Widening process and seasonal dynamics of the large-scale rift and its mélange in the 2nd largest ice shelf in Antarctica

Da Lv¹, Yuan Cheng¹*, Gang Hai¹
¹College of Surveying and Geo-Informatics, Tongji University, 1239 Siping Road, Shanghai, 200092, China; lvda@tongji.edu.cn; chengyuan_1994@tongji.edu.cn; ganghai@tongji.edu.cn; *Correspondence: chengyuan_1994@tongji.edu.cn;

Abstract

Rift plays an important role in ice shelf calving event, which forms the boundary of tabular detachments and the acts as precursor for ice shelf calving. Rift mélange shows the resistance to deform during rift propagation, which plays the role as stabilizing the rift. However, the detailed 3D propagation process of the rift, including the dynamics motion of its mélange, is not clearly investigated since then. In this paper, a long time series of 2D propagation rates are generated to provide an overview of all rifts throughout the FRIS, which reveals that the rift T1 and T2 were quite active and will dominate the next calving event. Then, the process of widening of rift T1 is detailed investigated, which is representative for rift propagation process. By utilizing REMA DEMs and ITS_LIVE ice velocity maps, the process of mélange widening and rift wall widening are estimated. The mélange widens linearly in space and rift wall widening is caused by collapse. The processes of mélange height decreasing and mélange widening both reveal linear patterns during rift widening process. Rift widening process shows seasonal variant, which is attributed to the seasonal variant of rift wall widening. However, mélange widening reveals a stable trend, which proves its stability. The seasonal variant of rift
wall widening is further explained by the collapsing process during different seasons. The process of rift propagation worth long-term monitoring both vertically and horizontally in the future, which is significant for ice shelf calving ice shelf instability studies.

**Keywords**

rift; mélange; ice shelf; Antarctica; iceberg calving

1. **Introduction**

Ice shelves play a significant role in ice sheet mass balance in Antarctica, providing resistance on adjacent ice sheet (Alley et al., 2016). Ice shelf collapse will accelerate mass loss and therefore increase the sea level rise rate. Ice shelf calving and basal melting are two main ways of ice shelf mass loss (Rignot et al., 2013). And ice shelf calving contributes about half of mass loss of entire Antarctica (Rignot et al., 2013). The calving process highly involves large scale rift. Rift is the full-penetrating fracture which forms the detachment boundaries of icebergs in calving events (Joughin and MacAyeal, 2005). Rift can propagate horizontally for decades before forming the tabular icebergs (Bassis and Ma, 2015). Therefore, as an important observational precursor of ice shelf calving, it is of great significance to monitor the rifts propagation and reveal the cause. Walker et al. (2013) extracted and monitored 78 rifts in 13 Antarctic ice shelves from MODIS imagery to investigate the cause of rift propagation trend. Bassis et al. (2008) detected the bursts of episodic rift propagation and analyzed simultaneous ancillary data such as wind speeds, tidal amplitudes and sea-ice fraction. And found that rifting process is primarily driven by the internal glaciological stress but not these environmental forcings. As a component of ice shelf rift system, mélange is a mixture
material filling the rifts, consisting of sea-ice, accumulated and wind-blown snow, ice fragments broken off the ice shelf and marine ice (MacAyeal et al., 1998). Mélange has mechanical competence to deform in response to different motion of two sides of rift and resist and halt the tabular iceberg detachment (Rignot and MacAyeal, 1998). There is no evidence of a seasonal change in mélange thickness. The observed seasonal changes in rift growth rates might be due to changes in mélange properties throughout the year (Fricker, 2005). But the detailed behavior of rift and mélange during widen process is not clear studied, including the horizontal motion and vertical change of mélange and the collapse process of during propagation. It is urgent to study the propagation process of ice shelf rift and internal mélange to better understand the rift propagation mechanism, which is beneficial for ice shelf calving monitoring and prediction.

Filchner-Ronne Ice Shelf (FRIS) is the second largest ice shelf in Antarctica (~430,000 km²) and represents the greatest volume of floating ice in the world (Bull et al., 2021; Rignot et al., 2013). FRIS consists of the Filchner Ice Shelf (FIS) in the east and the larger Ronne Ice Shelf (RIS) in the west. The two ice shelves are divided by Berkner Island in the northern seaward side while connected in the south. The previous major calving event of FIS occurred in April 1986 with an area of ~11500 km² (Ferrigno and Gould, 1987), which is directly led by a large rift called “Grand Chasm”. The previous calving in RIS took place in October 1998 and in May 2000 with an area of 16,000 km² (Oerter et al., 2000). The new calving for RIS has already been triggered by a large rift in May, 2021, with an iceberg of 4,320 km² collapsed from west RIS (LT Falon M. Essary, 2021).

In this paper, the rifts in FRIS are systematically investigated as examples to study the propagation process of rifts. The 2D propagation process of all rifts in FRIS since the previous calving event is estimated to reveal the most active rift, which is representative for rift propagation. The most active
rift is then focused and analyzed the propagation process. By utilizing DEMs with high resolution and ice velocity maps, processes of mélange widening and rift wall collapse are revealed and their temporal changes are obtained to investigate the pattern of rift widening.

2. Data

2.1 REMA DEM

The Reference Elevation Model of Antarctica (REMA) is a high resolution, time-stamped Digital Surface Model (DSM) of Antarctica at 2 or 8-meter spatial resolution (Howat et al., 2019). REMA was constructed from vast quantities of individual stereo digital elevation models (DEMs) extracted from a pair of sub-meter (0.32 to 0.5 m) resolution DigitalGlobe satellite images, including images from WorldView-1, WorldView-2, and WorldView-3, and a small amount of data from GeoEye-1, acquired between 2009 and 2017. REMA DEM consists of REMA strips and REMA Mosaic. No ground control or altimetry registration has been applied to the strips while mosaic is vertically registered to satellite altimetry measurements from Cryosat-2 and ICESat. REMA DEMs used in this study are REMA strips covering rift T1, spanning from 2012 to 2017. The spatial and temporal coverage of these REMA DEMs is shown in Figure 1. These DEMs are grouped by seasons and the acquisition date of each DEM is labelled. Dashed rectangle represents there is partially data missing in the DEM. Three profile lines Profile 1, Profile 2 and Profile 3 are shown as red lines, which are mentioned below.
2.2 Inter-mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE)

The Inter-mission Time Series of Land Ice Velocity and Elevation (ITS_LIVE) project provided comprehensive and temporally multi-sensor land velocity maps of Antarctica (Gardner et al., 2019). Image-pair velocities and yearly composite velocities are both provided. Both image-pair velocities and yearly velocities are applied in this study. Image-pair velocities are generated
from Landsat 8 optical imagery. The resolution of velocity map is 120 m. Yearly composite velocities are mosaiced from image-pair velocities.

2.3 Landsat imagery

Landsat images from 1986 to 2019 was applied to extract rifts of long time series and the ice shelf boundary of the previous calving event in FRIS, including Landsat 5 (TM), 7 (ETM+) and 8 (OLI). The resolution for Landsat 5, 7 and 8 are 30 m, 15 m and 15 m. Because some Landsat 7 image have SLC-off gaps, the Landsat 7 images with rift tips located in the gaps are not used for rift extraction because tips are necessary for 2D parameter measurement.

3. Methodology

The framework of rift propagation process analysis consists of 2D measurement and analysis of ice shelf-scale rifts and 3D measurements and analysis of the single critical rift (Figure 2).
First, all rifts in FRIS are extracted and measured and the temporal propagation rates of all rifts are estimated. The most critical rift $T_1$ was singled out for its active propagation and significance to the next calving event. Then, the widening process and the vertical dynamics of mélange in rift $T_1$ was demonstrated. The time series of widening rates for entire rift $T_1$, mélange and rift walls from 2013 to 2017 are generated for analysis on their seasonal variations.

3.1 2D Extraction & measurement of rifts
The rifts in FRIS are extracted and measured from Landsat images during a complete calving cycle to monitor the complete propagation process of rifts during two adjacent calving events. The previous calving cycle for RIS is from 1998/2000 to May 13, 2021, on which the latest calving event is first spotted in western RIS. For FIS, the previous calving event took place in 1986 and FIS is still in its calving cycle. The extraction is conducted during the calving cycle at intervals of ~5 years, in 1987, 1996, 2000, 2005, 2010, 2015 and 2021 for FIS, and 2005, 2010, 2015, 2021 for RIS. The length and width are measured under the projection of WGS 1984 Antarctic Polar Stereographic (EPSG 3031). And then the lengthening and widening rates of each interval is estimated and compared to access the activity of each rift.

All rifts in this calving cycle are compared with the boundary of ice shelf tabular detachments of last calving event. By comparison, the rifts which probably form the detachments in the next calving event are revealed. Based on the comprehensive analysis from these two aspects, the rift which shows the most activity and may lead to the next calving event is singled out and its 3D dynamics process is further analyzed in the next section.

3.2 Process of rift and mélange widening

3.2.1 Distribution of profiles

Rift T1 is a traverse rift in the ice shelf front, the propagation of which is driven by longitudinal tensile caused by ice flow (Cuffey and Paterson, 2010; Glasser et al., 2009). Therefore, T1 extends east to west, perpendicular to the local ice flow direction. Three profiles were generated along the ice flow direction (Figure 3) and the widening process of Rift T1 is subsequently analyzed along these profiles. Profile 1 and 3 are two streak lines extracted from the Landsat 8 image. Streak lines were generated in regions of positive relief upstream and formed parallel to ice flow. Profile 2 is
plotted in the middle of T1 as a necessary supplement to densify the profiles, which is plotted parallel to Profile 1 and 3. Then all measurements are performed along three profiles based on DEMs and optical images. For REMA DEM, the elevation data was extracted along the profiles with 2-m interval, which is the same as the resolution of REMA strip applied in this study. The ice velocity was also extracted from the ITS_LIVE maps along the profiles with 120-m interval, which is the same as the resolution of the velocity map.

![Figure 3. Distribution of profiles. The background image is Landsat 8 image (Scene ID: LC8188162014302LGN01)](image)

3.2.2 Measurement of rift width and mélange width

The rift width and mélange width are measured from rift boundary points and mélange boundary points extracted from DEM profiles. As shown in Figure 4, the profile is a symmetrical structure, consisting of ice shelf surface (south of A1 and north of A2) and rift (A1 to A2). And the rift profile further consists of south rift wall (A1 to B1), north rift wall (B1 to B2) and mélange surface (B2 to
A1 and A2 are the edges between ice shelf surface and rift walls whereby B1 and B2 are the edges between rift walls and mélange surface.

Figure 4. Examples of rift width and mélange width measurement from the DEM profile.

The rift boundary points (A1 and A2) and mélange boundary points (B1 and B2) are both extracted automatically according to the profile shape. Rift boundary point is the inflection of surface slope.

For each point \( i \), the absolute value of second-order differential of elevation \( ds_i \) are calculated as

\[
ds_i = \left| \frac{h_{i+1} - h_i}{w_i} - \frac{h_i - h_{i-1}}{w_i} \right| = \left| \frac{2h_i - h_{i+1} - h_{i-1}}{w_i} \right|, 1 < i < n
\]

where \( h_i \) is the elevation of the point \( i \), and \( h_{i-1} \) and \( h_{i+1} \) are the elevations of two adjacent points, \( w_i \) is the sample interval as 1 m in this study. To avoid mis-extracting infection points of the mélange surface, a constraint \( 50 < h_i < 80, \text{unit: m} \) is added. The mélange boundary point is the lowest points of the most outer two valleys. A search is conducted from the rift boundary point to the rift center. The first local lowest point, whose elevation is also lower than 30 m is selected as the mélange boundary point.

3.2.3 Rift widening and mélange widening
To investigate the widening process of the rift, two temporally adjacent profiles along the same profile line are compared to reveal the width changes. For example, as shown in Figure 5, two profiles of 2016/02/12 (Time 1) and 2016/11/16 (Time 2), which are in the winter of 2016, are compared. The rift widening during the period (2016/02/12-2016/11/16) can be calculated as 

$$\Delta w = w_2 - w_1,$$

where $w_1$ and $w_2$ are rift width of Time 1 and 2. In Figure 5, according to the rift width points $A_1$, $A_2$ of Time 1 and $A_1'$, $A_2'$ of Time 2, $w_1$ and $w_2$ are calculated as 1750 m and 1920 m, and $\Delta w$ is calculated as 170 m.

Since the rift width consists of the mélange width and the rift walls width as $w = w_m + w_w$ ($w_m$ and $w_w$ are mélange width and rift wall width), the widening of rift is also divided into mélange widening and rift wall widening as $\Delta w = \Delta w_m + \Delta w_w$ ($\Delta w_m$ and $\Delta w_w$ are mélange widening and rift wall widening). The mélange widens because the ice flow difference of ice shelves on the south and north sides gradually “pull the mélange open”, which is described in Section 3.3. The rift walls widen because the rift wall collapse with the adjacent ice shelf surface.

The mélange widening can be extracted from the comparison between profiles. As Figure 5 shows, the mélange features a series of peaks and valleys. The two profiles show the same shape and the spatial distribution of peaks and valleys, but the mélange of the Time 2 is wider. To investigate and quantify the widen process of the mélange, a series of match points between two profiles are selected to estimate their movements. If the match points generally cover the entire mélange densely, their movements are able to represent the widening process of the entire mélange. Peaks and valleys are alternative matching points for their spiky shapes. However, valleys are likely to be filled with snowfall, blowing snow and debris, which will change the shape and cause the extra horizontal displacement. Therefore, peaks are better choices than valleys. Those peaks with higher elevation,
remarkable and similar shapes have higher priority in selecting match points. As shown in Figure 5, the match peaks are blue dots for Time 1 (Figure 5a) and red dots for Time 2 (Figure 5b) and the corresponding peaks are linked with dashed arrows.

![Figure 5](image_url)

Figure 5. Example of peaks selected as match points from two profiles.

The movement pattern of the match peaks is analyzed by estimating displacements of peaks during the period. First, the horizontal distances of the peak to the south mélange boundary points $B_1$ and $B_1'$ are measured as $d_1$ (Time 1) and $d_2$ (Time 2). Then the displacement of the peak $\Delta d$ is calculated as $\Delta d = d_2 - d_1$. To investigate the relationship between displacement and horizontal distance of the peaks, $d_1$, $d_2$ and $\Delta d$ for all 9 peaks are calculated and visually plotted as scatters in Figure 5c, with $d_1$ as x coordinate and $\Delta d$ as y coordinate. And a linear fitting is
conducted on the scatters with $R^2$ as 0.9086, which indicates that the displacement of peaks is linearly related to their horizontal distance, which also represent that the widening of mélange is a linear and homogenization process to the horizontal distance. The fitting formula is $y = 0.0071x + 55.841$, which quantifies the mélange widening process. A widening ratio $\alpha$ can be obtained from the slope parameter of linear fitting formula as 0.0071, which indicates that 1 m-wide mélange will widen 0.0071 m from Time 1 to Time 2. So, the mélange widening $\Delta w_m$ can be calculated from the original mélange width as $\Delta w_m = \alpha w_{1m}$, where $w_{1m}$ is the mélange width of Time 1. In this example, the mélange width of 2016/02/12 is 1526 m and the mélange widening is calculated as 12.36 m from 2016/02/12 to 2016/11/16. The reason why not adopt the difference of mélange widths of two phases as the mélange widening ($\Delta w_m = w_{2m} - w_{1m}$, where $w_{1m}$ and $w_{2m}$ are mélange widths of Time 1 and Time 2) is because estimation by multi-peaks involves more observations, which will generates smaller error, which is explained in Appendix.

After rift widening and mélange widening are both estimated, the rift wall widening $\Delta w_w$ can be calculated as $\Delta w_w = \Delta w - \Delta w_m$. In order to analyze the difference in the widening of the entire rift, mélange and rift walls in different time span, the widening rate is calculated as $r_r = \frac{\Delta w}{\Delta t}, r_m = \frac{\Delta w_m}{\Delta t}, r_w = \frac{\Delta w_w}{\Delta t}$, where $r_r, r_m, r_w$ are rift widening rate, mélange widening rate and rift wall widening rate, $\Delta w, \Delta w_m, \Delta w_w$ are rift widening, mélange widening or rift walls widening, and $\Delta t$ is the corresponding time span with the unit as month.

### 3.3 Additional observations of mélange widening from ice velocity maps

In Section 3.2, DEMs are utilized to quantify the rift widening process. However, considering the
limited quantity of REMA DEMs, ice flow velocity maps and optical imagery are used as supplementary data to quantify the widening process as well. First, the rift width and mélange width of Time 1 are measured from the image. An example of width measurement from Landsat image of 2014/10/29 is shown in Figure 6. The measurement is based on that different topographies on the ice shelf features different textures in the Landsat 8 images. The mélange features rough texture as salt and pepper noise while rift walls feature bright or dark strips under the solar illumination. So, rift width points $A_1$ and $A_2$ are selected along the profile at the edge between ice shelf surface and rift walls. Mélange width points $B_1$ and $B_2$ are at the edge between mélange surface with rift walls. So, rift width and mélange width can both be measured from width points. Then, rift widening is calculated directly as the difference of rift widths of two phases as $\Delta w = w_2 - w_1$.

![Figure 6. The mélange measured from Landsat 8 image (Scene ID: LC81881162014302LGN01).](image_url)
Second, ITS_LIVE ice velocity maps derived from two Landsat 8 images of Time 1 and Time 2 are utilized to quantify the mélange widening. The mélange widening calculation is also derived from the movement of the entire mélange as REMA DEM, not the difference of melange widths of two phases. Figure 7 shows the data points extracted from the ITS_LIVE ice velocity map (2014/10/29 – 2015/02/18) along the Profile 2, with the horizontal distance along Profile 2 as x coordinate and the ice velocity as y coordinate. The points are divided into two categories based on the inflection: blue dots for ice shelf surface and orange dots for mélange. It is indicated that the velocity of ice shelf surface is relatively stable, but a distinct rupture of velocity took place at the region of mélange. The velocity difference on the two sides of the rift demonstrated the “pull the mélange open” process mentioned in 3.2.3. Then, a linear fitting was also conducted between horizontal distance and ice velocity of mélange. The fitting formula is \( y = 0.1258x + 686.84 \) with \( R^2 \) as 0.9774, which also proves a significant correlation between horizontal distance and mélange widening.

![Figure 7. The ice velocity profile of profile 2 from ITS_LIVE velocity pair.](image)

The slope parameter \( k \) (0.1258) of the fitting formula indicates that 1 m-wide mélange will widen 0.1258 m in one year. So, the mélange widening monthly rate can also be calculated as
\[ r_m = \frac{kw_{m1}}{\Delta t}. \] Rift widening rate \( r_r \) is also calculated as \( r_r = \frac{\Delta w}{\Delta t} \) where \( \Delta t \) is the time span of the velocity map (unit: month). Rift wall widening is calculated as \( r_w = r_r - r_m \).

### 3.4 mélange height and volume change/mélange

During the widening process of rift T1, the height and volume of mélange are in dynamic change under the comprehensive influence from mass supply and mélange widening. Mélange widening will decrease the mélange surface height while the mass supply will compensate the height decrease. Mass supply includes rift wall debris along with surface mass accumulation. Before investigating the temporal change of mélange surface height and volume, the profiles are vertically registered to eliminate the vertical movement of ice shelves caused by tidal motions. The vertical registration is conducted by aligning the ice shelf surfaces to the same height. The detailed method is as follows:

1. The range of data points for vertical registration is selected. To eliminate the influence from the rift wall collapse, as Figure 8 shows the red range are selected, including the data points start from 1km south of A1 and extends 1km southwards or start from 1km north of A2 and extends 1km northwards are selected. (2) All the profiles along the same profile line are vertically registered. For example, there are 6 profiles of different time along Profile 2, the average election of data in the range for each profile is calculated as \( H_i, (1 \leq i \leq 6) \) for each profile \( i \). Then, the average height of Profile 2 is calculated as \( H_{p2} = \frac{\sum H_i}{6} \) and the bias for each profile with \( H_{p2} \) is calculated as \( \Delta H_i = H_i - H_{p2} \). Finally, all the profiles along the Profile 2 are vertically registered by minus the bias \( \Delta H_i \) from the elevation of each point.
Figure 8. The range of data points for vertical registration.

After 6 profiles in Profile 2 are vertically registered, the average mélange height in a profile is estimated as

$$H_{\text{melange}} = \frac{\sum h_i}{n},$$

where $h_i$ is elevation of point in the mélange range. The freeboard profile volume of mélange is estimated by area integration as

$$V_{fb_{\text{melange}}} = \sum (h_i - h_{\text{sea level}})w_s,$$

where $h_{\text{sea level}}$ is the sea level, $w_s$ is the sample interval of the profile as 1m in this study. $h_{\text{sea level}}$ is averaged from the sea level of Weddle Sea, which derived from ATL06 of ICESat-2 as $-15$ m. All the volume parameter mentioned in this paper are cross-section area of the profile with the unit as m$^2$, which can be further applied to interpolate the volume of the entire rift if the profiles are dense enough. The total volume of mélange including freeboard part and under-water part can be also estimated by hydrostatic equilibrium as

$$V_{\text{total melange}} = \frac{\rho_{\text{water}}}{\rho_{\text{water}} - \rho_{\text{melange}}}V_{fb_{\text{melange}}},$$

where $\rho_{\text{water}}$ and $\rho_{\text{melange}}$ are adopted as 1028 kg/m$^3$ and 865 kg/m$^3$ (King E C. Observations of a rift in the Ronne Ice Shelf, Antarctica)

4. Results

4.1 Overview of the propagation of all rifts throughout FRIS

The temporal series of all the rifts of FRIS from are extracted in this calving cycle. Extraction result
of rifts of 2021 are shown as an example in Figure 9a, along with the extracted boundaries tabular detachments of the previous calving event. The lengthening propagation rates from 2000 to 2021 and the lengths of 2021 of all rifts are also estimated and shown in Figure 9b. The detailed measurements and propagation rates are shown in Table A1 in Appendix. The rifts are divided into three categories: longitudinal (L), traverse (T) and marginal (M) rifts. Each rift is named with category and number. Most rifts propagated at slow rates during the calving cycle but some fast-propagated rifts worth more focusing. As Figure 9a shows in RIS, L9a is short but active, which may cause a detachment calving when intersecting with L8. M8, which together with T18 mainly caused the calving event in 2021, showed a fast propagation rate before calving event. This indicated that when the marginal and traverse large-scale rifts advance to the place where the last calving happened, a calving event is probably triggered. L9 also shows a fast propagation rate, which may cause a small calving when intersecting with L8. T17 is also active and ~125km long, which may dominate a similar calving event as in 1998/2000 and 2021. In FIS, it is noteworthy that T1 and T2 are longest rifts and feature the highest propagation rates. Their high propagation rates are both attributed to length propagation ruptures of T1 and T2 in 2011 and 2006 respectively, which drove them propagated from small rifts to long rifts in a short period of 3 days to 22days. The length ruptures indicate that high strain stress tend to accumulate in the region of T1 and T2, which caused the critical activity of T1 and T2. Additionally, T1 and T2 exhibit similar length and shapes to the Grand Chasm, which dominant the previous calving event in FIS. But the distance between Grand chasm and T1-T2 is about ~50 km, which means T1 and T2 may not result in the calving event recently. But They still needs a long-term and continuous monitoring.
Figure 9. (a) Map of rifts of 2021 in FRIS. (b) The lengthening rates from 2000 to 2021 and lengths of 2021 of all rifts in FRIS

4.2 Seasonal widening of rift T1

The time series of the widening rates (unit: m/month) from winter 2013 to summer 2017 are estimated according to Section 3. Widening rates are plotted as scatters linked by smooth curves in Figure 10, including rift widening rate ($r_r$, blue), mélange widening rate ($r_m$, orange) and rift wall widening rate ($r_w$, gray). The x-coordinate of the scatter is the mid of the time span of two DEMs or the ITS_LIVE velocity map. And the widening rates of the same season but at different profile lines are also averaged to investigate the change pattern of entire rift T1. The time spans of local
polar night at the position of rift T1 are also calculated and shown with gray background in Figure 10. It is indicated that rift widening process features a critical seasonal variation, which is intense in summer and slight in winter. However, the mélange widening rate show a relative stable trend as a contributor to the rift widening rate. Therefore, as the other contributor to the rift widening rate, the rift walls widening rate also features seasonal variation as the rift widening rate. Both the mélange widening and mélange height decrease show the linear change patterns as time goes, which is corresponding with the linear process of mélange volume change.

A slight overall upward trend of rift, mélange and rift wall widening all can be observed. This accelerating trend of widening deserves more research and attention in the future.

Figure 10. The time series of widening rates (unit: m/month), including rift widening rate ($r_r$), mélange widening rate ($r_m$) and rift wall widening rate ($r_w$) from winter of 2013 to summer of 2017.

4.3 The temporal change of mélange height and volumes

T1 and T2 reveal high activity, which require further investigation. T1 is selected to study its 3D
dynamics detailed widening process because T1 is much wider than T2 and its 3D internal structural information is richer observed from DEMs. The temporal change of mélange height and freeboard volume along Profile 2 is shown in Figure 11 with linear fittings conducted respectively. The freeboard volume features a linear increasing trend over time with a high R2 of 0.9988. It is mainly attributed to the mass supply from debris of rift walls. On the contrary, the mélange height decreases over time, which also features an approximate linear relationship with R2 of 0.8431. This is because the widening of the rift caused the redistribution of the mélange and lower the mélange height, which cannot be totally compensated by the mass supply from rift wall debris.

![Figure 11. The temporal change of freeboard volume and mélange height of Profile 2 from 2012/12/28 to 21016/11/16.](image)

4.4 Collapse of rift wall

It is noteworthy that the rift wall widening rate reveal significant seasonal variation, which contributes to the seasonal change pattern of rift widening. Then, two examples of Profile 1 and Profile 2 are used to demonstrated that the rift wall widening process show different rates in
summer and winter. Multi profiles spanning the whole year (from 2016/02/12 to 2017/01/04) display the process of rift wall collapsing and forming the new peak of mélange in Figure 12. These profiles are both horizontally and vertically aligned to eliminate the dynamics caused by horizontal ice flow and vertical tidal motion, to explore the change only caused by the rift wall collapse. The profiles are horizontally aligned at the south mélange boundary point B2. In Figure 12, (a) and (b) show the rift wall collapse process of summer and winter along Profile 1, respectively. Similarly, (c) and (d) show the rift wall collapse process of summer and winter along Profile 2. As Figure 12a shows, during ~9 month in the summer (from 2016/02/12 to 2016/11/01), a piece of debris started to form from the top and gradually separated from rift wall (red to blue line); When it came to winter in as in Figure 12b, during ~two month from 2016/11/01 to 2016/12/19, that piece of debris rapidly fully collapsed from rift wall and fell into mélange, forming a new peak in the mélange (blue to orange); during the next ~one month (2016/12/19 to 2017/01/04), the new forming peak continuously cracked into two smaller peaks. The debris volume is calculated to quantify the rift wall collapse rate. The volume change of rift wall was estimated from the area enclosed by two profiles within the rift wall range as

\[
\Delta V = \sum_{i=1}^{n} (h_{2i} - h_{1i})w_{i},
\]

where \( h_{1i} \) and \( h_{2i} \) are registered elevations of two profiles and \( w_{i} \) is the sample interval of profile as 1 m. Then the collapsing rate is calculated as

\[
\frac{\Delta V}{\Delta t},
\]

where \( \Delta t \) is the time span of two DEMs. The collapsing rates of summer 2016 and winter 2016-2017 along Profile 1 are 0.8 m\(^3\)/d and 43.6 m\(^3\)/d, which reflects a considerable seasonal difference. Similarly, profile 2 also demonstrates the seasonal difference of rift wall collapse. As Figure 12c shows, during the summer of ~9 month (from 2016/02/12 to 2016/11/16), a crack deepened and a piece of debris began to detach and separate from the wall (red to brown).
During the winter of ~2 month (from 2016/11/16 to 2017/01/04), the crack continued to deepen, and the detachment process of the debris continued with the same magnitude but in a much shorter period. The collapsing rates of summer 2016 and winter 2016-2017 along Profile 1 are also estimated as 1.7 m$^2$/d and 2.8 m$^2$/d. Even though the seasonal difference of this example is not so considerable as the former one, the collapse rate of winter is still obviously higher than summer. Two examples demonstrate that rift wall collapse process reveals critical seasonal variation, which explains the seasonal difference of the rift wall widening rate. Fricker et al. (2005) discussed that the mélange property may show seasonal variant. Cold water in winter may enhance mechanical strength while warm water in summer might decrease mélange strength. It is inferred that the material toughness of meteoric ice on the rift walls and ice shelf surface changes under different temperature, which lead to the seasonal variant of rift wall collapse.

Figure 12. The collapse process of the south wall from 2016/02/12 to 2017/01/04 along Profile 1 and Profile 2.
5. Conclusion

Rift is an important observational precursor of ice shelf calving because it forms the detachment boundaries of icebergs in calving events. The time series of all rifts in FRIS are mapped and measured from the previous calving event. Based on the estimated lengthening rates of all rifts, rift T1 is quite active, which is also highly related with the next calving event. Time series of high-resolution REMA DEMs, ITS_LIVE ice velocity maps and Landsat 8 images are comprehensively applied to investigate the widening process of the rift T1 for the first time, including mélange widening and rift walls widening. The rift widening process reveals seasonal variation while mélange widening rate is generally stable. The seasonal variation of rift widening is attributed to rift wall collapse process, which is intense in summer and slight in winter. The cross-section volume of mélange linearly decreased as time, which is caused by linear decreasing mélange surface height and mélange widening. The dynamics of mélange and rift walls is beneficial for understanding the rift propagation mechanism and its impact on ice shelf calving. The widening process of rift T1 still worth further monitoring for its significant influence on the next calving event.

Appendix

Rifts measurements of FIS and RIS

Table A1. Length and width of rifts in FIS
### Table A2. Length and width of rifts in RIS

| Rift | Jan. - Feb. 2021 | Dec. 2014 - Feb. 2015 | Nov. 2009 - Feb. 2010 | Jan. - Mar. 2005 | Dec. 1999 - Dec. 2001 |
|------|-----------------|-----------------------|-----------------------|-----------------|-----------------------|
| L1   | 7,414           | 554                   | 2,749                 | 2,649           | 1,761                 |
| L2   | 14,527          | 1,600                 | 12,472                | 11,861          | 8,287                 |
| L3   | 17,535          | 4,646                 | 17,786                | 16,668          | 15,964                |
| L4   | 10,615          | 577                   | 6,985                 | 2,357           | 1,800                 |
| L5   | 39,513          | 277                   | 23,004                | 21,310          | 17,891                |
| L6   | 82,401          | 1,089                 | 77,712                | 73,044          | 69,724                |
| L7   | 10,268          | 1,378                 | 10,346                | 10,346          | 10,346                |
| L8   | 125,923         | 1,116                 | 99,113                | 85,816          | 80,554                |
| L9   | 110,229         | 1,947                 | 106,605               | 92,216          | 91,214                |
| L10  | 111,654         | 1,601                 | 106,815               | 98,819          | 97,544                |
| L11  | 93,922          | 1,178                 | 93,016                | 91,163          | 89,147                |
| L12  | 26,034          | 669                   | 25,641                | 24,824          | 24,765                |
| L13  | 14,820          | 198                   | 14,884                | 14,884          | 14,884                |
| L14  | 5,705           | 139                   | 5,483                 | 5,385           | 5,379                 |
| L15  | 34,741          | 1,140                 | 32,403                | 26,243          | 16,402                |
| L16  | 74,305          | 2,963                 | 30,485                | 24,730          | 20,552                |
| L17  | 16,158          | 421                   | 13,182                | 11,388          | 73                    |
| L18  | 3,118           | 619                   | 4,147                 | 4,002           | 3,956                 |
| L19  | 22,711          | 3,825                 | 20,524                | 16,402          | 16,158                |
| L20  | 78,597          | 9,084                 | 36,888                | 33,661          | 24,116                |

### Table A3. Length and width propagation rates of rifts in FIS
| Width | late 2014 - early 2019 | Length | early 2010 - early 2015 | Width | Length | early 2005 - early 2010 | Width | Length | late 1999 - early 2005 |
|-------|------------------------|--------|--------------------------|-------|--------|--------------------------|-------|--------|------------------------|
| T1    | 2335.8                 | 638    | 5%                       | 1238  | 599    | 5%                       | 928   | 468    | 5%                     |
| T2    | 879.6                 | 838    | 7%                       | 952   | 236    | 56%                      | 746   | 468    | 5%                     |
| T3    | -315.5                | -23    | -3%                      | -47   | -17    | 44%                      | -28   | -4     | 9%                     |
| T4    | 267.4                 | 67     | 2%                       | 208   | 41     | 6%                       | 127   | 35     | 0%                     |
| T5    | 469.9                 | 195    | 4%                       | 5557  | 1579   | 97%                      | 1100  | 220    | 23%                    |
| T6    | 87.4                  | 22     | 1%                       | 192   | 48     | 22%                      | 1070  | 214    | 22%                    |
| T7    | 175.3                 | 44     | 1%                       | 418   | 148    | 35%                      | 474   | 132    | 33%                    |
| T8    | -346.2                | -86    | -6%                      | -56   | -14    | 22%                      | -182  | 24     | 13%                    |
| T9    | 1125.0                | 303    | 10%                      | 55    | 14     | 5%                       | 85    | 17     | 3%                     |
| L1    | 1602.5                | 401    | 34%                      | 622   | 155    | 26%                      | 4066  | 162    | 41%                    |
| L2    | 2046.0                | 512    | 84%                      | 566   | 148    | 14%                      | 1307  | 341    | 26%                    |
| L3    | 770.9                 | 198    | 4%                       | 338   | 86     | 25%                      | 6088  | 1218   | 4%                     |
| L4    | 407.3                 | 1118   | 107%                     | 198   | 27     | 48%                      | 6560  | 1128   | 62%                    |
| L5    | 168.2                 | 282    | 28%                      | 426   | 87     | 65%                      | 2109  | 438    | 107%                   |
| M1    | 6952.9                | 1648   | 46%                      | 135   | 34     | 86%                      | 696   | 140    | 109%                   |
| M2    | 4517.7                | 1150   | 109%                     | 585   | 98     | 154%                     | 5000  | 1132   | 80%                    |
| M3    | 4528.5                | 1018   | 109%                     | 420   | 87     | 66%                      | 2400  | 482    | 179%                   |
| M4    | 8263.9                | 2091   | 38%                      | -61   | -15    | 45%                      | 1047  | 169    | 62%                    |
| M5    | 4722.8                | 1191   | -52%                     | 539   | 155    | 10%                      | 8675  | 2755   | 153%                   |
| Avg.  | 8964.0                | 2487   | 14%                      | 16    | 14     | 87%                      | 8675  | 2755   | 153%                   |
| Avg.  | 2036.6                | 577    | 15%                      | 1871  | 504    | 10%                      | 2036  | 569    | 26%                    |
### Rifts

| Rift | 1996-1999 Length (m) | Increasing Speed (m a\(^{-1}\)) | Width | Late 1987-1996 Length (m) | Increasing Speed (m a\(^{-1}\)) | Width | Overall Length (m) | Increasing Speed (m a\(^{-1}\)) | Width |
|------|----------------------|----------------------------------|-------|--------------------------|----------------------------------|-------|-------------------|----------------------------------|-------|
| T1   | 736                  | 245 (9%)                         | 3     | 1                        | 0%                               | 1439  | 167 (27%)         | 194 (18)                        | 28%   |
| T2   | 189                  | 63 (7%)                          | 7     | 2                        | 2%                               | 598   | 54 (29%)          | 43 (4)                           | 74%   |
| T3   | 0                    | 0%                               | 11    | 4                        | 3%                               | 836   | 78 (37%)          | 110 (10)                         | 199%  |
| T4   | 0                    | 0%                               | 0     | 0                        | 0%                               | 679   | 62 (16%)          | 3 (3)                            | 121%  |
| T5   | 0                    | 0%                               | 22    | 7                        | 3%                               | 1938  | 136 (24%)         | 44 (4)                           | 180%  |
| T6   | 0                    | 0%                               | 26    | 9                        | 1%                               | 3478  | 136 (30%)         | 657 (60)                         | 235%  |
| T7   | 0                    | 0%                               | 51    | 17                       | 9%                               | 2778  | 253 (81%)         | 505 (46)                         | 15%   |
| T8   | 0                    | 0%                               | 342   | 114                      | 191%                             | 4472  | 1118              | 108 (27)                         | 0.54  |
| L1   | 5688                 | 632 (11%)                        | 1755  | 417                      | 328 (9%)                         | 342   | 114 (191%)        | 4472 (1118)                      | 108 (27) |
| L2   | 2846                 | 818 (28%)                        | 232   | 66                       | 24%                              | 1118  | 108 (27)          | 4472 (1118)                      | 108 (27) |
| L3   | 3122                 | 1041 (97%)                       | 342   | 114                      | 191%                             | 4472  | 1118              | 108 (27)                         | 0.54  |
| L4   | 1.35                 | 0.39 (39)                        | 335   | 173                      | 53%                              | 1.35  | 0.39 (39)         | 1.35 (0.39)                      | 0.39  |
| L5   | 1.0                  | 1.0 (100%)                       | 1.0   | 1.0                      | 1.0 (100%)                      | 1.0   | 1.0 (100%)        | 1.0 (1.0)                        | 1.0 (1.0) |
| L6   | 729                  | 810 (110%)                       | 303   | 98                       | 0.96                             | 729   | 810 (110%)        | 303 (98)                         | 0.96  |
| M1   | 4522                 | 1130 (246%)                      | 1219  | 246%                      | 0.53                             | 4522  | 1130 (246%)       | 1219 (246%)                      | 0.53  |
| M2   | 4324                 | 1081 (249%)                      | 1219  | 246%                      | 0.53                             | 4324  | 1081 (249%)       | 1219 (246%)                      | 0.53  |
| M3   | 2166                 | 155 (72%)                        | 569   | 41%                      | 0.15                             | 2166  | 155 (72%)         | 569 (41%)                        | 0.15  |
| M4   | 9146                 | 633 (69%)                        | 834   | 75%                      | 0.65                             | 9146  | 633 (69%)         | 834 (75%)                        | 0.65  |
| Avg. T | 132                 | 44 (34%)                        | 1758  | 158 (92%)                  | 14127 (92%)                      | 14127 | 9229 (83%)        | 14127 (92%)                      | 14127 |
| Avg. L | 3122                | 1041 (97%)                      | 342   | 114                      | 1.9                               | 3122  | 1041 (97%)        | 342 (114)                        | 1.9   |
| Avg. M | 5499.8              | 7659 (138%)                      | 1931  | 199 (103%)                 | 2402.3 (135%)                    | 2402.3 | 199 (103%)        | 1931 (199)                       | 2402.3 |
### Table A4: Length and width propagation rates of rifts in RIS

| Code | Early 2005 - Early 2010 | Early 2010 - Early 2015 | Late 2014 - Early 2021 |
|------|-------------------------|-------------------------|------------------------|
|      | Length | Width  | Length | Width  | Length | Width  |
|      | (m)    | (m)    | (m)    | (m)    | (m)    | (m)    |
|      | speed (m a⁻¹) | rate (m) | speed (m a⁻¹) | rate (m) | speed (m a⁻¹) | rate (m) |
| T10 | 4665   | 1166   | 170%   | 301    | 75     | 119%   |
| T11 | 2055   | 514    | 16%    | -43    | -11    | -3%    |
| T12 | 251    | -63    | 0%     | 1177   | 294    | 34%    |
| T13 | 3630   | 908    | 52%    | 215    | 59     | 60%    |
| T14 | 16500  | 4172   | 72%    | 81     | 21     | 41%    |
| T15 | -4665  | 1172   | 6%     | 177    | 44     | 19%    |
| T16 | -78    | -19    | 0%     | 94     | 24     | 7%     |
| T17 | 2680   | 6702   | 27%    | -26    | -7     | -2%    |
| T18 | 1624   | 990    | 3%     | 116    | 29     | 6%     |
| T19 | 4339   | 1210   | 5%     | -19    | -5     | -1%    |
| T20 | 906    | 226    | 1%     | 61     | 15     | 5%     |
| L7  | 99     | 98     | 2%     | 124    | 31     | 21%    |
| L7a | -64    | -16    | 0%     | -132   | -33    | -40%   |
| L7b | 222    | 55     | 4%     | -233   | -58    | -63%   |
| L8  | 2348   | 962    | 7%     | 343    | 86     | 47%    |
| L9  | 4321   | 9185   | 14.4%  | 1524   | 383    | 16.6%  |
| M6  | -1029  | -257   | -25%   | 44     | 11     | -8%    |
| M7  | 2187   | 547    | 11%    | 867    | 217    | 29%    |
| M8  | 41709  | 10427  | 11.3%  | 3685   | 921    | 69%    |

**Notes:**
- Rates are calculated over the indicated time periods.
- Increments and rates are calculated based on initial and final measurements.
- Percentages indicate changes from previous period.

- **L7**
  - Initial: 393 m, Width: 98 m, Increasing rate: 1%, Increasing speed: 2 m/a
  - Late 2014 - Early 2021:
    - Length: 1166 m, Width: 119 m
    - Increasing rate: 22%, Increasing speed: 51 m/a
  - Early 2005 - Early 2010:
    - Length: 2055 m, Width: 16 m
    - Increasing rate: 9%, Increasing speed: 22 m/a

- **M7**
  - Initial: 867 m, Width: 217 m, Increasing rate: 11%
  - Late 2014 - Early 2021:
    - Length: 3685 m, Width: 921 m
    - Increasing rate: 29%, Increasing speed: 14 m/a
  - Early 2005 - Early 2010:
    - Length: 2187 m, Width: 11 m
    - Increasing rate: 26%, Increasing speed: 54 m/a

**Conclusion:**
The propagation rates of rifts in RIS show significant variability across different periods, with notable increases in both length and width, particularly in the early 2010 - early 2015 period, indicating accelerated rift activity.
| RR  | late 1999- early 2005 | early 2005 - early 2021 | Overall rate | 2005-2021 lengthening rate (m a⁻¹) |
|-----|----------------------|--------------------------|--------------|-----------------------------------|
|     | length | Width | length | Width | length | Width | length | Width |
|     | increment (m) | Increasing speed (m a⁻¹) | Increasing rate | increment (m) | Increasing speed (m a⁻¹) | Increasing rate | increment (m) | Increasing speed (m a⁻¹) | Increasing rate |
| T10 | 1039 | 208 | 144% | 50 | 10 | 83% | 5653 | 404 | 321% | 6692 | 352 | 927% |
| T11 | 4038 | 812 | 96% | 1039 | 212 | 456% | 6240 | 446 | 75% | 8298 | 542 | 344% |
| T12 | 8148 | 1630 | 104% | 1234 | 25 | 12% | 1571 | 112 | 10% | 9719 | 512 | 23% |
| T13 | 602 | 133 | 50% | 0 | 0 | 0% | 8815 | 650 | 490% | 9482 | 499 | 837% |
| T14 | 7232 | 1808 | 68% | 27 | 5 | 55% | 21622 | 1544 | 121% | 28854 | 1539 | 217% |
| T15 | 2022 | 674 | 8% | 540 | 880 | 154% | 12677 | 905 | 18% | 14698 | 863 | 22% |
| T16 | 478 | 159 | 5% | 0 | 0 | 0% | -78 | -6 | -1% | 400 | 24 | 4% |
| T17 | 3305 | 1102 | 4% | 474 | 158 | 98% | 45369 | 3241 | 56% | 48674 | 2863 | 63% |
| T18 | 2430 | 605 | 3% | 67 | 17 | 4% | 19015 | 1358 | 21% | 21435 | 1191 | 24% |
| T19 | 2608 | 702 | 3% | 0 | 0 | 0% | 14140 | 1008 | 14% | 16918 | 940 | 18% |
| T20 | 711 | 178 | 1% | 55 | 14 | 5% | 4774 | 341 | 5% | 5466 | 305 | 6% |
| L7  | 13377 | 2675 | 117% | 131 | 26 | 179% | 1269 | 91 | 5% | 14646 | 771 | 129% |
| L7a | -64 | -5 | 0% | -64 | -5 | 0% | -127 | -9 | -3% | -309 | -15 | -6% |
| L7b | 326 | 23 | 6% | 326 | 23 | 6% | -309 | -15 | -6% | 326 | 23 | 6% |
| L8  | 5239 | 1044 | 47% | 85 | 17 | 50% | 18339 | 1310 | 112% | 23538 | 1240 | 211% |
| L9  | 63753 | 4554 | 604% | 63753 | 4554 | 604% | 2976 | 744 | 23% | 2622 | 66 | 26% |
| L9a | -178 | -13 | -5% | -178 | -13 | -5% | 437 | 31 | 21% | 437 | 31 | 21% |
| M7  | 19517 | 1394 | 611% | 19517 | 1394 | 611% | 3616 | 258 | 173% | 3616 | 258 | 173% |
| M8  | 2940 | 588 | 12% | 1465 | 293 | 72% | 51541 | 3881 | 190% | 54881 | 2867 | 226% |

**Error of widening ratio:**
- **T10:** 144%
- **T11:** 96%
- **T12:** 104%
- **T13:** 50%
- **T14:** 68%
- **T15:** 8%
- **T16:** 5%
- **T17:** 4%
- **T18:** 3%
- **T19:** 3%
- **T20:** 1%
- **L7:** 117%
- **L7a:** 0%
- **L7b:** 6%
- **L8:** 47%
- **L9:** 604%
- **L9a:** -5%
- **M7:** 611%
- **M8:** 12%
There are two methods estimating the mélange widening as follows. Their error calculation is also presented according to error propagation law.

1. Difference of mélange widths of two times

Mélange widening is estimated by \( \Delta w_m = w_{2m} - w_{1m} \), where \( w_{1m} \) and \( w_{2m} \) are mélange widths of Time 1 and Time 2. The error of a point (e.g. a peak or a width measure point) \( \delta_p \) is the interval of profile points as 1 m. The error of mélange width is \( \delta_{w_{1m}}^2 = 2\delta_p^2 \).

The error of mélange widening of this method is estimated as

\[
\delta_{\Delta w_m}^2 = \delta_{w_{1m}}^2 + \delta_{w_{2m}}^2 = 4\delta_p^2
\]

2. Linear fitting from mélange peaks

Mélange widening is estimated by \( \Delta w_m = \alpha w_{1m} \), where widening ratio \( \alpha \) is obtained from the slope parameter of linear fitting and \( w_{1m} \) is the mélange width of Time 1. The error of mélange widening is \( \delta_{\Delta w_m}^2 = \alpha^2 \delta_{w_{1m}}^2 + w_{1m} \delta_{\alpha}^2 = 2\alpha^2 \delta_p^2 + w_{1m} \delta_{\alpha}^2 \). Then, two errors \( 4\delta_p^2 \) and \( 2\alpha^2 \delta_p^2 + w_{1m} \delta_{\alpha}^2 \) are compared. For the first term, \( \alpha \) is \( 10^{-4} \) order of magnitude (e.g. \( \alpha = 0.0071 \) in the example used in the paper) so \( \alpha^2 \delta_p^2 \ll \delta_p^2 \). For the second term, \( \delta_{\alpha}^2 \) is also obvious greater than \( \delta_p^2 \). Because only the DEM with \( R^2 \geq 0.9 \) is applied in mélange widening calculation, \( \sum (y_j - \alpha x_j - b)^2 \) is close to zero. \( n \sum x_i^2 - \sum x_j^2 = (n-1) \sum x_i^2 - 2 \sum x_i x_j \), where \( (n-1) \sum x_i^2 \) is also obvious greater than \( 2 \sum x_i x_j \). In the example in this paper, \( \delta_{\alpha}^2 \) is calculated as \( 7.28 \times 10^{-7} \), which is much less than \( \delta_p^2 \). Therefore, estimating mélange widening from linear fitting generates smaller error.
Reference:

Alley, K.E., Scambos, T.A., Siegfried, M.R., & Fricker, H.A. (2016). Impacts of warm water on Antarctic ice shelf stability through basal channel formation. *Nature Geoscience, 9*, 290-+, https://doi.org/10.1038/ngeo2675

Bassis, J.N., Fricker, H.A., Coleman, R., & Minster, J.-B. (2008). An investigation into the forces that drive ice-shelf rift propagation on the Amery Ice Shelf, East Antarctica. *Journal of Glaciology, 54*, 17-27, https://doi.org/10.3189/002214308784409116

Bassis, J.N., & Ma, Y. (2015). Evolution of basal crevasses links ice shelf stability to ocean forcing. *Earth and Planetary Science Letters, 409*, 203-211, https://doi.org/10.1016/j.epsl.2014.11.003

Bull, C.Y.S., Jenkins, A., Jourdain, N.C., Vaňková, I., Holland, P.R., Mathiot, P., Hausmann, U., & Sallée, J.B. (2021). Remote Control of Filchner–Ronne Ice Shelf Melt Rates by the Antarctic Slope Current. *Journal of Geophysical Research: Oceans, 126*, https://doi.org/10.1029/2020jc016550

Cuffey, K.M., & Paterson, W.S.B. (2010). *The physics of glaciers*. Academic Press

Ferrigno, J.G., & Gould, W.G. (1987). Substantial changes in the coastline of Antarctica revealed by satellite imagery. *Polar Record, 23*, 577-583, https://doi.org/10.1017/S003224740000807X

Fricker, H.A. (2005). Multi-year monitoring of rift propagation on the Amery Ice Shelf, East Antarctica. *Geophysical Research Letters, 32*, https://doi.org/10.1029/2004gl021036

Gardner, A.S., Fahnestock, M.A., & Scambos, T.A. (2019). MEaSUREs ITS_LIVE Landsat Image-Pair Glacier and Ice Sheet Surface Velocities: Version 1, https://doi.org/10.5067/IMR9D3PEI28U

Glasser, N.F., Kulessa, B., Luckman, A., Jansen, D., King, E.C., Sammonds, P.R., Scambos, T.A., & Jezek, K.C. (2009). Surface structure and stability of the Larsen C ice shelf, Antarctic Peninsula. *Journal of Glaciology, 55*, 400-410, https://doi.org/10.3189/002214309788816597

Howat, I.M., Porter, C., Smith, B.E., Noh, M.J., & Morin, P. (2019). The Reference Elevation Model of Antarctica. *Cryosphere, 13*, 665-674, https://doi.org/10.5194/tc-13-665-2019

Joughin, I., & MacAyeal, D.R. (2005). Calving of large tabular icebergs from ice shelf rift systems. *Geophysical Research Letters, 32*, https://doi.org/10.1029/2004GL020978

LT Falon M. Essary, U. (2021). Iceberg A-76 Calves from the Ronne Ice Shelf in the Weddell Sea, Largest Iceberg in the World. In, *U.S. National Ice Center*

MacAyeal, D.R., Rignot, E., & Hulbe, C.L. (1998). Ice-shelf dynamics near the front of the Filchner-Ronne Ice Shelf, Antarctica, revealed by SAR interferometry: model/interferogram comparison. *Journal of Glaciology, 44*, 419-428, https://doi.org/10.3189/S0022143000002744

Oerter, H., Wilhelms, F., Jung-Rothenhäuser, F., Göktas, F., Miller, H., Graf, W., & Sommer, S. (2000). Accumulation rates in Dronning Maud Land, Antarctica, as revealed by dielectric-profiling measurements of shallow firm cores. *Annals of Glaciology, 30*, 27-34, https://doi.org/10.3189/172756400781820705

Rignot, E., Jacobs, S., Mouginot, J., & Scheuchl, B. (2013). Ice-shelf melting around Antarctica. *Science, 341*, 266-270, https://doi.org/10.1126/science.1235798

Rignot, E., & MacAyeal, D.R. (1998). Ice-shelf dynamics near the front of the Filchner—Ronne Ice Shelf, Antarctica, revealed by SAR interferometry. *Journal of Glaciology, 44*, 405-418, https://doi.org/10.3189/S0022143000002732

Walker, C.C., Bassis, J.N., Fricker, H.A., & Czerwinski, R.J. (2013). Structural and environmental controls on Antarctic ice shelf rift propagation inferred from satellite monitoring. *Journal of Geophysical Research: Earth Surface, 118*, 2354-2364, https://doi.org/10.1002/2013jf002742