 (Yang et al., 2014) causes re-orientation of the crystal along the horizontal direction. This leads to SH waves traveling faster than SV waves. Overall, we infer that the observed anisotropy at Dome A region is primarily attributed to effective anisotropy and intrinsic anisotropy."

(2) We showed the sensitivity kernels of multi-modal Love and Rayleigh waves (Fig. A2, which is also added in Appendix A in the revised manuscript). Overall, the inclusion of higher modes extends the usable frequency range, enhances the constraints on the inversion, and improves the accuracy of the results.

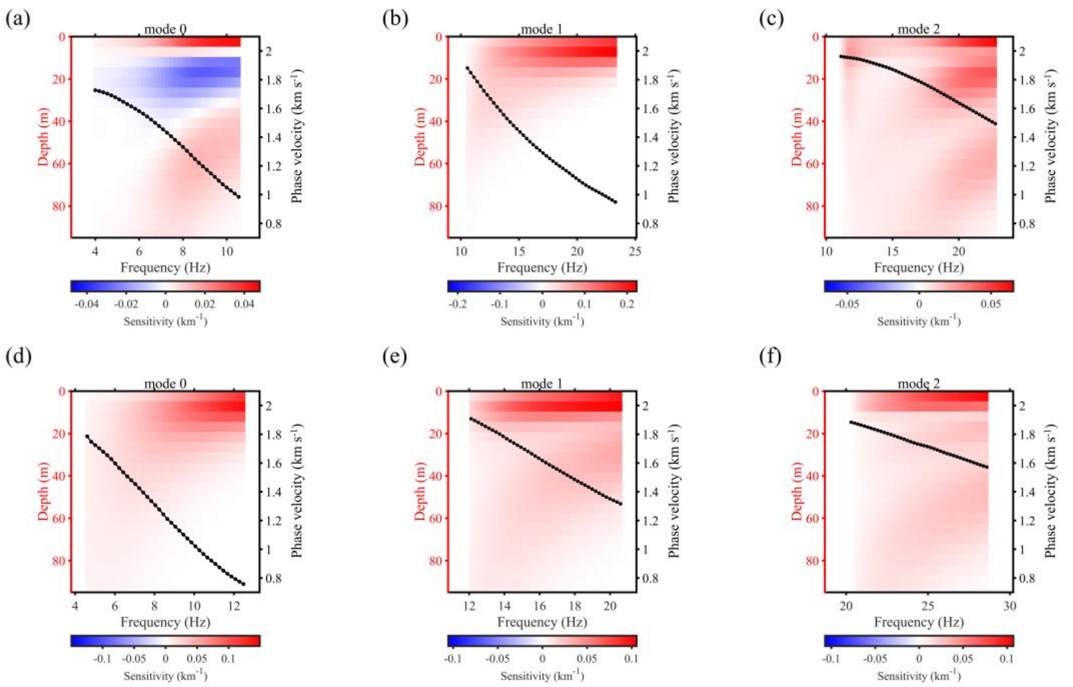

Figure A2. Depth sensitivity kernels at different frequencies for Rayleigh (a-c) and Love (d-f) waves for the fundamental (mode 0), first high (mode 1), and second high (mode 2) mode. The black dotted lines represent the dispersion curves for each mode.

(3) In the original manuscript, Figure 3a and b show the solutions of V_{SH} and V_{SV}, respectively. The radial anisotropy ($V_{SH}/V_{SV} - 1$) shown by the grey lines in Figure 4a is calculated from all solutions in these two sets. To help readers better understand the relationship between V_{SH} and V_{SV}, we have now plotted their solution sets and mean solutions in a single figure (Fig. A3, which is also added in Appendix A in the revised manuscript) using different colors for clarity.

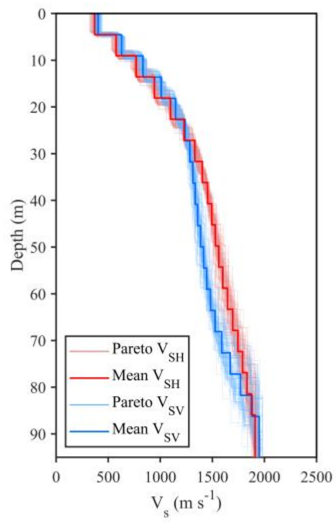

Figure A3. Pareto solution sets of V_{SH} (light red lines) and V_{SV} (light blue lines). The mean solutions of V_{SH} and V_{SV} are marked by red and blue lines, respectively. These results are the same as those presented in Figure 3a and b of the main text.

Discussion:

7.The discussion would benefit from a sharper focus on the specific insights gained from studying firn at Dome A. While comparing firn conditions across East and West Antarctica may seem appealing, such comparisons must be made cautiously due to the highly localized nature of firn compaction processes. The current manuscript draws broad conclusions about regional differences that are not strongly supported by the data and may oversimplify the complexity of firn behaviour. To strengthen the paper, the discussion should centre on the local significance of the Dome A firn profile, and what new insights are gained from applying ambient noise methods in this specific setting.

We accepted your suggestion and revised the discussion accordingly. In the revised manuscript, we have emphasized that our results are based on one-dimensional velocity structures with limited spatial coverage, and thus may only reflect local differences in the regions where data were collected. These constraints are not sufficient to comprehensively assess the differences between East and West Antarctica:

"Figure 5a suggests slightly higher V_S in the shallow regions in West Antarctica. However, it should be noted that the firn densification process exhibits regional variability and is influenced by multiple factors, such as temperature and ice velocity. The annual mean temperature in the West Antarctic region is generally higher than that of the East Antarctic Plateau by approximately 20–30 °C (Nielsen et al., 2023; Wang et al., 2023), which may contribute to the differences in velocity structure. Different localized ice velocities, heat flux, sublimation, and blowing snow erosion (Goujon et al., 2003) at these specific sites might also influence the shallow structure. Although Fig. 5a indicates a significant difference in the V_S structures between East and West Antarctica, the observations are not sufficiently large to draw conclusion at the current stage." (Lines 253-259 in the revised manuscript)

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