



POLAR SCIENCE FOR PLANET EARTH

Bed-character dependent microseismicity clustering at Rutford Ice Stream, West Antarctica

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Sofia-Katerina Kufner^{1*}, Alex Brisbourne¹, Andy Smith¹, Sridhar Anandakrishnan², Tavi Murray³, Rebecca Schlegel³, Keith Nicholls¹, Dominic Hodgson¹, Keith Makinson¹, Michael Kendall⁴, Ian Lee², and Thomas Hudson⁴

¹British Antarctic Survey, Cambridge, UK

²Penn State, Pennsylvania, USA

³Swansea University, Swansea, UK

⁴University of Oxford, Oxford, UK

* contact: sofner@bas.ac.uk

Do you wonder how icequakes sound? - have a
look at the work of musician Steve Garrett
<https://stevegarrettguitar.bandcamp.com/track/the-song-of-the-ice-icequakes-bonus-track>



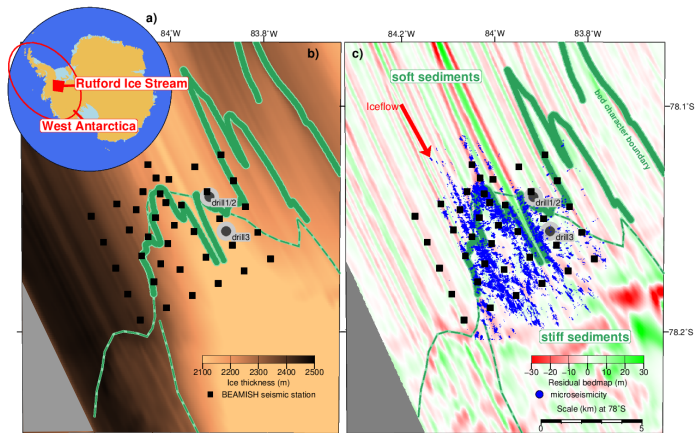
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Motivation & Overview

Microseismicity, induced by the sliding of a glacier over its bed and through bed deformation, can be used to characterize frictional properties of the ice-bed interface. Together with ice column deformation, these characteristics form the key parameters controlling ice stream flow. Here, we use naturally occurring seismicity to monitor temporal and spatial changes in bed properties at Rutford Ice Stream (RIS), West Antarctica (Fig. a), in order to characterize ongoing basal deformation and sliding. RIS is a significant contributor to the outflow of ice from West Antarctica, with speeds of ~ 1.1 m/day. Past geological and geophysical surveys, including drilling into the bed itself, have revealed pronounced bed topography and a sharp change in bed character along flow direction from presumably soft deformable to stiffer sediments (Figs. c/d).

- ▶ We use three months of seismic recordings from a 35-station seismic network, located ~ 40 km upstream the grounding line of RIS (Fig. b). This dataset has been collected in the framework of the BEAMISH project during the 2018/19 field season.
[▶ more info](#)
- ▶ We apply automated detection and relocation algorithms to detect microseismicity (including magnitudes & rupture mechanisms).
[▶ more info](#)
- ▶ We find that microseismicity occurs exclusively near the ice-bed interface and is concentrated in the transition region between presumed-soft and presumed-hard sediments. Further seismicity occurs predominantly along topographic lows (Fig. c).
[▶ more info](#)



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1. Event locations

- ▶ Initial event locations are obtained from the continuous waveform data using a coalescence based earthquake detection and location procedure (software : QuakeMigrate [1]).
- ▶ Events are relocated based on QuakeMigrate-derived P- and S picks using a probabilistic location scheme (NonLinLoc [2]).
- ▶ Quality restrictions in terms of number of picks, location error and individual pick- and event-residuals are applied to derive the final event catalog.

The QuakeMigrate velocity model is set to be homogeneous ($v_p = 3.841 \text{ km/s}$); For NonLinLoc, a 100 m thick firn layer ($v_p = 2.839 \text{ km/s}$) is included on-top of the ice. Velocity parameters are constraint from seismic surveys [3]. A v_p/v_s ratio of 1.95 is obtained from a Wadati-diagram.

2. Focal mechanisms are determined from automatically derived first motion polarities and P-S amplitude ratios (HASH [4])

[▶ more info](#)

Fault slip data are then inverted to find the best-fit stress tensor (slick [5])

[▶ more info](#)

3. Magnitudes: for events with focal mechanisms, the moment magnitude (M_W ; resp. M_0) is determined via the frequency spectrum of the event [6]. The focal mechanism is used to calculate the radiation pattern. For all other events, an empirical local magnitude scale is derived from the maximum amplitude of the horizontal waveforms.

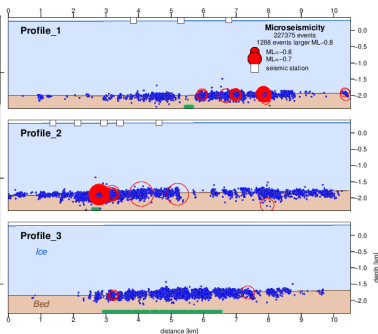
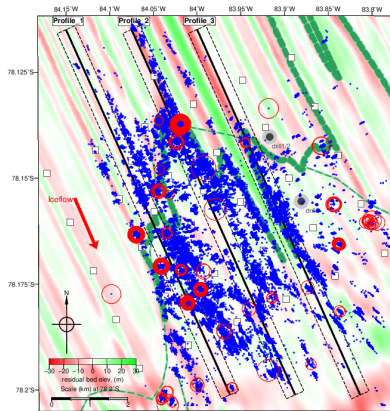
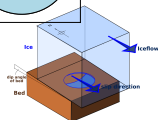
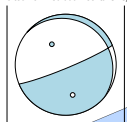
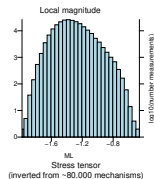
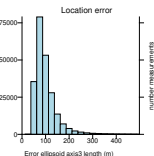
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References:

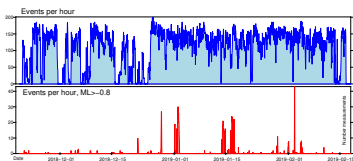
- [1] Smith, J.D., White, R.S., Avouac, JP, and S. Bourne (2020), Probabilistic earthquake locations of induced seismicity in the Groningen region, Netherlands, Geophysical Journal International. <https://github.com/QuakeMigrate/QuakeMigrate>
- [2] Lomax, A., A. Michelini, A. Curtis, 2009. Earthquake Location, Direct, Global-Search Methods, in Complexity In Encyclopedia of Complexity and System Science, Part 5, Springer, New York, pp. 2449-2473. <http://alomax.free.fr/nlloc/>
- [3] Smith, A. (1997), Basal conditions on Rutford Ice Stream, West Antarctica, from seismic observations, J. Geophys. Res., 102 (B1), 543–552.
- [4] Hardebeck, J. L., & Shearer, P. M. (2008). HASH: A FORTRAN Program for Computing Earthquake First-Motion Focal Mechanisms–v1. 2–January 31, 2008.
- [5] Michael, A. J. (1987). Use of focal mechanisms to determine stress: a control study. Journal of Geophysical Research: Solid Earth, 92(B1), 357-368. <https://www.usgs.gov/software/slick-package>
- [6] T. Hudson (2020, submitted), PhD thesis, University of Cambridge, UK



Results & Summary ~230,000 icequakes in a ~10x10km domain beneath Rutford Ice Stream during 90 days observation in 2018/19



- Spatial distribution:** events concentrated in the transition region between presumed-soft and presumed-hard sediments; fewer events in soft sediments, predominantly along topographic lows; more events in hard sediments cluster in focused spots of particular high activity.
- Magnitudes:** all events small (mostly $< ML-0.7$); larger events occur during short time spans in repeating events.
- Rupture mechanisms:** dominantly shallow dipping normal faulting with slip-vectors in flow-direction and dip angle re-sampling the slope of the glacial bed (see sketch to the bottom left).
 - events likely caused by glacial sliding along ice-bed interface with the bed character boundary forming a major obstacle. The repeated seismic activity at restricted spatial locations suggests *sticky spots* within a more ductile deforming matrix.
- Temporal distribution:** Number of events relatively constant over time; decreased detection rate rather affected by noise level (wind/bad weather). Larger events show temporal clustering with roughly ~ 15 day periodicity.
 - Possible link to spring-neap tidal cycle; \sim to be investigate further.



Methods - add-on information



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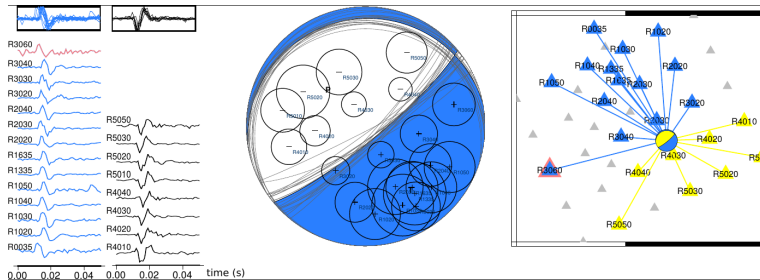


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First motion focal mechanisms [▶ Back to methods](#)

1. For each station, P polarities were determined automatically on the vertical trace of the seismogram using a gradient picker. The maximum P and S amplitudes were obtained as the maxima on the Cartesian sum trace of all three components within windows around P and S onset (Bloch et al., 2018).
2. Prior to the inversion for the focal mechanism, we calculated cross-correlations from all P-wave onsets available for one event. Based on the cross-correlation coefficient wrongly picked polarities can be identified and the polarities are changed accordingly. Further, stations with too low cross-correlation coefficient were excluded.
3. HASH was then used to invert for the double couple source that best fits the observed radiation pattern. Take-off angles were derived from a layered 1D velocity model (firm and ice layer). To account for errors in the polarity picks, 15% outliers (non-matching polarities in the final solution) were allowed during the inversion. We further performed multiple inversions while perturbing take-off angles (standard deviation of 5°) to access uncertainties in the velocity model and the event location.
4. The final set of good solutions was derived based on quality criteria (stability of solution upon variations of input, azimuthal gap, number of picks).

References: Bloch, W., Schurr, B., Kummerow, J., Salazar, P., & Shapiro, S. A. (2018). GRL, 45(11), 5407-5416.



Event example: (Left) P waveforms, sorted by polarity. Amplitudes are normalized to 1. The top traces plots all traces with same polarity on top of each other. The red traces had been flipped to positive polarity based on its cross-correlation coefficient. (Middle) Derived focal mechanism, plotted as beach ball (lower hemisphere projection). The most likely mechanism is highlighted in blue. The gray lines represent the spread of possible mechanisms upon variations in input parameters. The circles surrounding single station polarities represent the amplitude ratio used as input together with polarities. (Right) map-view of event and station locations. Stations are color coded based on polarity. Gray stations were not included in the inversion.



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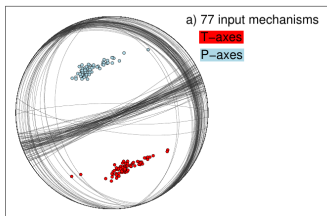
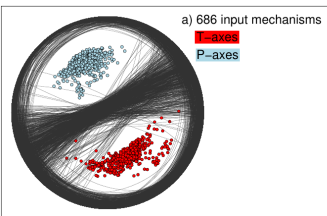
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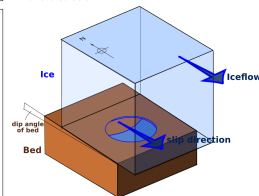
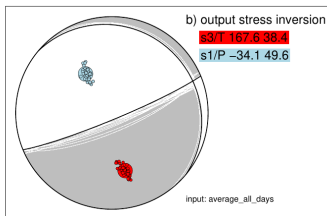
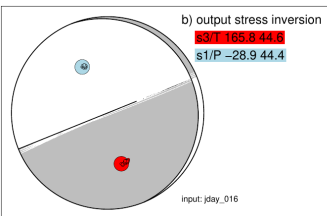
Stress inversion ▶ Back to methods

- ▶ Fault plane solutions were inverted to estimate the regional stress field using the software slick (Michael, 1987). Slick performs a linear inversion to minimize the number of rotations around an arbitrary axis necessary to rotate the input focal mechanisms to fit a uniform stress tensor.
- ▶ Here, we first calculated stress tensors for each day within our observation period using all available mechanisms of this day (example in left figure below). We then used these single-day solutions to calculate an average stress tensor for the entire observation period (right figure below).
- ▶ We accessed the quality of the solution via a bootstrap test. The data were resampled 100 times while the selected fault slip direction was flipped in 10% of these cases. The spread of the results obtained from bootstrap inversions provides a measure of inversion robustness.



Slick inversion example: (left) Single day solution: input are all single event focal mechanisms from Julian day 016. (right) Long time average: input are all day-averaged stress-inversion results within the deployment period (for days with more than 100 individual event measurements).

a) input data: only nodal planes and P/T axes are plotted. b) Most likely stress tensor plotted as beach ball representative in gray. White nodal planes and small P/T axes show results from bootstrap tests. The scatter of these results is an indicator for the robustness of the solution.



Sketch illustrating the dominant type of faulting: slip-vectors in flow-direction and dip angle re-sampling the slope of the glacial bed.



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Moment Magnitude(M_W)-Local Magnitude(M_L) scaling [▶ Back to methods](#)

We aimed to derive a local magnitude scale to obtain a magnitude estimate from the raw data recordings once an event is located. Our local magnitude scale follows the general equation:

$$M_L = \log_{10}(A) + m \times \text{epicentral_distance} - t$$

with the following parameters:

- ▶ A is the maximum amplitude of either of the two horizontal components (in instrument counts; taking into account the instrument type).
- ▶ m is a distance term. m was determined from a data subset (1 day, 2978 events, average 14 S-picks per event). For all events within this subset the linear regression between $\log_{10}(A)$ and the epicentral distance (epicentral_distance; in km) was calculated (Fig. 1). The average slope of all results with a R^2 value larger than 0.4 was used as distance term ($t=0.24$, $\text{std}=0.05$, $R^2=0.75$). We used the epicentral distance instead of the hypocentral distance as the latter yielded smaller correlation coefficients. This effect might result from all events in our dataset being located at comparable event depths.
- ▶ t is a constant that bridges the offset between M_L and M_W . We determined t for the same data subset than used to derive m , however, considering only events for which a M_W value was available (1517 events). From this subset, we derived a t value of -3.6 (Fig. 2).

Based on these parameters we roughly obtained a 1:1 (± 0.25) fit between M_W and M_L throughout the magnitude range considered here (Fig. 3). A constant term for M_W - M_L scaling is likely sufficient for our dataset as the total range of magnitudes spans only ~ 1.5 magnitude units.

