A deep subglacial embayment adjacent to the grounding line of Institute Ice Stream, West Antarctica

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Abstract: The Institute Ice Stream (IIS) in West Antarctica may be increasingly vulnerable to melting at the grounding line through modifications in ocean circulation. Understanding such change requires knowledge of grounding-line boundary conditions, including the topography on which it rests. Here, we discuss evidence from new radio-echo sounding (RES) data on the subglacial topography adjacent to the grounding line of the IIS. In doing so, we reveal a previously unknown subglacial embayment immediately inland of the IIS grounding zone which is not represented in the Bedmap2 compilation. We discuss whether there is an open-water connection between the embayment and the ice-shelf cavity. The exact location of the grounding line over the embayment has been the subject of considerable uncertainty, with several positions being proposed recently. From our compilation of data, we are able to explain which of these grounding lines is most likely and, in doing so, highlight the need for accurate bed topography in conjunction with satellite observations to fully comprehend ice-sheet processes in this region and other vulnerable locations at the grounded margin of Antarctica.

There is major concern about the long-term stability of the West Antarctic Ice Sheet (WAIS), the bulk of which rests on a bed below sea level and is thought to be susceptible to 'marine ice-sheet instability' (MISI) (Mercer 1978). MISI occurs where the grounding line, which separates ice resting on its bed from that floating, retreats over topography that deepens upstream. Such a configuration is thought to support continual acceleration of grounding-line retreat once it commences (Weertman 1974; Schoof 2007; Vaughan & Arthern 2007; Durand *et al.* 2009). One region where such change has been predicted to occur late in the twenty-first century is the Weddell Sea sector of the WAIS (Hellmer *et al.* 2012). Ice-sheet modelling acknowledges the ice streams of the Weddell Sea sector as highly vulnerable to potential grounding-line melting (Wright *et al.* 2014*a*; Cornford *et al.* 2015; Ritz *et al.* 2015), with the Institute Ice Stream (IIS) being most sensitive. In addition, analysis of englacial layering shows that the nearby Bungenstock Ice Rise has experienced a major ice-flow change in the last few thousand years (possibly as recently as a few hundred years ago). This would have been associated with substantial reorganization of the IIS (Siegert *et al.* 2013), with likely modification to the grounding-line position.

Our ability to define the exact location of the grounding line across this sensitive region has been inhibited by limited measurements of the subglacial environment. Furthermore, a large tidal range of *c.* 8 m in this region and the presence of glaciological phenomena, such as ice plains close to the mouth of the IIS, provide ambiguity as to the landward limit of ice flexure (Scambos *et al.* 2004; Fricker & Padman 2006; Lambrecht *et al.* 2007;

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Brunt *et al.* 2011). As a consequence, several different grounding-line positions have been proposed (Bohlander & Scambos 2007; Brunt *et al.* 2010; Bindschadler *et al.* 2011; Rignot *et al.* 2011*a*) based solely on satellite data, and without geophysical measurement of the bed.

Evidence from geophysical surveying in this region reveals the IIS grounding line to be resting on a bed *c.* 1 km below sea level, dipping upstream towards the *c.* 1.8 km deep Robin Subglacial Basin (Ross *et al.* 2012). Ice-sheet models treat the grounding interface crudely however, despite recent advances in modelling technology (Wright *et al.* 2014*a*; Martin *et al.* 2015; Ritz *et al.* 2015; Thoma *et al.* 2015) and recognition of the importance of grounding-line processes in modulating ice-sheet change (Hellmer *et al.* 2012; Favier *et al.* 2014; Joughin *et al.* 2014; Rignot *et al.* 2014; Khazendar *et al.* 2016; Siegert *et al.* 2016). Bed topography, basal conditions and subglacial processes are neither known precisely nor modelled realistically at this critical interface of the ice-sheet system across the whole of the Antarctic ice-sheet margin. Existing observations of grounding lines (e.g. Horgan *et al.* 2013) point to a complex transition between floating and grounded ice that needs to be understood fully and characterized well if we are to predict how ice sheets behave in such places. Here, we analyse radio-echo sounding (RES) data from the grounding line adjacent to the IIS to highlight the previously unknown complexity of this subglacial environment, and infer how this may influence the future evolution of the ice sheet.

Dataset and methods

We analyse RES datasets collected by the British Antarctic Survey (BAS) in the austral summer of 2006–07 and the austral summer of 2010–11, supplemented with those acquired by the Center for the Remote Sensing of Ice Sheets (CReSIS) during the Operation Ice Bridge (OIB) programme in 2014, which add substantially to data forming the previously published subglacial bed topography (Bedmap2) across the IIS (Fretwell *et al.* 2013) (Fig. 1a). The BAS Polarimetric Airborne Survey Instrument (PASIN) is a coherent radar system with a carrier frequency of 150 MHz, 12 MHz bandwidth and a pulse-coded waveform acquisition rate of 312.5 Hz. Two global positioning system (GPS) receivers were installed in the aircraft and corrected with two Leica 500 GPS base stations to obtain the position of the aircraft (Jordan *et al.* 2013). In 2014 CReSIS adopted a radar system operating with 50 MHz bandwidth from 165 MHz to 215 MHz, which was an upgraded version from the radar in 2012 used to acquire profiles inland of the IIS grounding line, with a waveform acquisition rate of 150 MHz (Gogineni 2012). The aircraft was positioned with GPS and inertial navigation systems (Rodriguez-Morales *et al.* 2014). All radar data were SAR-focused (synthetic aperture radar; Hélière *et al.* 2007; Gogineni *et al.* 2014).

Ice surface elevation (Fig. 1a, b) was derived from altimetric data from the European Remote Sensing Satellite-1 (ERS-1) radar and the Ice Cloud and land Elevation Satellite (ICESat) laser satellite altimetry (Bamber *et al.* 2009). Grounding-line positions, derived from several satellite products, are illustrated in Figure 1b. Surface ice velocities (Fig. 1c) derived from interferometric SAR (InSAR) data (Rignot *et al.* 2011*b*) allow the flow structure to be quantified and the shear margin, separating fast and slow flowing ice, to be located.

We mapped bed topography over the IIS region using the RES data. The topography was computed by subtracting a new ice thickness digital elevation model (DEM) from the satellite-derived ice-sheet surface elevation. The DEM was calculated from the along-track RES datasets and interpolated using the ‘Topo to Raster’ function in ArcGIS based on the Australian National University Digital Elevation Model gridding algorithm, which creates a smooth and hydrologically sound surface (Hutchinson 1988). The ice thickness, ice-sheet surface elevation and bed topography DEMs were then gridded at a uniform 1 km spacing. The WGS 84 Polar Stereographic projection (Snyder 1987) was used as a reference.

Subglacial water pressure was calculated using the hydraulic potentiometric surface, which assumes that the basal water pressure is balanced by the overriding ice pressure, expressed as:

$$\varphi = (\rho_w \times g \times y) + (\rho_i \times g \times h) \qquad (1)$$

where φ is the theoretical hydropotential surface, y is the bed elevation, h is the ice thickness, ρ_w and ρ_i are the density of water (1000 kg m^{-3}) and ice (920 kg m^{-3}), respectively, and g is the gravitational constant (9.81 m s^{-2}) (Shreve 1972).

A deep subglacial embayment near the Institute Ice Stream

Immediately west of the IIS grounding line, RES data reveal a previously unknown deep subglacial embayment (Fig. 2). The embayment measures *c.* 10 km (north–south) by *c.* 23 km (east–west), and is less than *c.* 10 km from both the grounding line and the southern shear margin of the IIS. The embayment is surrounded on three sides by highlands (Fig. 2a, b), with another side potentially open to the ice-shelf cavity (Fig. 2c, d). The elevation of

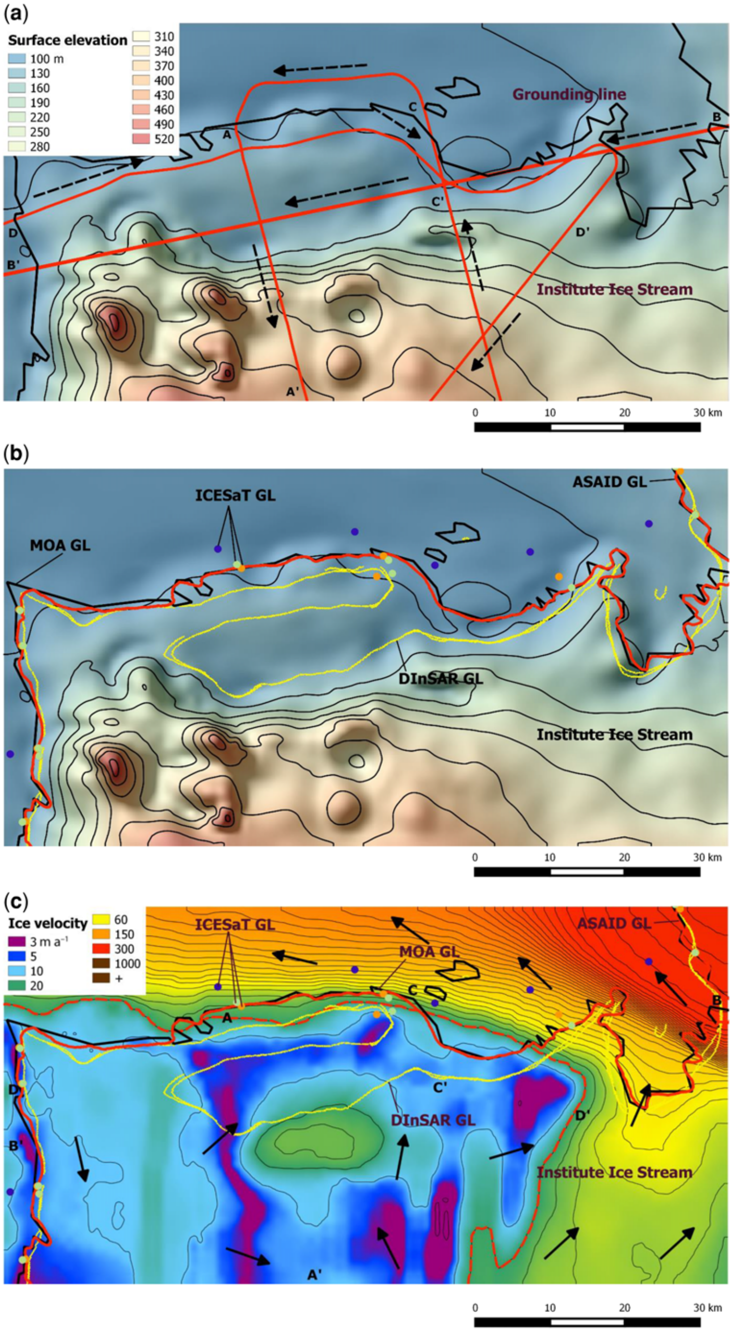

Fig. 1. Boundary conditions across the Institute Ice Stream. (**a**) The British Antarctic Survey and NASA Operation IceBridge/Center for Remote Sensing of Ice Sheets (CReSIS) flightlines (red lines) superimposed over ice-sheet surface elevation (Bamber *et al.* 2009). Arrows indicate direction of aerogeophysical flights. (**b**) Grounding line obtained from ICESat laser altimetry (blue: hydrostatic point; orange: ice flexure landward limit; green: break in slope) (Brunt *et al.* 2010), the Antarctic Surface Accumulation and Ice Discharge (ASAID) project (red line) (Bindschadler *et al.* 2011), the Mosaic of Antarctica (MOA) (black line) (Bohlander & Scambos 2007) and NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) program (yellow line) (Rignot *et al.* 2011*a*, *c*). (**c**) InSAR-derived ice-surface velocities (Rignot *et al.* 2011*b*). Arrows indicate the ice flow directions.

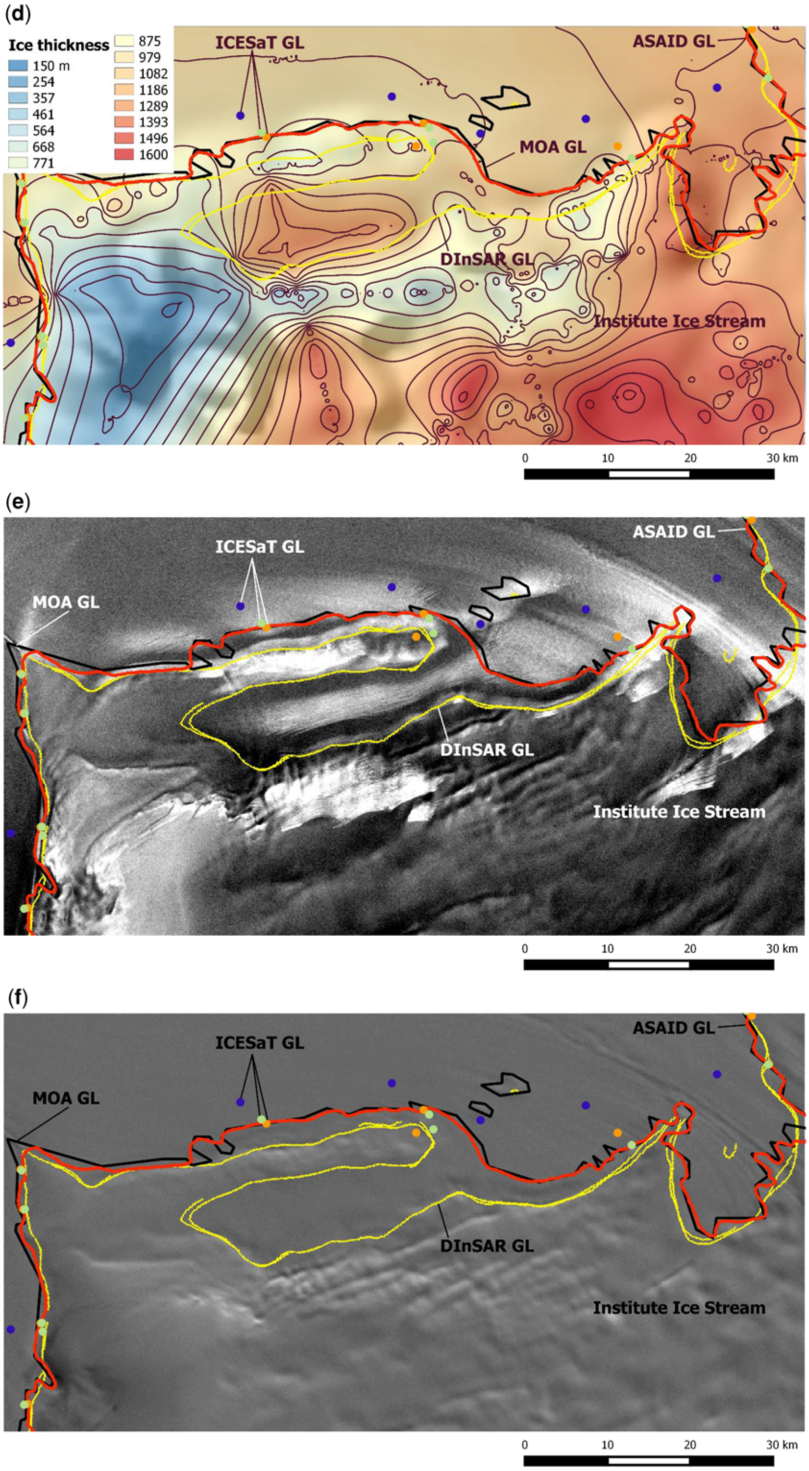

Fig. 1. (*Continued*) (**d**) Ice thickness DEM of the subglacial embayment. (**e**) RADARSAT (25 m) satellite radar image (Jezek 2002). (**f**) 2003–04 austral summer MODIS satellite imagery (Bohlander & Scambos 2007).

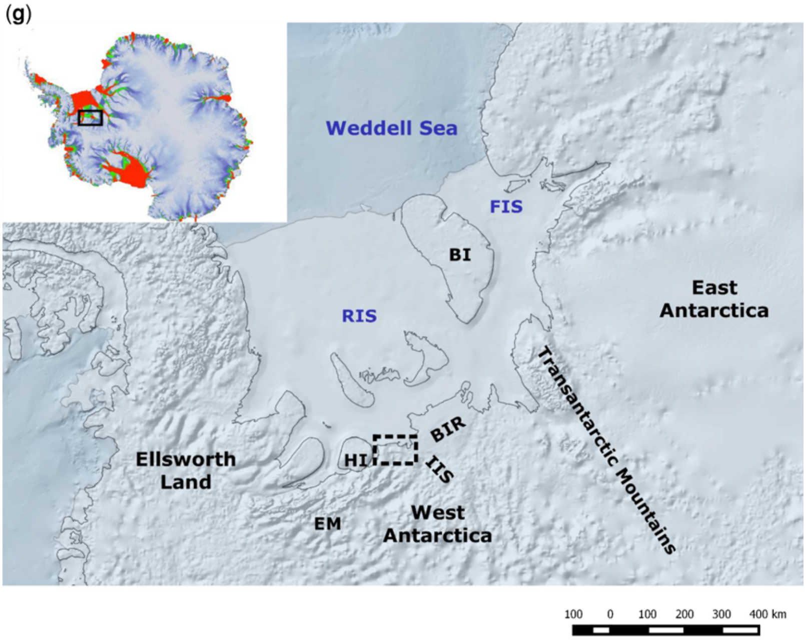

Fig. 1. (*Continued*) (**g**) Regional map showing the location of the subglacial embayment (the rectangle in dashed lines) adjacent to the Institute Ice Stream. FIS, Filchner Ice Shelf; RIS, Ronne Ice Shelf; BI, Berkner Island; BIR, Bungenstock Ice Rise; HI, Hercules Inlet; EM, Ellsworth Mountain; IIS, Institute Ice Stream.

the high ground is *c.* 579 m above sea level, with slope gradients ranging over 1–8° (Fig. 3). The ice thickness over the centre of the embayment is around 1450 m. The ice over the embayment is *c.* 200 m thicker than the ice shelf at its known point of floatation adjacent to the IIS. The embayment manifests in satellite-derived Antarctic mosaics (Fig. 1e, f) as a set of linear crevasse zones (RADARSAT) (Jezek 2002) and as a smooth central zone surrounded by a horseshoe of rougher ice (MODerate resolution Imaging Spectroradiometer or MODIS) (Scambos *et al.* 2007).

Each of the PASIN and MCoRDS (Multichannel Coherent Radar Depth Sounder) RES transects (Fig. 2, Profile A–A′ and B–B′) show a bright reflector across the embayment, indicative of the presence of either water (Wolovick *et al.* 2013; Ashmore & Bingham 2014; Wright *et al.* 2014*b*) or water-saturated sediments, similar to RES data collected over Subglacial Lake Whillans (Christianson *et al.* 2012; Horgan *et al.* 2012). This reveals two possibilities: first, that the basal ice is at the melting point above loose sediments; or, second, that there exists a pathway for sea water to penetrate the subglacial embayment. While there are insufficient data to determine between these two possibilities conclusively, given the relatively thin ice, for the ice to be at the pressure melting point enhanced geothermal heat would likely be needed. As there is no sign of a geological anomaly over the embayment (Jordan *et al.* 2013), the latter option (i.e. the embayment is underlain by sea water) seems to be more likely.

Although the existing RES data cannot unequivocally determine whether an open-water connection exists between the sub-ice cavities of the ice shelf and embayment, satellite data offer additional assistance through the assessments of the grounding-line position. While there is some agreement between the differential InSAR (DInSAR), Antarctic Surface Accumulation and Ice Discharge (ASAID) and Mosaic of Antarctica (MOA) grounding lines at the region of fast-flowing ice, differences prevail in the area of slow-moving ice (Fig. 1b); DInSAR suggests the embayment is part of the ice shelf, but others point to grounded ice between the ice shelf and the cavity located *c.* 33 km seaward from the DInSAR-derived position. These differences can be explained because DInSAR uses measurements of tidal flexure to determine the grounding line (Rignot *et al.* 2011*c*). DInSAR and ICESat have good agreement in other parts of Antarctica since they use the same detection methods. However, relatively sparse ICESat observations between the IIS and Hercules inlet (*c.* six spot-measurements of flexure points) limit the usefulness of the ICESat data for defining the embayment (Fig. 1b). At the southern boundary of the embayment (Fig. 1c), the ice velocity is measured

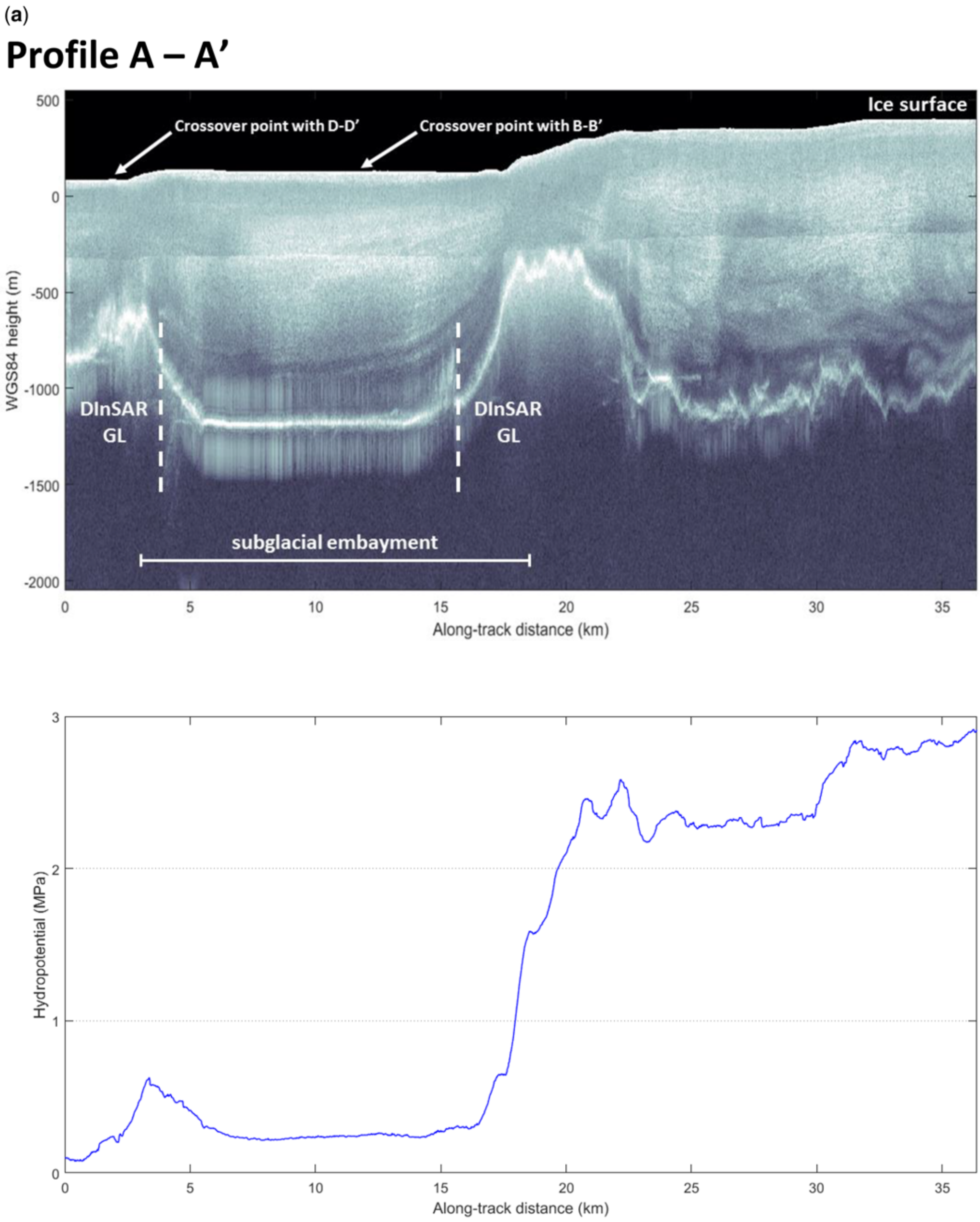

Fig. 2. Radar sounding profile acquired by (**a**) the British Antarctic survey 2010/2011 (A–A′) and (**b**) the Center for the Remote Sensing of Ice Sheets in 2014 (B–B′), revealing the subglacial embayment close to the shear zone and the Institute Ice Stream and RES transects at the mouth of the embayment acquired by the BAS survey in (**c**) 2010–11 (C–C′) and (**d**) 2006–07 (D–D′). Graphs of basal hydropotential surface are shown below each RES transect.

at 10–20 m a^{-1}. However, the ice flowing at the edge of the embayment facing the Ronne Ice Shelf is slower, ranging over 3–5 m a^{-1}. This change in velocity is due to a higher elevation at the border of the embayment inland relative to the edge of the embayment close to the grounding line (profile A–A′, Fig. 2). The high elevation inland of the embayment generates a steep ice-surface gradient

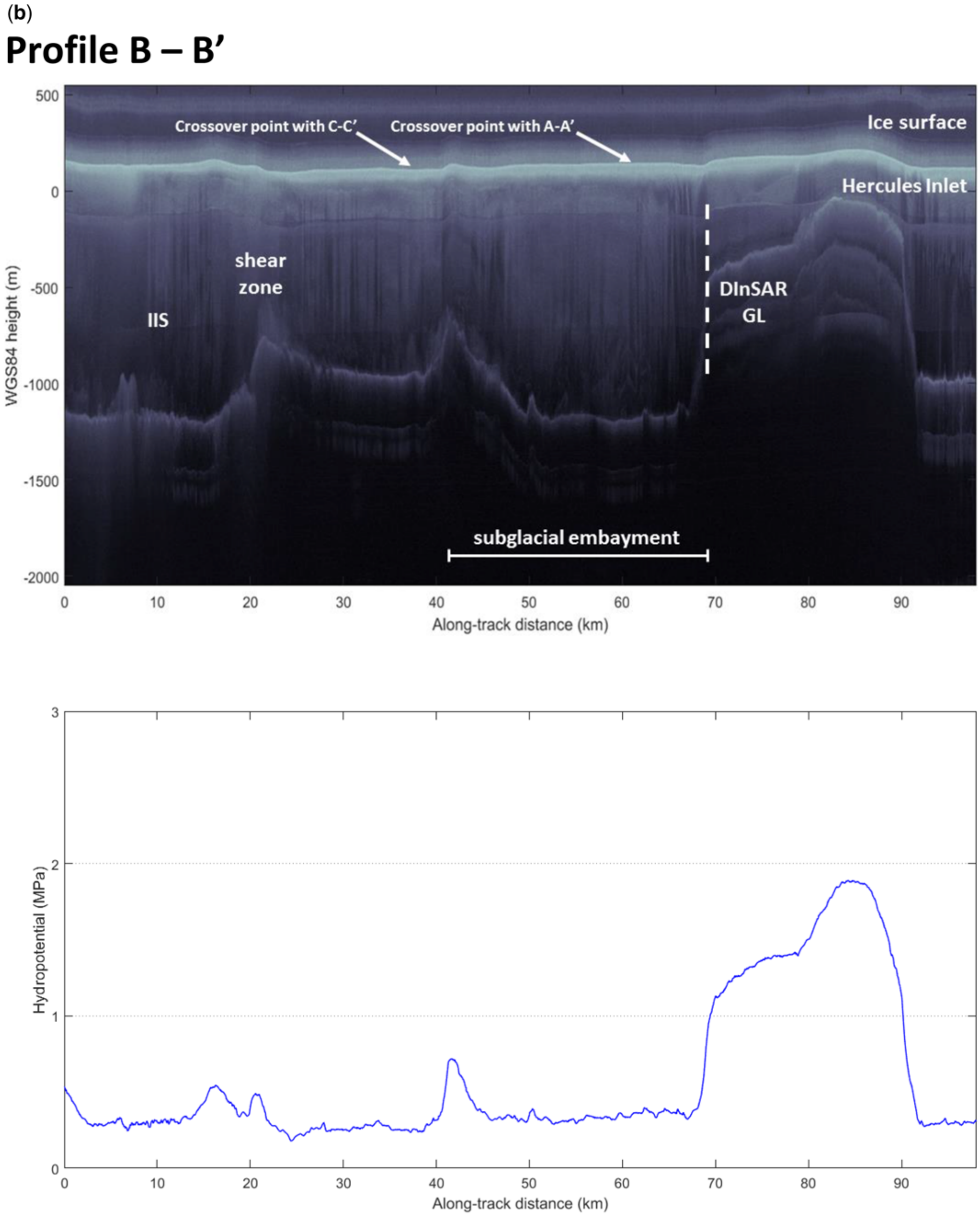

Fig. 2. *Continued.*

down to the embayment (Fig. 1a), driving the localized circular anomaly of high-flow velocity (Fig. 1c) and a zone of extensional surface crevassing (Fig. 1d).

We use the along-track qualitative brightness of the ice-bed interface and the along-track calculation of hydropotential to determine where the ice sheet is likely to be overlying water (Fig. 2). We find that our RES data are consistent with the grounding line as defined by the DInSAR data. The zones of flat hydropotential ranging over 0.1–0.5 MPa across the basin are uniform with the bright ice-based reflection suggesting the presence of basal water. A mini-basin between the IIS shear zone and the subglacial

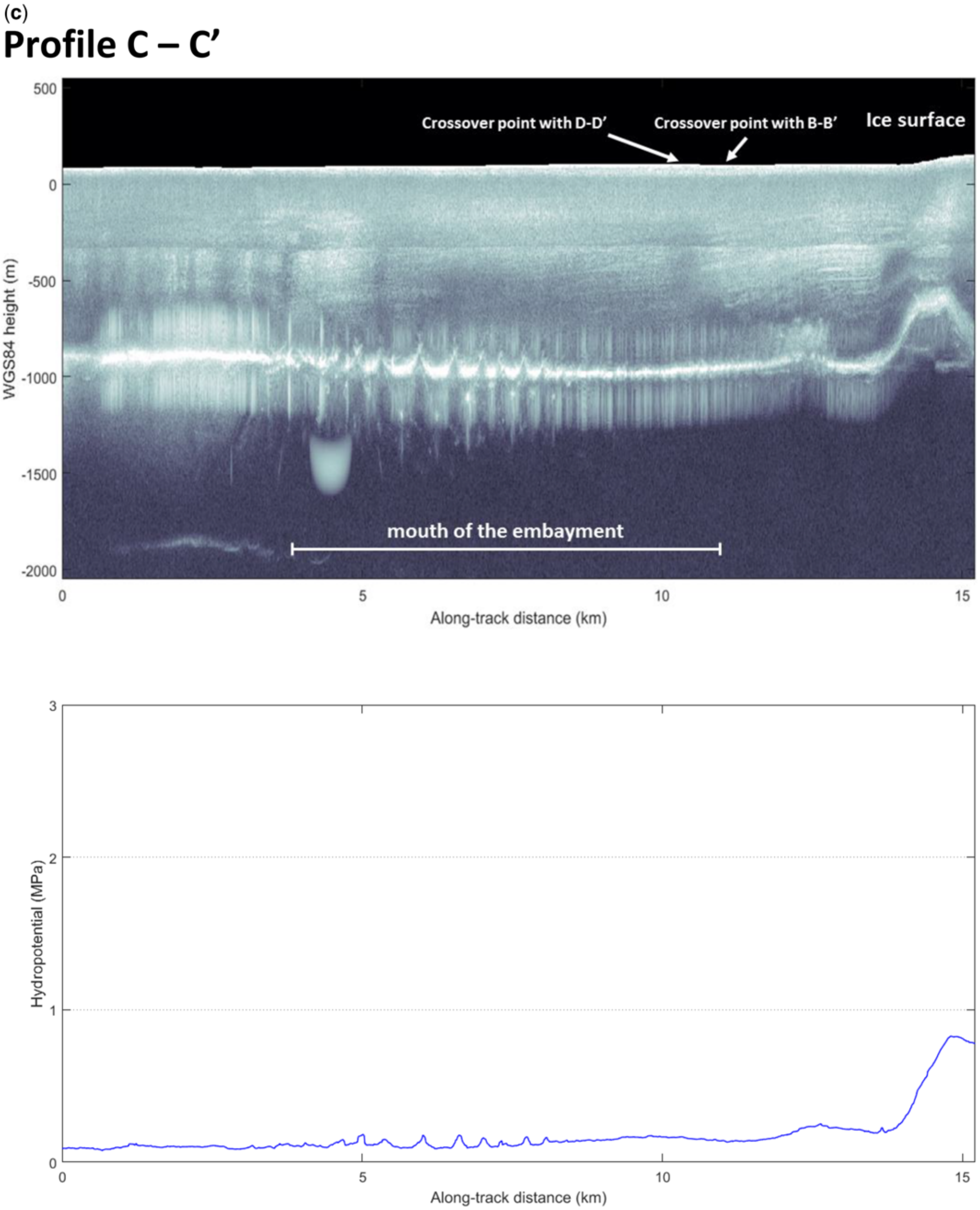

Fig. 2. *Continued.*

embayment (profile B–B′, Fig. 2) is also potentially underlain with sea water judging by the flat hydropotential surface across the feature. It is also noted that the flat hydropotential zone within the embayment (profile B–B′, Fig. 2) presents the possibility of an open connection with the ice shelf. RES data also reveal variable basal water pressures to the south (profile A–A′, Fig. 2) and west (profile B–B′, Fig. 2) over the boundary of the DInSAR grounding line, which appears consistent with grounded ice.

The basal reflection at the mouth of the embayment (profiles C–C′ and D–D′, Fig. 2) is relatively flat and bright. Interestingly, however, the basal reflection is characterized by a series of ‘jagged’

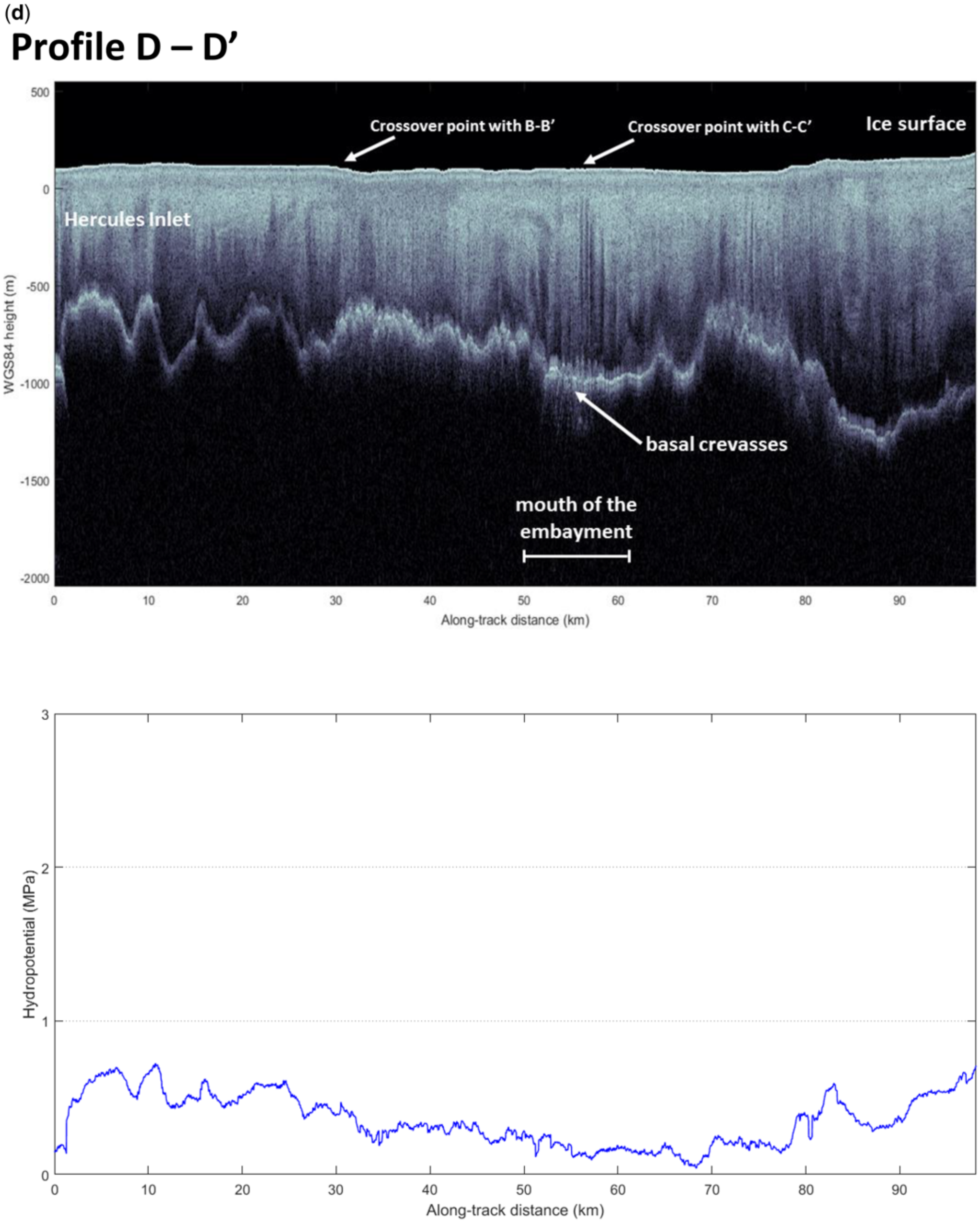

Fig. 2. *Continued.*

notches. While these distinct features may be associated with basal crevasses or ice rumples given their uniform character, constant separation of 100–300 m and elevation of 20–120 m, they could also be associated with the transfer of basal or sea water (i.e. they are cross-sections of channels incised into the overlying ice). Further evidence of channels may be apparent at the edges of the embayment (profile A–A′, Fig. 2). The bright relatively flat basal reflector that characterizes the embayment mouth is also coincident with the flat hydropotential surface across profile C–C′, consistent with a

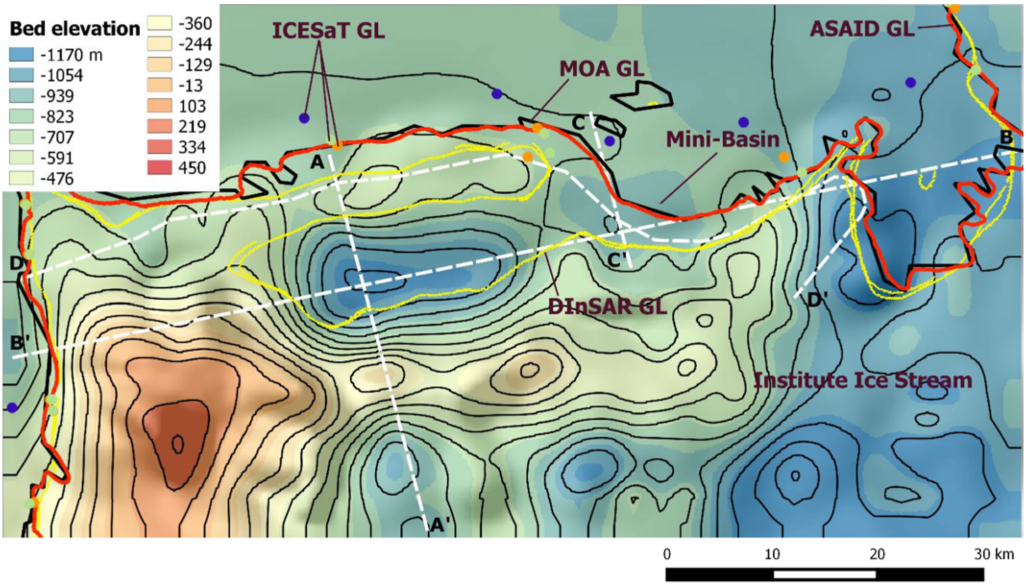

Fig. 3. Grounding line obtained from ICESat laser altimetry (blue: hydrostatic point; orange: ice flexure landward limit; green: break in slope) (Brunt *et al.* 2010), the Antarctic Surface Accumulation and Ice Discharge (ASAID) project (red line) (Bindschadler *et al.* 2011), the Mosaic of Antarctica (MOA) (black line) (Bohlander & Scambos 2007) and NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) program (yellow) (Rignot *et al.* 2011*a*) superimposed on the bed topography DEM. The bed elevation across the subglacial embayment is presumably the ice base elevation. The locations of profiles A–A′, B–B′, C–C′ and D–D′ are shown (white dashed lines).

connection with the sea water and further supporting the existence of an open-water connection between the embayment and the ice-shelf cavity.

On the basis of the currently available datasets, we cannot assess what role the large tidal range (*c.* 8 m) of this part of the Filchner–Ronne Ice Shelf plays in the persistence of this open-water connection over tidal cycles. Repeat InSAR or laser surveys of the ice-sheet surface at high temporal resolution (e.g. ICESat2) could determine this, however. If the embayment is open to the ice-shelf cavity, and given the large tidal range, the jagged ice base at the embayment mouth could be the result of large-scale flushing of water associated with rising and falling tides. We acknowledge that this is an unorthodox interpretation, but note that basal ice-shelf features associated with differential melt have been identified at the base of Pine Island Glacier ice shelf in West Antarctica and Petermann Glacier, Greenland (Dutrieux *et al.* 2014).

Implications for ice-sheet change

The grounding line across the IIS has not been observed to change in satellite altimetric data (Pritchard *et al.* 2012). However, RES data reveal it to be at a physical threshold of substantial change (Ross *et al.* 2012). Ice-sheet modelling suggests that the grounding line here is highly sensitive to the ocean-driven melting, with the possibility of major ice loss within the next 2000 years (Pollard & DeConto 2009; Wright *et al.* 2014*a*; Cornford *et al.* 2015; DeConto & Pollard 2016). In these models it is noted that once grounding-line retreat begins the ice sheet is unable to re-establish equilibrium, resulting in accelerated and unstoppable ice-stream mass loss. It is also worth noting that ice-sheet models overlook the subglacial embayment in this highly sensitive region, or other grounding-line complexities. Through discovering the embayment, we highlight the possibility that grounding-line migration may be heavily influenced by the local basal topography, and would perhaps be more complex than indicated by existing numerical modelling studies.

The subglacial embayment lies adjacent to the IIS shear margin (*c.* 9 km away). Rapid grounding-line retreat, possibly influenced by the subglacial embayment, could widen the enhanced flow area of IIS, increasing the amount of ice feeding into the ocean and accelerating further mass loss. In addition, changing local-to-regional sub-shelf water circulation patterns in this area could result in the inflow of warm ocean water into the subglacial embayment, altering rates of basal ice melting as has been suggested for Totten Glacier, East Antarctica (Greenbaum *et al.* 2015). Under this scenario, it would be possible that the ice-sheet configuration of the Weddell Sea sector could undergo dynamically driven glaciological change (Bentley *et al.* 2010; Ross *et al.* 2012; Rippin *et al.* 2014; Martin *et al.* 2015). Such a hypothesis is certainly worth testing by numerical ice-sheet models, with fuller appreciation of the known bed conditions. In contrast, the topographic ridges enclosing the embayment could act to delay grounding-line retreat and maintain ice-sheet stability in this region.

Stability of the ice sheet may also be promoted by the basal topography inland of the embayment. RES transects (Fig. 2; Winter *et al.* 2015) reveal complex topography similar to the embayment inland of the IIS with multiple subglacial mountains, basins and troughs (e.g. the Horseshoe Valley and the Independence and Ellsworth troughs). Under the current ice-flow configuration, these linear topographic highs exert buttressing on the primary flow direction of the IIS and impact wider-scale ice dynamics by acting to resist the current orientation of fast ice flow (Gagliardini *et al.* 2010; Matsuoka *et al.* 2015). The ridges surrounding the margin of the embayment therefore potentially inhibit any future grounding-line retreat, affecting the timing and rate of future deglaciation occurring in this region by acting as pinning points. That said, were the configuration of ice flow to change (i.e. more ice flow to be sourced from the vicinity of the Ellsworth Subglacial Highlands, as proposed for the region in the Late Holocene; Siegert *et al.* 2013) this basal topography may lead to ice between the grounded features flowing more rapidly, similar to the three major tributaries flowing into the ice stream (Winter *et al.* 2015). Under a scenario of regional grounding-line retreat, a change in ice-flow direction could therefore permit preferential and focused flow with the troughs; this would remove the buttressing influence of the topographic highs, and lead to further accelerated ice loss within the troughs.

Summary

Our geophysical data reveal a subglacial embayment adjacent to the grounding line and shear margin of the IIS. This discovery highlights the complexities along the grounding line in this region, which are likely present in other regions of the ice sheet. The location of the embayment coincides with a variety of possible grounding line locations from several satellite data products. In the grounding-line dataset which our geophysical data are most consistent with (Rignot *et al.* 2011*a*) the grounding line loops within the embayment itself, meaning it is incorporated as part of the ice-shelf cavity. Further RES data from the mouth of the embayment are needed to test conclusively whether this is the case. As it is so close to the shear margin of the IIS, ice loss over the embayment may lead to its lateral migration. In such circumstances, the embayment we have identified could inhibit and/or exacerbate grounding-line retreat. The enclosing ridges may act as pinning points, resisting flow, while the embayment may enable access of warm ocean waters to the deep grounding line. This grounding-line complexity illustrates the need for detailed three-dimensional characterization of Antarctic grounding lines and their incorporation into numerical models, which can then assess the true effects these complexities can have on local ice dynamics and sub-shelf ocean circulation. The scenarios we propose above are testable with numerical models, but only when accurate knowledge of the bed is included and realistically modelled (i.e. at a sufficiently high resolution).

The data used in this project are available at the Center for the Remote Sensing of Ice Sheets (CReSIS) data portal https://data.cresis.ku.edu/ and at the UK Airborne Geophysics data portal https://secure.antarc-tica.ac.uk/data/aerogeo/. P.G. and J.L. acknowledge funding by NASA for CReSIS data collection and development of radars, M. J.S. acknowledges funding from the NERC Antarctic Funding Initiative (NE/G013071/1) and H.J. acknowledges funding from the Ministry of Higher Education, Malaysia.

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