Deep, dark and dynamic: Converted-wave seismology to explore the physical properties of Antarctic glacier ice

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Highlights

- Quantitative seismic analysis holds the key to establishing the mechanical properties of glaciers – the very properties which are required to accurately parameterise predictive models of glacier dynamics.
- Global sea levels are predicted to rise by ~1 m over the next 100 years, but such estimates are uncertain. Improved predictions require a comprehensive description of all aspects of the glacier system.
- Seismic surveys are a powerful means of accessing the deep, dynamic underbelly of an ice mass. Hitherto, converted-wave seismology has been largely overlooked but could offer a new source of valuable interpretative insight.
- This project explores the scope of converted-wave seismology to quantify fundamental glaciological properties. Test data will be acquired during the project on Norway's Hardangerjøkulen ice cap with existing datasets provided, by the British Antarctic Survey and the Thwaites Glacier *TIME* project, at two priority Antarctic sites.
- The successful development of converted-wave methodologies will broaden the glaciological seismic toolbox, providing novel insight at sites of current research interest.

Rationale and Motivation

Significant research effort is directed towards improving forecasts of glacier dynamics and their associated impacts on sea-level rise, particularly for ice masses on the Antarctic continent[1,2]. Innovative methodologies are required to fully capture the physics of the glacier system. The study sites in this project are considered critical for the stability of two Antarctic regions: Korff Ice Rise, which influences the dynamics of the vast Filchner-Ronne Ice Shelf; and Thwaites Glacier, considered to be the vulnerable pinning-point of the West Antarctic Ice Sheet. Improved insight at these stability-critical sites will benefit all subsequent models for assessment of entire regions of Antarctic ice dynamics.

Background

Glacier flow is influenced by internal ice properties (e.g., water content, temperature) and the characteristics of the material immediately beneath the glacier bed[3,4,5]. These properties can be quantified using seismic reflection methods: ice temperature is related to seismic attenuation[4], and amplitude-versus-offset (AVO)[5] methods allow the physical properties of the subglacial environment to be diagnosed. However, these methods are typically applied only for the compressional (P-) wave component of the seismic wavefield, and other components may be overlooked. The value of mode-converted reflections (i.e., energy that impinges on an interface as a P-wave, but excites shear (S-) wave particle motion; Figure 1a) is yet to be explored, but could offer a valuable source of constraint for quantitative assessments of physical ice properties.

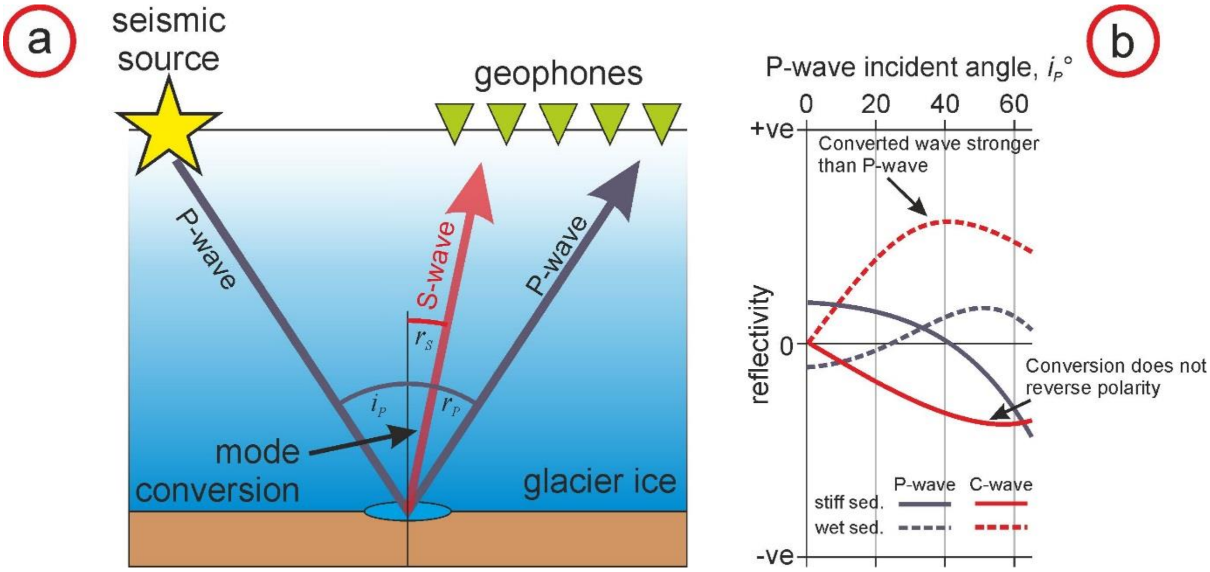

***Figure 1.** a) Schematic diagram of the mode-conversion of incident P-wave to reflected S-wave energy. By combining aspects of both P- and S-wave propagation, the converted-wave may offer significant interpretative constraint. b) Theoretical AVO curves for glacier bed reflections, where ice overlies (blue) stiff and (red) wet sediment. Converted-waves show stronger reflectivity at certain offsets than P-waves; combined analysis of P- and converted-wave reflectivity would greatly reduce the ambiguity in a subsurface interpretation.*

In some cases, the value of the converted-wave may exceed that of its P-wave counterpart. AVO studies are a particular case in point: Figure 1b shows that the theoretical reflectivity[5,6] for ice overlying wet sediment can be stronger for the converted-wave than it is the P-wave. Glaciers accelerate when flowing over saturated sediment, therefore monitoring the distribution of subglacial water is key to predicting long-term glacier stability. Converted-wave AVO could therefore offer a sensitive new tool to studies of subglacial hydrology.

During this project, you will have the opportunity to test acquisition criteria for converted-wave compliant surveying on Norway's Hardangerjøkulen ice cap[7] (Figure 2), itself an important study area for predicting how isolated glaciers will respond to climate warming. You will use seismic reflection data from two key study sites: Korff Ice Rise[8] (Figure 3) and the shear margins of Thwaites Glacier[9], provided respectively by the British Antarctic Survey and the NERC/NSF-funded *TIME* project.

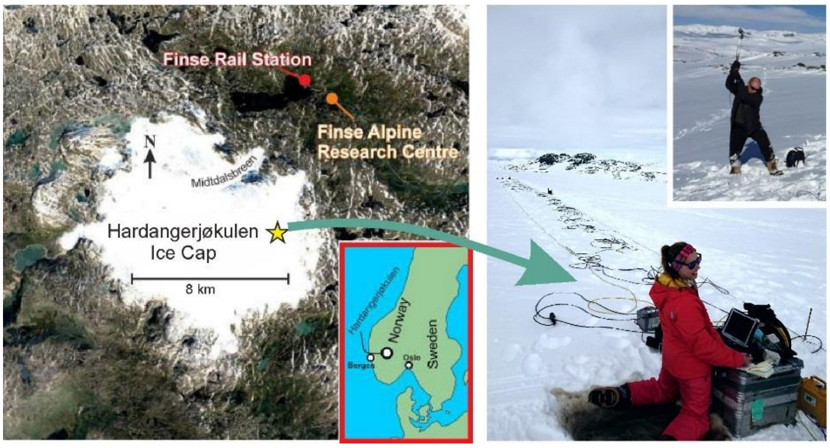

***Figure 2.** University of Leeds seismic survey on Norway's Hardangerjøkulen ice cap. The shrinkage of this ice cap has significant implications for water resources management in south-west Norway hence it is continuously monitored by various instruments. It is also a convenient and accessible test-bed for the development of new analytic approaches: we have recently been exploring new seismic inversion methods at the site.*

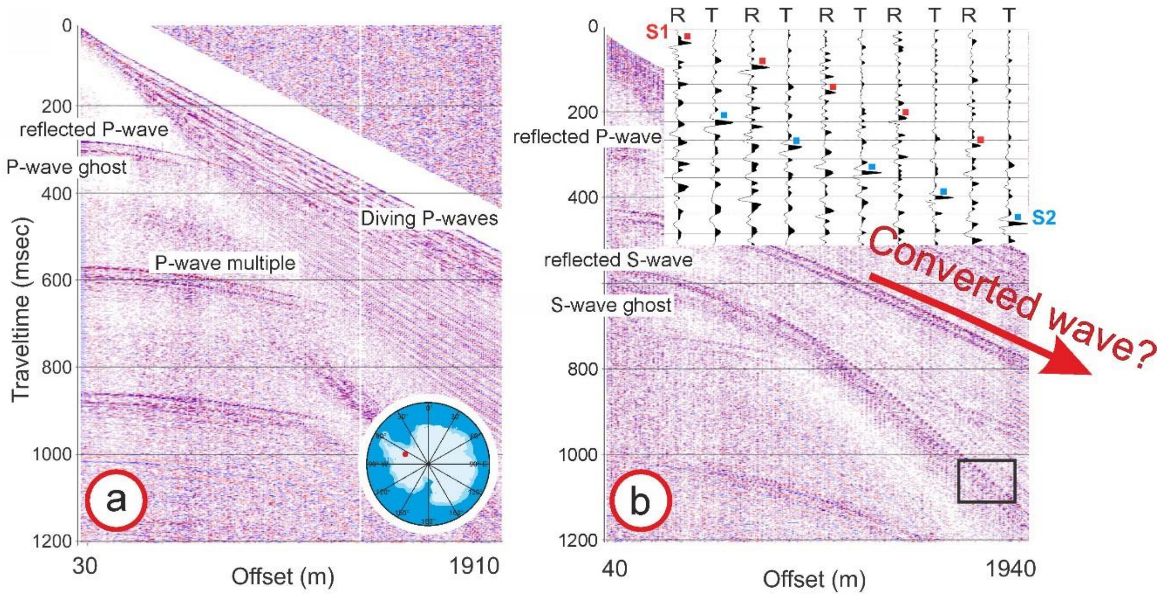

Figure 3. *BAS Seismic records from Korff Ice Rise on the Filchner-Ronne ice shelf (inset map). Vertical-component data (a) show P-wave reflections from the ice bed, with the horizontal-component (b) highlighting equivalent S-wave responses. However, the strong converted wave in (b), with t0 ≈ 420 ms, is currently not included in any analysis and warrants further investigation to constrain both P- and S-wave reflectivity models.*

Aim and Objectives

With the overall aim of exploring the scope, potential and added-value of converted-wave methods in glacier seismology, you will work towards the following objectives:

1) **Assess and test the criteria for reliable acquisition of converted-wave reflections, at a test site at Hardangerjøkulen;**
2) **Undertake an analysis of compressional- and converted-wave characteristics (AVO, but potentially extending to attenuation and velocity) at two Antarctic sites;**
3) **Provide a comprehensive interpretation of the englacial and subglacial material properties at Korff Ice Rise and Thwaites Glacier, drawing on your novel converted-wave methodologies;**
4) **Recommend 'best practice' for the application of converted-wave methodologies at wider glaciological survey sites.**

Potential for High Impact Outcomes

Quantitative seismic analysis holds the key to establishing the mechanical properties of glaciers – the very properties which need to be parameterised in predictive flow models. The development and demonstration of new tools, which demonstrate the capacity to improve this parameterisation, provides the opportunity to publish key results in world-leading international journals. Such innovations will generate interest in their own right, but have the potential to become highly-cited impactful works when coupled with insight at two active research sites. Korff Ice Rise and Thwaites Glacier are both areas of active international focus, underpinning the stability of their respective regions of Antarctica.

Training

This project will be led by Dr Adam Booth, an expert in glacier seismology and seismic acquisition, and supported by Dr Roger Clark, an authority on seismic processing and attenuation analyses. You will also receive close support from Dr Alex Brisbourne at the British Antarctic Survey, who also provides the BAS dataset from Korff Ice Rise.

The Applied Geophysics Group, in Leeds' Institute of Applied Geoscience, includes 2 PhD students working on glacier seismology, and a further 2 working on advanced seismic imaging. We operate a modern suite of seismic analysis software, including Landmark Solutions *SeisSpace* and Shearwater *Reveal*, and maintain a large stock of modern geophysical field equipment (e.g., Geometrics *Geode* seismic system, Sensors&Software *PulseEKKO PRO* GPR). PhD students can access the modules of our MSc Exploration Geophysics programme, either contributing as a student teaching assistant or refreshing knowledge by 'sitting in' on classes. Additionally, a range of training courses (e.g., thesis writing, communication, conference skills, software programming) are provided through the DTP.

Specific training in glaciological research questions, theory and field methods will be provided by project supervisors, and by undertaking an MSc-level course at The University Centre in Svalbard.

Completion of this PhD opens a range of career options. Knowledge of contemporary glaciological topics and cutting-edge methodologies clearly offers a continuing research career as a postdoctoral scientist; glaciology will remain an active research field given the international focus on the consequences and mitigation of climate warming. As a leader in seismic acquisition and quantitative interpretation, you would be highly employable in any sector that relies on physical properties extracted from seismic data, whether in as an industrial geophysicist or in a parallel research setting.

Student Profile

Applications are welcome from graduates in Geophysical Sciences, or any other cognate numerate discipline. You will have experience with handling and processing seismic data, either through your degree or via previous industrial experience, and a firm understanding of the fundamental theory of seismic propagation. A willingness to undertake computer programming (e.g., in MatLab, Python or equivalent) is essential, as is the ability to undertake outdoor fieldwork in cold regions. A familiarity with glaciological research questions is beneficial, but not essential.

Further Reading

1. Joughin *et al.*, 2014; *Marine ice sheet collapse potentially underway for the Thwaites Glacier Basin, West Antarctica*. Science, 1249055.
2. Shepherd *et al.*, 2018; *Mass balance of the Antarctic Ice Sheet from 1992 to 2017*. Nature, 558, 219-222.
3. Murray *et al.*, 2007; *Water-content of glacier ice: Limitations on estimates of velocity analysis of surface GPR surveys.* Journal of Environmental and Engineering Geophysics, 12(1), 87-100.
4. Peters *et al.*, 2012; *Seismic attenuation in glacier ice: a proxy for englacial temperature.* 117, F02008.
5. Booth *et al.*, 2012; *Thin layer effects in glaciological seismic AVA analysis: implications for characterising a subglacial till unit, Russell Glacier, West Greenland.* The Cryosphere, 6, 909-922.
6. Chopra and Castagna, 2014; *AVO*; Investigations in Geophysics No. 16, SEG, Tulsa OK.
7. Åkesson *et al.*, 2017; *Simulating the evolution of Hardangerjokulen ice cap in southern Norway since the mid-Holocene and its sensitivity to climate change.* The Cryosphere, 11, 281-302.
8. Matsuoka *et al.*, 2015; *Antarctic ice rises and rumples: their properties and significance for ice-sheet dynamics and evolution.* Earth-Science Reviews, 150, 724-745.
9. Schroeder *et al.*, 2013; *Evidence for variable grounding-zone and shear-margin basal conditions across Thwaites Glacier, West Antarctica.* Geophysics, 81(1), WA35-WA43.