Response to Anonymous Reviewer 3

This paper presents a welcome iteration in ambient noise methods applied to imaging firn media, with a focus here on Dome A in East Antarctica. The authors use data collected from linear nodal arrays and leverage human camp noise to recover multi-modal surface waves to perform a near-surface velocity inversion. The paper is methodologically simple, in that the methods are well established, and the results are well presented.

As do the other reviewers, I have a few issues with the interpretation of results and the relative simplicity of the analysis in the global context of firn formation and structure:

Dear Anonymous Reviewer 3,

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.

1. Fig 3c: I agree with reviewer 1 on the velocity/density relationship you used here from Diez 2014, and the probable necessity for an updated form. The accumulation and strain environment of West Antarctica significantly differs from East Antarctica, and that could easily account for your disparities.

Thank you for your suggestion and we 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/m^3 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).

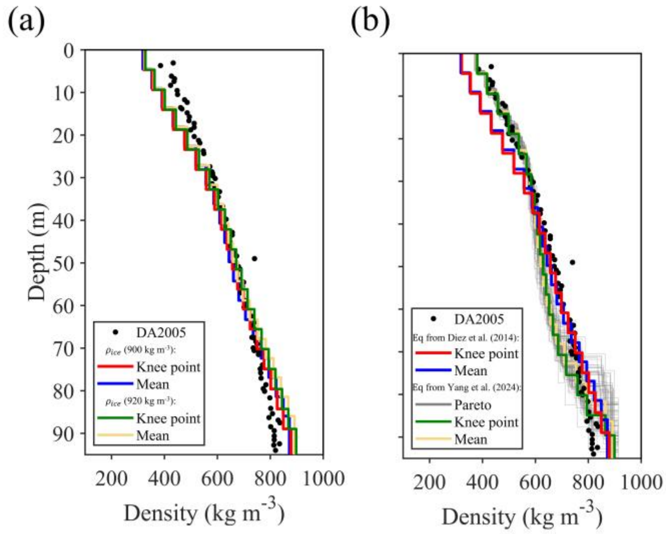

Figure A1. Density estimated by empirical relationship. **(a)** Using a relationship from Diez et al. (2014) with V_{SH}. The red and blue lines use an ice density of 900 kg m^{-3}, while the green and yellow lines use 920 kg m^{-3}. **(b)** Using the relationship from Yang, Zhan et al. (2024) with V_{SV} (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. Firn anisotropy in East Antarctica very likely can be explained almost entirely from radial anisotropy given the minimal ice flow, but when comparing to West Antarctica, you should be cautious. For instance, flowing ice and firn has been shown to have multiple azimuthal anisotropy mechanisms related to fracturing and firn plasticity, and these can impact estimates of the magnitude of radial anisotropy estimates. Have a look at:

Chaput J, Aster R, Karplus M, Nakata N, Gerstoft P, Bromirski PD, Nyblade A, Stephen RA, Wiens DA (2023). Near-surface seismic anisotropy in Antarctic glacial snow and ice revealed by high-frequency ambient noise. Journal of Glaciology 69(276), 773 – 789. https://doi.org/10.1017/jog.2022.98

Advected fractures and other embedded features can also affect the local velocity model in West Antarctica firn, so it's certainly worth mentioning the ultra-local side of firn profiles.

Expanding on the discussion in terms of firn formation differences would be an improvement here, though given that edits will be largely constrained to discussion (with the exception of perhaps a test related to point 1 above), I think minor reviews are appropriate.

(1) Thank you for your valuable suggestion. We have added explanations of the anisotropy results 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 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)

References:

Chaput, J., Aster, R., Karplus, M., Nakata, N., Gerstoft, P., Bromirski, P. D., Nyblade, A., Stephen. R. A., and Wiens, D. A.: Near-surface seismic anisotropy in Antarctic glacial snow and ice revealed by high-frequency ambient noise, J. Glaciol., 69, 773-789, https://doi.org/10.1017/jog.2022.98, 2023.

Forster, R. R., Box, J. E., van den Broeke, M. R., Miège, C., Burgess, E. W., van Angelen, J. H., Lenaerts, J. T. M., Koenig, L. S., Paden, J., Lewis, C., Gogineni, S. P., Leuschen, C., and McConnell, J. R., Extensive liquid meltwater storage in firn within the Greenland ice sheet, Nat. Geosci., 7, 95-98, https://doi.org/10.1038/ngeo2043, 2014.

Gerber, T. A., Lilien, D. A., Rathmann, N. M., Franke, S., Young, T. J., Valero-Delgado, F., Ershadi, M. R., Drews, R., Zeising, O., Humbert, A., and Stoll, N.: Crystal orientation fabric anisotropy causes directional hardening of the Northeast Greenland Ice Stream, Nat. Commun., 14, 2653, https://doi.org/10.1038/s41467-023-38139-8, 2023.

Kirchner, H., Michot, G., Narita, H., Suzuki, T.: Snow as a foam of ice: Plasticity, fracture and the brittle-to-ductile transition, Philos. Mag. A., 81, 2161-2181, https://doi.org/10.1080/01418610108217141, 2001.

Kowalewski, S., Helm, V., Morris, E. M., and Eisen, O.: The regional-scale surface mass balance of Pine Island Glacier, West Antarctica, over the period 2005–2014, derived from airborne radar soundings and neutron probe measurements, The Cryosphere, 15, 1285 – 1305, https://doi.org/10.5194/tc-15-1285-2021, 2021.

Medley, B., Neumann, T. A., Zwally, H. J., Smith, B. E., and Stevens, C. M.: Simulations of firn processes over the Greenland and Antarctic ice sheets: 1980–2021, The Cryosphere, 16, 3971–4011, https://doi.org/10.5194/tc-16-3971-2022, 2022.

Miller, O., Solomon, D. K., Miège, C., Koenig, L., Forster, R., Schmerr, N., Ligtenberg, R. M., and Montgomery, L.: Direct evidence of meltwater flow within a firn aquifer in southeast Greenland, Geophys. Res. Lett., 45, 207-215, https://doi.org/10.1002/2017GL075707, 2018.

Narita, H.: An experimental study on the tensile fracture of snow, Contrib. Inst. Low Temp. Sci., 32, 1–37, http://hdl.handle.net/2115/20246, 1984.

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.

Preiswerk, L. E., Walter, F.: High-Frequency (> 2 Hz) Ambient Seismic Noise on High-Melt Glaciers: Green's Function Estimation and Source Characterization, J. Geophys. Res. Earth Surf., 123, 1667-1681, https://doi.org/10.1029/2017JF004498, 2018.

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.

Schwander, J., Sowers, T., Barnola, J. M., Blunier, T., Fuchs, A., Malaizé, B.: Age scale of the air in the summit ice: Implication for glacial-interglacial temperature change, J. Geophys. Res. Atmos, 102, 19483-19493, https://doi.org/10.1029/97JD01309, 1997.

Sergeant, A., Chmiel, M., Lindner, F., Walter, F., Roux, P., Chaput, J., Gimbert, F., and Mordret, A.: On the Green's function emergence from interferometry of seismic wave fields generated in high-melt glaciers: implications for passive imaging and monitoring, The Cryosphere, 14, 1139–1171, https://doi.org/10.5194/tc-14-1139-2020, 2020.

Smith, B. E., Medley, B., Fettweis, X., Sutterley, T., Alexander, P., Porter, D., and Tedesco, M.: Evaluating Greenland surface-mass-balance and firn-densification data using ICESat-2 altimetry, The Cryosphere, 17, 789–808, https://doi.org/10.5194/tc-17-789-2023, 2023.

van Ginkel, J., Walter, F., Lindner, F., Hallo, M., Huss, M., and Fäh, D.: Spectral characteristics of seismic ambient vibrations reveal changes in the subglacial environment of Glacier de la Plaine Morte, Switzerland, The Cryosphere, 19, 1469–1490, https://doi.org/10.5194/tc-19-1469-2025, 2025.

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.

Wilkinson, D. S.: A pressure-sintering model for the densification of polar firn and glacier ice, J. Glaciol., 34, 40–45, https://doi.org/10.3189/s0022143000009047, 1988.

Yang, W., Dou, Y., Zhao, B., Guo, J., Tang, X., Zuo, G., Wang, Y., Chen, Y., and Zhang, Y.: Inversion for the density–depth profile of Dome A, East Antarctica, using frequency-modulated continuous wave radar, J. Glaciol., 67, 1213–1227, https://doi.org/10.1017/jog.2021.70, 2021.

Yang, Y., Sun, B., Wang, Z., Ding, M., Hwang, C., Ai, S., Wang, L., Du, Y., and E, D.: GPS-derived velocity and strain fields around Dome Argus, Antarctica, J. Glaciol., 60, 735 – 742, https://doi.org/10.3189/2014JoG14J078, 2014.