Basal Seisimicity Forced by Surface Water Supply on a Stepped-Bed Glacier: Saskatchewan Glacier, Alberta, Canada

May 4. 2020

EGU2020-10952: Session CR2.1

Nathan T. Stevens[1*], Collin J. Roland[1], Dougal D. Hansen[1], Emily Schwans[2], Lucas K. Zoet[1]

1 Department of Geosciences, University of Wisconsin – Madison, WI, USA

2 Department of Geosciences, Penn State University, University Park, PA, USA

Acknowledgments

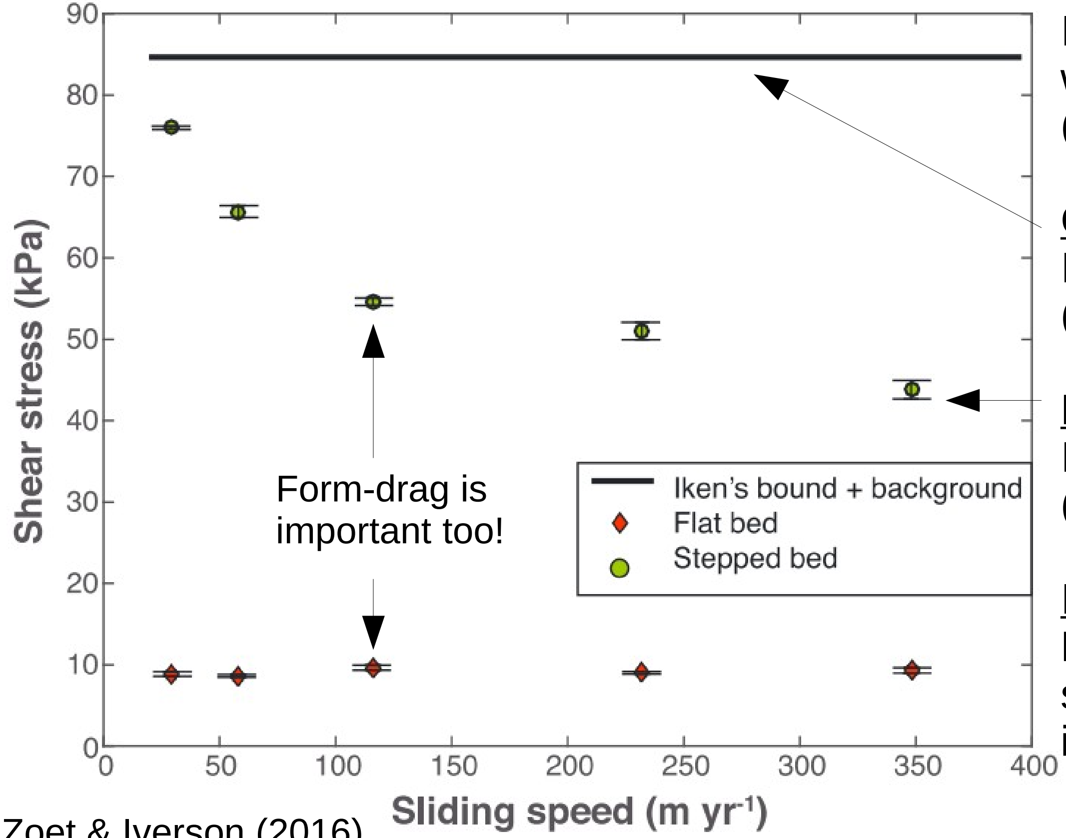
<u>Funding</u>:
WARF Fall Research Competition Award, 2019
University of Wisconsin – Madison, Department of Geoscience
NSF-PLR 1738913
Penn State Evan Pugh Research Endowment

<u>Research Permission</u>:
Parks Canada – Research Permit 38645

<u>Instrumentation</u>:
IRIS/PASSCAL GEOICE

Photos are the work of N.T. Stevens unless otherwise stated

Experimental & Numerical Sliding Theory: Stepped Beds with Water Filled Cavities



Zoet & Iverson (2016)

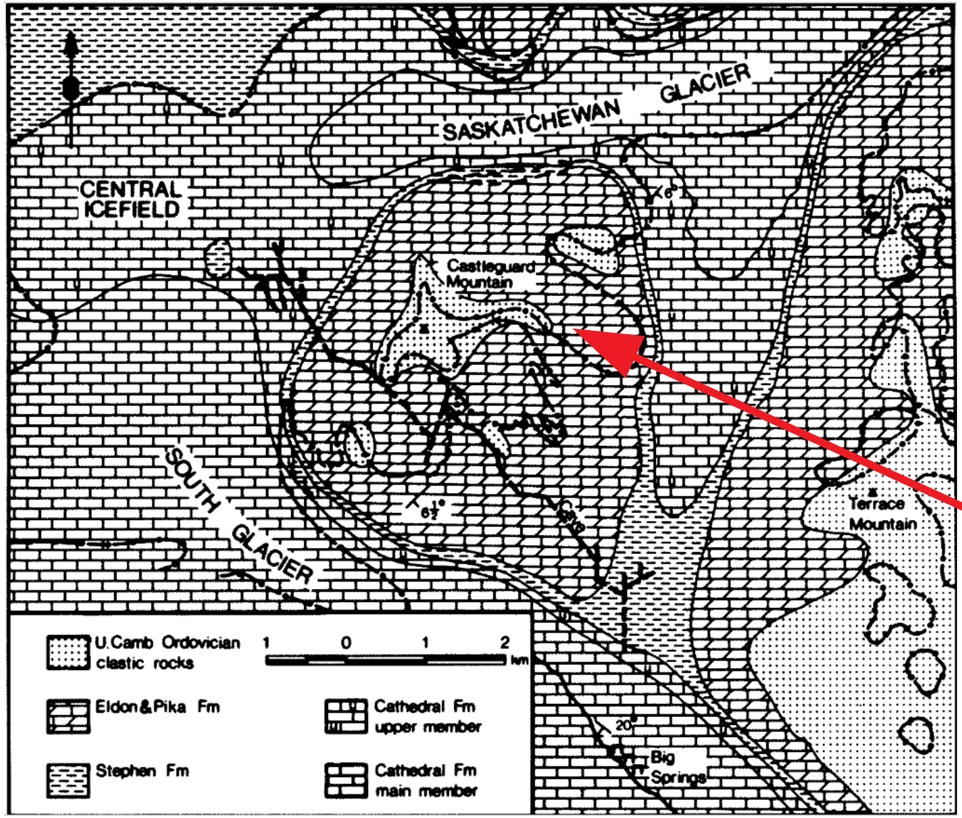
Increasing bed water pressure has a similar effect on water-filled cavities as increasing sliding velocity (e.g., Iverson, 1991; Hooke, 1991)

Classic Theory (Iken, 1981):
Increasing V (or P) doesn't change drag from the bed (**Rate Neutral Sliding**)

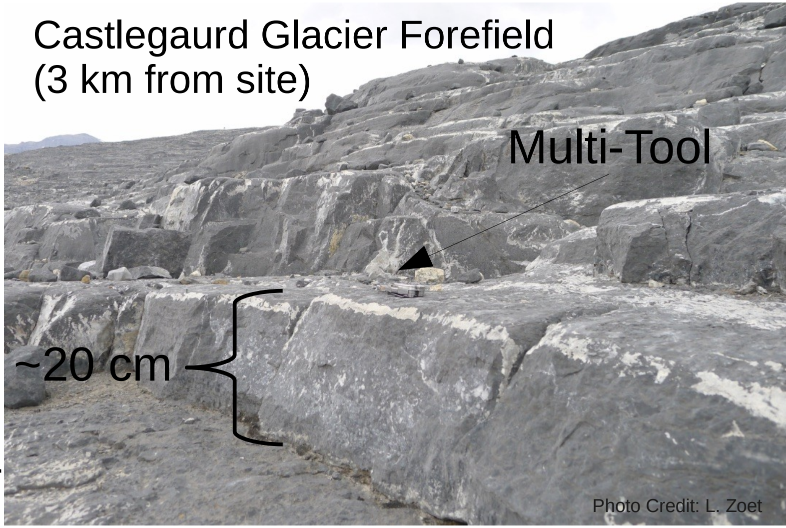
Experimental Results (Zoet & Iverson, 2016):
Increasing V (or P) decreases drag from the bed (**Rate Weakening Sliding**)

Importance:
Rate weakening sliding laws tend to decrease the stability of glaciers (e.g., Schoof, 2005) and greatly impact forecasts of sea-level rise.

Saskatchewan Glacier
A Natural Laboratory

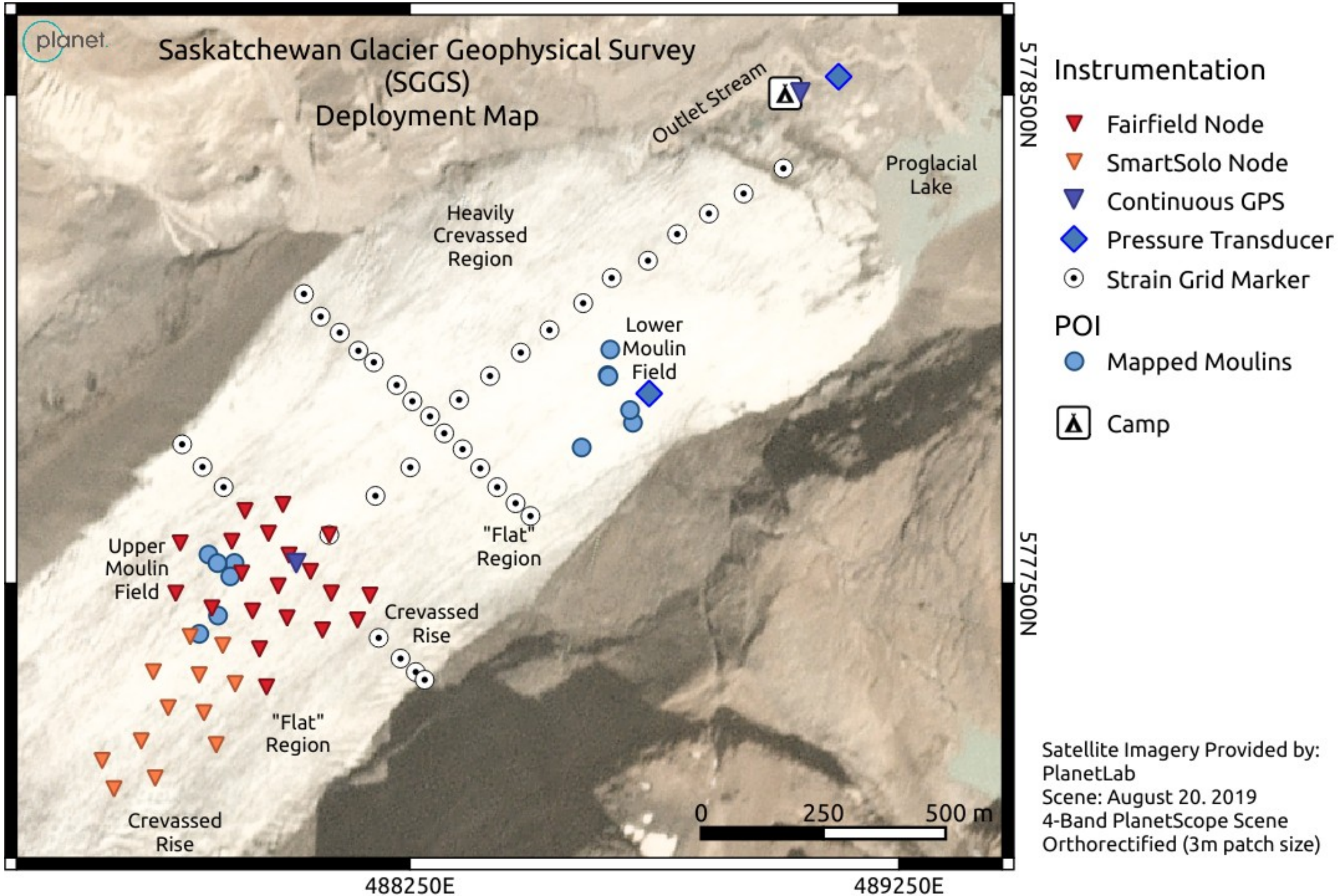


In the Literature:
Cathedral Fm: 1-12 m bedding (above)
Pika Fm: 0.1-0.5 m bedding (below)
(Ford, 1983)



Bedding thickness scales step size (e.g., Woodard et al., 2019)
→ Multi-meter scale steps anticipated beneath Saskatchewan Glacier

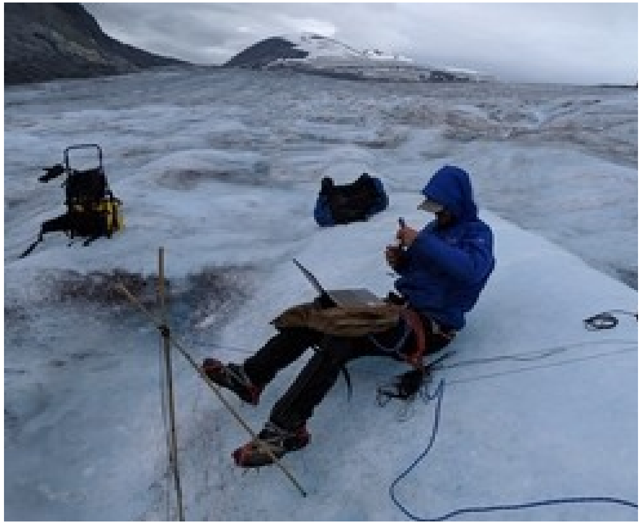
Geophysical Survey Components



- Passive Seismic Monitoring: 32 Instruments
- Active Source Shots: 4000+ hammer blows
- Refraction & Zero-Offset Surveys
- Continuous GPS
- Continuous Weather
- Continuous Stream & Moulin Stage
- Ablation & Strain Grid: 3-4 day repeat surveys

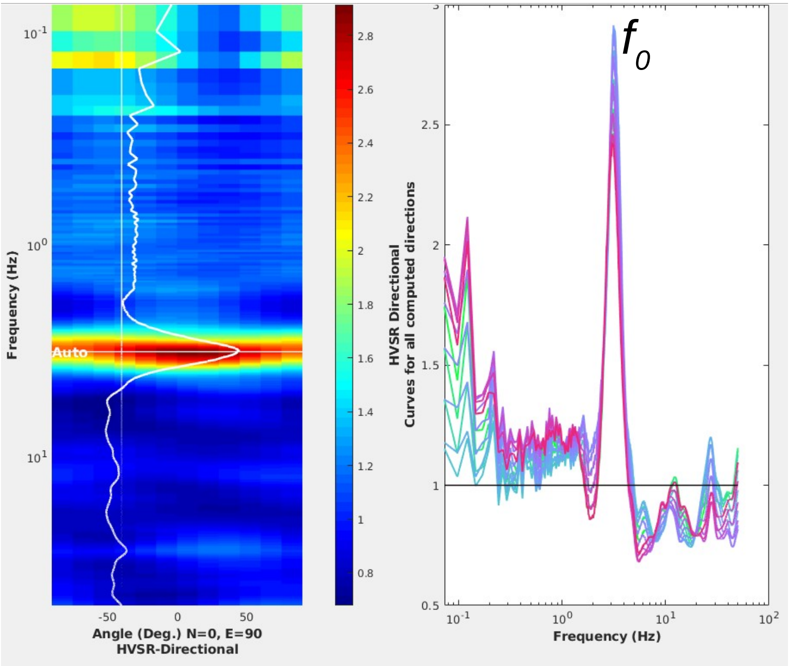
Event Detection & Location Workflow

- Pre-processing: 80 – 430 Hz Bandpass
- Detection: Moving window kurtosis CRF + noise adaptive detection threshold on vertical channels. (McBrearty et al., 2020 + Carmichael et al., 2015).
- Association: network coincidence trigger in ObsPy (Kirscher et al., 2015)
- Phase picking: adaptation of P-detection routine from Akazawa (2004) for P- & S-phases.
- Event location: NonLinLoc (Lomax et al., 2000). Ice-only velocity model.
  - Events with #data $\geq$ 20
  - V_P: 3.7 km/s, from refraction survey
  - V_P/V_S: 1.95, e.g., Smith et al. (2015)

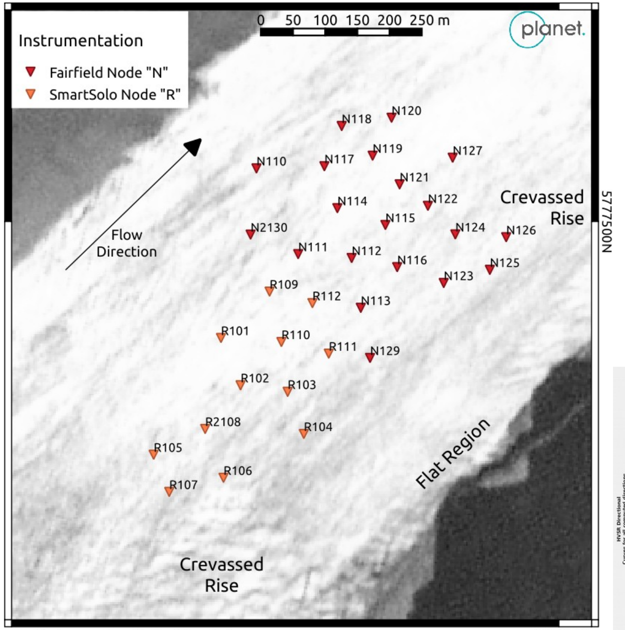


H/V Ice Thickness Modelling

Station N117
H/V Azimuthal Image & Curves



Processed with OpenHVSR (Bignardi et al., 2018)



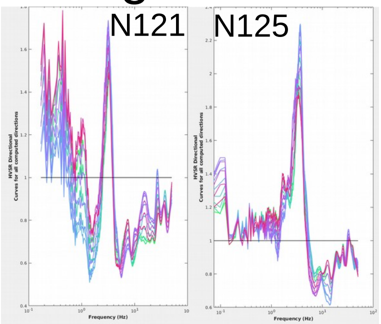
Satellite Imagery Provided by: PlanetLab
Scene: August 20. 2019 4-Band PlanetScope Scene
Orthorectified (3m patch size)

$$\hat{h}_{ice} = \frac{V_{S,ice}}{4 f_0}$$

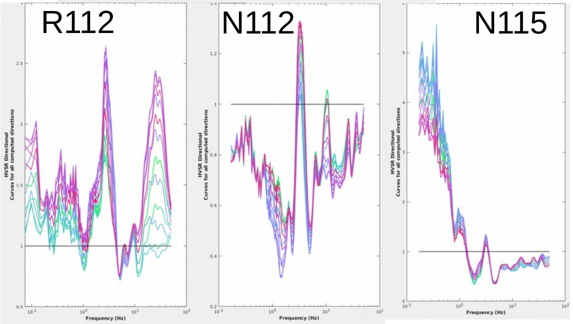
$$V_{S,ice} \approx 1900\, m/s$$

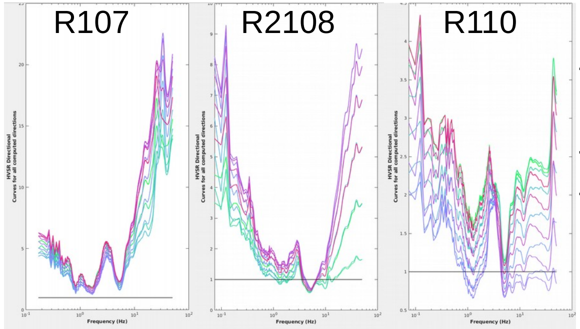
Quarter-wavelength approximation for ice thickness holds for azimuthally invariant H/V peaks (see Preiswerk et al., 2018)

Along-Flow Examples



H/V Peaks amplitudes do not vary with azimuth for most sites.





Proximity to upper crevasse field begins to degrade azimuthal invariance

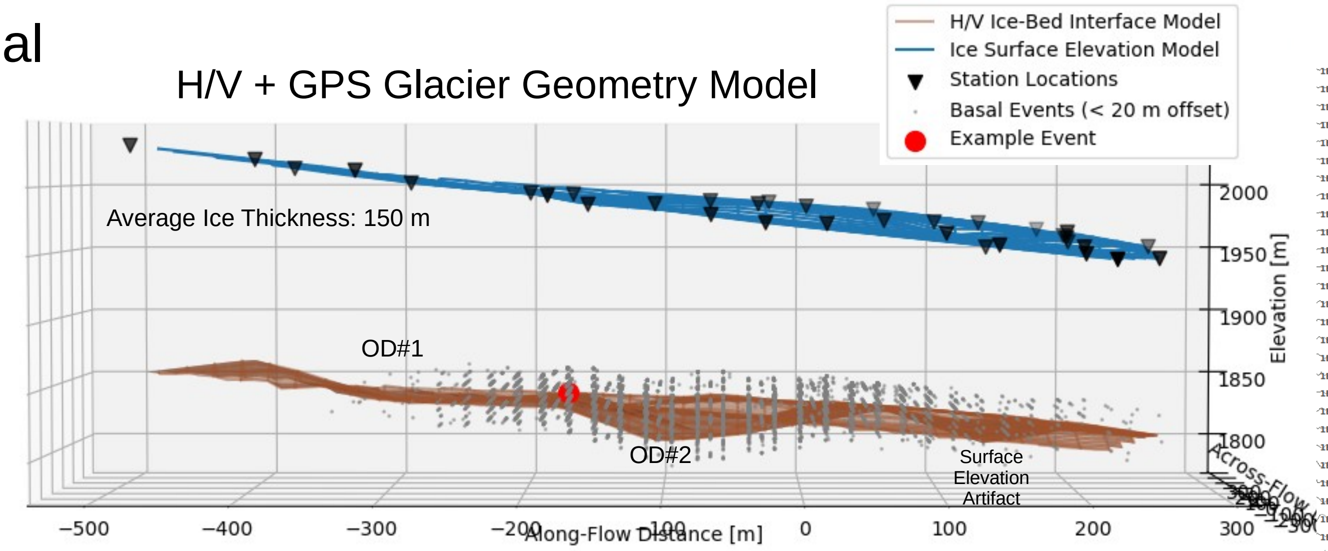
Bed Model & Basal Seismicity Rates

Ice-bed interface model suggests 2x overdeepenings (OD), ~200m in length and 30-50m in relief.

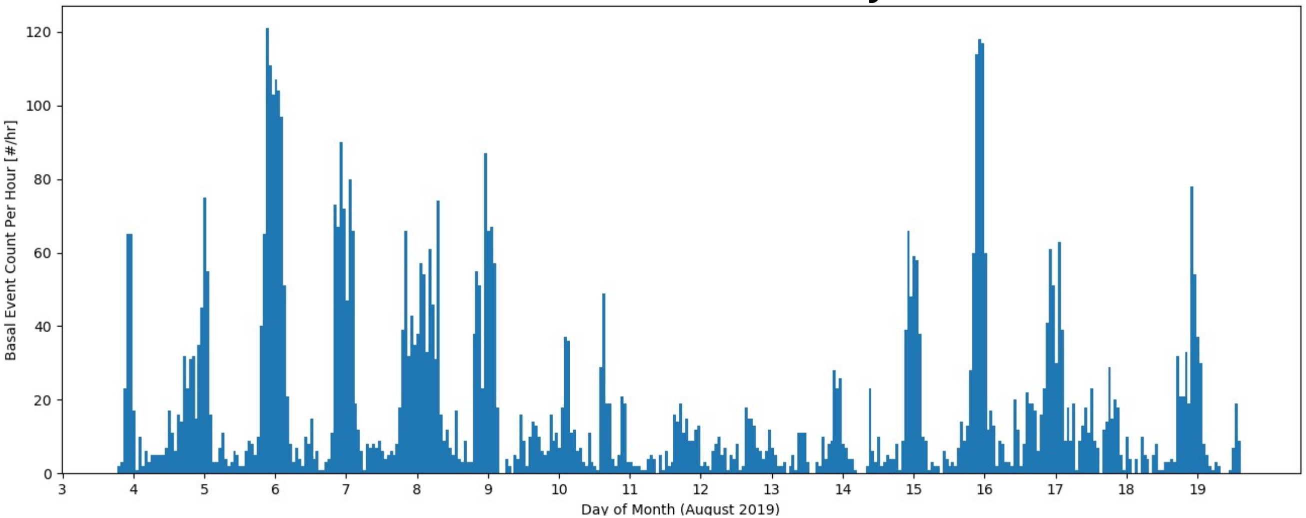
6616 of 92277 preliminary event locations within 20m of ice-bed interface model

Event rate shows a strong diurnal signal.

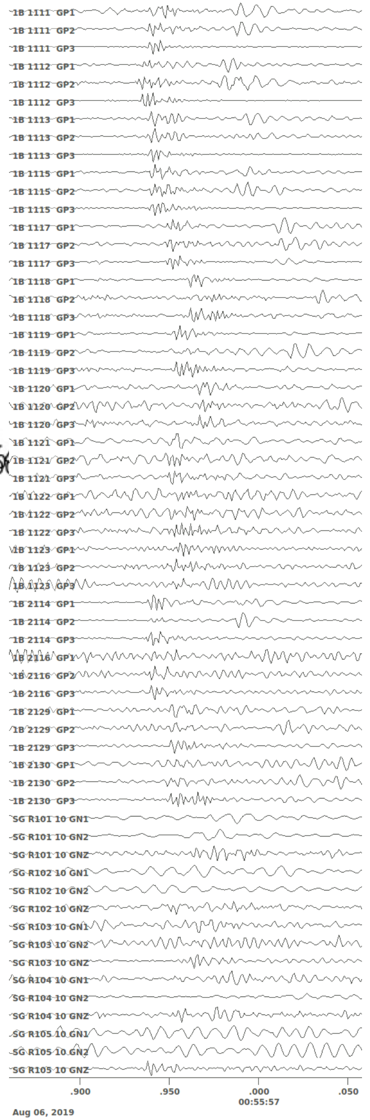
H/V + GPS Glacier Geometry Model

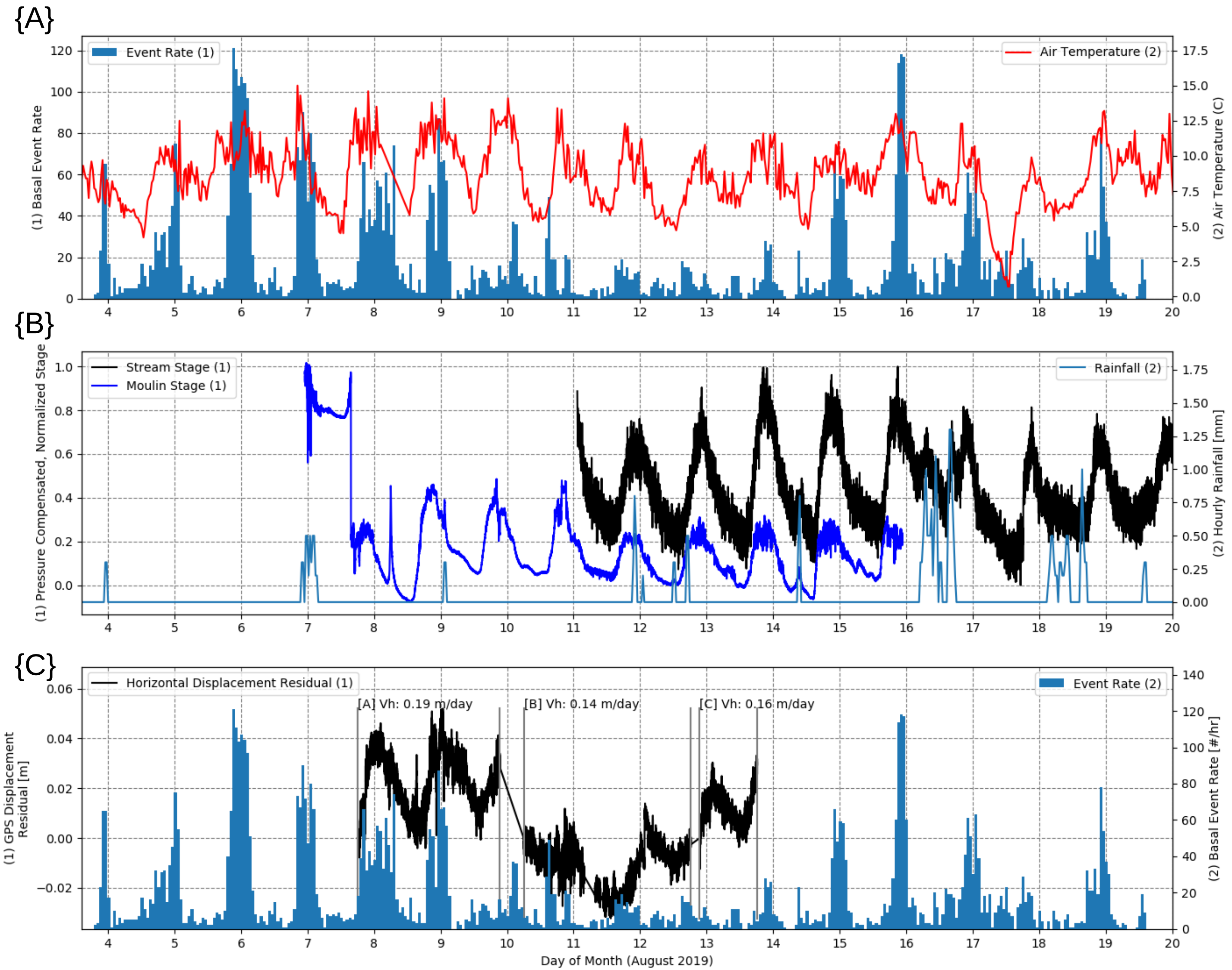


Basal Event Subset, Hourly Rate



Example Basal Event Near OD#2 Headwall





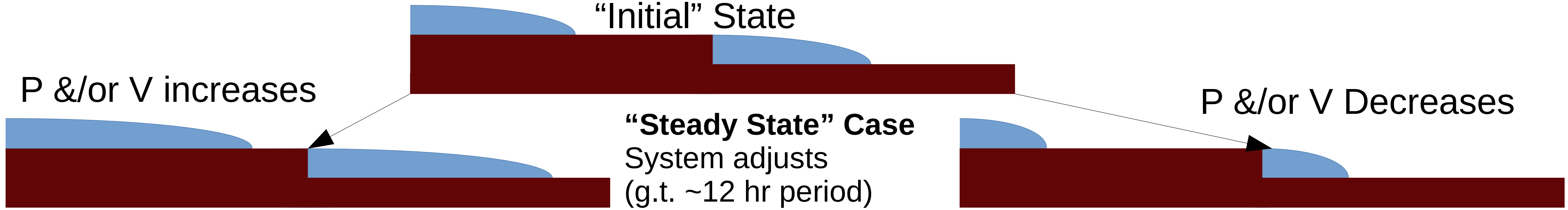
Forcing Characterization

Peak seismic rates:

- Lag peak air temperature by 1-4 hrs {A}
- Lag peak stream & moulin stage by 1-4 hrs {B}
- Coincide with with rain events {B}
- Trail greatest surface velocity acceleration by 1-4 hrs {C}

Seismic quiescence coincides with multi-day falling air temperatures, stage, and displacement residuals. {A,B}

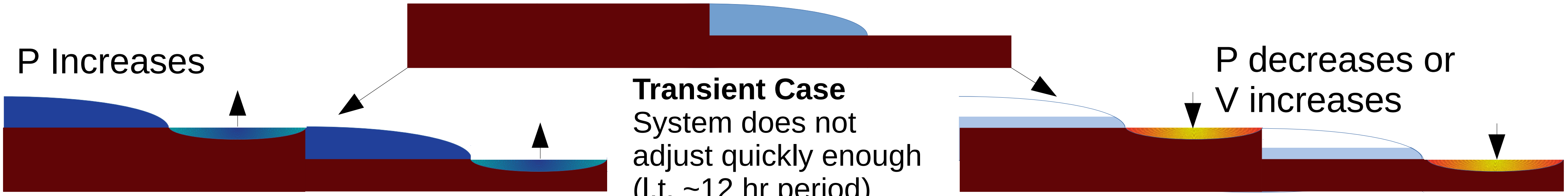
Proposed Mechanism:
Transient Response of Lee-Side Cavities



Cavities **Grow** in Length

"Steady State" Case
System adjusts
(g.t. ~12 hr period)
Bed stress remains
~Constant

Cavities **Shrink** in Length



Cavities **pressurize & locally float** ice, accommodating load. Favors stable sliding?

Transient Case
System does not
adjust quickly enough
(l.t. ~12 hr period)
Load redistributes

Cavities **drain & focus** ice loads on ice-bed contacts. Favors stick-slip.

The short time-scale (0-8 hr) of changes in water delivery to the bed of Saskatchewan Glacier corresponds with rapid changes in the rates of basal seismicity, favoring transient processes.

Conclusions

- Abundant seismicity at the bed of Saskatchewan Glacier indicates rate-weakening phenomena on hard, step-shaped beds in a natural setting.
- Rates of seismicity are strongly correlated to diurnal melt water supply, trailing peak subglacial throughput and accelerated glacier motion.
- These observations support consideration of transient, rate-weakening sliding relationships for stepped beds.

Questions?

- Corresponding author
  - E-mail: ntstevens@wisc.edu
  - Twitter: @nt_stevens
    - Plus:
      - @lzoet (LZ)
      - @WaterAndHazards (CJR)
      - @schwantarctic (ES)

References

Akazawa, T. (2004). A Technique for Automatic Detection of Onset Time of P- and S-Phases in Strong Motion Records. *13 Th World Conference on Earthquake Engineering*, (786), 786.

Bignardi, S., Yezzi, A. J., Fiussello, S., & Comelli, A. (2018). OpenHVSR - Processing toolkit : Enhanced HVSR processing of distributed microtremor measurements and spatial variation of their informative content. *Computers and Geosciences*, *120*(July), 10–20. https://doi.org/10.1016/j.cageo.2018.07.006

Carmichael, J. D., Joughin, I., Behn, M. D., Das, S., King, M. A., Stevens, L., & Lizarralde, D. (2015). Seismicity on the western Greenland Ice Sheet: Surface fracture in the vicinity of active moulins. *Journal of Geophysical Research: Earth Surface*, *120*, 1082–1106. https://doi.org/10.1002/2014JF003398

Ford, D. C. (1983). The Physiography of the Castleguard Karst and Columbia Icefields Area , Alberta , Canada. *Arctic and Alpine Research*, *15*(4), 427–436.

Hooke, R. L. (1991). Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geological Society Of America Bulletin*, *103*(August), 1104–1108. https://doi.org/10.1130/0016-7606(1991)103<1104

Iken, A. (1981). The Effect of the Subglacial Water Pressure on the Sliding of a Glacier in an Idealized Numerical Model. *Journal of Glaciology*, *27*(97).

Iverson, N. R. (1991). Potential effects of subglacial water-pressure fluctuations on quarrying. *Journal of Glaciology*, *37*(125), 27–36. https://doi.org/10.3189/s0022143000042763

Krischer, L., Megies, T., Barsch, R., Beyreuther, M., Lecocq, T., Caudron, C., & Wassermann, J. (2015). ObsPy: A bridge for seismology into the scientific Python ecosystem. *Computational Science and Discovery*, *8*(1). https://doi.org/10.1088/1749-4699/8/1/014003

Mcbrearty, I. W., Zoet, L. K., & Anandakrishnan, S. (2020). Seismicity of the Northeast Greenland Ice Stream. *Journal of Glaciology*, 1–17.

Preiswerk, L. E., Michel, C., Walter, F., & Fäh, D. (2018). Effects of geometry on the seismic wavefield of Alpine glaciers. *Annals of Glaciology*, 1–13. https://doi.org/10.1017/aog.2018.27

Schoof, C. (2005). The effect of cavitation on glacier sliding. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *461*(2055), 609–627. https://doi.org/10.1098/rspa.2004.1350

Smith, E. C., Smith, A. M., White, R. S., Brisbourne, A. M., & Pritchard, H. D. (2015). Mapping the ice-bed interface characteristics of Rutford Ice Stream, West Antarctica, using microseismicity. *Journal of Geophysical Research F: Earth Surface*, *120*(9), 1881–1894. https://doi.org/10.1002/2015JF003587

Woodard, J. B., Zoet, L. K., Iverson, N. R., & Helanow, C. (2019). Linking bedrock discontinuities to glacial quarrying. *Annals of Glaciology*, 1–7. https://doi.org/https://doi.org/10.1017/aog.2019.36

Zoet, L. K., & Iverson, N. R. (2016). Rate-weakening drag during glacier sliding. *Journal of Geophysical Research: Earth Surface*, *121*, 1328–1350. https://doi.org/10.1002/2016JF003909