Age-Depth Stratigraphy of Pine Island Glacier Inferred from Airborne Radars and Ice-Core Chronology

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Abstract

Understanding the contribution of the West Antarctic Ice Sheet (WAIS) to past and future sea level has emerged as a scientific priority over the last three decades. In recent years, observed thinning and ice-flow acceleration of the marine-based Pine Island Glacier has demonstrated that dynamic changes are central to the long-term stability of the WAIS. However, significantly less is known about the evolution of the catchment during the Holocene. Internal Reflecting Horizons (IRHs) provide a cumulative record of accumulation, basal melt and ice dynamics that, if dated, can be used to inform ice flow models to project spatial and temporal mass changes. Here, we use airborne radars to trace four consistent IRHs spanning the Holocene across the Pine Island Glacier catchment. We use the WAIS Divide ice-core chronology to assign discrete ages to three IRHs: 4.72 ± 0.08, 6.94 ± 0.11, and 16.50 ± 0.62 ka. We use a 1D model, constrained by observational and modelled accumulation rates, to produce an independent validation of our ice-core-derived ages and provide an age estimate for our shallowest IRH (2.31-2.92 ka). We find that significantly older ice is present below our deepest reflector, but the absence of continuous radar-observed reflectors at depth currently limits our understanding of pre-Holocene ice dynamical history. The clear correspondence between our IRH package and the one previously identified over Institute Ice Stream, altogether representing ~20% of the WAIS, suggests that a unique set of stratigraphic markers spanning the Holocene exist widely across West Antarctica.

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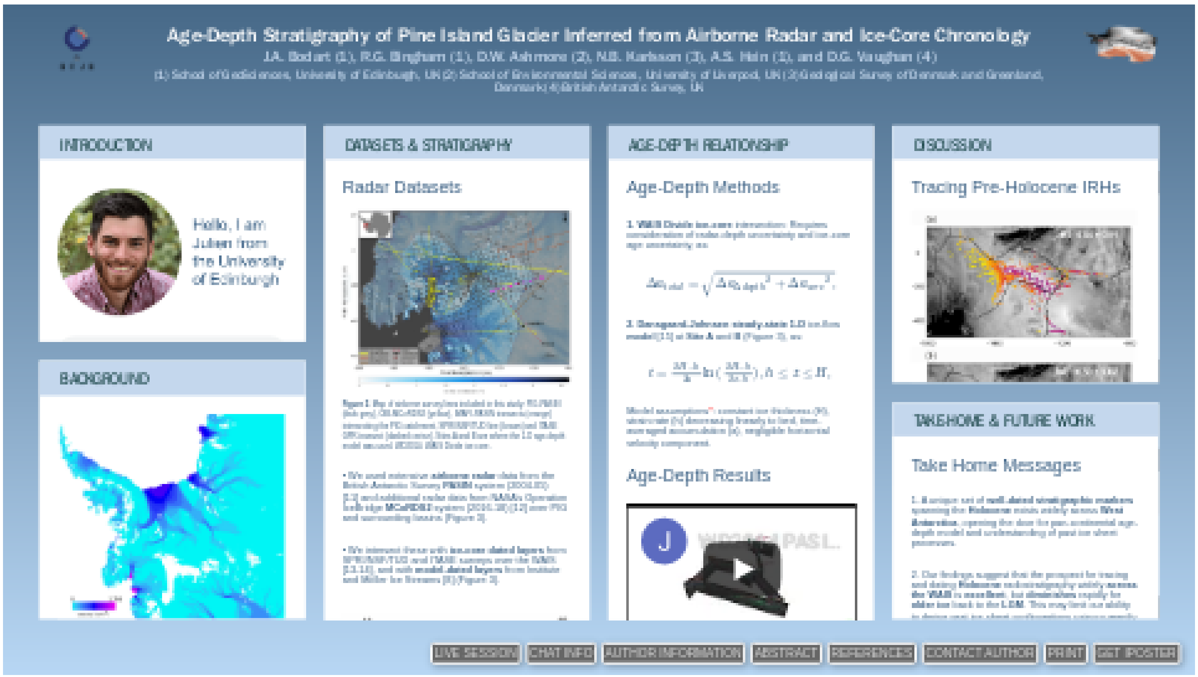

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PRESENTED AT:

INTRODUCTION

Hello, I am Julien from the University of Edinburgh

Play me!

In case you cannot hear the audio, my poster discusses our most recent research on the use of airborne radar to trace and date Internal Reflecting Horizons (IRHs) across Pine Island Glacier and nearby catchments. We start by highlighting the key motivations for this project, and then describe the datasets and methods used to trace and date our IRHs. We show our results via a set of figures and short animations throughout the presentation.

If you have any questions or comments regarding this presentation, feel free to send these to my email address which I have placed in the take-home message section. Thank you!

BACKGROUND

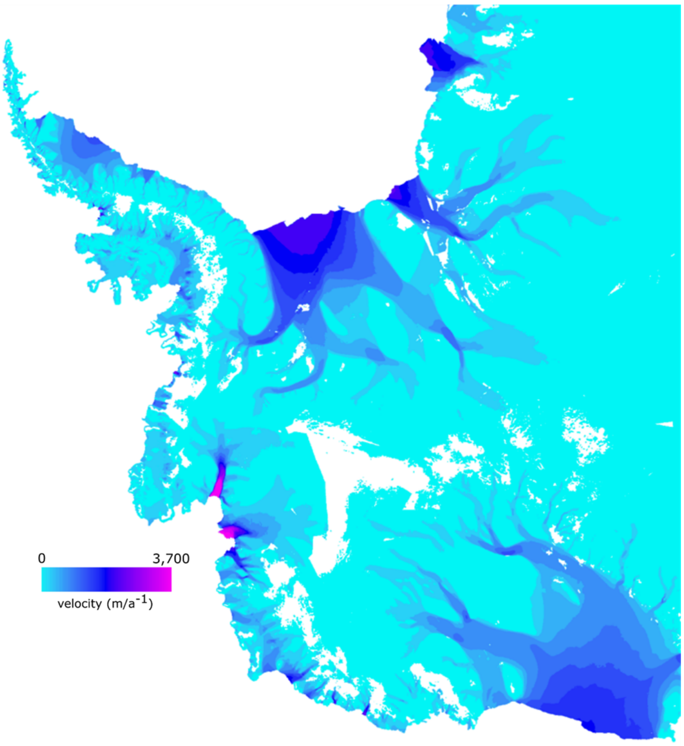

Figure 1. Ice-flow velocities over the Amundsen Sea Embayment (ASE) and West Antarctic Ice Sheet (WAIS) [1]

ASE Mass Loss

• **Pine Island Glacier** (PIG), one of the fastest flowing Antarctic ice streams (Figure 1), has experienced an increase in speed of 73% since 1974 and is **responsible** for **half** (~3 mm) of the **WAIS**' total **sea level rise** contribution [2].

• **Predictions** for **21st** and **22nd centuries** suggest that the grounding line will likely retreat further inland with **large uncertainty** in the **rate of retreat**; and a full collapse of PIG's main trunk is possible [3].

• The **evolution of PIG** and the rest of the ASE since the Last Glacial Maximum (**LGM**, ~20 ka) and over the course of the **Holocene** (~11.5 ka) is **less known**.

• Point-based **cosmogenic measurements** suggest **significant** ice **thinning** occured during the early- to mid-**Holocene** in the central **ASE** [4-7].

• **Spatially-extensive knowledge** of past ice sheet configuration is **required** in order to confirm the spatial extent of this thinning trend and, ultimately, **to inform and calibrate models**.

Internal Reflecting Horizons

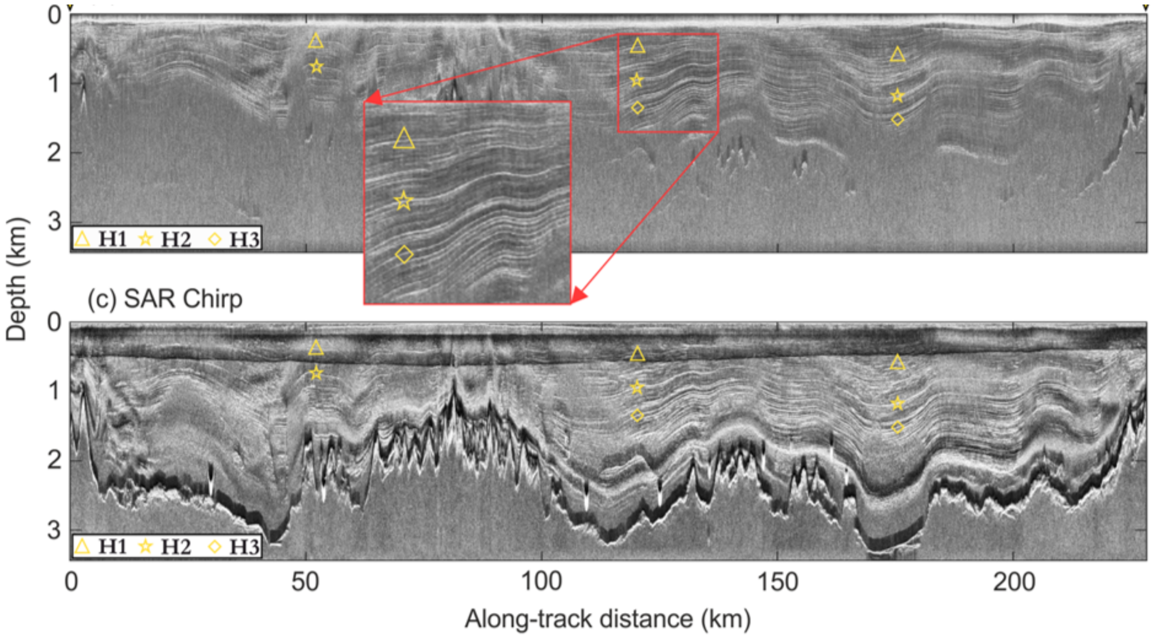

Figure 2. Internal Reflecting Horizons over Institute and Möller Ice Streams using the BAS PASIN radar system (see also Figure 3) [8].

• Knowledge of past ice-sheet configuration can be derived from **radar**-detected Internal Reflecting Horizons (**IRHs**) (Figure 2). When continuous, IRHs can be traced for 100s kilometres and provide a **record** of **accumulation**, **basal melt**, and **ice dynamics**.

• They can serve as a **proxy** for **past surface mass balance** and **ice flow** over large scales, and if dated, **constrain ice-flow models** [9-10].

Key Aims

1. Assess the **englacial conditions** of this sensitive sector of West Antarctica **using** available **airborne radar** data.

2. **Constrain** the **age** of each radar-detected reflector by intersecting **IRHs** through deep **ice core** and using **age-depth modelling**.

3. **Connect** this sector with **other regions** of Antarctica to better constrain **past ice-sheet evolution**, as motivated by the AntArchitecture (https://www.scar.org/science/antarchitecture/about/)initiative.

DATASETS & STRATIGRAPHY

Radar Datasets

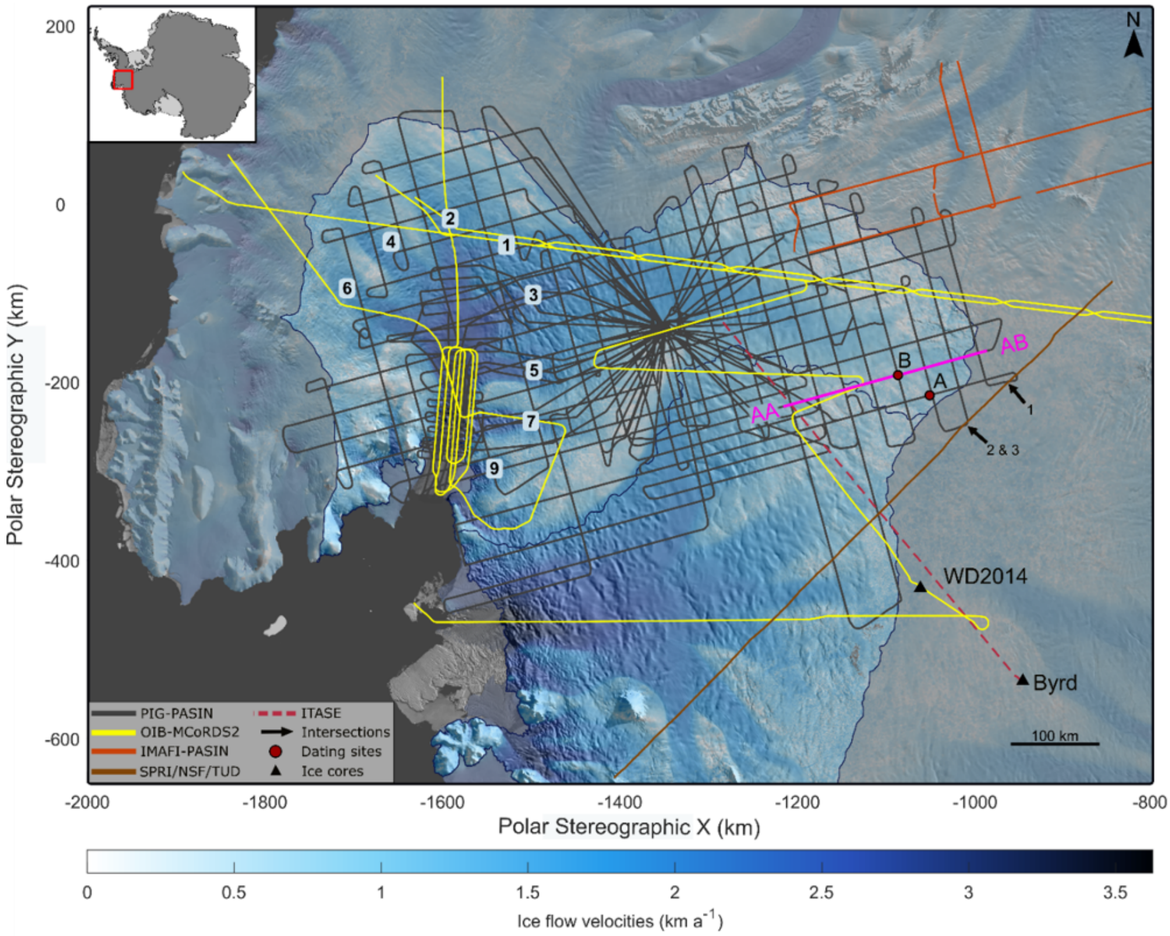

Figure 3. Map of airborne survey lines included in this study: PIG-PASIN (dark grey), OIB-MCoRDS2 (yellow), IMAFI-PASIN transects (orange) intersecting the PIG catchment, SPRI/NSF/TUD line (brown) and ITASE GPR-transect (dashed cerise). Sites A and B are where the 1-D age-depth model was used. WD2014: WAIS Divide ice core.

• We used extensive **airborne radar** data from the British Antarctic Survey **PASIN** system (2004-05) [11] and additional radar data from NASA's Operation IceBridge **MCoRDS2** system (2016-18) [12] over PIG and surrounding basins (Figure 3).

• We intersect these with **ice-core dated layers** from SPRI/NSF/TUD and ITASE surveys over the WAIS [13-14], and with **model-dated layers** from Institute and Möller Ice Streams [8] (Figure 3).

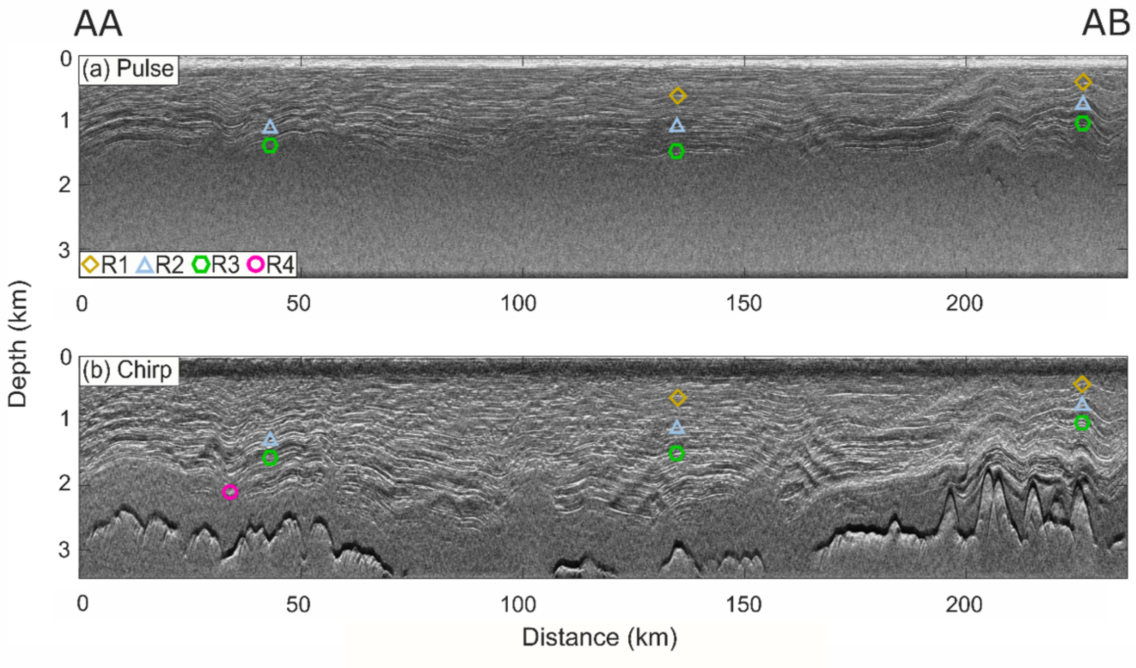

Figure 4. Subset of the control line with the unmodulated pulse (a) and chirp (b) radar modes from the PIG-PASIN survey along transect AA– AB (see Figure 3). Traced IRHs are marked as per the legend on panel (a).

• We traced **4x** clear, reflective and **continuous IRHs** using semi-automated tracing algorithm (Figure 4). Their high SNR likely results from contrast in acidity from **past volcanic eruptions,** and thus the **layers** can be considered **isochronous**.

Englacial Stratigraphy

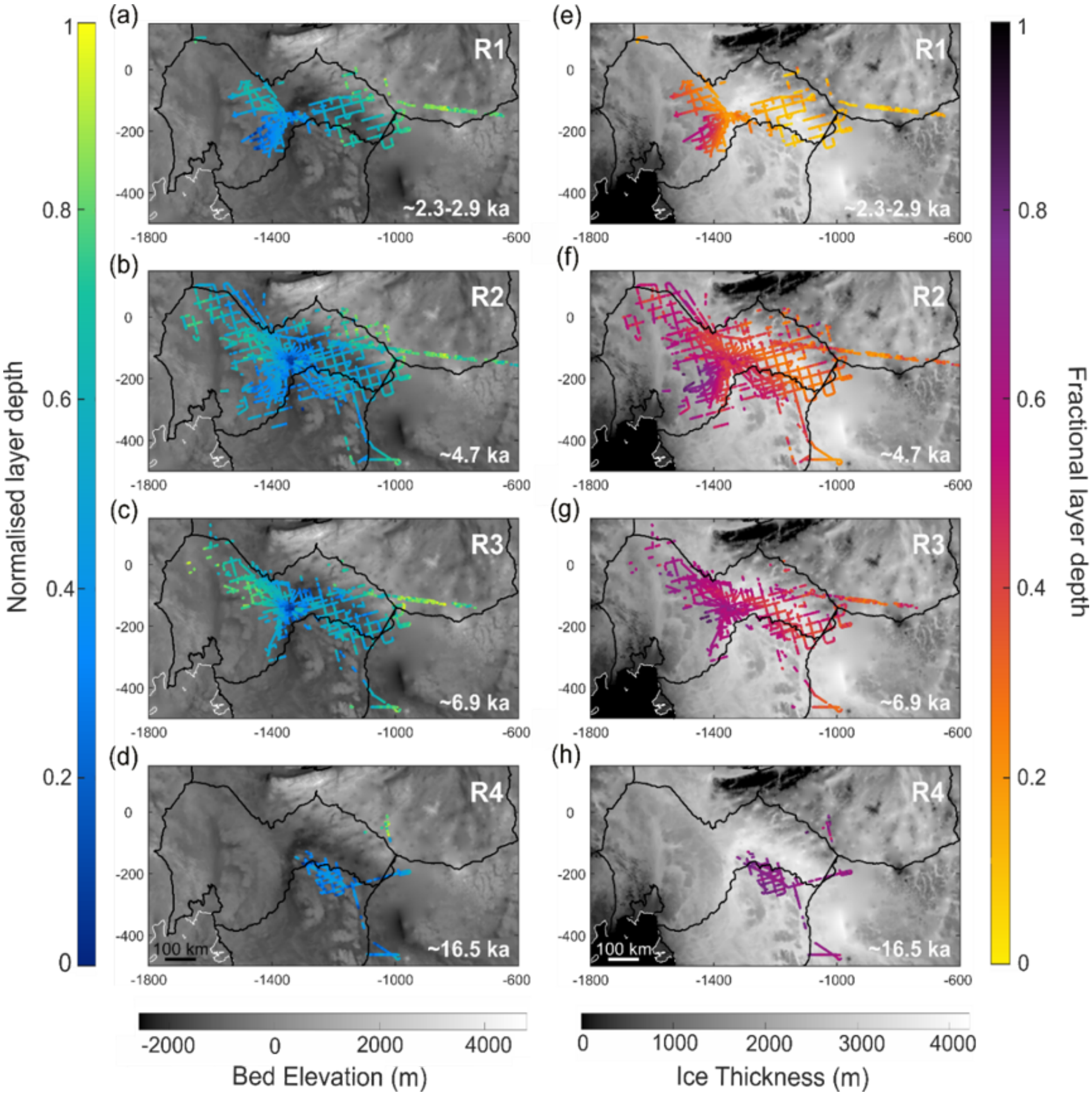

Figure 5. Normalised (a-d) and fractional (e-h) depth for the four IRHs traced over the PIG-PASIN and OIB-MCoRDS2 data from shallowest to deepest. For (a-d), lower (blue) values correspond to relatively deep IRH depths, higher (yellow) values correspond to shallow IRH depths. For (e-h), lower (yellow) values correspond to the ice surface, higher (purple) values correspond to the bed.

• **IRHs R1-4** were traced across Pine Island, Upper Thwaites, and Upper Institute Ice Stream catchments and are found between **30%** and **68%** of the **ice column** (Figure 5, Animation 1).

• **IRH geometry** is primarily **constrained by topography**: deeper in Pine Island centre; shallower at divide with Institute Ice Stream and Thwaites (Figure 5).

[VIDEO] https://www.youtube.com/embed/hHtT_iSShyg?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Animation 1. Overview of R1-4 and subset of PIG-PASIN and OIB-MCoRDS2 radar profiles over the Pine Island and Thwaites glacier catchments. The position of the WAIS Divide ice core is marked in red. IRH colour: R1 (red), R2 (blue), R3 (green), R4 (pink).

AGE-DEPTH RELATIONSHIP

Age-Depth Methods

1. WAIS Divide ice-core intersection**:** Requires consideration of radar-depth uncertainty and ice-core age uncertainty, as:

$$\Delta a_{total} = \sqrt{{\Delta a_{\Delta depth}}^2 + {\Delta a_{core}}^2},$$

2. Dansgaard-Johnsen steady-state 1-D ice-flow **model** [15] at **Site A** and **B** (Figure 3), as:

$$t = \frac{2H-h}{2a} \ln\left(\frac{2H-h}{2z-h}\right), h \leq z \leq H,$$

Model assumptions*: constant ice thickness (H), strain rate (h) decreasing linearly to bed, time-averaged accumulation (a), negligible horizontal velocity component.

Age-Depth Results

[VIDEO] https://www.youtube.com/embed/gu0qqiMdowY?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Animation 2. Radar connection between Pine Island Glacier and the WAIS Divide ice core (red dotted line) with R2-4 shown. Also shown is the intersection between the PIG-PASIN and OIB-MCoRDS2 radar profiles (blue dotted line). IRH colour: R1 (red), R2 (blue), R3 (green), R4 (pink). See Figure 6 for more details.

• **WAIS Divide ice-core ages (R2-4):**

R2: 4.72 ± 0.08 ka

R3: 6.94 ± 0.11 ka

R4: 16.50 ± 0.62 ka

• **1-D model ages (R1-4):**

R1: 2.32 – 2.92 ka

R2: 4.46 – 5.82 ka - good match with ice core

R3: 6.75 – 9.15 ka - good match with ice core

R4: 19.69 – 26.87 ka - model overestimates*

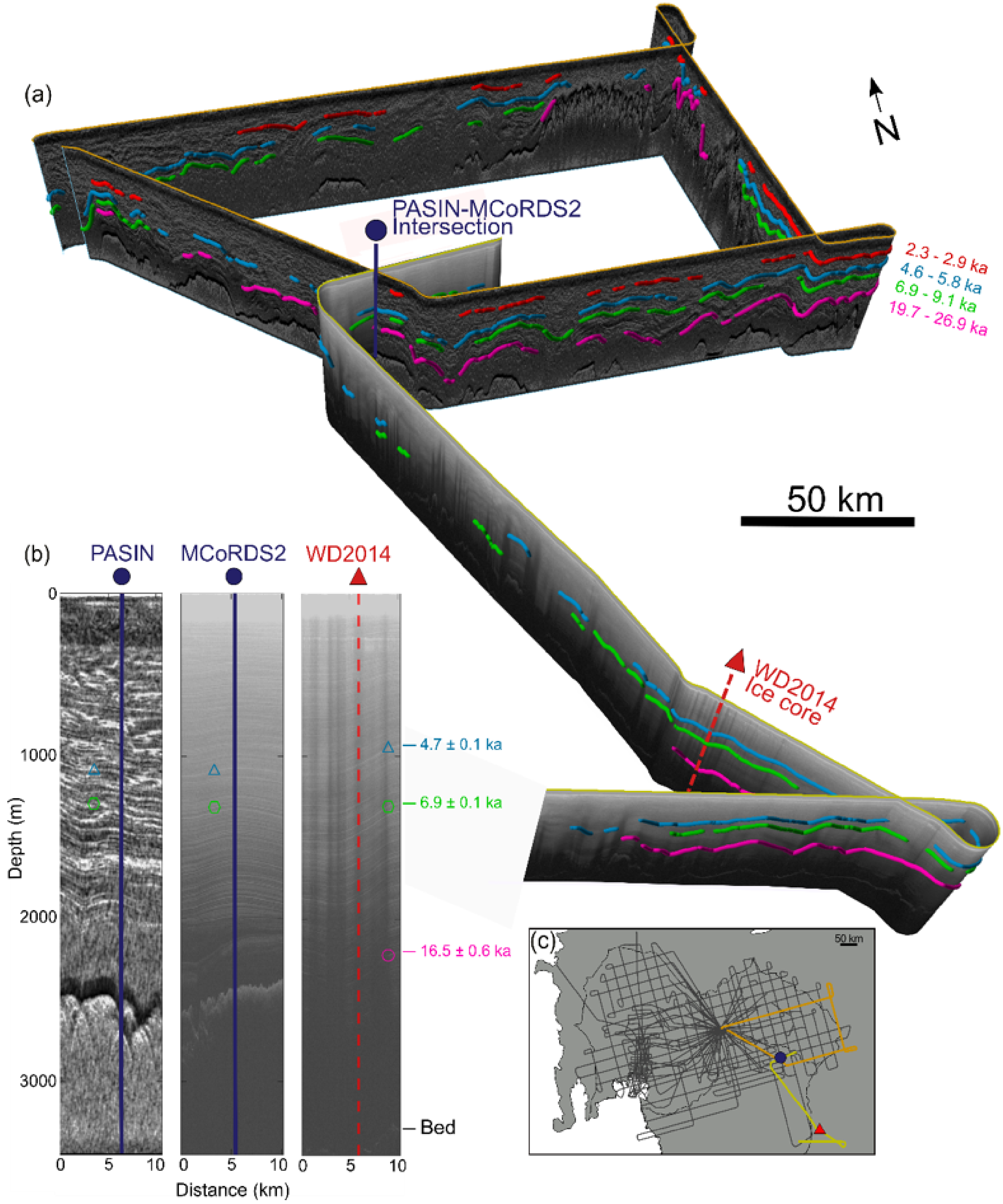

Figure 6. (a) Intersecting radar profiles from PIG-PASIN and OIB-MCoRDS2 with IRHs R1 (red), R2 (blue), R3 (green) and R4 (pink) shown. WD2014: WAIS Divide ice core.

DISCUSSION

Tracing Pre-Holocene IRHs

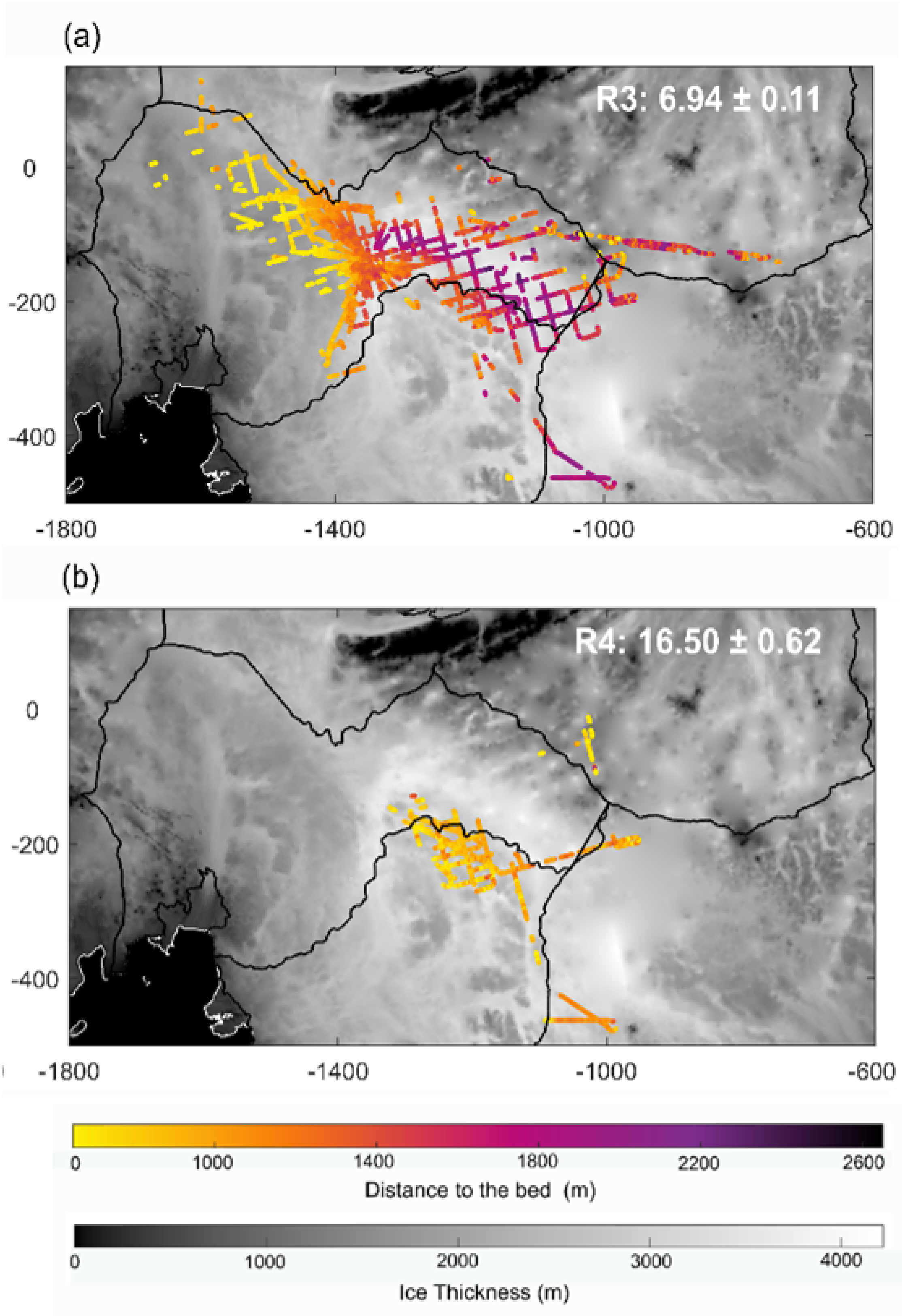

Figure 7. Ice thickness (m) below R3 (a) and R4 (b) traced over the PIG-PASIN and OIB-MCoRDS2 data. The ages are from the intersection with the WAIS Divide ice-core site.

• Deepest continuous IRH, **R4 (16.50 ± 0.62 ka)**, is **equivalent** to **25%** of **oldest ice** recovered at the **WAIS Divide** ice core (~68 ka).

• Much deeper and older ice is present below R4 (~900 m; Figure 7). However, the **presence** of **continuous IRHs** dating back to the **LGM** and beyond is **limited across** the **WAIS** using currently available datasets.

IRHs Comparison

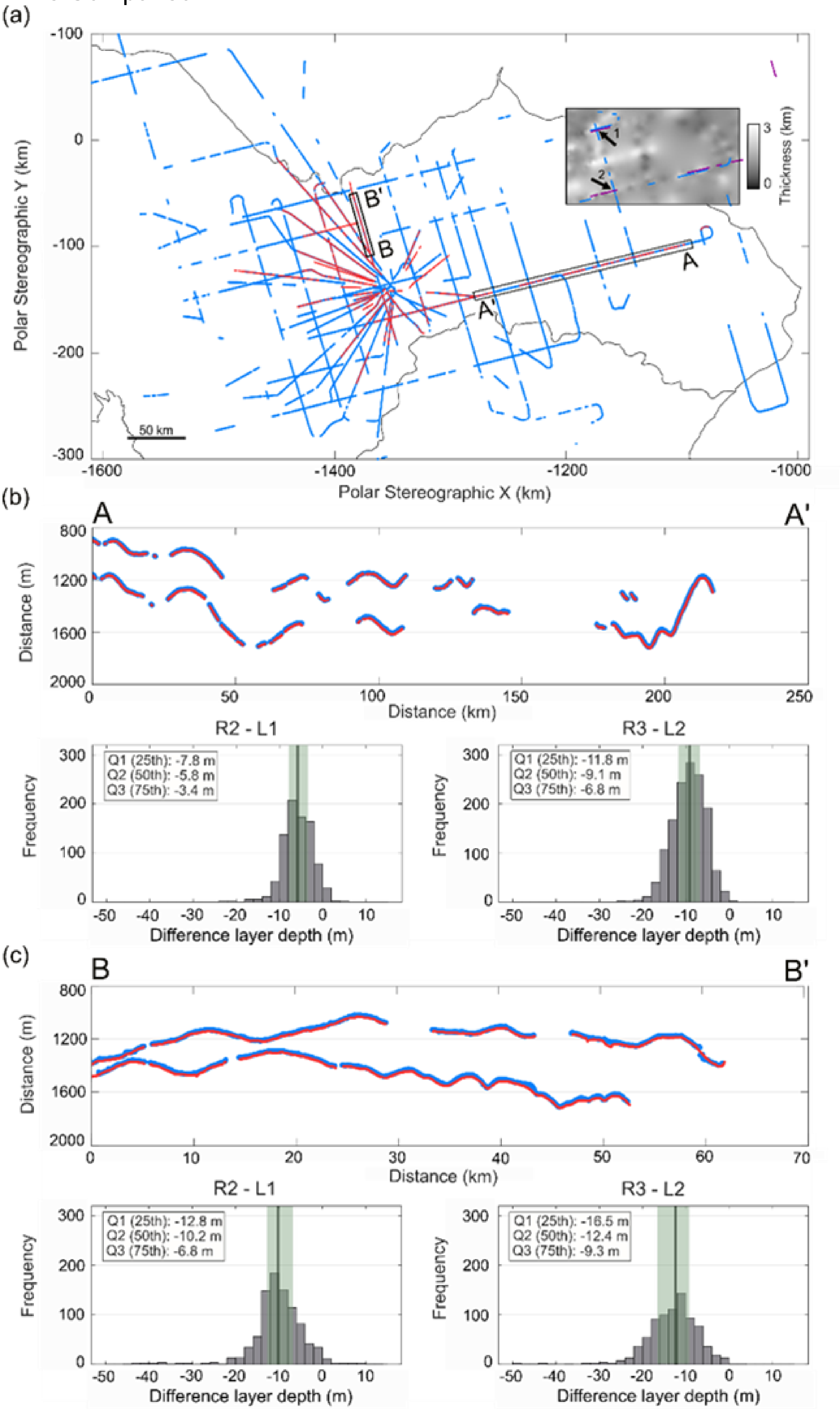

Figure 8. Comparison between our layer package and IRHs from [8] and [16]. The black arrows in (a) are where we directly compare IRH H2 from [8] and our R2. (b-c) Comparison between our R2-3 (blue) and L1-2 from [16] (cerise).

• **R1-3 correspond** to traced **IRHs** over **Institute Ice Stream** [8] and **PIG** [16]; totalling **~20% of WAIS**. Mean difference between sets of IRHs is < 15 m over Institute Ice Stream and < 12 m over PIG (Figure 8).

• **R2 (4.72 ± 0.08 ka)** is the **most spatially extensive IRH** traced over Institute and Möller Ice Streams [8] and PIG [16, this study]; and is **similar** in age to **another spatially-extensive** IRH over **Marie Byrd Land** [17].

• This suggests the presence of a **West Antarctic-wide timemarker** connecting the Ross Sea with the Weddell Sea.

Holocene Accumulation

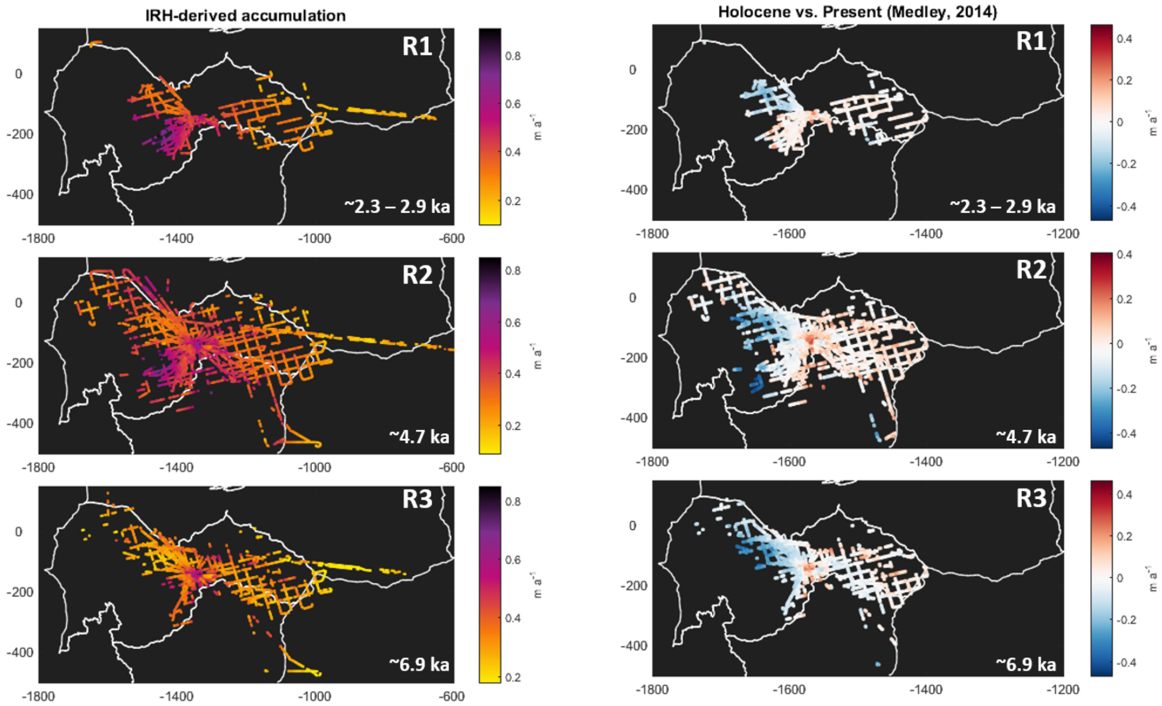

Figure 9. Preliminary results showing Holocene accumulation (left) and difference between Holocene and present SMB from [18] for R1-3 using the 1-D Dansgaard-Johnsen model.

• Preliminary results for **past accumulation rates** over the Western Divide and central PIG suggest accumulation patterns remained **stable** there **between** the **present** and the **last ~7 ka** (Figure 9).

• This is also confirmed by the **asynchrony** between **ice-core** and **modelled** ages for **R2-3** (Figure 7), and supports previous findings reporting similar accumulation patterns between the Holocene and the present [10, 13].

TAKE-HOME & FUTURE WORK

Take Home Messages

1. A unique set of **well-dated stratigraphic markers** spanning the **Holocene** exists widely across **West Antarctica**, opening the door for pan-continental age-depth model and understanding of past ice sheet processes.

2. Our findings suggest that the prospect for tracing and dating **Holocene** radiostratigraphy widely **across the WAIS** is **excellent**, but **diminishes** rapidly for **older ice** back to the **LGM**. This may limit our ability to derive past ice-sheet configurations using currently available datasets.

3. The asynchrony between ice-core and 1-D model, as well as the results for modelled accumulation rates (Figure 9) suggest **accumulation patterns** have remained **stable for at least the last ~7 ka** across the **divide** and into the **central PIG** catchment.

Future Work

1. **Compare** the modelled **accumulation rates** from the Dansgaard-Johnsen model with other 1-D models (i.e. Nye, Quasi-Nye) to confirm the **Holocene accumulation** trends in Figure 8.

2. **Model balance velocities** for the last **~7 ka** across the PIG, Upper Thwaites, and Institute and Möller Ice Stream catchments and **compare** these with **modern** surface flow **velocities**, as previously conducted over the Greeland Ice Sheet [19].

Questions or comments:

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AUTHOR INFORMATION

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ABSTRACT

Understanding the contribution of the West Antarctic Ice Sheet (WAIS) to past and future sea level has been a major scientific priority over the last three decades. In recent years, observed thinning and ice-flow acceleration of the marine-based Pine Island Glacier has highlighted that understanding dynamic changes is critical to predicting the long-term stability of the WAIS. However, relatively little is known about the evolution of the catchment during the Holocene. Internal Reflecting Horizons (IRHs) provide a cumulative record of accumulation, basal melt and ice dynamics that, if dated, can be used to constrain ice-flow models. Here, we use airborne radars to trace four consistent IRHs deposited in the late Quaternary across the Pine Island Glacier catchment. We use the WAIS Divide ice-core chronology to assign ages to three IRHs: 4.72 ± 0.08, 6.94 ± 0.11, and 16.50 ± 0.62 ka. We use a 1-D model, constrained by observational and modelled accumulation rates, to produce an independent validation of our ice-core-derived ages and provide an age estimate for our shallowest IRH (2.31-2.92 ka). We find that significantly older ice is present below our deepest reflector, but the absence of continuous IRHs detected in our dataset at depth currently limits our ability to trace ice older than the Last Glacial Maximum. The clear correspondence between our IRH package and the one previously identified over the Weddell Sea Sector, altogether representing ~20% of the WAIS, indicates that a unique set of stratigraphic markers spanning the Holocene exists widely across West Antarctica.

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