Supporting Information: Detailed seismic bathymetry beneath Ekström Ice Shelf, Antarctica: Implications for glacial history and ice-ocean interaction

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Contents of this file

1. Text S1 to S4

Introduction This supporting information contains the following information about methods used in this study. The information is not crucial to the understanding of the main text, but will be of interest to some readers and those who may want to perform similar analysis.

- S1 - details of seismic data processing
- S2 - seismic velocity determination for depth conversion
- S3 - uncertainty calculations for the seismic bathymetry
- S4 - CTD data processing

S1: Seismic Data Processing

The following is a full description of the seismic vibroseis data processing steps, this process was followed for each seismic line in the survey:

1. Raw seismic vibroseis data were read from SEG2 field records into the Paradigm *EPOS* processing system.

2. Data were cross-correlated with the appropriate input vibroseis sweep to produce shot gathers.

3. Geometry was applied to locate the source and receiver positions and calculate common midpoint (CMP) positions.

4. Data were manually checked and compared to field logs to identify low quality shots and noisy or dead channels, which were then removed from further processing.

5. The data was bandpass filtered (survey dependent) and a notch filter at 206 Hz was applied, to remove known spurious noise from the geophones.

6. Data are then re-sorted into common midpoint (CMP) gathers.

7. CMP gathers with fold > 3 are used for velocity analysis, to determine the seismic-wave velocity (V_{stack}) of different layers within the sub-surface. This is done by fitting a normal moveout (NMO) velocity curve to the CMP gathers and in some areas using constant velocity stacks.

8. The velocity field produce by the above analysis is used for NMO correction of CMP gathers.

9. NMO corrected CMP gathers are stacked to produce one stacked trace for each CMP location, improving signal-to-noise ratio.

10. This stacked traces for each CMP location make up a time-stacked seismic section (example in main manuscript Fig. 2). It is the two-way traveltime of the reflection horizons on a time-stacked seismic section that are used to create the bathymetry map of the sea floor.

S2: Determination of Seismic Velocities for Depth Conversion

The seismic velocity used for depth conversion of the ice was derived from the average stacking velocity V_{stack}, determined during velocity analysis (Supporting Information S1). The value of V_{stack} can be assumed equal to the interval velocity (V_{int}) for ice, as it is a quasi-homogenous layer, and the reflection is from a near-horizontal surface (base of the ice shelf). The determined values of V_{stack} ranged from 3597 ms^{-1} to 3606 ms^{-1}, with an average value of 3601 ms^{-1}.

The depth-averaged seismic velocity value for the water column was determined using CTD profiles (main manuscript, Section 2.4) taken through the hot-water drilled access holes (main manuscript, Fig. 1c, blue circles). The TEOS-10 Matlab toolbox (McDougall & Barker, 2011) was used to make this calculation. The TEOS-10 toolbox implements the International Thermodynamic Equations Of Seawater - 2010 (IOC et al., 2010). The resulting seismic velocity values ranged from 1448 ms^{-1} to 1453 ms^{-1}, with an average of 1451 ms^{-1}. This value is comparable to values determined from CTD data under other Antarctic ice shelves (Brisbourne et al., 2014; Nøst, 2004; Rosier et al., 2018).

S3: Error Calculations for Seismic Derived Sea-floor Depths

Uncertainties in the sea-floor depth come from four sources, these will be analysed below: (1) accuracy of the horizon picking, (2) velocities used for depth conversion of these horizons, (3) errors in the REMA DEM used for surface elevation corrections and (4) depth errors from unmigrated data.

1. The error in horizon picking can be quantified by assessing the possible travel time mis-pick and converting this into a depth error. In the area of the main grid, the 2017 and 2018 surveys are high fold and the horizons are clear meaning picking of the peak of a reflection is possible to better than $\pm$ 1.5 ms. In the 2010 and 2011 surveys, the lower frequency Failing Y-1100 vibroseis source was used, which has a longer wavelength and lower resolution, such that picks are possible to $\pm$ 3 ms. However, with the exception of the far north eastern protrusion from the main seismic grid, picks from the 2017 and 2018 surveys were used preferentially in the gridding, therefore a picking error corresponding to $\pm$ 1.5 ms is appropriate for this region, giving a depth error of $\pm$ 7.6 m for the sea floor. The 2014 survey data is single fold, this doesn't affect the pick of the ice base, which is still possible to $\pm$ 1.5 ms, as it is largely horizontal. However, picks of the sea floor, in areas of rough topography are only possible to $\pm$ 15 ms, in the extreme case. This corresponds to a possible depth error of $\pm$ 27.2 m at the sea floor in the areas covered by these lines. As a result, the bathymetry map is significantly more accurate in the area of the main grid than the single lines that extend south across the grounding line.

2. The error in seismic velocity of the ice can be quantified by looking at the minimum and maximum velocities determined during velocity analysis (see S1). This yields a range

of ice velocities from 3597 ms^{-1} to 3606 ms^{-1}. The range of water column velocities determined from CTD measurements was 1448 ms^{-1} to 1453 ms^{-1}, giving a depth error at the deepest part of the sea floor from velocity errors of ± 4 m.

3. Seismic energy reflected from the sea floor is assumed to have reflected at the mid-point of the source and received, known as the CMP (see S1). However, for dipping interfaces this is not strictly true introducing an error, which is greatest for the deepest and steepest dipping interfaces. Using the dip-correction equations of (Yilmaz, 1987), an error of ± 2.4 m was calculated for the steepest dipping and deepest section of the sea floor.

4. The quoted error for the REMA DEM is ± 0.75 m in this region.

Summing these four error sources leads to a cumulative error at the sea floor of ± 14.8 m under the main data grid (at the ice shelf front) and ± 34.4 in the areas of the 2014 seismic lines, these values are stated in the main article.

S4: CTD Data Processing

CTD data were processed using the RBR Ruskin software, which was used to export pressure, in-situ temperature, and practical salinity data based on the sensor calibration that was obtained in October 2018 before the field season. The CTD profiles were split into individual down casts and up casts at each location and all data were inspected manually. Profiles showing obvious sensor drift and noise, which are often related to temporary accretion of ice crystals inside the conductivity cell in these environments, were discarded. The remaining data showed plausible water mass properties and structures beneath the ice shelf. Pre-season calibration data of the sensors was collected by the manufacturer, however, post-season calibration data were not available. Based on comparison of the data with established water mass properties in the region, uncertainties are assumed for in situ temperature (0.02°C) and salinity (0.03), yielding an accuracy that is similar to other datasets where post-calibration is not available (e.g. Treasure et al., 2017).

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