Improving West Antarctic Ice Sheet Reconstructions from Compiling Local GPR Observations

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Summary

Geologic records of ice elevation and thickness changes along the margins of the West Antarctic Ice Sheet (WAIS) are required to constrain past ice volumes and sea level contributions. Cosmogenic nuclide dating of bedrock and erratic boulders along elevation transects on ice-free terrain adjacent to ice margins has been applied in numerous locations across the WAIS and has greatly improved our understanding of glacial history since the LGM. Recently, this technique has extended to subglacial samples to constrain interglacial ice volumes. In concert with these studies, ground-penetrating radar (GPR) has been used to identify potential drill sites and evaluate past changes in the extent of locally-sourced ice fields near cosmogenic sampling transects. Englacial stratigraphic observations from GPR along ice sheet margins also provide direct spatial and temporal evidence of glacier retreat or advance in the form of englacial unconformities. GPR data can provide information about atmospheric conditions or processes which are important to consider when extrapolating from local to regional scale. Unlike geological observations, GPR data from discrete ice margin locations across Antarctica have not yet been compiled, despite the prominence of GPR surveying. We provide examples of GPR observations across West Antarctica that suggest englacial structures observed within GPR data could be used to better estimate local-to-regional variability of accumulation or ablation processes and ultimately improve LGM or longer reconstructions of WAIS elevation, thickness, and extent.

Introduction

Reconstructing past thickness and volume of the Antarctic Ice Sheet is important for understanding the causes and impacts of current sea level change and, potentially, in the future. For example, field evidence and modeling suggest that the West Antarctic Ice Sheet (WAIS) has collapsed within the past 5 million years during many interglacial time periods (e.g. Pollard and Deconto 2009; Spector et al., 2018; Dutton et al., 2015). It is unlikely that all glacier ice disappeared from West Antarctica during any collapse; valley glaciers and ice caps remained on highlands above the marine limit. Therefore, it is plausible that pockets of pre-collapse ice are retained within the present ice sheet. It is also likely that regions of WAIS contain evidence of multiple advance and retreat events where pockets of ice are constrained or stagnated by bedrock (Turney et al 2020 and refs therein). This ice would be of significant value to the science community because it could 1) be used to establish longer ice core climate records than currently available (defined herein as old ice or ice $\gtrsim$ 800 ka in age), and 2) may provide direct dates of one or more advance or retreat events which can be extrapolated across broader regions. However, determining structural boundaries between these ice units from surface observations can be challenging to impossible. GPR represents a rapid method to acquire two or three-dimensional englacial structural information in support of surface observations to address this challenge.

Sub-glacial bedrock exposure dating has the potential to spot-check numerical models and significantly contribute to our understanding of WAIS change over time (Spector et al., 2018). However, to date, most historical ice sheet elevation observations are from above-ice bedrock exposures near the periphery of the WAIS. These sample sites are typically local ablation areas which may have different atmospheric and glacier dynamics than broader accumulation regions in which they occur. GPR can provide local stratigraphic context relative to the broader region (e.g. Campbell et al., 2013) and delineate ice units through identification of englacial unconformities, thereby reconciling the two issues outlined herein. Coupling geological and radio-glaciological observations at local regions is perhaps the most powerful combination of data available to better constrain multiple advance and retreat events across WAIS or other large Polar glacier systems.

Valley glaciers within the Transantarctic or other mountain ranges peripheral to WAIS and proximal to maximum sources of precipitation and colder temperatures (particularly, during interglacial periods) represent the most probable retainers of pre-collapse ice (e.g. Steig et al., 2015). This ice can likely be distinguished via GPR from englacial unconformities relative to surrounding stratigraphy associated with WAIS re-advance. Numerical and climate modeling would be helpful for predicting locations most probable to contain old ice. However, GPR provides the most direct evidence of temporal unconformities between recent and older ice. Herein, we show examples of stratigraphic unconformities imaged across WAIS from the Pensacola Mountains, Ohio Range, Mount Murphy, and Mount Waesche, as examples of advance, retreat, and distinguishing between local to regional dynamics. Most studies aimed at reconstructing past ice thickness changes have focused on geological and geochemical evidence from bedrock and erratic boulder surfaces, that can be used to establish either that rock surfaces now exposed were ice-covered in the past, or currently subglacial rock surfaces were once ice-free. Our purpose in this article is to describe how the internal stratigraphy of marginal regions of ice sheets, observed by GPR can also be used for this purpose.

Methods

GPR profiles herein were collected from Pensacola Mountains (2010-2012), Ohio Range (2014-2015), Mount Waesche (2018-2019), and Thwaites Glacier (2019-2020) in support of ice marginal areal and sub-glacial bedrock sampling. We used a commercial Geophysical Survey Systems Incorporated (GSSI) SIR-3000 or SIR-4000 impulse radar control unit with a GSSI MLF 15-80 MHz, 100 MHz, or 400 MHz antenna for data collection. We also used a Blue Systems Integrated Ice Radar Acquisition System with 5 or 10 MHz center-frequency resistivity-loaded dipole antennas and either a 550 V 512 KHz transmitter or high-power (±2000 V) and 1500 KHz Kentech transmitter. The Ice Radar is a coherent system which maintains the phase and amplitude of echo responses. All GSSI and Ice Radar systems were set up with continuously logging GPS for geo-referencing profiles.

Case Study 1: Mount Murphy

Thwaites and Pine Island Glaciers have been the focus of much concern over the past few decades due to its reverse bed slope, increased velocities, thinning, and retreat (e.g. Joughin et al., 2014). Thwaites drains roughly 15% of West

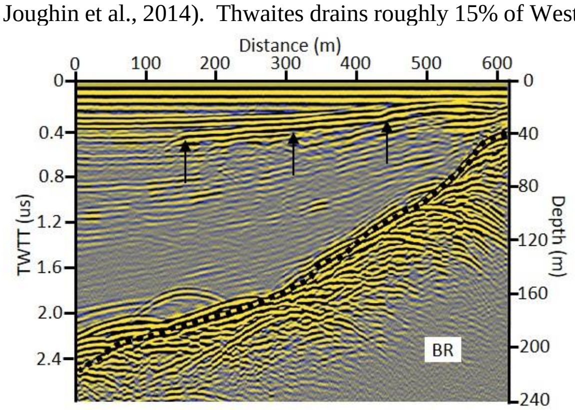

Figure 1. *10 MHz Ice Radar profile from Mount Murphy, Thwaites Glacier, showing shallow unconformity near 30 m depth (black arrows), and bedrock (BR) at and below approximate dashed line.*

Antarctica; concern exists that if Thwaites retreats beyond the present grounding zone, the marine based WAIS will be vulnerable to further rapid collapse. As part of the International Thwaites Glacier Collaboration, our goal has been to determine if Thwaites has exhibited significant grounding line retreat and surface elevation decrease earlier during the Holocene. This information will be useful to determine if there is precedent for retreat. To accomplish this goal, we collected GPR along the Thwaites grounding zone near Mount Murphy where we predict that ice thickness is dynamically linked to grounding line position in the Thwaites system. Along with using GPR to search for evidence of glacier advance or retreat we used it to select sub-glacial bedrock drill sites in the same region. A 10 MHz GPR profile near Mount Murphy reveals an unconformity that trends to near 30 m depth which we interpret as a potential prior retreat and re-advance during the recent Holocene. Pending analysis of recently collected sub-glacial bedrock cores may support this interpretation (Fig 1).

Case Study 2: Mount Waesche

Mount Waesche is a relatively young (< 1 Ma) volcano, located within Marie Byrd Land. The mountain is 50 km grid east from the Thwaites Glacier ice divide, grid west of the Ross Ice Shelf, and it represents the southernmost volcano of the Executive Committee Range. Extensive blue ice with tephra layers as old as 108 ka (Dunbar et al., 2007) occur on the northern side of Waesche. Mapping in 1996-97 and 2018-2019 indicated multiple exposed olivine-bearing flows that appear to continue under the current glacier ice extent. Exposed lavas (<350 ka) along the flanks of Waesche show no evidence of interaction with ice, limiting intervals when ice could have been higher than present. However, exposure ages of moraine boulders indicate ~40 m higher ice elevations ~10 ka (Ackert et al. 1999). On the north side of the mountain, a buried and relatively continuous englacial deposit of thick debris located 15-30 m deep was imaged with GPR. This deposit suggests that the ice was at least 15 m thinner at some point in the recent past and thickening of ice has since covered the debris (Fig 2a). A radar profile collected perpendicular to the current bedrock exposure on the flanks of Waesche reveals an unconformity reaching 120 m in depth revealing a similar situation, and the age of transition from retreat to advance indicated by this boundary is also unknown (Fig 2b). However, it appears that the unconformity at 15-30 m depth may represent a local scale event, whereas the deeper unconformity may represent a more regional event based on surface conformable continuous stratigraphy from the second unconformity extending at least 6 km from Waesche.

Case Study 3: Pensacola Mountains

The Pensacola Mountains reside along the lateral margin of the Foundation Ice Stream which feeds the Ronne-Filchner Ice Shelf. It is the Northernmost extension of the Transantarctic Mountains however it is separated from the Southern Transantarctic Mountains by ice flowing into the Foundation Ice Stream from East Antarctica. Hence, any evidence of ice elevation change represents a change in both

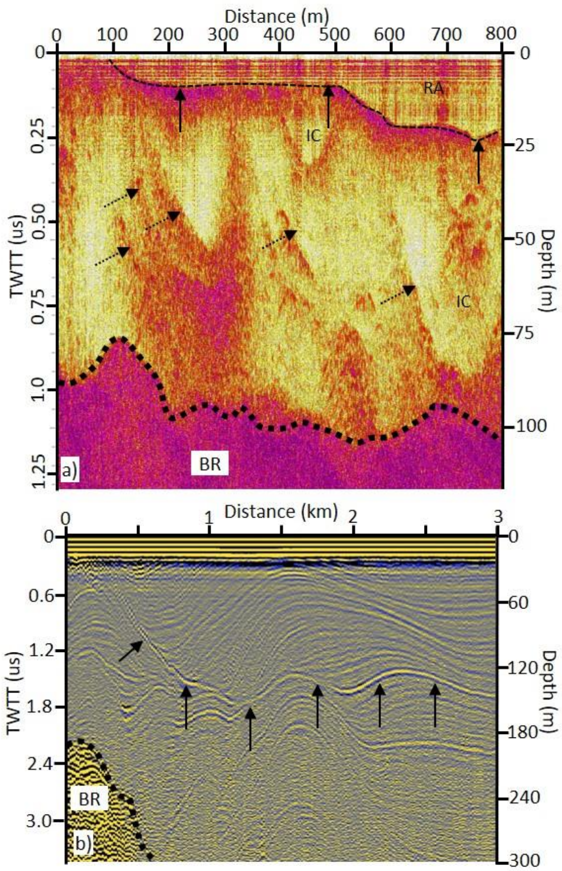

Figure 2. *a) 100 MHz GPR Profile along the flank of Mount Waesche showing re-advanced ice (RA) over debris (dashed black line, arrows), dipping debris bands within deeper ice, ice cored features (IC), and bedrock (BR). b) 5 MHz GPR profile showing unconformity reaching 120 m depth and surface conformable stratigraphy distal to Mount Waesche.*

East and West Antarctica. Recent cosmogenic results from this region revealed significant (250-500 m) surface lowering during the Holocene but likely multiple advance and retreat stages, pre-Holocene (Balco et al., 2016). We acquired radar profiles near the Schmidt, Williams, and Thomas Hills in The Pensacola Mountains between 2010-2012. Profiles from all three ranges reveal numerous unconformities. Some unconformities and complex englacial features represented local scale wind-erosion and depositional processes which are likely steady state, at least on the short term. Other observations were interpreted as melting, refreezing, accumulation, and flow derived structures (e.g. Campbell et al., 2013). However, several unconformities appear to delineate entirely separate ice units, in some cases one unit overriding another stagnated ice lobe. These stagnated ice deposits appear to be controlled or dominated by sub-glacial bedrock topographic rises which block flow once the ice surface lowered to the bedrock elevation during its retreat stage (Fig 3a).

Case Study 4: Ohio Range

The Ohio Range is in interior West Antarctica along the Transantarctic Mountains. Geological and glaciological evidence of change from this region thereby provide elevation constraints near the WAIS ice divide. Ice surrounding this region originates from East and West Antarctica, so like the Pensacola Mountains, observations here provide a measure of change within both regions. Erratic exposure ages ~100 m above the present ice elevation are 10-12 ka (Ackert et al. 2007). Most of the surveyed region is heavily deformed blue ice with a series of complex sheared lateral moraines that have been dated by previous efforts to between Holocene and 80 ka (Ackert et al., 2013). GPR profiling and GPS ice flow velocity measurements revealed complex subglacial topography along the lateral moraines and a bedrock rise that has entirely stagnated ice of unknown age. However, this stagnated ice is perhaps some of the oldest across WAIS due to its high elevation and associated cold temperatures (Fig 3b).

Conclusions

Ice margin field sites from across West Antarctica consistently reveal englacial unconformities within radar-derived stratigraphic records suggesting that their occurrence is widespread. Each location discussed here also shows the potential for using GPR-imaged stratigraphy to quantify advance and retreat events, particularly if coupled with ice core geochemistry across selected unconformities and both areal and sub-glacial exposure dating of bedrock. GPR has progressed rapidly in recent years to allow nearly simultaneous processing and interpretation for rapid site selection of ice core or sub-glacial bedrock sampling in support of this combined approach. Perhaps the greatest challenge with using GPR-derived stratigraphy for interpretations is differentiating unconformable events that occur within steady state conditions from those which are representative of transient events.

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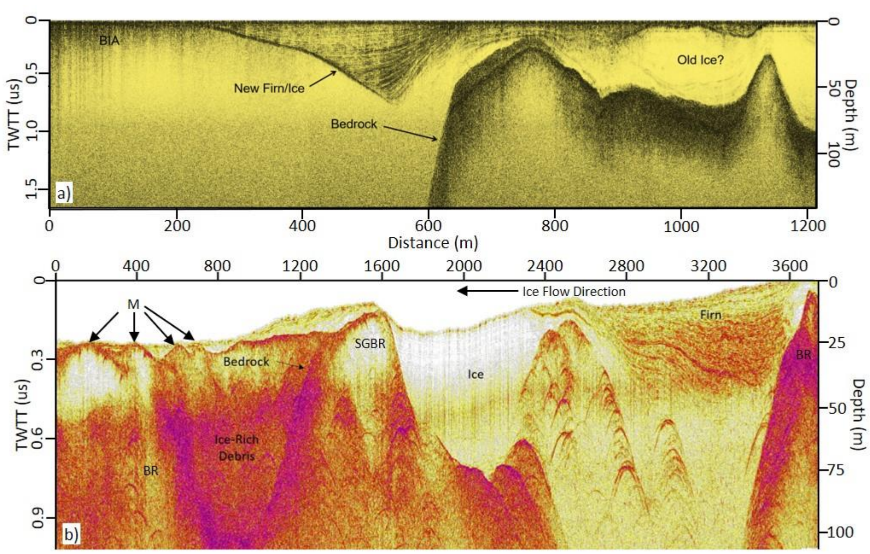

Figure 3*. a) 100 MHz GPR profile from Pensacola Mountains, showing new firn deposited over blue ice, a bedrock rise, and likely old stagnated ice due to topographic blocking of flow. The profile is oriented approximately parallel to ice flow from Thomas Hills (right) towards Foundation Ice Stream (left). b) 100 MHz profile from Ohio Range showing firn over blue ice that is stagnated against a sub-glacial bedrock rise (SGBR) and a series of ice cored moraines (M) over ice-rich debris.*