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Revealing firn structure at Dome A region in East Antarctica using cultural seismic noise

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Abstract. Antarctica is mostly covered by snow, firn, and glacier ice, and the transformation from snow to firn and glacier ice influences energy transfer and material transport in polar regions. In this paper, we deployed three linear seismic arrays near Dome A in East Antarctica during China's 39th Antarctic scientific expedition and used seismic ambient noise to reconstruct the firn structure nearby. The result shows that the ambient noise mainly comes from the Kunlun Station and is related to human activities. We resolved empirical Green's function that contains abundant multi-modal surface waves from 3 to 35 Hz, and reconstructed the shallow S-wave velocity, density, and radial anisotropy structures by inverting them. The reliability of the structure was validated by the ice-core data, which demonstrates the effectiveness of using cultural seismic noise for the reconstruction of shallow structures in Antarctica. The result shows that the S-wave velocity increases rapidly with a negative radial anisotropy (SH wave travels slower than SV wave) in the top 28 m, which corresponds to the transformation from snow to firn. The firn layer shows a fairly strong positive radial anisotropy (SH wave travels faster than SV wave) between 40 m and 70 m in depth, which corresponds to the recrystallization of firn. The radial anisotropy vanishes to zero at around 84 m in depth, denoting the transformation from firn to glacier ice. Overall, the multi-parameter results clearly show the transformation from snow to ice, and the internal evolution of firn at Dome A region. Furthermore, we compared several existing S-wave velocity profiles of firn structures in West and East Antarctica and found a relatively shallower transformation depth from firn to ice in West Antarctica, which indicates a faster accumulation rate of snow in West than in East Antarctica.

1 Introduction

The majority of Antarctica is covered by glacier ice all year round, holding enough water to raise the global sea level by 58 meters (Fretwell et al., 2013). Antarctica plays a significant role in climate change, sea-level change, and ecosystem evolution.

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Over recent decades, the contribution of ice loss from Antarctica to sea-level rise has been accelerating (Gardner et al., 2018; Shepherd et al., 2019). Influenced by warm ocean currents, the West Antarctic Ice Sheet (WAIS) is the region with the most severe mass loss, making it the most vulnerable, unstable, and sensitive to climate change. In contrast, the East Antarctic Ice Sheet (EAIS) was more stable with less mass loss (Smith et al., 2020; Velicogna et al., 2020). However, some recent observations suggest that the EAIS is also sensitive to climate change (Stokes et al., 2022; Wang et al., 2021).

Firn, formed through snow accumulation and subsequent compaction, represents the transitional layer between snow and glacial ice, while also playing a crucial role in material transport (MacAyeal, 2018). The current measurement of ice sheet mass changes often relies on satellite altimetry (Boening et al., 2012). Furthermore, it has low sensitivity to the firn layer, making it difficult to distinguish whether changes in the ice sheet are due to surface accumulation (increased snowfall) or internal density changes (firn compaction; Ligtenberg et al., 2011; Yang et al., 2024). Consequently, complementary approaches are essential to provide a more detailed characterization of the subsurface structure, thereby enabling a more precise assessment of ice sheet changes.

Seismic ambient-noise interferometry has been widely used to study subsurface structure (Nakata et al., 2019). Ambient noises related to both natural and cultural sources are used to characterize the Earth models across scales (Mi et al., 2022; Liu et al., 2023; Zhao et al., 2023; Feng et al., 2024). Seismic interferometry utilizes the cross-correlation functions (CCFs) of the seismic wavefields between station pairs to obtain the empirical Green's function, which can be used to analyze the S-wave velocity and anisotropic structure. Ambient-noise tomography has been successfully used in Antarctica to obtain its structures down to hundreds to thousands of meters (e.g., Fu et al., 2022; Chaput et al., 2022). The use of active-source seismic data further improves the accuracy of the shallow structures not only in Antarctica (e.g., Qin et al., 2024; Yang et al., 2024; Zhang et al., 2022) but also in Greenland (Fichtner et al., 2023). Most of the existing studies on the firn structure are in the WAIS, mainly because more scientific activities were conducted in West Antarctica. However, in recent years, seismic methods along with gravity, radar, and ice core measurements (e.g., Yang and Li, 2022; Tang et al., 2020) have played an increasingly important role in advancing scientific exploration in the EAIS.

Dome A is the highest point of the EAIS with an elevation of about 4093 m. It maintains extreme environmental conditions characterized by low temperatures and low snow accumulation rate (Hou et al., 2007). It preserves ice core records with extended temporal continuity and stratigraphic integrity, maintaining paleoclimate information that enhances our understanding of global climate change (Ma et al., 2010). Some studies suggest that Dome A may contain ice older than 1 million years (Sun et al., 2014). Investigations of its meteorological conditions, surface geomorphology, ice thickness, subglacial topography, ice flow, and internal stratigraphy offer key constraints on the evolution of EAIS (Tang et al., 2012).

In this study, we collected three-component ambient-noise data during China's 39th Antarctic scientific expedition to study the shallow structure at Dome A region in the EAIS. After processing and analyzing the data, we obtained the multi-modal dispersion curves of Rayleigh- and Love-waves and derived the SV- and SH-wave velocity (V_{SV} and V_{SH}), respectively. The presence of human activities, acting as stable seismic sources, improves the robustness of our results. We used the data to investigate the firn structure at Dome A region by reconstructing its S-wave velocity, density, and radial anisotropy profiles.

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These results are compared with previous studies in other regions in Antarctica to analyze the shallow firn structures of the entire Antarctica.

2 Data and Methods

We deployed a total of 73 three-component seismic nodes near Dome A and the Kunlun Station, which is located about 7.3 km southwest of Dome A (Fig 1a). In this study, we mainly used 19 seismic nodes with a 500 m interval (Line 1) to reconstruct the shallow structure at Dome A region. In addition, 18 seismic nodes deployed with a 500 m interval on the south side of the Kunlun station (Line 2), and 7 seismic nodes deployed on the north part of Line 1 with irregular intervals ranging from ~90 m to 1000 m (Line 3) were used to analyze the distribution of ambient-noise source and to help identifying multi-modal dispersion curves, respectively. Three lines acquired the seismic data with a length of 9 days, 6 days, and 14 days, respectively. Line 1 and Line 2 are located to the northeast and southeast of the Kunlun Station, respectively. Unlike the study which shows that inland seismic noise in Antarctica is typically dominated by the secondary and primary microseism bands (Anthony et al., 2015), the dominant frequencies of the data are about 8 Hz and 15 Hz, indicating strong high-frequency noise in this region. We analyze the ambient-noise source of seismic data in Line 1 and Line 2 by beamforming. Figures 1b-e show the energy distribution of ambient noise for the two linear arrays at the two dominant frequencies, respectively. The energy peaks in Line 1 (Fig. 1b and c) are more prominent than those in Line 2 (Fig. 1d and e), suggesting a more concentrated noise source in the data acquired by Line 1.

Results of Line 1 and Line 2 show a unidirectional noise source at both 8 Hz and 15 Hz. The dominant source is around 217° in the data acquired by Line 1 and 340° in Line 2. It suggests that the ambient-noise source mainly comes from the Kunlun Station (Fig. 1a) and is mainly related to human activities during China's 39th Antarctic scientific expedition. The primary peak at 8 Hz corresponds to the fundamental-mode surface wave, while the two peaks at 15 Hz correspond to higher modes. In other words, we mainly used cultural ambient-noise in this paper to reconstruct the near-surface structure at Dome A region.

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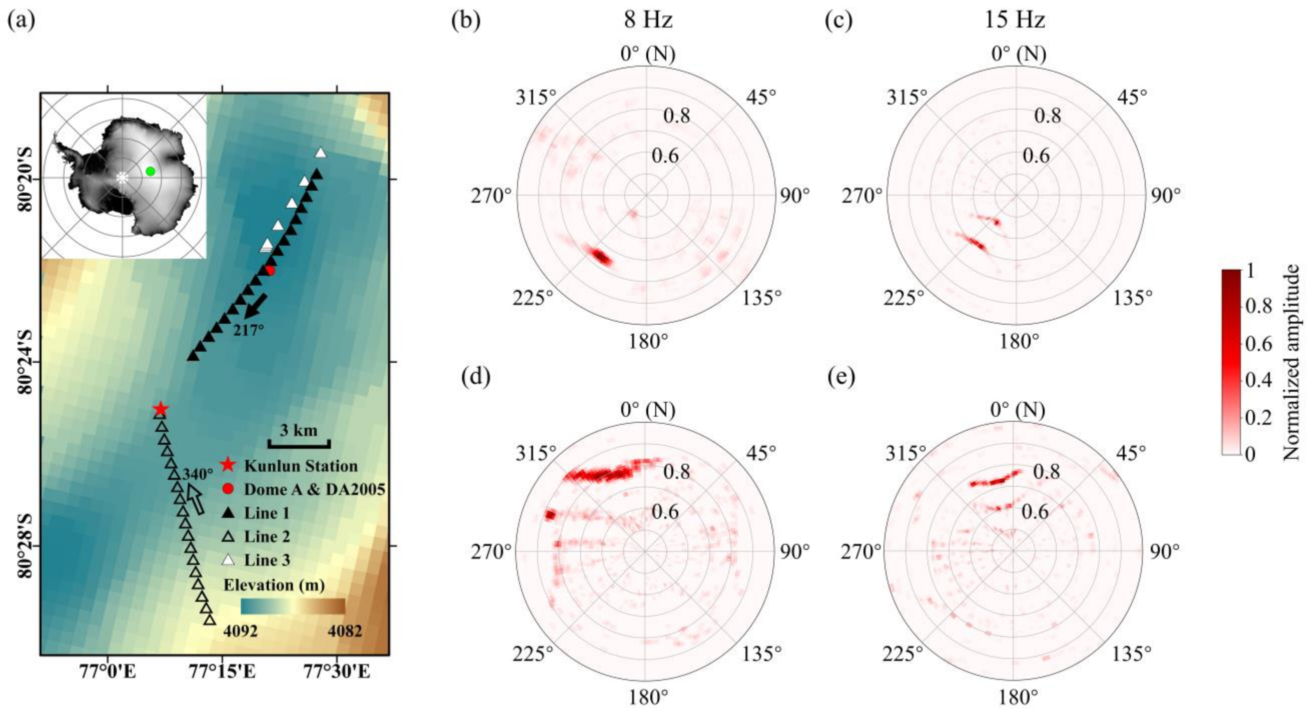

Figure 1. Arrays information and estimation of ambient-noise source location. **(a)** Line 1 (black triangles) and Line 2 (black hollow triangles) were collected in January 2023, and Line 3 (white triangles) was collected in January 2024. The Kunlun Station (red pentagram), Dome A and the ice core (DA2005) (red circle) are also marked. The inset provides an overview of the study location (green circle) on the whole Antarctica. Beamforming results of the vertical component at frequencies **(b)** 8 Hz and **(c)** 15 Hz for Line 1, and **(d)** and **(e)** at the same frequencies for Line 2. The back azimuths are from 0° (north) to 360° and slowness is from 0.4 to 1.0 s km^{-1}. Two arrows in **(a)** denote the primary back azimuths from the beamforming results.

We processed the ambient-noise data acquired by Line 1 using seismic interferometry (Bensen et al., 2007). Dome A is located approximately at the center point of Line 1. The ambient-noise data was cut into 10-minute segments. We applied both running absolute mean normalization and spectral whitening to the data and used cross-correlation and phase-weighted stacking (Schimmel and Paulssen, 1997) to recover empirical Green's functions. The CCFs of vertical-vertical (ZZ), radial-radial (RR), and transverse-transverse (TT) components are strongly asymmetric (Fig. 2a and c) due to the existence of a strong directional source. The CCFs that correspond to the cultural seismic noise from the Kunlun Station are clear and of high signal-to-noise ratio (up to 80 dB).

We obtained the dispersion spectra of Line 1 and Line 3 (Fig. 2b and d) by the phase shift method (Park et al., 1999), respectively. Relatively strong spatial aliasing (Cheng et al., 2023), which is caused by relatively large inter-station distances (~500 m), is observed in the high-frequency range of data in Line 1 (Fig. 2b). Line 3 was designed with irregular spacing containing a shortest inter-station distance of 90 m, which greatly helps with the identification of multi-modal surface-wave dispersion curves. By considering the dispersion spectra from CCFs of Line 1 and Line 3 simultaneously, we can obtain multi-modal dispersion curves accurately. A total of five modes in Rayleigh waves and four modes in Love waves are identified

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(arrows in Fig. 2b and d), while the first three modes are recognized with relatively higher confidence (white arrows in Fig. 2b and d). Noise data from Line 1 and Line 3, which were collected at different times, show high consistency in the multi-modal dispersion curves. The estimated dispersion curves agree with the slowness values in the beamforming results (Figures 1b and 1c), which further proves the reliability of the multi-modal dispersion curves.

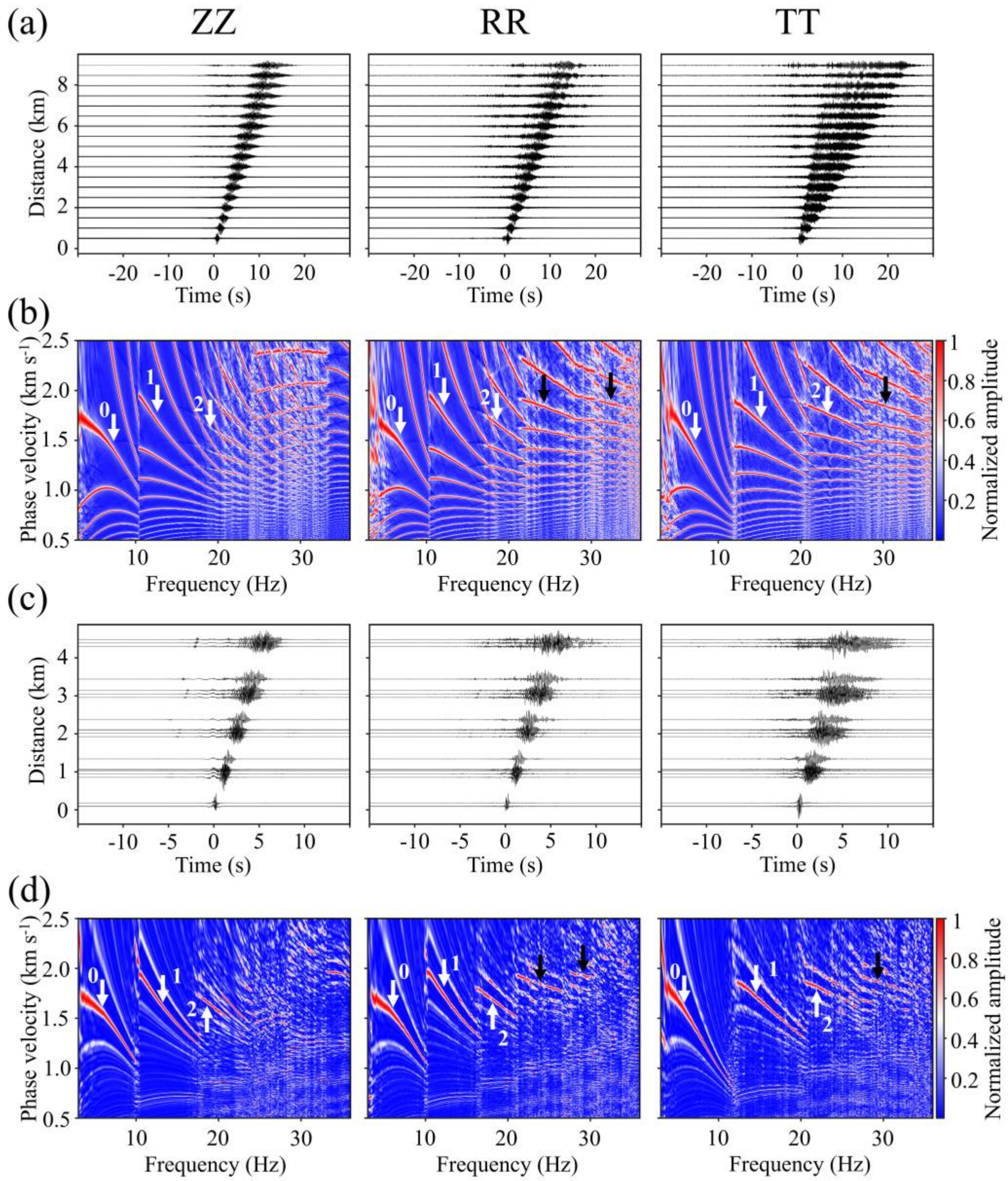

Figure 2. Ambient-noise CCFs and dispersion spectra. **(a)** CCFs of vertical-vertical (ZZ), radial-radial (RR), and transverse-transverse (TT) components between 3 and 35 Hz for Line 1. **(b)** shows the dispersion spectra corresponding to the CCFs in **(a)**. **(c)** and **(d)** CCFs and dispersion spectra for Line 3. The white arrows with numbers 0, 1, 2 in **(b)** and **(d)** show the picked fundamental-mode, first high-mode, and second high-mode dispersion curves. The black arrows indicate potential higher modes which are not used in the inversion.

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3 Inversion and Results

We invert the dispersion curves of the first three modes simultaneously with a multi-objective function (Wang et al., 2023):

$$\boldsymbol{\varphi}(m) = \left[\left\|d_0^{syn} - d_0^{obs}\right\|, \left\|d_1^{syn} - d_1^{obs}\right\|, \left\|d_2^{syn} - d_2^{obs}\right\|\right], \quad (1)$$

in which d_0, d_1, and d_2 represent the dispersion curve of the fundamental mode, first high mode, and second high mode, respectively; d^{syn} and d^{obs} represent the synthetic and observed dispersion curves, respectively. In this algorithm, we treat the fitting of dispersion curves corresponding to different modes independently in a vector-valued multi-objective function (Eq. 1).

The multi-objective optimization problem is solved with a multi-objective particle swarm optimization algorithm (MOPSO). The inversion result consists of a group of Pareto optimal solutions, which represent the best solutions in a multi-objective optimization problem. For a Pareto solution, we cannot decrease one of its objective values without increasing at least one of the other two objective values (Eq. 1). The difference among the Pareto optimal solutions represents the trade-off among the three objectives.

The V_{SH} profile is estimated by using the TT component, and V_{SV} profile is resolved by using ZZ and RR components simultaneously. A 20-layer model with its S-wave velocity varying between 300 and 2100 m s^{-1} is used as the search space. Similarly, the P-wave velocity is limited between 600 and 4100 m s^{-1}. The density is evaluated from V_S using the empirical relationship presented in Diez et al. (2014):

$$\rho(z) = \frac{\rho_{ice}}{1+[(V_{S,ice}-V_S(z))/950]^{1.17}}, \quad (2)$$

where ρ_{ice} and $V_{S,ice}$ are the density and S-wave velocity of ice, respectively. We set a value of 900 kg m^{-3} for ρ_{ice} from Zhang et al. (2022) and 1960 m s^{-1} for $V_{S,ice}$, which is estimated from the phase velocity of higher modes at their cut-off frequencies (Fig. 3).

Taking the Love wave as an example, the inversion converges after 300 iterations and provides 83 Pareto optimal solutions. Similarly, we obtained 78 V_{SV} models from Rayleigh-wave case. In both V_{SH} and V_{SV} results, the Pareto solutions show fairly high consistency (Fig. 3a and b), especially in the region between 30 and 70 m in depth. The knee point solution, which is located at the convex region on the surface defined by the Pareto solution set, shows high similarity with the mean value of the Pareto solutions (red and blue curves in Fig. 3a and b). The fitting between the multi-modal dispersion curve is fairly good (Fig 3d and e), not only for the first three modes used in the inversion, but also for the fourth and fifth modes that are not used in the inversion (modes with arrows in Fig. 3d and e).

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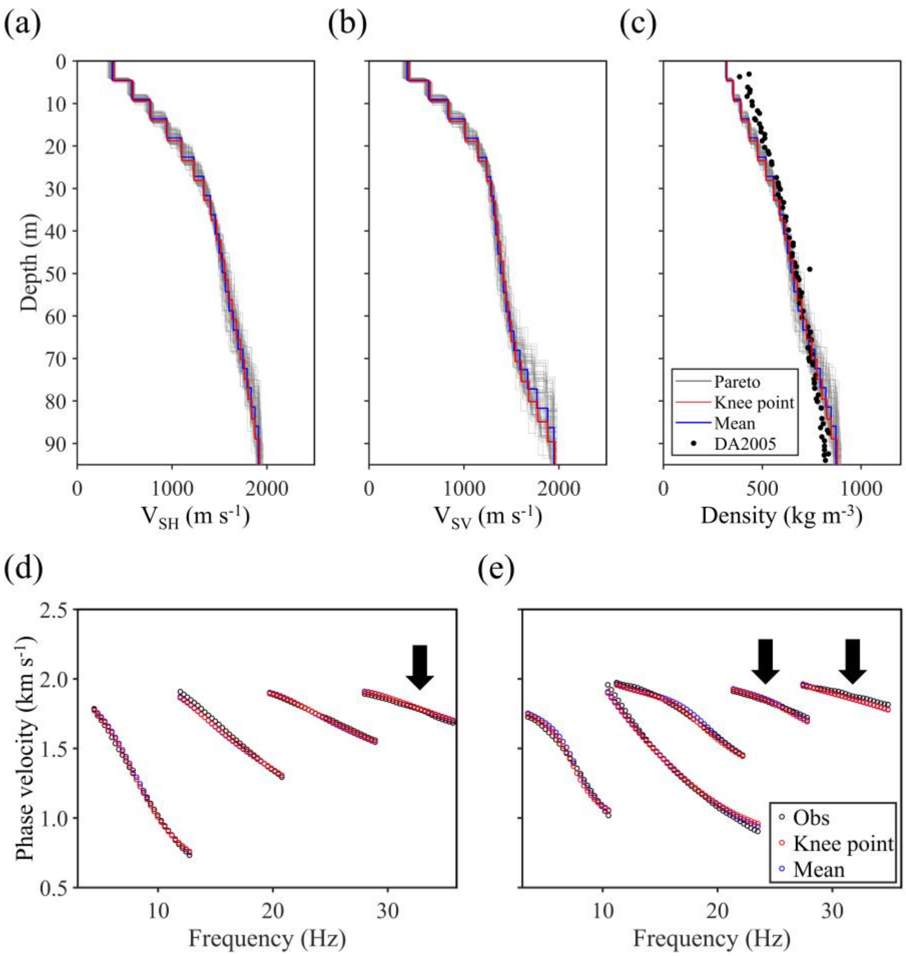

Figure 3. Inverted firn structure and model fitting. **(a)** 1-D $\boldsymbol{V_{SH}}$ profile estimated by using the TT component and **(b)** 1-D $\boldsymbol{V_{SV}}$ profile estimated by using ZZ and RR components from Line 1. The grey, red, and blue lines represent all Pareto optimal solutions, the knee point solution, and the mean solution, respectively. **(c)** Density estimated by empirical relationship given in Eq. (2) with $\boldsymbol{V_{SH}}$, and the filled circles show the ice core (DA2005) density near Dome A. Fitting between the observed and synthetic dispersion curves for **(d)** Love- and **(e)** Rayleigh-wave. The black arrows denote the modes that have not been used in the inversion.

We compare the density profiles corresponding to the V_{SH} results with ice-core data (DA2005) collected around 300 m away from Dome A (Jiang et al., 2012; Yang et al., 2021). The core density was measured in situ using the weight-volume method (Xiao et al., 2008). Our model fits the ice-core data fairly well and only shows some deviation from the ice-core data in the shallow part (depth < 20 m). Three possible reasons for the difference are the errors in the velocity-density empirical relationship for the shallow air-snow layer, the temporal (18 years between the times when the ice-core and seismic data were acquired) and spatial variation in the glacier (the ice core is 500 m away from our survey line), and the relatively low sensitivity of our observed dispersion curve due to the lack of short-wavelength data. Overall, the nice fitting between the synthetic and observed data, as well as between our model and the ice-core data suggest that our reconstructed models are reliable.

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4 Shallow structure at Dome A region

The inversion results show a notable discrepancy between V_{SH} and V_{SV} (Fig. 3a and b), which indicates the presence of radial anisotropy in the firn layer (Fig. 4a). For each solution in the V_{SH} Pareto set, we calculated the differences with every solution in the V_{SV} Pareto set (grey lines in Fig. 4a). All solution-to-solution anisotropy results and the mean value (red line in Fig. 4a) show a clear depth-dependent trend. The results show that V_{SV} is faster than V_{SH} in the shallow part, while their relationship is reversed after reaching the first critical depth (28.1 m, corresponding to the critical density of 550 kg m^{-3}).

Taking into consideration of both density and anisotropy profiles, we can resolve the variation of shallow material with depth at Dome A region. The material transforms from snow to firn and eventually to glacier ice within the top 100 m at Dome A region (Fig. 4b). The shallow material contains freshly fallen snow, which typically takes a hexagonal shape and is filled with air. The V_{SV} is relatively higher than V_{SH} in the snow layer, indicating a preferential orientation of snow grains in the vertical direction. With the rounding of snow grains and the densification process (Amory et al., 2024), the snow becomes more spherical. Accompanied by the settling and grain growth, snow gradually transforms into firn, and the process continues as the density reaches 400 kg m^{-3}. It leads to a fast increase in density and the disappearance of radial anisotropy when the first critical depth (~ 28 m) is reached.

Subsequently, as the depth continues to increase, the densification rate decreases, and the recrystallization and deformation processes become dominant. The radial anisotropy gradually increases with depth, and reaches a maximum of approximately 11 %. As the density increases to 800 kg m^{-3}, sintering occurs in firn, and radial anisotropy decreases accordingly. Reaching the second critical depth at 84.3 m, which corresponds to the pore close-off density (830 kg m^{-3}), the firn gradually transforms into glacier ice, and radial anisotropy decreases to approximately zero.

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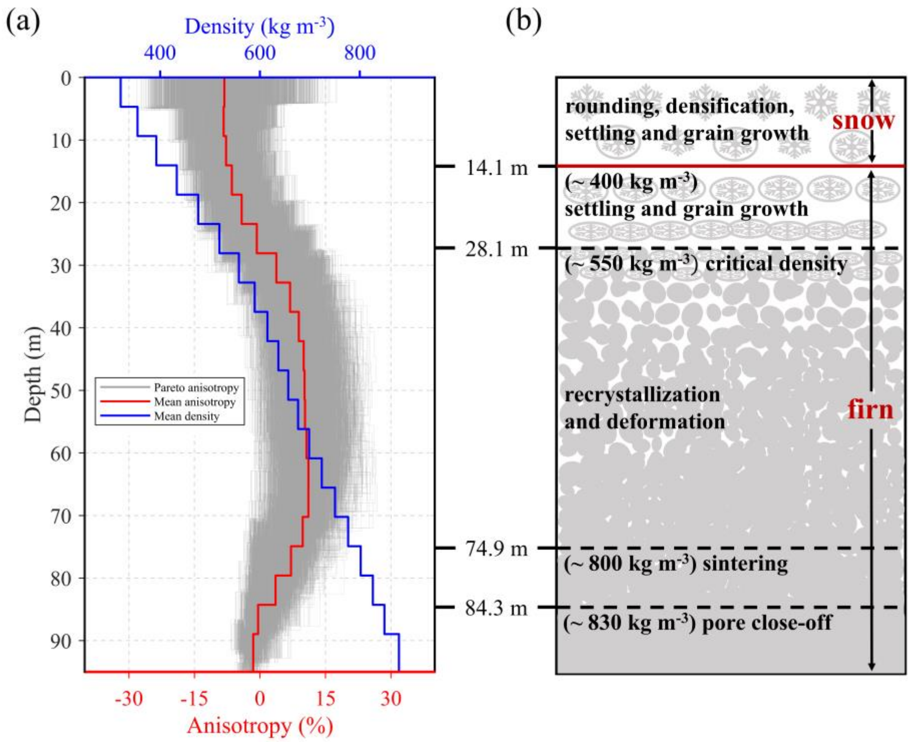

Figure 4. Radial anisotropy and shallow material transformation. **(a)** Radial anisotropy ($\boldsymbol{V_{SH}/V_{SV} - 1}$) (grey lines) for all pairs of $\boldsymbol{V_{SH}}$ and $\boldsymbol{V_{SV}}$, along with the mean (red line) solution. Mean density (blue line) from Fig. 3c is also denoted. **(b)** Schematic picture of possible shallow structure in our study area.

The notable difference between the V_{SV} and V_{SH} in the firn layer is influenced by the effective anisotropy and the intrinsic anisotropy simultaneously. The effective anisotropy is related to the existence of numerous thin (~ mm thick) layers that lead to different elastic properties in vertical and horizontal directions (Diez et al., 2016). The intrinsic anisotropy is caused by the preferred orientation of the anisotropic and hexagonal ice crystals (Picotti et al., 2015; Pearce et al., 2024). The horizontal thin layers in the mesoscale and preferred orientation of ice crystals along the horizontal direction in the microscale produce a transversely isotropic firn with a vertical axis of symmetry.

5 Discussion

In our study, the cultural seismic noise provides an efficient source for the accurate reconstruction of shallow velocity structures. The surface waves remain clear in the CCFs in the station 12 km away from the Kunlun Station (last trace in Fig. 2a), thanks to the dominance of energetic cultural noise and the simple horizontally layered structure with a low level of scattering effect. It shows that the noise generated by daily activities or research activities at scientific camp can rapidly and

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accurately reveal the shallow structure within tens of kilometers, which significantly reduces workload compared with explosive seismic source.

We also compare the 1D near-surface S-wave velocity profiles acquired from different regions of Antarctica (Fig. 5a and b), including Dome A (this study), the Ross Ice Shelf (Diez et al., 2016), the Rutford Ice Stream (Zhou et al., 2022), the Whillans Ice Stream (Picotti et al., 2024), the WAIS Divide camp (Qin et al., 2024; Zhang et al., 2024), and the Polar point (Yang et al., 2024). All of them show a rapid increase in S-wave velocity within the upper 20 to 30 m, followed by a gradual decrease in the rate of increase, ultimately approaching the ice velocity of around 2000 m s^{-1} (Fig. 5a).

It is noted that the S-wave velocity of firn between 30 and 40 m in depth up to 20 % higher in WAIS than that in EAIS. The depth of firn-ice boundary is also shallower in the WAIS. It suggests a faster densification rate of firn in WAIS than EAIS. This difference might be related to the rapid increase in snow accumulation in West Antarctica during the 20th century, which was primarily influenced by the Amundsen Sea Low and large-scale atmospheric circulation (Thomas et al., 2015). In contrast, accumulation in the East Antarctic Plateau is generally low, and synoptically-driven snowfall occurs much less frequently (Thomas et al., 2017). Therefore, the relatively higher elevations, lower temperatures, and less snowfall slow down the accumulation and transformation in EAIS (Cuffey and Paterson, 2010), resulting in the notable difference between the firn in West and East Antarctica. Besides, different ice velocities, heat flux, sublimation, and blowing snow erosion (Goujon et al., 2003) might also influence the shallow structure at the mentioned sites in the WAIS and EAIS.

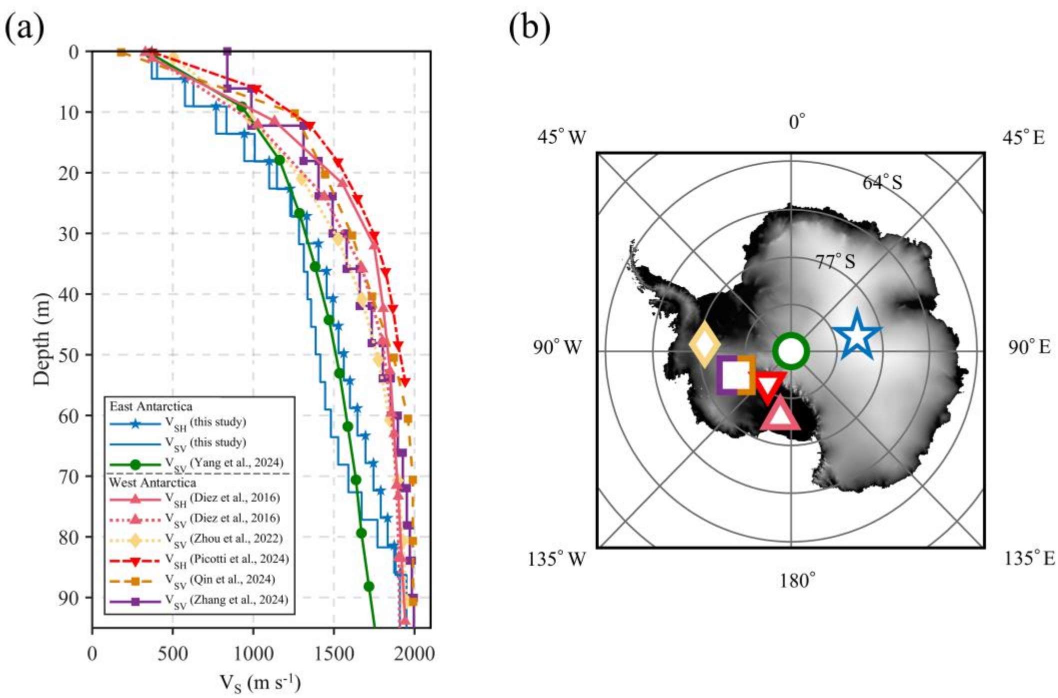

Figure 5. S-wave velocity from East and West Antarctica. **(a)** East Antarctica: $\boldsymbol{V_{SH}}$, $\boldsymbol{V_{SV}}$ from this study (blue line with pentagrams and blue line), and $\boldsymbol{V_{SV}}$ from Yang et al. (2024) (green curve with circles). West Antarctica: $\boldsymbol{V_{SH}}$ and $\boldsymbol{V_{SV}}$ from Diez et al. (2016) (pink curve with triangles and pink dotted curve with triangles), $\boldsymbol{V_{SV}}$ from Zhou et al. (2022) (yellow dotted curve with diamonds), $\boldsymbol{V_{SH}}$ from Picotti et al.

(2024) (red dash-dot curve with inverted triangles), $\boldsymbol{V_{SV}}$ from Qin et al. (2024) (brown dashed curve with squares), and $\boldsymbol{V_{SV}}$ from Zhang et al. (2024) (purple line with squares). The markers in **(b)** corresponding to **(a)** represent the respective study areas from different research works in Antarctica.

6 Conclusion

We analyzed the seismic ambient-noise data and reconstructed shallow subsurface models at Dome A region in Antarctica. The results of beamforming showed that the seismic ambient-noise source mainly comes from the Kunlun Station and is related to human expedition works. We obtained multi-modal surface-wave dispersion curves up to 35 Hz using seismic interferometry and reconstructed both V_{SH} and V_{SV} models down to about 100 m depth. The inversion results, including both the density profile derived empirically from the S-wave velocity and the anisotropy profile, show a clear transformation of material from snow to firn and firn to ice, and the internal evolution of firn in the top 100 m. Our density profile nicely agrees with ice-core data nearby, indicating fairly high reliability of the subsurface model reconstructed at Dome A region. Our study also suggests that cultural ambient-noise can serve as a nice source for the investigation of shallow structures in the polar regions.

Data availability

The density, V_{SH} and V_{SV} models in this study are available at Song et al. (2025).

Author contribution

YP, JL, YY, KL, XT and XZ planned the campaign; YY and KL performed the measurements; ZS, YP, JL, HP and YW analyzed the data; ZS and YP wrote the manuscript draft; JL, HP, YY, KL, XT and XZ reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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