Ice Shelf Calving due to Shear Stresses: Observing the Response of Brunt Ice Shelf and Halloween Crack to Iceberg Calving using ICESat-2 Laser Altimetry, Satellite Imagery, and Ice Flow Models

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Abstract. ~~Ice shelves influence the mass balance of the Antarctic Ice Sheet by restricting the flow of ice across the grounding zone. Their ability to restrict ice flow is sensitive to changes in their extent or thickness. Full thickness~~ Full thickness ice shelf fractures, known as rifts, create tabular icebergs ~~which~~ that can reduce ice shelf extent ~~. We present a method for measuring rift width~~ and thereby jeopardize overall marine ice sheet stability. Low confidence in the scientific understanding of ice shelf calving processes results in uncertainties in ice sheet evolution. Here, we investigate rift evolution and calving on the Brunt Ice Shelf, East Antarctica, using ICESat-2 laser altimetry, ~~as part of a larger effort to detect, catalog and measure various characteristics of Antarctic rifts. We validate the results using optical satellite imagery and data from Global Navigation Satellite System (GNSS) receivers around “Halloween Crack” on~~ ground-based geodesy, satellite imagery, and ice flow models. We find that shear stresses played a decisive role in rift propagation, widening, calving, and stabilization during the period surrounding the calving of Iceberg A-74 from the North Rift on the Brunt Ice Shelf~~, East Antarctica. During the study period a further rift, “North Rift ” formed and rapidly calved a ∼1270 iceberg. In response to this second rift, the opening of Halloween Crack approached stagnation before returning to opening at a reduced rate. We suggest the opening rate is controlled by the ice shelf geometry and degree of contact with a pinning point at~~ . The North Rift propagated along a fracture path that was optimally oriented to maximize shear stresses. Following the calving of A-74, reduced contact with local pinning points at the McDonald Ice Rumples ~~, and its influence on the large-scale ice flow field. We replicate the general pattern of opening using an inverse finite element model, and discuss the response of~~ reduced shear stresses and the ~~ice shelf to the calving~~ opening rate of the Halloween Crack, an inboard rift. We use the historical record to investigate the calving cycle and demonstrate that the calving of Iceberg A-74 closely mimics previous calving events. Shear stresses likely play a role in tabular iceberg calving events on other ice shelves. Yet horizontal shear stresses are in the null space of most ice shelf calving laws. We propose modifications to widely used calving laws that improve their sensitivity to the shearing mode of fracture. ~~We use historical satellite imagery and previously published ice-front positions to demonstrate the importance of McDonald Ice Rumples to the long-term calving and advance cycle of Brunt Ice Shelf.~~

1 Introduction

The Antarctic Ice Sheet gains mass through the accumulation of snowfall and loses mass primarily where it comes into contact with the ocean. Floating ice shelves fringe 75 % of the ice sheet margin (Rignot et al., 2013), buttressing the flow of ice streams inland (Dupont and Alley, 2005; Fürst et al., 2016) due to flow resistance at lateral boundaries, ice rises and ice rumples (Matsuoka et al., 2015). Ice shelves gain mass through the flow of ice across the grounding zone, snowfall, and potentially basal accretion, and lose mass through basal melting and iceberg calving. These mass loss processes occur in roughly equal proportions at the continental scale, but vary strongly regionally (Rignot et al., 2013; Depoorter et al., 2013; Greene et al., 2022). Where mass losses exceed mass gains, ice shelves retreat and/or thin, ~~reducing buttressing and increasing the~~ with modeling suggesting these processes have resulted in similar reductions in ice shelf buttressing (Greene et al., 2022). If the ice lost was providing buttressing the flow speed of grounded ice ~~(Scambos et al., 2004; Rott et al., 2011; Joughin et al., 2021; MacGregor et al., 2012; Pritchard e~~ will increase (Fürst et al., 2016; Reese et al., 2018; Rott et al., 2011; Joughin et al., 2021; MacGregor et al., 2012; Pritchard et al., 2012; M . Ice shelves thus exert a key control on Antarctic Ice Sheet mass balance and global sea level variations (Fox-Kemper et al., 2021). Radar altimetry satellites have been used to map ice shelf topography and monitor thickness changes (Paolo et al., 2015; Zwally et al., 2005), however, their coarse spatial resolution has restricted their use for examining processes occurring at smaller scales. Only with the launch of the first Ice, Cloud and Land Elevation Satellite (ICESat) laser altimeter was satellite altimetry applied to the study of the rifting and iceberg calving process (Fricker et al., 2005a).

Rifts are full thickness fractures through ice shelves which often form in ice shelf margins, the grounding zone, at the ~~calving~~ ice front, or near ice rises and ice rumples (Benn et al., 2007). A range of factors influencing rift propagation have been identified, including glaciological stresses (Walker et al., 2013; Joughin and MacAyeal, 2005; Hulbe et al., 2010; Bassis et al., 2005, 2007, 2008; Heeszel et al., 2014; Lipovsky, 2020; Olinger et al., 2022), the thickness and mechanical strength of ice mélange within rifts (Fricker et al., 2005b; Larour et al., 2004, 2021; MacAyeal et al., 1998; Rignot and MacAyeal, 1998), heterogeneity of ice properties and the presence of marine ice (Borstad et al., 2017; McGrath et al., 2014; Kulessa et al., 2014) , sea surface slopes driven by large-scale atmospheric conditions (Francis et al., 2021, 2022; Christie et al., 2022) or tides (Olinger et al., 2019), ocean waves and the concentration of protective sea ice (Massom et al., 2018; Christie et al., 2022; Cathles IV et al., 2009; Aster et al., 2021; Bromirski et al., 2010; Bromirski and Stephen, 2012; MacAyeal et al., 2006; Banwell et al., 2017; Lipovsky, 2018), and Tsunami-generated swell (Walker et al., 2015, 2013; Brunt et al., 2011).

Walker et al. (2013) used moderate resolution satellite imagery to observe 78 rifts around the Antarctic continent between 2002 and 2012, finding a spectrum of decadal behavior from complete dormancy, through intermittent or sudden bursts of extension, to continuous activity. Detailed *in situ* and remote sensing studies of individual rifts or small numbers of rifts suggest that propagation occurs as episodic short bursts lasting seconds ~~(Banwell et al., 2017)~~ (Banwell et al., 2017; Olinger et al., 2024) to hours (Bassis et al., 2005, 2007), with opening widths increasing steadily (Joughin and MacAyeal, 2005). Propagation is often arrested or slowed at suture zones, where fracture toughness can be higher (Borstad et al., 2017; Hulbe et al., 2010; Bassis et al., 2007). Once rifts propagate sufficiently to intersect the ice shelf front or other rifts, tabular iceberg calving occurs. Ice shelves typically exhibit "calving cycles", with long periods of advance separating sequential large calving events (Fricker et al., 2002;

Wang et al., 2022; Cheng et al., 2021a; Giles, 2017). Although the calving cycle is commonly envisioned as a steady-state process on decadal timescales (Greene et al., 2022), recent studies have examined the degradation of regular calving cycles and the associated loss of grounded ice mass (Joughin et al., 2021). ~~Greene et al. (2022) showed that since 1997 Antarctic ice shelves have exhibited comparable net ice losses due to calving (5,874 ± 396) and basal melt (6,113 ± 452), with modeling suggesting this resulted in similar reductions in ice shelf buttressing.~~

Launched in 2018, NASA's Ice, Cloud and Land Elevation Satellite-2 (ICESat-2) carries the Advanced Topographic Laser Altimeter System (ATLAS), a photon counting laser altimeter (see Sect. 3.1) which provides both extensive spatial coverage and fine spatial resolution (Markus et al., 2017; Abdalati et al., 2010). ICESat-2 is able to measure rift width and other parameters in the vertical dimension such as ice mélange thickness, ~~seaward-landward offset (Walker and Gardner, 2019) and~~ rift flank topography (Walker et al., 2021; Fricker et al., 2005a) ~~.~~ and the offset between rift flank height on opposite sides of the rift resulting from asymmetric buoyancy forces on a rift deviating by 1-5° from vertical (i.e. "seaward-landward offset", Walker and Gardner, 2
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In this paper we describe the measurement of a time series of rift widths using ICESat-2 laser altimetry, and validation using other remote-sensing and field-based datasets, using "Halloween Crack" (HC) on Brunt Ice Shelf (BIS), East Antarctica as a case study (Fig. 1). We observe changes in the ice shelf flow field and changes in rift behavior following calving from "North Rift" (NR), which we investigate using remote sensing data and a finite element ice flow model. We place these contemporary changes in a long-term perspective by examining the calving cycle at BIS using historical remote sensing data and published observations.

2 Study area

~~BIS (~~The Brunt Ice Shelf (BIS, 75.3° S to 75.8° S, 24.0° W to 27.0° W), drains ice from Coats Land, East Antarctica into the Weddell Sea (Fig. 1). Ice blocks which detach in the steeply sloping grounding zone are bound together by sea ice channels which become increasingly filled by snow and firn as the ice advects through the shelf (King et al., 2018; Fretwell et al., 2013). Ice blocks from grounding zone troughs are thicker and more closely packed than from adjacent shallower, slower flowing areas (King et al., 2018). ~~The ice shelf is grounded on a~~ There is a prominent bathymetric high point called McDonald Ice Rumples (MIR) ~~,~~ located at 75.44° S, 26.3° W. This exerts a strong control on the spatial pattern of present ice flow (Figs. 1 and S1), past and ongoing ice flow variability ~~(Gudmundsson et al., 2017; De Rydt et al., 2018, 2019)~~ (Gudmundsson et al., 2017; De Rydt et al., 2018, 2019; Marsh et al., 2024) and stresses within the ice shelf (De Rydt et al., 2019).

The earliest observations of BIS date back to the 1914/15 voyage of HMS *Endurance*, thus capturing the entire calving cycle (~~Fig~~Figs. 2 and 3), albeit with low temporal resolution prior to the satellite period. In 1971 BIS calved back to a number of large rifts which had formed in 1968 (Thomas, 1973; Gudmundsson et al., 2017). Measurements from across BIS show almost a doubling in ice flow velocity in the 1970s, which was sustained through the 1980s and 1990s. More recent GPS measurements

Figure 1. Key glaciological features of Brunt Ice Shelf, instrument locations and ICESat-2 ground tracks. (**a**) Landsat-8 image from 2020-02-20 showing Chasm 1, Halloween Crack (HC) and North Rift (NR) in solid red lines; McDonald Ice Rumples (MIR); the grounding zone (Bindschadler et al., 2011) with a dashed red line; Halley VI station with red star; GNSS receivers with gray squares, flow direction and magnitude with arrows; extent of c and d with dashed boxes; ICESat-2 reference ground track (RGT) with green lines. Inset shows the location of Brunt Ice Shelf in East Antarctica (Data from the SCAR Antarctic Digital Database, accessed 2023). (**b**) ~~Surface~~ Composite surface flow speed field (Gardner et al., 2018, 2020). Note the impact on the flow field of the pinning point at McDonald Ice Rumples (enlarged in inset). (**c**) Section of the ice shelf near the western end of HC, showing the location of the six beams (three pairs) of ICESat-2 passes along RGT 215, RGT 1160 and RGT 786. The dashed box shows the extent of Fig. 4f. (**d**) Section of the ice shelf near the eastern end of HC, showing ICESat-2 passes along RGT 283, RGT 725 and RGT 1099. Beam colors in c and d correspond to graphs in Figs. 5, 6 and 7. Colored points show the movement of the GNSS receivers through the deployment. Projection is Antarctic Polar Stereographic (EPSG: 3031).

show the velocity decreasing through the 2000s, reaching pre-1970s levels by ∼2010, with a further period of acceleration starting in 2012 (Simmons and Rouse, 1984; Gudmundsson et al., 2017). Gudmundsson et al. (2017) ~~modelled the impact on ice flow velocity on~~ modeled the ice flow response to the opening of a rift between BIS and adjacent Stancomb-Wills Ice Tongue (SWIT), the opening of the dormant Chasm 1 rift which had formed in the grounding zone in the 1970s (De Rydt et al., 2018, 2019), and the loss of contact with MIR following the 1971 calving. The closest match to the observed magnitude and pattern of velocity increase resulted from the simulated loss of mechanical contact between BIS and the pinning point at MIR. Over the next three decades the ice shelf gradually re-advanced, and by ∼1997 buttressing from MIR was sufficient for velocities to begin to decrease (Gudmundsson et al., 2017; De Rydt et al., 2018). The reorganization of internal stresses resulting from the increase in buttressing from MIR resulted in the reactivation of Chasm 1 rift, potentially explaining the increase in velocity after 2012 (Gudmundsson et al., 2017).

Here, we focus on three active rifts that have resulted in two tabular iceberg calving events. The first major rift is the Chasm 1 rift, described above. A second major rift, Halloween Crack (HC), formed in October 2016, in a similar location to the rift from which the 1971 iceberg calved (Thomas, 1973; De Rydt et al., 2018). HC ~~propagated in both directions~~ initiated from a point approximately 15 km east of MIR, and propagated in both a westerly direction toward MIR and an easterly direction towards SWIT, slowing where it encountered thicker ice originating from the grounding zone troughs (De Rydt et al., 2018; King et al., 2018). A third major rift, North Rift (NR), seaward of HC, was observed to be propagating in November 2020 (British Antarctic Survey Press Office, 2021), resulting in the calving of a ∼1270 km^2 iceberg (A-74) ~~in February 2021~~ on 2021-02-26 (Francis et al., 2022; Libert et al., 2022; Cheng et al., 2021b; British Antarctic Survey Press Office, 2021). A further ∼~~1550~~1500 km^2 iceberg (A-81) calved from Chasm 1 on ~~2023-01-23 (British Antarctic Survey Press Office, 2023; U. S. National Ice Center, 2023).~~ 2023-01-22 (Marsh et al., 2024; British Antarctic Survey Press Office, 2023; U. S. National Ice Center, 2023), resulting in a reduction in buttressing at MIR and a rapid acceleration in flow speed (Marsh et al., 2024). HC would ultimately calve a ∼380 km^2 iceberg (A-83) on 2024-05-20 (British Antarctic Survey Press Office, 2024; U. S. National Ice Center, 2024). BIS has thus exhibited a cycle of rifting and calving, accompanied by dynamic changes related to the degree of buttressing provided

Figure 2. Calving (**a**) Ice front position of BIS and SWIT since between 1914, showing cyclic rifting /15 and calving east of MIR2023 from satellite imagery and Thomas (1973). (**ab**) The 2020 front (Landsat-8 image) compared to the 1914/15 (red) position from HMS *Endurance* (digitized from Thomas, 1973). Inset Dashed box shows the calving front positions location of the wider area between 1914/15 and 2023. (imagery subsets in Fig. 3**b**-**i**. (**c**) Iceberg calving (A-74) from NR and HC position in February 2021 (Copernicus Sentinel-2 data [2021]), compared to 1967/68 front (blue), rift (dashed black) and area which calved in 1971 (dashed blue) (all digitized from Thomas, 1973)). White area shows parts of the 1967/68 shelf composed of sea ice. Blue arrow shows a potential partial rift. (**ed**) Iceberg calving (A-81) from Chasm 1 on 2023-01-23 2023-01-22 (Copernicus Sentinel-2 data [2023]).(**d**) Part of an aerial photograph from 1969 looking north towards MIR, showing the rift which calved in 1971. (**e–l**) Landsat-1 to Landsat-9 and Sentinel-2 imagery of BIS in the vicinity of MIR between 1973 and 2023, showing the re-advance east of MIR and subsequent calving. Dashed red and blue boxes in l show the extent of m–p and q–t respectively. (**m–p**) Propagation and opening of Chasm 1 and a smaller frontal rift leading to the calving of iceberg A-81. (**q–t**) The accumulation of damage upstream of MIR to the nascent iceberg between HC and the ice front following calving from NR. Points in t show the path of the western tip of HC between 2020 and 2023.

Figure 3. Time series of BIS geometry in the vicinity of MIR between 1969 and 2023 from aerial and satellite imagery. (**a**) Part of an aerial photograph from 1969 looking north towards MIR, showing the rift which calved in 1971. (**b–i**) Landsat-1 to Landsat-9 and Sentinel-2 imagery of BIS in the vicinity of MIR between 1973 and 2023, showing the re-advance east of MIR and subsequent calving.

by MIR (Gudmundsson et al., 2017; De Rydt et al., 2019). A further calving event may occur as a result of the propagation of HC. This will determine the immediate (Gudmundsson et al., 2017; De Rydt et al., 2019; Marsh et al., 2024). The future of BIS , dependent on may now be dependent on whether the remainder of the level of contact maintained with MIR following the calving, and the response of the remaining ice shelf to potential unpinning (Hodgson et al., 2019; De Rydt et al., 2019). ice shelf can re-establish contact with the bathymetric high point at MIR. (Marsh et al., 2024; Hodgson et al., 2019).

3 Data and Methods

3.1 ICESat-2 Data and Rift Catalog

ICESat-2 is a photon counting laser altimetry satellite with an orbital inclination of 92° (allowing data collection to 88° S and full coverage of Antarctic ice shelves), and an orbital repeat cycle of 91 days. The platform carries the ATLAS instrument, star trackers and an inertial measurement unit for pointing determination, and GPS receivers for positioning (Neumann et al., 2019). ATLAS is a photon counting laser altimeter designed to overcome the limitations of ICESat (Abdalati et al., 2010; Markus et al., 2017). It splits the transmitted 532 nm laser pulses into 6 beams (are split into 3 pairs), increasing spatial coverage and allowing calculation of across track slopebeam pairs. Each beam pair consists of a strong beam and weak beam separated by 90 m. One beam pair is at satellite nadir, the other pairs are 3.3 km to each side(Markus et al., 2017). Each beam pair consists of a strong beam and weak beam (with one quarter the energy) separated by 90 . The platform pointing is maintained such that one beam in each pair is either side of a 'Reference Ground Track' , requiring pointing precision better than 45 (Markus et al., 2017).

Telemetered data include platform positioning, pointing, and individual photon time of flight (ATL02), from which the three dimensional reflection point of individual photons can be calculated (latitude, longitude, height above ellipsoid). The ATL03 product is a point cloud of individual classified signal and background photon detections (Neumann et al., 2019). The (Markus et al., 2017). The ATL06 land ice elevation product (ATL06) takes 40 m along-track segments of ATL03 (photon detections (ATL03), spaced 20 m apart) and , fits a surface to signal photons, iteratively rejecting background photons. Each segment is assigned the elevation of the surface at the segment center (Smith et al., 2019). ATL06 greatly reduces data volume whilst maintaining sufficient detail for rift detection and measurement (Wang et al., 2021, Fig. 1c).

and calculates the segment elevation (Smith et al., 2019; Neumann et al., 2019). ICESat-2 data can supplement optical satellite imagery to provide year-round and ice-sheet-wide observations of the ice surface limited only by the presence of cloud cover. For example, it has been used previously to study crevassing, rifting riftings and calving (Li et al., 2021; Walker et al., 2021; Wang et al., 2021; Becker et al., 2021). Of particular relevance, Wang et al. (2021) automated fracture detection in ICESat-2 , with the ATL06 data by iteratively identifying low points and simulating filling them with water, until no further depressions could be found, then building a hierarchical structure linking depressions nested across multiple scales, and working top-down to identify individual fractures which satisfy specified criteriaproduct maintaining sufficient detail for rift detection and measurement (Fig. 1c of Wang et al., 2021).

The cataloging of rifts is a two step process: firstly identifying potential rifts, and secondly measuring various characteristics such as width (Fig. 4), ice mélange thickness, seaward-landward offset (Walker and Gardner, 2019), and rift flank topography (Walker et al., 2021; Fricker et al., 2005a). Before embarking on this process, we first subsetted ATL06 data to BIS using the BedMachine Antarctica floating ice mask (Morlighem, 2020; Morlighem et al., 2020). Each beam was then filtered We found the ATL06 quality flags incompatible with our methodolgy, as (apparently) valid height measurements in the area of the rift were often flagged as low quality. Whilst we used the quality flags to skip beams containing a large proportion of low quality data, and to place confidence intervals of our rift detections, we developed a bespoke filtering algorithm. We experimented with different algorithms and found that filtering each beam of each satellite pass by discarding any ~4 km section with >20 % of measurements flagged as low qualityand , discarding unrealistic elevations (>100 m). Any beams with , and skipping the beam entirely if >3 % of along-track gaps between elevation measurements exceeding exceeded 25 m were also discardedproduced satisfactory results.

Potential rifts were identified using by applying a 10 km running mean to create the ATL06 data, creating a smoothed ice shelf surface, any elevations below . The running mean elevations were very similar to the measured elevations across flat portions of the ice shelf, but differed where the running mean smoothed out rifts. Any ATL06 elevation that was less than 50 % of this were identified as potential rifts (Fig. 4a)the corresponding running mean elevation was identified as potentially being within a rift. For each potential rift, defined as contiguous points below the 50 % threshold, an expanded search area was defined , (light red box in Fig. 4b) centered on the lowest point (point with the lowest elevation (red circle in Fig. 4b). Working outwards in both directions from this point (toward the seaward and landward rift walls), upward sloping regions (groups of ATL06 points continuously increasing elevations with increasing distance from the lowest elevation point, black lines in Fig. 4b) were identified. The probable rift walls (red line for landward wall in Fig. 4b) were identified as the first

Figure 4. Example rift detection and measurement along RGT 215 1L on 2021-01-07. (**a**) ICESat-2 ATL06 transect with potential rifts shown as light red bars. Dashed box around HC shows the extent of b and e. (**b**) Expanded search area (light red box) centered on the lowest point in the rift (red circle). The mostly likely rift wall (red) is selected from the possibilities (black). Dashed box shows the extent of c and d. (**c**) The steepest section of the rift wall (red line) is selected from measurements of slope along 200 m sections (gray lines). (**d**) The location of the rift wall (dashed red line) is defined as the average location of points in steepest section (red line). (**e**) The process is repeated for the opposite rift wall. (**f**) Rift detections (red circles) along the six beams of RGT 215 overlaid on a Landsat-8 image from the same day. The dashed line traces the manually-defined large-scale rift axis, which does not follow all small-scale variability in the rift, and is used to ~~estimate rift widths from~~ convert oblique measurements of apparent width in ICESat-2 RGT geometry to estimated rift width perpendicular to the large-scale rift axis. The same elevation colorbar is used throughout.

~~upward sloping region to exceed~~ upward sloping regions closest to the lowest point which met one of two criteria: 50 % of rift depth (relative to the running mean surface), or the ~~largest~~ upward sloping region with the largest elevation change within the search region if none ~~exceed~~ exceeded 50 %.

We ~~then~~ measured rift width using the following workflow~~:~~. First, the slope was calculated for ∼200 m sections centered on each ATL06 measurement along the probable rift wall (Fig. 4c), with the average location of ATL06 points making up the steepest slope taken to be representative of wall location (Fig. 4d). The apparent rift width is the distance between the two rift walls (Fig. 4e); this was converted to actual width according to the angular offset between the ground track and a plane perpendicular to the manually-defined large-scale rift axis (Fig. 4f). ~~Where the rift is bisected by a block (e.g. Figs. S7a–f~~Large icebergs or semi-detached ice blocks held in place by ice mélange occur at several locations along HC, originating from the initiation of rifting (Fig. S6). If an ICESat-2 beam passes over one of these *in situ* blocks, the rift will be divided into two closely spaced troughs (Figs. S8a–f, ~~S9d–i)~~S10d–k, ~~both the “wall-to-wall width” and “opening width” were cataloged (Fig. S4~~S11d–f, S12a–i, S13a–c). As validation of the workflow, ICESat-2-derived widths and opening rates were compared with measurements from digitized optical satellite imagery and the separation of GNSS receivers. To do so it is necessary to combine the measured widths of the two troughs where the rift is bisected by a block. In this case, we catalogue both the “opening width”, the sum of the two troughs of the bisected rift, equal to the distance the rift has opened and hence appropriate for comparison with the separation of GNSS receivers and the “wall-to-wall” width, the total distance from the most landward wall to the most seaward wall of the rift (Fig. S5).

3.2 Satellite Imagery

We examined Landsat-8, Landsat-9 and MAXAR WorldView-1-3 optical satellite imagery of HC during cloud-free days in Austral summer. Forty nine Landsat-8 and Landsat-9 images covered the entirety of HC (Table S5), 20 WorldView-1-3 images covered western HC (Table S1), and 18 covered eastern HC (Table S2). Relevant ~~RGTs~~ ICESat-2 Reference Ground Tracks (RGTs) were overlain on the satellite imagery in QGIS, and rift width measured using the “measure” tool. Opening widths were calculated and apparent widths converted to actual widths in the same way as the ICESat-2 measurements. Digitization error was assumed to be two pixels ~~for~~ (60 m for Landsat, 1 m for WorldView) for each wall, meaning a greater error where the rift is bisected by a block.

We also used Landsat-1, Landsat-5, Landsat-7, Landsat-8, Landsat-9 and Sentinel-2 satellite imagery spanning half a century, combined with historical aerial photographs, and digitized ~~calving~~ ice front and rift positions from Thomas (1973) to provide context for recent rifting events and to investigate the long-term behavior of BIS, updating the record of Anderson et al. (2014). The three oldest ice front positions (all from Thomas, 1973) are from 1914/15 (red line in Fig. 2a and b; from Shackleton's HMS *Endurance* expedition), 1955 (green line in Fig. 2a; from Argentine icebreaker *General San Martín*), and 1967/68 (blue line in Fig. 2a and c; combined ship and field data). We supplement these with ice front positions from 2020, 2021 and 2023 (orange, yellow and magenta lines respectively in Fig. 2a; from Landsat-8 and Sentinel-2 imagery), book-ending the calving of a ∼1270 km^2 iceberg from NR in February 2021 (Francis et al., 2022; Libert et al., 2022; Cheng et al., 2021b; British Antarctic Survey Pre , and a ∼1500 km^2 iceberg from Chasm 1 in January 2023 (Marsh et al., 2024; British Antarctic Survey Press Office, 2023; U. S. National I .

3.3 Global Navigation Satellite System

The British Antarctic Survey ~~maintain~~ operated a network of Leica GS-10 GNSS receivers both landward and seaward of HC to monitor its growth between 2017 and 2024 (Figs. 1, ~~S2 and~~ S3 and S4). These ~~record~~ recorded at 30 second intervals for two hours each day between 14:00 and 16:00 UTC. Daily averaged positions ~~are~~ were calculated using precise point positioning. Receivers tt05 and hh00 (hereafter the "western pair") form a baseline approximately perpendicular to the rift axis and aligned with RGT 215 1LR and RGT 1160 3LR. RGT 786 2LR measures the same area of the rift, but is oblique to the rift-perpendicular plane (Fig. 1c). Likewise, the baseline between receivers tt04 and ss00 (the "eastern pair") is approximately aligned with RGT 283 1LR and RGT 725 3LR, and oblique to RGT 1099 2LR (Fig. 1d), with all somewhat oblique to the rift-perpendicular plane. This configuration provides an excellent dataset for validation of the workflow for measurement of apparent rift width and conversion to actual width.

Polar Stereographic coordinates representative of the positions of each GNSS receiver on 15th of each month were calculated by ~~fitting lines of best fit to~~ linear regression of points in any month with >15 daily positions. Time series of monthly GNSS separation were then calculated for each GNSS pair, and the angle of the monthly baseline used to calculate the rift-perpendicular component. Finally, an estimate for the rate of rift-perpendicular ice divergence was calculated by extracting the velocity components at the mean locations of the GNSS receivers from a pre-HC initiation (2015) velocity map (Gardner et al., 2018, 2020), and subtracted from the rift-perpendicular separation time series. This has the effect of removing residual horizontal strain within the intact ice shelf adjacent to the rift. This then provides a better approximation of the rift opening rate that would be measured by GNSS receivers placed close to the rift walls. This correction is however subject to any error in the underlying velocity product caused by, for example, the projection of tracked velocity down the steepest slope of the DEM used during processing.

3.4 ~~Ice Flow Model~~

~~We compare HC opening rates from the three datasets to opening rates calculated using modeled ice flow fields for three periods centred on the calving event from NR; labeled “pre-calving”, “calving” and “post-calving” inverse models (Table S8). We also examine the response of wider ice shelf flow field to the calving event. We use the Python-based finite element glacier and ice sheet flow modeling library *icepack*, and the *Firedrake* partial differential equation solver package on which it is built (Shapero et al., 2021; Rathgeber et al., 2016). *icepack* includes solvers for common glaciological modeling problems, including the shallow shelf approximation used here (“IceShelf” model class).~~

3.4 Velocity and ice thickness maps

We produced velocity fields using Sentinel-1 image pairs, assuming a constant velocity error of 5 ma^{-1} in the X and Y directions. We produced a new thickness map from ICESat-2 and smoothed it in *icepack*. We ~~produce modeled velocity and fluidity fields using an inverse model which takes as inputs an initial-guess velocity field and a smoothed ice shelf thickness map. We also use these output velocity and fluidity fields as inputs to additional model runs to investigate the relative importance of geometry, velocity and fluidity changes. We~~ used the co-registration and offset tracking functions of the SeNtinel Applications Platform (SNAP) to produce velocity fields from 12-day repeat Sentinel-1 SAR image pairs, then applied a 15–by–15 pixel averaging filter to suppress noise. The platform did not provide an error map, hence the assumed uniform 5 ma^{-1} error in the X and Y directions. The thickness map was produced using ICESat-2 SlideRule (Swinski et al., 2022) data and smoothed ~~using~~ in *icepack* (Shapero et al., 2021) to ensure sensible estimation of driving stress ~~. The~~ by minimising a function which penalises large deviations from the unfiltered thickness map and sharp oscillations over a distance of 2 km (See Supplementary text S4).

3.5 Ice Flow Model

We create ice flow models (Morris and Lipovsky, 2023) intended to capture the behavior of the BIS during three unique snapshots in time: approximately one-year prior to calving (“pre-calving”), one month surrounding calving (“propagation”), and nine months post-calving (“post-calving”). The exact time windows for these periods are listed in Table S8. For each time period, we determine the ice fluidity field using an inverse approach that takes as input the unique ice front position, rift geometry, and velocity field during that time period. We then used the inferred fluidity fields to examine a suite of models aimed at investigating the relative importance various factors control rift opening rates.

We modeled ice flow using *icepack*, an open source finite element implementation of the shallow shelf approximation (SSA) built in the *Firedrake* ecosystem (MacAyeal, 1989; Shapero et al., 2021; Rathgeber et al., 2016). The model domains were bound by the grounding line, MIR, ~~calving~~ ice fronts east and west of MIR, and a divide between BIS and SWIT defined by the extent of the observed velocity fields. We ~~define~~ digitised the extent of HC~~and other smaller fractures in the vicinity of MIR (including the narrow ,~~ , the narrow ∼13 km-long beginning of NR ~~in the “pre-calving” model), but not Chasm 1 (which consists of multiple~~ when present, and other smaller fractures in the vicinity of MIR using contemporaneous optical satellite imagery. These rifts were treated as holes in the mesh with Neumann-type boundary conditions. Chasm-1, which consisted of multiple smaller fractures and a large area of damaged ice and mélange~~), meaning it is~~ , was not specifically delineated, and hence was modeled as an area of ~~low~~ high fluidity. Ice flows into the domain across the grounding line, the grounding line of MIR, and the BIS/SWIT divide. ~~The inverse model is then used to~~

We use *icepack* to carry out a parameter inversion to estimate the fluidity coefficient A in Glen's flow law (Glen, 1955):

$$\dot{\epsilon}_{ij} = A\tau_E^{n-1}\tau_{ij} \quad (1)$$

where $n = 3$, $\dot{\epsilon}_{ij}$ and ~~τij~~ τ_{ij} are the strain rate and deviatoric stress tensors, and $\tau_E = \sqrt{\tau_{ij}\tau_{ij}/2}$ is the effective deviatoric stress. During inversion, ~~we iteratively alter~~ the fluidity field ~~until it produces~~ was iteratively refined until it produced a velocity field that ~~matches~~ matched the input within ~~a given tolerance (Shapero et al., 2021).~~ given tolerances (Shapero et al., 2021). We resampled the modeled velocity and fluidity fields onto regular grids. This allowed fields to be used interchangeably regardless of the advection of rifts with ice flow, or changes in calving front position between the three model periods. We used the *fill* tool in QGIS to interpolate across rifts and extrapolate beyond the calving front. We used the fluidity field from the pre-calving inverse model to test the impact of resampling and interpolation (Diagnostic$_1$ in Table S9).

The rate of ~~rift opening is~~ HC opening was calculated as the difference in the rift perpendicular components of velocity extracted from locations within the modeled velocity fields along the baselines between the two GNSS pairs, and 100 m from the rifts walls. We also examined the changes in the wider ice shelf flow field resulting from the calving event, and calculated and analysed the principal stress fields (See Supplementary text S5), updating the stress field records of De Rydt et al. (2019) beyond the calving from NR.

We carried out a set of experiments that only changed the ice shelf geometry (Diagnostic$_2$ to Diagnostic$_5$ in Table S9). These experiments captured the change to the ice shelf geometry due to the calving of iceberg A-74 while not allowing the fluidity field or boundary velocities to react to calving. We also carried out separate experiments where the growth of rifts was included or excluded from the ice shelf geometry, in order to isolate effects from this process. Similarly, we also carried out a set of experiments that updated the boundary velocities through the three stages but held the fluidity field fixed (Diagnostic$_6$ to Diagnostic$_9$ in Table S9). Finally, we ran each experiment (Diagnostic$_1$ to Diagnostic$_9$ in Table S9) twice, once each with a different initial guess ice rheology fields based entirely on spatially uniform ice temperatures of 253 K and 260 K. This was done in order to quantify the nonuniqueness of the inversion.

4 Results

4.1 Historical Behavior of Brunt Ice Shelf

~~We used Landsat and Sentinel-2 imagery spanning half a century, and digitized maps from Thomas (1973) to examine the~~

We analysed satellite imagery spanning half a century and digitized maps from Thomas (1973) to examine long-term ~~rifting and calving behavior and resultant ice front positions of BIS and SWIT, building on the record of Anderson et al. (2014). The three oldest ice front positions (all from Thomas (1973)) are from 1914/15 (red line in Fig. 2a and inset; from Shackleton's HMS *Endurance* expedition), 1955 (green line in Fig. 2 inset; from Argentine icebreaker *General San Martín*), and 1967/68 (blue line in Fig. 2b and inset; combined ship and field data). We supplement these with ice front positions from 2020, 2021~~

~~and 2023 (orange, yellow and magenta lines respectively in Fig. 2 inset; from Landsat-8 and Sentinel-2 imagery) , book-ending the calving of a ~1270 iceberg from NR in February 2021, and a ~1550 iceberg from Chasm 1 in January 2023. We~~ rifting and calving behavior and resultant ice front positions. We discuss changes in three areas: SWIT, BIS east of MIR (area of HC and NR), and BIS west of MIR (area of Chasm 1). The SWIT ice front was similarly advanced in 1914/15 and 2020/21, and ∼70 km landward in 1955 and 1967/68 (Fig. 2~~inset~~a). One or more large calving events from SWIT must have occurred between 1914/15 and 1955, and with the 2020/21 ice front close to the 1914/15 position, another may be expected in the coming decades. Between SWIT and MIR the 1914/15 BIS ice front is not as advanced as the 2020 ice front (Fig. 2~~a~~b) and in the vicinity of MIR is more comparable to the ice front in ∼2000 (e.g. Fig. ~~2g–h~~3d–e). The 1967/68 and 2021 ice fronts are largely the same, barring an area to the east where a small ~~area~~ part of the shelf was partially detached along a short fracture (blue arrow in Fig. 2~~b~~c). There is a gap in the 1955 ice front in this area, but Anderson et al. (2014) present a 1958 ice front and suggest no large calving events occurred between 1958 and 1967/68. In 1968 a rift formed in largely the same location as HC (white arrow in Fig. ~~2d~~ 3a and black dashed line in ~~b~~Fig. 2c, note HC visible in the satellite imagery). This calved in 1971 (Thomas, 1973), resulting in the most retreated ice front position observed (blue dashed line in Fig. 2~~b). Calving~~ c), until the calving of iceberg A-83 from HC in ~~the near future would result in a comparably~~ May 2024 (British Antarctic Survey Press Office, 2024; U. S. National Ice Center, 2024; Marsh et al., 2024) which resulted in a similarly retreated ice front position. To the west of MIR the 1914/15 ice front was more advanced than the 1967/68 ice front, ~~evincing~~ indicating a calving event sometime during this interval (Fig. 2a~~inset~~). The 2020/21 ice front was considerably more advanced than either of the previous observations, and the reactivation of Chasm 1 around 2012 (De Rydt et al., 2018, 2019) suggested calving was imminent. Chasm 1 and a smaller rift initiating from the damaged ice front immediately downstream of MIR propagated and widened through the early 2020s until a ∼~~1550~~1500 km^2 iceberg (A-81) calved on ~~2023-01-23 (Fig~~2023-01-22 (Figs. 2~~e, m–p).~~ d and S2).

4.2 Rift Measurement Algorithm Performance and ~~Halloween Crack Behavior~~Comparison

4.2.1 Rift Measurement Algorithm Performance

Our rift measurement algorithm ~~successfully produced 375~~ produced 380 measurements of HC width along 17 RGTs (Table 1, Fig. ~~S2). Five additional~~ S3), of which 375 were successful. Five measurements were underestimated by ∼100 m as a result of a block dividing the rift into two troughs and all ATL06 measurements ~~in one part~~ within the narrower trough being flagged as low quality. This occurs where the ICESat-2 beam passes close to the location where a semi-detached ice block maintains limited connection to the rift wall, or where part of a rotated iceberg is very close to the rift wall from which it has detached. This compares to 440 times HC could be identified manually in the ICESat-2 data (86 %). The percentage is higher at the center of HC, where the rift is widest, and decreases towards the rift tips (Table 1). The 60 times HC was not recorded were times the segment of the beam was not processed due to poor data quality, or elevation measurements along one or both rift walls did not satisfy a number of confidence criteria. Rift wall identifications were discarded if they contained fewer than three

Table 1. The number of times HC could be manually identified in ICESat-2 ATL06 data spanning 2018-10-14 to 2021-07-15, compared to the number of times it was found and measured by the rift detection and measurement algorithm. RGTs are listed from the western ("McDonald Ice Rumples") tip of HC to the eastern ("Stancomb-Wills Ice Tongue") tip (Fig. S3). The RGTs Highlighted in bold are the RGTs used in the validation of the rift measurement algorithm (RGTs for which two of the six beams intersect HC in the area between the western and eastern GNSS pairs (Figs.5–7)). The five errors were rift width underestimations caused by semi-detached ice blocks bisecting the rift resulting in a pair of troughs in the ATL06 data and all the points within one part the narrower trough being flagged as low quality.

Figure 5. Time series of HC actual widths from the application of the rift measurement algorithm to ICESat-2 ATL06 data (circles), digitization on WorldView-1-3 (squares) and Landsat-8 (triangles) satellite imagery, and the component of the separation of the western pair of GNSS receivers (Fig. 1c) perpendicular to the local rift axis and corrected for divergence (gray circles) for (**a–c**) RGT 1160 3LR, (**d–f**) RGT 215 1LR and (**g–i**) RGT 786 2LR. Colors correspond to the beam colors in Fig. 1c. Error bars on WorldView-1-3 and Landsat-8 points denote a two pixel margin for digitization error, and therefore are twice as large where an ice block bisects the rift. Dashed lines denote the timing of the first observation of Halloween Crack (**HC**), the launch of ICESat-2 (**ICESat-2**), the observation of North Rift propagation (**NR**), and the calving of an iceberg from North Rift (**Calved**). ICESat-2 derived widths from passes with large satellite pointing errors were excluded from this analysis.

elevation measurements, if more than 25 % of measurements were flagged as low quality, or if the measurement density was low (defined as the average along-track separation exceeding 50 m).

Five of the six reference ground tracks used for validation exceed the average measurement success percentage (RGT 215, RGT 1160, RGT 283, RGT 725 and RGT 1099 (Table 1), with RGT 786 2 % below average. However, this includes beam pairs which are not used, and the corresponding measurement success percentages for the individual beam pairs were: RGT 215 1LR 94 %; RGT 1160 3LR 100 %; RGT 786 2LR 83 %; RGT 283 1LR 100 %; RGT 725 3LR 73 %; RGT 1099 2LR 100 %. Removing width measurements effected affected by satellite pointing errors early in the ICESat-2 mission leaves between 3 and 8 width measurements per beam (mean: 4.6, median: 4). This allows us to validate HC width estimates from ICESat-2 with independent estimates from satellite imagery and field-based measurements on a beam-by-beam basis (Figs. 5 and 6), but to ensure a sufficient number of points for robust estimation of rift opening rate it was necessary to combine all width measurements for each GNSS pair (Fig. 7).

4.2.2 Comparison with Satellite Imagery and GNSS Observations

We compare the western GNSS receivers to RGT 215 1LR, RGT 1060 3LR, and RGT 786 2LR. The western GNSS receivers move apart at an almost constant rate, with no apparent seasonal variability. (We present detailed rift opening rate calculations in the next subsection.) Rift initiation ('HC') precedes the first GNSS measurements by around about a year, but the trend suggests a similar rate of opening through this first year. The seaward GNSS receiver (hh00, Fig. S2S3) was located seaward of NR which began propagating in late-2020 (Fig. 1a), and was removed just prior to calving in February 2021. As a result, the HC width time series calculated from the separation of the western GNSS pair ends at the end of 2020. Throughout the period

Figure 6. As Fig. 5 for (**a–c**) RGT 283 1LR, (**d–f**) RGT 725 3LR and (**g–i**) RGT 1099 2LR. Colors correspond to the beam colors in Fig. 1d.

between the initiation of HC and calving from NR, estimates of HC width from ICESat-2 and digitized satellite imagery were generally consistent with the GNSS estimates, with some variability around the trend line. Measurements from ICESat-2 and digitized satellite imagery continue after the calving from NR, and show that rift opening stagnated temporarily in the period immediately following the calving (Fig. 5d and f).

We compare the eastern GNSS receivers with RGT 283 1LR, RGT 725 3LR, and RGT 1099 2LR. The seaward GNSS of the eastern pair was located between HC and NR (Fig. 1a), and therefore the GNSS record continues after the calving from NR (Fig. 6), clearly showing the considerable reduction in HC opening rate following NR calving, then a gradual increase remaining below the pre-calving rate for the remainder of the study period. Close examination of the eastern GNSS pair record suggests this reduction in HC opening rate occurred between the timing of NR propagation and eventual calving (We use 2021-01-01 as the threshold between before and after calving opening rates in Fig. 7 and Table 2). The individual HC width estimates from ICESat-2 and digitized satellite imagery again generally follow the trend line, although individual ICESat-2 measurements and groups of satellite imagery-derived measurements exhibit larger offsets from the width reconstructed from GNSS receiver separation (e.g. along RGT 283 1LR immediately following calving from the NR).

4.2.3 ~~Rift Opening Rates~~

4.3 Observed Rift Opening Rates

~~Given that the three RGTs used in each comparison with GNSS pairs measure almost the same portion of HC~~ Averaged over the entire HC rift, the pre-calving opening rate was $158.2 \pm 107.9\ \mathrm{m\,a^{-1}}$ and the post-calving opening rate was $-112.8 \pm 159.7\ \mathrm{m\,a^{-1}}$. The corresponding minimum/maximum rift opening rates for these two periods were -156.2/404.7 $\mathrm{m\,a^{-1}}$ and -512.2/78.0 $\mathrm{m\,a^{-1}}$, respectively. Whilst this suggests a reversal in the sense of opening of HC from widening during the pre-calving period to closing during the post-calving period, we note that the eastern GNSS pair exhibits more gradual opening in the post-calving period, including possible stagnation in the immediate post-calving period (Fig. ~~1c and d), it is possible to combine all widths from~~ 7b). The opening rates from satellite imagery and ICESat-2 ~~and all widths from satellite imagery to estimate opening rates for rift areas between the western and eastern GNSS pairs using the three independent datasets (~~are influenced by rift meanders (Fig. S7) and advection. We therefore refer to the post-calving period as a period of greatly reduced opening, possibly to the point of stagnation.

Fig. 7 ~~, Table 2~~shows opening rates measured using ICESat-2, satellite imagery, and GNSS. GNSS rates were converted to an Eulerian reference frame (Sect. 5.5 and Figure S16). We calculate opening rates for the periods before and after calving from NR. The pre-calving rates calculated from ICESat-2 and satellite imagery agreed to within ~25 $\mathrm{m\,a^{-1}}$ (246.3 $\mathrm{m\,a^{-1}}$; 270.6 $\mathrm{m\,a^{-1}}$) for western HC, and to within ~15 $\mathrm{m\,a^{-1}}$ (144.0 $\mathrm{m\,a^{-1}}$; 158.0 $\mathrm{m\,a^{-1}}$) for eastern HC. The rates were also consistent with the estimated rift opening rate from the GNSS separations within ~30 $\mathrm{m\,a^{-1}}$ (254.5 $\mathrm{m\,a^{-1}}$ for western pair, 176.9 $\mathrm{m\,a^{-1}}$ for eastern pair). The northernmost GNSS of the western pair was removed prior to calving, leaving only the

Table 2. Multi-observation Halloween Crack (HC) opening rates and one standard deviation confidence intervals (m/a). Confidence intervals are interpreted to dominantly reflect spatiotemporal variability rather than measurement uncertainty (see Discussion Section 5.5). For ICESat-2 and satellite measurements, results from three RGTs are combined (RGT 215 1LR, RGT 1160 3LR, and RGT 786 2LR for the western GNSS pair, RGT 283 1LR, RGT 725 3LR, and RGT 1099 2LR for the eastern GNSS pair). The seaward GNSS receiver of the western pair was removed prior to calving from NR in February 2021.

Figure 7. Independent estimates from the three datasets of the rates of HC opening in the vicinity of the GNSS pairs before and after calving from NR. (**a**, **b**) Time series of the component of the separation of the pairs of GNSS receivers perpendicular to the local rift axis (gray squares) and corrected for divergence (gray circles). (**c**) Combined time series of HC width from WorldView-1-3 (squares) and Landsat-8 (triangles) for RGT 215 1LR, RGT 1160 3LR, and RGT 786 2LR. (**d**) As c for RGT 283 1LR, RGT 725 3LR and RGT 1099 2LR. (**e**) Combined time series of HC width from ICESat-2 (circles) for RGT 215 1LR, RGT 1160 3LR, and RGT 786 2LR. (**f**) as e for RGT 283 1LR, RGT 725 3LR and RGT 1099 2LR. Point colors in c and e correspond to Figs. 1c and 5, point colors in d and f correspond to Figs. 1d and 6. Dashed lines show rates of HC opening before (blue) and after (red) 2021-01-01 using a linear fit. Light blue and red regions show corresponding 95 % confidence intervals.

eastern pair. This measured a post-calving opening rate of 46.1 $\mathrm{m\,a^{-1}}$, with an acceleration in opening rate (from 23.3 $\mathrm{m\,a^{-1}}$ to 66.9 $\mathrm{m\,a^{-1}}$) apparent if the after calving record is split at 2021-06-30. This is the only reliable post calving opening rate, those from ICESat-2 and satellite imagery vary between -84.9 $\mathrm{m\,a^{-1}}$ and 32.5 $\mathrm{m\,a^{-1}}$, though with low R^2 values and in the case of ICESat-2 low confidence in the calculated opening rates ~~evinced~~ indicated by the wide 95 % confidence intervals resulting from short time series with high spread, and few ICESat-2 measurements. Taken together, the three datasets are evidence of a reduction in the rate of HC opening following calving from NR, including possible short-lived stagnation.

4.3.1 ~~Comparison with Modeled Ice Flow~~

4.4 Modeled Opening Rates, Stresses, and Velocities

~~HC opening rates were calculated as the difference between the rift perpendicular components of modeled ice flow at the intersection of the rift and eastern and western GNSS receiver pair baselines (Fig. 8a–i). Modeled opening rates show good agreement with observations during the "~~

Our models generally follow a pattern of rapid opening followed by stagnation, and concluding with slow opening during the pre-calving~~" period. During this time, modeled rates on HC~~, rift-propagation, and post-calving stages respectively. The inverse modeled opening rates during these time periods were 257.0, 53.6, and 136.5 $\mathrm{m\,a^{-1}}$ for the ~~western pair~~ Western GNSS Pair, and 193.1, 36.4, and 87.6 $\mathrm{m\,a^{-1}}$ for the ~~eastern pair (Fig. 8a, d–e). This is consistent with the western pair observations, and ~20–50 greater than the eastern pair observations, though the pattern of greater opening in the west is correctly modeled. Following calving,~~ Eastern GNSS Pair. When the ice rheology was held fixed at pre-calving values, the ~~modeled opening rates drop to 53.6 and~~ post-calving opening rate increased from 36.4 ~~respectively (Fig. 8b, f–g). The (low~~

Results of *icepack* inverse modeling of HC opening rates for "pre-calving", "calving" and "post-calving" periods. (**a–c**) Modeled ice flow speed within the model domain (dashed red line). (**d–i**) Modeled ice velocity (black arrow) and rift perpendicular component (gray arrow) either side of HC from which opening rate is calculated for the western and eastern GNSS pairs. Solid black boxes in a–c show the locations of d–i. (**j**, **k**) Modeled ice flow direction and magnitude change. Colored arrows show the angular change in flow direction for the "calving" and "post-calving" periods compared to the "pre-calving" period (black arrows). Dashed black box in k shows the location of l–n. (**l–n**) Modeled ice velocity and degree of contact between BIS and MIR during the three periods. (**o**, **p**) Change in the modeled fluidity parameter (A) between between the "calving" and "pre-calving" periods (o) and "post-calving" and "pre-calving" periods (p). Dashed regions in p outline areas with large changes in modeled fluidity.

Figure 8. Results of *icepack* inverse modeling of HC opening rates for "pre-calving", "propagation" and "post-calving" periods. (**a–c**) Modeled ice flow speed within the model domain (dashed red line). (**d–i**) Modeled ice velocity (black arrow) and rift perpendicular component (gray arrow) either side of HC from which opening rate is calculated for the western and eastern GNSS pairs. Solid black boxes in a–c show the locations of d–i. (**j–l**) principal stresses inferred from modeling. (**m**, **n**) Modeled ice flow direction and magnitude change. Colored arrows show the angular change in flow direction for the "propagation" and "post-calving" periods compared to the "pre-calving" period (black arrows).

confidence) stagnation or even gradual closing suggested by the ICESat-2 measurements particularly between the western pair (Fig. 5) is not replicated, though the modeled rates are far lower than those from the "pre-calving" and "post-calving" models, and are consistent with the gradual opening calculated from the eastern GNSS pair. The "post-calving" rates of 136.5 and 87.6 (Fig. 8c, h–i) are consistent in pattern with the renewed but more gradual than before calving opening observed by the eastern GNSS pair, though are larger in magnitude (Figs. 6 and 7b). The inverse models therefore replicate the general pattern of opening rates, but may underestimate the degree of transient stagnation following calvingfrom NR .We carried out a set of modeling experiments with the goal of determining the cause of the deceleration of opening rates along HC. First we carried out a set of experiments in whichwe only changed the ice geometry, simulating the calving of iceberg A-74 (using the "calving" and "post-calving" domains). These model runs (Diagnostic$_2$ to Diagnostic$_5$ in Table S9) used the inferred fluidity field and domain boundary velocity field from the "pre-calving" inverse model. These models do not replicate the observed reduction in HC opening rates. The ice geometry is therefore not solely responsible for the change in opening rates. Next we carried out a set of experiments in which we changed the ice geometry and domain boundary velocity fields (using the output velocity fields from the "calving" and "post-calving" inverse models), keeping the inferred fluidity field fixed (Diagnostic$_6$ to Diagnostic$_9$ in Table S9). These models captured the decrease in HC opening rates during the "calving" period (66.7 and m/a to 55.8 for west and east respectively compared to 53.6 and 36.4 from the inverse model). They also capture, but overestimate, the increase in HC opening rate during the "post-calving" period (181.5 and m/a. Similarly, holding the ice rheology fixed resulted in post-calving rates increasing from 87.6 to 154.8 $\mathrm{m\,a^{-1}}$ for west and east respectively compared to . These stated values are for the Eastern GNSS Pair. For the Western GNSS Pair, the equivalent values are 53.6 to 66.7 m/a and 136.5 and 87.6 from the inverse model). to 181.5 m/a, respectively. The results of additional experiments that checked for inversion, interpolation, and other artifacts are given in Table S9.

~~Across the wider ice shelf, the inverse models show~~

The modeled principal stress fields show regions of uniaxial compression in the vicinity upstream of the MIR (Fig. 8j–l). Prior to calving, NR was oriented approximately 45° to the principal axes, which, as we discuss in Section 5.1, is the angle that resolves the maximum shear stress on the rift. HC, in contrast, shows two orientations to the principal axes: it is oriented approximately orthogonal to the direction of maximum tension in the west, and is oriented 45° to the principal axes in the east. Following calving, stresses in the nascent iceberg become dominated by a state of biaxial extension. Relatively little rotation of the principal axes occurred, with most changes through the post calving stages reflecting changes in the principal stress amplitude and sign.

Modeled ice flow speeds (and by extension feature tracked ice flow speeds~~increased (compare black "pre-calving" arrow length to colored "calving " and "post-calving" arrow length in~~) increased following calving (Fig. 8~~j, k), as happened following calving in 1971 (Gudmundsson et al., 2017). The colored arrows denote the angular redirection of ice flow following calving. To the west of BIS the ice flow~~ m, n). Following calving the ice flow also became more convergent toward the MIR. This convergence was accommodated through rotation of the flow towards the MIR. Specifically, ice seaward of Chasm ~~-~~1 rotated clockwise ~~as the nascent iceberg (~~toward MIR (red arrows in Fig. 8m, n) as iceberg A-81 ~~) which would calve on 2023-01-23~~ pivoted about the remaining connection to the ~~remainder of the shelf (Fig. 2m–p; (Cheng et al., 2021b)). Across the east and the nascent iceberg between HC and the new calving front the flow direction rotated anti-clockwise.~~ ice shelf, and much of the east of the ice shelf rotated counter clockwise toward the MIR (blue arrows). The ice flow direction in the central portion of the shelf remained largely unchanged. ~~The change in fluidity parameter (dashed areas in Fig. 8p)shows the advection of Chasm 1 (decreasing upstream and increasing downstream, as well as some errors in the feature tracked velocity field in this area) and an increase in the grounding zone.~~ We do not observe large changes in ice thickness which could have significantly altered the force balance at the ice front (Figs. S20–S23).

~~HC opening rates for the areas between the western and eastern GNSS pairs from GNSS separation measurements, Landsat-8/WorldView (Satellite) width measurements, ICESat-2 width measurements, and ice flow modeling. For ICESat-2 and satellite measurements, results from three RGTs are combined (RGT 215 1LR, RGT 1160 3LR, and RGT 786 2LR for the western GNSS pair, RGT 283 1LR, RGT 725 3LR, and RGT 1099 2LR for the eastern GNSS pair). Opening rates for before and after 2021-01-01 (between NR propagation and calving) are shown for GNSS, Satellite and ICESat-2 measurements. Modeled opening rates are calculated for the "pre-calving", "calving" and "post-calving" periods as the difference of the rift perpendicular components of ice flow, as shown in Fig. 8. Descriptions and observed opening rates with high (low) confidence are shown in bold (regular). The seaward GNSS receiver of the western pair was removed prior to calving from NR in February 2021.~~

5 Discussion

5.1 Validation of Rift Measurement AlgorithmOptical remote sensing and the GNSS receivers installed to monitor the growth of HC provide two independent datasets with which to validate the individual HC width measurements and rate of HC opening measurements from ICESat-2. Measurements of HC width between the western pair from the three datasets show excellent agreement (Fig. 5). In the vicinity of the western pair, the rift is largely straight-sided, with only occasional small-scale topography leading to minor offsets between the three datasets. Larger offsets are apparent for the eastern GNSS pair (Fig. 6), though the individual detections of apparent width appear robust (Figs. S13 to S15). The offsets are the result of small-scale meanders in HC formed as it propagated between meteoric ice blocks and deviated from the large-scale rift axis (De Rydt et al., 2018; King et al., 2018), leading to increases in measured width (Fig. S6).Combining the three RGT beam pairs for each GNSS pair allows the calculation of the rate of rift opening from the three datasets (Fig. 7 and Table 2). Prior to propagation and calving from NR there was good agreement (due to shear stresses

We observe rift propagation and calving that is consistent with the dynamics of shearing mode cracks. Shear stresses were generated in BIS as ice flowed into MIR. As the ice was decelerated at this ice shelf pinning point, a cross stream gradient in streamwise velocities was generated. Rift propagation on NR began in November 2020 and ultimately lead to the calving of a ∼25) between rates of HC opening from ICESat-2, from digitization of optical satellite imagery, and from pairs of GNSS receivers separated by >10 , despite varying temporal ranges, rift wall topography, and uncertainty in the divergence correction to the GNSS measurements. This provides validation for the rift measurement workflow presented here. The close agreement also indicates that rift widening, at least in the case of HC, is dominated by rift wall divergence rather than calving along the rift walls. Large-scale calving occurs primarily along fractures originating from the initial stages of rift formation, while small-scale collapses of material from the rift walls are very localized. The differences between the rates of rift wall separation (ICESat-2 and satellite imagery) and rates reconstructed from GNSS separation are likely explained by uncertainty in the ice flow divergence calculation caused by any lateral offset of the GNSS receivers from the rift-perpendicular axis in the vicinity of the ICESat-2 ground tracks. It is also possible that differences arise as a result of the differing reference frames; the ICESat-2 RGTs along which ICESat-2 and Satellite imagery width were measured are fixed in space (Eulerian reference frame), whereas the rift and the GNSS receivers move with ice flow (Lagrangian reference frame). The rift parallel component of ice flow near the GNSS pairs (∼700–1000) is much smaller than the length of HC (∼50), so the resulting uncertainty in rift opening rate due to differing reference frames is <10 (Fig. S15), within the assumed divergence correction uncertainty.During the period of NR propagation and calving the rate of HC opening reduced or even stagnated (with some observations suggesting rift closing, though with high uncertainty in the case of ICESat-2 between the western GNSS pair (Fig. 7e) and the potential for meandering rift wall topography to mask the opening rate signal in the case of the satellite imagery between the eastern GNSS pair 1270 km^2 iceberg in February 2021. We analyze this propagation in terms of the shear stress resolved on a plane in an arbitrary stress field (Mase et al., 2009),

$$\tau = (\sigma_1 - \sigma_2)\sin(2\theta), \tag{2}$$

where θ is the angle between the plane and the principal stress axes and σ_1 and σ_2 are the principal stresses. The shear stress is therefore maximized at a diagonal 45° orientation to the axes, where the shear stress takes the value,

$$\tau_{\max} = \frac{\sigma_1 - \sigma_2}{2}. \tag{3}$$

NR propagated along a path that was optimally oriented for shear, i.e., at approximately 45° to the principal axes (Fig. 7d)). The most complete record, from the eastern GNSS pair suggests this reduced opening/stagnation was transient, with the rate of HC opening gradually increasing through to the end of the record (approximately one year after calving). Whilst not influenced by variable rift wall topography, there is uncertainty associated with the divergence correction. However, it is clear that a significant change in HC behavior occurred during the period in which NR was propagating and eventually calving. From a validation point of view, the spread in opening rate measurements after calving caution against over-interpretation of temporally short records or those with opening rates close to 0 , where uncertainties resulting from rift wall topography, rift advection, and random measurement errors could be greater than the signal. For example, in Fig. 7c-d the large number of satellite measurements leads to small uncertainties in the opening rates (narrow 95 confidence intervals), but the west and east show contrasting behavior. We attribute this to the effect of meandering rift wall topography in the east. In Fig. 7e-f the small number of ICESat-2 measurements, high spread, and short record results in low confidence opening rates (broad 95 confidence intervals). Fig. 7f is the only record for which a continuation or increase of rapid opening following NR calving is within the 95 confidence interval. Taken together, the three datasets are evidence of reduction in the rate of HC opening, including the possibility of transient stagnation.

5.2 Behaviour of Halloween Crack and Brunt Ice Shelf from observations and modeling

The observations and ice flow modeling allow us to observe the response of floating ice and a rift to a calving event. Many studies have looked at grounded ice after ice shelf calving, but few if any have looked at the details of ice shelf flow and fracture in 8j). This observation supports the view that NR was a shearing mode (Mode II) fracture. As NR propagated northward, it made two large steps to the immediate post-calving period. Between the initiation of HC and left (at approximately 1445 km and 1459 km grid north). These two steps correlate with previously described pre-existing weaknesses in the ice shelf (King et al., 2018). The gradual arc formed by the rift parallels the gradual rotation of the principal axes across the ice shelf. The stress state captured in our model likely captures the propagation of NR , the rate of opening was essentially constant on an inter-annual timescale, with no substantial seasonal modulation (Figs. 5 and 6) resulting from any variation in ice mélange mechanical strength or other potential external forcing mechanisms. This suggests that the rate of HC opening was controlled primarily by glaciological stresses. In November 2020 a further rift (NR) propagated seaward of HC, calving a ~1270 iceberg in February 2021. The widening of HC slowed (possibly to the point of stagnation) in the months immediately following calving, before returning to opening at a reduced rate (Figs. 5, 6 and 7). Given the lack of sensitivity of HC to seasonal forcing prior

~~to calving, the close timing of calving and reduced opening, and the mid-summer timing of the calving event, it is extremely unlikely that increased ice mélange mechanical strength contributed to the reduced opening rate. We also do not observe large changes in ice thickness which could have significantly altered the force balance at the calving front (Figs. S18–S21).~~ by about 20 km between 2020-11-18 and 2020-12-22. Near the middle of our modeled domain, our model predicts lower stress amplitudes, likely explaining the pause in rift propagation that occurred until 2021-01-12, when NR grew by an additional 8 km.

These patterns in the stress field can be understood in terms of the ice flow itself. Prior to calving~~(and since ~2000 (Fig. 2f, g)), ice flowed "head-on" into MIR , resulting in~~ , ice ~~rumples~~ flowed head-on into MIR resulting in shear strain, ice rumples, and damage in the form of fractures visible up- and down-glacier. Ice bifurcated, flowing to the north and south of MIR. This ~~divergence of flow vectors~~ behavior has been ongoing since ~2000 (Fig. ~~8l), and the tensile stresses generated upstream of the zone of compression, likely combine to drive initiation and widening of HC and NR~~2). Shear occurred as the ice was decelerated at the ice rumples, creating a gradient in velocities orthogonal to the flow direction. Following calving, ~~all ice flow is~~ ice flow was almost entirely to the south of MIR, contact between the ice shelf and the pinning point was reduced, and the stresses generated upstream were relieved. Ice flow across much of the east of the shelf and nascent iceberg ~~between HC and the new calving front~~ rotated anti-clockwise (Fig. 8~~j, k~~m, n), resulting in a reduction in the rift perpendicular component of ice flow seaward of HC, ~~thereby reducing the opening rate (compare~~ contributing to the reduced opening rate.

Although outside of our study period, we expect that similar processes to those observed for NR led to the final propagation of HC and to the creation of iceberg A-83 on 2024-05-20. The final detachment of A-83 occurred as the HC took a 90 degree turn seaward (British Antarctic Survey Press Office, 2024; U. S. National Ice Center, 2024). This rift path is optimally oriented to maximize shear stresses in our post-calving (i.e., post-A-74-calving) stress state (Fig. 8~~d and f~~k). The ~~additional model runs (Table S9) elucidate on the mechanisms responsible for the pattern of changes in HC opening rate.~~ observed calving behavior of A-83 is therefore consistent with progressive regrounding of the BIS on the MIR gradually increasing the amplitude of these stresses without causing significant principal axes rotations.

5.2 Calving parameterizations that include shear

The importance of horizontal shear stresses at our study site suggests an ingredient that may be missing from parameterizations of ice shelf calving. We now discuss the degree to which several widely used calving parameterizations capture or do not capture horizontal shear stresses. The eigencalving (Levermann et al., 2012), von Mises (Morlighem et al., 2016), and crevasse depth (Pollard et al., 2015) calving laws are given by,

$$c \propto \max(0, \dot{\epsilon}_1 \dot{\epsilon}_2), \tag{4}$$

$$c \propto \max(0, \dot{\epsilon}_1) + \max(0, \dot{\epsilon}_2), \tag{5}$$

$$d \propto \sigma_1 + \sigma_2, \tag{6}$$

respectively. In these equations, c is the calving rate and $\dot{\epsilon}_1$ and $\dot{\epsilon}_2$ are the principal strain rates. In the crevasse depth law d is the crevasse depth. The eigencalving and von Mises laws prescribe a rate of front retreat whereas the crevasse depth law requires tracking basal and surface crevasse depths, both of which follow a rule of the form in Equation 6, and then removing ice when basal and surface crevasses connect. Note that the distinction between stresses and strains is not particularly important here given that the first two equations are heuristic and could equally well have been formulated in terms of stresses. None of the above calving laws are sensitive to horizontal shear stress. Shear stresses fundamentally occur because of the differential stress $\sigma_1 - \sigma_2$, and this quantity is in the nullspace of the above calving laws.

We propose an extension of these laws that preserves their useful features while adding additional sensitivity to shear stress. Our observations suggest that calving laws should depend $\tau_{\max}$. Mechanically, a dependence on $\tau_{\max}$ reflects the view that shear fractures will form in whatever plane is optimally oriented in a given stress field (King et al., 1994). One simple way that this could be done would be to model the calving rate or crevasse depth from opening and from shear additively. For example,

$$c = \begin{cases} k_I c_I + k_{II} c_{II} & \sigma_1 > 0 \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where k_I and k_{II} are tuning parameters, and c_I and c_{II} are the contributions to the calving rate from Mode I (opening) and Mode II (shearing). The model runs in which we only changed the ice geometry did not replicate the observations. The model runs in which we changed the ice geometry and domain boundary velocity fields but kept the inferred fluidity field constant qualitatively match the observations, exhibiting a decrease to very low opening ratesin the "calving" period and a resumption of opening in the "post-calving" period, though remaining lower than the opening rates in the "pre-calving" period. However, quantitatively the agreement between opening mode contribution c_I could be taken to be the calving rate predicted from Equation 4 or 5. The shearing mode contribution to calving could be taken as proportional to the absolute value of the inverse and additional model runs for the "calving" period are much closer than the "maximum resolved shear stress,

$$c_{II} \propto |\tau_{\max}|, \tag{8}$$

where the absolute value is used so that the calving rate is the same for left-lateral and right-lateral shearing. In equation 7, the condition $\sigma_1 > 0$ is used to require at least uniaxial tension, similar to the von Mises calving law; the additional condition that $\sigma_2 > 0$ could also be used which would be similar to the eigencalving law. Intercomparison using models (e.g., Choi et al., 2018; Wilner et a and observations (e.g., Enderlin and Bartholomaus, 2020) will be valuable to assess the practical utility of shear-resolving calving laws.

5.3 Post-calving rift stabilization

Our results demonstrate a clear change in the opening rate of HC following calving from NR in February 2021. Whilst some of our results appear to show closing of HC, this may be an artifact of a short post-calving " period. Taken together, this suggests that the primary driver is the change in geometry and resultant change in large-scale ice flow, though changes in fluidity,

~~including the increase in fluidity in the grounding zone (likely indicative of fracture growth; dashed region in Fig. 8p)make a secondary contribution. The resumption of HC opening at a slower rate following the period of stagnation shown by the eastern GNSS pair (Fig. 6) and "post-calving" model (Fig. 8c, h, i) may suggest stagnation was a transient response to calving, but is more likely due to deformation and the accumulation of damage on the nascent iceberg ~3 upstream of MIR, as the western tip of HC moves clockwise around the south of MIR~~ time series and the meandering of the rift, cautioning against the over-interpretation of short records with low magnitude signals. The most reliable time series, that from the eastern GNSS pair shows a pronounced reduction in the rate of HC opening to the point of short lived stagnation. Prior to calving, rift widening occurred on HC as the state of uniaxial compression created by contact with the MIR resulted in tensile stresses resolved onto the HC (Fig. ~~2q–t). In spite of the transient pause in HC opening, with the eastern tip approaching an area of fragmented shelf ice with large areas of sea ice , and damage accumulating immediately upstream of MIR, calving from HC in the coming years cannot be ruled out.~~ 8j). Following calving, BIS contact with MIR was reduced, resulting in a simultaneous acceleration of the ice shelf and a reduction of the ice shelf shear stresses. These reduced shear stresses corresponded to the removal of normal stress resolved on HC, thereby causing rift stagnation.

Our ice flow models are able to qualitatively capture the observed reduction/stagnation in rift opening, with some also predicting small rift closure rates rates ($-7.4\,\mathrm{m\,a^{-1}}$; Table S9). The model that produces these closing rates does not update the rheology field through time and instead holds the ice rheology fixed to that from the pre-calving period (Diagnostic$_8$), consistent with previous work that found geometry to be the dominant control on rift propagation on Brunt (De Rydt et al., 2019). It also suggests that widespread fracturing did not affect the ice rheology during rift propagation (Borstad et al., 2017).

5.4 Historical ~~Behavior~~ Context of the Observed Changes on the Brunt Ice Shelf

Our analysis of Landsat imagery and digitized maps allows us to investigate the calving cycle at BIS (section 4.1). It is possible that the BIS ice front east of MIR advanced after 1914/15, reaching a position similar to that in the 2010s, with a significant area of ice north of MIR. One or more calving events, possibly an event similar to the 2021 calving, must have occurred sometime between 1914/15 and 1955. The position of the 1914/15 front in the vicinity of MIR being similar to that in ~2000 (Fig. ~~2g–h~~3d–e; ~20 years before the 2021 calving event) likely favoring the mid to latter part of this interval. An alternative interpretation could be repeating smaller calving events between 1914/15 and 1955 from similarly placed rifts. It is notable that the area between the 1967/68 and 1971 fronts is similar to the area between the 2021 front/NR and HC (Fig. 2~~b~~c). A hypothesized repeating pattern of dual rift formation and twin calving events, with the smaller event (1971 calving from the 1968 rift and ~~future~~ 2024 calving from HC) delayed relative to the larger event (hypothesized 1914/15–1955 calving and 2021 calving from NR) is therefore consistent with the available data. However, the timing of rift initiation would be different, with the 1968 rift forming decades after the hypothesized calving between 1914/15 and 1955, whereas HC and NR formed close together in time and in the opposite order (HC in 2016 and NR in 2020). ~~Figure 2d~~ Fig. 3a does show a more significant area of ice to the north of MIR than in 2021 following calving from NR (Fig. ~~2k~~3h), possibly suggesting considerable advance since the previous calving event. Regardless of the sequence of events, the importance MIR and local ice geometry to rift initiation is apparent.

To the west of MIR, a ∼1500 km^2 iceberg (A-81) calved from Chasm 1 in January 2023 (Marsh et al., 2024; British Antarctic Survey Pre . This did not immediately reduce the degree of contact between MIR and BIS was not immediately reduced as a consequence of the calving in January 2023. This amounts , which amounted to ∼2350 m, of which ∼1500 m is was with ice between HC and the new ice front following calving from NR, and ∼850 m is was with the remainder of the shelf . Damage is accumulating (Fig. S2d). However, damage accumulated within the nascent HC iceberg ∼3 km upstream of MIR (Fig. 2q–t S2a-d), allowing the resumption of opening of the bulk of the rift. The degree of contact maintained between MIR and the remainder of the shelf following any future calving from HC will be crucial in determining the response of BIS to calving (Hodgson et al., 2019). , and ultimately breaking through (Fig. S2e). Further, the western tip of HC was advected along the east and south of MIR, intersecting the new western ice front of BIS (former Chasm 1 inland rift wall) following a small calving event in June 2023 (Marsh et al., 2024).

Focusing on MIR (Fig. 2d–l 3a–i), we show that BIS maintained contact following the 1971 calving event, with visible pressure ridges and damage to the ice downstream demonstrating that it was providing some buttressing to the ice shelf throughout. However, ice flow is largely parallel to the 1973, 1986 and 1997 calving ice fronts in the vicinity of MIR (Figs. 2e–g 3b–d and 1b inset), so in the three decades following the 1971 calving event MIR was a source of lateral drag. By ∼2000 (Fig. 2 g–h 3d–e) the ice front east of MIR had re-advanced sufficiently to flow "head-on" into MIR. This results in divergent and ultimately bifurcating ice flow, and generates tensile stresses upstream to the east of MIR which are ultimately responsible for the initiation and opening of HC and NR rifts (and previously the 1968 rift). Gudmundsson et al. (2017) observed a gradual decrease of BIS flow velocities (which had doubled following the 1971 calving) after ∼2000 as a result of the increased flow resistance. These observations suggest that the flow velocity could more than double should calving from HC result in a there be a complete loss of contact between BIS and MIR. This would be unprecedented in the observational record, and could have implications of the stability of BIS (Hodgson et al., 2019). , consistent with the observed rapid accelerations since the calving of iceberg A-81 from Chasm 1 and smaller calving event (Marsh et al., 2024) which resulted in HC intersecting the new western ice front.

We have presented a method for the measurement of ice shelf rift width and opening rate from

5.5 Opening rate consistency between independent observations

We use optical imagery and GNSS as validation datasets for our ICESat-2 ATL06 data. For each rift detection, the algorithm searches for the most likely landward and seaward walls, and calculates the slope for overlapping ∼200 sections, defining the rift wall location as the mean of the points in the steepest section. Where the rift is divided in two by a semi-detached block or iceberg, both the "opening width" and "wall-to-wall width" are calculated.Finally, Halloween Crack (HC) opening rate measurements. These independent measurements show excellent agreement at the western pair site (Fig. 5). In the vicinity of the western pair, the rift is largely straight-sided, with only occasional small-scale topography leading to minor biases between the three datasets. Larger biases are apparent for the eastern GNSS pair (Fig. 6), though the individual detections of apparent width appear robust (Figs. S13 to S15). The biases are the result of small-scale meanders in HC formed as it propagated between meteoric ice blocks and deviated from the apparent rift width is converted to an estimate of actual width using the angular offset between the ICESat-2 track and a plane perpendicular to the large-scale rift axis .The rift width measurement algorithm and resulting estimates of opening rate were validated using Halloween Crack on Brunt Ice Shelf as a case study.HC width was digitized on optical Landsat-8 and WorldView-1-3 satellite (De Rydt et al., 2018; King et al., 2018), leading to increases in measured width (Fig. S7).

HC opening rates from ICESat-2, optical imagery, and a time-series of ice flow divergence-corrected, rift-perpendicular separation distance calculated from the locations of two pairs of GNSS receivers. Between the western GNSS pair, where HC is straight-sided, measurement success was 84–94 (Table 1) and the three datasets exhibited good consistency in individual width measurements and rates of rift opening GNSS show good agreement prior to calving from NR (Figs. 5 and 7). Between the eastern pair (88–100), there were some deviations in individual rift width measurements caused by Fig. 7 and Table 2). This agreement validates our rift measurement workflow and demonstrates robustness to varying temporal ranges, rift wall topography, and uncertainty in the divergence correction to the GNSS measurements. The close agreement also indicates that rift widening, at least in the case of HC, is dominated by rift wall divergence rather than calving along the rift walls. Large-scale calving occurs primarily along fractures originating from the initial stages of rift formation, while small-scale meandering of the rift (Fig. 6), but equivalent consistency between rates of rift opening calculated from the three datasets. The consistency of rift measurements prior to calving from NR from remote sensing datasets and reconstructed using GNSS measurements, along with visual inspection of the measurements (Figs. S7–S14), gives confidence in the performance of the algorithm. It also demonstrates the growth of HCis largely due to wall divergence , with calving from the walls being a minor contributor. Following the 2021 calving from NR, HC opening rate dropped significantly, possibly to the point of stagnation, before returning to opening at a reduced rate. In this period the difference between the three opening rate datasets was greater due to collapses of material from the rift walls are very localized.

HC opening rates do exhibit small scale differences between the different measurements. An important contributor to these differences is errors from the ice flow divergence calculation caused by any lateral offset of the proportionally larger effect of uncertainties, cautioning against the over-interpretation of short records with low magnitude signals. We attribute the changes in behavior primarily to changes in the geometry of the ice shelf in the vicinity of MIR, and GNSS receivers from the rift-perpendicular axis in the resulting reorganization of the ice shelf flow field. Prior to calving BIS flowed “head-on” into MIR, with some ice passing to the north of the pinning point. This generated tensile stresses and highly divergent ice flow upglacier vicinity of the ICESat-2 ground tracks. It is also possible that differences arise as a result of the differing reference frames; the ICESat-2 RGTs along which ICESat-2 and Satellite imagery width were measured are fixed in space (Eulerian reference frame), whereas the rift and the GNSS receivers move with ice flow (Lagrangian reference frame). The rift parallel component of ice flow near the GNSS pairs (∼700–1000 $\mathrm{m\,a^{-1}}$) is much smaller than the length of HC (∼50 km), so the resulting uncertainty in rift opening rate due to differing reference frames is <10 $\mathrm{m\,a^{-1}}$ (Fig. 8l), sufficient to initiate ice fracture and maintain the high opening rates observed in the early part of the record. Calving from NR in February 2021 removed ice flowing to the north of MIR, reducing flow resistance and resulting in a reorganization of ice flow across the east of the shelf and the nascent iceberg between HC and the new calvingfront (Fig. 8j, k, m, n). The anti-clockwise rotation of flow reduced the difference in rift perpendicular components of ice flow (e.g. Fig. 8d, f, h), leading to the observed stagnation/lower opening

S16), within the assumed divergence correction uncertainty. However, we acknowledge that this may be an underestimate for the meandering eastern part of HC and may not be the case for other rifts, for example where ice flow is fast (and not aligned with the ICESat-2 RGT), the rift broader wall-to-wall but shorter tip-to-tip, or the timescale of measurement longer.

HC opening rates reduced or even stagnated in the months following calving. The most complete record from the eastern GNSS pair suggests this reduced opening rate was transient, with the rate of HC . The flow of the ice shelf appears to be accelerating in response to the reduction in flow resistance at MIR, as previously occurred following calving in 1971 (Gudmundsson et al., 2017). The calving of a ∼1550 iceberg (A-81) from Chasm 1 in January 2023 did not immediately result in a further reduction in the level of contact between BIS and MIR (opening gradually increasing through to the end of the record, approximately one year after calving. Challenges in interpreting the detailed patterns of rift opening occur due to the obfuscation of representative, large-scale opening rates by small scale heterogeneity such as a meandering rift wall topography and also from uncertainty associated with the divergence correction. From a validation point of view, the variability in opening rate measurements after calving caution against over-interpretation of temporally short records or those with near-zero opening rates, where uncertainties resulting from rift wall topography, rift advection, and random measurement errors could be greater than the signal. For example, in Fig. 2c, m–p), though the accumulation of damage on the nascent HC iceberg ∼3 upstream of MIR and the resumption of HC opening are signs that a further calving event may occur (Fig. 2q–t). We used satellite imagery and historical observations to study the calving cycle at BIS (7c-d the large number of satellite measurements leads to small uncertainties in the opening rates (narrow 95 % confidence intervals), but the west and east show contrasting behavior. We attribute this to the effect of meandering rift wall topography in the east. In Fig. 2), demonstrating the remarkable similarity in 7e-f the small number of ICESat-2 measurements, high spread, and short record results in a lack of consistency between neighboring ICESat-2 tracks. Taken together, the three independent measurements of HC opening rate provide consistently describe a reduced rate of HC opening following calving.

5.6 Conclusions

Our main conclusion is that shear stresses played an essential role in the locations of HC and a rift that calved in 1971, and NR/post-calving ice front and the 1967/68 ice front (Thomas, 1973). So, whilst calving from a HC-like rift is not unprecedented, evolution of system of rifts on BIS. Shear stresses at the MIR, a pinning point of BIS, were responsible for the nucleation and propagation of NR. The calving of iceberg A-74 in February 2021 reduced the pinning of BIS at MIR. Although the ice shelf accelerated during this time, the western tip of the 1971 rift had not propagated clockwise around MIR to the degree HC has. The future behavior of BIS will depend on the development of HC and the level of contact maintained between BIS and MIRfollowing a calving event. A complete loss of contact with MIR would be unprecedented in the observational record. This could lead to ice flow speeds more than doubling, and have implications for the stability of BIS (Hodgson et al., 2019). More widely, ice rises and ice rumples are prevalent across Antarctica (Matsuoka et al., 2015) suggesting the potential for further instances of changes in the dynamics of floating ice and neighboring rifts (as well as the widely studied changes in grounding zone flux) in response to calving events. simultaneous reduction of shear stresses lead to the reduced widening of Halloween Crack.

These conclusions were strengthened by ICESat-2 observations. We have shown that ICESat-2 can ~~supplement optical satellite~~ compliment optical imagery for the spaceborne monitoring of ice shelf rifts~~, with~~ . As a laser altimeter, ICESat-2 has the advantage of year-round observations ~~only~~ limited by the presence of cloud cover. ~~The algorithm presented here~~We have presented and validated an algorithm for the measurement of ice shelf rift width and opening rate from ICESat-2 ATL06 data that, when combined with a validated rift detection algorithm ~~(that distinguishes between rifts and crevasses) is readily~~ is scalable to the entire Antarctic Ice Sheet. ~~It is hoped that making available a catalog of rift characteristics such as width, ice mélange thickness, and rift topography~~ Making a continent-wide rift catalog through the duration of the lifetime of ICESat-2 will facilitate further study into ice shelf fracture and calving processes, and thus contribute to better constraint of the likely future mass balance of the Antarctic Ice Sheet.

Our main conclusion about the importance of shear stress in tabular iceberg calving extends beyond time period of study. Our analysis of historical observations demonstrates the remarkable similarity in the locations of HC and a rift that calved in 1971, and NR/post-calving ice front and the 1967/68 ice front (Thomas, 1973). Our conclusions are also more broadly applicable to other ice shelves. Pinning points, ice rises, and ice rumples are prevalent across Antarctica (Matsuoka et al., 2015; Miles and Bingham, 2024) and their importance in ice shelf stability has been documented (Wild et al., 2022). We have taken a first step toward incorporating shear stresses into calving law parameterizations by highlighting observational and theoretical reasons why the shear stress on optimally oriented fractures, $\tau_{\max}$, should be incorporated into calving laws. We conclude that shear stresses play an important role in the tabular iceberg calving process and that their incorporation into ice sheet-scale parameterizations will therefore enable a more accurate representation of ice sheet evolution.

Code and data availability. Scripts used to detect and measure rifts as part of the “Antarctic Rift Catalog” project are available at https://doi.org/10.5281/zenodo.7839138 (Morris et al., 2023). These scripts will be updated as the project progresses. *icepack* is an open source ice flow modeling package available at https://github.com/icepack/icepack. *icepack* model runs detailed here are available at https://doi.org/10.5281/zenodo.7796399 (Morris and Lipovsky, 2023).

Appendix A

Author contributions. AM led the research. AM and BPL led the writing of the manuscript, with contributions from all authors. BPL and CCW designed the ‘Antarctic Rift Catalog’ Project and supervised the research. BPL contributed to code development. OJM processed GNSS data from Brunt Ice Shelf.

Competing interests. The authors declare no competing interests

Table A1. List of Acronyms

Abbreviation	Definition
ATLAS	Advanced Topographic Laser Altimeter System
ATL02	ICESat-2 photon time of flight, spacecraft positioning and pointing data
ATL03	ICESat-2 Global Geolocated Photon data
ATL06	ICESat-2 Land ice elevation product
BIS	Brunt Ice Shelf
GNSS	Global Navigation Satellite System
HC	Halloween crack
ICESat	Ice, Cloud, and Land Elevation Satellite
ICESat-2	Ice, Cloud, and Land Elevation Satellite 2
MIR	McDonald Ice Rumples
NASA	National Aeronautics and Space Administration
NR	North Rift
RGT	ICESat-2 Reference Ground Track
RGT 215 1LR	Reference Ground Track 215 beam pair 1
RGT 1160 3LR	Reference Ground Track 1160 beam pair 3
RGT 786 2LR	Reference Ground Track 786 beam pair 2
RGT 283 1LR	Reference Ground Track 283 beam pair 1
RGT 725 3LR	Reference Ground Track 725 beam pair 3
RGT 1099 2LR	Reference Ground Track 1099 beam pair 2
SNAP	SeNtinel Applications Platform
SWIT	Stancomb-Wills Ice Tongue

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Andersen and Knudsen (2009); British Antarctic Survey Press Office (2023); De Rydt et al. (2018); Gardner et al. (2018, 2020); Glen (1955); King et al.

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