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Localised, ephemeral grounding of the Fimbul Ice Shelf, East Antarctica, as revealed from tidally modulated cryoseismicity

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Seismic records from the permanent, international network in Dronning Maud Land, East Antarctica (continuous data on stations SNAA, TROLL and selected records from the Watzmann seismic array), have revealed a source of highly repetitive cryogenic seismicity at a location on the Fimbul Ice Shelf between the eastern edge of the Trolltunga ice tongue and the margin of the outlet of the Jutulstraumen ice stream. The use of waveform cross-correlation detectors on two decades of data (1997 – 2018) revealed that related cryoseismicity spans an interval of about 14 years, from 2003 to end 2016, with variable activity levels; from a few events per day in 2003 and a long period of almost complete quiescence between 2004 and late 2011, to significantly increased levels thereafter with several tens of events per day in 2013 and 2015 (Figure 1).

Due to the small magnitude of the events ($M < 1.2$) and their sources being located at near-regional distances from the recording stations, only the largest ones could be located. To this purpose, phase picks were performed on summation traces of highly similar events (multiplets), as well as on the Watzmann-array beam. Waveform cross-correlation time differences were used as a proxy of epicentral distance variations to devise a rough relative location scheme that provides an estimate of the extent of the activated source region. The repetitive character of the events favored the use of a cross-correlation detector (Gibbons and Ringdal, 2006) to populate the employed cryoseismicity catalog, while its efficiency as a method was verified by comparison to the detections of a machine-learning Hidden Markov Model technique (Hammer et al., 2013). For event magnitudes, we employed the logarithm of the maximum amplitude as measured on the rotated horizontal components, thus constructing a self-consistent scale that describes accurately the relation between events in terms of magnitude for this specific catalog.

An intense activity phase between August and October 2013 has been used to design a simple, mechanical model that would shed light on the mechanisms behind these cryoseismic events (Pirli et al., 2018). This specific interval was selected based on the satisfactory completeness of the event catalog, as well as a set of specific characteristics exhibited by this seismicity: (i) Events exhibited highly similar waveforms, with well-developed SH phases, in the highest SNR frequency range between 2 – 6 Hz. (ii) Their recurrence was modulated by the 14-day and semidiurnal cycles of the ocean tide, with activity intensifying with tidal amplitude and pausing during low tide, most events separated by interevent times of 8 ± 2 s. (iii) The magnitude of the events also exhibited modulation by the tide, opposing trends occurring near spring and neap tides. (iv) The epicenters of the events showed a southward migration within each semidiurnal tidal cycle.

Based on these characteristics, a model assuming stick-slip motion on a pinning point (i.e., a location where the ice shelf grounds on a bathymetric shoal) was constructed. The system is forced by variations in ice-flow velocity that induce changes in shear stress, as well as variations in tidal height that additionally affect normal stress. Slip occurs when the Coulomb Failure Stress exceeds a specific threshold, taking place along the contact area between the pinning point and the ice shelf. The length of this area is a function of tidal height and the elevation of the bottom of the shelf relative to the peak of the underlying bedrock. The latter constitutes the main modeling variable, effecting on the state of stress, event hypocenters and magnitudes.

Our simple model succeeded in reproducing well most of the unique characteristics of the recorded observations (i.e., the event recurrence, magnitude and migration patterns). This suggests that, at the source, the ice shelf is grounded on a pinning point, event migration reflecting the migration of the local grounding line in response to the ocean tide (e.g., Sayag and Worster, 2013, Tsai and Gudmundsson, 2015). The availability of long data records and the variations in seismicity levels and event magnitudes further reveal that larger magnitude events are only triggered for higher tidal amplitudes, allowing us to model a thickness variation for the ice shelf at the source region in the order of 0.5 m, between 2012 and 2015. Combining these results, we propose the following interpretation: that a minimum thickness of the ice shelf is required for it to ground on this specific pinning point, and that before this happens, there are no events. With increasing ice-shelf thickness and the establishment of contact, stick-slip occurs at rising tides and events take place, first at lower tidal amplitudes, so that the contact is maintained, and then at higher amplitudes when also larger events occur (Figure 2).

The significance of this work arises from the fact that it constitutes independent evidence of slight variations in ice-shelf thickness and of ephemeral grounding on an unmapped pinning point with a resolution that cannot be achieved by other means (e.g., satellite-based techniques).

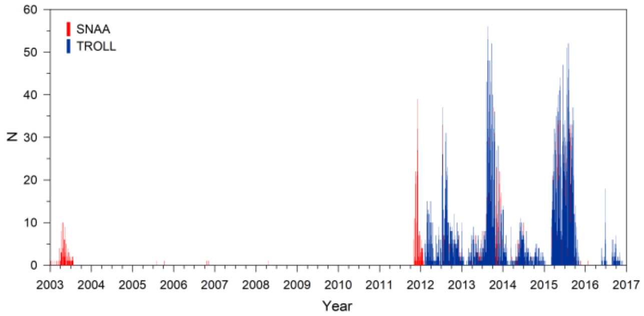

Figure 1. Histogram of number of events per day at station SNAA and TROLL between 2003 and 2017.

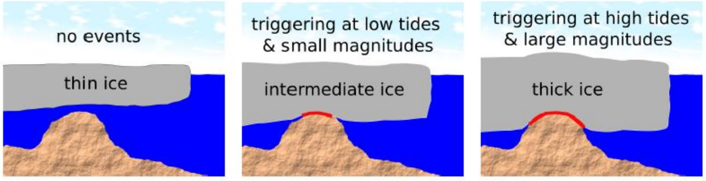

Figure 2. Interpretation of the long-term cryoseismicity mechanism. The red line denotes the length of the contact area between the ice shelf and the pinning point, where stick-slip occurs.

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