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Supplement of

A seismic analysis of subglacial lake D2 (Subglacial Lake Cheongsuk) beneath David Glacier, Antarctica

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S1. Seismic data acquisition

Table S1: Seismic survey work schedules

Date (dd/mm/yy)	Job	Work day (day)
01/12/21	GPR survey	1
04/12/21 – 05/12/21	Marked shot position	2
06/12/21 – 28/12/21	Hot water drilling (25 m) and explosive installation (4 lines, total 144 points)	14
12/12/21 – 02/01/22	Seismic survey (4 lines)	11

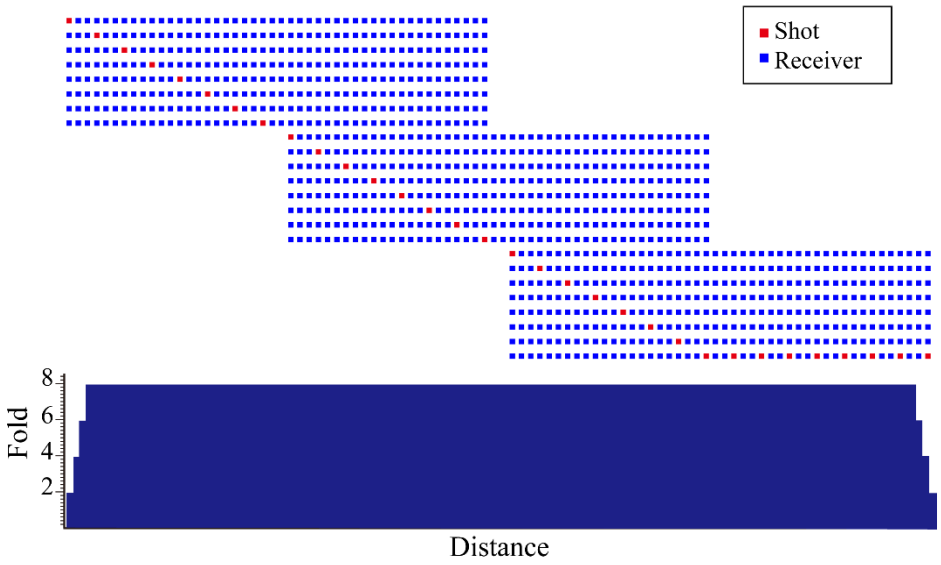

Figure S1: In the seismic survey layout, only the odd-numbered receivers are displayed, that is, one receiver marked every two channels.

S2. Seismic data processed parameters and results

This study utilized the Omega geophysical data processing platform (SLB) for seismic data processing. Among the various processing steps, we provide below the key parameters applied during procedures that directly influence the ice–bedrock interface signal, such as noise attenuation.

1. Anomalous amplitude attenuation (AAA) for the 1st round

AAA is a frequency-domain filtering technique designed to suppress spatially coherent anomalous amplitudes such as swell noise and rig noise, by comparing amplitude spectra across traces and attenuating outliers based on spatial median statistics. The method identifies frequency bands with anomalous energy by comparing each trace's amplitude spectrum within a spatial window to the median of its neighboring traces. Detected anomalies are either scaled or replaced using interpolated values from adjacent traces, preserving relative amplitude relationships. Key parameters include TIME, which defines the temporal window of threshold application; THRESHOLD FACTOR, which sets the amplitude level considered anomalous; and SPATIAL MEDIAN WIDTH, which specifies the number of adjacent traces used for median computation. Proper tuning of these parameters is essential to avoid signal distortion while effectively attenuating coherent noise. AAA is particularly useful in prestack data conditioning as it enhances seismic data quality without compromising true subsurface reflections (SLB, 2025a).

- SPATIAL MEDIAN WIDTH: 21 traces
- Threshold factor tables:

TIME	THRESHOLD FACTOR
0	15
1000	10
3000	7
4000	6

2. Curvelet transform-based filter for 1st round

Curvelet Transform is a multi-scale, multi-directional decomposition technique that provides a sparse representation of seismic data by capturing curved wavefronts more efficiently than conventional fourier or wavelet transforms. An important aspect of the Curvelet Transform implementation involves user-defined control over the scale and angle bounds that determine which components of the data will be transformed. The LOWER BOUND OF SCALE and HIGHER BOUND OF SCALE specify the range of spatial frequencies (scales) to be included in the transform. Lower scales correspond to coarse, low-frequency components, while higher scales capture fine, high-frequency structural details. The LOWER BOUND OF ANGLE and

HIGHER BOUND OF ANGLE define the directional sectors (angles) within each scale to be analyzed. This allows selective enhancement or suppression of events based on their dip or propagation direction (SLB, 2025b). Figure S2 illustrates how the f–k domain is partitioned into curvelet panels by scale and angle. Adjusting these bounds allows for targeted signal processing, such as isolating curved events or attenuating directionally coherent noise. These parameters provide valuable flexibility in customizing the transform for specific seismic applications.

- Panel manager

LOWER BOUND OF THE SCALE	HIGHER BOUND OF THE SCALE	LOWER BOUND OF THE ANGLE	HIGHER BOUND OF THE ANGLE
2	2	1	3
2	2	8	10
3	3	1	6
3	3	13	18
4	4	1	6
4	4	13	18

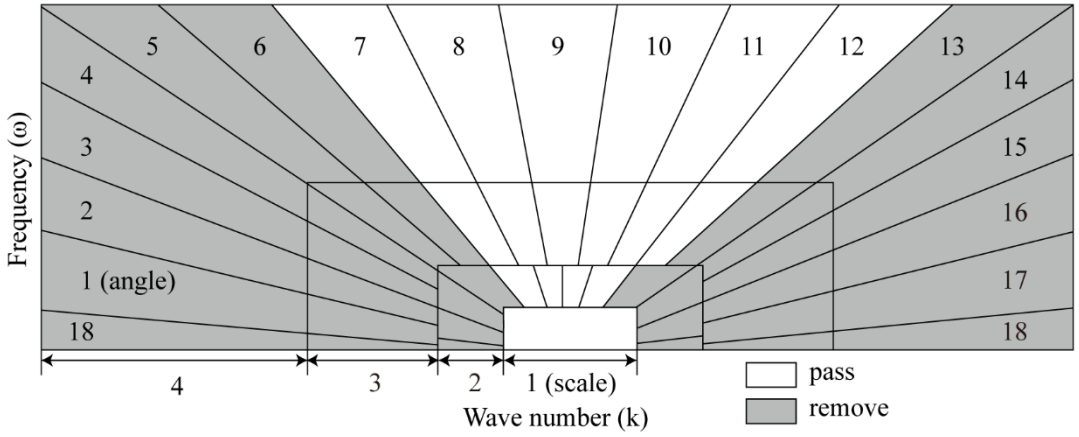

Figure S2: Illustration of the panel manager. In the f-k domain, the hatched area is identified as noise and removed accordingly.

3. Surface-consistent deconvolution

Surface-Consistent Deconvolution is a technique for generating and applying deconvolution operators that are consistent across seismic sources, receivers, offset ranges, and CMP locations (SLB, 2025c; Yilmaz, 2001).

Key processing parameters used in this workflow include:

- CONSTANT_ACOR_LENGTH = 100: Defines the half-length of the autocorrelation window used in operator design, balancing spectral resolution and filter stability.

- WHITE NOISE PERCENT = 0.01: Adds 1% white noise to stabilize the autocorrelation estimation and prevent over-whitening of the signal.
- PREDICTION DISTANCE = 2.5: Specifies the prediction lag in the predictive filter design; this parameter controls the temporal range of the filter's effect, influencing multiple suppression and resolution.

4. Anomalous amplitude attenuation (AAA) for the 2nd round
   - Spatial median width: 11 traces
   - Threshold factor tables:

Time	Threshold factor
0	8
1000	6
3000	4
4000	3

5. Curvelet transform-based filter for the 1st round: same as 1st round parameter

6. Frequency-offset coherent noise suppression (Figure S4.c)

The frequency–offset (F-X) Coherent Noise Suppression (FXCNS) module is designed to attenuate near-surface shot-generated coherent noise, such as dispersive surface waves and trapped modes, which interfere with primary seismic reflections, particularly in 3D shot or receiver gathers with irregular spatial sampling (Hildebrand, 1982). FXCNS operates in the frequency domain by modeling coherent noise using fan filters and estimating it in a least-squares sense for each trace based on local neighbors within a specified azimuthal sector. The estimated coherent noise is then subtracted from the original signal, preserving true reflection events (SLB, 2025d).

- LOW PASS VELOCITY: 100
- LOW STOP VELOCITY: 300
- HIGH PASS VELOCITY: 8000
- HIGH STOP VELOCITY: 10000

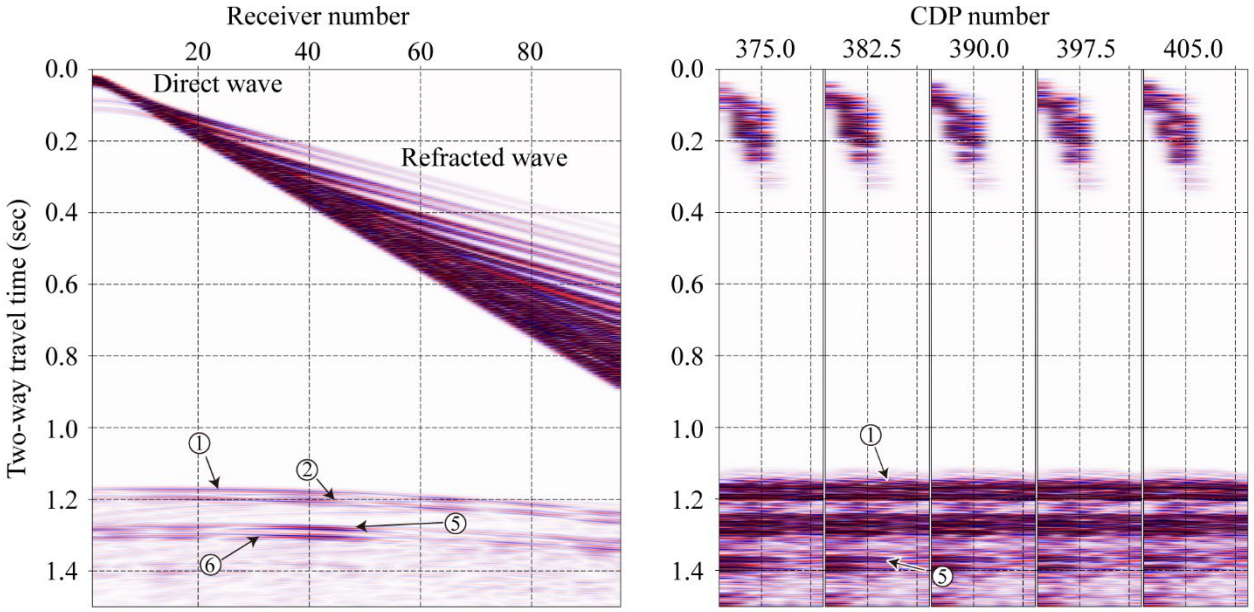

Figure S3: Results before and after data processing. (a) Synthetic data of shot gather #1. (b) Result after pre-stack time migration. Symbols (see Table 2).

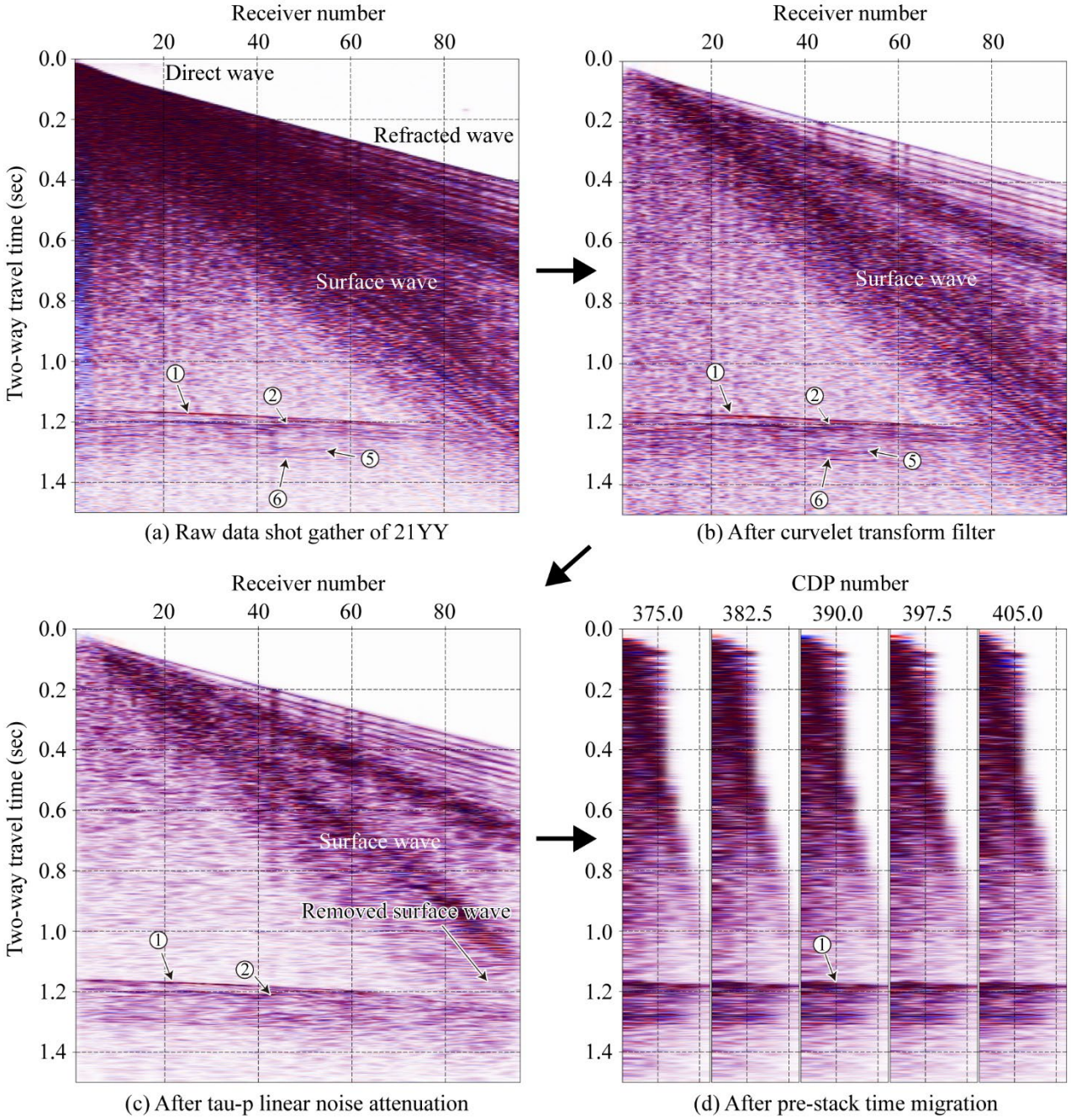

Figure S4: Results at each stage of data processing. (a) Shot gather #1 from 21YY. (b) Removal of high-frequency random noise and coherent linear noise. (c) Application of a frequency-offset coherent noise filter and tau-p linear noise attenuation for surface wave removal. (d) Result after applying pre-stack time migration.

S3. Seismic data acquisition

1. IPR data uncertainty in glacier thickness estimates

The vertical uncertainty of the GNSS data was estimated to be 0.98 m. At the 99% confidence level, the uncertainties in surface and bed elevation measurements were calculated as ±6.9 m and ±32.7 m, respectively (Figure S5). When incorporating the GNSS vertical uncertainty, the total uncertainties in surface and bed elevations increased slightly to ±7.0 m and ±32.7 m, respectively. Consequently, the overall uncertainty of the IPR-derived ice thickness was estimated to be ±33.4 m.

$$U_{IPR} = \sqrt{(\pm 7.0\ \mathrm{m})^2 + (\pm 32.7\ \mathrm{m})^2} = \pm 33.4\ \mathrm{m}. \quad \text{S3.1}$$

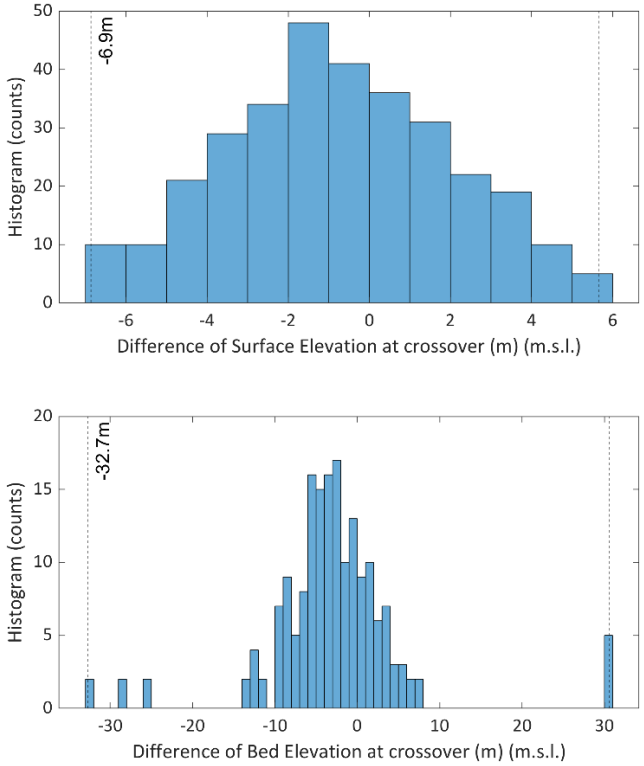

Figure S5. Measurement uncertainty results of surface and ice bottom elevations from IPR data.

2. Seismic data uncertainty in glacier thickness estimates

The uncertainty associated with seismic picking arises from the presence of noise and is quantified as picking uncertainty (U_{pick}), which can be estimated using the following equation (Abakunov et al., 2020):

$$\sigma_{pick} = 2\sqrt{\frac{T^2}{4\pi^2}\frac{1}{SNR}}, \quad \text{S3.2}$$

where T is the period of the central frequency and SNR is the signal-to-noise ratio. Based on this formulation, the SNRs of the first arrival and the ice–water interface signals were determined to be 88.8 dB and 10 dB, yielding vertical uncertainties of 0.2 m and 2.1 m, respectively.

$$U_{pick} = 2.58\,\sigma_{pick} = \pm 5.4\ \text{m}. \quad \text{S3.3}$$

The total picking uncertainty at the 99% confidence level is 5.4 m. Under glacial temperature conditions of –2 ± 2 °C, where the average P-wave velocity in ice is 3800 ± 5 m s^{-1} (Kohnen, 1974), the uncertainty associated with the variability in seismic velocity is estimated to be ±5.3 m. Assuming a firn layer thickness of 100 m, the combined measurement uncertainty of the seismic results at the 99% confidence level is calculated to be 7.6 m.

$$U_{Seis} = \sqrt{(\pm 5.4\ \text{m})^2 + (\pm 5.3\ \text{m})^2} = \pm 7.6\ \text{m}. \quad \text{S3.4}$$

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