Response to Reviewer 1 (Yan Yang)

General comments:

This manuscript presents results using high-frequency cultural seismic noise from the Kunlun Station to image the shallow firn structure in the Dome A region of East Antarctica. The work resolves S-wave velocity and radial anisotropy down to ~100 m in the firn and validates the results with nearby ice-core data and results from other sites in Antarctica. The study offers an application of passive seismic methods in a remote polar region with limited prior coverage. The paper is well organized. The results are well illustrated. The implications for regional differences in firn compaction and accumulation rates are relevant. Overall, I believe this manuscript is well suited for publication in The Cryosphere after minor revisions.

Dear Dr. Yan Yang,

Thank you very much for your constructive comments and suggestions! We have carefully revised our manuscript accordingly. Please find our point-to-point responses below.

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

Specific comments:

1. In Figure 3c, the density model generally agrees with borehole studies, but some misfit is still present—specifically, overestimation below ~50 m and underestimation above ~30 m. A similar misfit pattern is reported in the cited study by Yang, Zhan et al. (2024), which motivated the development of an East Antarctica–specific empirical velocity–density relationship to better match observed firn density profiles. I see that you use Equation (2) from Diez et al. (2014), which is based on SH-wave velocity. Since you also resolve Vsv and your site is in the East Antarctic Plateau, I am curious how the results would compare if you applied the Yang, Zhan et al. (2024) relationship using your Vsv model. Additionally, Equation (2) assumes an ice density of 900 kg/m³—would using a more conventional value such as 920 kg/m³ change your results significantly? I understand the need for site-specific relations, but a brief comparison or discussion would strengthen this section.

We followed your suggestion and compared the results obtained using different parameter values in the empirical relationship.

(1) The results using different ice densities (900 and 920 kg m^{-3}, Figure A1a) are very similar. Relatively speaking, the estimated density profile using an ice density of 920 kg/m³ is slightly closer to the borehole data (DA2005) in the region shallower than 50 m depth, and slightly further from DA2005 in the region deeper than 50 m depth (blue and yellow lines in Figure A1a). It indicates that the choice of ice density has a minor impact on the result.

(2) In Figure A1b, the density result also generally agrees with the borehole data (DA2005). The result based on the relationship from Yang, Zhan et al. (2024) improves the fit within the upper ~30 m compared to that of Diez et al. (2014) but also shows some deviations at greater depths. The RMSE results (Table A1) indicate that the densities estimated using different empirical relationships and ice density values generally agree with the ice core data.

(3) We also agree that a site-specific velocity-density relationship may be beneficial. Given the spatial distance and difference in acquisition time between the borehole and our linear array, the borehole data serve only as a reference density result. Further borehole measurements,

ideally closer in both space and time to the array, may help to establish a representative empirical relationship near the Dome A region.

We added this information in the Appendix A (Figure A1 and Table A1).

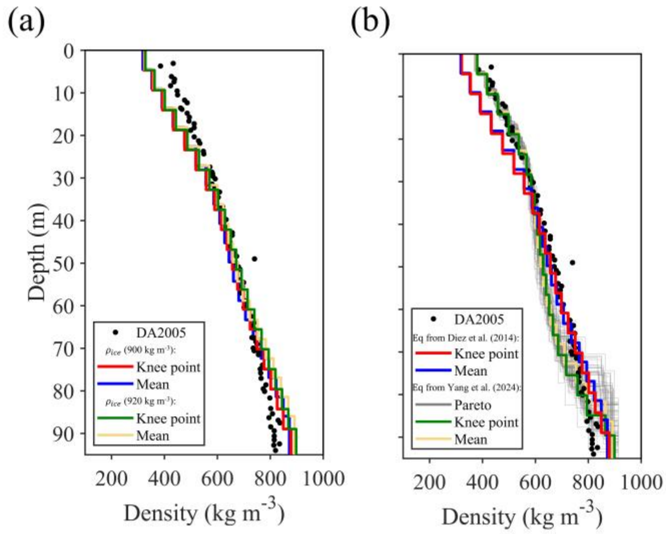

Figure A1. Density estimated by empirical relationship. **(a)** Using a relationship from Diez et al. (2014) with V_{SH}. The red and blue lines use an ice density of 900 kg m^{-3}, while the green and yellow lines use 920 kg m^{-3}. **(b)** Using the relationship from Yang, Zhan et al. (2024) with V_{SV} (grey, green, and yellow lines). The filled circles show the ice core (DA2005) density near Dome A. The red and blue lines in (a) and (b) are consistent with Fig. 3c in the main text.

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.

2. You have cited studies reporting radial anisotropy in firn at levels of 10–15% for several West Antarctic sites. I suggest also citing Schlegel et al. (2019), which examines radial anisotropy at the Kohnen site in East Antarctica. Additionally, I am curious about the robustness of the radial anisotropy inferred above 20 m depth. The cited study Pearce et al. (2024), using similar frequency bands, noted a lack of sensitivity to the top ~20 m in surface-wave inversions and therefore did not interpret their observed shallow radial anisotropy. Could you show the Rayleigh wave sensitivity kernel and comment on whether your inversion results are similarly limited in sensitivity in the

uppermost firn?

We have added an introduction to Schlegel et al. (2019) in the revised manuscript (Lines 77, 212, and 222).

We showed the sensitivity kernels for multi-modal Love and Rayleigh waves (Fig. A2, which is also added in Appendix A in the revised manuscript). The inclusion of higher modes improves the sensitivity of surface waves to the shallow region. However, on the one hand, the sensitivity to the structures shallower than 20 m is overall limited, and on the other hand, the Pareto results (Fig. A3; consistent with Fig. 4a in the original manuscript) show relatively greater uncertainty of radial anisotropy in the shallow region. Therefore, we didn’t interpret the result in the top 20 m.

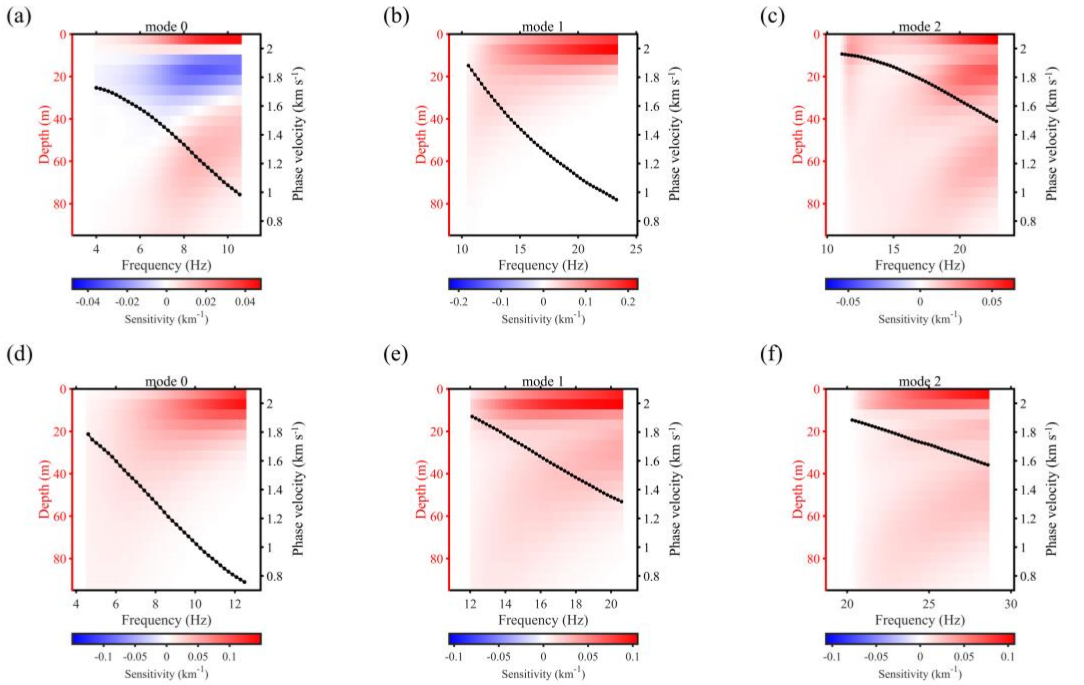

Figure A2. Depth sensitivity kernels at different frequencies for Rayleigh (a-c) and Love (d-f) waves for the fundamental (mode 0), first high (mode 1), and second high (mode 2) mode. The black dotted lines represent the dispersion curves for each mode.

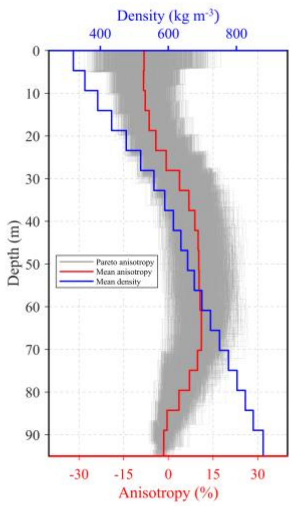

Figure A3. Radial anisotropy. The figure is taken from Figure 4a of the original manuscript.

3. Lines 1 and 2 are oriented in different azimuths, providing an excellent opportunity to investigate azimuthal anisotropy. Applying the same dispersion analysis workflow to Line 2 could help evaluate directional dependence of seismic velocities, which may relate to ice flow direction or crystal fabric. Is there a reason why dispersion analysis was not performed on Line 2—perhaps due to the absence of a short-spacing array needed for resolving higher modes? Regardless, I suggest including a discussion on the potential for azimuthal anisotropy and how it might be constrained by the existing dataset.

In this manuscript, we mainly used the data along Line 1 in order to estimate the radial anisotropy at the Dome A region. We didn't use the data from Line 2 because it is located further away from Dome A compared to Line 1. We agree that the differing orientations of Line 1 and Line 2 make the investigation of azimuthal anisotropy possible. We added the following content to the "Discussion" in the revised manuscript (Lines 260-263):

"In addition, Line 1 and Line 2 are oriented along different azimuths, making the investigation of azimuthal anisotropy possible. The azimuthal anisotropy might provide additional information about the direction of ice flow or the orientation of crystal fabric, and strengthen our knowledge about the ice in the inland area of East Antarctica. The estimation of azimuthal anisotropy deserves further study in the future."

4. The observed difference in firn density profiles between East and West Antarctica is interpreted as a result of differences in snow accumulation rates. Temperature is another factor that significantly affects firn densification rates. Could you provide information or discussion on the differences in mean annual temperature between your site and the West Antarctic sites included in your comparison?

The comparison between the temperature in East and West Antarctica has been studied by Nielsen et al. (2023) and Wang et al. (2023). Their results show that the annual mean temperature in the West Antarctic region is generally higher than that of the East Antarctic Plateau by approximately 20–30 °C. We added this information in the revised manuscript (Lines 255-256):

"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."

References:

Nielsen, E. B., Katurji, M., Zawar-Reza, P., and Meyer, H.: Antarctic daily mesoscale air temperature dataset derived from MODIS land and ice surface temperature, Sci. Data, 10, 833. https://doi.org/10.1038/s41597-023-02720-z, 2023.

Schlegel, R., Diez, A., Löwe, H., Mayer, C., Lambrecht, A., Freitag, J., Miller, H., Hofstede, C., and Eisen, O.: Comparison of elastic moduli from seismic diving-wave and ice-core microstructure analysis in Antarctic polar firn, Ann. Glaciol., 60, 220-230, https://doi.org/10.1017/aog.2019.10, 2019.

Wang, Y., Zhang, X., Ning, W., Lazzara, M. A., Ding, M., Reijmer, C. H., Smeets, P. C. J. P., Grigioni, P., Heil, P., Thomas, E. R., Mikolajczyk, D., Welhouse, L. J., Keller, L. M., Zhai, Z., Sun, Y., and Hou, S.: The AntAWS dataset: a compilation of Antarctic automatic weather station observations, Earth Syst. Sci. Data, 15, 411–429, https://doi.org/10.5194/essd-15-411-2023, 2023.