Locating Basal Microseismicity in Rutford Ice Stream, West Antarctica using QuakeMigrate, for Statistical Pattern Recognition

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Abstract

The Antarctic Ice Sheet remains one of the greatest sources of uncertainty for improving predictions of sea level rise, and constraining this uncertainty has long been a difficult challenge within glaciology and climate science. Cryoseismology, paired with the meteoric rise of data science applications within the geosciences, has emerged as a promising field well suited to answering these challenges as the improvement of sampling technology and access have resulted in a proliferation of Antarctic seismic data. Ice flow dynamics in Antarctica are significantly influenced by features and processes at the bed, and basal microseismicity from tremors as ice moves across the bed can yield valuable information for resolving the glacier subsurface. We deployed high-frequency (up to 1000 Hz) geophone arrays at Rutford Ice Stream over the 2018-2019 austral summer to monitor the natural source seismicity from the base of the ice and generate an event catalog. To efficiently process the enormous volumes of cryoseismic data to locate events, we used the Python package QuakeMigrate which utilizes a parallelized waveform stacking algorithm to detect coherent seismic phase arrivals across our network. Over three months of data, we located over 1,700,000 seismic events (majority which were microseismic) within a 4 km x 4 km square grid around our 13-station, ~3.25 km2 area array. The detection and location of icequakes at this resolution provides a unique opportunity to investigate the temporal, location, and size relations between events, and we present the findings from our data mined event catalog and document the QuakeMigrate parameter tuning to optimize event location. The significant amounts of data collected of the region over the past decades mean that the literature and documentation of conditions at Rutford is more complete relative to most of Antarctica, and our work aims to contribute towards a comprehensive survey of an Antarctic region.

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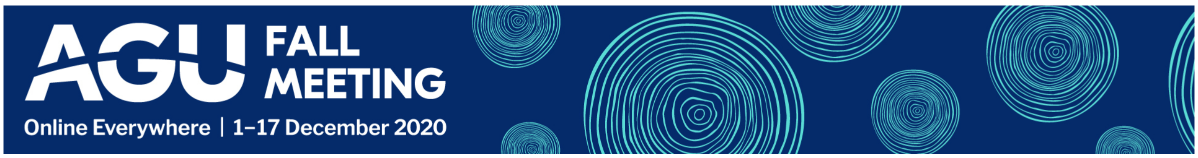


INTRODUCTION

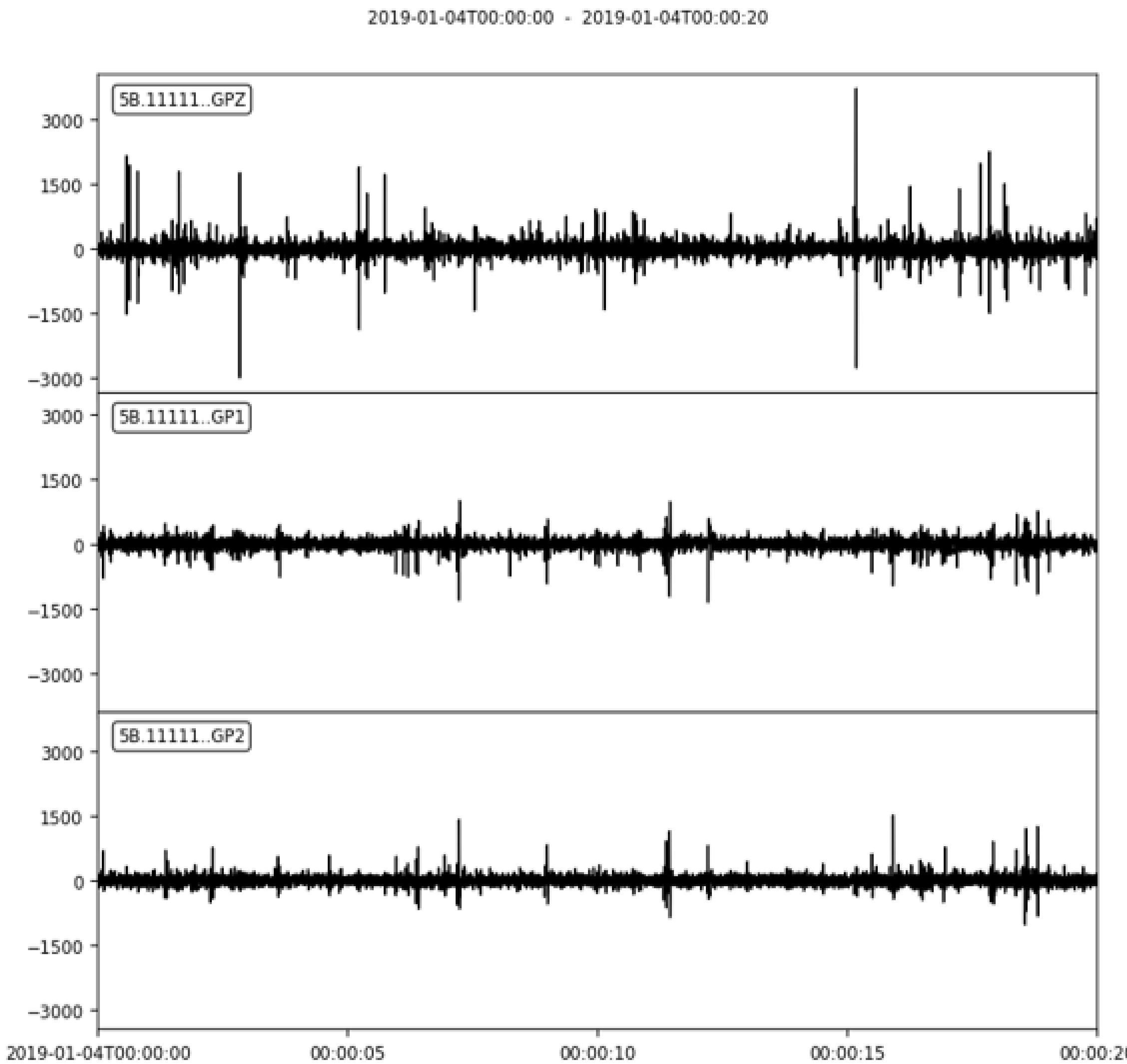
The Antarctic Ice Sheet has been a major source of uncertainty in projections of sea level rise, and reducing this uncertainty has been a difficult, long-standing challenge within glaciology and climate science.

This difficulty stems from our incomplete understanding of ice stream dynamics. Basal conditions and the sliding process strongly influence ice stream dynamics, and unfortunately our lack of detailed information about the bed results in our difficulties. ~90% of discharge from the Antarctic Ice Sheet is from ice streams.

A popular technique of observing the basal environment of ice streams is by monitoring natural source seismicity (*Anandakrishnan and Bentley, 1993*). When the glacier slides over its bed, small magnitude ($M < 0$) microseisms are generated. In recent years, logistical improvements in Antarctica have led to the proliferation of seismic data, that provide us the opportunity to generate event catalogs of high-resolution basal microseismicity that can aid in our efforts to better understand the bed.

QUAKEMIGRATE

To efficiently detect and locate events from our large volume of seismic data, we used the QuakeMigrate (*Winder et al., 2020*) software. QuakeMigrate is a python package which utilizes a parallelized waveform stacking algorithm to detect coherent seismic phase arrivals across our network. From our array data we observe that ambient noise levels are very low (due to how remote RIS and Antarctica are) which lead to extremely high-quality, clean signals. Due to the low individual energy outputs of microseism, this causes QuakeMigrate to be a particularly ideal detection tool due to its method of coalescing signals from all free (available) stations instead of using individual station triggers.



QuakeMigrate outputs event origin times, locations, phase picks and their associated uncertainty estimates. Prior to running our array data through QuakeMigrate, we spent time optimizing our runs for each array and used a mixture of validation curves & grid search to tune individual or multiple parameters. We developed a set of optimization criteria and guides (with advice from the developers) to help us evaluate our outputs and determine the optimal set of parameters (for each array).

Available criteria are:

- **Depth range** - RIS has a thickness of 2,100 m at our drill site, which decreases to 1,800 m toward the grounding line (*King et al., 2009*). 'Good' (basal) events should be ±300 m of the bed.
- **Proximity of XYZ and Gaussian XYZ locations** - Each event has P- and S-onset functions for every station that detected an event. The onset function is a probability density function for the phase arrival (within some limited period of time around that phase arrival). The coalescence is the product of onset functions, and the

XYZ location is the location of maximum coalescence. Each onset function also has Gaussian properties, and we can stack them with the geometric mean to generate posterior probability function for earthquake origin times. By connection with the wave equation, we can calculate Gaussian XYZ location. Both location types should remain close, assuming coherent signals.

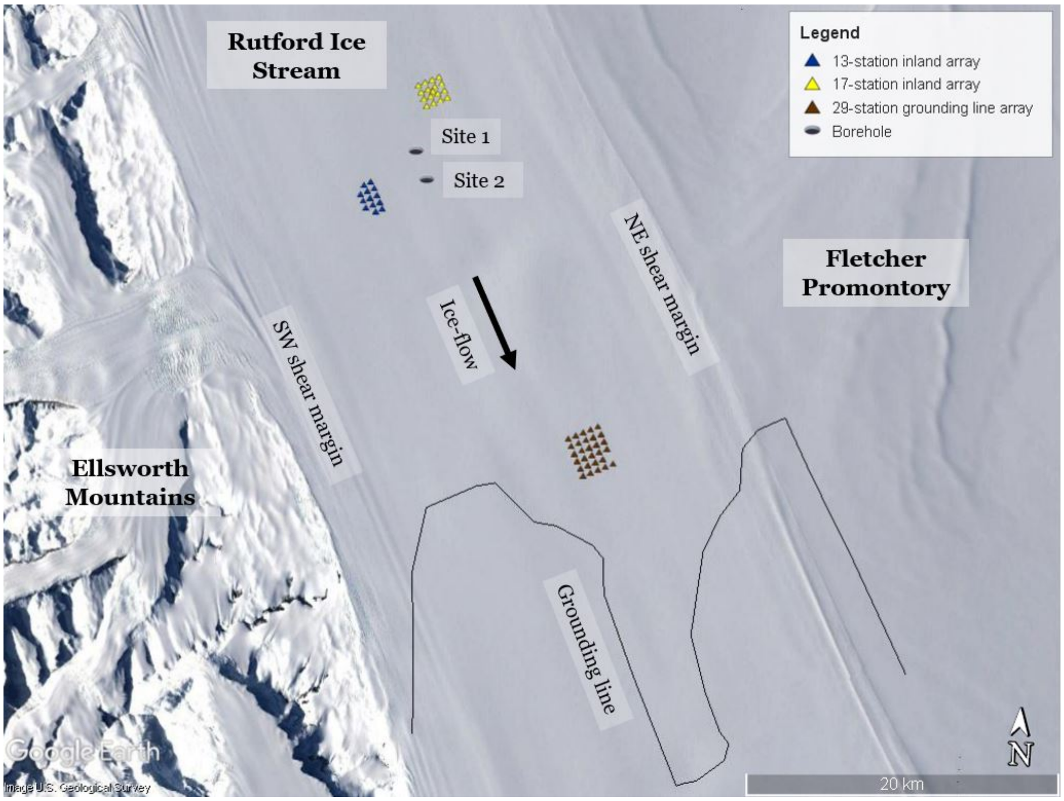
- **Location errors** - We compare location errors between similar events from different runs.
- **Picking performance** - We compare number of successfully made phase arrival picks, pick errors and signal-to-noise (SNR) ratios between similar events from different runs.
- $\boldsymbol{Vp/Vs}$ **ratios** - We calculate ratios using either event-station velocities or from Wadati plots, and select for runs with output events with ratios closer to expected ice values with no error (1.95–1.98).
- **Relative phase arrival picks** - Based on the projected event location, stations close to the event would have earlier phase picks. Due to grid resolution and peak station energy not always coinciding at similar times, the QuakeMigrate picks might sometimes be off by a few milliseconds. Factoring in some leeway, we typically remove errors greater than ~10 ms.

Other optimization criteria are still being developed (detection density, unique events, etc.), and all are based on the QuakeMigrate outputs.

We performed QuakeMigrate processing on our seismic data on the Penn State's Institute for Computational and Data Sciences' Roar supercomputer. As QuakeMigrate uses all the seismic data regardless of quality to detect and locate the earthquakes, but produces high-quality estimated pick uncertainties, we can refine our locations by using relocation software like HypoDD or NonLinLoc.

RUTFORD ICE STREAM

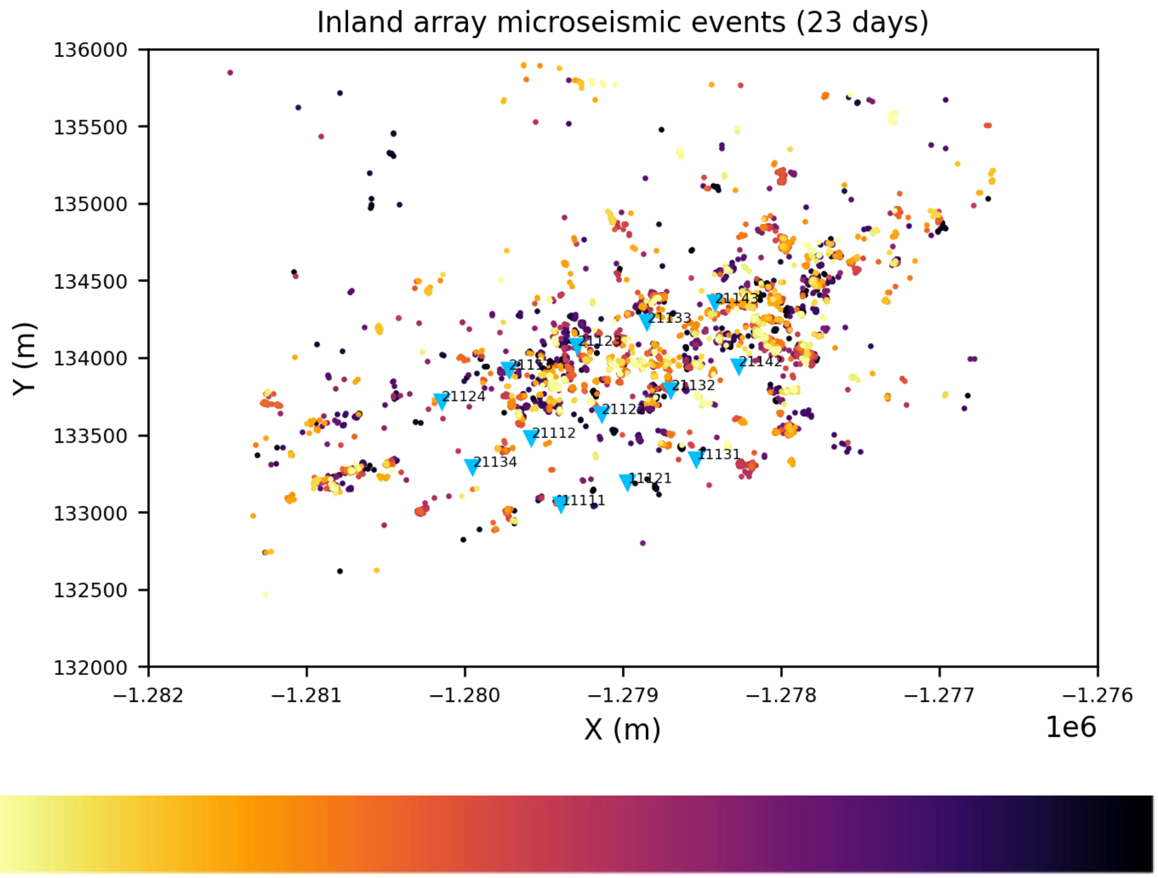
The Rutford Ice Stream (RIS) is a highly studied fast-flowing ice stream in West Antarctica. During the 2018/19 BEAMISH season (*A.M. Smith et al., 2020*), the British Antarctic Survey (BAS) drilled three access holes to the RIS bed to study basal conditions on RIS. In collaboration, we deployed several geophone arrays over 53 days in the vicinity of the drill sites and at the grounding line to monitor natural source seismicity pre and post drilling.



Our stations had a sampling frequency of 1000 Hz, which produced up to 5TB of data/month.

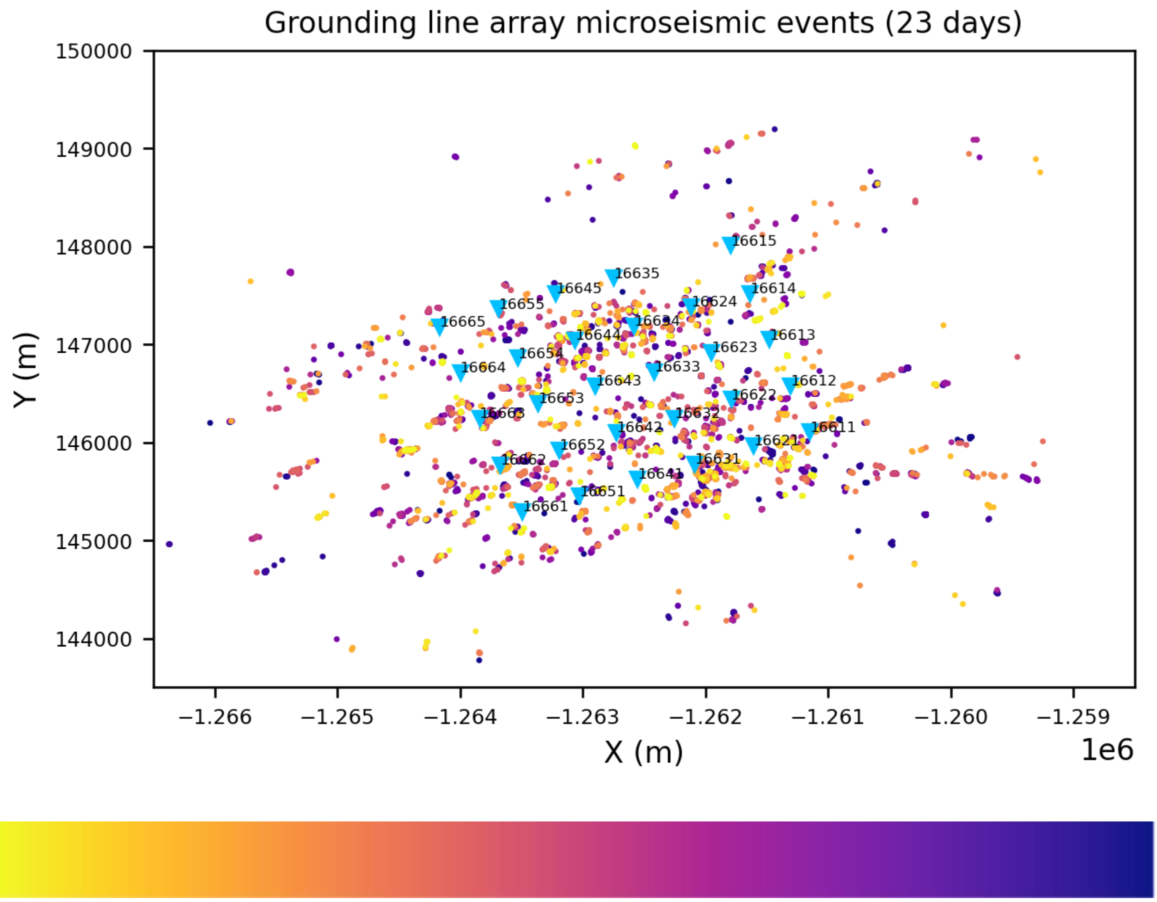
PRELIMINARY RESULTS

After filtering, we detected and located over 300,000 microseismic events/month within each array's search grid. We show some results from our 13-station inland array, with the color indicating nucleation times (from left to right). To prevent graphic clutter, we have displayed only 2% of the total events.



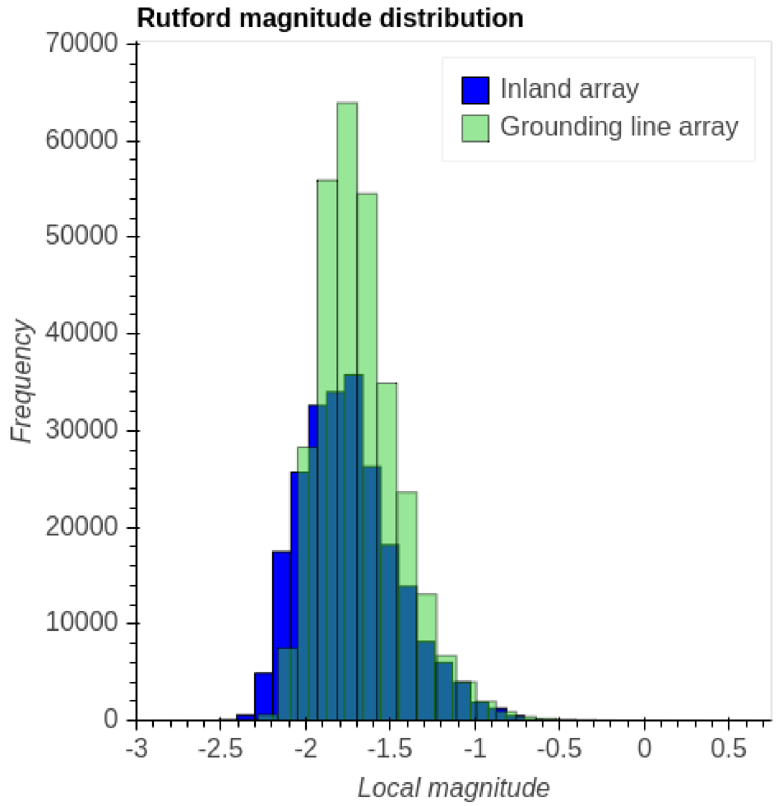
*Coordinates in polar stereographic

We also show some results from our 29-station grounding line array, with the same format as above.



With these event catalogs of high-resolution basal microseismicity, this provides us with a dataset with which we can perform detailed investigations into basal conditions on RIS. A couple ongoing investigations:

- **Induced microseismicity reveals zone of stress concentration** - We deployed our arrays at the drill sites as we were interested in observing what happened seismically upon completion of each borehole, when the drill breaks through to the bed. We hypothesized that excess water melted from the hot-water drill would lubricate the bed and induce more sliding and microseismicity. For time periods following the completion of a borehole, we can check our datasets and pressure logs for an uptick in seismic activity. Stick-slip sliding occurs at sticky spots or asperities which are continuously built up and destroyed from the accumulated stress, so such nucleation zones can reveal weak spots along the RIS bed.
- **Resolving the glacier subsurface topography** - We can superimpose bed topography maps onto our data set and observe if there are correlations between event nucleation zones and basal structures. We have also extracted samples of basal material during drilling, which can help us get an idea of the basal properties and conditions in the greater RIS region.
- **The degree of influence of sliding and the tides on microseismicity** - It is well documented that tidal cycles at RIS can modulate ice-flow velocity by ~10-20% (*Gudmundsson, 2007*) which can play a part in influencing basal seismicity, particularly for arrays closer to the grounding line. If the grounding line array produce events that are less strongly coupled to observed basal conditions like water pressure or drilling induced microseismicity, compared to inland arrays, that could be attributed to the known tide cycles.
- **Stress regime of our regions** - We produced a local magnitude scale of our events to investigate stress regime, given that the seismic distribution of event magnitudes (through the seismic b-value) can provide information about the stress regime.



In concluding, we found QuakeMigrate to be a robust yet sensitive detection tool that can produce datasets that are highly conducive for data mining. We aim to explore our dataset to better resolve and recognize patterns between microseismicity and basal properties + other RIS processes (tides and natural events like calving/crevassing) to better determine basal conditions on RIS, and assist ice-sheet modelers to better account for the sliding process.

Acknowledgements

We thank Andy Smith and the BEAMISH team for their assistance during deployment and collection of our seismic data. We also thank the QuakeMigrate developers (Conor Bacon, Tom Hudson, Jonathan Smith & Tom Winder) for the countless hours of support to troubleshoot and answer questions about the software.

ABSTRACT

The Antarctic Ice Sheet remains one of the greatest sources of uncertainty for improving predictions of sea level rise, and constraining this uncertainty has long been a difficult challenge within glaciology and climate science. Cryoseismology, paired with the meteoric rise of data science applications within the geosciences, has emerged as a promising field well suited to answering these challenges as the improvement of sampling technology and access have resulted in a proliferation of Antarctic seismic data. Ice flow dynamics in Antarctica are significantly influenced by features and processes at the bed, and basal microseismicity from tremors as ice moves across the bed can yield valuable information for resolving the glacier subsurface. We deployed high-frequency (up to 1000 Hz) geophone arrays at Rutford Ice Stream over the 2018-2019 austral summer to monitor the natural source seismicity from the base of the ice and generate an event catalog. To efficiently process the enormous volumes of cryoseismic data to locate events, we used the Python package QuakeMigrate which utilizes a parallelized waveform stacking algorithm to detect coherent seismic phase arrivals across our network. Over three months of data, we located over 1,700,000 seismic events (majority which were microseismic) within a 4 km x 4 km square grid around our 13-station, ~3.25 km^2 area array. The detection and location of icequakes at this resolution provides a unique opportunity to investigate the temporal, location, and size relations between events, and we present the findings from our data mined event catalog and document the QuakeMigrate parameter tuning to optimize event location. The significant amounts of data collected of the region over the past decades mean that the literature and documentation of conditions at Rutford is more complete relative to most of Antarctica, and our work aims to contribute towards a comprehensive survey of an Antarctic region.

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