Evaluating Transience of a Potential Geothermal Flux Anomaly Beneath a Tributary Ice Stream of Thwaites Glacier, West Antarctica

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The Amundsen Sea Embayment of the West Antarctic ice sheet (WAIS) is currently one of the most rapidly changing sectors of a continental ice sheet. As a marine ice sheet, the WAIS is in a potentially unstable configuration. A model is proposed to evaluate the effect of geothermal flux on flow in ice streams using ice layer drawdown anomalies, features identifiable by a thick layer package resting on top of deformed ice. Drawdown anomalies represent either significant loss or mechanical deformation of basal ice.

Several features with the geometry of drawdown anomalies are identified in Thwaites Glacier along an ice stream tributary near Mt. Takahe. These anomalies correlate with the surface ice velocity and have thick layer packages that age at a constant rate, implying deformation at a single origin corresponding to an upstream edifice. The abnormal amplitude of upstream drawdown anomalies implies a thermal event at the same edifice 1000-2000 years ago.

This provides another example of high heterogeneous geothermal flux in the WAIS.

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1 Introduction

The Antarctic Ice Sheet is the Earth's largest grounded ice reservoir, and has a variety of geologic controls on its ice flow[4]. The Antarctic bed topography (Fig 1) reveals very different stories behind the flow of ice in East Antarctica, which is above sea level, and the marine West Antarctic Ice Sheet (WAIS), which lies significantly below sea level. Thwaites Glacier in the WAIS discharges into the Amundsen Sea Embayment, has poorly understood geologic constraints, and is potentially critically unstable[6]. In particular, geothermal flux is often neglected because ice is a good thermal insulator and the continental background flux is small, usually generating only 6 mm/yr of meltwater[15]. When geothermal flux is accounted for, it is often assumed to be constant and uniform for computational simplicity. However, geothermal flux can vary greatly in both space and time, making it an important geologic constraint on ice flow.

There have been many cases shown in which a high geothermal flux can generate significant melt to constrain ice flow. Mt. CASERTZ[6] serves as an example of a subglacial volcano in the WAIS, identified using a combination of surface and bed morphology identified using airborne radar sounding data, laser altimetry data and magnetic data. In addition, areas of high basal melt can be identified in radar sounding data by comparing the ice thickness between ice layers in the middle and basal sections of the ice column. If the ice is thinning between the basal layer and the bed topography while thickening between the layers in the middle and basal sections, or vice versa, this can be

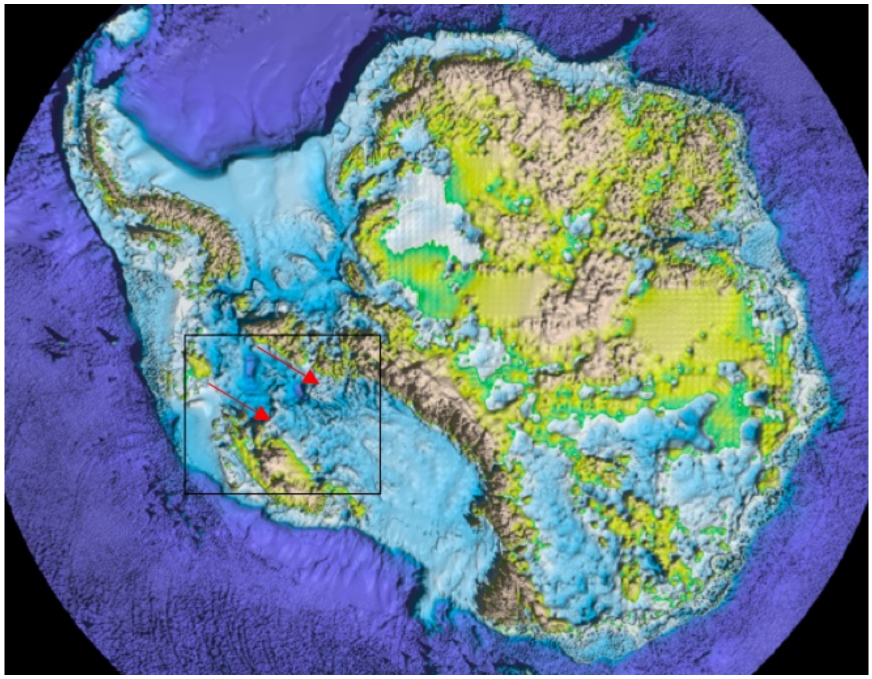

Figure 1: Bed topography of Antarctica after accounting for isostatic rebound. The WAIS is boxed, and the locations of studies by Blankenship et al.[6] and Danque[9] are highlighted. Borrowed from [9] and originally modified from [13].

taken as evidence for basal melt or freeze-on, respectively. These anticorrelation techniques have been shown to be effective in identifying areas of high basal melt due to geothermal flux in Thwaites Glacier[9][5].

The goal of this study is to identify how high geothermal flux can influence ice flow. This is done by constructing a methodology to identify and constrain how areas of high geothermal flux vary in space and time. A tributary of Thwaites Glacier is used as a test for the method because of its proximity to volcanoes such as Mt. Takahe as well as the good data coverage in the region.

2 Background

2.1 Basic Glaciologic Models

The basic model of the ice flow of a glacier can be derived from the conservation laws of mass and momentum, linked through a constitutive relationship referred to as Glen's flow law[15]:

$$\nabla \cdot \vec{u} = 0$$

$$\nabla \bar{\sigma} + \rho \vec{g} = 0$$

$$\dot{\epsilon}_{xy} \propto A \tau_{xy}^{n}$$

where $\vec{u}$ is the velocity of the ice, $\bar{\sigma}$ is the stress tensor of the ice, ρ is the ice density, $\vec{g}$ is the acceleration due to gravity, $\dot{\epsilon}_{xy}$ is a strain rate in the ice with τ_{xy} being the corresponding deviatoric stress, and A and n are empirically derived constants.

Conservation of mass can be used to constrain the velocity profile of a glacier by assuming ice is incompressible. Thus, when a piece of ice enters into a region within a glacier, an equal volume of ice must exit the region if the height of the ice column is to remain constant. Conservation of momentum governs the balance of forces acting upon the ice. In general, the primary driving stress is assumed to be due to gravity, written as

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

where τ_d is the driving stress, h is the thickness of the ice column and α is the surface slope. This can be used to explain why marine ice sheets are unstable; the bed of a marine glacier dips inland rather than seaward, causing the ice to thicken more rapidly towards the interior of a marine ice sheet than a normal one. Thus, if the grounding line is perturbed and moves inland, perhaps due to intrusion of warm seawater, the thickness at the grounding line will increase. If the thickness increases, the driving stress at the grounding line will also increase, causing ice to be discharged into the ocean at a higher rate. In addition, the surface area, and thus accumulation area, of the ice sheet decreases, making it more difficult to replace the ice that is discharged at the grounding line[21]. This fuels greater ice discharge and causes a positive feedback loop. Glen's flow law is an empirical relationship describing the flow of ice. It is assumed to be a power law relationship with $n = 3$.

As ice flows downstream, it sinks due to snow accumulating above it, thinning as a function of its position in the ice column. The Nye model for ice thinning[14] is particularly useful for understanding this phenomenon. This model assumes a constant vertical strain rate within an ice column and a zero vertical velocity at the bed. As a result, a correction factor for the change in size of an ice feature or layer as it sinks can be written:

$$\frac{l_{current}}{l_{initial}} = \frac{h_{current}}{h}$$

where l denotes the thickness of a feature and $h_{current}$ the current height of the feature. According to this correction factor, a feature will thin by 10% if it sinks 10% of the total ice thickness from the surface, and so on.

2.2 Ice Stream Mechanics

An ice stream consists of ice flowing much faster than its surrounding ice sheet, akin to a river or stream. The traditional theory is that fast motion occurs because of large amounts of basal lubrication, likely due to frictional heating[3]. However, ice streams can also be the result of a deforming till layer at the base of the glacier[1].

Fast motion of tributary ice streams in Thwaites Glacier are more likely due to a combination of deforming till and basal lubrication because of the high specularity (energy directly reflected rather than dispersed at an interface) at the bed often seen in airborne sounding profiles[20]. This is interpreted as a network of canals eroded into sediment beneath the ice, providing evidence for both basal lubrication and deformable till beneath the glacier.

2.3 Glaciologic Background of Thwaites Glacier

Thwaites Glacier is a marine outlet glacier of the WAIS. A significant portiion of the ice in Thwaites Glacier is below sea level because it rests on a bed below sea level that slopes inland[12], causing it to be potentially unstable

(Fig 2). Thwaites Glacier holds enough ice to cause 59 cm of sea-level rise[12], and is fed by multiple tributary ice streams with velocities above 100 m/yr, which reach a maximum velocity of 1 km/yr at the 80 km wide grounding line of the glacier (Fig 3). The tributaries are controlled by a network of basal topographic valleys that fan outward from the trunk. Of particular note are the multiple bed features such as Mount Takahe that have a topographic relief of nearly 4 km and are found exclusively in the half of the Thwaites Glacier most proximal to Marie Byrd Land. In addition to volcanoes such as Mount Takahe that peak above the surface of the ice, evidence for subglacial volcanism has also been identified near the ice divide[9]. These volcanic features, coupled with the thin, hot crust the WAIS rests upon, provide an argument that geothermal flux could be significant in regions of Thwaites Glacier adjacent to Marie Byrd Land.

2.4 Ice Penetrating Radar

Ice penetrating radar can be used as a tool to study ice sheets. Radar waves reflect off of layers of varying dielectric constant within the ice column[10]. Since the major parameter controlling the dielectric constant is density, these ice layers are interpreted as having varying acid content from volcanic eruptions incorporated into the annual snow accumulation. Thus, a major assumption in any layer interpretation is that ice layers are isochronous.

There are two basic types of radar: incoherent radar that records only the amplitude of the signal and coherent radar that records both the amplitude and phase. The advantage of coherent radar is that the extra phase information allows synthetic aperture radar (SAR) images to be created[17]. SAR has data in two dimensions: the azimuth dimension (with improved resolution compared to incoherent radar) and the range dimension, which can be converted to depth. SAR can be convolved with a reference function dependent upon the radar chirp and focus aperture to further improve azimuthal resolution and resolve steeper slope interfaces[16].

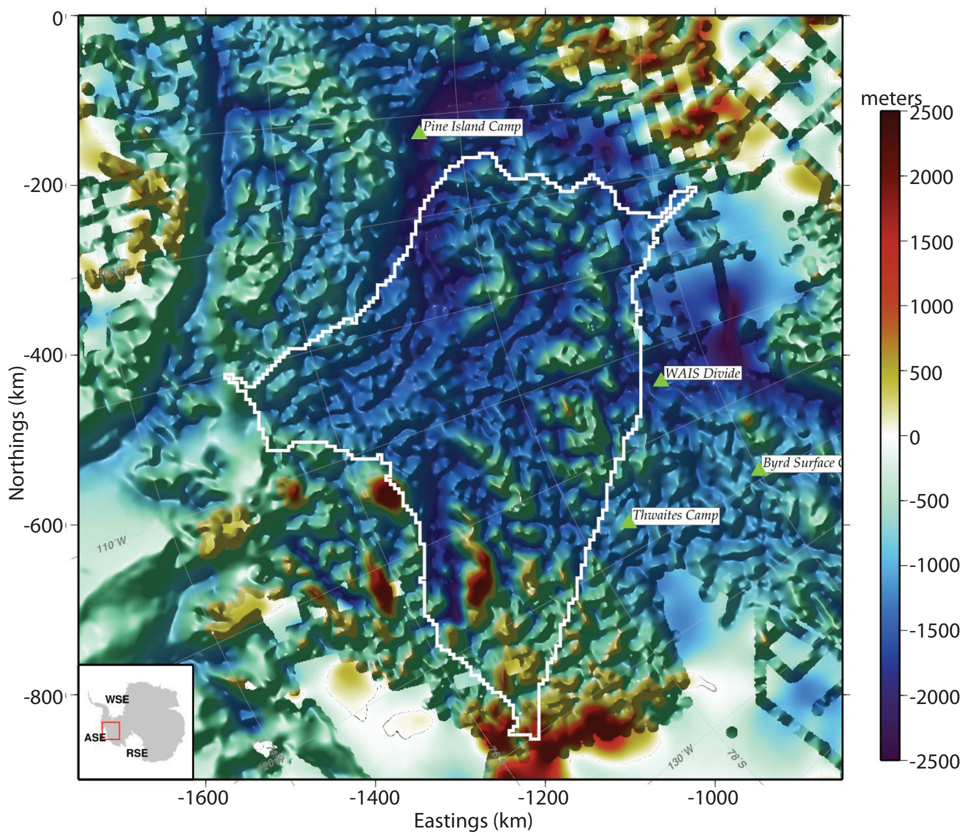

Figure 2: Bed topography of Thwaites glacier[12]. The ice divide is labeled in white.

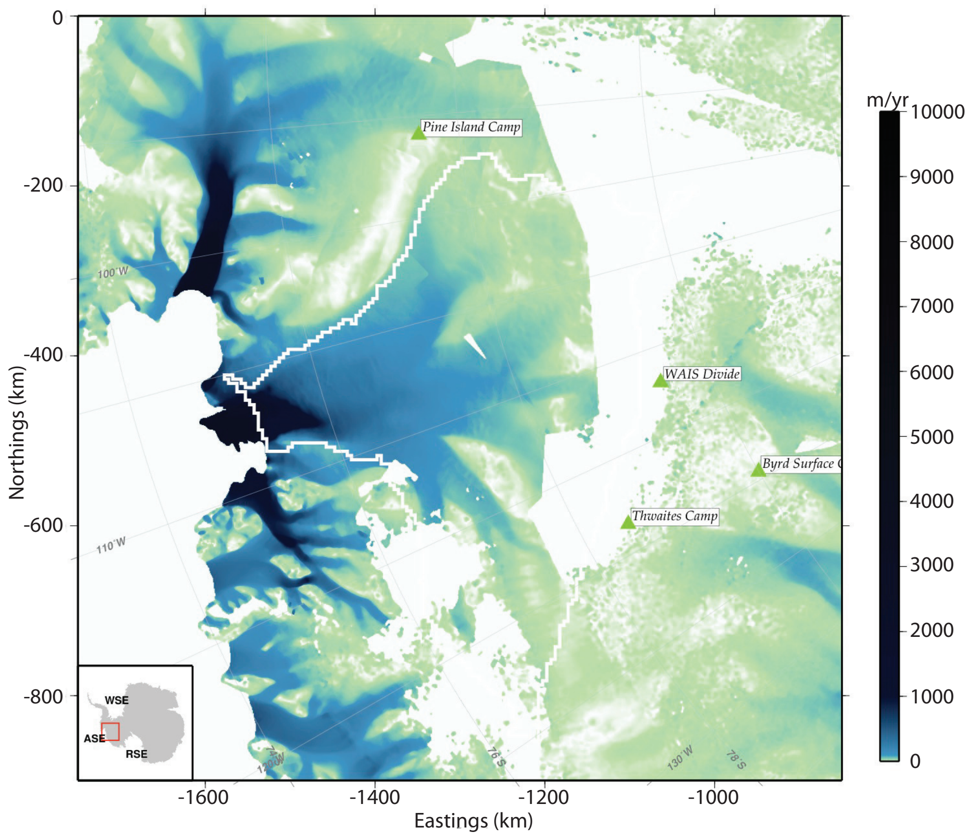

Figure 3: 2011 InSAR derived surface velocities of Thwaites glacier[19]. The ice divide and regions of no data are shown in white.

3 Methods

3.1 Theoretical Models

3.1.1 1-Dimensional Drawdown

Consider a thought experiment involving an ice column at equilibrium height with a normal layer assemblage. Now allow the ice to be deformed (henceforth referred to as drawdown) over a short period of time such that the ice layers sink. This causes ice layers deeper in the ice column to have greater ice thicknesses between them than normal as a result of being relatively young. Although the drawdown is damped in the upper ice column, it will cause a surface depression if it is of a high enough amplitude. Although accumulation is generally constant over small areas, snow will now preferentially accumulate in the surface depression as it is blown about by winds, causing thicker annual ice layers to form directly above the drawdown until the equilibrium ice column height is reestablished. At this point, ice layers of a normal thickness will once again accumulate, and the resulting package of thickened ice layers will sink and thin according to the Nye model.

3.1.2 Variations of the Thought Experiment

First, let's expand the 1-dimensional case into 2 dimensions. This time, consider an along-flow profile of an ice stream (Fig 4a). Now, consider thermal drawdown due to basal melt in a focused area (Fig 4b). Assume the drawdown signal propagates through the ice column nearly instantaneously and at a constant amplitude. Neither of these assumptions are realistic as ice deformation takes time and drawdown amplitude is damped in ice layers high in the ice column[8]; however, these assumptions help to simply illustrate how ice deformation propagates through an ice stream. As a result, the ice above the location melt is drawn down, but ice upstream and downstream is unaffected, forming a surface anomaly. In addition, the lower ice layers are destroyed due to melting. Now, the increased driving stress due to the high surface slope will cause ice around the anomaly to fill it up. However, if this happens at a smaller rate than the drawdown, the surface anomaly will persist, allowing a package of thick ice layers to form (Fig 4c, Fig 4d). The thickened ice layer package sinks and is expressed in older ice layers as it moves downstream.

Next, consider mechanical drawdown due to a high-relief obstacle (Fig 4e). In this case, the bottom ice layers are not melted, thus ice layers will not intersect the bed. Rather, the entire ice column thins as it passes over and around the obstacle. Aside from the bottom ice layers, the along-flow ice layer profile is similar to the previous case.

Finally, consider the combined case of both mechanical and thermal drawdown (Fig 4f). Since the drawdown is being caused by multiple sources, it will be of a higher amplitude. In addition, basal melt will destroy a greater age range of the ice column because of the thinning that occurs during mechanical drawdown. However, it is important to note that the topography changes over a much longer timescale than the heat flux that causes basal melt. Thus thermal drawdown can be thought of as a temporal signal superimposed upon a background signal of mechanical drawdown.

3.1.3 Cross-flow Drawdown Geometry

Although useful in explaining the evolution and basic geometry of a drawdown anomaly, the above thought experiments have less direct use for identifying the anomalies in a radar profile. Few radargrams are parallel to the flow of ice, and the thickened ice layer package is a subtle feature that is difficult to identify without proper context. As a result, it is useful to predict the cross-flow geometry of a drawdown anomaly (Fig 5).

Cross-flow drawdown anomalies are easier to identify due to the short wavelength, high amplitude drawdown signal that generally does not follow the general trend of the bed topography. In addition, a thickened ice layer package can be identified above the drawdown anomaly just as in the along flow thought experiments. Deep ice layers, if visible, can provide strong evidence for thermal drawdown if they intersect with the bed, as this is direct evidence for basal melt.

3.2 Data Analysis Techniques

3.2.1 Data Sets

This study uses the airborne radar sounding survey of Thwaites Glacier (Fig 2) collected as part of the AGASEA Project[12]. This SAR data has been coherently focused and is analyzed using the interpretation software GeoFrame. This provides significant constraints on the ice thickness, bed topography and ice layer structure of the ice sheet. In addition, ice layers picked in GeoFrame can be correlated to the Byrd ice core for timing constraints[11].

Drawdown anomalies are directly identified in along-track radar profiles, according to the crossflow geometry discussed above (Fig 5). Other features that may be present but are not necessarily diagnostic are a highly reflective bed and radar "fingers" beside the drawdown. A reflective bed may signify some basal melt, while the "fingers" are areas of no radar returns caused by high slope specular layers (greater than about 10°) reflecting energy away from the plane during data acquisition.

Surface velocity data[18][19] is also used in this study to analyze the spatial characteristics of drawdown anomalies. Anomaly locations are mapped against surface velocity to determine whether a given set of anomalies are multiple isolated features or a single broad feature. If drawdown locations correlate well with surface velocity, they are assumed to be a single coherent feature that has been propogating downstream from a single origin. If drawdown features do not correlate well with velocity, they are likely unrelated features with separate origins.

3.2.2 Determining Spatial Transcience

Spatial variations of drawdown can be determined for a set of related drawdown anomalies as long as the affected ice layers can be dated. First, the thick ice layer packages above the drawdown anomalies in each radar profile must be dated. Since these packages are assumed to form relatively quickly and soon after drawdown occurs, they can be used as a proxy for the age of the drawdown event recorded in a radar profile. If these layer packages are sufficiently high in the ice column, they should sink at a relatively constant rate governed primarily by the local accumulation rate. Thus, a plot of drawdown age vs. flowline should show a linear relationship if there has been no additional drawdown since the point of origin. Nonlinear trends can show the flowline positions where there is significant deviation in accumulation or subsequent drawdown events.

3.2.3 Determining Temporal Transience

In order to determine how drawdown from a particular source has been varying over time, it is useful to define the drawdown amplitude. This quantity can be defined for a given ice layer in a drawdown profile by taking the height difference between where the ice layer is drawn down and not drawn down (Fig 5). Drawdown amplitude is defined for as many ice layers in the radar profile as possible and then plotted as a function of the ice layer age. The shape of the resultant graph (Fig 6) is supported by the 1D drawdown thought experiment discussed earlier. The older, deeper layers were present when drawdown occurred, and thus have drawdown amplitudes that are relatively constant or steadily decreasing as the ice gets younger. The kink in the graph represents the surface anomaly that formed as a result of drawdown, and the rapidly declining amplitude corresponds to the thick layer package predicted in the models discussed earlier. Finally, layers above the thickened ice layer package were not affected by drawdown and thus have no drawdown amplitude.

Drawdown amplitude curves are generated for each radar profile to see how they vary along flow. Should there be no temporal variation in drawdown, the curves will subside due to normal thinning as described by the Nye model[14]. Amplitude curves that diverge from the Nye model are interpreted as indicating time periods in which more or less drawdown occurred.

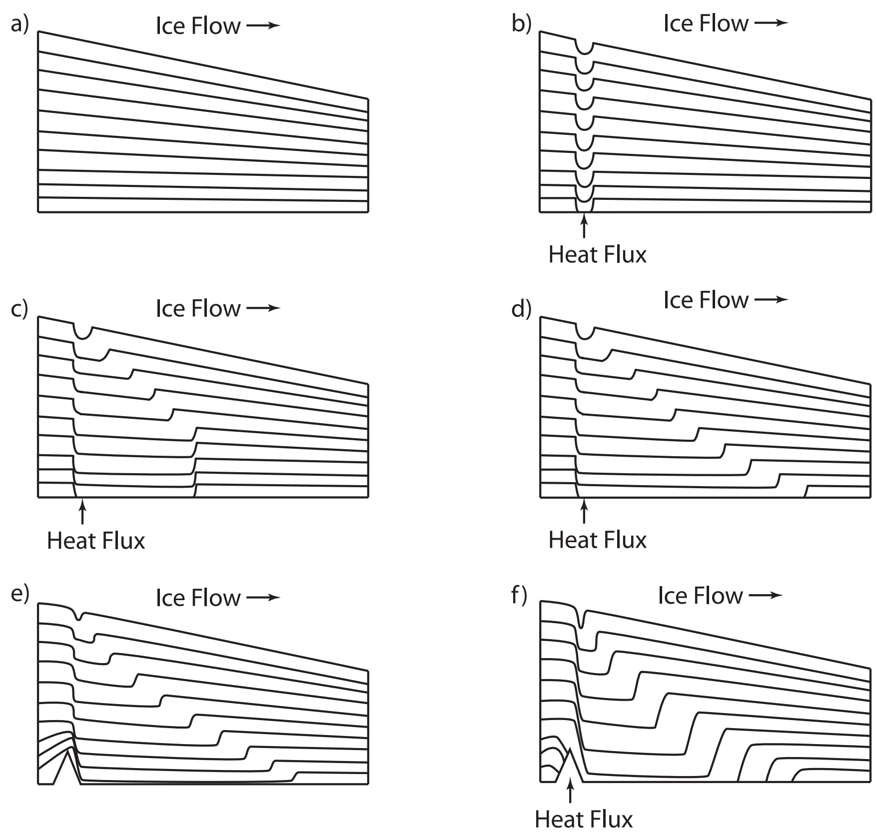

Figure 4: Schematic diagrams of hypothetical along-flow radar profiles affected by drawdown. a) is a simplified ice stream profile in steady state. b) is the same profile after being immediately deformed via upstream thermal drawdown. c) is the transient response of the ice stream to b) as the drawdown propagates downstream, and d) illustrates the steady state profile due to constant thermal drawdown. e) is a similar steady state profile due to mechanical drawdown. f) is the steady state profile due to both mechanical and thermal drawdown.

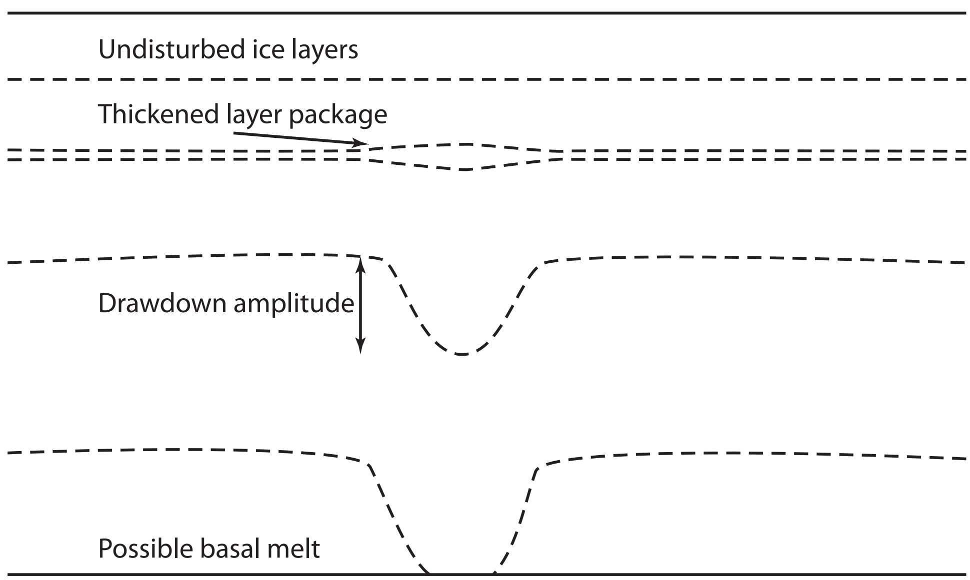

Figure 5: Schematic diagram of the geometry of a drawdown anomaly in a cross-flow profile. Horizontal scale is arbitrary but small, no greater than a few kilometers.

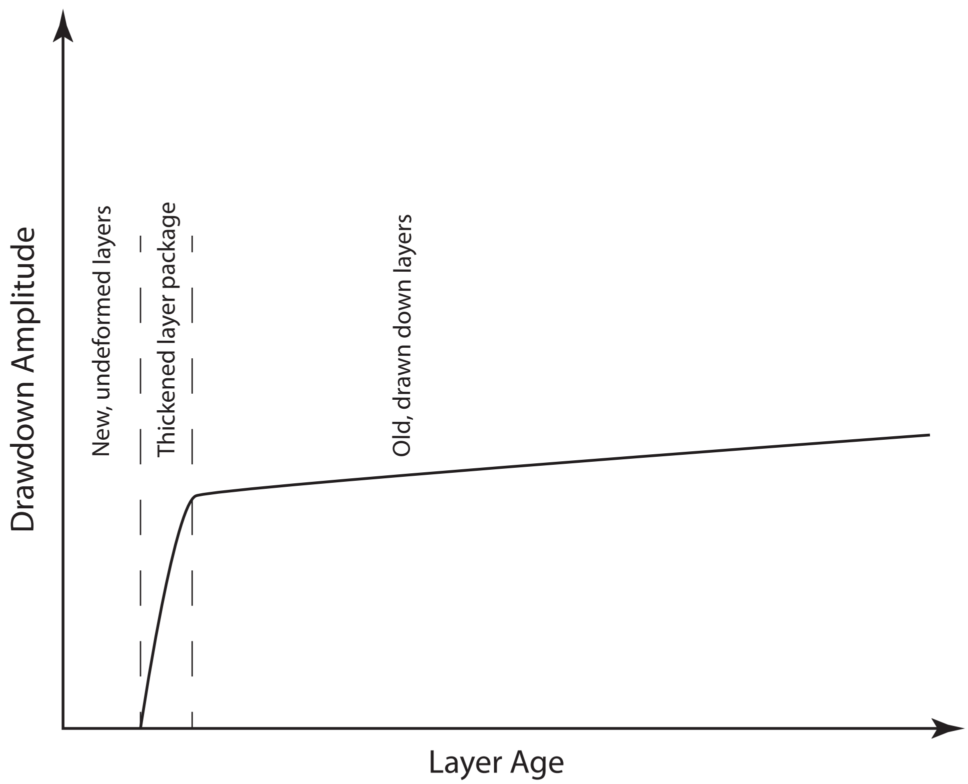

Figure 6: Hypothetical relationship between drawdown amplitude and layer age.

4 Results

Ten drawdown anomalies were identified in the tributary flowing between Mount Takahe and the Crary Mountains (Fig 7). There is a good correlation between the drawdown locations and the surface velocity, suggesting the possibility of a single coherent feature. In addition, the locations of these drawdown anomalies are constrained to a valley which bends around Mount Takahe towards the Amundsen Sea Embayment (Fig 8).

Interpretation	Color	Age (ka)
jbd1	yellow	1.7
jbd2	green	3.2
emp3	red	4.6
emp2	yellow	5.5
emp1	green	6.0
mrw3	purple	13.0
adj1	pink	17.1

Table 1: Ages and color (see Fig 9) of radar interpretations used in this study.

Seven ice layers were picked to evaluate the geometry of the drawdown anomalies, which span an age range of approximately one order of magnitude (Table 1). The oldest ice layer is relatively young for its depth, consistent with having been drawn down. In addition, the thickened ice layer package is present, and it sinks as the drawdown anomaly moves downstream. This is easiest to see in younger ice layers that are deformed in upstream profiles but not in downstream profiles (Fig 9). The drawdown amplitude decreases in downstream profiles, consistent with thinning according to the Nye model. Radar "fingers" are present, making it difficult to track layers continuously across the drawdown anomalies. The interpretations were made by identifying and matching a consistent ice layer sequence in the radar profiles.

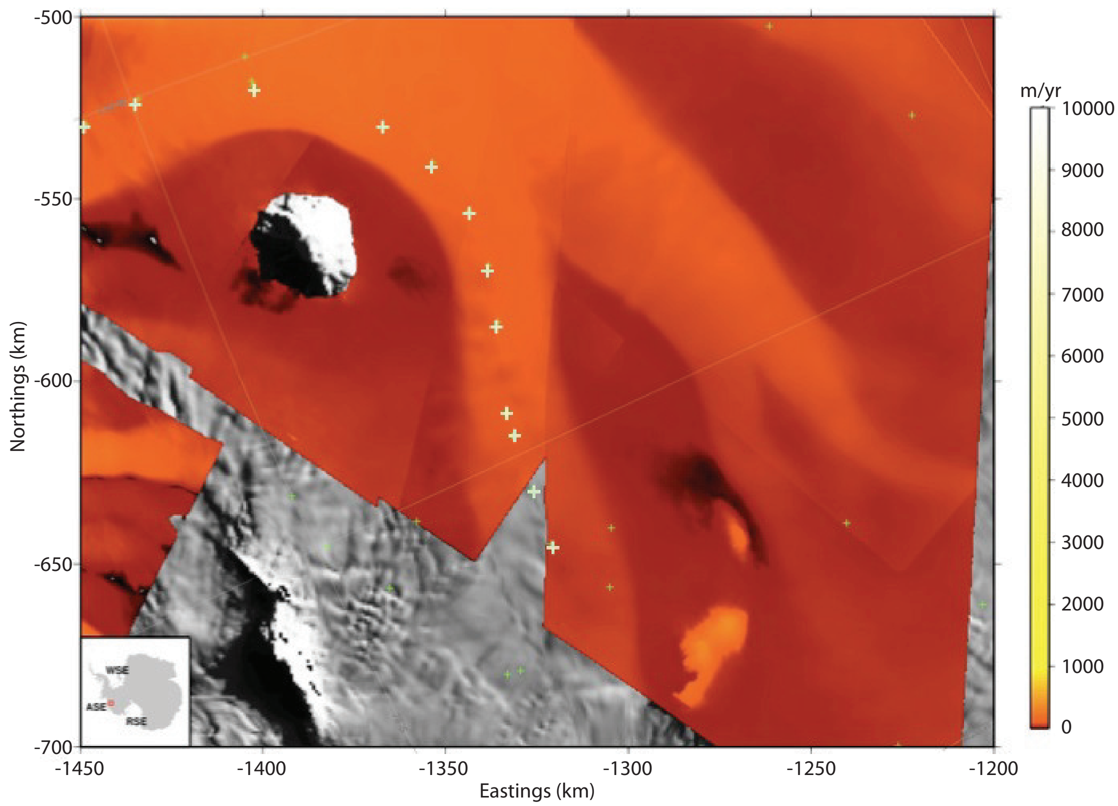

Figure 7: 1996 surface velocities of Thwaites glacier in the vicinity of Mount Takahe[18]. Drawdown anomaly locations are denoted by crosses.

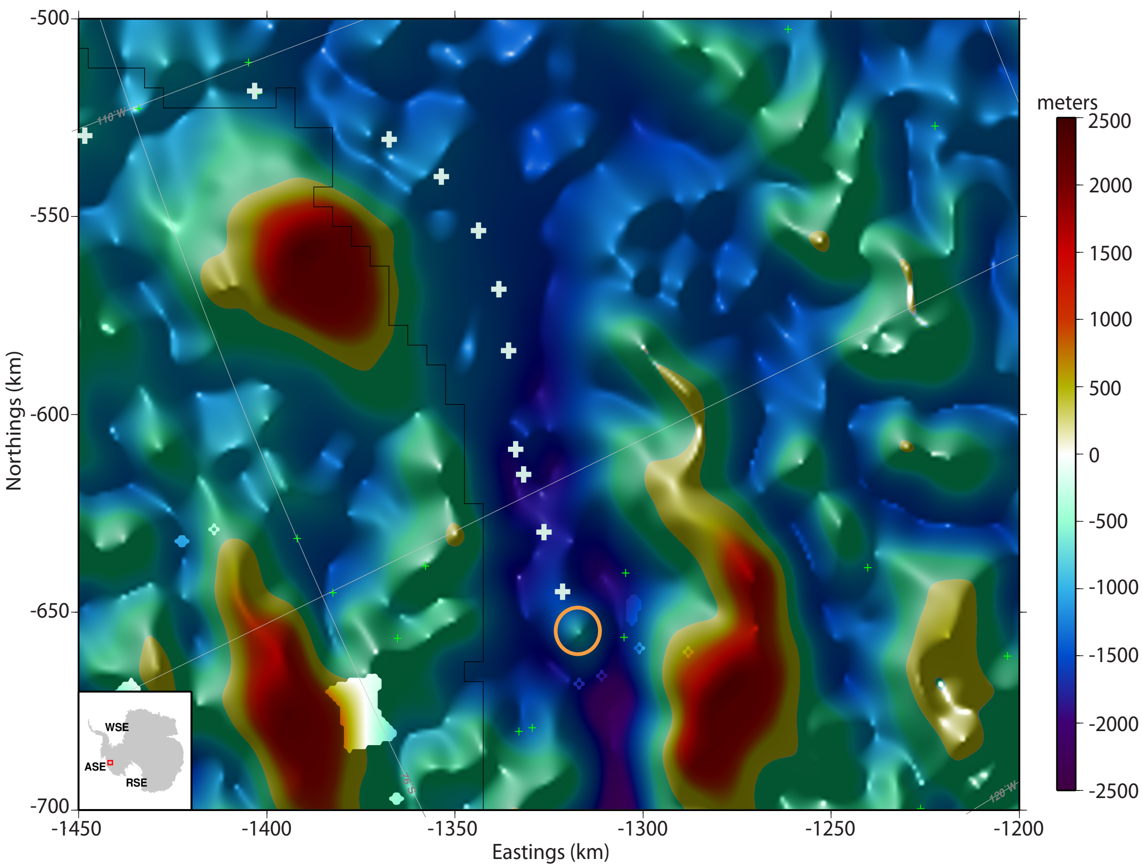

Figure 8: Bed topography of Thwaites glacier in the vicinity of Mount Takahe[12]. Drawdown anomaly locations are denoted by crosses, and an upstream topographic edifice is also marked.

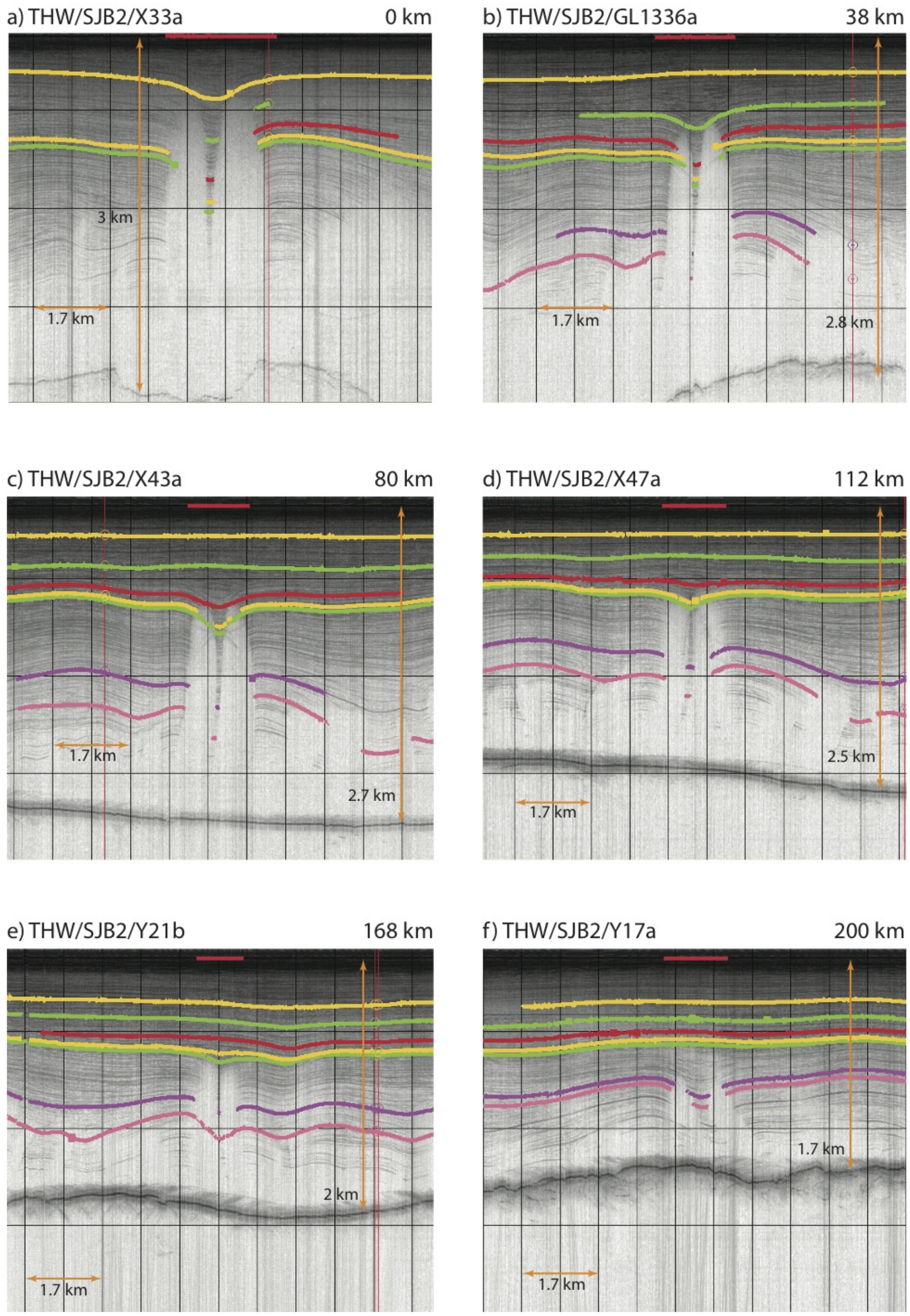

Figure 9: Radar transects showing the drawdown anomaly. Ice flow is into the page for all radar transects. Distance along flow is given, assuming the most upstream transect (X33a) to be the origin. Colored interpretations of ice layers are shown.

5 Analysis

5.1 Preliminary Interpretations

About 15 km upstream of the X33a drawdown anomaly is a topographic edifice. This edifice has a relief of 1 km with the surrounding bed, making it a possible source of mechanical drawdown. A potential geologic interpretation of the edifice is that it could be related to Mount Takahe and a source of thermal drawdown. However, this is much more difficult to prove without confirmation from other data sources, similar to the analysis that led to the discovery of Mount CASERTZ[6].

5.2 Evaluating Spatial Transience

There is a clear linear relationship between the drawdown age and flow-line distance (Fig 10). Since the thick layer package that marks the drawdown age is near the surface of the ice sheet, its vertical velocity should be roughly constant if undisturbed, determined by the accumulation rate. This is consistent with the linear trend of Fig 10, implying the thick layer package has not been disturbed since formation. Thus, there is no additional drawdown occurring in the radar survey along the tributary ice stream. In addition, the trend intercepts the x-axis at 22 km upstream of the X33a radargram, at the approximate location of topographic edifice. This verifies the hypothesis that the edifice is a source of drawdown. However, although it is a possibility the edifice is the only source of drawdown, this is a non-unique solution because there could be other drawdown sources upstream that are not resolvable with the current data.

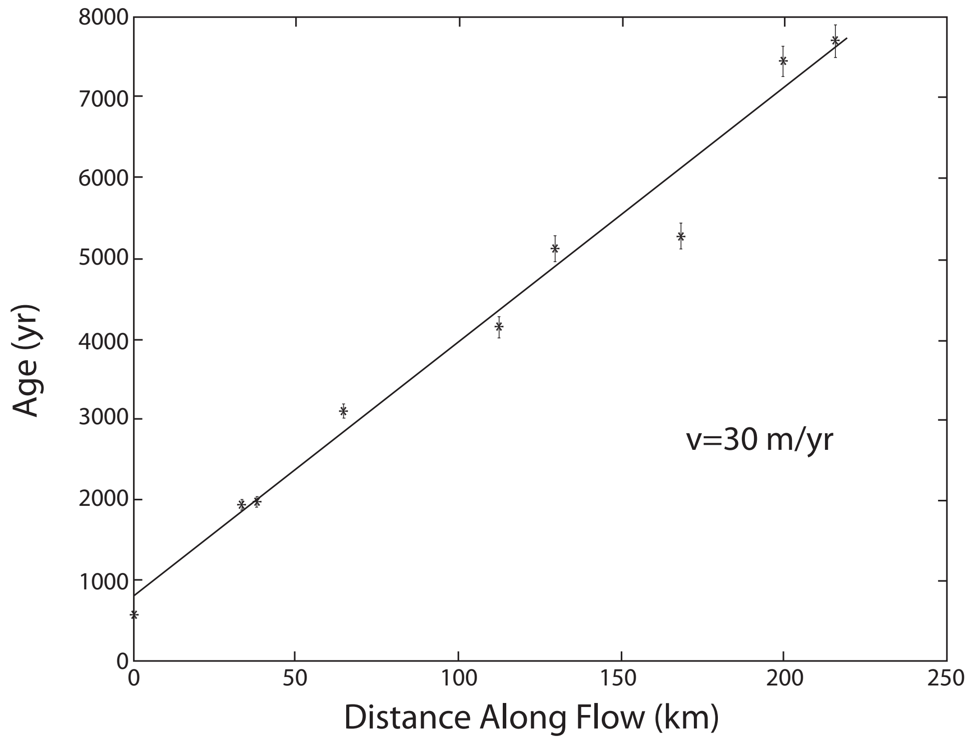

Figure 10: Drawdown anomaly age as a function of along flow distance.

5.3 Evaluating Temporal Transience

The drawdown amplitude profiles follow the predicted trend of roughly constant drawdown in older ice layers rapidly trending to zero after reaching a kink in the graph (Fig 11). As expected, the older, downstream profiles have smaller drawdown amplitudes due to glacial thinning, implying little variation in drawdown with time. Thus the main source of drawdown seen in this tributary ice stream is likely due to the constant mechanical drawdown of the edifice. However, the most upstream, X33a profile has an amplitude twice as large as the other profiles. Since the height of drawdown anomalies in downstream radar profiles has not decreased by a factor of two (Fig 9), this is inconsistent with the thinning predicted by the Nye model. This suggests the possibility of a recent thermal event causing additional drawdown in addition to the mechanical drawdown. This thermal event would have taken place at the approximate age of the youngest ice layers affected, about 1000-2000 years ago. The thermal event may also be associated with the upstream edifice because of the lack of identifiable spatial transience.

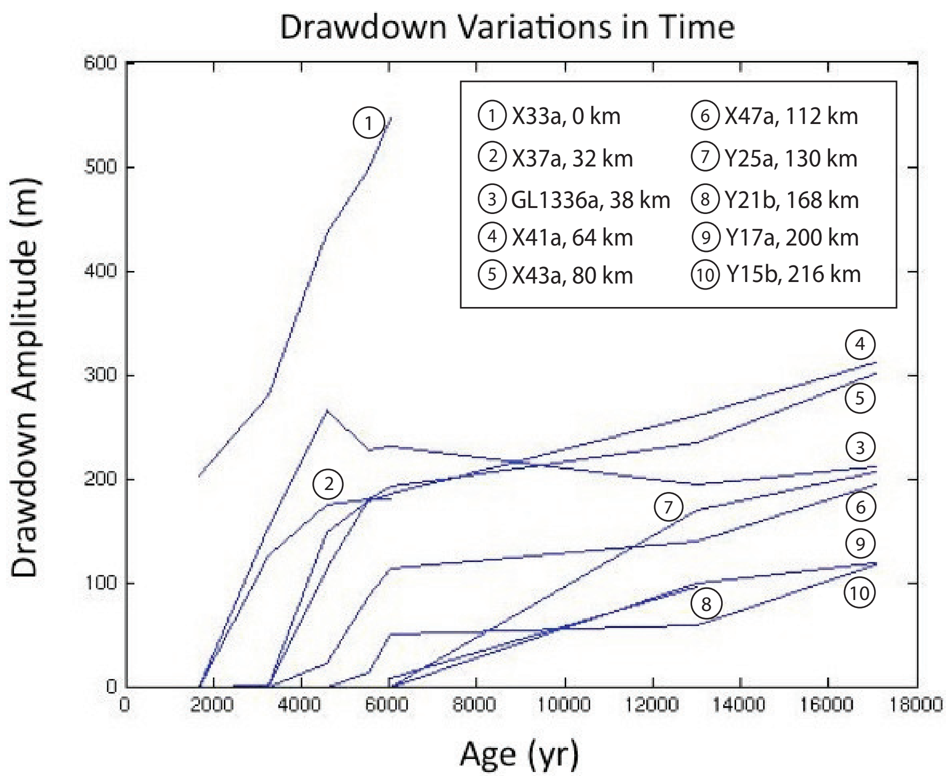

Figure 11: Drawdown amplitude profiles. The transect and distance along flow of each drawdown amplitude profile is given. The X33a transect is assumed to be the origin. Upstream profiles have higher amplitudes while downstream profiles have low amplitudes.

6 Conclusions

Drawdown anomalies are significant ice features that can persist in an ice stream for hundreds of kilometers, consisting of a thick ice layer package resting on top of deformed ice. The thick layer package is a result of high-amplitude ice drawdown and can be used to constrain the timing of the ice deformation. From this information, the spatial variation of drawdown can be inferred. Analyzing the variation of drawdown amplitude in successive radar profiles can constrain the temporal transience of drawdown. This information is useful in determining whether the origin of ice drawdown is mechanical, thermal or a combination of multiple geologic processes.

As predicted by the model, a package of thick ice layers was observed above drawdown anomalies in radar sounding profiles. This thick ice layer package sinks in both absolute depth and in the affected ice layers as it moves downstream, supporting the hypothesis that it was formed due to preferential accumulation within a surface anomaly. In addition, the thick ice layer package was observed to age at a roughly constant rate, implying drawdown genesis at a single point associated with a topographic edifice.

The high amplitude of the X33a drawdown implies a thermal event at 1000-2000 years ago that caused additional thermal drawdown in addition the background mechanical drawdown signal. This thermal drawdown would have taken place at the same edifice associated with mechanical drawdown (or upstream in a more complicated case) because of the lack of identified spatial transience. Thus, there is no spatial transience in the geothermal flux in the region of this tributary, but the ice flow may be affected by punctuated upstream thermal events. This provides an example of another area in the WAIS that shows evidence of high heterogeneous geothermal flux. The methods used in this study can be applied to constrain the effect of geothermal flux in other ice streams.

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