

# USING THE ENGLACIAL GEOMETRY OF WEST ANTARCTICA TO DETERMINE ITS FUTURE STABILITY

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## THE DISCIPLINE'S OBJECTIVE:

Determine the state of the modern ice sheets (West Antarctica, East Antarctica, and Greenland), and provide policymakers with reliable estimates of future sea-level rise.

## THE GLACIOLOGICAL CHALLENGE

Accurate projections of future sea-level rise require that we understand the processes that drive the modern ice sheets, and that we constrain the boundary conditions necessary to solve the controlling physical equations. These boundary conditions are often supplied by other models (predictions of future atmospheric and ocean conditions), but some, like the elevation and frictional properties of the glacial substrate, require high resolution observations of the current ice-sheet system. While airborne radar data can provide a low cost means of determining the geometry of the ice bed, there is currently no geophysical method that can reliably determine the frictional properties of the system.

### SCIENTIFIC HYPOTHESIS:

We can use **internal reflector slope** information from radar images to improve our understanding of the frictional properties of the glacial substrate, and thereby reduce uncertainty in projections of future sea-level rise.

### THE CURRENT METHOD

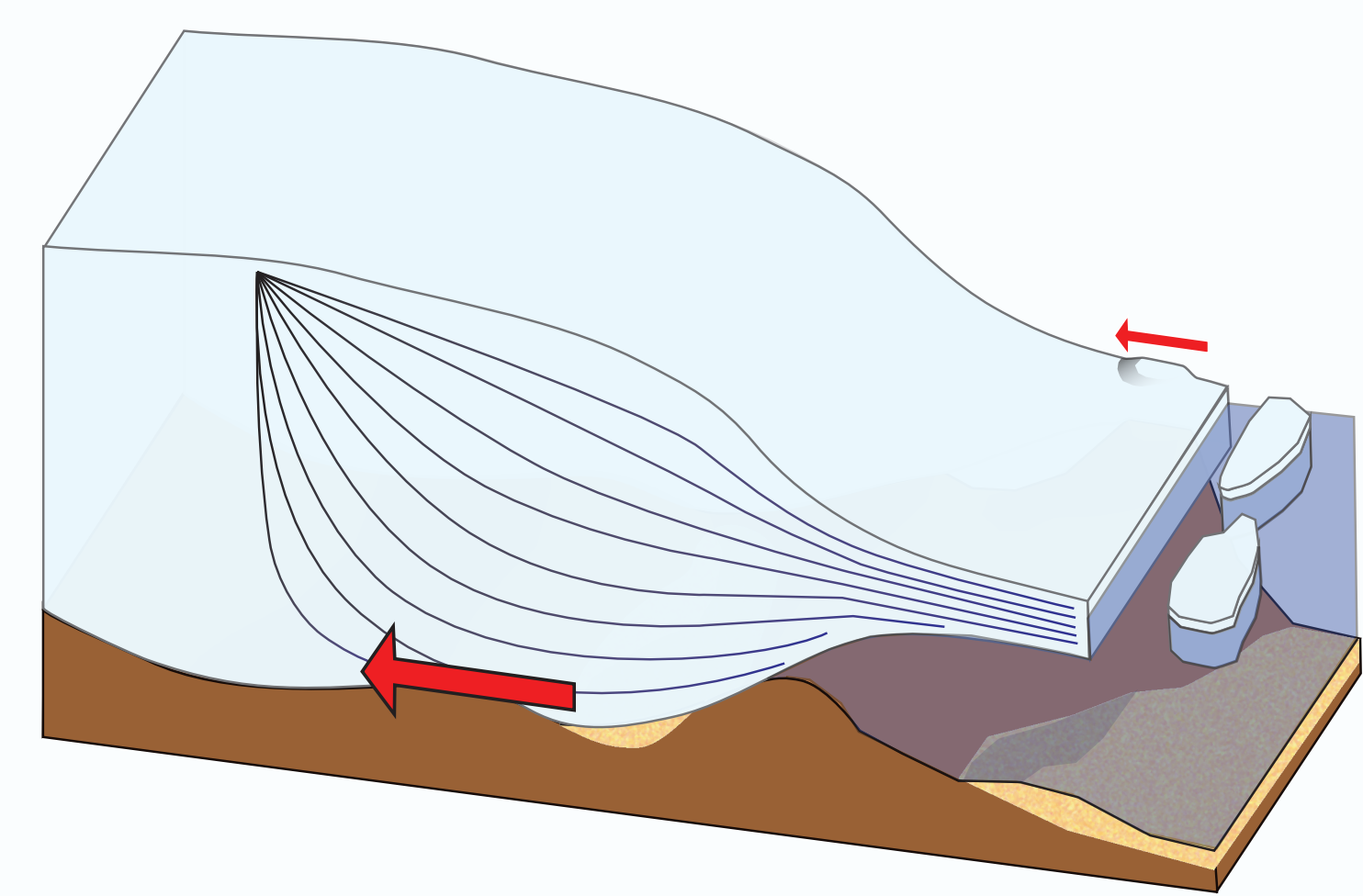
Without a reliable way to measure the frictional properties of the bed, glaciologists currently use our understanding of glacial physics to invert for the modern bed friction. Figure 1.1 provides a general schematic of the system: Ice flows from the interior of the continent to the margins according to its driving stress ( $\tau_d$ ), where it melts and contributes to sea level rise:

$$\tau_d = \rho g H \sin(\alpha)$$

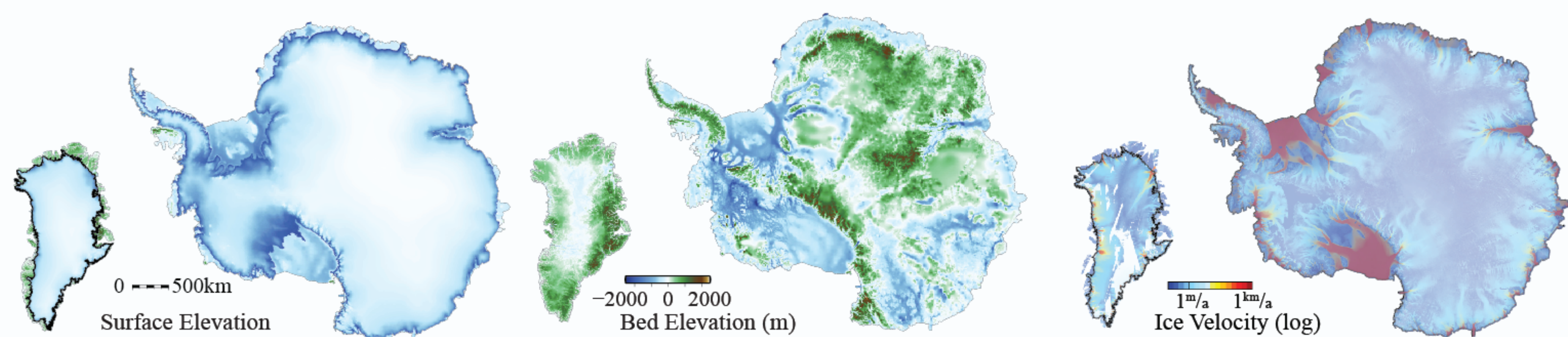
( $\rho$ ) is the density of glacial ice, ( $g$ ) is the acceleration due to gravity, ( $H$ ) is the ice thickness, and ( $\alpha$ ) is the surface slope. **In equilibrium, the driving stress must be equal to the frictional resistive stresses.** As with all frictional forces, these scale with velocity and the frictional parameters of the interfaces involved, the primary of which is friction at the bed ( $\tau_b$ ):

$$\tau_b = B u \left( \frac{1}{m} \right)$$

Internal resistance to flow and buttressing by the ice shelf are primarily a function of the ice viscosity (which has been experimentally derived in the lab), leaving friction at the bed as the only truly unknown frictional force in the system. Therefore, if we can measure the velocity and ice thickness of the modern ice sheet (Fig 1.2), it is possible to back out the basal shear stress. Using this method, there is not enough information to disentangle the individual contributions of the basal friction parameters ( $B$  and  $m$ ) to  $\tau_b$ . As a result, the basal rheology ( $m$ ) is assumed, and  $B$  is computed.



**Figure 1.1** - Schematic of the ice-sheet system. Ice flow is driven by the weight of the interior ice column, while internal resistance, friction at the bed, and ice shelf buttressing resist flow.



**Figure 1.2** - Surface Elevation, Bed Elevation (Bamber et al. 2011, Fretwell et al. 2011), and Surface Velocities (Joughin et al 2010, Rignot et al. 2011) for the Antarctic and Greenlandic Ice Sheets.

Different values for the assumed bed rheology lead to dramatically different projections for West Antarctica, with low values predicting collapse within 300 years and high values predicting much longer-term stability.

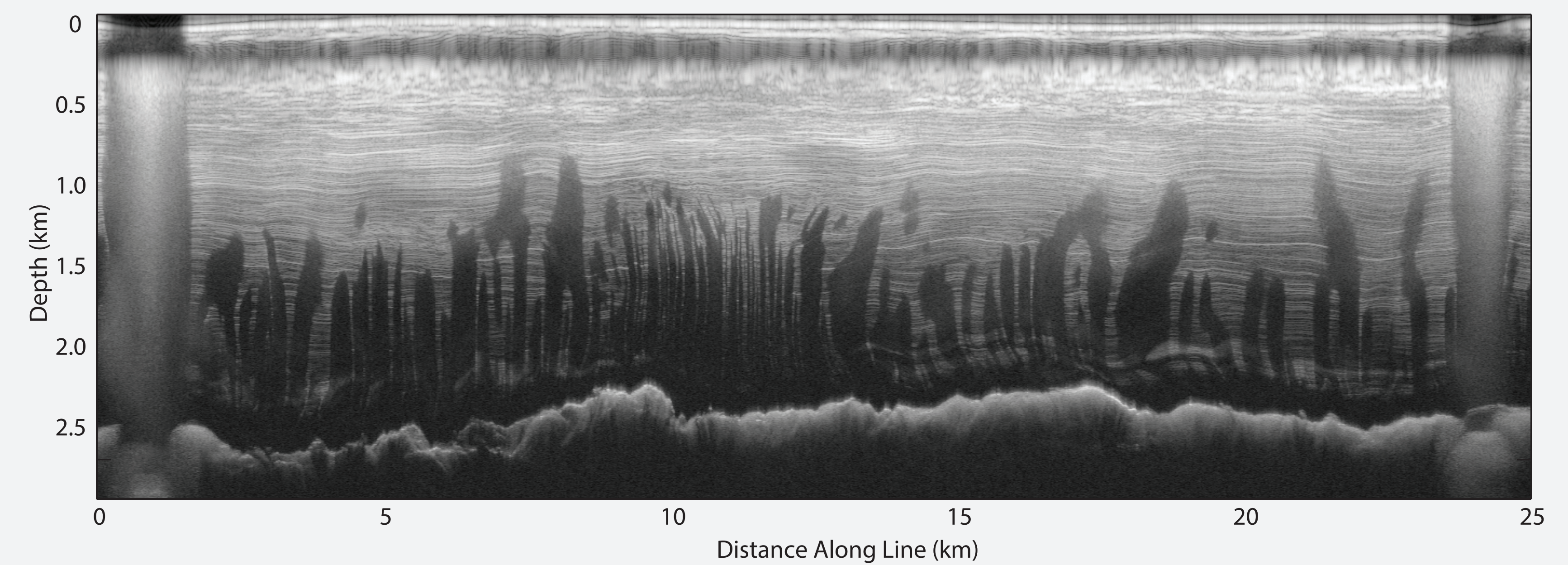
**The Solution:** By picking slopes in internal reflectors over large areas (which can be treated as a proxy for the internal velocity field), we can use them in concert with surface velocity and ice thickness to better constrain values of  $B$  and  $m$ .

## THE GEOPHYSICAL CHALLENGE

Airborne radar is a valuable tool for imaging the basal and interior structure of the major ice sheets. Areas of strong ice deformation are often the hardest to image, yet they occur where imaging is most critical for our understanding of the system (e.g. regions with steep gradients in the physical properties of the bed). Modern data processing methods focus the radar image using the same set of parameters everywhere, which nicely resolve flat layers, but often this processing leads to the defocusing and loss of steeply dipping internal layers in the image.

### TECHNICAL HYPOTHESIS:

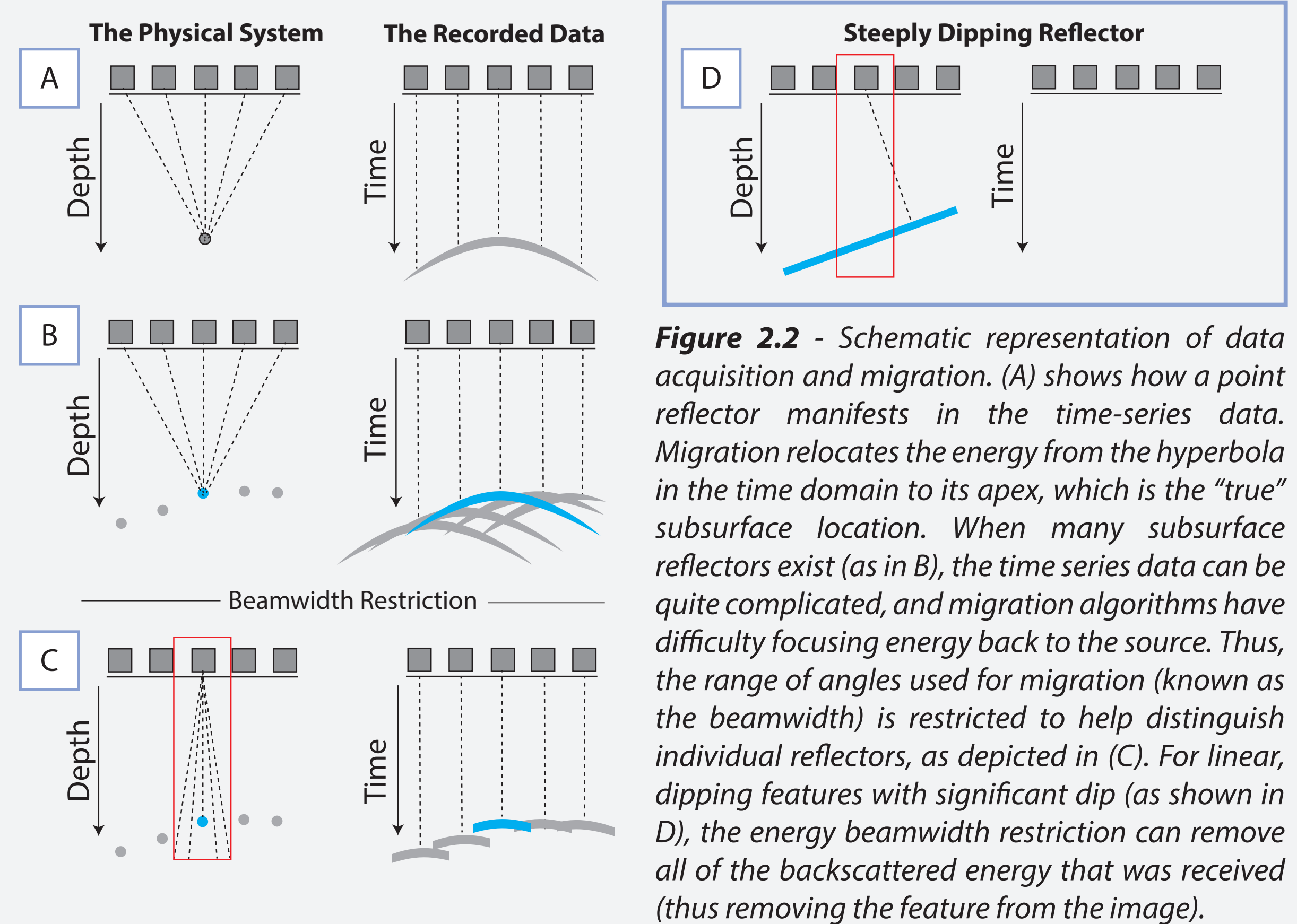
We can inform radar focusing techniques with pre-processed **internal reflector slope** information to better resolve areas of interest in the post-processed radar echograms.



**Figure 2.1** - Radioechogram collected during the 2009/10 Austral Summer by NASA's Operation Ice Bridge, using the Center for Remote Sensing of Ice Sheets 140-150 MHz radar system on a Twin Otter platform. The lower half of the echogram exhibits data losses from processing, in areas of steep reflector dip.

### THE CURRENT METHOD

Radar systems provide information about the structure of ice sheets by transmitting electromagnetic waves into the subsurface and detecting the resulting reflections off of englacial and subglacial structures. The amount of time between transmission and detection provides information about the distance to the subsurface reflector; however, with a single time series, there is no way of discriminating between energy coming from directly below the system and energy reflected from off-axis. As the radar moves over the surface and collects traces (as in Fig 2.2a), you image the same feature from multiple locations and can use information from adjacent radar traces to determine the true subsurface location for reflectors through a process called **migration**. In the migration algorithm, there is a trade-off between the maximum resolvable angle and noise in the image. Noise reduction is typically prioritized, resulting in the loss of steep internal features in radar imagery.



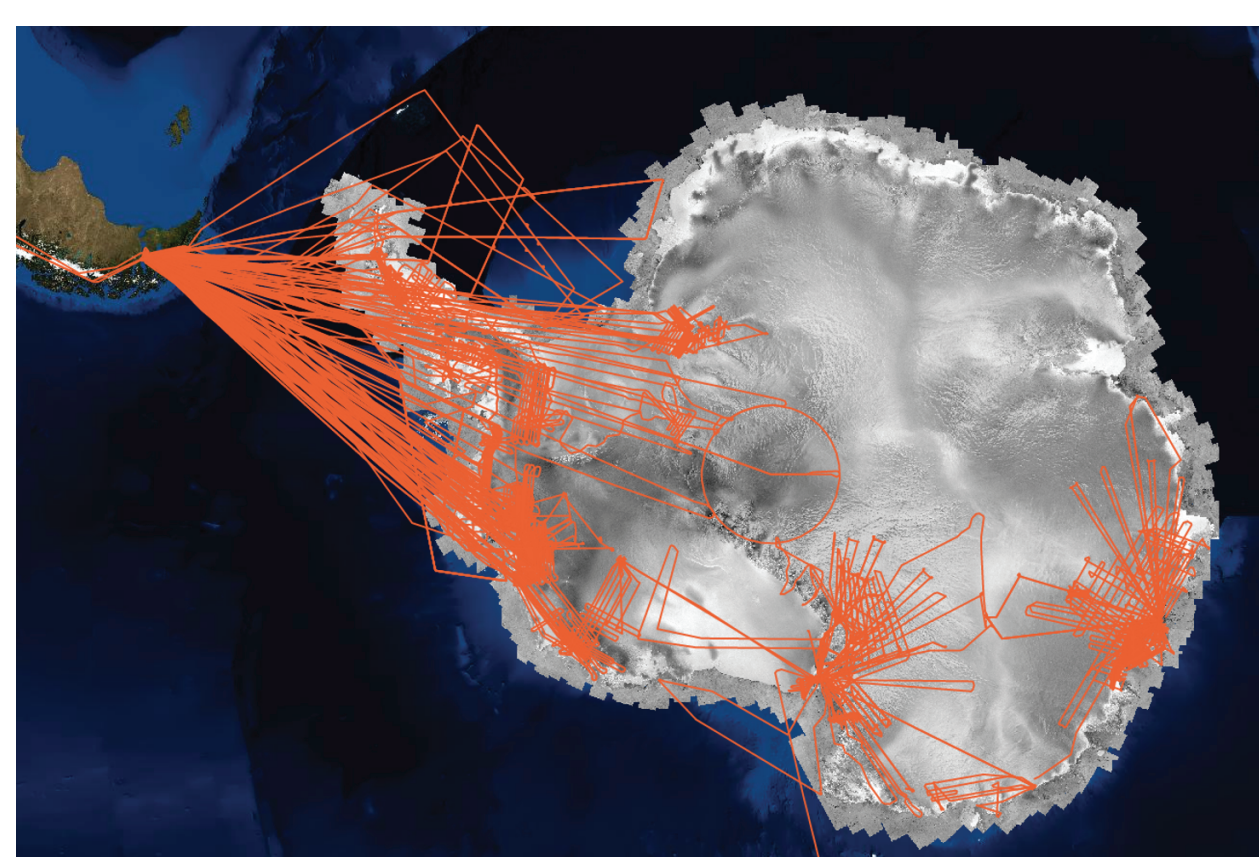
**Figure 2.2** - Schematic representation of data acquisition and migration. (A) shows how a point reflector manifests in the time-series data. Migration relocates the energy from the hyperbola in the time domain to its apex, which is the "true" subsurface location. When many subsurface reflectors exist (as in B), the time series data can be quite complicated, and migration algorithms have difficulty focusing energy back to the source. Thus, the range of angles used for migration (known as the beamwidth) is restricted to help distinguish individual reflectors, as depicted in (C). For linear, dipping features with significant dip (as shown in D), the energy beamwidth restriction can remove all of the backscattered energy that was received (thus removing the feature from the image).

Radar data processing schemes are ignorant of the underlying data, and are optimized to resolve high noise, low slope features, despite the fact that areas of glaciological interest are often characterized by steep dips and complex features.

**The Solution:** By determining average slopes for internal reflectors in the raw radar data before migration, we can update the beamwidth restriction for different regions to optimally resolve both areas of shallow slopes and areas with steep slopes.

## (PRELIMINARY) IMPROVED METHODS AND RESULTS

The wealth of data collected by Operation Ice Bridge (Fig 3.1) has the potential to provide slope information for the internal structures over the continent's primary glaciological targets, however it is too large for each line to be analyzed and reprocessed individually. It is important, therefore, that any new method developed is accurate, automated, and computationally simple. Layer tracing methods break down in areas of low signal to noise, and require a continuous layer from one end of the computation domain to the other. Our goal was to develop an algorithm for slope analysis that did not depend on any information outside of a local region, where the average slope can be calculated across layers. We use the numerical properties of the Radon Transform to do this:

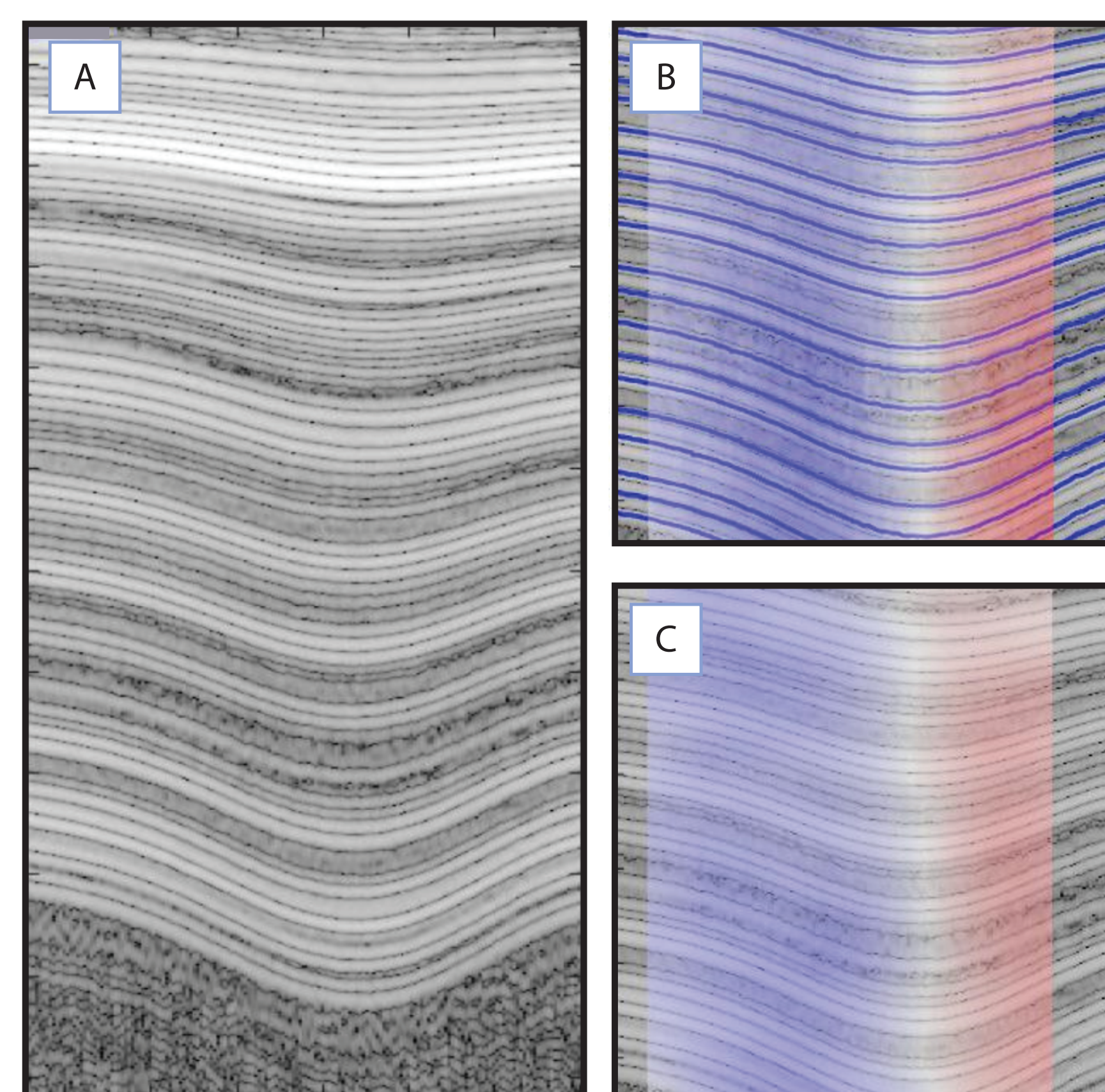


**Figure 3.1** - Plot of all Antarctic geophysical flight lines collected as a part of Operation Ice Bridge.

$$Rf(\alpha, S) = \int_{L(\alpha)} f(x) dx$$

The Radon Transform can be thought of as a set of line integrals calculated at an angle relative to the x axis ( $\alpha$ ) over some two-dimensional domain ( $S$ ). For a subset of a radioechogram, the angle that maximizes the value of the Radon Transform (ie the reflections over the domain of interest are best aligned) defines the reflector slope.

Because we are computing the radon transform over a rectangular domain, corrections must be applied for the number of samples in each line integral, as well as edge effects that result from very few samples at the boundaries of the domain. Optimizing the pre-conditioning, filtering, and smoothing is still in progress, however preliminary results of the Radon transform method are presented in Fig 3.2.



**Figure 3.2** - Results of the automatic slope picking on properly migrated data. (A) provides an example of radar data where steeply dipping features have been properly resolved. Individual layers were hand picked, and their slope fields computed (B). Additionally, the automatic Radon Transform algorithm was applied to predict layer slopes over the image (C). Comparison between the hand picked (B) and automated (C) layer slopes shows high reliability for the Radon Transform method.

### FUTURE WORK

We are beginning to reprocess the Operation Ice Bridge data in an effort to improve the image quality in areas of steep slope, after which we can apply our Radon Transform algorithm and produce slope field data products for West Antarctica. We are working with the model of Parizek et al. (2013) to develop an inversion scheme which uses the following updated cost function to better constrain the basal friction parameters:

$$\text{Error} = (\text{Velocity}_{\text{Obs}} - \text{Velocity}_{\text{Mod}}) + (\text{Reflector Slope} - V_{\text{Mod\_Vertical}} / V_{\text{Mod\_horizontal}})$$

With the additional constraint, it is possible to separate the effects of  $B$  and  $m$  on basal shear-stress, improving the accuracy of long-term projection efforts for the West Antarctic Ice sheet. This work has started with synthetic examples as proof of concept, and will continue with inversions for Thwaites Glacier and Pine Island Glacier in the Amundsen Sea Embayment.

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