Using Single Station Seismology to Determine the Structure Beneath the Ross Ice Shelf, Antarctica

GEOL 394 Student: Siobhan Light

Advisor: Dr. Nicholas Schmerr

Introduction

- Icy-ocean worlds, including Europa and Enceladus, have fascinating astrobiological potential so there is strong interest in understanding their physical properties
- The Ross Ice Shelf in Antarctica offers one of the closest terrestrial analog environments to these worlds

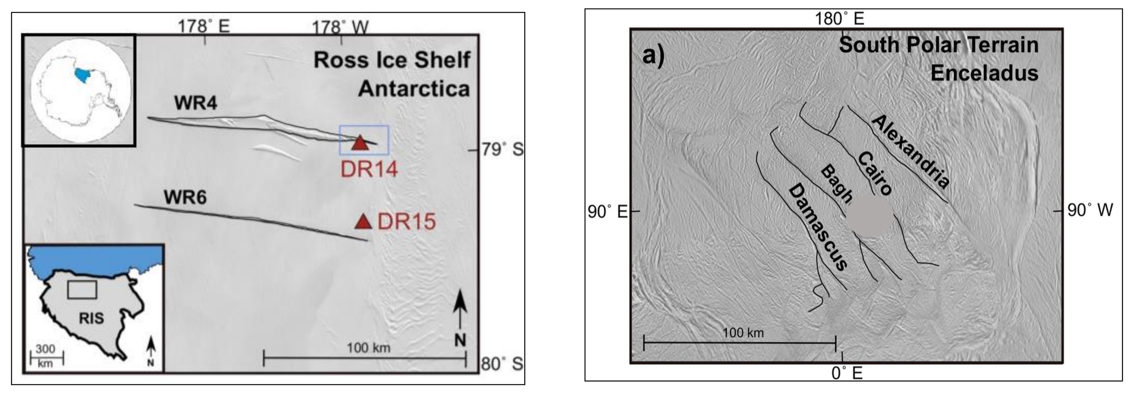

Figure 1: This study draws on seismological data recorded by seismic station DR14, whose location on the Ross Ice Shelf is shown on the left panel near rift WR4. The rift is close in size and shape to the four tiger stripe fractures located near Enceladus' south pole, shown on the right panel. Based on Figure 1 in Olsen et al. (2021).

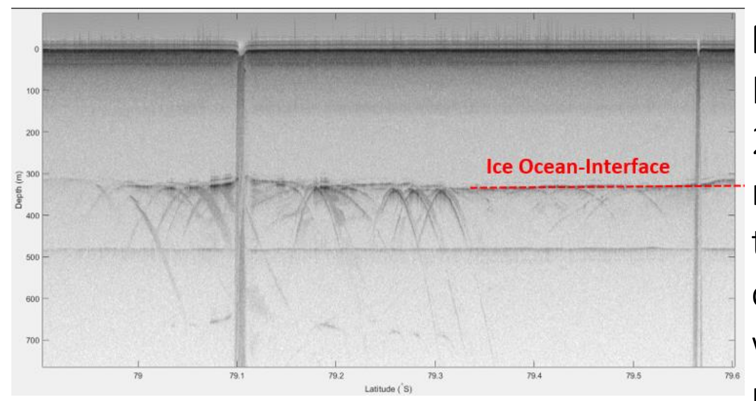

Figure 2: ROSETTA Deep ICE Radar (Das et al., 2020) image of the DR14 rift with a line highlighting the location of the ice-ocean interface, an area whose structure is poorly understood.

Hypothesis

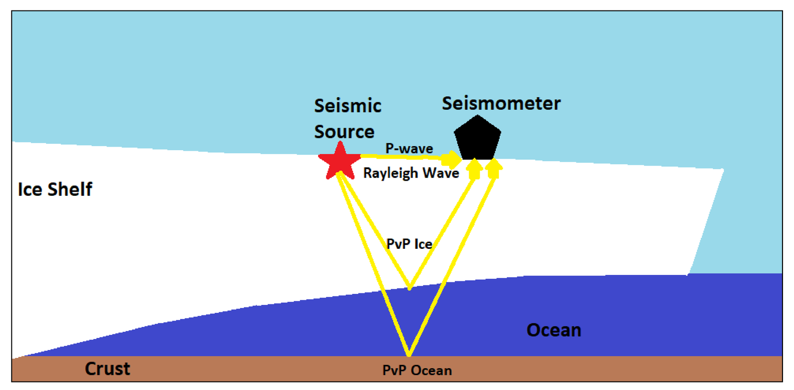

Figure 3: Hypothetical ice shelf diagram. The red star represents a seismic source and the black pentagon represents a seismometer. The arrows represent several potential paths seismic waves could take between the seismic source and the seismometer. Note relative vertical exaggeration of the ice thickness relative to the ocean.

- First this study looked at whether it was possible to distinguish wave phases that reflected off the ice-ocean interface
- If such wave phases are found, it becomes possible to estimate several physical characteristics of the ice shelf such as its thickness, attenuation, and reflection coefficient at the interface
- Null hypothesis: Seismic reflections reveal a sharp transition at the ice-ocean interface and a flat structure
- Alternative: A gradual transition implying a "mushy layer"

Data

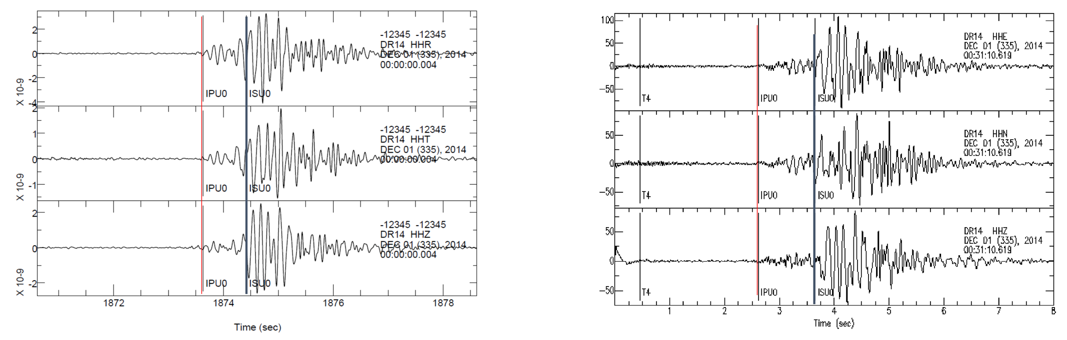

Figure 4: Seismograms displayed in Seismic Analysis Code (SAC). The left shows data in the original bandpass filter of 5-20 Hz, while the right has the expanded range of 1.25-25 Hz. The red line indicates the manual P-wave arrival pick and the black line is the picked Rayleigh-wave arrival.

- We examined seismic data recorded from December 2014 to December 2016 by the DR14 seismic station, located approximately two kilometres south of Ross Ice Shelf rift WR4
- Initial analysis employed a short-term-average/long-term average algorithm (Allen 1978; Trnkoczy 2009; Olsen et al., 2021) to locate icequakes in the data; 13,780 were found

Methods

- At first, 924 seismic events filtered to 5-20 Hz were analysed with SAC to see if surface and body wave phases could be manually identified
- Manual confidence labels were assigned to picks
- Using P-wave and Rayleigh-wave arrival times, back-azimuth values previously calculated for these icequake events (Olsen et al., 2021), and the velocities of these wave phases previously measured for the Ross Ice Shelf in the literature, the distance to the icequake sources from the seismic station could be calculated

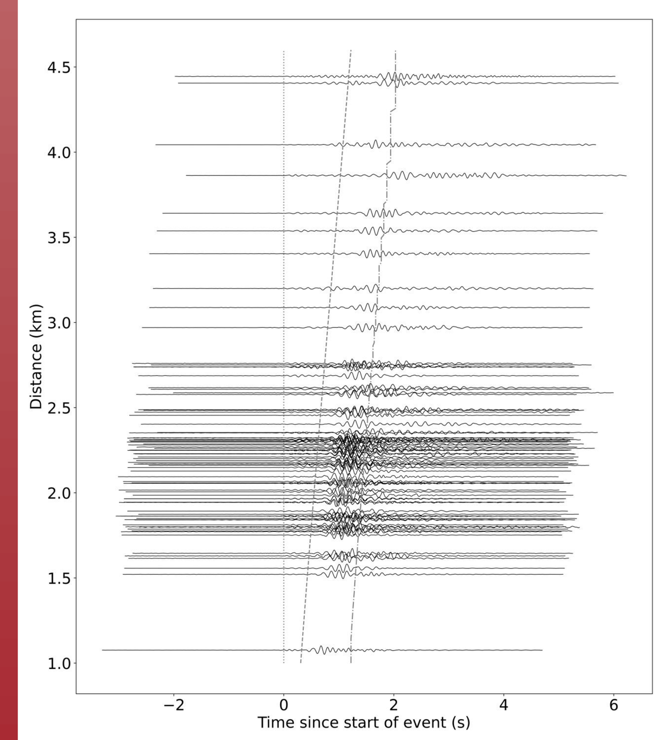

Figure 5: 85 seismograms with manually labelled P-wave and Rayleigh-wave arrival times given the "best quality label aligned on the time axis by their P-wave arrival time and sorted on the y-axis by their distance from the seismic station. The dotted line represents predicted direct P-wave arrivals, the dashed line represents predicted P-wave reflections from the bottom of the ice shelf, and the dashed/dotted line represents predicted P-wave reflections from the bottom of the ocean. These predictions assume a 0.3 km thick ice shelf and 0.7 km thick ocean layer.

Methods Continued

- As shown in Figure 5, individual icequakes appeared to show normal moveout (NMO)
- As a result, we decide to focus on individual icequakes and improve existing wave phase picks
- The raw seismic data was re-filtered to between 1.25-25 Hertz applied since some relevant seismic wave frequencies may have been filtered out in the initial analysis

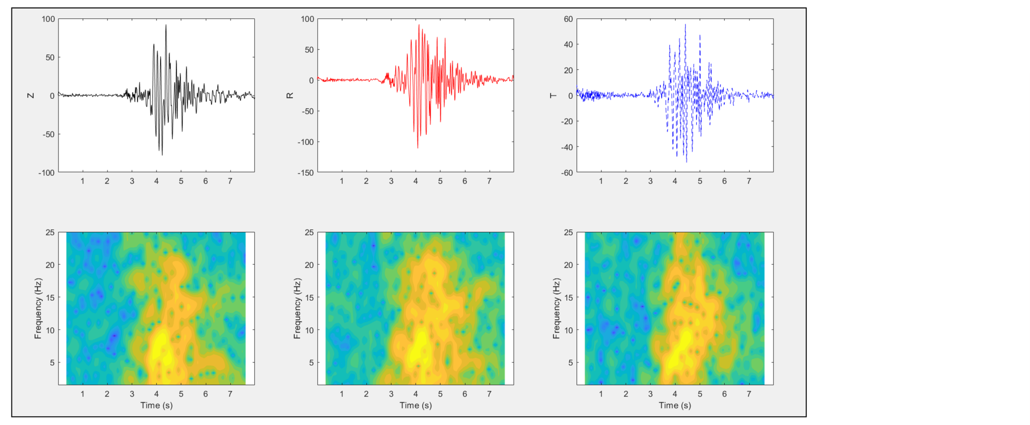

Figure 6: Seismograms (top row) and corresponding spectrograms (bottom row) split by the three components (Z, R, and T), where the data has been rotated by previously calculated back-azimuth values.

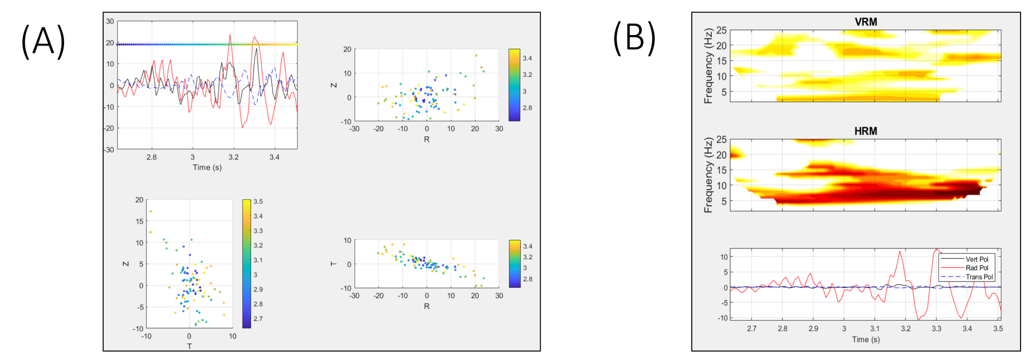

Figure 7: (a) Comparison of relative motion between seismic components. (B) Results of frequency-dependent polarization analysis. Both types of analysis assisted in making seismic wave phase picks.

Results

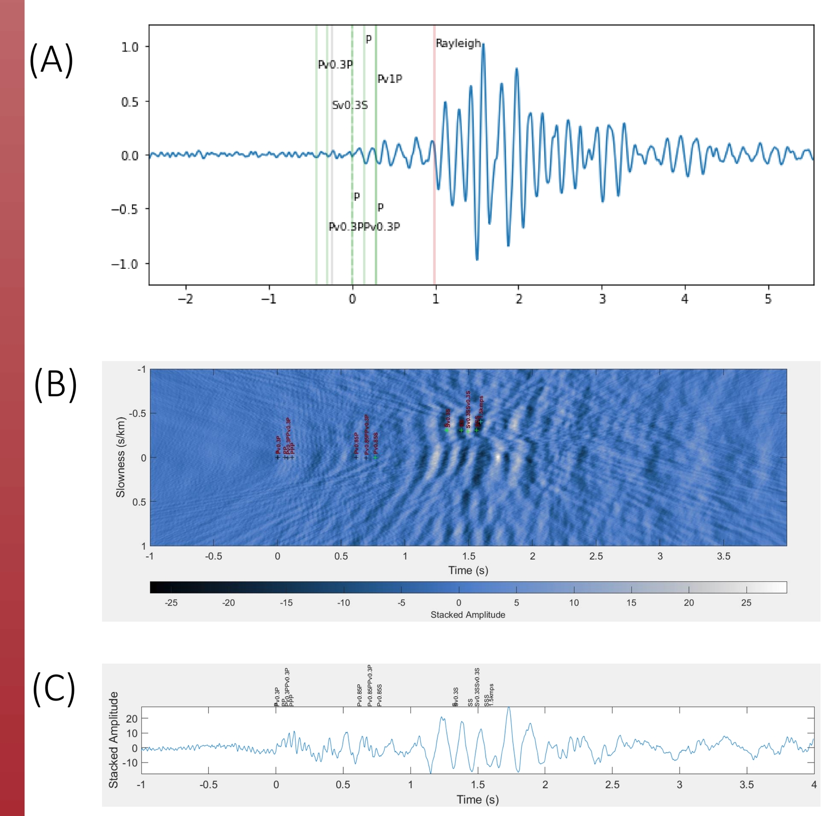

Figure 8: (a) The TauP toolkit (Crotwell et al., 1999) was used to calculated predicted wave phase arrival times for a sample seismic event given a source to station distance and an assumed ice shelf structure. (b) Resulting vespagram from 65 seismic events aligned by their p-wave arrival, stacked, and analysed with velocity spectral analysis (vespa). Select wave phase arrivals predicted by the TauP velocity model are labelled. (c) Predicted wave phase arrivals labelled in relation to stacked waveform.

Discussion

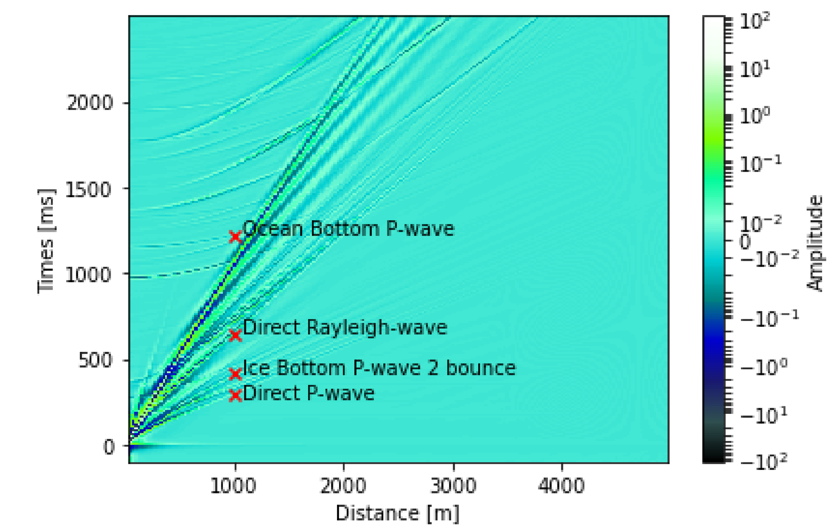

Figure 9: Comparisons can be made between the actual wave phase arrival times for icequakes generated at different distances and wave phase arrival times predicted by a synthetic model. Plot of cumulative synthetic seismograms generated for a possible ice shelf structure (0.3 km thick ice shelf, 0.7 km thick ocean) every 25 meters out to 5000 meters with select wave phases labelled with red "x" markers.

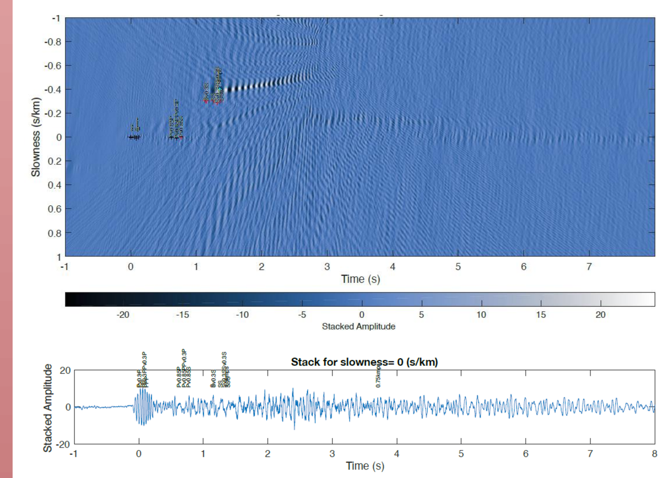

Figure 10: Vespagram (top) and summed stacked waveform (bottom) for the synthetic seismic data. Predicted wave phase arrivals are labelled in both plots. Comparing wave phase arrivals between the synthetic and actual data will lend insight into the ice shelf structure.

Conclusions

- Comparison between the actual and synthetic data was insufficient to conclude a variable ice-ocean interface structure
- More work is needed to see how phase arrival times in the data compares to those from a wide variety of ice shelf models

Citations

Crotwell, H. P., T. J. Owens, and J. Ritsema (1999). The TauP Toolkit: Flexible seismic travel-time and ray-path utilities, Seismological Research Letters 70, 154–160.

Das, I., Padman, L., Bell, R. E., Fricker, H. A., Tinto, K. J., Hulbe, C. L., ... & Siegfried, M. R. (2020). Multidecadal basal melt rates and structure of the Ross Ice Shelf, Antarctica, using airborne ice penetrating radar. Journal of Geophysical Research: Earth Surface, 125(3), e2019JF005241.

Olsen, K. G., Hurford, T. A., Schmerr, N. C., Huang, M. H., Brunt, K. M., Zipparo, S., ... & Aster, R. C. (2021). Projected Seismic Activity at the Tiger Stripe Fractures on Enceladus, Saturn from an Analog Study of Tidally Modulated Icequakes within the Ross Ice Shelf, Antarctica. Journal of Geophysical Research: Planets, e2021JE006862.

Vance, S. D., Kedar, S., Panning, M. P., Stähler, S. C., Bills, B. G., Lorenz, R. D., ... & Rhoden, A. R. (2018). Vital signs: seismology of icy ocean worlds. Astrobiology, 18(1), 37-53.

Wiens, D., Aster, R., & Bromirski, P. (2014). Collaborative Research: Collaborative Research: Dynamic Response of the Ross Ice Shelf to Ocean Waves and Structure and Dynamics of the Ross Sea from a Passive Seismic Deployment on the Ross Ice Shelf [Data set]. International Federation of Digital Seismograph Networks.

Acknowledgements

Support for the initial stages of this research came from the NASA ColdTECH program and NASA grant 80NSSC18K1628. Thank you to Nicholas Schmerr for his guidance throughout the project. I would also like to thank Kira Olsen for guiding me through the initial stages of the project. I appreciated the assistance of Vedran Lekic for helping provide code and guidance for the polarization analysis. I am also grateful for the help of Mong-han Huang for feedback on mapping the icequake locations.