Below the Ice:

Investigating the Subsurface Environment of Thwaites Glacier through Radio Echo Sounding

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Background: Thwaites Glacier

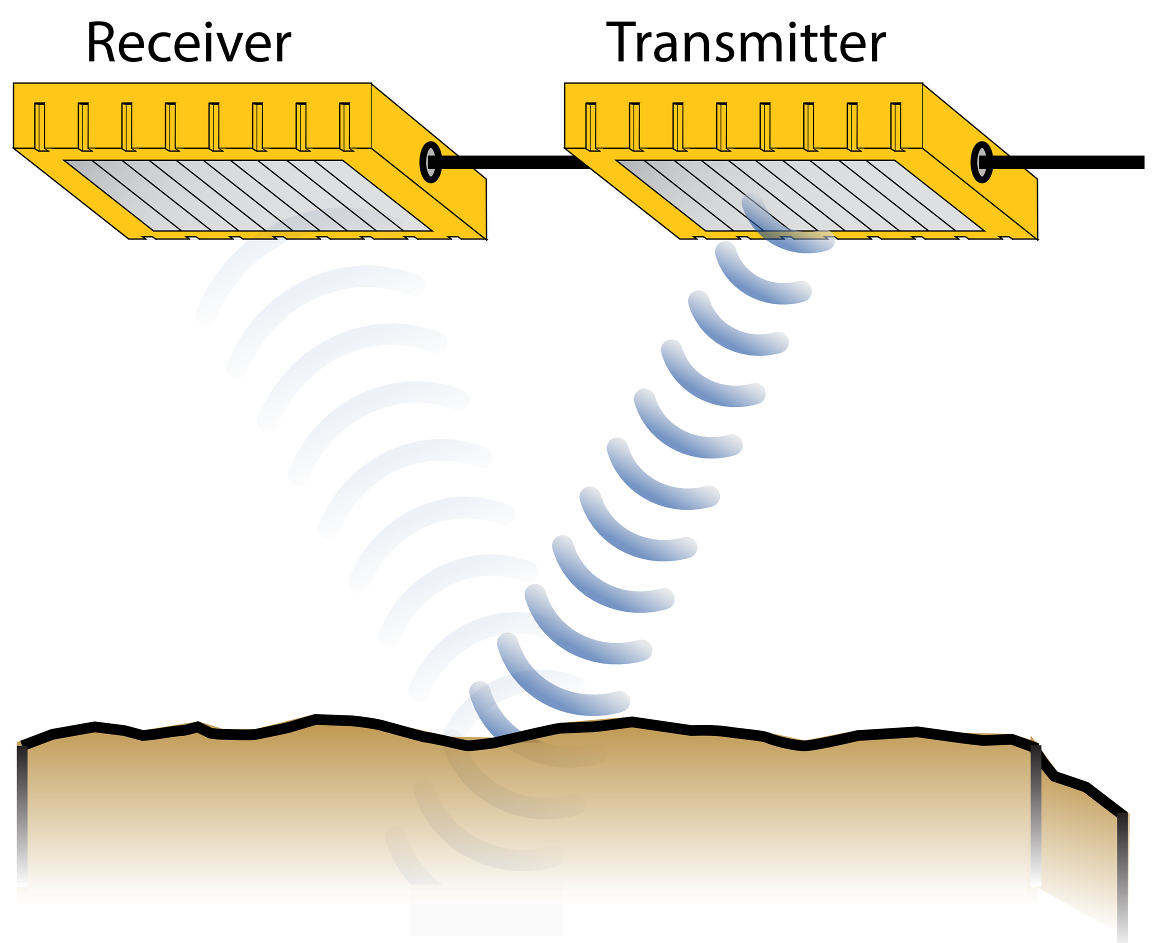
Antarctica is broadly defined by two regions: East Antarctica, and West Antarctica. East Antarctica, which is covered by the East Antarctic Ice Sheet (EAIS), is a tectonically stable craton derived by the Precambrian crust of Gondwanaland. Wast Antarctica, which is covered by the West Antarctic Ice Sheet (WAIS), is defined by the younger crust of the West Antarctic Rift System. The bedrock of the East Antarctic craton is almost entirely above sea-level, which has resulted in the long-term stability of the ice in the region, but WAIS rests on a bed which is mostly below sea-level, and has been prone to collapse throughout historic warm periods.

Thwaites Glacier, one of the ice streams which drains ice from the interior of the continent out to the ocean, is particularly important for forecasting future impacts of climate change. The Amundsen Sea, which Thwaites and Pine Island Glaciers drain into, has been previously described as the "weak underbelly" of the West Antarctic Ice Sheet; due to their particular geometry, the retreat of Thwaites Glacier into the Amundsen Sea will almost certainly result in the full collapse of WAIS. In order to fully characterize the current flow regime of Thwaites glacier, as well as predict its future behavior, it is first necessary to survey the bed below the ice.

RES: Data Collection

There are many techniques commonly used for subsurface analysis in Antarctica, however the two best subsurface imaging methods are Seismic Reflection Surveys and Radio Echo Sounding (RES) surveys. These both operate on the same principle: emit energy into the subsurface, allow it to interact with the material, reflect off of interfaces, and finally return to a receiver at the surface. Analysis of the "echos" makes it possible to determine many different characteristics of the structure below.

In the case of Radio Echo Sounding, electro-magnetic waves are transmitted by a radar as it is either dragged along or flown over the surface of the ice. In a homogenous medium, the waves simply travel through and no data are produced. However, when the wave front crosses into a new medium with different dielectric properties, the wave reflects. Some fraction of the transmitted energy is sent back toward the radar where it is logged in a computer, while the remaining energy continues through toward the next interface (as shown in the cartoon below). Using our knowldge of the speed of light in ice, combined with the length of time between the transmission of the wave and the detection of subsequent reflections, it is possible to calculate the distance between the radar and any given reflection surface. Because the dielectric properties of ice and rock are quite different, this technique is ideal for determining the thickness of the ice (and therefore location of the bed) in West Antarctica.

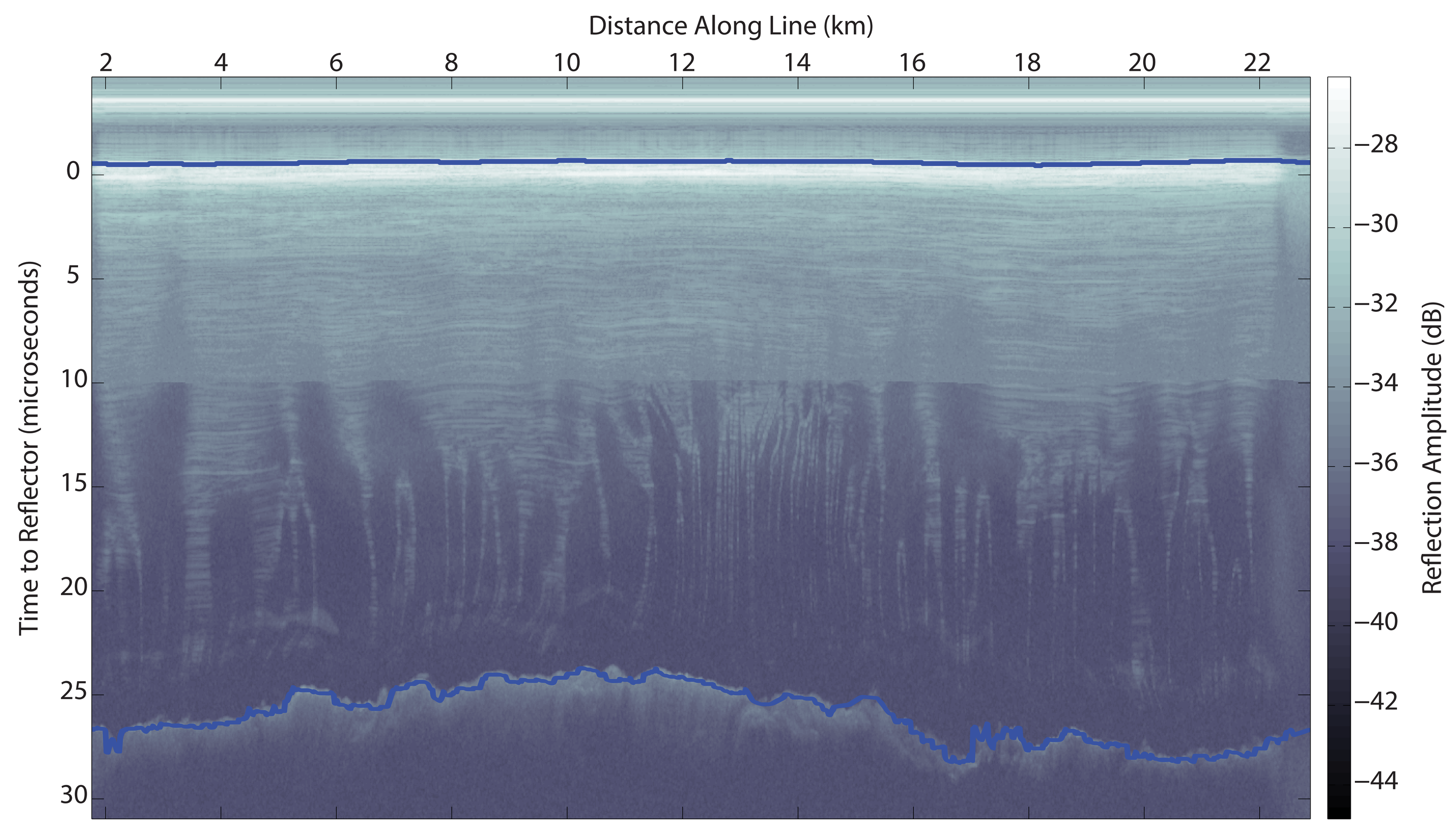


Radar Processing

Once the data have been collected in the field, there are several stages of post-processing that must occur before scientific interpretation can begin. Those steps include the following:

- GPS data associated with the moving radar must be processed. Geolocation is one of the most critical steps in the process; inaccurate locations for bed features can dramatically change results of modeling efforts.
- The amplitudes of the radar returns must be corrected for several factors. As the wavefront being transmitted expands, the transmitted energy is distributed over a larger and larger area, reducing the energy density with distance. This must be corrected for, along with any energy lost to the medium through which the energy travels.
- If it appears the dip angle of the reflectors is significant, a correction process called migration must be performed to correct for reflection off of surfaces not directly below the radar.

Once these steps are completed, a radar line like the one below is produced.



Data Analysis

Bed Reflector

The brightest (non-surface) reflector in the above data is the ice-rock interface. The thickness of the ice (and therefore the depth to the bed) is typically the first piece of information derived from a radar survey in the Antarctic.

Internal Layering

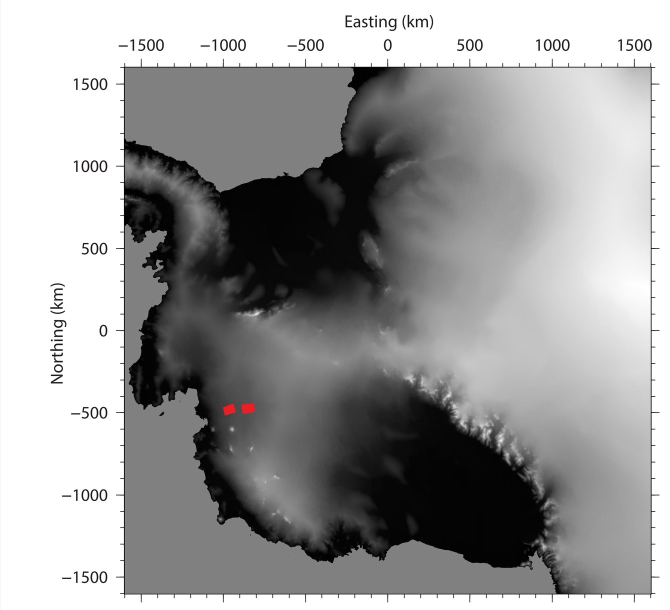
As seen in the above figure, there are also dimmer reflectors running throughout the ice column. The structure of these internal layers provides information about the flow of Thwaites Glacier. Glacial ice is originally deposited as flat lying beds of snow, therefore any non-horizontal features seen within the ice column must be due to subsequent deformation.

Reflection Amplitude

By comparing the amplitudes of a reflector in different traces along line, it is possible to locate changes in material properties over space. The most common use of this technique is locating water at the ice-bed interface. The dielectric contrast between ice and water is much greater than the contrast between ice and rock, resulting in brighter reflections in the presence of water.

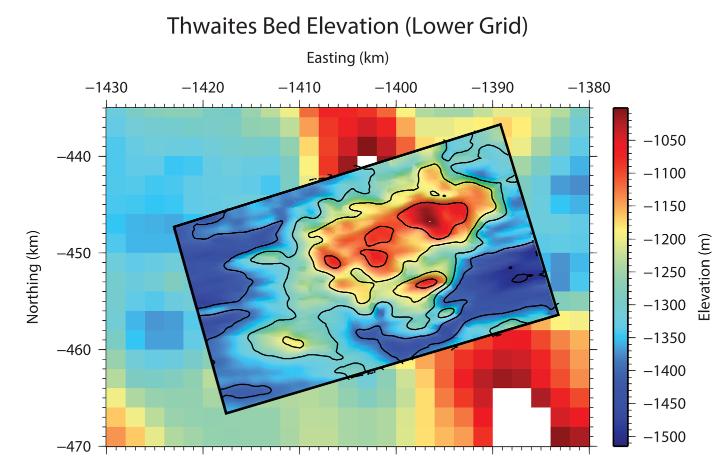
Glaciological Interpretation

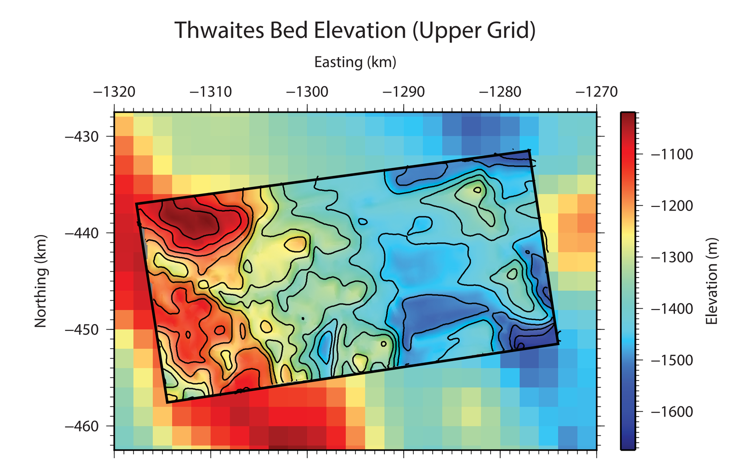
Two radar grids were flown over Thwaites Glacier for this project, indicated in red on the figure to the right. They were flown over two prominent subsurface ridges, one upstream of the grounding line by about 100km and the other approximately 60km further inland. Twahites Glacier's ability to retreat during warm periods is mitigated by these prominent sub-glacial ridges on which the ice can ground itself, so understanding their geometry and spatial continuity is important when predicting the evolution of the West Antartic Ice Sheet. The radar data was collected with this focus in mind.



Bed Topography

The calculated bed topography was interpolated between the radar lines to produce the grids below. These are plotted on the prevailing data set describing bed topography in the region. What appeared to be laterally continuous ridges actually have quite a bit of 2D variability. In the lower grid, you can see a deep trough cross cutting the ridge, implying that it may actually be a series of sub-glacial peaks as opposed to a continuous feature. Compared to the previous bed topography, these peaks would not stabalize Thwaites' retreat as effectively.

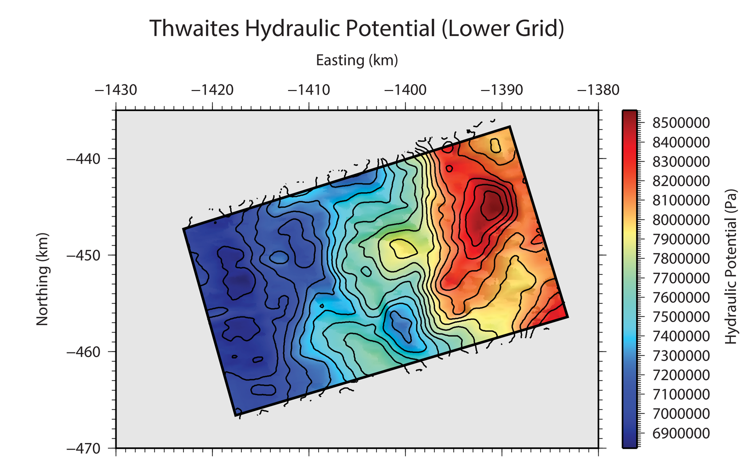


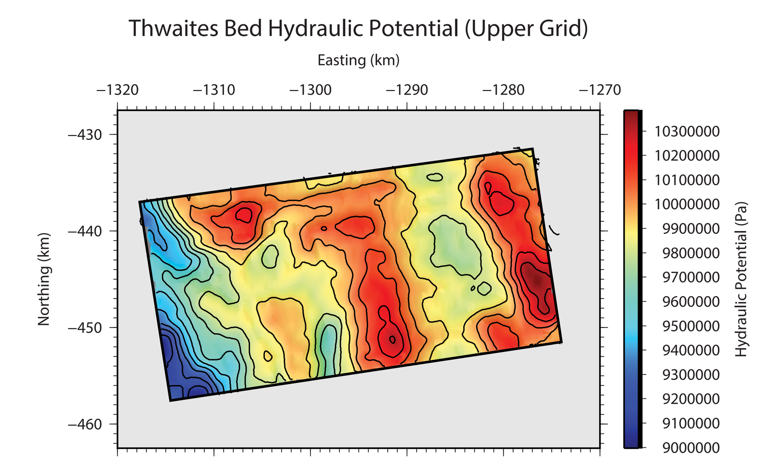


Hydraulic Potential

With information about the ice surface elevation and underlying bed elevation, it is possible to calculate the pressures acting at the bed of the glacier. This value, called the hydraulic potential, provides insight into theoretical water flow patterns; areas of high pressure will drive water away and areas of low pressure will be pooling locations for subglacial water. Below are hydraulic potential maps for these two grids. The ridges are both clear hydropotential highs, which indicates water will be driven away from them and they will act as restraints to ice flow.

$$\Phi = \rho_w g H_b + \rho_I g (H_S - H_b)$$





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