Observed and Modelled Surface Meltwater-Induced Flexure and Fracture on North George VI Ice Shelf, Antarctica

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1. Background

- Stress variations associated with surface and shallow subsurface meltwater ponding across Antarctica's floating ice shelves may have important implications for their stability.

2. Aim

- To characterize the flexure and fracture behaviour of a mature 'doline' (i.e. a drained lake feature; *Warner et al.* 2021) on north George VI Ice Shelf, (**Fig. 1**), in response to a central lake filling and draining during the 32-year record-high melt season of 2019/2020 (**Fig. 1**, poster background image & *Banwell et al.* 2021).

Fig 1. Widespread lakes on N George VI Ice Shelf in January 2020. *Credit: Thomas Simons.*

3. Study site

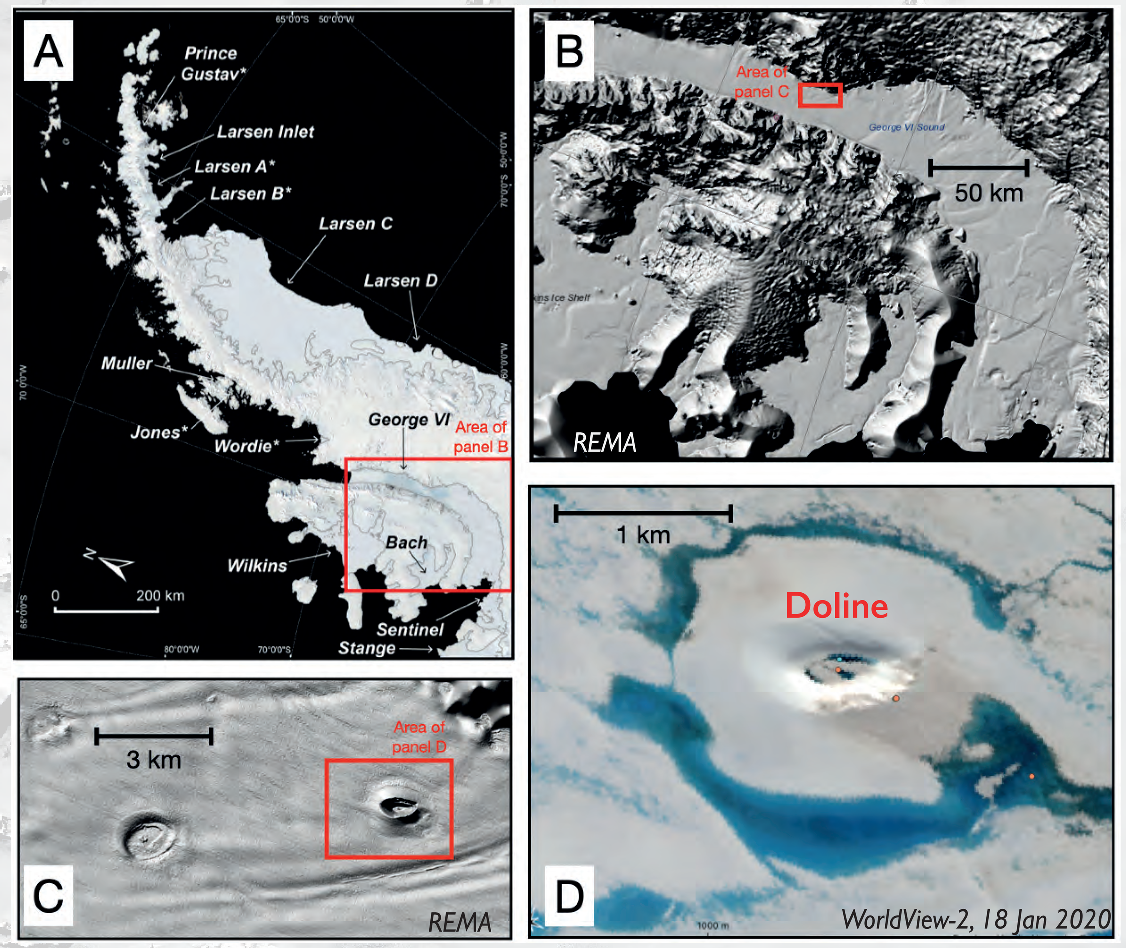


Fig 2. Location of the doline (D) and its surrounding area (C) on the north George VI Ice Shelf (B), southwest Antarctic Peninsula (A).

4. GNSS & time-lapse camera set-up

- Instruments were deployed in Nov 2019, but not retrieved until Nov 2021 due to Covid. Only 2 of 4 original GNSS stations were working.
- Field instruments were deployed in/around a doline because:

 1) Location of the central lake is predictable (elsewhere on ice shelves, lake locations are hard to predict due to flat surface topography).

 2) Lake is self-contained, as the uplifted doline rim prevents water from entering the doline centre. This is useful from a modelling perspective.

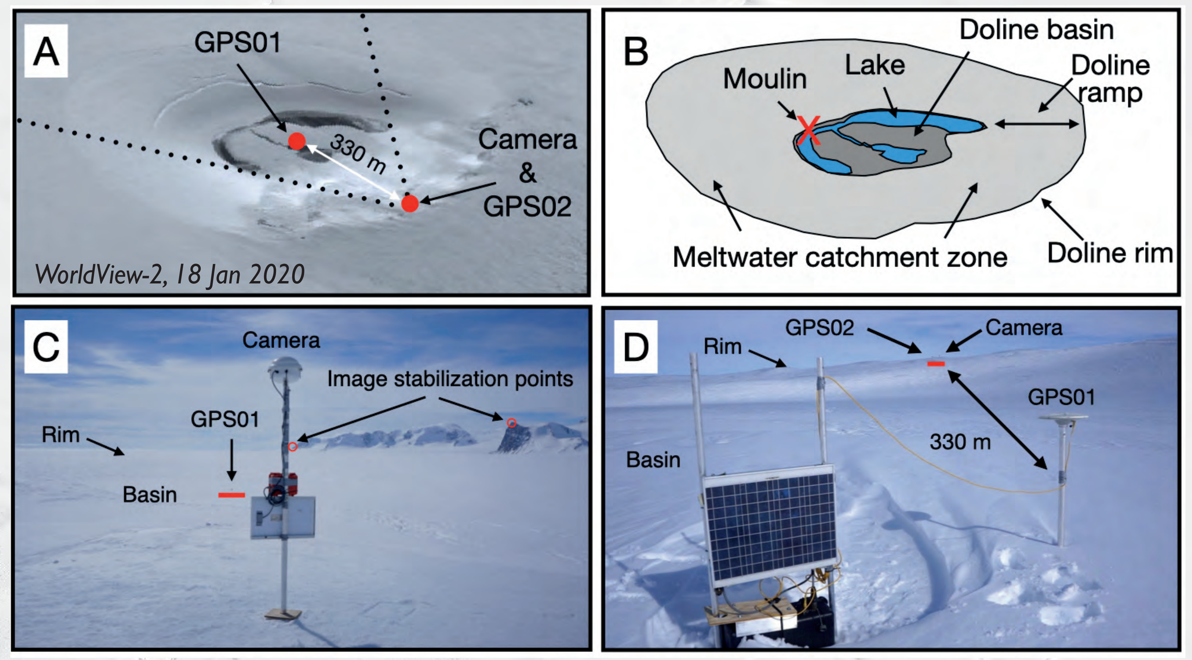


Fig 3. (A) Instrument locations in/around doline. Dotted lines show camera field of view. (B) Interpretation of WorldView-2 image in A. (C) Photo of the time-lapse camera set-up looking N towards GPS01 (taken Nov. 2021). (D) Photo looking south from GPS01 inside the doline basin (taken Nov. 2021).

5. Time-lapse imagery analysis

- Photos taken every 30 mins through the 2019/2020 melt season (Fig. 4).
- Image orthorectification process used to re-cast oblique views of basin to a directly overhead views. Lake areas then manually digitised (Fig. 5).

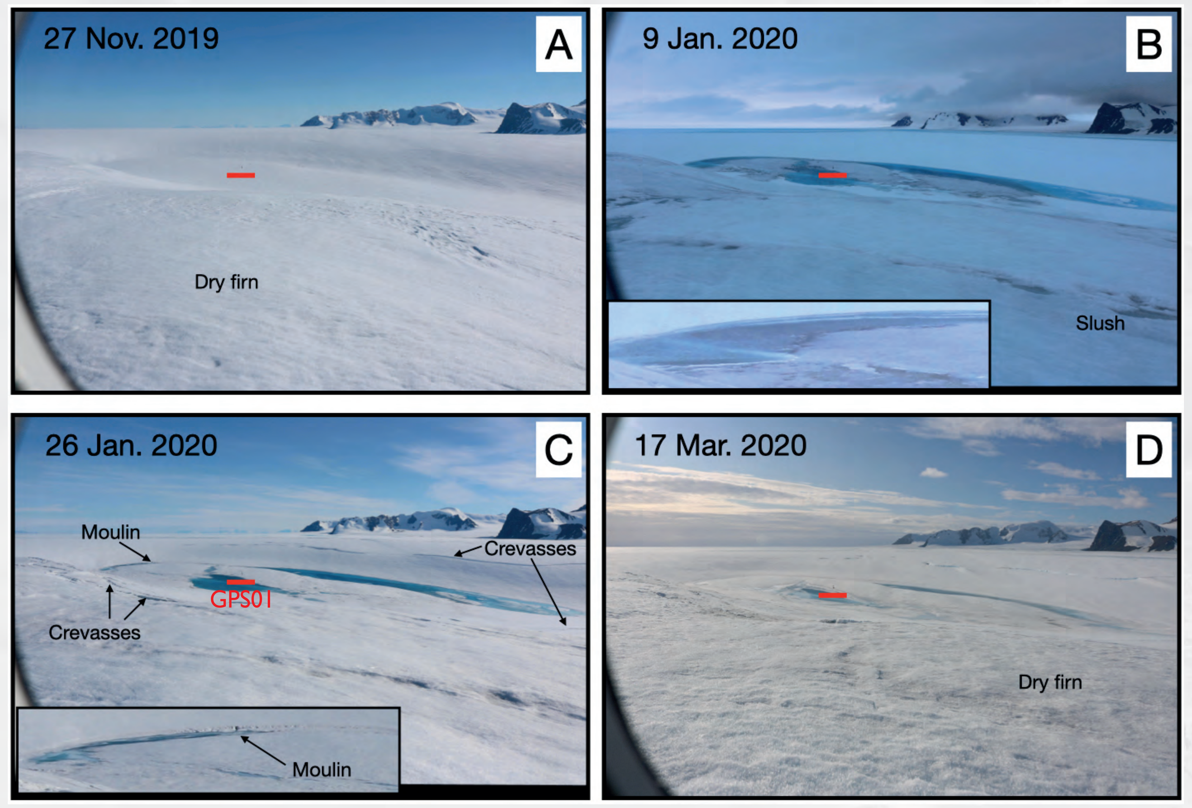


Fig 4. Time-lapse photos taken from the doline's south rim (**Fig. 3A**) through the 2019/2020 melt season, corrected for camera tilt/vibration using fiducial points (**Fig. 3C**). Insets in panels B and C show cropped close-ups of the moulin area. Crevasses which align with the curve of the doline rim are indicated in panel C.

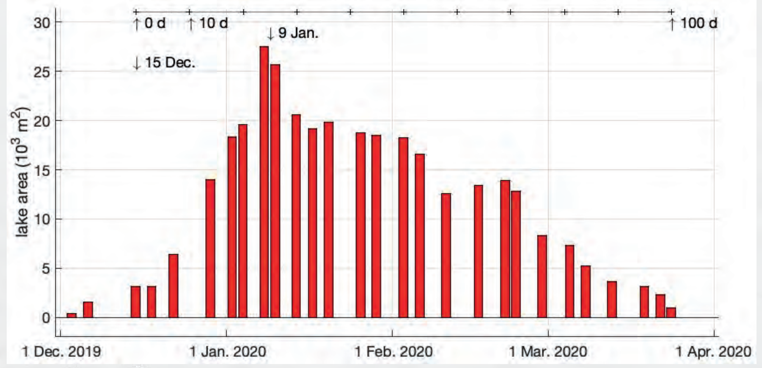


Fig 5. Lake area in the doline basin determined by delineating orthorectified time-lapse photos (**Fig. 4**). Max. lake area occurs on Jan 9 due to a moulin opening (**Figs. 4B, C**).

Background image:
North George VI Ice Shelf
Sentinel-2, January 19, 2020

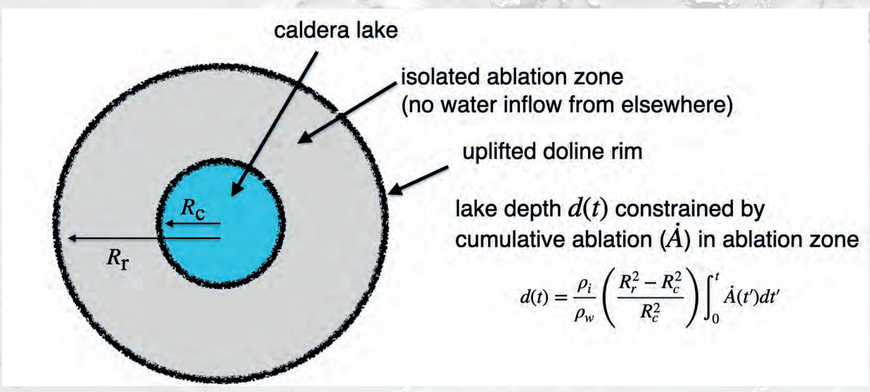
0 20 km

Doline (Fig. 2D)

6. Model set-up

- Use a simple numerical model of ice-shelf flexure and flow based on that described in *MacAyeal et al.* (2021).
- Constructed in the commercial finite-element package; COMSOL.
- Solves for ice deformation in the idealised doline domain using the Stokes equations and an effective viscosity based on Glen's flow law.

Fig 6. Schematic birds-eye view of a doline in the model.



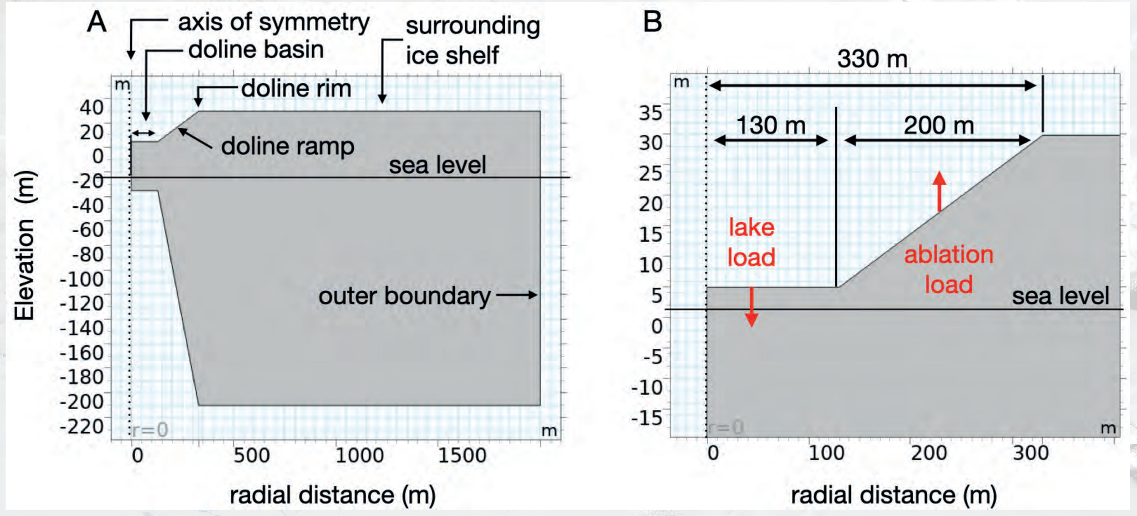


Fig 7. Idealised, axisymmetric geometry of the doline's model domain as set-up in COMSOL. (A) Full side view; (B) Close-up side view of the doline basin and its rim.

7. GNSS observations & model results

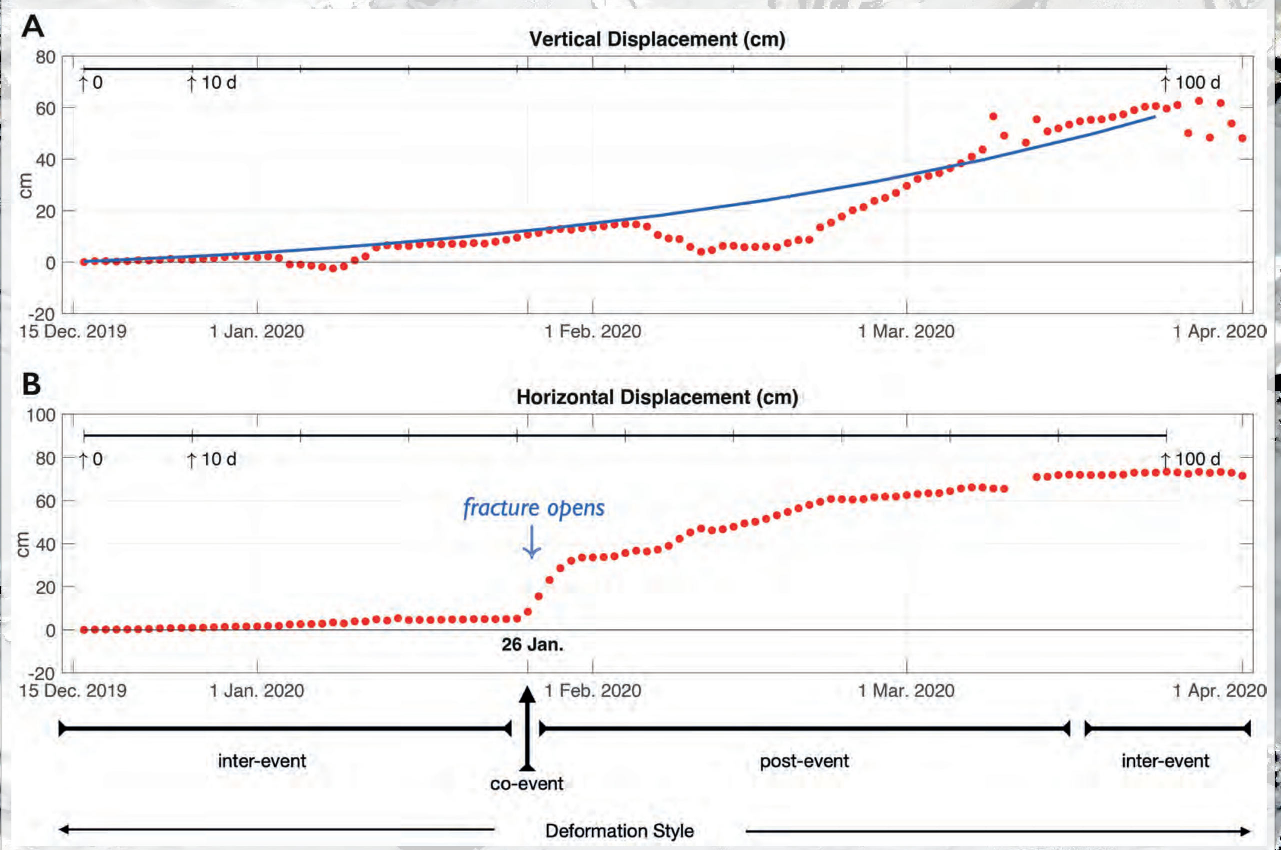


Fig 8. (A) Vertical and (B) horizontal displacement of GPS02 relative to GPS01 (**Fig. 3A**) during the 2019/2020 melt season. Red dots show GNSS displacement since 15 Dec. 2019. The blue line in A shows the model result. Positive values of vertical displacement indicate the doline centre (GPS01) is lowering relative to the doline rim (GPS02). Below panel B, the deformation style is indicated relative to a fracture opening on 26 Jan. 2020.

8. Conclusions

- GNSS timeseries shows a downward vertical displacement of the doline centre with respect to the doline rim of ~80 cm (**Fig. 8A**), in response to loading from the central meltwater lake.
- Viscous flexural modelling indicates that this vertical displacement generates flexure stresses of ~> 75 kPa; sufficient to cause fracture.
- GNSS data also indicates a rapid onset (~26 Jan), exponentially decaying, horizontal displacement (over ~30 days) where the doline rim moves ~70 cm further from the doline centre (**Fig. 8B**). We interpret this as fracture initiation and/or widening.
- We make the first observations of 'ring fractures' (**Fig. 4C**), equivalent to those proposed as part of the chain-reaction lake drainage style process involved in the 2002 break-up of Larsen B (*Banwell et al.* 2013).
- We also observe the opening of a moulin ~9 Jan 2020 (**Fig. 4B**), which acts like a safety drain in a bathtub, limiting the lake's depth (**Fig. 5**).

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