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Abstract We observe two (M3) long-period (10–30 s) seismic events that originate from the terminus of Thwaites Glacier, Antarctica. Serendipitous acquisition of satellite images confirm that the seismic events were glacial earthquakes generated during the capsizing of icebergs. The glacial earthquakes were preceded by 6 days of discrete high-frequency seismic events that can be observed at distances exceeding 250 km. The high-frequency seismicity displays an increasing rate of occurrence, culminating in several hours of sustained tremor coeval with the long-period events. A series of satellite images collected during this prescient time period show that the high-frequency events and tremor are the result of accelerating growth of ancillary fractures prior to the culminating calving event. This study indicates that seismic data have the potential to elucidate the processes by which Thwaites Glacier discharges into the ocean, thus improving our ability to constrain future sea level rise.

Plain Language Summary Thwaites Glacier is one of the largest sources of Antarctic ice mass loss; however, the physics of the processes that control its discharge into the ocean remains incomplete. The long-term stability of glaciers, such as Thwaites, that discharge directly into the ocean is linked to the rate of calving, the process of iceberg production. Spaceborne observations are crucial to understanding the calving processes; however, the typical repeat time of a satellite imagery is much longer than the typical duration of a calving event (minutes to hours). Increasingly, the seismic signals generated during calving are being used to complement other observations. For larger calving events, seismic energy can be recorded by remote seismic observation (hundreds to thousands of kilometers away from a glacier). While these glacier earthquakes are now regularly used to study calving in Greenland, only a limited number of glacial earthquakes have been observed in Antarctica. We show that Thwaites Glacier has now begun generating glacial earthquakes similar to those observed in Greenland. Additionally, we show that enhanced rates of fracturing can be seismically observed before the event. Our observations open a new avenue for understanding the behavior of Antarctica’s leading source of mass loss.

1. Introduction

Thwaites Glacier, located in the Amundsen Sea sector of the West Antarctic Ice Sheet, has undergone significant thinning and retreat during the past several decades (Mouginot et al., 2014) and now has an annual mass loss of ~37 Gt/year (Rignot et al., 2019). Several studies have inferred that a runaway instability of the ice sheet may be underway, leading to the potential collapse of the Thwaites Glacier and several meters of sea level rise at the century time scale (Joughin et al., 2014; Rignot et al., 2014). The future stability of Thwaites Glacier, and the rate of further retreat, is strongly controlled by the conditions and processes active near the grounding zone, where the ice sheet goes afloat (i.e., DeConto & Pollard, 2016).

At present, the grounding zone of Thwaites Glacier is characterized by three glaciologically distinct regimes (Figure 1). The eastern side of the glacier flows into a 50 km long buttressed ice shelf, a feature that provides some resistance to ice discharge. During the past four decades, thinning of the Thwaites ice shelf in this area has led to a decrease of buttressing along this sector of the glacier (Mouginot et al., 2014). The central portion of the glacier discharges into an ice tongue, an unconfined floating ice shelf that provides only minimal buttressing (Fürst et al., 2016). The western portion of the glacier flows into a mélange composed of icebergs and sea ice, the broken remains of the ice tongue that completely detached in this area in 2010 (MacGregor et al.,...
2012), and now has a relatively minor (<5 km) floating extension (Milillo et al., 2019), a geometry similar to many Greenland outlet glaciers (Amundson et al., 2010).

In grounding zone regions with minimal floating extensions (i.e., the western portion of Thwaites) calving mechanics play an important role in the evolution of the ice sheet margin. However, processes associated with fracture initiation and propagation in ice are not completely understood (Benn et al., 2007) due, in part, to the challenging nature of making direct observations of the fracture processes. For example, satellite observations often provide high spatial resolution, but the temporal resolution (>1 day) often remains too coarse to resolve the calving processes that may occur at short time scales (seconds to hours). While in situ optical and radar observations are often possible on smaller glaciers where topography provides an observational perch (i.e., Amundson et al., 2010), the scale of Antarctic calving fronts preclude this opportunity in most instances. One increasing opportunity to remotely observe the calving process in detail is with teleseismic (Ekström et al., 2003), regional-scale seismicity (Bartholomaus et al., 2012; Köhler et al., 2012; O’Neel et al., 2010) as well as local-scale seismic activity observed with focused deployments on ice shelves (Bassis et al., 2005). In Antarctica, signals generated by glacier sliding have been observed at regional and teleseismic distances (Wiens et al., 2008; Zoet et al., 2012). However, teleseismic studies show that Antarctica produces few long-period “glacial earthquakes” compared to Greenland, and such events have not been identified in the Thwaites region (Chen et al., 2011; Nettles & Ekström, 2010). In addition, regional seismic stations are too sparsely distributed for routine location and monitoring of smaller short-period glacial signals.

Figure 1. (a) Thwaites Glacier region. Background image is November 2018 Sentinel-1 image overlain with surface velocity (Rignot et al., 2011) and grounding line and ice front positions (Scambos et al., 2007). (b) Location of seismographs used in this study and location of Thwaites Glacier. (c, d) Sequential Sentinel-1 images showing the evolution of the ice front associated with the 8 November calving event and the approximate location of all seismic signals. (c) Major rifts (R1–R4) associated with the calving event are identified. Location of images in Figures 3a–3d are indicated. (d) Earliest image showing the generation of new icebergs. Circles outline regions that calve in the subsequent 48 min. (e) Red polygons outline examples of capsized icebergs formed during the preceding 48 min. (f) Image showing the postcalving event geometry.
Here we show that remote seismic observations can be used to study the calving events of Thwaites Glacier. We focus on an event from 8 November 2018 that is well captured by both seismic and satellite observations. We document the generation of two ($M_S \sim 3$) long-period (>10 s) seismic signals, similar to those generated during buoyant iceberg calving of Greenland outlet glaciers (Murray et al., 2015; Nettles & Ekström, 2010). Additionally, we observed days of precursory seismic activity associated with fracturing leading up to calving initiation, and 3 hr of sustained high-frequency tremor during the calving event, providing constraints on the timing and mechanics of the calving process.

2. Data

We utilize seismic data and satellite imagery to track the spatiotemporal evolution of the ice shelf during the week preceding the 8 November calving event. Our seismic observations rely on a subset of stations composing the Polar Earth Observatory Network in West Antarctica, a broadband seismic network that has been running since 2009 (Chaput et al., 2014). In particular, we rely on the closest station DNTW located 125 km upstream from the Thwaites calving front to document the evolving character of seismic emissions. Additional seismic data utilized are from the Global Seismic Network station at South Pole (QSPA). Optical images were retrieved from both the Landsat 8 mission (15 m resolution) as well as the Sentinel-2 mission (10 m resolution). While the optical images provide excellent spatial resolution, significant cloud coverage in the region limits the number of usable scenes. Thus, to complement the optical images, we also utilize Sentinel-1 C-band synthetic aperture radar images, which are not sensitive to cloud coverage but have lower spatial resolution. Over Antarctica, Sentinel-1 data are typically acquired in an extra-wide-swath mode (20 m by 40 m resolution) or less frequently an interferometric-wide-swath (5 m by 20 m resolution).

3. Thwaites Glacial Earthquakes

We observe two large-amplitude ($M_S 2.95$ and $M_S 3.05$) long-period (10–30 s) seismic events that originate from the Thwaites Glacier calving front on 8 November at 04:30 and at 05:06 (Figure 1 and supporting information Figures Data S1 and S2). The events are observed on seismographs across Antarctica, including station QSPA located ~1,600 km from the calving front (Figure 2). Each event is characterized by long-duration (~60 s) surface waves and devoid of any discernable prior body-wave arrivals. These events are smaller than the previously detected glacial earthquakes in Antarctica which have a $M_S$ of approximately 4 or higher (Chen et al., 2011; Nettles & Ekström, 2010).

The serendipitous acquisitions by Sentinel 1 show active calving of the Thwaites Glacier (the source region of the seismic events) during the time period that encompasses the generation of the long-period seismic signals. An image acquired at 04:19 on 8 November (Figure 1d), ~10 min prior to the first seismic event, shows that significant calving has occurred since the previous day (Figure 1c). The subsequent image acquired at 05:07 (Figure 1e), just after the second seismic event, indicates that calving continued during the hour that separates the two seismic events. Comparison of the imagery on 9 November (Figure 1f) indicates that most of the calving activity was accomplished by 5:07 on 8 November (see also supporting information Figure S3).

While the most conspicuous postcalving event features are large (several kilometers in length) tabular icebergs, we can also identify several capsized icebergs as well. Capsized icebergs appear dark in the radar imagery as a result of the decreased backscatter of ice relative to the snow surface of the tabular icebergs (Figure 1e). Additionally, capsized icebergs are identifiable in optical imagery by their lack of surface texture resembling that of the precalving surface (i.e., crevasses) when compared with tabular icebergs (Figure 3d).
Thus, satellite observations indicate a hybrid-style calving for the western region of Thwaites Glacier that generates both tabular and capsized icebergs on a time scale of less than a day.

The observed pulses of long-period seismic energy during the calving event lack high-frequency body arrivals suggesting a long-duration seismic source (>10 s), similar to the previous observations of glacial earthquakes of Greenland and Antarctica (Nettles & Ekström, 2010). While the largest tabular icebergs are detached prior to the generation of the long-period pulses, several smaller tabular icebergs form during the time period that could in part be responsible for the long-period seismic generation. However, previous work has shown that it is the capsizing of the icebergs that is the most viable mechanism for the generation of long-period seismic waves at calving front (Murray et al., 2015; Tsai et al., 2008; Walter et al., 2012). Capsized icebergs arise as the result of buoyant forces that rotate the iceberg after it detaches. During rotation, it is then possible for forces generated by the newly formed iceberg impacting the glacier terminus as well as hydrodynamic processes associated with capsizing to be transmitted into the solid Earth (Murray et al., 2015). While capsized icebergs are a necessary component of glacial earthquake generation, not all capsized icebergs will impact the calving front and generate seismic energy. At least five capsized icebergs

Figure 3. (a–d) Set of optical images showing evolution of the ice front. Ancillary fractures (F1–F3) are indicated. (e) High-frequency seismogram (1–5 Hz) and the cumulative number of events observed at DNTW between 2 November and 8 November. (f) High-frequency seismogram for several hours bounding the calving event.
with a minimal exposed dimension exceeding 500 m were generated during the calving event. These icebergs are comparable in size to the icebergs that generate smaller glacial earthquakes in Greenland (Olsen & Nettles, 2019). However, since it is possible for icebergs to fragment subsequent to detachment, it is possible that fewer than five capsized icebergs were formed directly by calving.

4. Precursory Seismicity of Thwaites Glacier Calving

In the days preceding the calving event, we observed an increase in the detection of discrete high-frequency seismic events (1–5 Hz) at seismic station DNTW to rates well above the typical rate (<20 events per day), increasing to >300 events/day during the day prior to the calving event (Figure 3e). The larger events (∼ML 2) are observable at three stations within the Amundsen Sea region (DNTW, BEAR, and UPTW, Figure 1) at distances exceeding 250 km. The locations of these precursory events are consistent with the region of incipient calving associated with the generation of the long-period glacial earthquakes (supporting information Figure S4). The high-frequency events we observed on Thwaites are similar in size to regional-scale high-frequency seismicity associated with fracturing during iceberg calving observed in the Northern Hemisphere (i.e., O’Neel et al., 2010).

We infer that the increased levels of discrete high-frequency seismic activity prior to calving is most likely generated via elevated rates of fracture propagation in the region of incipient tabular iceberg formation prior to the calving that is seen in the optical imagery. The dominant structural features of incipient calving are observed in the imagery collected prior to the 8 November 2018 event and consist of several major rifts (R1, R2, R3, and R4; Figure 1) that grow in the months preceding the calving. However, in the week preceding the calving event (coeval with the increase in high-frequency seismic events) we observe several new ancillary fractures initiate and propagate (F1, F2, and F3; Figures 3a–3d). For example, by 15:16 on 7 November, less than 24 hr before the calving event, F1 has nearly connected R1 with the ice front, while F2 is within a few hundred meters of connecting R3 and R4 (Figure 3c). While we have not made an exhaustive inventory of all fractures in the satellite imagery, we infer that fractures at a range of scales contribute to the generation of the precursory seismic activity.

The high-frequency signal at DNTW ceases to be characterized by discrete events and transitions into continuous high-amplitude tremor at approximately 03:30 on 8 November, approximately 50 min before the first satellite confirmation that calving has initiated and 1 hr before the first low-frequency glacial earthquake. While the amplitude of tremor does modulate, with elevated levels likely related to iceberg generation, it remains well above background noise levels for several more hours, until approximately 06:00 on 8 November, after which the amplitude of the tremor decreases to background noise levels that are typical to the days before preceding the calving event, and the number of discrete seismic signals returns to typical background rates (Figure 3f). This tremor is similar to that observed during Greenland calving events and is likely generated by several processes including pervasive brittle failure associated with the onset of calving, iceberg-mélange interactions, and iceberg collapse (Amundson et al., 2010). We interpret the onset of high-frequency tremor as the seismic signature of the initiation of large-scale iceberg formation that is subsequently visible in the satellite imagery approximately 50 min later. Likewise, we infer that the decrease in tremor below background levels by 06:30 as the termination of the calving event and may be associated with dynamic jamming of the mélange, similar to observations in Greenland (Peters et al., 2015).

Precursory seismic activity similar to that observed for the 8 November 2018 event is observed prior to the previous large calving event from this area on 10 April 2017 (supporting information Figure S5). Likewise, long-period seismic waves from this calving event are also detected at large distances (supporting information Figure S5d). Thus, both long-period and high-frequency seismic events appear to be a ubiquitous feature of calving along this portion of the Thwaites terminus.

5. Conclusions

The generation of long-period glacial earthquakes during calving and the high-frequency seismic activity that preceded calving point toward a new observational platform to investigate the mechanics of Thwaites Glacier calving at time scales ranging from days to seconds. For example, the increasing rate of seismic events prior to the initiation of calving is similar to precursory behavior for material failure in both laboratory and field environments (i.e., Voight, 1988).
The western terminus of Thwaites Glacier has undergone a significant transition over the past decade. It now calves directly into the ocean within a few kilometers of its grounding zone. In Greenland, glacial earthquakes are regularly detected, but previous systematic efforts have revealed only few events emanating from Antarctica (Chen et al., 2011; Lough, 2014; Nettles & Ekström, 2010). This discrepancy has been attributed to the different calving style that dominates in Antarctica (tabular) versus Greenland (capsized). While we observe other similar calving seismic events from Thwaites (supporting information Figure S5), they only occur within the region of minimal floating extension (<2 km). Additionally, the absence of Thwaites glacial earthquakes in the 2009–2011 catalog of long-period Antarctic events (Lough, 2014), using the same Polar Earth Observatory Network seismic stations used here, suggests that the observed long-period seismic events are associated with the recent loss of an extensive floating ice extension in this region. A significant characteristic of the Thwaites Glacier is that we observe glacial earthquakes during calving events that produce both tabular and capsized icebergs. In contrast, the episodic growth of floating ice tongues in Greenland tends to suppress glacial earthquake formation until the terminus returns to a nearly grounded position (Olsen & Nettles, 2017; Veitch & Nettles, 2012).

The continued degradation of the Thwaites Glacier ice tongue has the potential to leave the fastest flowing portions of Thwaites with only a minimal floating extension. In this scenario, continued seismic observations will provide an observational platform for tracking the future evolution of Thwaites Glacier as well gaining a better understanding of physical processes of calving (i.e., Sergeant et al., 2016) that can be incorporated into ice sheet scale models.

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References

Chaput, J., Aster, R. C., Huerta, A., Sun, X., Lloyd, A., Wiens, D., et al. (2014). The crustal thickness of West Antarctica. Geophysical Research Letters, 41, 1738934. All seismic data utilized in this study can be obtained from the IRIS Data Management Center (www.iris.edu), and all satellite imagery can be obtained from ESA (https://scihub.copernicus.eu/) and the USGS (https://earthexplorer.usgs.gov) data centers. We thank the many people involved in the successful deployment of the ANET seismic stations as well as Raytheon Polar Services, Antarctic Support Contract, the New York Air National Guard, and Ken Borek Air for logistical support. We thank the many people involved in the successful deployment of the ANET seismic stations as well as Raytheon Polar Services, Antarctic Support Contract, the New York Air National Guard, and Ken Borek Air for logistical support.


