Tidal and Thermal Stresses Drive Seismicity along a Major Ross Ice Shelf Rift

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Key Points:

\begin{itemize}
  \item 2515 icequakes associated with rift deformation on the Ross Ice Shelf are located using a double difference location algorithm.
  \item Icequake timing correlates with tidal phase on a diurnal timescale and inversely correlates with air temperature on multi-day and seasonal timescales.
  \item Ocean swell, infragravity waves and a significant tsunami arrival are not correlated with increased rift activity.
\end{itemize}

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Abstract

Understanding deformation in ice shelves is necessary to evaluate the response of ice shelves to thinning. We study microseismicity associated with ice shelf deformation using 9 broadband seismographs deployed near a rift on the Ross Ice Shelf. From December 2014 - November 2016, we detect 5948 icequakes generated by rift deformation. Locations were determined for 2515 events using a least squares grid-search and double-difference algorithm. Ocean swell, infragravity waves and a significant tsunami arrival do not affect seismicity. Instead, seismicity correlates with tidal phase on diurnal timescales and inversely correlates with air temperature on multi-day and seasonal timescales. Spatial variability in tidal elevation tilts the ice shelf, and seismicity is concentrated while the shelf slopes downward toward the ice front. During especially cold periods, thermal stress and embrittlement enhance fracture along the rift. We propose that thermal stress and tidally-driven gravitational stress produce rift seismicity with peak activity in the winter.

Plain Language Summary

In Antarctica, large bodies of floating ice called ice shelves help prevent ice on land from sliding into the ocean. To predict how Antarctica might respond to climate change, we need to understand how ice shelves interact with the environment, including the atmosphere and the ocean. The largest ice shelf, the Ross Ice Shelf, is over 500,000 km$^2$ in area, making it the largest body of floating ice in the world. In this study, we deployed 9 seismographs, the same instruments used to study earthquakes, to monitor vibrations and cracking within the Ross Ice Shelf over a two-year period. During that time, the instruments detected nearly 6000 fracture events along a 120 km long crack in the ice shelf. We compared the timing of the cracking to air temperature data, ocean wave activity, and tides to see whether these factors influenced the crack’s behavior. We found that fracture occurs most frequently just after high tide during winter, when the air is very cold. We also found that fracture at the rift is not triggered by ocean waves. This work demonstrates that Antarctic ice shelves are very sensitive to the environment and highlights the need to continue studying them.
1 Introduction

The need to understand marine ice sheet stability under various climate scenarios has fueled ongoing discourse about the nature and forcing of fracturing processes in floating ice shelves. Brittle deformation of large ice shelves is dominated by the propagation of large, through-cutting fracture-propagated rifts (Benn et al., 2007). Debate has largely focused on the relative importance and interactions of ocean wave-induced stresses (Holdsworth & Glynn, 1978; MacAyeal et al., 2008; Cathles et al., 2009; K. M. Brunt et al., 2011; Bromirski et al., 2010; Bromirski & Stephen, 2012; Bromirski et al., 2015; Banwell, 2017; Masson et al., 2018), glacial stresses (Bassis et al., 2005; Hulbe et al., 2010a; LeDoux et al., 2017), and rift-filling melange (Fricker et al., 2005; Larour et al., 2004; Rignot & MacAyeal, 1998; MacAyeal et al., 1998). Seismic observations have the ability to quantify small scale brittle deformation in the form of icequakes, and thus provide an efficient means to investigate the spatial and temporal extent of ice shelf fracture processes (Bassis et al., 2007; Heeszel et al., 2014; Hulbe et al., 2016; Lipovsky, 2018).

As part of two coupled projects to study the dynamics of the Ross Ice Shelf (RIS) and the solid Earth structure beneath (Bromirski et al., 2015), 9 broadband seismographs were deployed spanning both sides of a large rift located about 150 km south of the RIS front (Figure 1), denoted as WR4 (Walker et al., 2013). This deployment provides an important opportunity to investigate the role of various processes that drive ice shelf fracture. LeDoux et al. (2017) found that rift WR4's eastern tip currently is located adjacent to a suture zone, a region of deformed ice that arrests rift propagation, and multi-year imagery has confirmed that WR4 is not actively propagating (Walker et al., 2013). Despite WR4's apparent inactivity, the RIS array detected numerous icequakes in the vicinity of the rift, which we use to determine whether the rift is undergoing active brittle deformation and to provide constraints on the forces influencing rift propagation.

2 Data

2.1 Seismic Data

This study uses data collected by two simultaneous collaborative seismograph deployments on the Ross Ice Shelf. We use 9 seismic stations deployed along two lines that intersect near 78.96°S, 179.88°W (Figure 1). These stations are a subset of the 34 seismic stations that were deployed across a much larger region (Figure 1). Each station con-
sisted of a Nanometrics T120 PHQ broadband seismometer buried about 1 meter into
the firn recording at 200 samples per second and a Quanterra Q330 datalogger. The equip-
ment was powered by solar panels in the austral summer and by lithium batteries in the
winter. The instruments were deployed in November 2014 and the first year of data was
retrieved November - December of 2015. The instruments were recovered, and the final
year of data was retrieved in November - December of 2016.

2.2 Weather and Environmental Data

Temperature data from the Automatic Weather Station (AWS) project was used
to investigate whether seismicity is correlated with meteorological phenomena. The AWS
weather stations are deployed across Antarctica and record temperature, pressure, wind
speed, and humidity (Lazzara et al., 2012). Because of its proximity to the array and
the completeness of its records, we use data from station Gill, located at 79.823°S, 178.536°W
at a distance of 80 km from the center of the array.

3 Methods

3.1 Detection and Location

We utilized an automated short-term average/long-term average (STA/LTA) event
detection routine to form a catalog of any local activity recorded on stations with a high
signal-to-noise ratio. We detected 5948 unique events throughout both years of data af-
fer manually removing all detections of non-local seismicity. To generate arrival times
and to analyze the similarity of the detected events, we applied a cross-correlation and
clustering algorithm to the entire dataset. However, the events did not exhibit high cor-
relation values, and the clusters generated were not consistent across different stations
and components, indicating that, unlike many icequakes, the events are not true repeating
events. A typical event waveform is shown in Supplementary Figure 1.

We initially located a subset of the largest events from 2015 using manually-picked
P and S wave arrival times. However, direct P and S wave arrivals were often small and
e emergent, making it difficult to pick arrival times consistently. Because vertical compo-
ent Rayleigh wave arrivals were much easier to identify, we located the entire dataset
using Rayleigh wave arrival times. We calculated envelope functions for each event wave-
form on DR14, DR13, DR12, DR11, DR10, DR09, DR08, DR07, and RS04. Because these
Icequake waveforms are dominated by surface waves, the maximum value of each envelope function corresponds to the arrival of Rayleigh waves. A STA/LTA threshold was also applied to prevent incorrect identification of arrivals. Using this process, Rayleigh arrival times were automatically generated for all 5948 events.

We located the events that had Rayleigh phase arrivals on more than five stations. We first used a simple grid-search algorithm that minimized the misfit between observed and predicted Rayleigh arrivals by calculating a summed squared error for each potential location in the grid and selecting the lowest error point. In order to calculate misfit, we back-propagated the arrivals and took the mean time as the origin time. Once satisfactory locations were obtained from the grid-search, we removed arrivals from stations with travel time residuals greater than 1 second for each event. Events now with less than five arrivals were removed, and the remaining events were relocated using a standard iterative least-squares inversion. From the resulting locations, those with location and origin time standard deviations greater than 2 km and 2 seconds were removed, and the remaining 2515 events were relocated using a double-difference relative location method.

To determine an accurate Rayleigh phase velocity for use in event relocation, grid-search locations were calculated using an initial velocity of 1.5 km/s. We then selected all events aligned with DR13, DR12, and DR10 and calculated the time difference between arrivals on DR13 and DR12, DR13 and DR10, and DR12 and DR10 to obtain estimates of Rayleigh velocity largely independent of source locations. A least-squares inversion was then used to determine the velocity that minimized the misfit between the observed and predicted arrival time differences calculated using the known distances between stations. This calculation resulted in a Rayleigh velocity of 1.55 km/s, which was then used in the grid-search, linearized inversion, and double-difference location methods. This Rayleigh wave velocity is similar to that predicted for a structure of slow velocity firn overlying ice.

3.2 Comparison with Environmental and Weather Phenomena

To investigate the relationship between rift seismicity and the atmosphere, we compare the timing of seismicity with Automatic Weather Station air temperature data from 2015 and 2016 (Lazzara et al., 2012). We also compare the timing of events with tidal phase and tidal slope. Tidal heights were obtained by running the CATS2008 model, an
update to the model described by Padman, Fricker, Coleman, Howard, and Erofeeva (2002), for the duration of the deployment at the center of the array (DR10). To find the time of each high tide, local maxima were calculated for the dataset. We then calculated the difference in time between each event and the most recent high tide. The resulting times were binned by hour, yielding the number of events that occur in each hour after high tide. Finally, we divided by the total length of the corresponding tidal cycle to yield a measure of event timing binned by tidal phase. We calculated the slope at the ice shelf by running the CATS2008 model at both the grounding line (82°S, 164°E) and the front (78.5°S, 179°E), finding their difference, and dividing by the distance between the two points.

To investigate swell and infragravity waves, we made a spectrogram of the long period horizontal north-south component data from DR10. Previous work by Bromirski et al. (2017) found that IG waves generate greater horizontal displacements than vertical displacements on RIS, so we used the horizontal component data for our analysis of ocean swell and IG waves. Before generating a spectrogram, we first removed the instrument response to displacement on the frequency band 0.015 Hz - 0.2 Hz. To find swell band power, we integrated the spectrogram over the frequency band 0.03 Hz - 0.15 Hz for each window used to produce the spectrogram. To find IG band power, we integrated the spectrogram over the frequency band 0.015 Hz - 0.03 Hz for each window used to produce the spectrogram. These frequency limits were selected based on the ocean wave classification presented in Toffoli and Bitner-Gregersen (2017).

4 Characteristics and Locations of Rift Seismicity

Icequakes with high signal-to-noise exhibit distinct P, S, surface wave, and longitudinal plate wave arrivals (Press & Ewing, 1951). Icequake events are lower frequency than similarly-sized tectonic earthquakes (Aki, 1967) with peak amplitudes between 1-4 Hz. In all cases, the icequake-associated surface waves have the largest amplitudes. We find that the icequakes range in size from $M_L = -2.5$ to $M_L = 0$ (Equation 1), and there is evidence for a $b$-value greater than 1 based on the statistics of larger magnitude events, indicating that this sequence of icequakes has a higher ratio of small to large events than predicted by a standard Gutenberg-Richter distribution. Typical waveforms are shown in Supplementary Figure 1.
The icequake epicenters were located using a double difference method and automated picks of peak Rayleigh wave arrival times on the vertical component seismogram. The icequakes are located along a 30 km segment of the rift (Figure 1), associated with three broad regional patterns of icequake activity. First, icequakes located east of about 180°E are aligned with the central axis of the rift. Because the observed icequakes have high amplitude surface waves relative to body waves, it is likely that the icequakes occur near the ice shelf surface (Lough et al., 2015). Possible sources include fracture along the upper edges of the rift walls and collision, settling, or fracture of the blocks of ice within the melange.

Second, many of the icequakes west of about 180°E occur along a series of en echelon features within the wider region of rift-filling melange. Because the standard deviations of relative icequake locations are typically around 100 m and because of the strong spatial association of the events with the en echelon shear zone features, we are confident that these events originated within the melange and were not incorrectly located events occurring along the rift walls. We therefore interpret this second group of icequakes to be caused by deformation of the rift-filling melange. Because events in the melange
begin to occur where the rift widens, we speculate that the type of brittle ice shelf de-
formation recorded here may cause widening at the middle of the rift. See Supplementary
Figure 2 for a more detailed view of rift morphology.

Third, events decrease in number west of about 179.5°E and distant events are typ-
ically less precisely located. To determine whether the apparent concentration of icequakes
is an artifact of our network geometry, we examined the magnitude of the events at var-
ious positions along the rift. We find that the prevalence of low magnitude events de-
creases with distance from the intersection of the array and the rift, suggesting that the
apparent decrease in seismicity away from the network may be the result of attenuation
of similar-sized signals from more distant icequakes. It is therefore possible that relatively
uniform levels of seismicity occur along the entire rift.

Icequakes are not clustered in front of the rift tip as was previously observed at the
actively-propagating Loose Tooth Rift in the Amery Ice Shelf (Bassis et al., 2008; Heeszel
et al., 2014) but instead cease abruptly where the rift reaches the adjacent suture zone
at around 179.5°W. This decrease in seismicity is not due to reduced array detection ca-
pability to the west, as very small events are detected in the rift near the rift tip. We
interpret the lack of icequakes at the rift tip to indicate a lack of brittle deformation in
this region. Since westward propagation of the WR4 rift tip has currently stagnated (Walker
et al., 2013; LeDoux et al., 2017), our inferred lack of brittle deformation is therefore con-
sistent with rift stagnation in suture zones (Hulbe et al., 2010b; McGrath et al., 2014;
Kulessa et al., 2014; Borstad et al., 2017).

5 Ice Shelf Slope from Ocean Tides Controls Diurnal Patterns in Seis-
micity

We observe tidal modulation of the icequake activity (Figure 2a). As tides rise, the
level of seismicity increases until about 5 hours after high tide, when the level of seis-
micity begins to fall. The timing of events within a day is well-correlated with the tidally-
modulated slope of the ice shelf, with the highest seismicity rates when the entire Ross
Ice Shelf slopes downwards toward the ocean (Figure 2b). When the shelf tilts, a hor-
izontal component of gravitational force arises in the plane of the ice shelf. If the shelf
is tilted towards the continent, the rift is under compression and we see low levels of seis-
micity; if the shelf is tilted seawards, the rift is subjected to additional extensional stress
and we see high levels of seismicity. Using the CATS2008 tide model (Padman et al., 2002),
we find that this 5-hour delay corresponds to a maximum tidally-induced tilt of the entire Ross Ice Shelf (Figure 2). We calculate the maximum stretching stress that could affect the rift associated with this tilt to be $\rho_i g \alpha L$ where $\rho_i$ is the ice density, $g$ is the acceleration due to gravity, $L$ is the distance from the rift to the ice front, and $\alpha$ is the tidally-induced tilt angle. For $\alpha = 10^7$, this suggests maximum stretching stresses on the order of 1 kPa, in agreement with stress due to sea surface tilt calculated by Bassis et al. (2008). Our findings are consistent with previous observations of tidally-modulated glacial seismicity (Barruol et al., 2013; Podolskiy et al., 2016) and tidally-modulated ice shelf flow (K. Brunt et al., 2010; Makinson et al., 2012). Furthermore, they suggest that stretching stresses from tidal cycles are preferentially released at rifts and may be associated with the processes that widen rifts after formation.
6 Temperature Controls Multi-day and Seasonal Patterns in Seismicity

The detected icequakes exhibit a distinct seasonality that correlates with surface temperature data (Figure 3a). Temperature data was recorded by station Gill (Figure
1) of the Antarctic Weather Stations project (Lazzara et al., 2012), at a distance of 80 km from the center of the array. In the Antarctic summer (Dec/Jan/Feb), very low levels of seismicity are observed. However, as soon as temperatures begin to decline rapidly at the beginning of winter in both 2015 and 2016, the average number of events per day increases dramatically, with days containing over 20 events becoming common. Furthermore, large and rapid decreases in temperature appear to be associated with days of particularly high activity. The coldest periods of 2015 and 2016 both correspond to days with the largest number of icequakes. Although seismic noise levels are highest in the summer, examination of the temporal pattern of the larger events shows that the seasonal pattern of seismicity is not due to the seasonality of the seismic noise floor (Supplementary Information and Supplementary Figure 3).

There are two potential mechanisms that could account for the correlation between icequake activity and temperature. First, ice experiences low temperature embrittlement when loaded in compression (Petrovic, 2003). It is therefore plausible that tidal stresses result in ductile deformation at high temperatures but brittle icequake-related deformation at lower temperatures. This explanation is consistent with studies that find seasonal variability of ice shelf material properties (Bromirski & Stephen, 2012).

Second, the uppermost portion of the ice experiences thermal contraction in response to rapid temperature drops, and would thus be under tensional stress, as is observed for sea ice during cold weather (Evans & Untersteiner, 1971; Richter-Menge & Elder, 1998; Dempsey et al., 2018). Similar behavior has been observed in some alpine glaciers, which exhibit thermal fracturing in response to cold night-time temperatures (Podolskiy et al., 2018; Zhang et al., 2019). Although we have not obtained source parameters for these events, the association between the icequakes and tensional tidal stress, and their location in a rift zone, suggest that the events are dominantly tensional. Since both the tidal and the thermal mechanisms produce horizontal tensional stress, it is likely that they act in concert. Because short-period temperature fluctuations only propagate to a depth of several meters in glacial ice (Giese & Hawley, 2015), shallow icequake locations are consistent with the correlation between icequake activity and surface air temperatures. However, we note the possibility that enhanced cold air circulation within the rift may cause thermal contraction deeper in the ice than would otherwise be possible.
7 Rift Seismicity is Insensitive to Ocean Swell and Infragravity Waves

Both ocean swell and infragravity (IG) waves are poorly correlated with seismicity at WR4. We analyze the contribution of swell and IG waves by spectral analysis of the horizontal north-south component data from station DR10, since ocean waves generate large horizontal displacements on RIS (Bromirski et al., 2017). Because sea ice attenuates ocean waves (Massom et al., 2018), swell energy only reaches the array during the austral summer, when seasonal sea ice is minimal in extent. Rift seismicity is far less frequent in the austral summer than in the winter, and periods that contain significant swell energy correspond to very low levels of seismicity at the rift (Figure 3b, 3c). Furthermore, when peak levels of seismicity are observed during wintertime icequake swarms, minimal power is observed in the swell band.

Infragravity waves are damped less effectively than swell by winter sea ice (Bromirski & Stephen, 2012), and IG wave excitation of the RIS is detected by the array year-round (Figure 3b). We find that IG band power is poorly correlated with seismicity (Figure 3d). Most swarms occur on days that lack significant IG band power, and the largest IG events recorded at the array do not correspond to swarms of seismicity. Finally, the baseline level of IG power is nearly constant throughout the year and does not explain the seasonality observed in rift seismicity. On September 17, 2015, a tsunami generated by the $M_w$ 8.3 Illapel, Chile earthquake reached the ice shelf, exciting horizontal displacements of about 7 cm at DR10 (Bromirski et al., 2017). The tsunami arrival is marked in Figure 3 and is particularly visible in the swell power time-series. However, the tsunami does not correspond to an increase in seismicity at WR4. This is consistent with previous findings that only rifts open to the ocean at the calving front propagate when a tsunami arrives (Walker et al., 2013), further suggesting that WR4 is not subject to significant wave-induced fracture.

8 Conclusions

Two primary environmental factors control rift seismicity at WR4. Diurnally, the timing of events is well-correlated with tidally-driven changes in ice shelf slope. Over longer time periods, the timing of events is well-correlated with air temperature, with peak levels of activity in the winter and swarms of events on particularly cold days. The combination of these two factors explains the temporal patterns in seismicity that we observe.
Figure 4. Density plot of number of events as a function of tidal phase and temperature. Temperature data is from weather station Gill (Figure 1). Peak levels of seismicity are observed when temperature is low and when the shelf is most highly sloped downward toward the ice front during falling tide.

here and demonstrates the high environmental sensitivity of rift deformation. Figure 4 illustrates that maximal icequake activity occurs during cold periods when the ice shelf is sloping downward toward the ice front. We note that while low levels of icequake activity are observed at low tide, no rift seismicity is observed above -10°C. From this analysis, we conclude that although thermal and tidal stresses are both important in generating shallow icequake activity, temperature exerts the most significant control on brittle deformation at WR4.
The sequence of WR4 icequakes differs from patterns of seismicity seen in propagating rifts, and the correspondence of the locations to en echelon shear zone features suggests that fracture may occur within the melange filling the rift. Swell and IG waves were not correlated with rift seismicity, though they may still exert some influence on rift behavior at RIS and at other ice shelves. The timing of rift activity at WR4 appears to be primarily modulated by thermal and tidal stresses arising from fluctuations in air temperature and changes in ice shelf slope, and this work represents a novel demonstration of tidal influence on ice shelf processes far from the grounding line. On the Ross Ice Shelf, thermal and tidal stresses act in concert with ice shelf stresses, but not wave-induced stresses, to drive brittle deformation that may widen a major rift.

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