A Detailed Geophysical Investigation of the Grounding of Henry Ice Rise, with Implications for Holocene Ice-Sheet Extent

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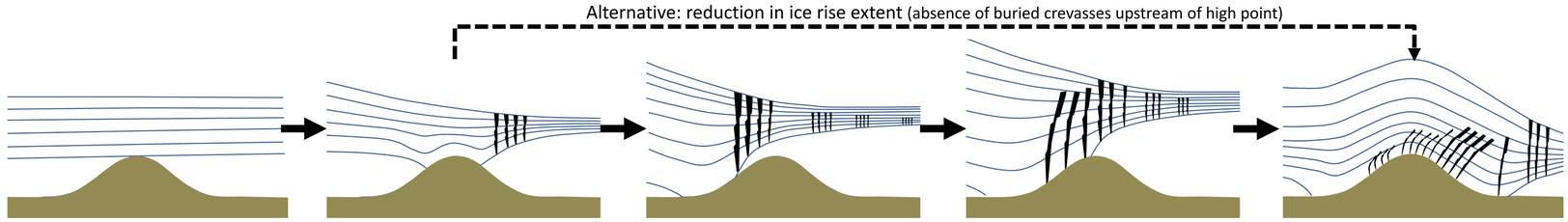
Introduction

An accurate history of ice-sheet extent and thickness is important for ice-sheet model spin-up and GIA corrections to mass balance calculations from surface altimetry. In West Antarctica studies have concluded that the grounding line may have re-advanced during the Holocene, following a post-LGM retreat[1,2], contrary to long-standing assumptions of monotonic retreat[3].

Here we use a dense grid of ice-penetrating radar profiles to infer the Holocene ice history of Henry Ice Rise (HIR) in the Ronne Ice Shelf and propose a theory for its formation.

Grounding: Ice Rumples to Ice Rise



1) Initial grounding
- Uplift of bed or thickening of shelf

2) Initial Rumple Formation
- Crevassing in extensive zone

3) Retreat from high point
- Thickening upstream
- Old crevasses buried and advected

4) Thickening & Advance
- Ground & bury relic crevasses

5) Ice Rise Formation
- Flow onto grounded area ends
- Buried crevasses vertically sheared

Present-day Flow

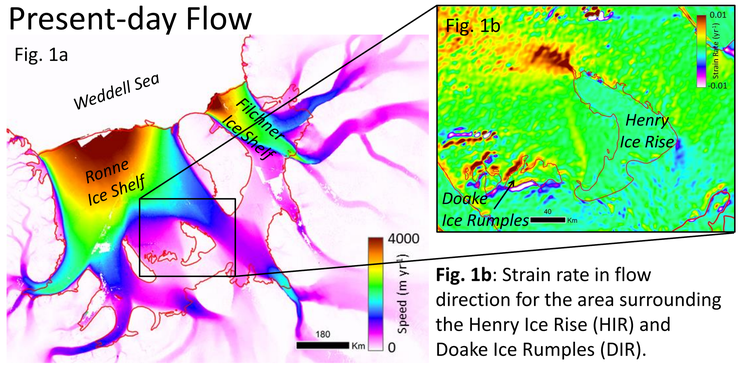
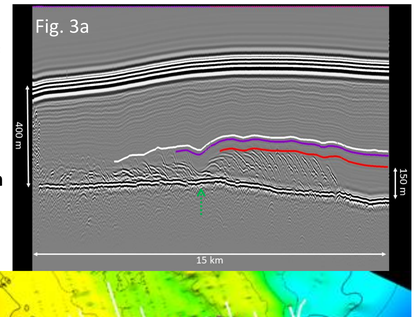


Fig. 1b: Strain rate in flow direction for the area surrounding the Henry Ice Rise (HIR) and Doake Ice Rumples (DIR).

Fig. 1a: Surface speed for the Ronne-Filchner Ice Shelf[4]. Grounding line is shown in red[5].

Buried crevasses

Fig. 3: Radar profiles at the northern end of HIR reveal an extensive area of buried crevasses (**Fig. 3a**). These buried crevasses disrupt the isochronal layers at the base of the ice rise. **These crevasses could not be formed with the current flow configuration** in this area of grounded ice, where strain rate is low. The highlighted isochrones indicate crevasse-capping isochrones that span the extent of non-crevassed layers. The buried crevasses are tilted due to vertical shear.



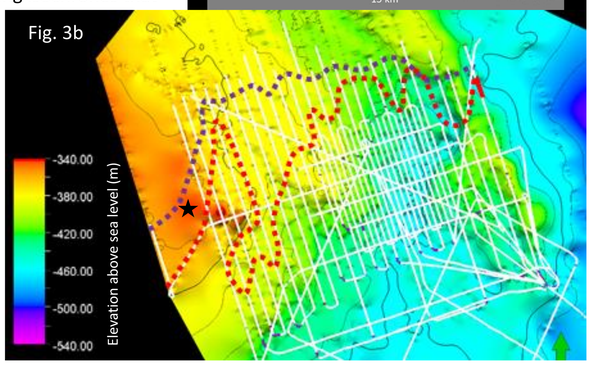


Fig. 3b: Bed elevation above sea level, overlain with extent of crevasse-capping isochrones. White lines indicate extent of upper highlighted isochrone in **Fig. 3a**. Dashed contours correspond to deeper highlighted isochrones in **Fig. 3a**. This indicates the stepwise **advance of the grounding line** in this area (Stages 4 & 5 above) and absence of grounding over the bathymetric high (★) in initial stages (3 & 4 above) of grounding. (See white square in Fig. 2a for extent.)

Transect Profiles

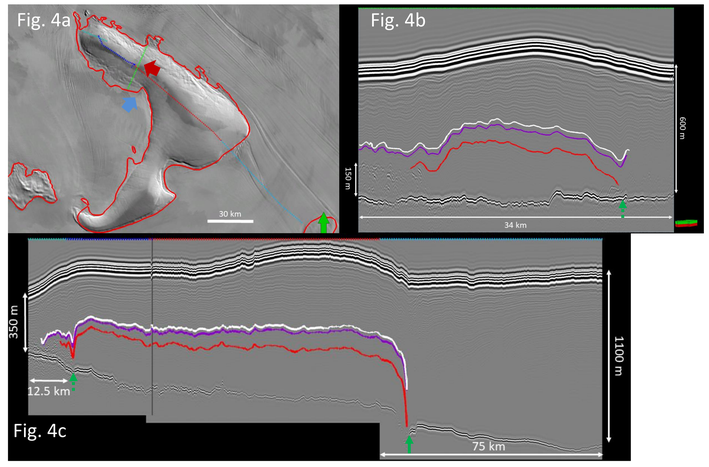


Fig. 4a: Locations of radar profiles **Fig 4b** (with viewing arrow) and **Fig 4c** (with viewing arrow). **Fig. 4b**: Deepest capping isochrone (red) intersects the buried crevasses on both flanks of the ridge. Upper two highlighted isochrones cap the buried crevasses on the West flank, but become distorted on the East flank. **Fig. 4c**: Buried crevasses are found in the final 12.5 km of the profile, but are absent elsewhere. At the southern grounding line there is a large dip in the isochrones ( ) suggesting a large gradient in basal melting[8]. The absence of melting in the profile north and south of this suggests this has been a long term grounding line position. Symbols indicate other areas (near northern edge and flanks) where previous melting is likely to have occurred but is currently grounded (see Fig. 3a, 4b & 4c).

Doake Ice Rumples

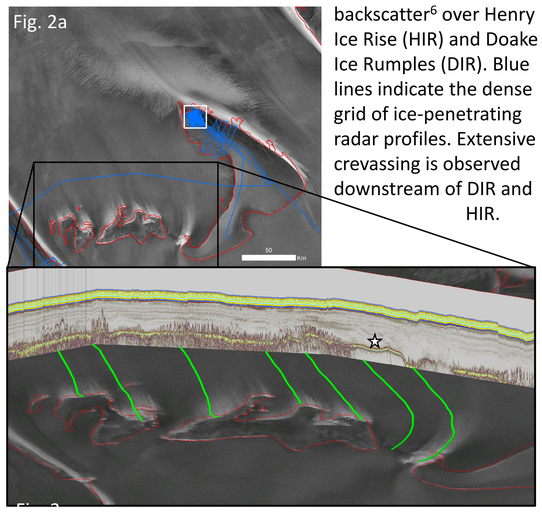


Fig. 2a: RAMP radar backscatter[6] over Henry Ice Rise (HIR) and Doake Ice Rumples (DIR). Blue lines indicate the dense grid of ice-penetrating radar profiles. Extensive crevassing is observed downstream of DIR and HIR.

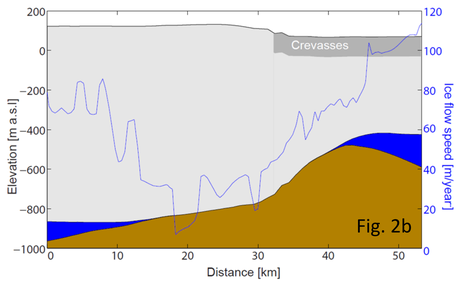


Fig. 2b: Vertical profile over DIR, showing ice surface and base, bed rock profile (from BEDMAP2[7]) and ice surface speed. Notice **ice ungrounded at high point** – Stages 3 & 4.

Fig. 2c: Projected view of DIR, with streamlines (green) from downstream edge of DIR to the radar transect. Crevasses are advected and buried. They are observed at the ice-shelf base at all points on the radar transect apart from where ice has passed between DIR and HIR (☆). This indicates that the **crevasses penetrate the full ice depth**.

Key Processes:

- Full ice-depth crevasses form downstream and in shear margins of ice rumples and ice rises, where strain/shear rates are high.
- These crevasses are then buried and advected with ice flow.
- Crevasses can be captured and buried when grounding line advances. This indicates how the grounding line of HIR has advanced.
- Buried/relic crevasses become deformed and tilted with vertical shear when grounded.
- For HIR, numerous crevasses capped by the same isochrone suggests stepwise advance of the grounding line.
- Melt features observed at southern edge of HIR ( ) and amongst buried crevasses ( ) indicating current and previous grounding line locations.
- The absence of earliest crevasses over bathymetric high suggests transition from rumples to ice rise, rather than solely variations in ice-rise extent.
- Preliminary dating estimates suggest an age of approximately 6 kyr for first set of crevasses.

References:
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[2] Bradley, S. L. et al. Low post-glacial rebound rates in the Weddell Sea due to Late Holocene ice-sheet readvance. *Earth Planet. Sci. Lett.* 413, 79–89 (2015).
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