Calving and Rifting on the McMurdo Ice Shelf, Antarctica

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1. Introduction

- Ice shelf brittle behaviour, leading to fracture, iceberg calving & disintegration, is challenging to study because events are often: i) not noticed until after they occur, ii) hidden from view; iii) difficult to anticipate; iv) hard to monitor with sensors operating periodically.
- Previous studies of rifting/calving typically used one observational system (e.g. satellite remote-sensing), making it hard to determine exact timing & potential cause(s).
- Here, we report on a calving and rifting event on the McMurdo (McM) Ice Shelf that fortuitously happened when/where multiple genres of observations were available to assess its causes.
- A better understanding of ice-shelf changes caused by brittle behaviour is required to more accurately predict future ice-shelf calving & breakup.

2. Field Area

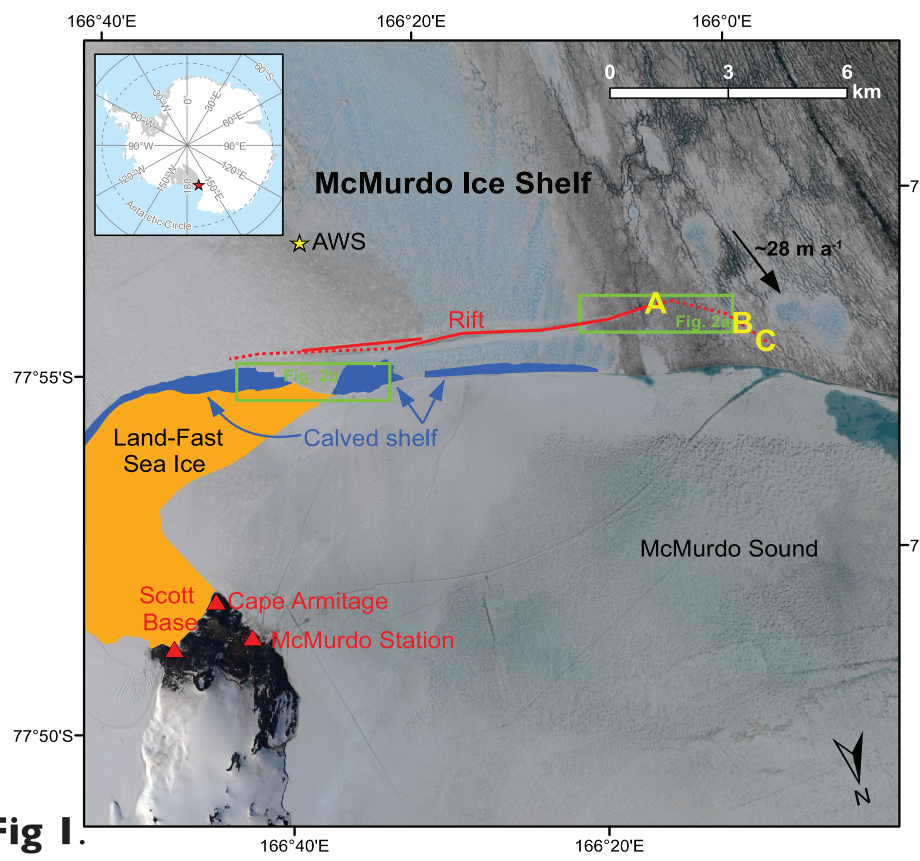

Fig 1.

3. Data

- **Satellite imagery** (Worldview 1 & 2, Landsat 8) used to determine spatial geometries of rifting/calving.
- **Ground-based camera imagery** (real time & time-lapse) to constrain calving timing & sea swell periodicity.
- **Broadband seismometer data** from the NZ Scott Base 'SBA' Station (1 Hz sample rate vertical channel) to analyse sea-swell.
- **Automatic weather station** (AWS) data from <4 km away (Fig. 1).
- **Ground-based survey** (on foot) of the propagated rift.

4. Chronology of Events

- **Jan/Feb 2016**: Fast ice in McM Sound began breaking up & drifted northwards; the largest change in sea-ice conditons prior to main calving/rifting event (2 Mar).
- **1 Mar 2016**: Small area of fast ice in narrow bight near Cape Armitage broke-out (yellow area, Fig 1).
- **2 Mar 2016**: Tabular icebergs calved from the McM Ice Sheet (blue areas, Fig. 1) & an ice-front parallel rift that had been static for >4 years, widened and lengthened westward by >3 km (dotted red line, Fig.1). This rift extension narrows to a point of un-rifted ice, ~1 km from the ice front, preventing the complete detatchment of a 14 km^2 iceberg.

5. Analysis: *Satellite Imagery:*

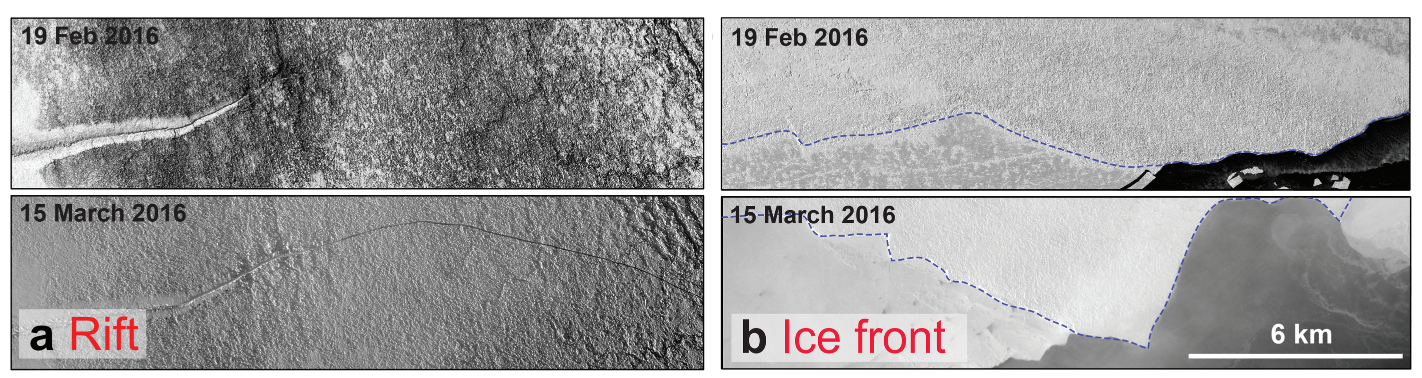

Fig. 2: Worldview-2 imagery **before and after calving/rifting** on 2 Feb 2016 of: **a) the rift**, and **b) the ice front** (see Fig. 1 for image locations). (a) Shows the rift extension to a terminus beyond the right-hand edge of the frame; (b) shows the change in ice front position (blue dashed line) due to calving.

Ground Survey of the Rift:

Fig 3. The rift extension on 10 Nov. 2016 (~8 months after it opened). (a) Here the rift was ~11 m wide & snow-filled (Fig. 1, loc. A). (b) 1.5 km W of a), the rift was ~3 m wide, & where it was not snow-filled, the rift side freeboard was ~2 m (consistent with ~20 m ice thickness) & showed little lateral displacement (Fig. 1, loc. B). Icicles draping the rift's sides may indicate a breached active sub-surface water system during rifting. (c) 500 m NW of b), the rift was only ~0.2 m wide & ~0.4 m deep (Fig. 1, loc. C).

Ground-Based Camera Imagery:

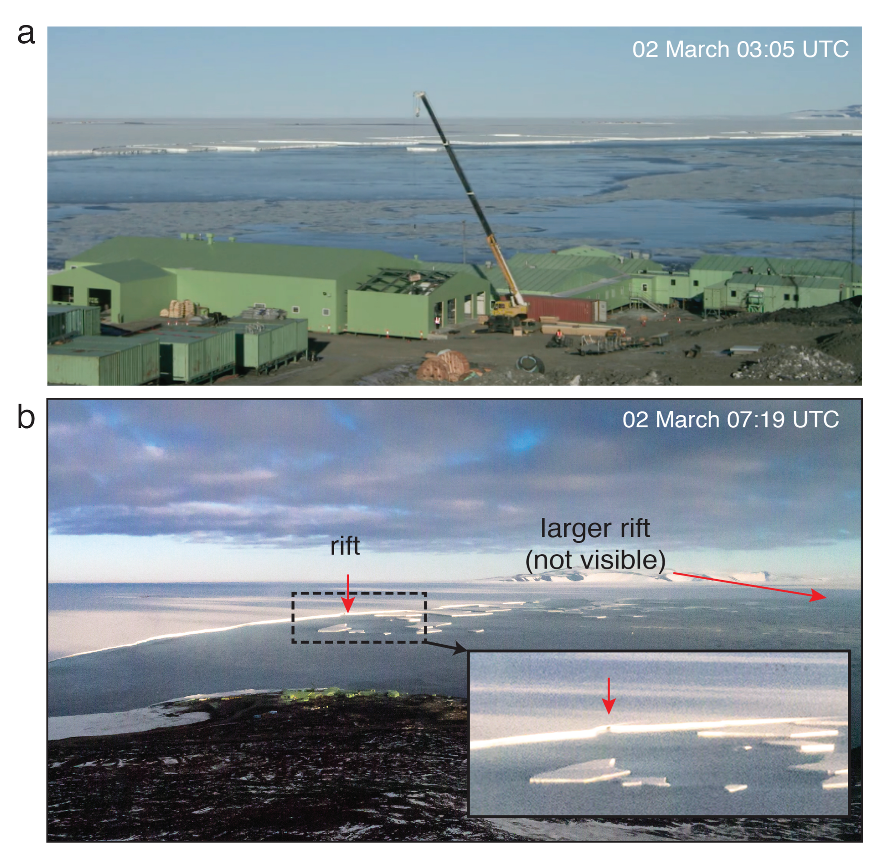

Fig. 4. Tabular icebergs seconds (a) & 4 hours (b) after the McM Ice Shelf calved, SE of Scott Base (green buildings). (a) A still from the video: Frozen South: ice breakout" by A. Powell. (b) Taken ~200 m above Scott Base & shows a remnant rift (vertical red arrow) intersecting the ice front that failed to fully detach any icebergs. The large rift that this study focusses on is not visible (its relative location is shown by the horizontal red arrow.)

Sea Swell (viewed by seismometer):

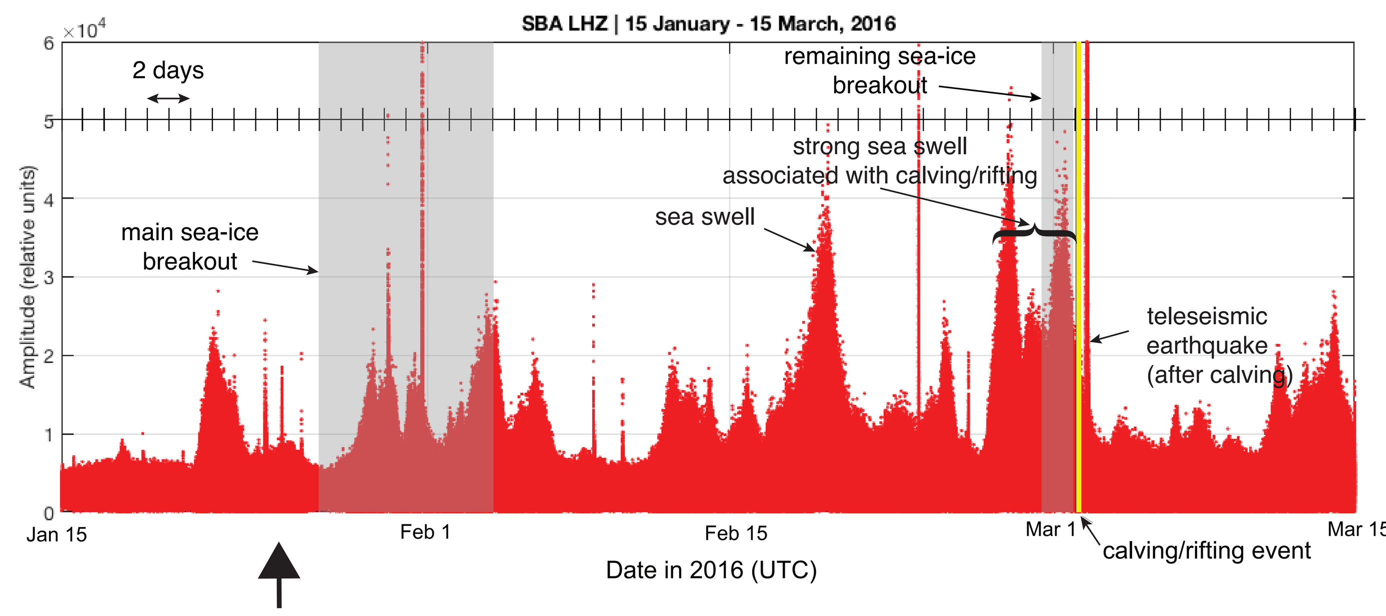

Fig. 5: Seismometer signal amplitude envelope from SBA (Scott Base), from 15 Jan - 15 Mar 2016. Broad zones of increased amplitude are caused by sea-swell associated microseism. Sharp, high-amplitude spikes are teleseismic earthquakes. Note the double-peaked high amplitude sea-swell event immediately before the calving/rifting event (yellow line).

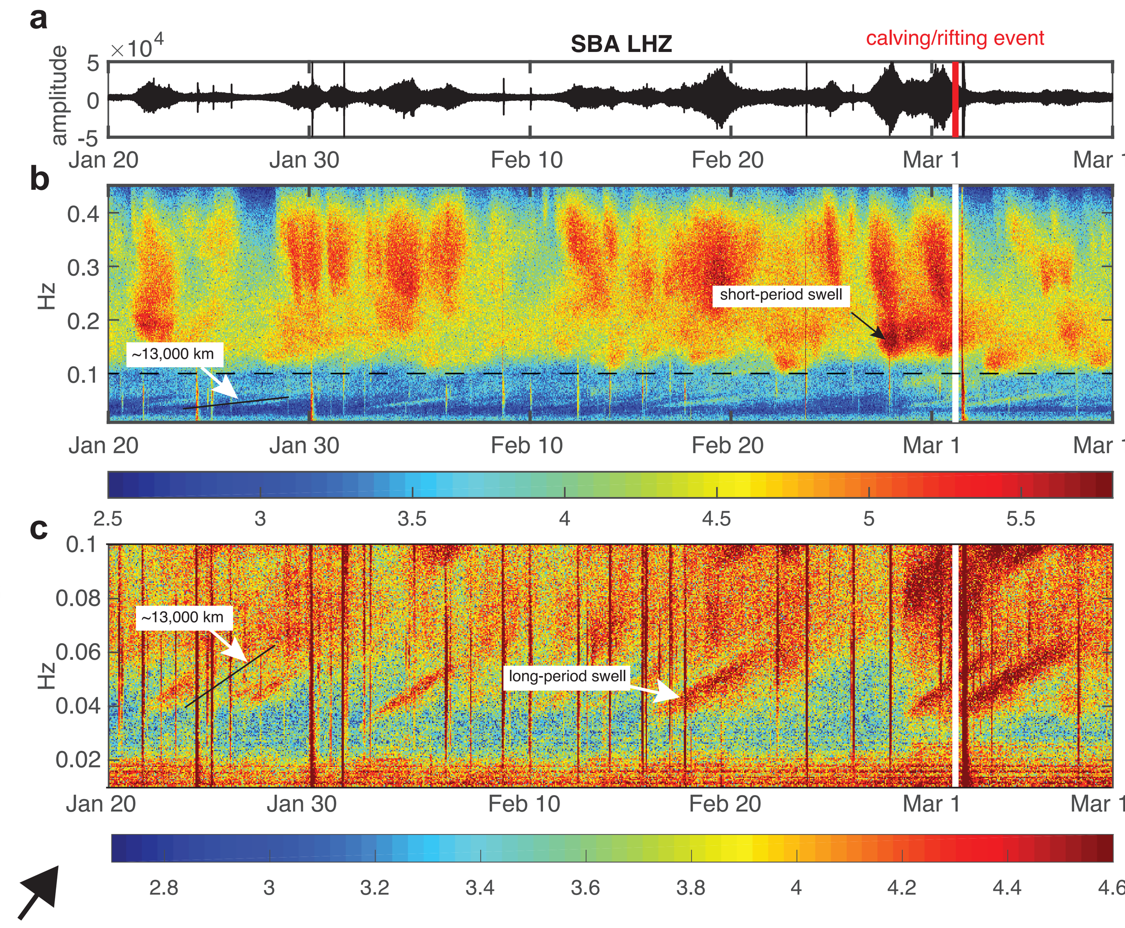

Fig. 6: Seismogram of (a) vertical displacement (units: relative amp.), & **spectrograms for the (b) 0.01 - 0.45 & (c) 0.01 - 0.10 Hz bands** (units: log amp. squared per sec.) from SBA. In (b), energy >0.10 Hz is caused by local short-period sea swell, is mostly broadband & un-dispersed, with sudden onsets likely due to local weather. In (c), swaths of energy (deep red coloured areas that tilt from lower left to upper right) indicate arrival of dispersed, long-period, sea swell. All sea swell arrivals in (c) have dispersion slope df/dt, where f = frequency & t = time, associated with storm centres ~13,000 km (slope indicated by black line) from McM Sound, placeing the source in the Gulf of Alaska. Both long- & short/medium-period sea-swell is very intense in the 4 days before the calving/rifting (white line).

Sea Swell (viewed by video):

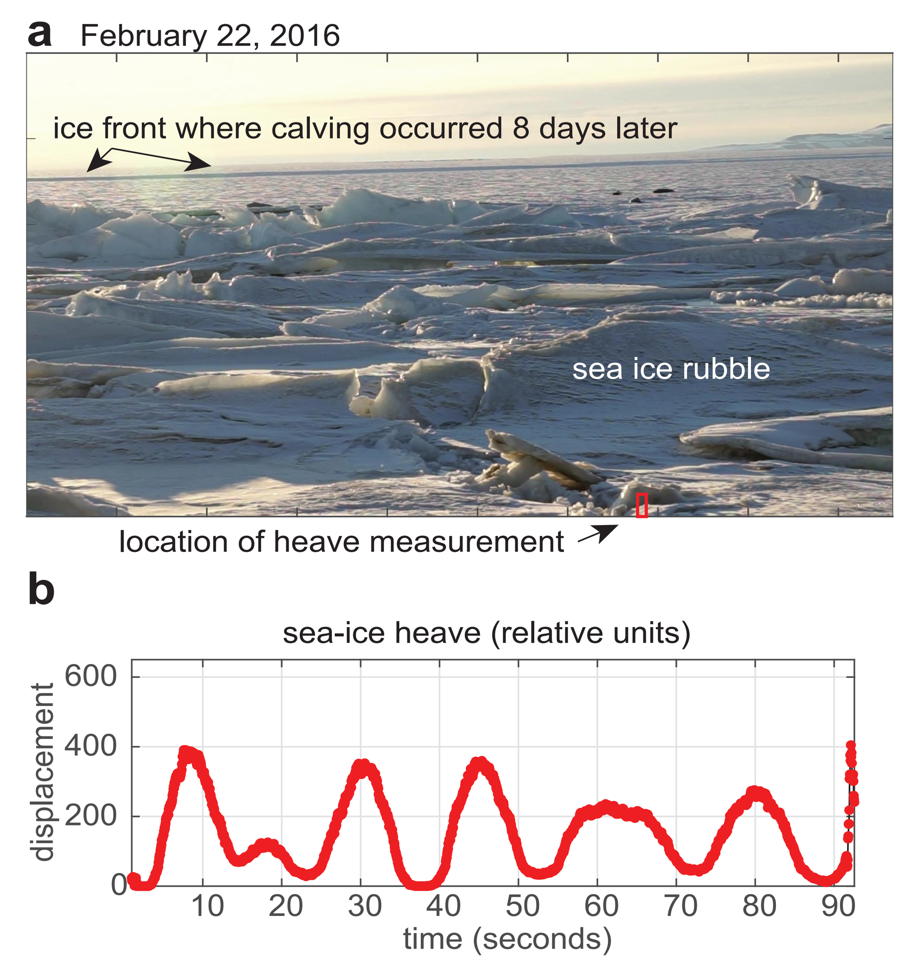

Fig. 7. Analysis of sea-ice heave (up & down motion driven by sea swell) along the shore of Scott Base on 22 Feb 2016, ~8 days before the calving/rifting. **(a) Single video frame** (25 frame per sec.); **(b) Inferred vertical motion of sea-ice particle** indicated by red box in (a), suggesting a periodicity of 15 - 20 s, consistent with the long-period swell identified in Fig. 6.

AWS data:

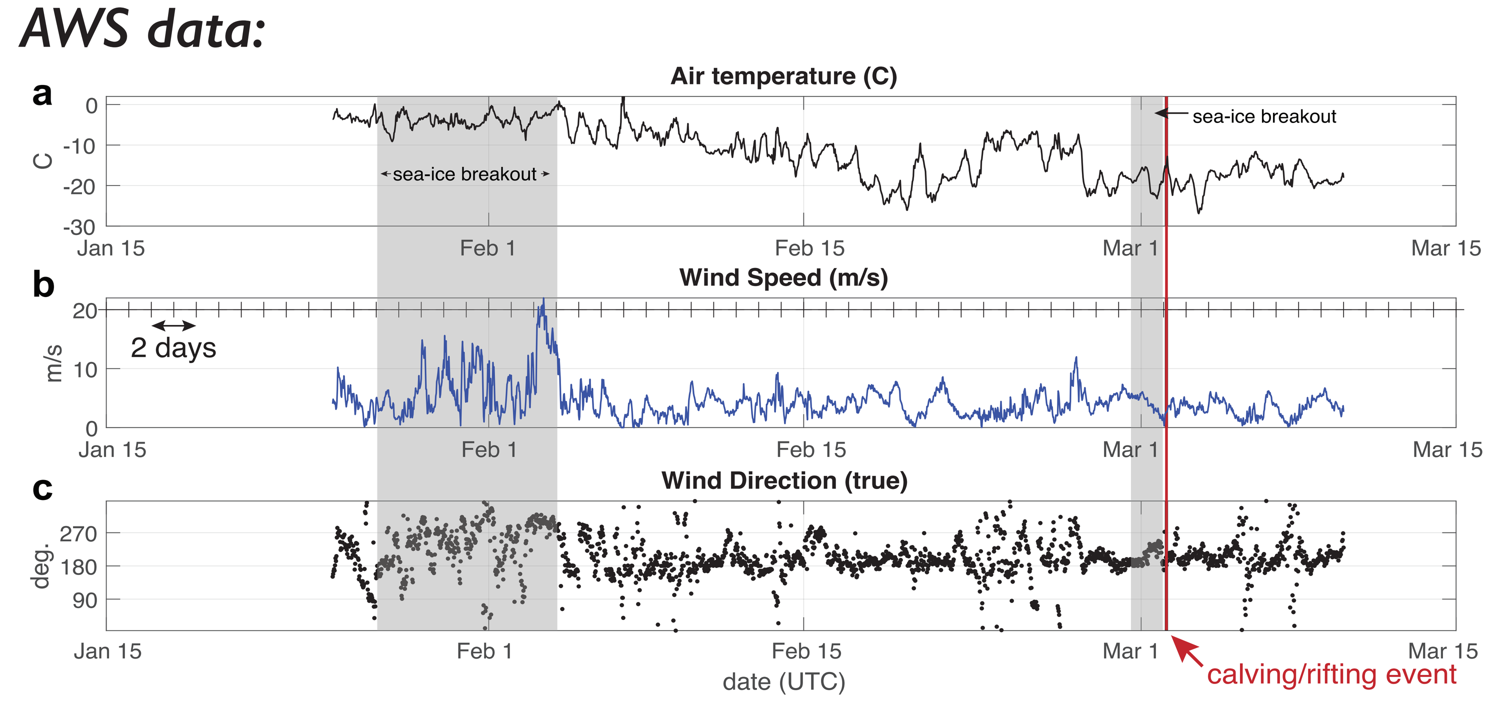

Fig. 8: a) Temperature; b) wind speed; c) wind direction from 15 Jan - 15 Mar 2016. Vertical grey shading shows periods of fast ice breakout. Strong winds may have contributed to the first phase of sea-ice breakout, but the second breakout event on 1 Mar (immediately before the main calving/rifting; red line) occured during low wind speeds & cold temperatures.

6. Proposed Cause of Calving/Rifting

- Of all the environmental conditions documented prior to the calving/rifting event, the one that shows the greatest change around the time of the event is the high sea swell recorded by the SBA seismometer & ground-based cameras near Scott Base. The alternatives (presence or absence of fast ice, melting at the ice shelf's surface or base, glaciological stresses, wind conditions) do not show extraordinary change or development over the days leading up to, and during, the calving/rifting event on 2 March 2016.
- Therefore, we suggest that the 4-day period of high amplitude (short/medium- & long-period) sea swell in McM Sound *first* caused the remnant sea ice to breakout on 1 March, which removed any stabilizing effect to the ice front from the sea ice. And *second*, it introduced elastic flexure to the ice shelf itself, fatiguing & weakening it, which ultimately caused the calving of tabular icebergs & rifting on 2 March.

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