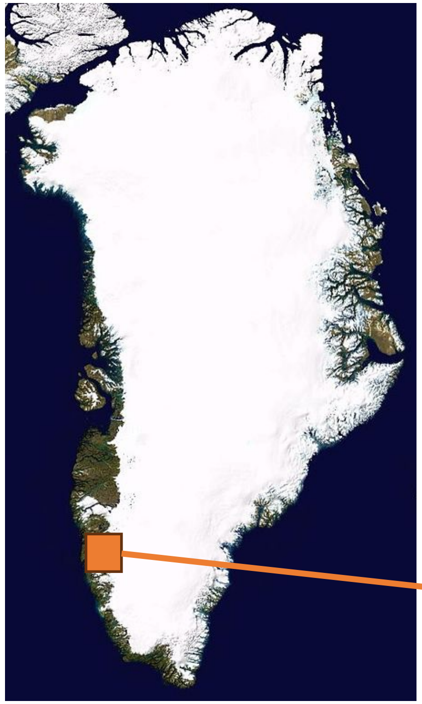
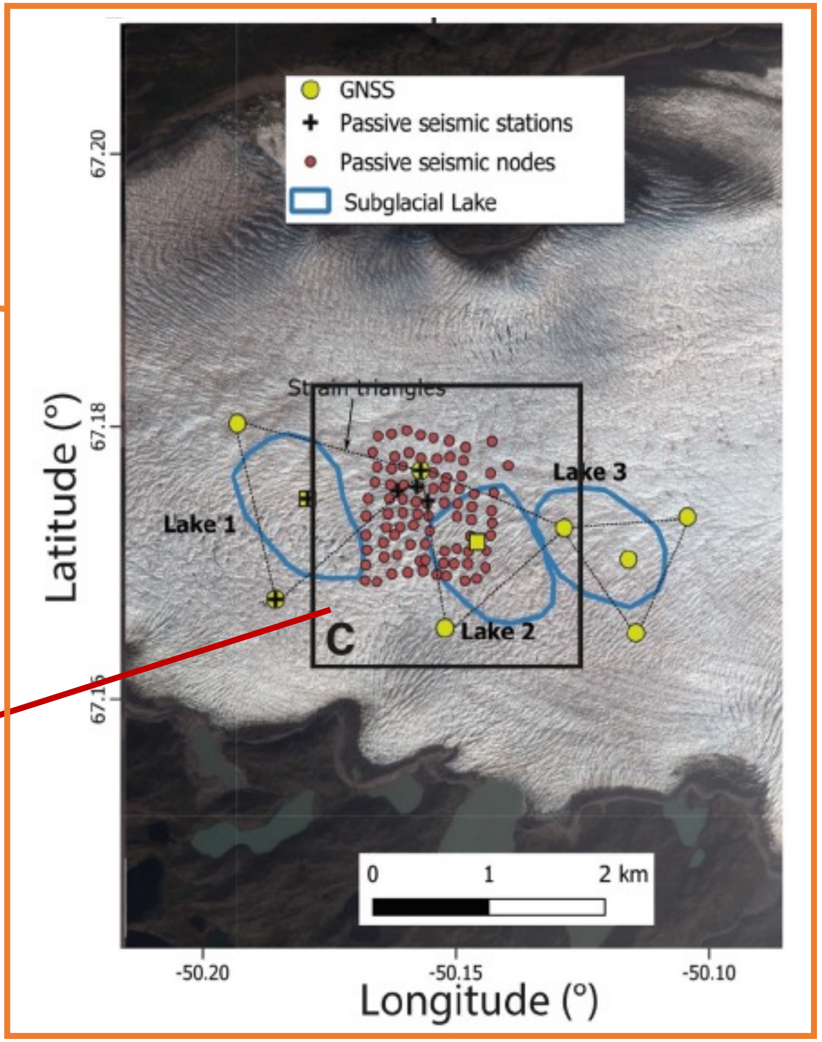
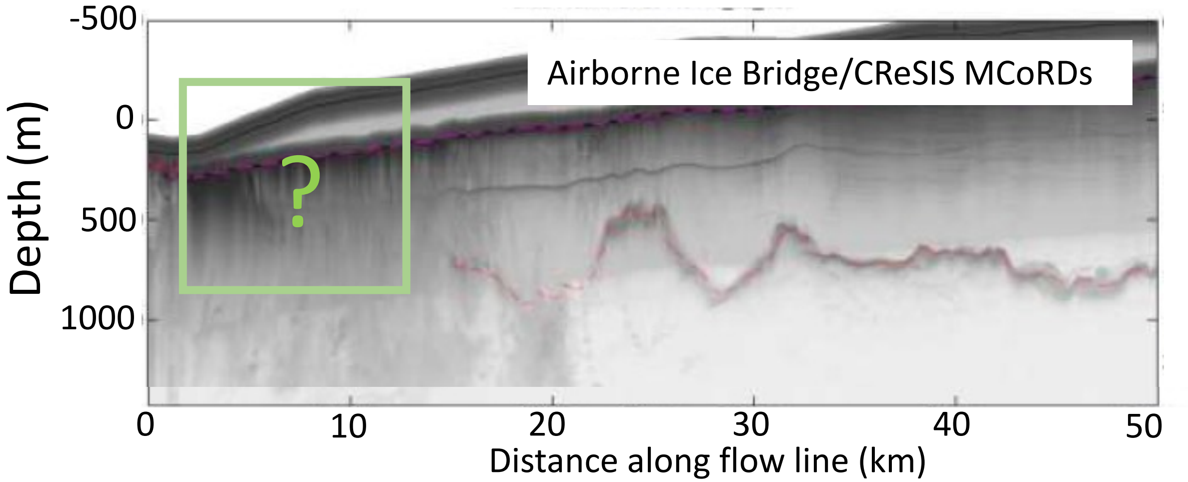
Probing glacier physics and structure with passive seismics at Isunguata Glacier, Western Greenland

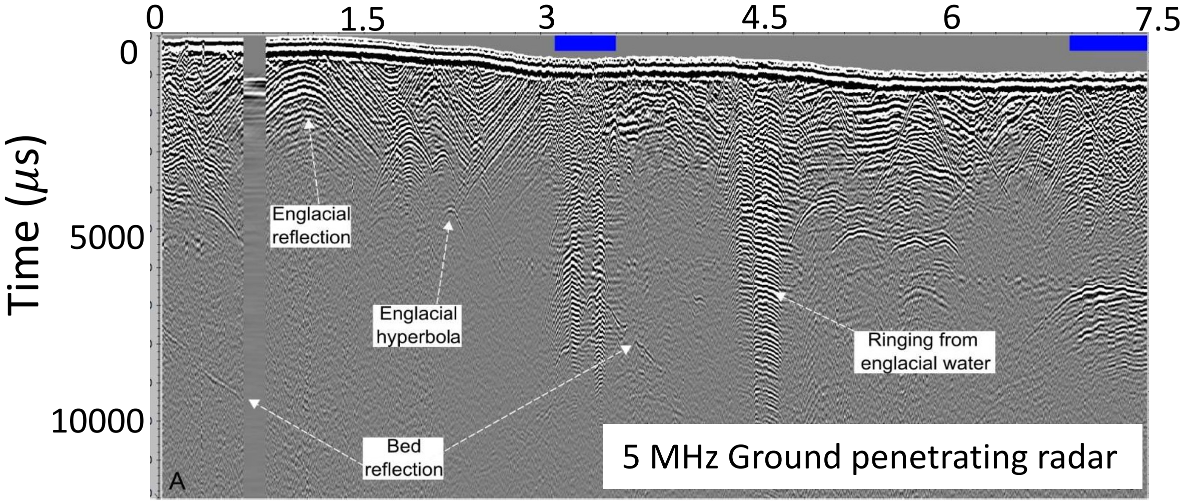
Florent Gimbert[1], Neil Ross[2], Tifenn Le Bris[1], Guilhem Barruol[1], Tun Jan Young[3], Samuel Doyle[4,5], Stephen Livingstone[4], Andrew Sole[4], Adrien Gilbert[1], Ryan Ing[6], Liz Bagshaw[7], Mike Prior-Jones[8], and Laura Edwards[9]



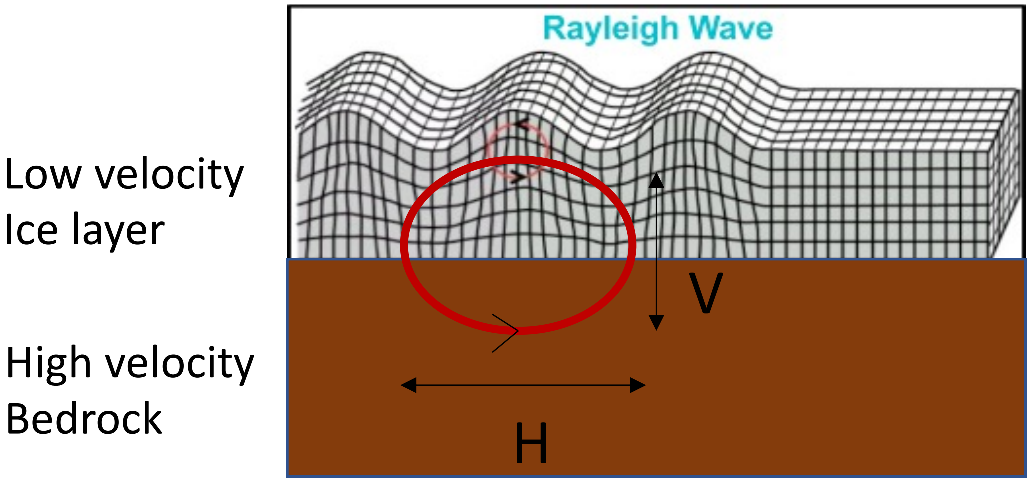


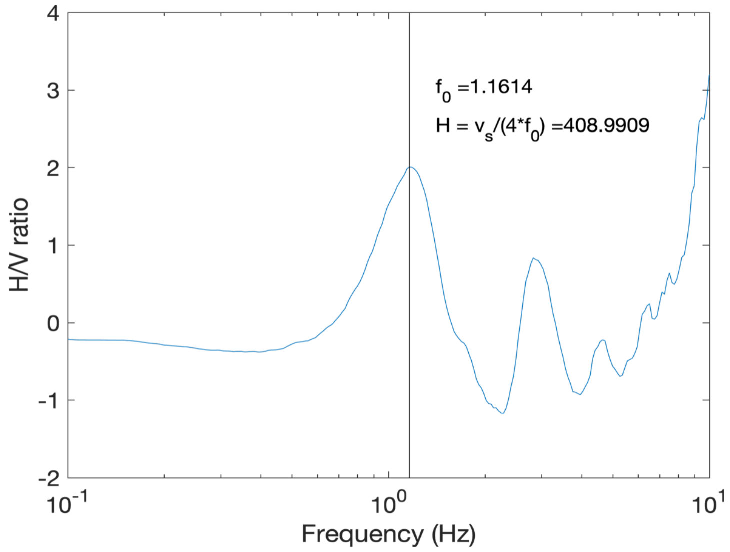
Glacier bed topography from radar

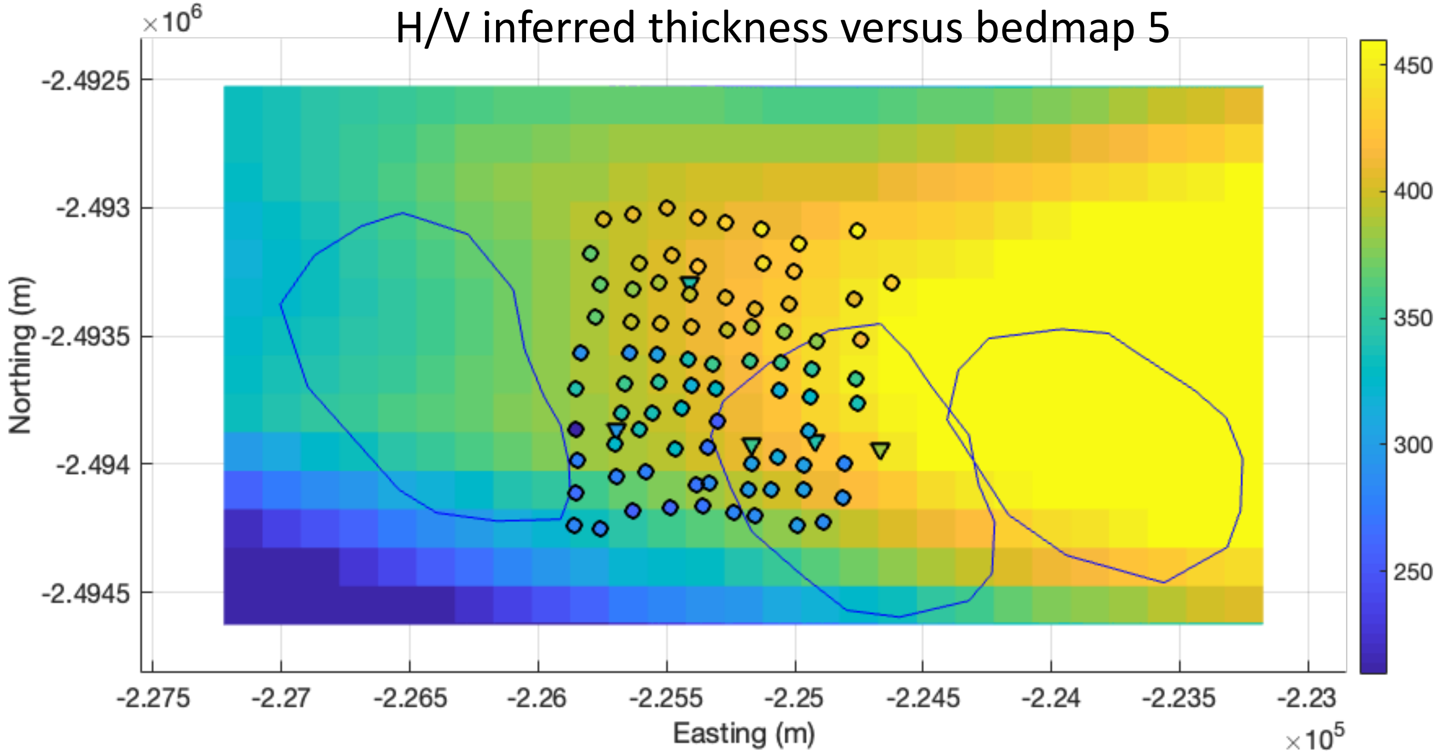


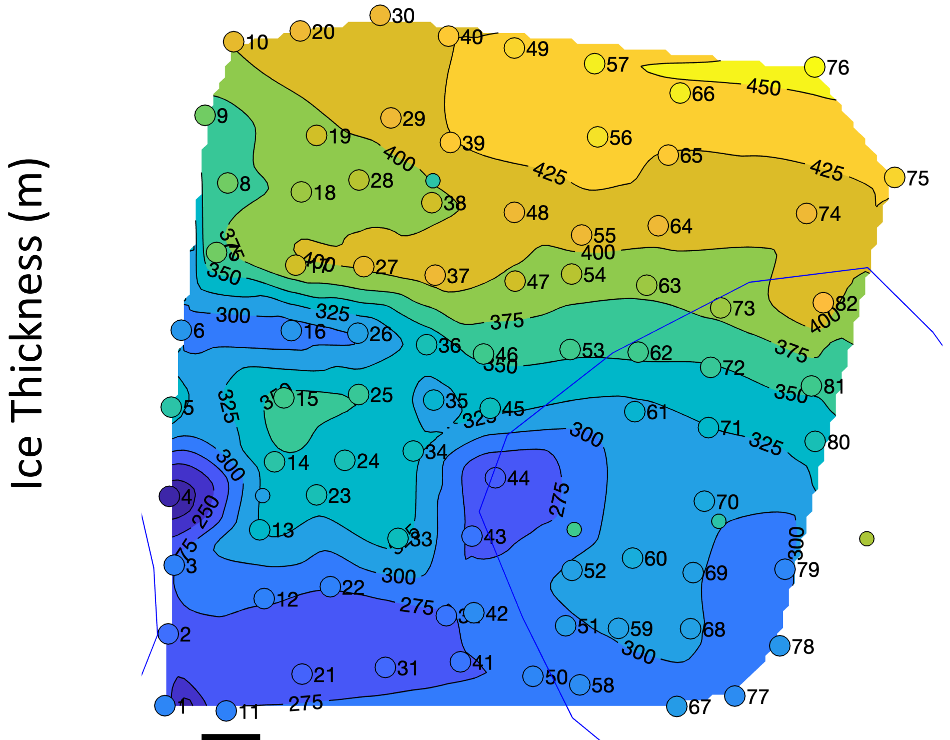


Thickness from H/V analysis









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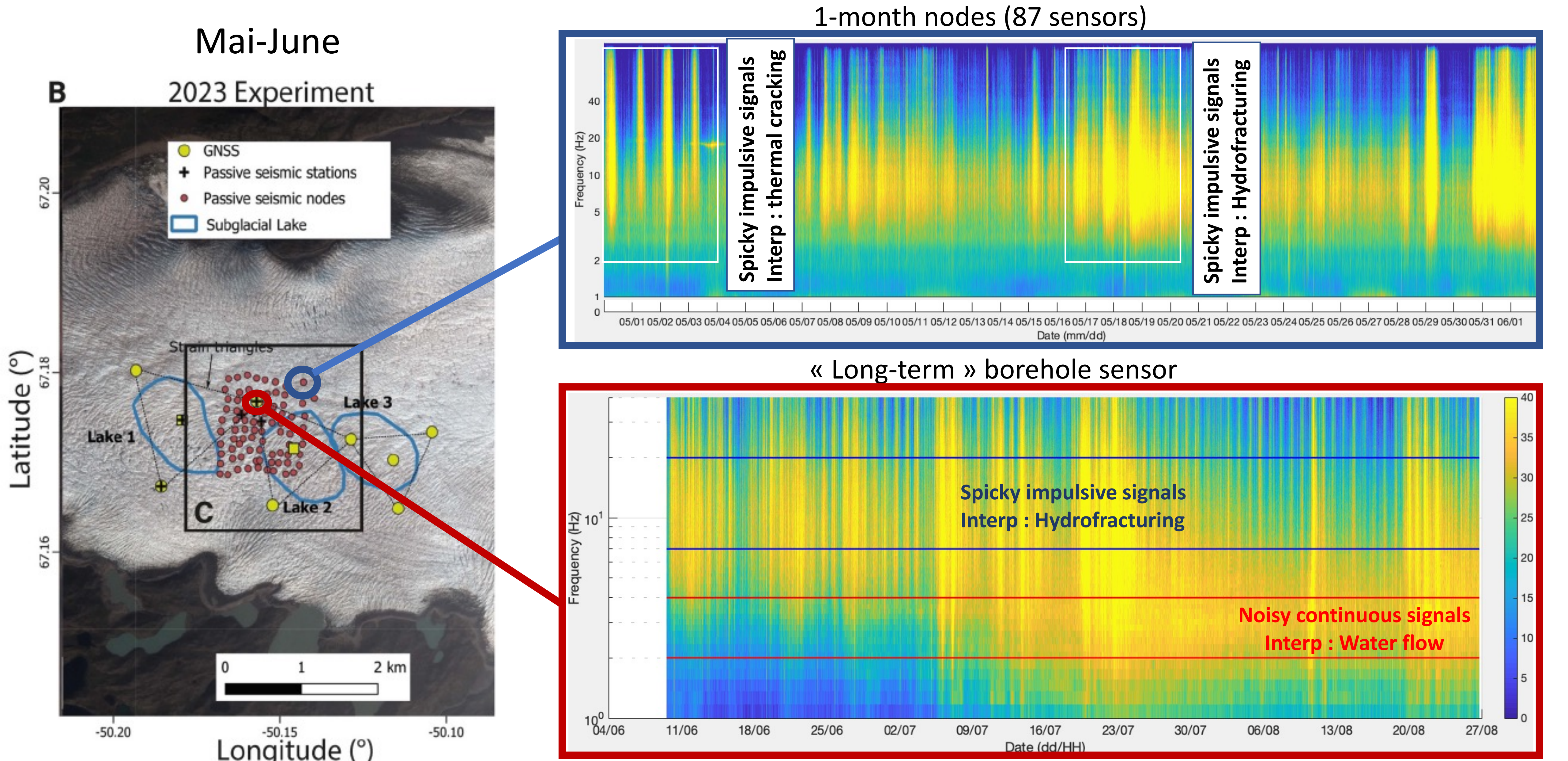
Probing glacier physics and structure with passive seismics



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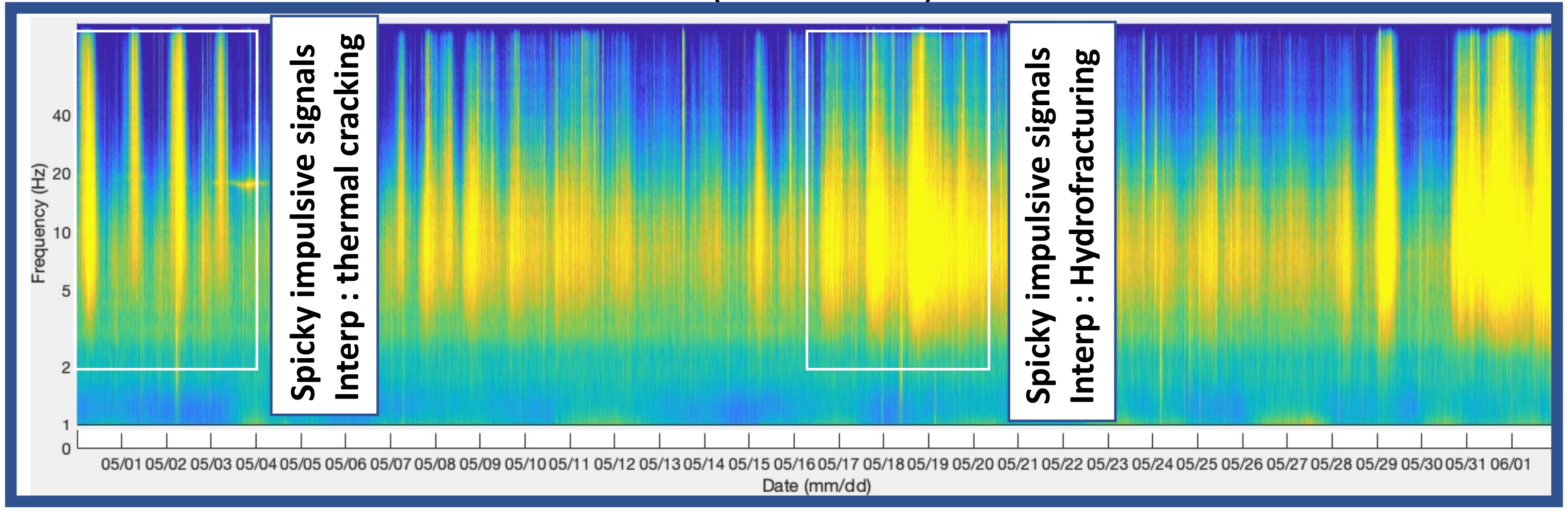
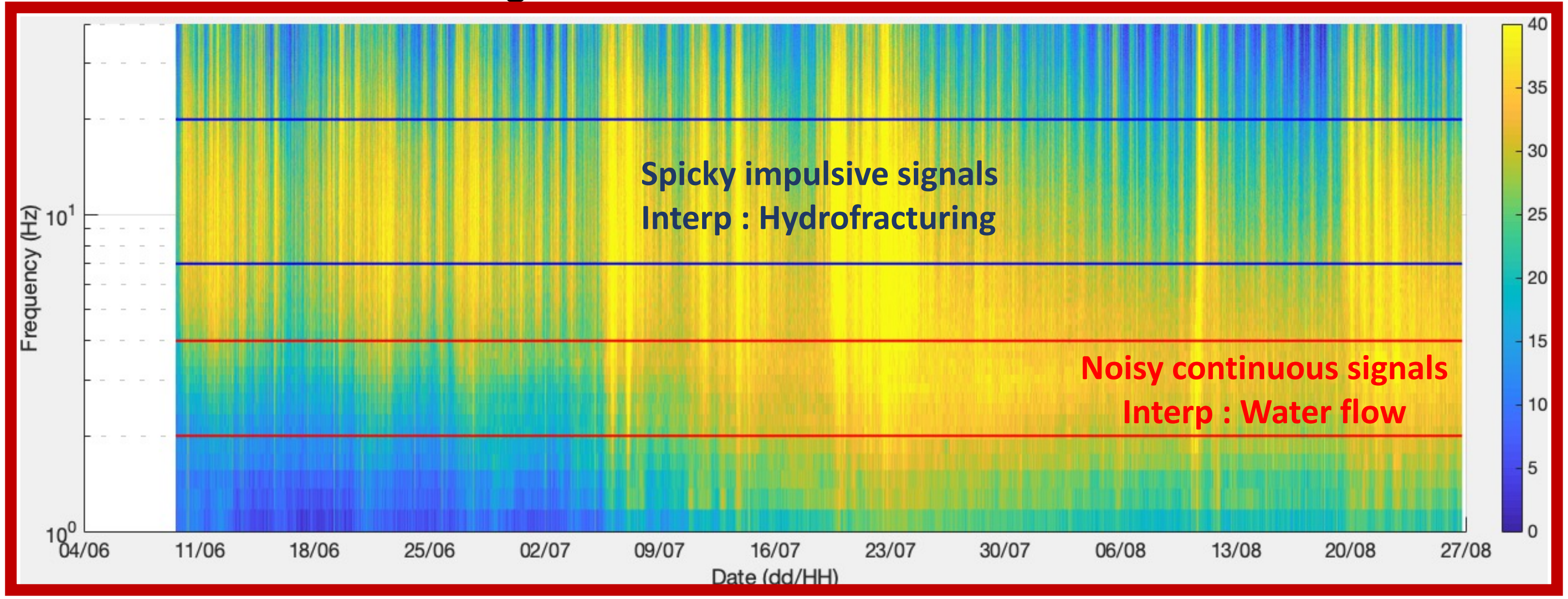
Source analysis

1-month nodes (87 sensors)



« Long-term » borehole sensor



Ice deformation and englacial water percolation

Source location:
Beamforming - e.g. Gimbert et al., 2021

Subglacial drainage from the generated noise

Source physics: infer changes in channel flow conditions (e.g. sizes and pressure - Gimbert et al., 2016)

Source location:
Beamforming - e.g. Nanni et al., 2021;
PCA analysis - e.g. Journeau et al., 2022

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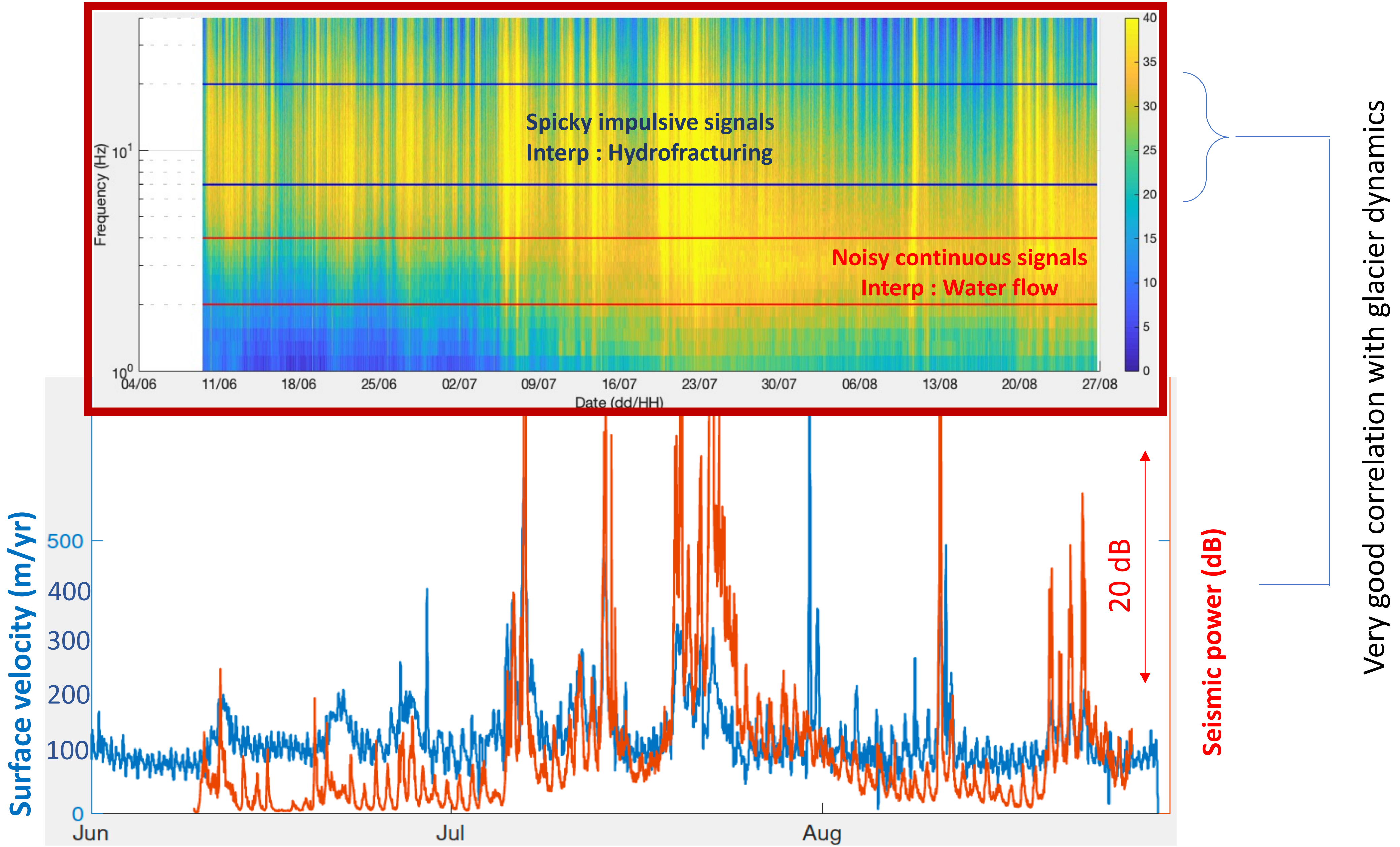
Ice deformation and englacial water percolation



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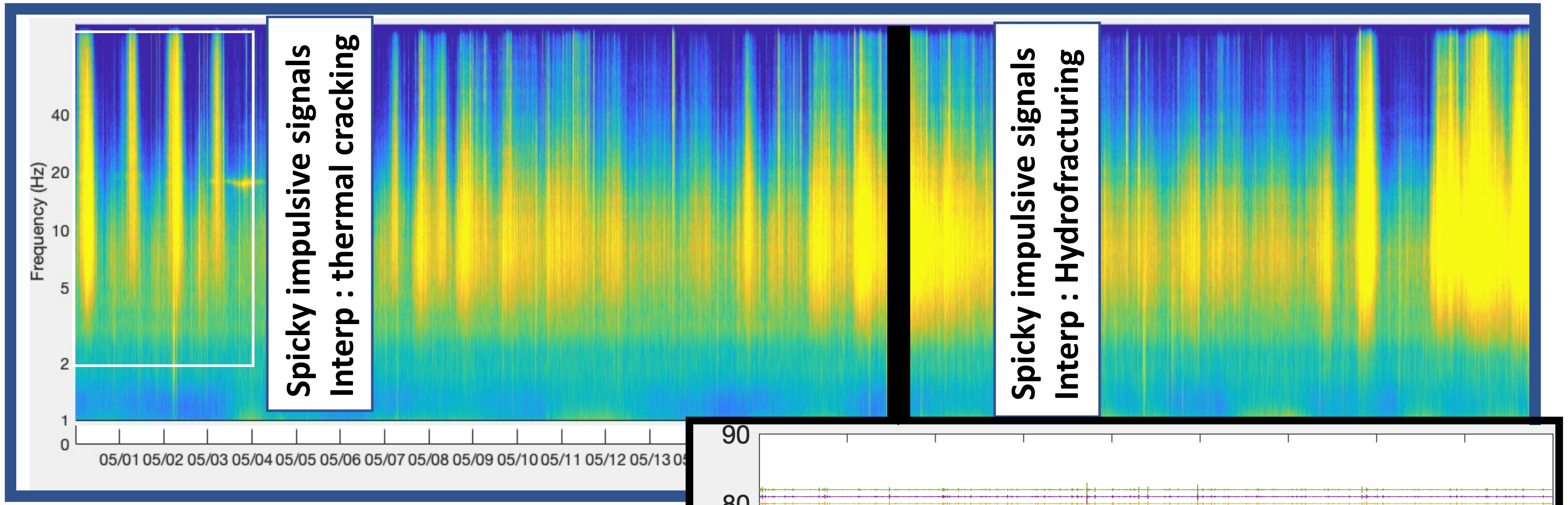

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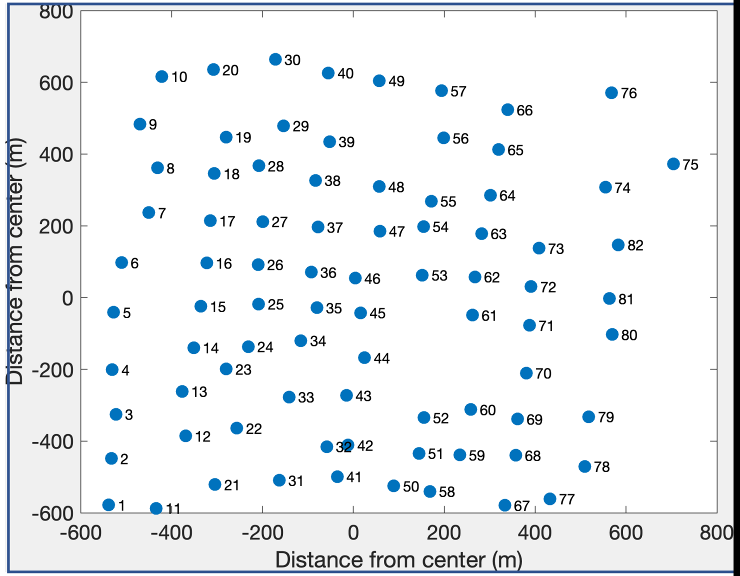

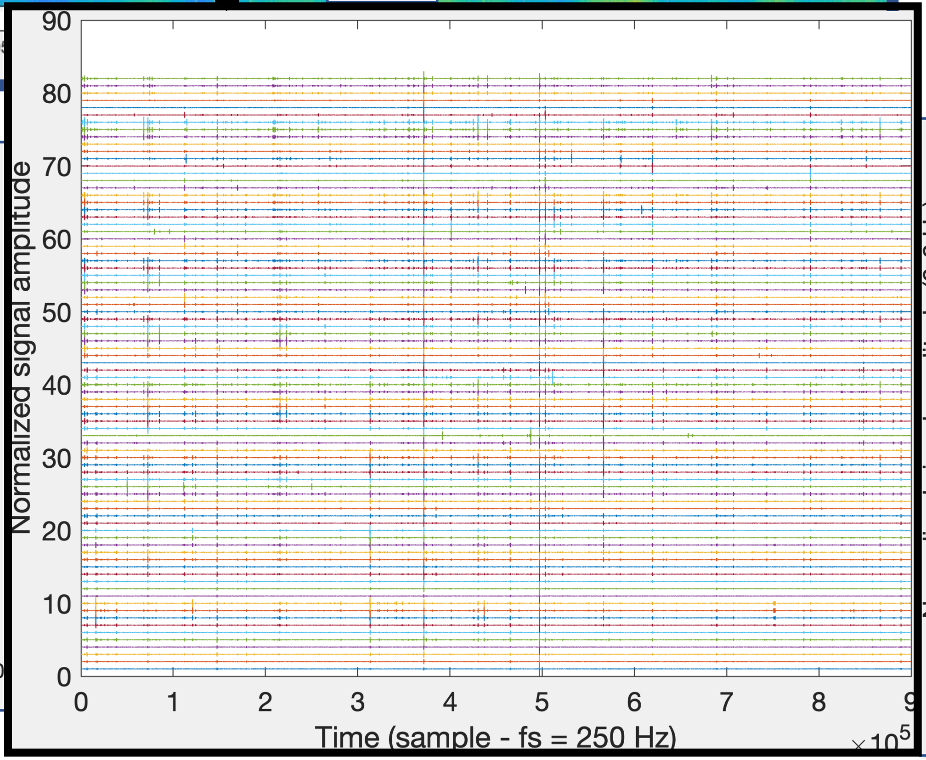

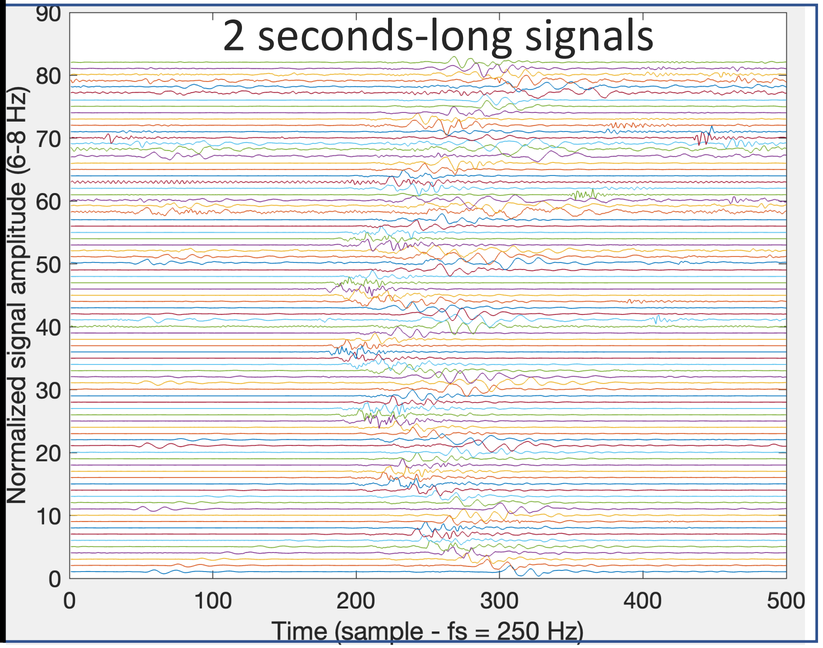

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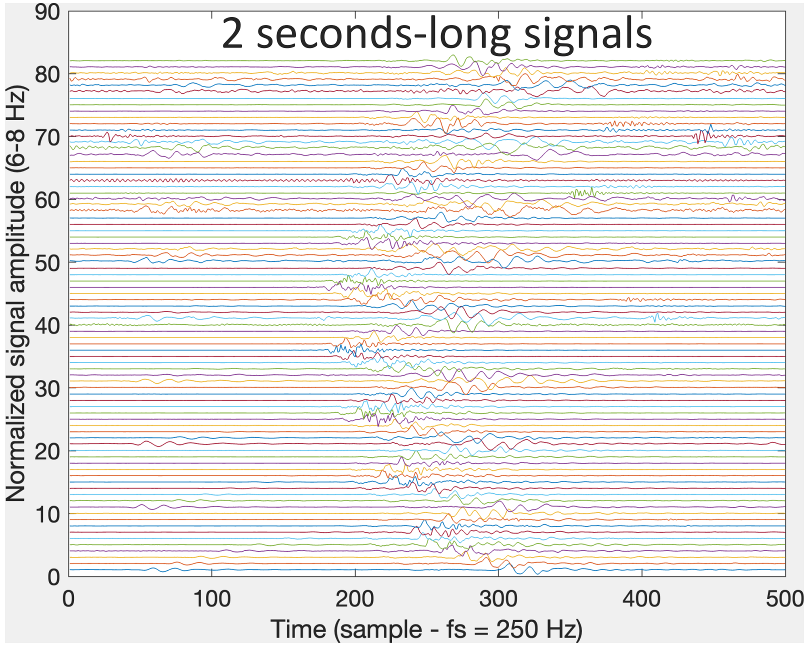
Icequakes locations using beamforming



- Calculate the cross-spectral density matrix as

$$K(\omega) = d(\omega)d^H(\omega),$$

with $d(\omega)$ the complex data vector and H the Hermitian (conjugate) transpose

- Evaluate the match between the observed and modelled phases in a 4 dimensional space as

$$B_{Bartlett}(\omega_c, a) = \frac{1}{N_\omega * N_d^2} \sum_{\omega} \left| \tilde{d}(\omega, a)^H K(\omega) \tilde{d}(\omega, a) \right|$$

with $\tilde{d}(\omega, a) = \exp\left(i\omega r_a / c \right)$ the complex model vector and r_a the distance to the trial source a

See Gimbert et al., 2021, Nanni et al., 2021,2022

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Icequakes locations using beamforming

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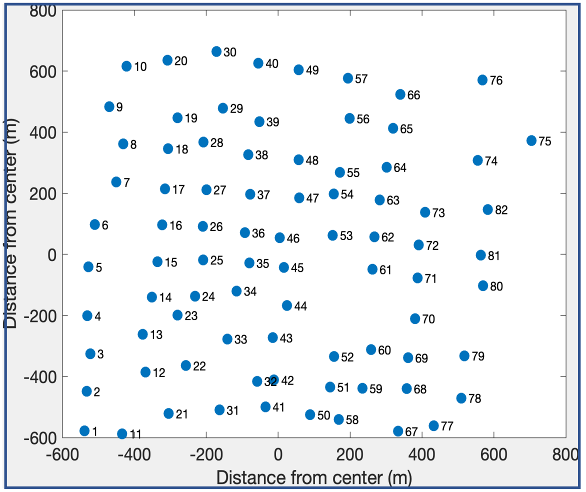

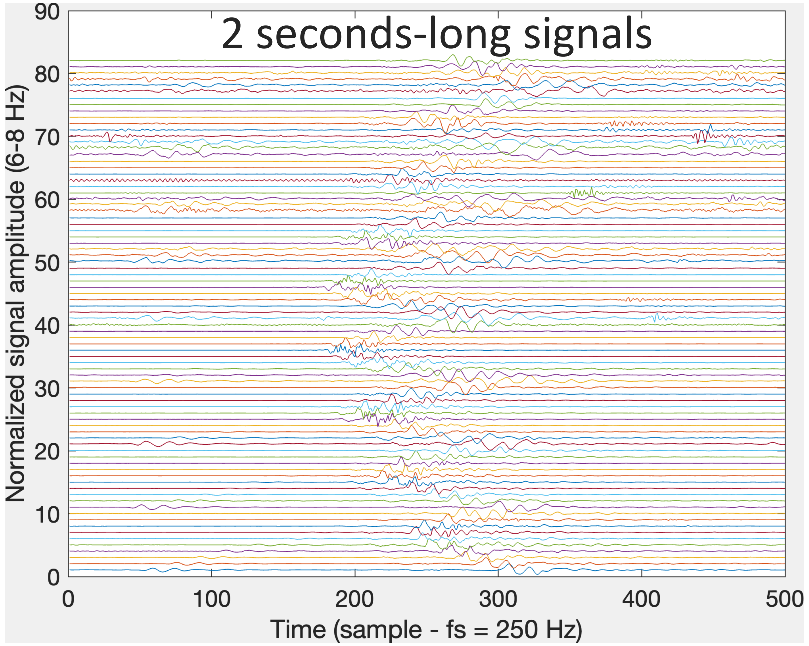

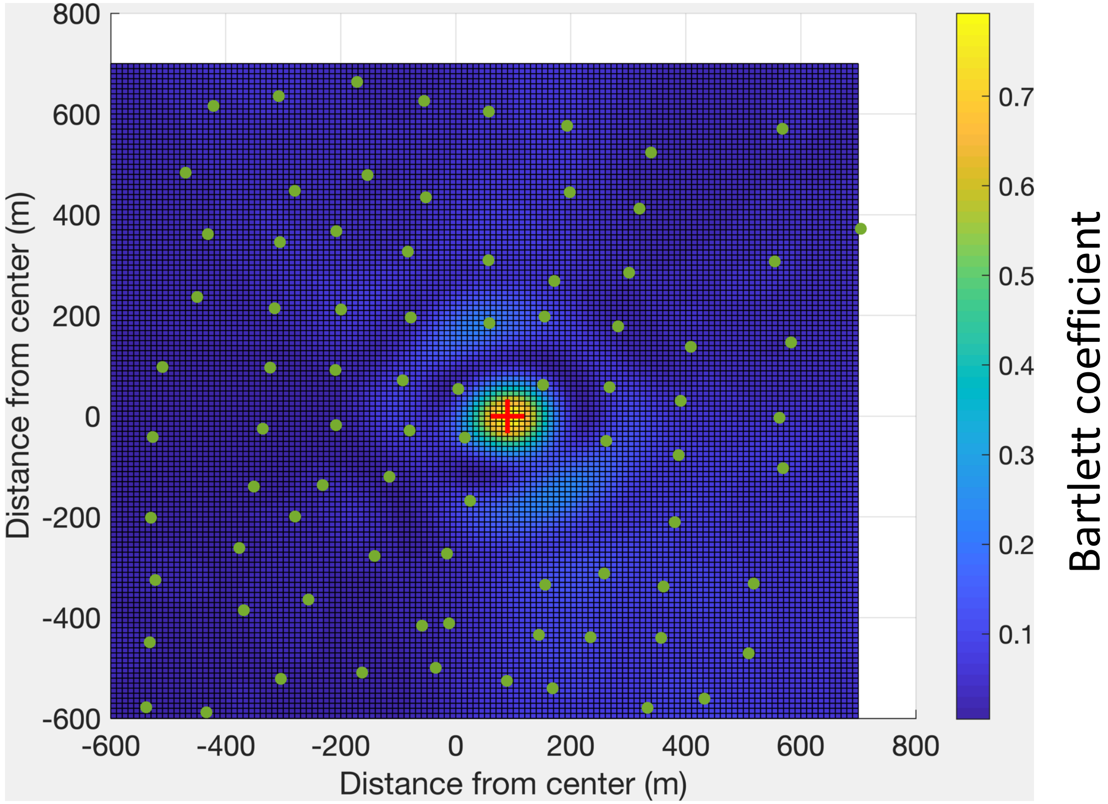

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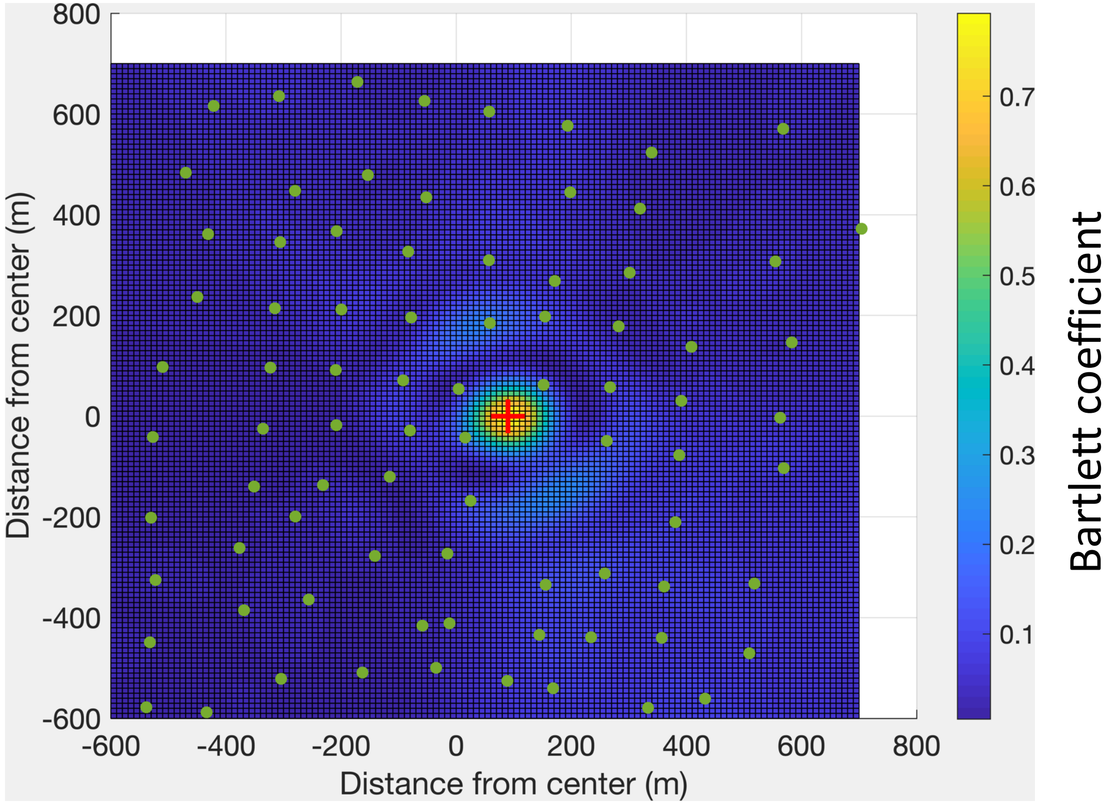
Icequakes locations using beamforming

Systematic source locations using optimization

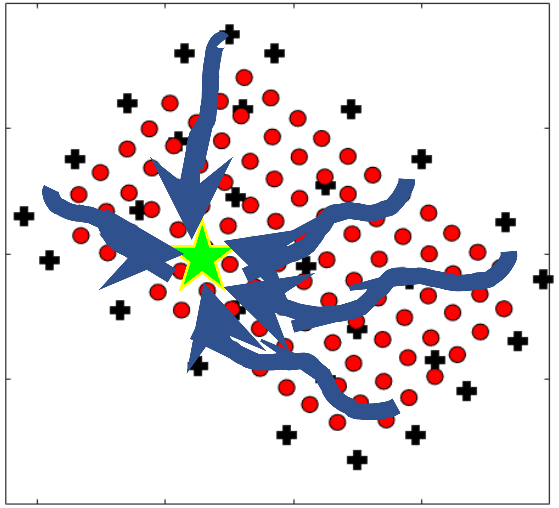
$$B_{Bartlett}(\omega_c, a) = \frac{1}{N_\omega * N_d^2} \sum_{\omega} \left| \tilde{d}(\omega, a)^H K(\omega) \tilde{d}(\omega, a) \right|$$

- Use of a gradient-based minimization algorithm (Nelder-Mead optimization)
- Efficiently converge to the best match
- Use multiple starting points to
  - Increase the likelihood that the global best match is found
  - Keep track of local best matches

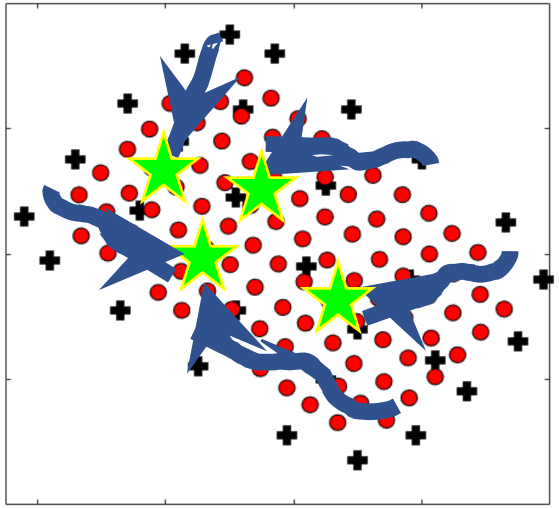
1 day (May 18) ←



Coherent wavefield



More incoherent wavefield



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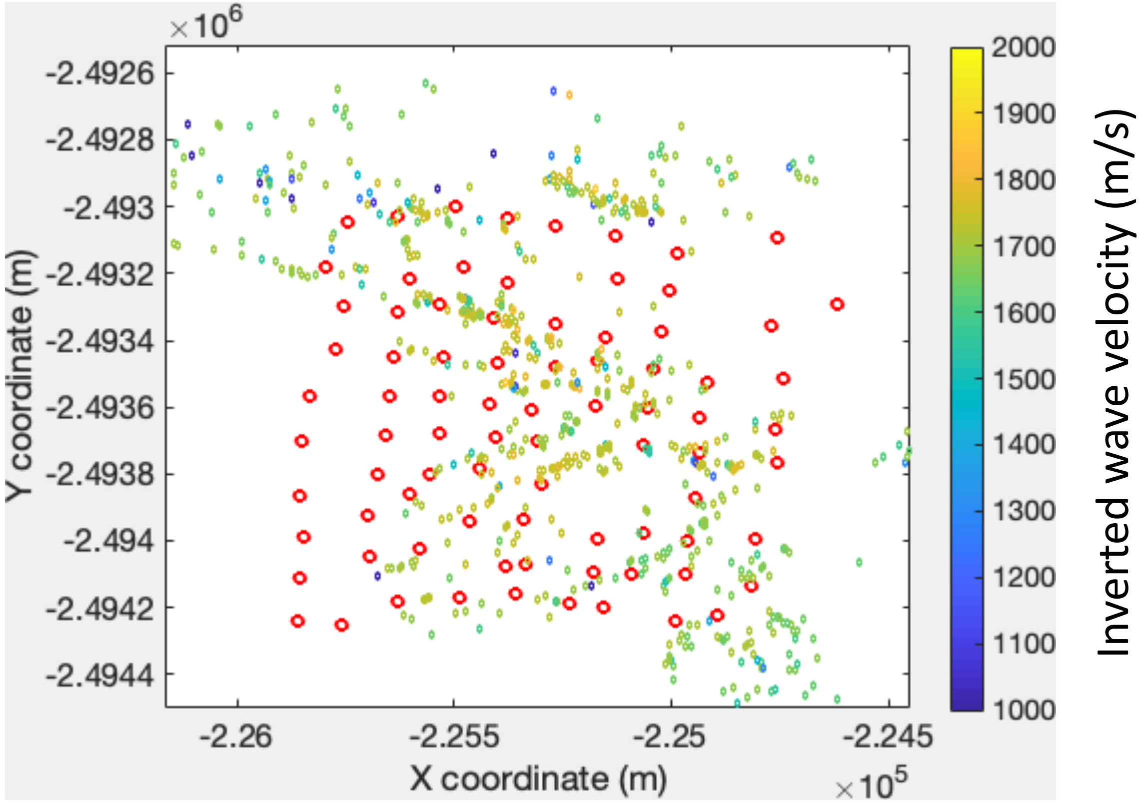

1 day
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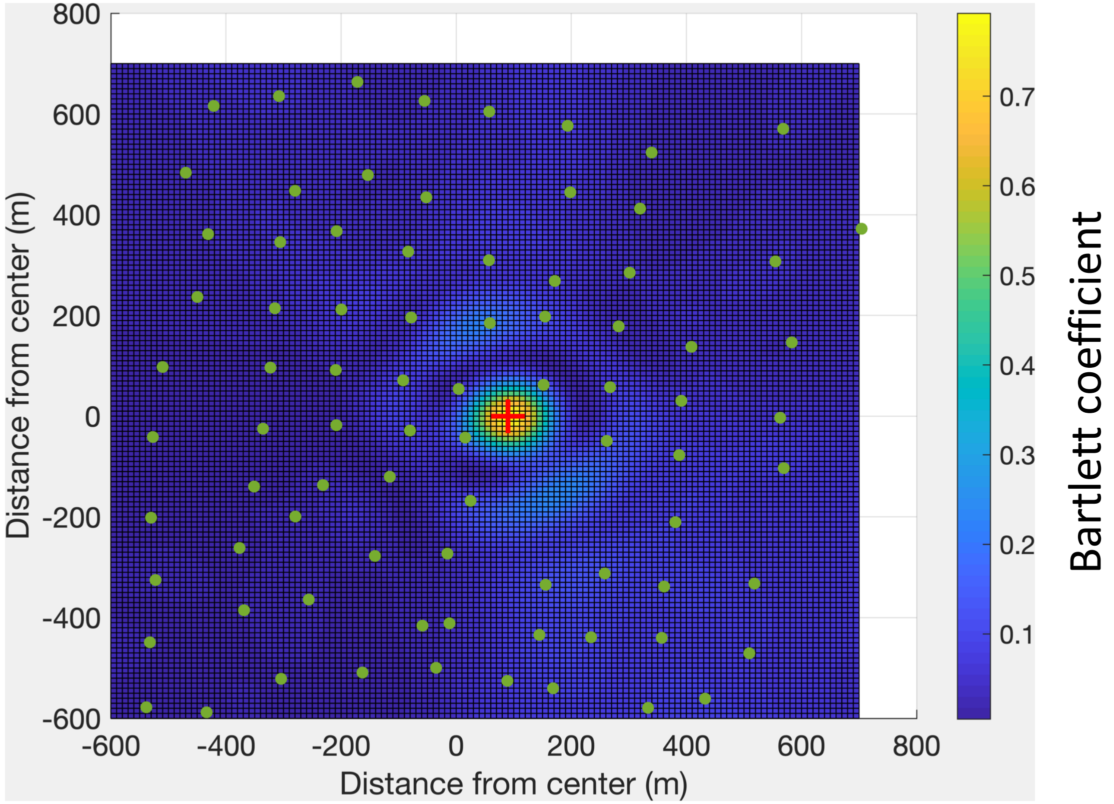

Used B > 0.5

- only 3 starting points
- only 1 day

Did not look at spatial and temporal variability

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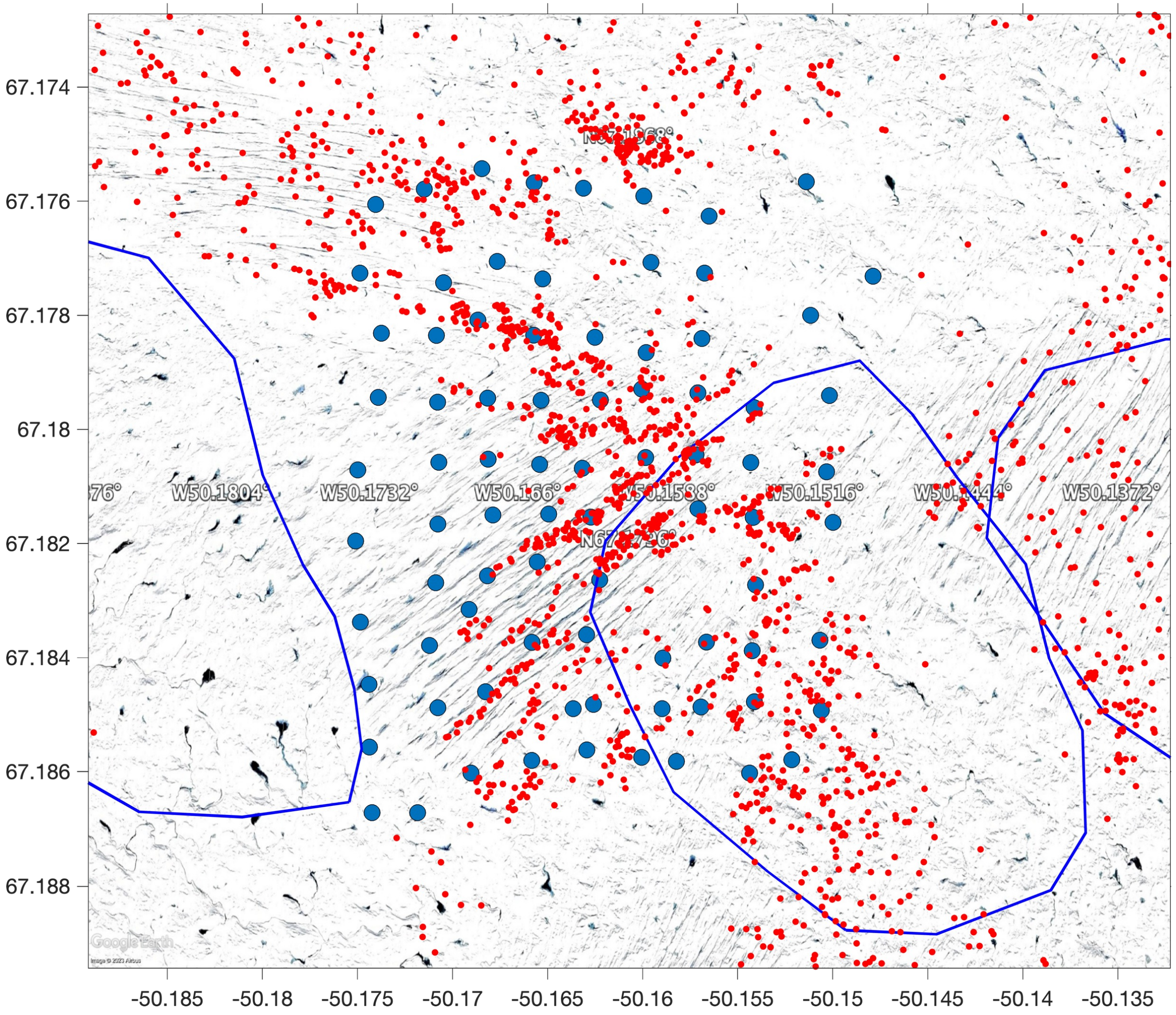
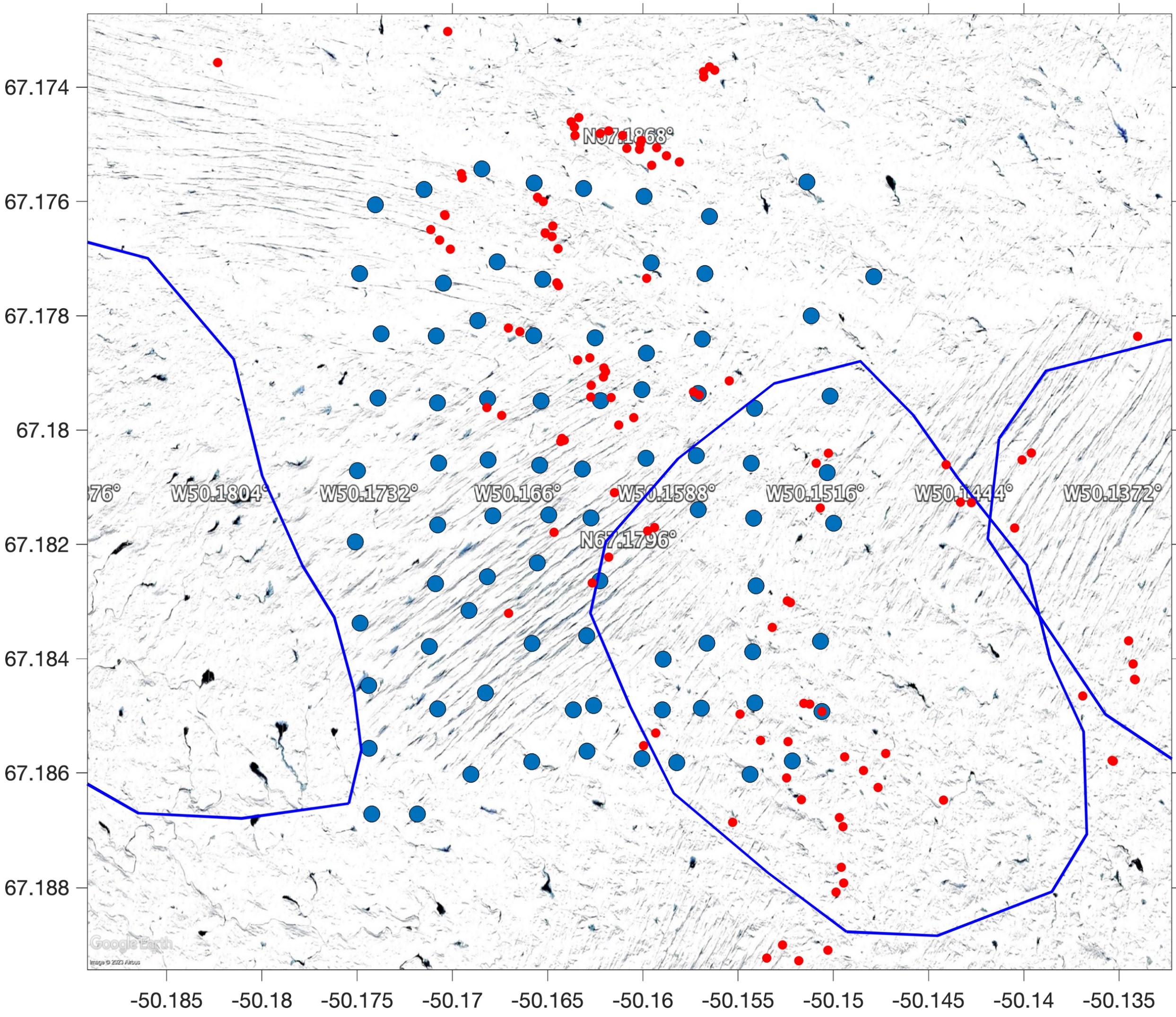
Icequakes locations using beamforming

Systematic source locations using optimization

0.3 < B < 0.8



B > 0.8



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Icequakes locations using beamforming

Project 1: recover more accurate and systematic maps, establish links with englacial water pathways, hydrofracturing, etc…

→ Project 2: Identify subglacial hydrology sources ?

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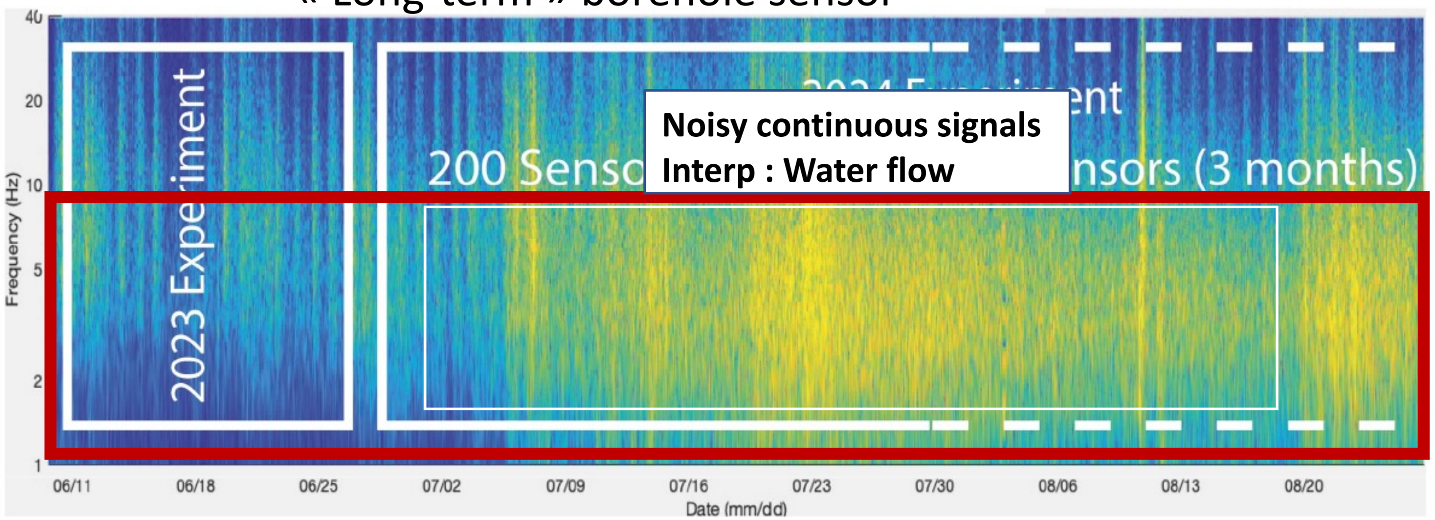

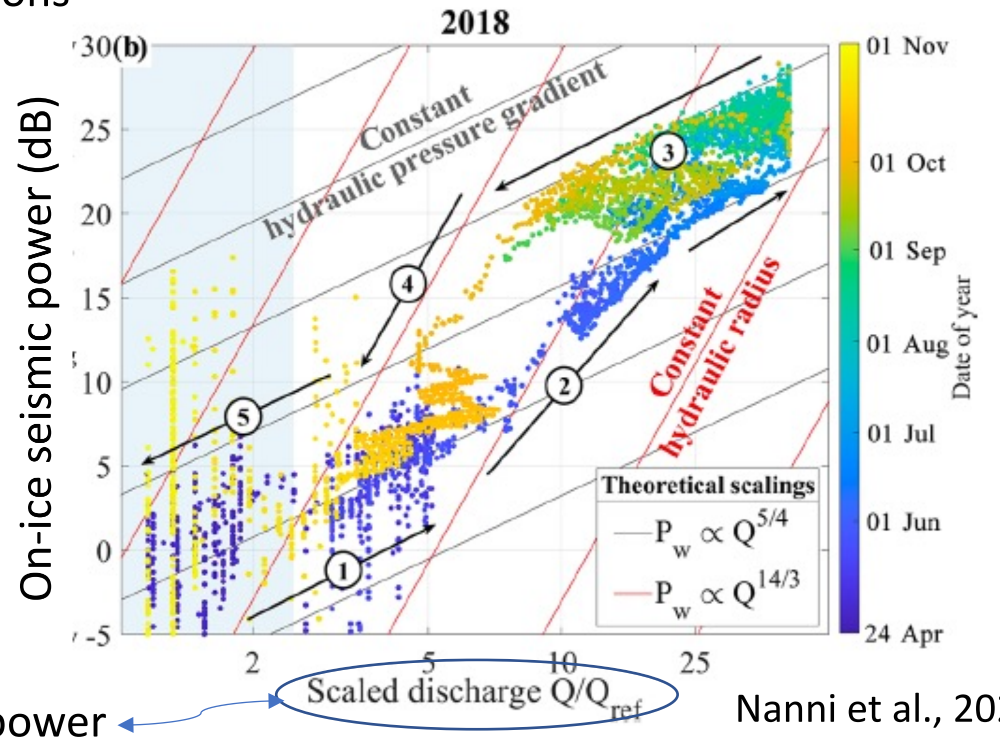

Off-ice seismic power

Gimbert et al., 2014, 2016

Nanni et al., 2020

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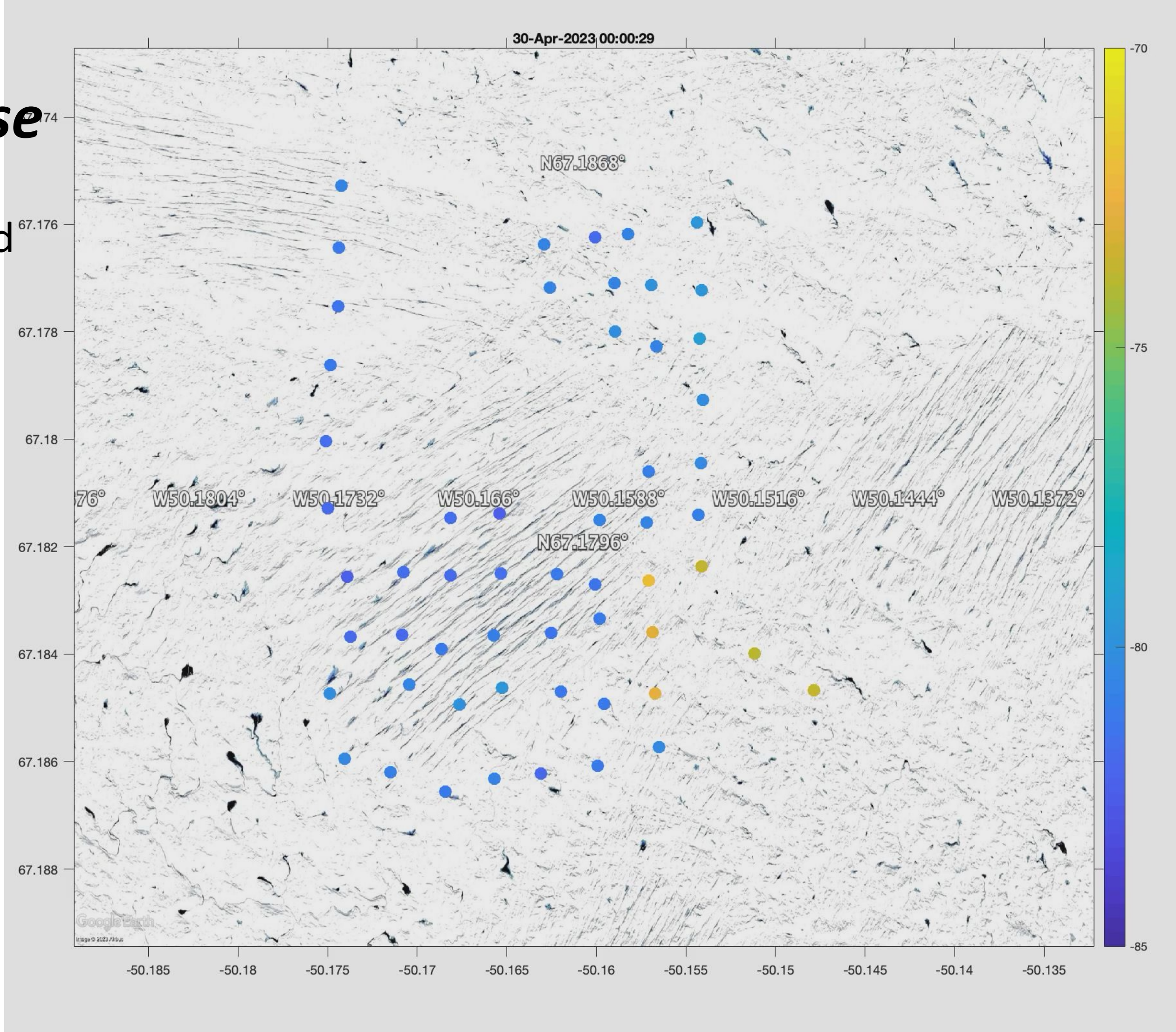
GLACIER STRUCTURE ?



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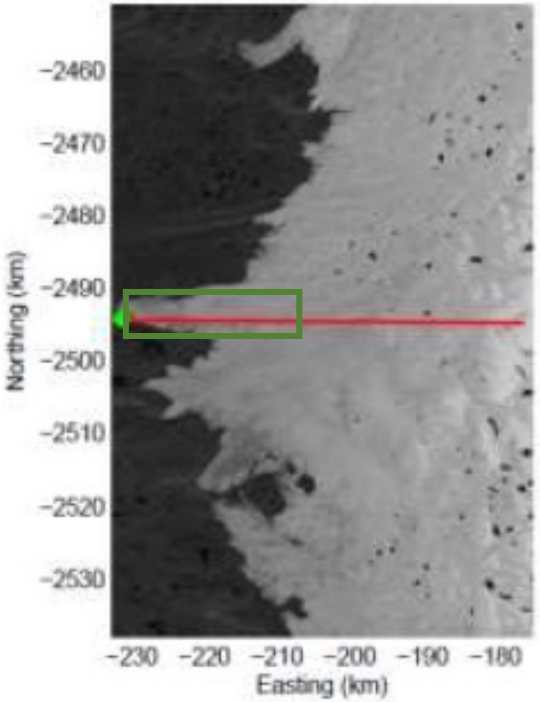
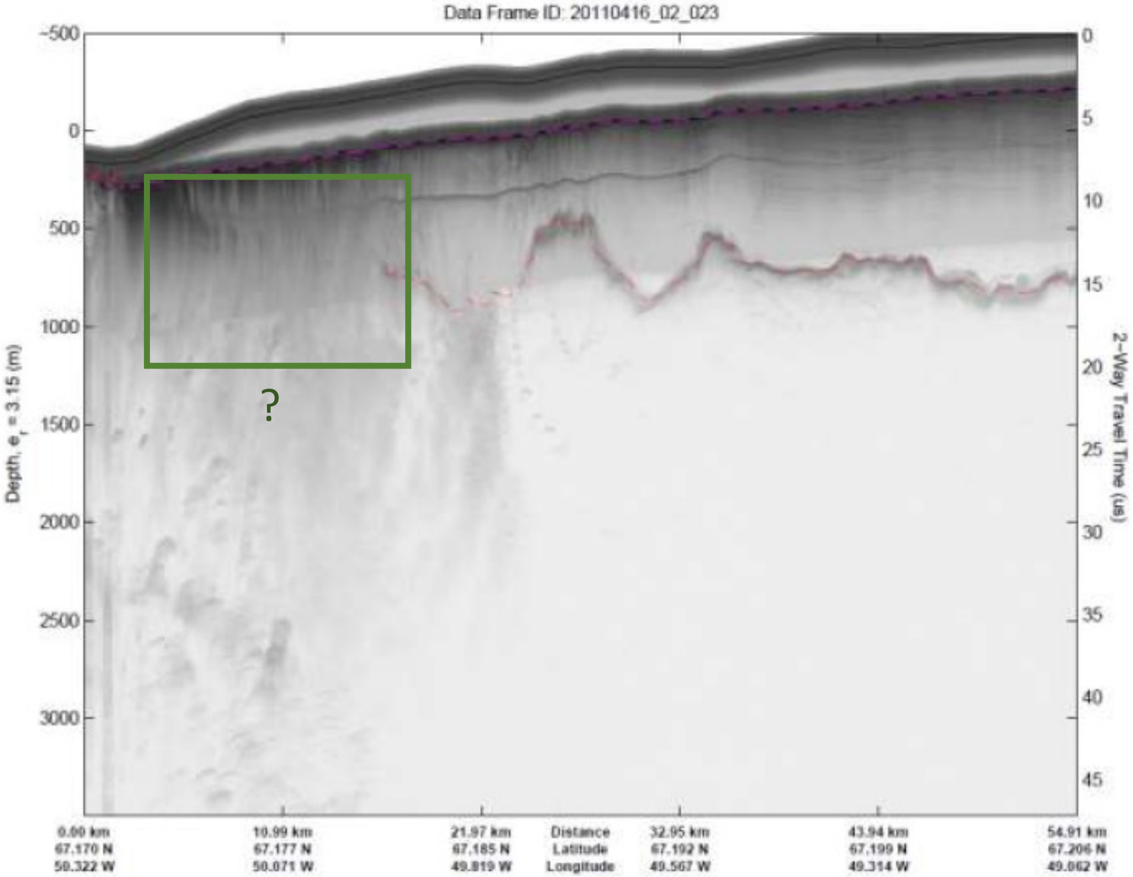
GLACIER STRUCTURE ?

Insights from airborne radar





Taken from Neil Ross's report

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GLACIER STRUCTURE ?

Insights from terrestrial radar

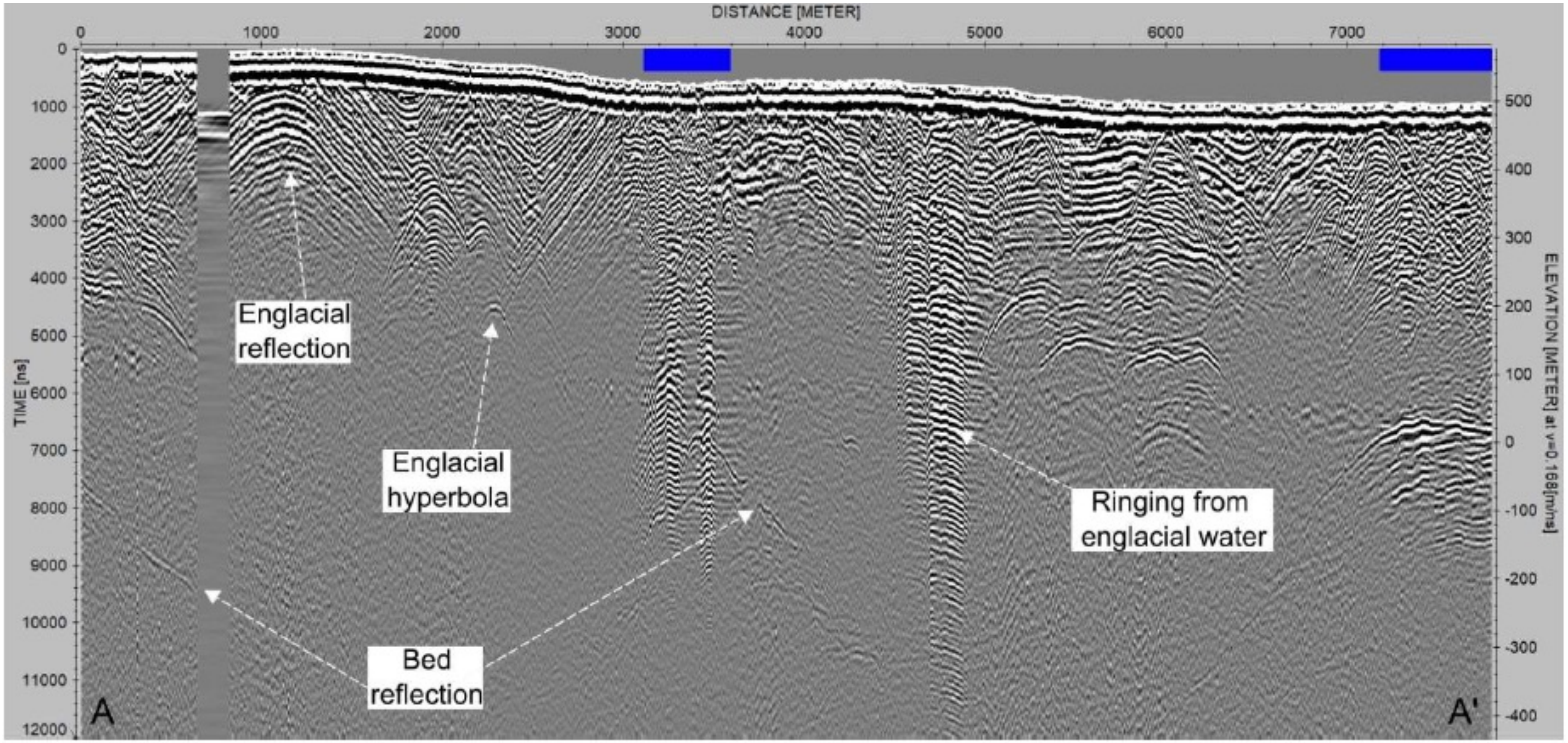

Figure 11: Elevation-corrected bu unmigrated 5 MHz ice-penetrating radar data from Isunnguata

Taken from Neil Ross's report

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GLACIER STRUCTURE ?

What can we do with seismics ?

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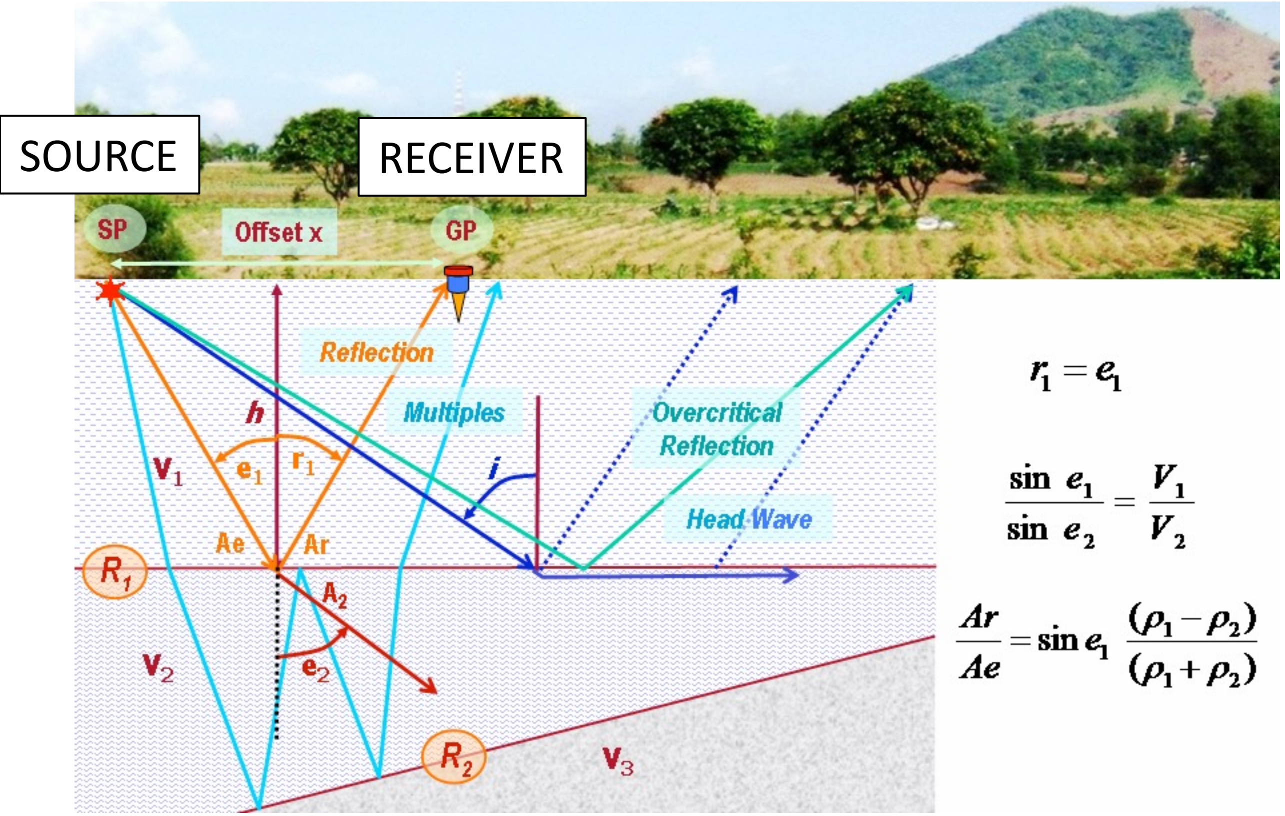
GLACIER STRUCTURE ?

What can we do with seismics ?

Classical techniques:

active seismic reflection



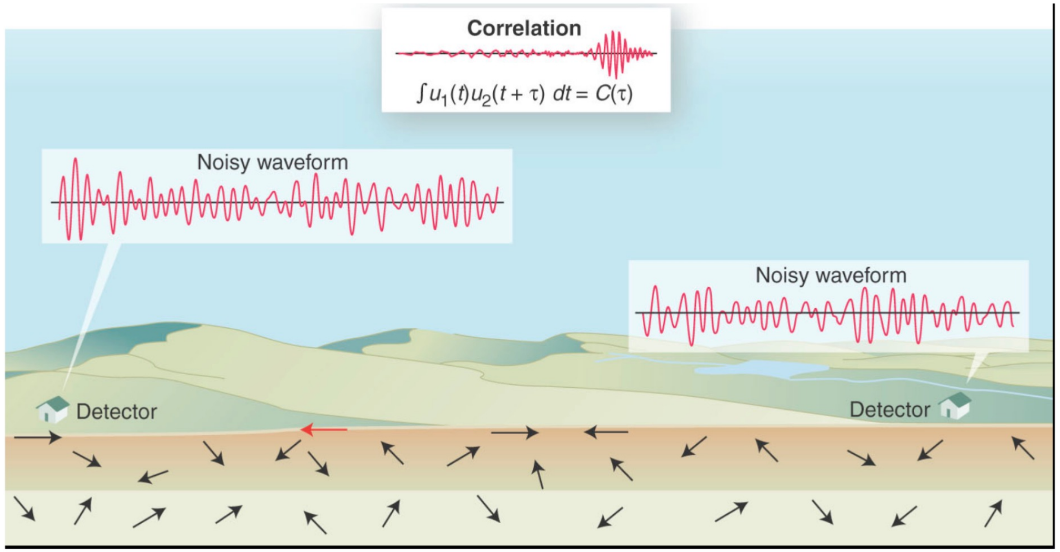
$$r_1 = e_1$$

$$\frac{\sin e_1}{\sin e_2} = \frac{V_1}{V_2}$$

$$\frac{Ar}{Ae} = \sin e_1 \frac{(\rho_1 - \rho_2)}{(\rho_1 + \rho_2)}$$

Wikipedia

passive seismic interferommetry



R. Weaver

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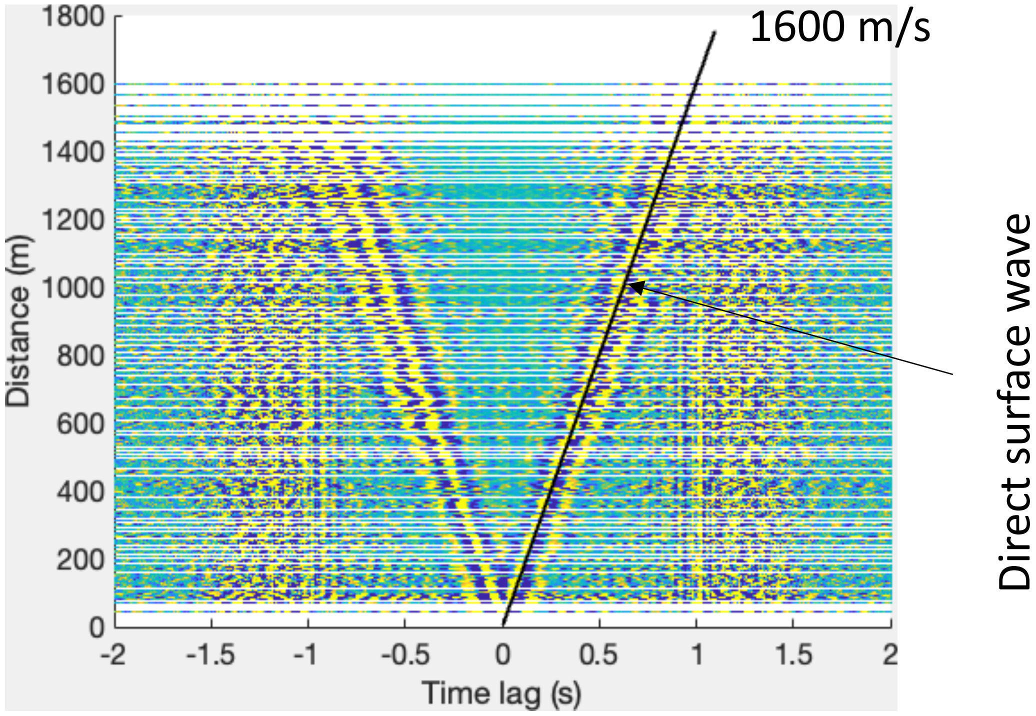
GLACIER STRUCTURE ?

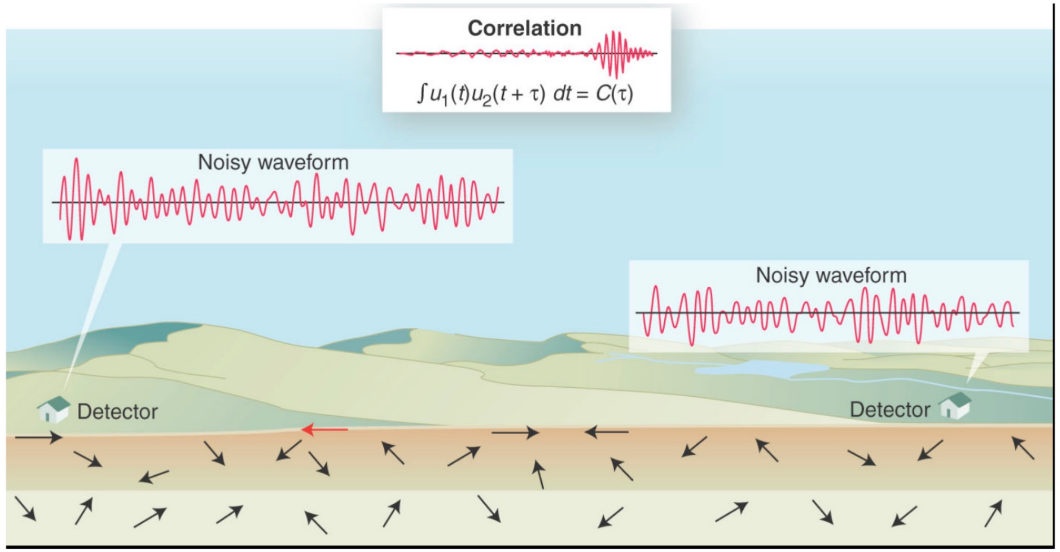
What can we do with seismics ?

Classical techniques:

All Period Long Noise cross-correlations (5-100 Hz)



passive seismic interferommetry



R. Weaver

Wave dispersion to recover bed topography (Sergent et al., 2020)

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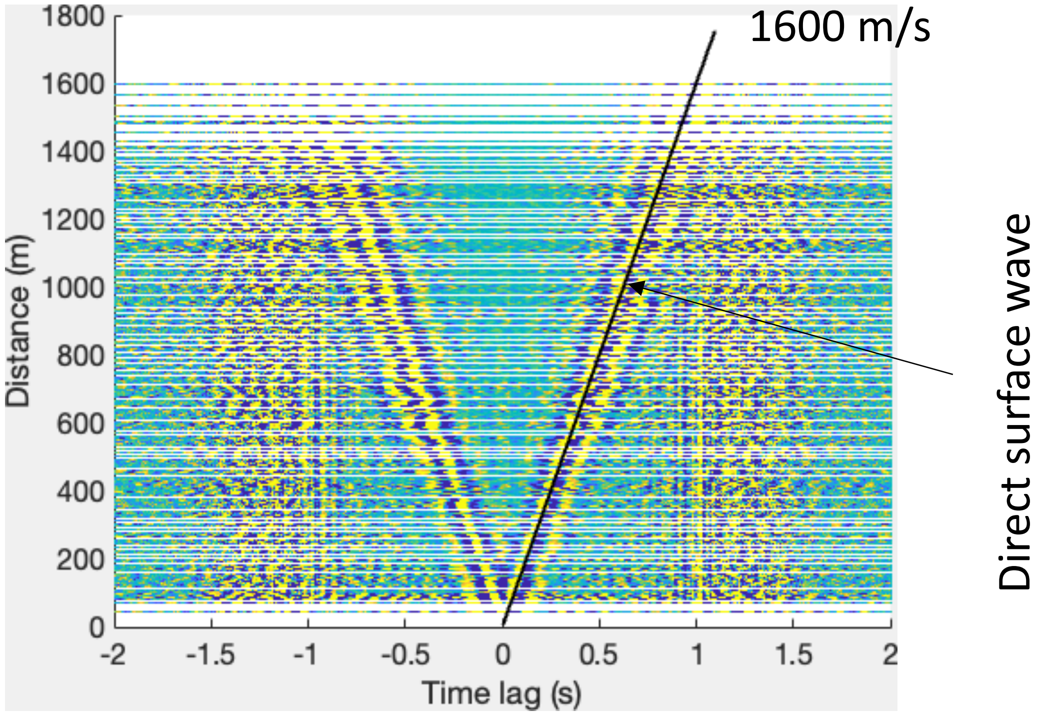
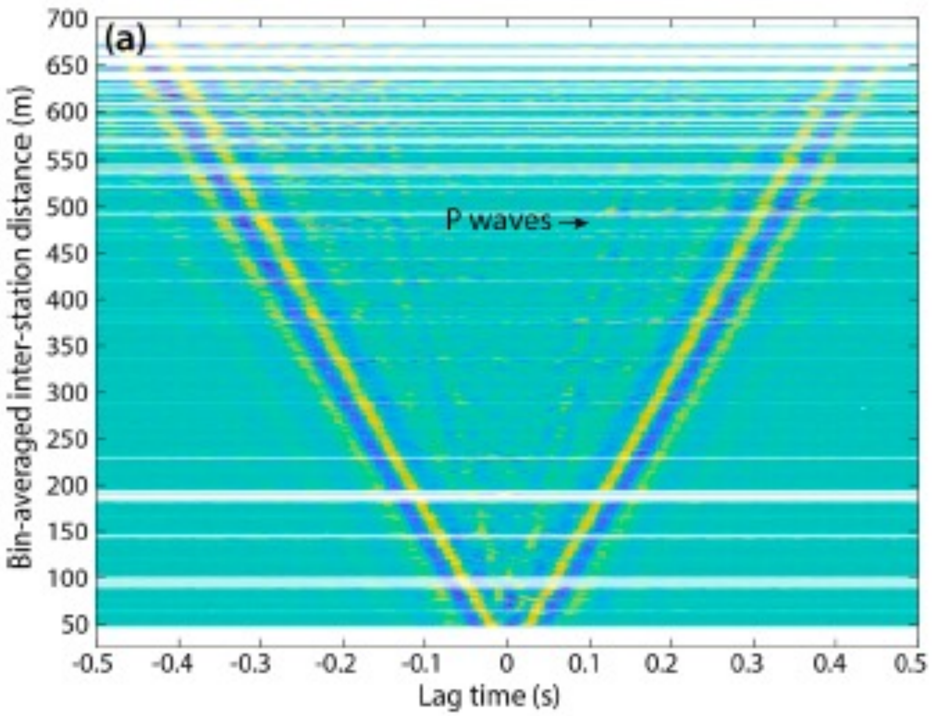


Glacier d'Argentière



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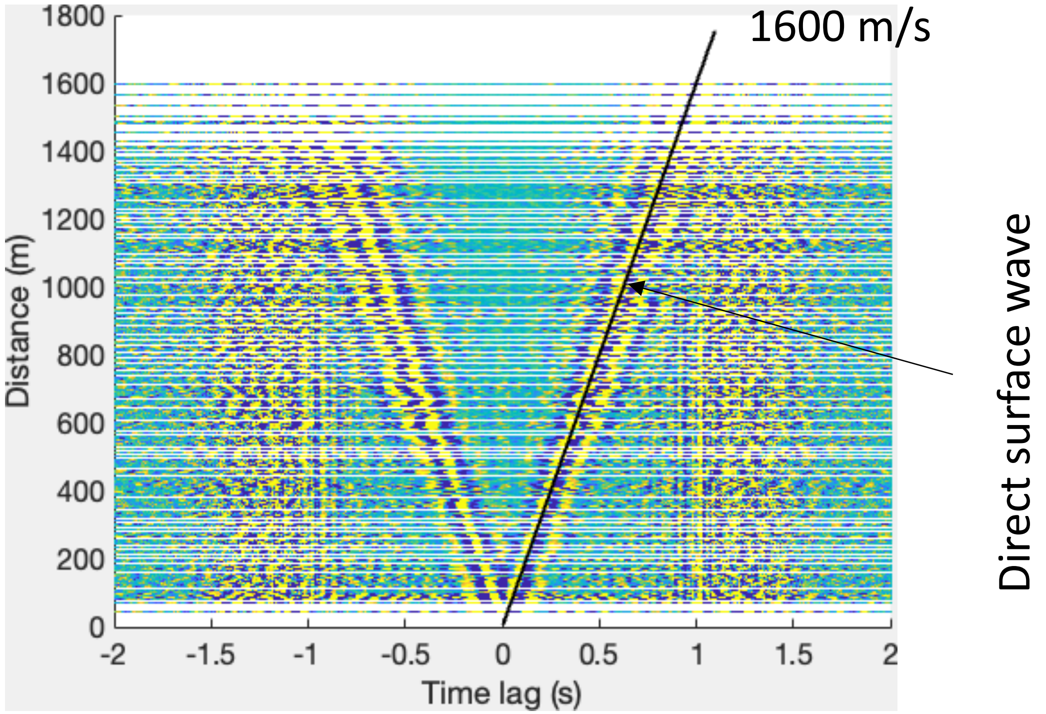

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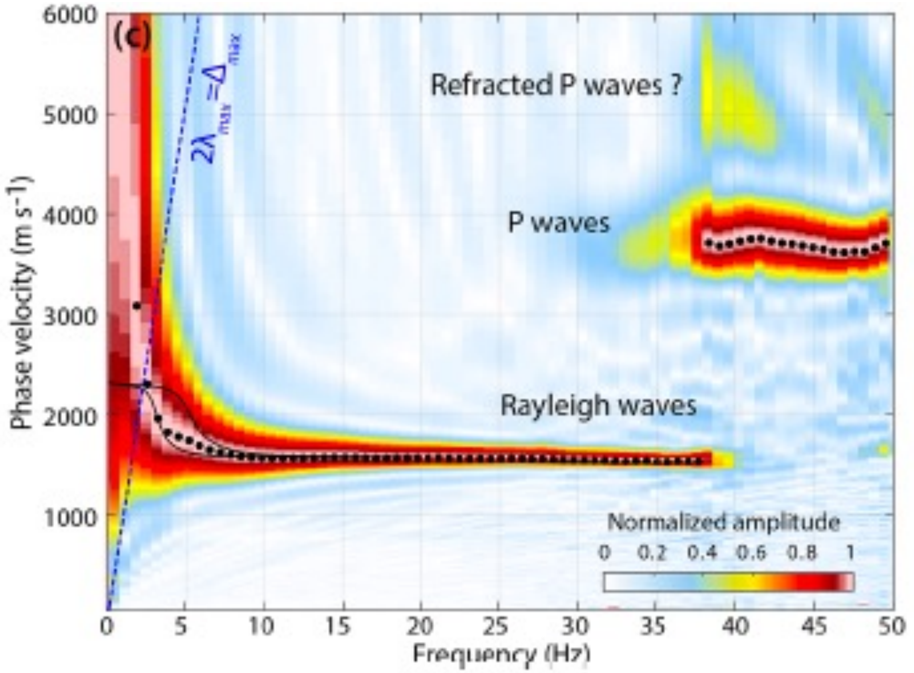

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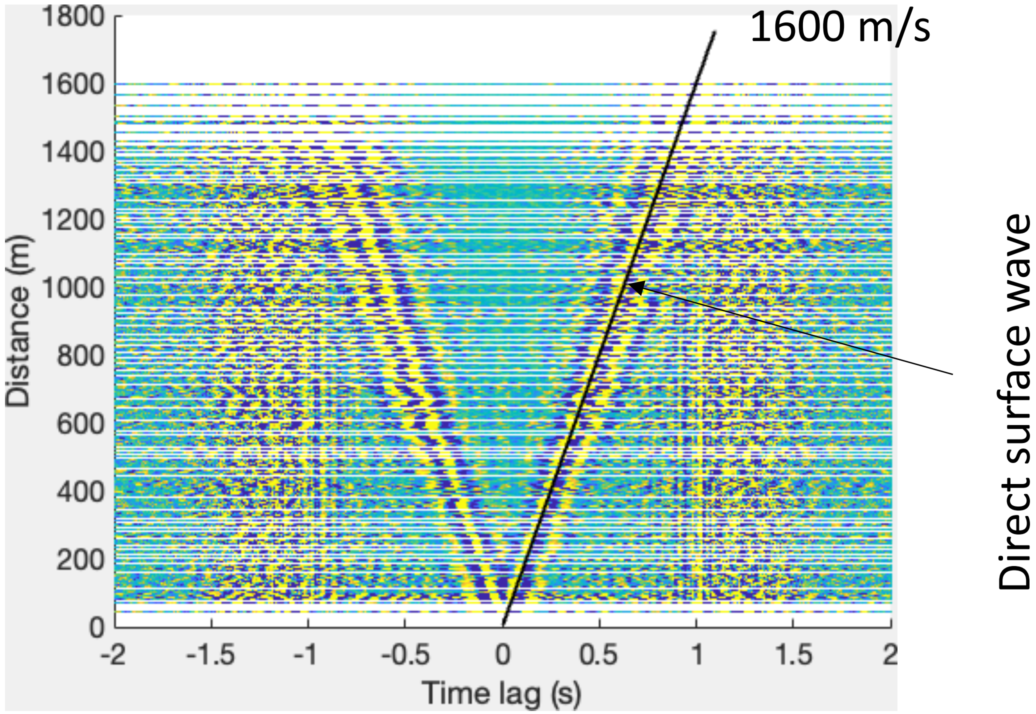

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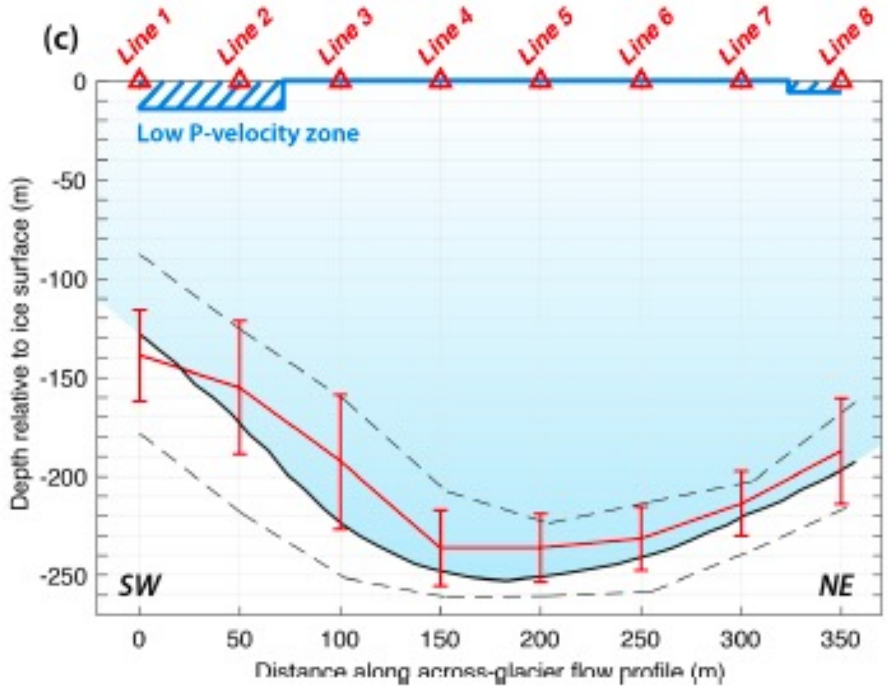

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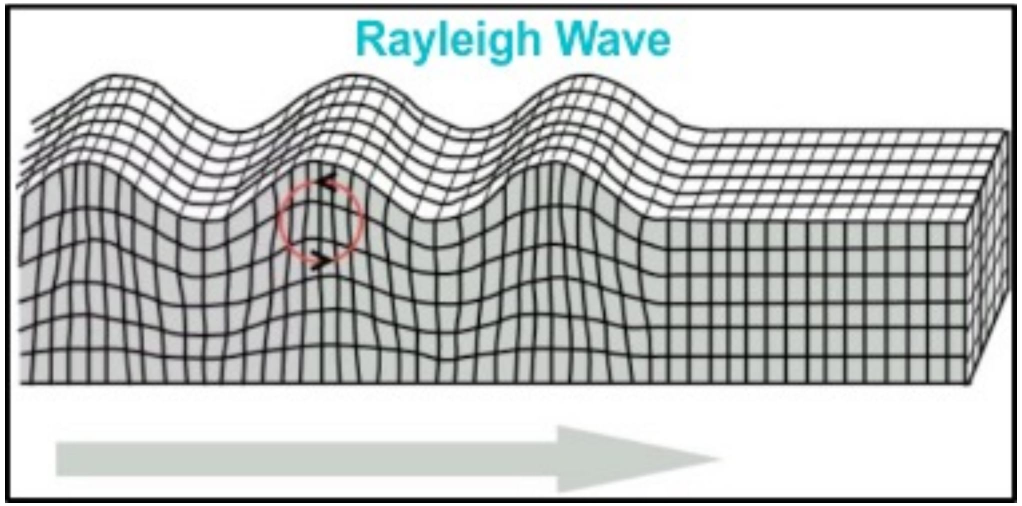

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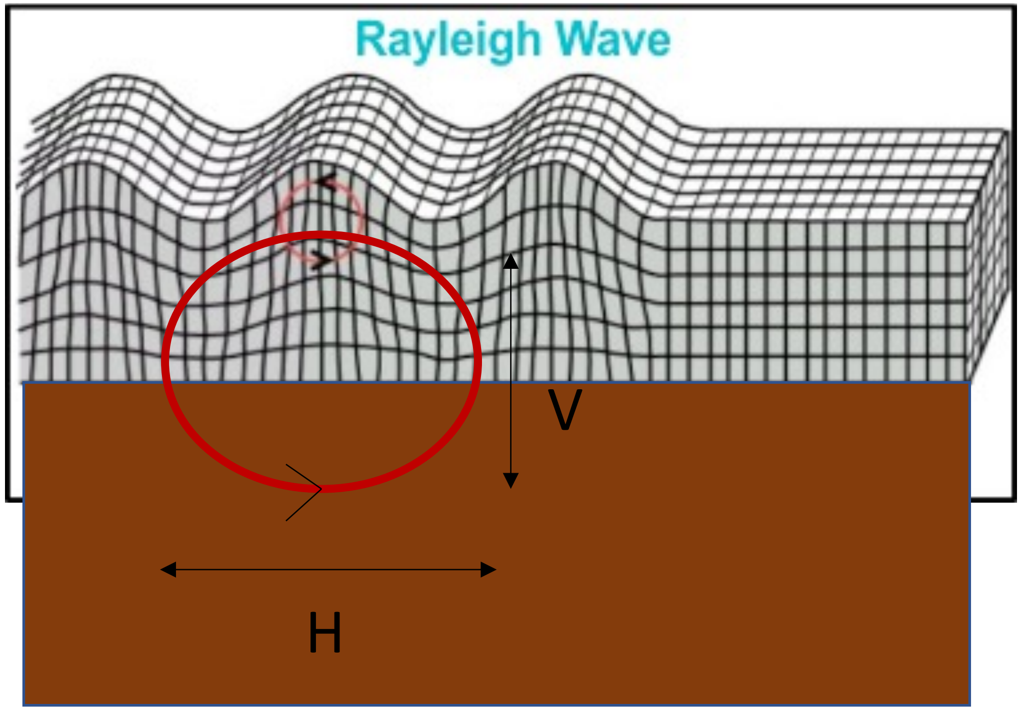
Low velocity



High velocity

H/V is high at frequency $f \sim v_s/(4H)$

Where v_s is shear wave speed in the low velocity layer
H is the low velocity layer thickness

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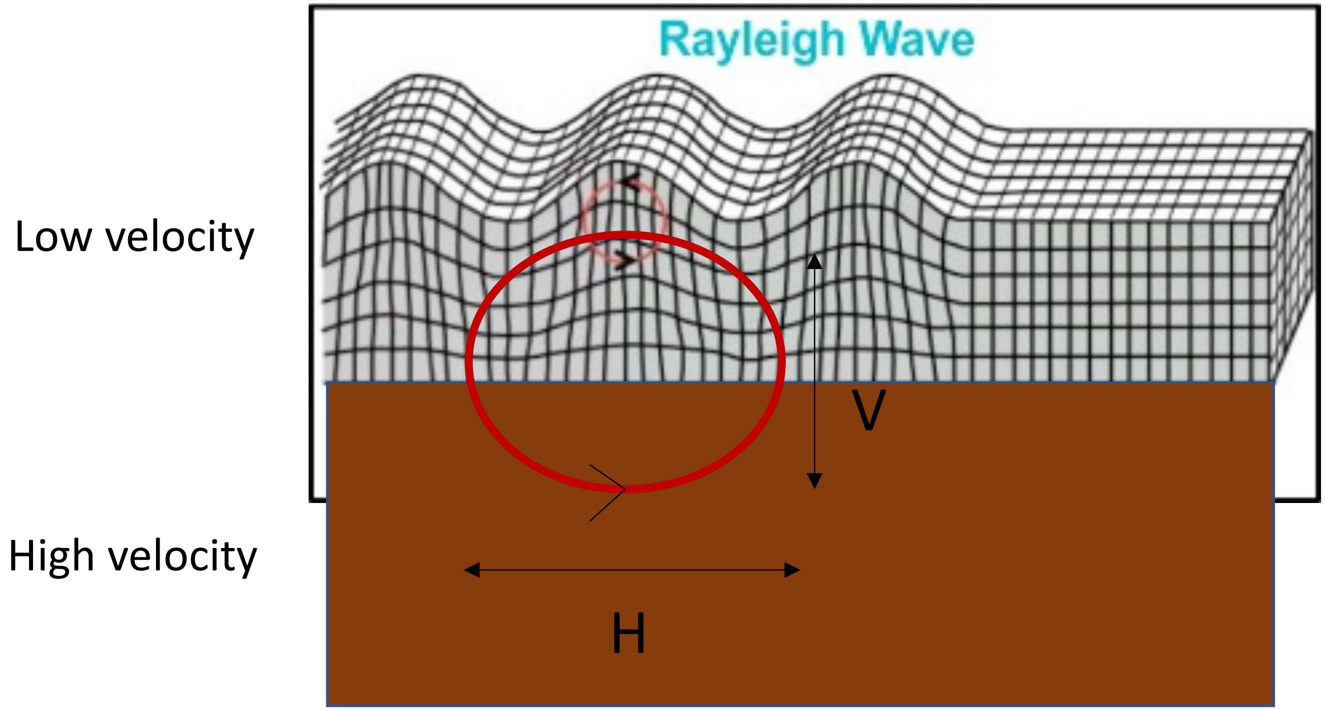
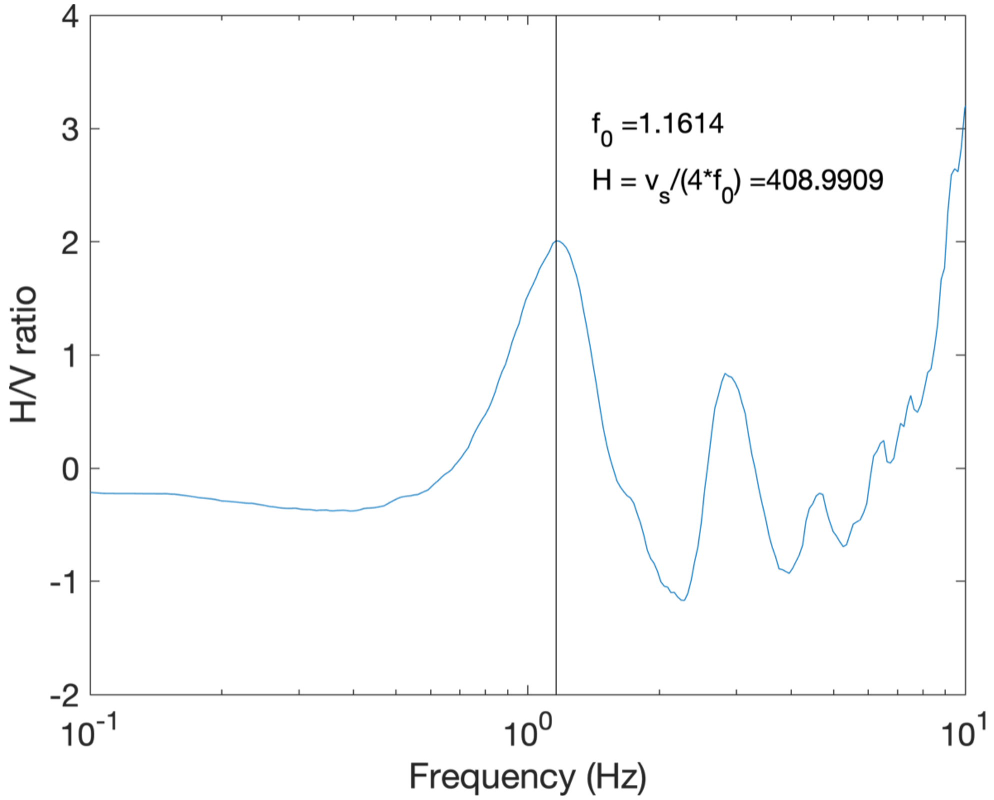


Application to Isunguata



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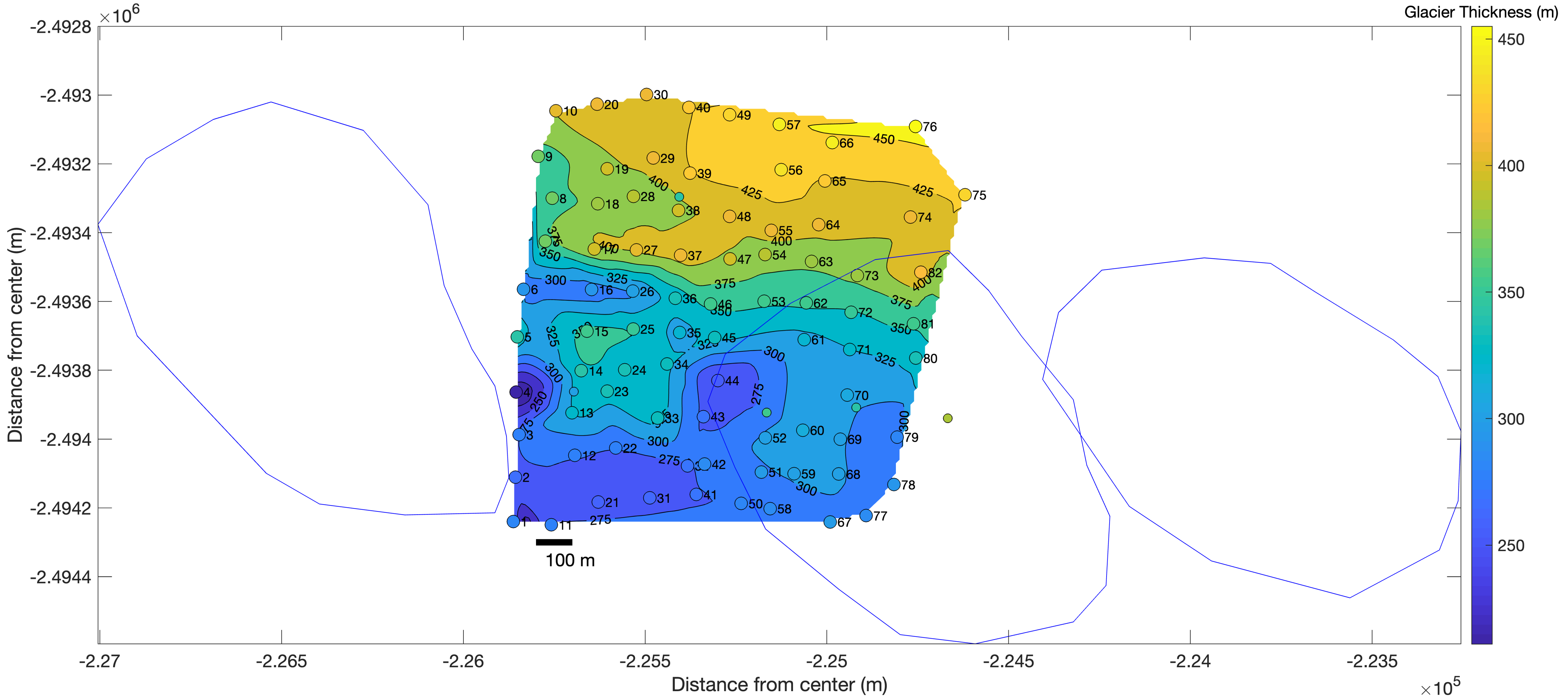
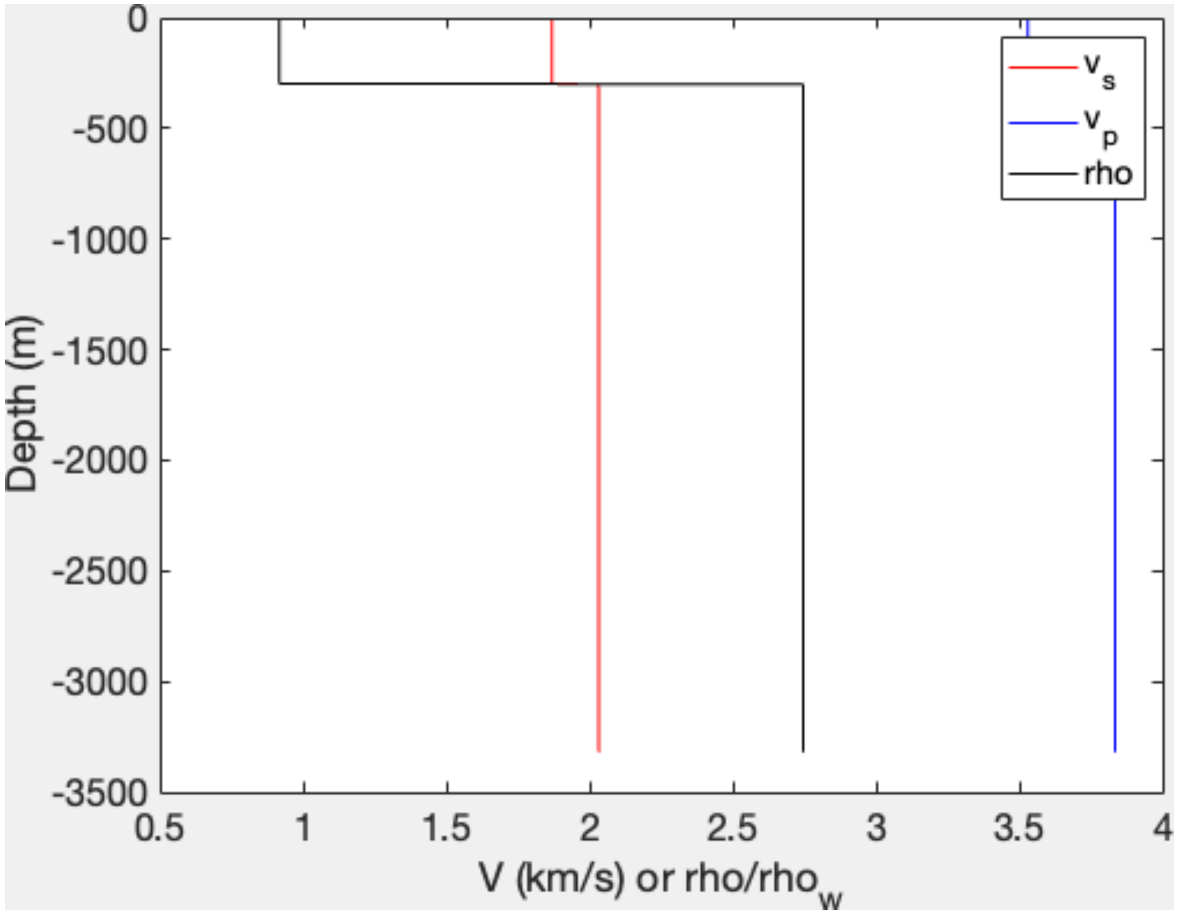
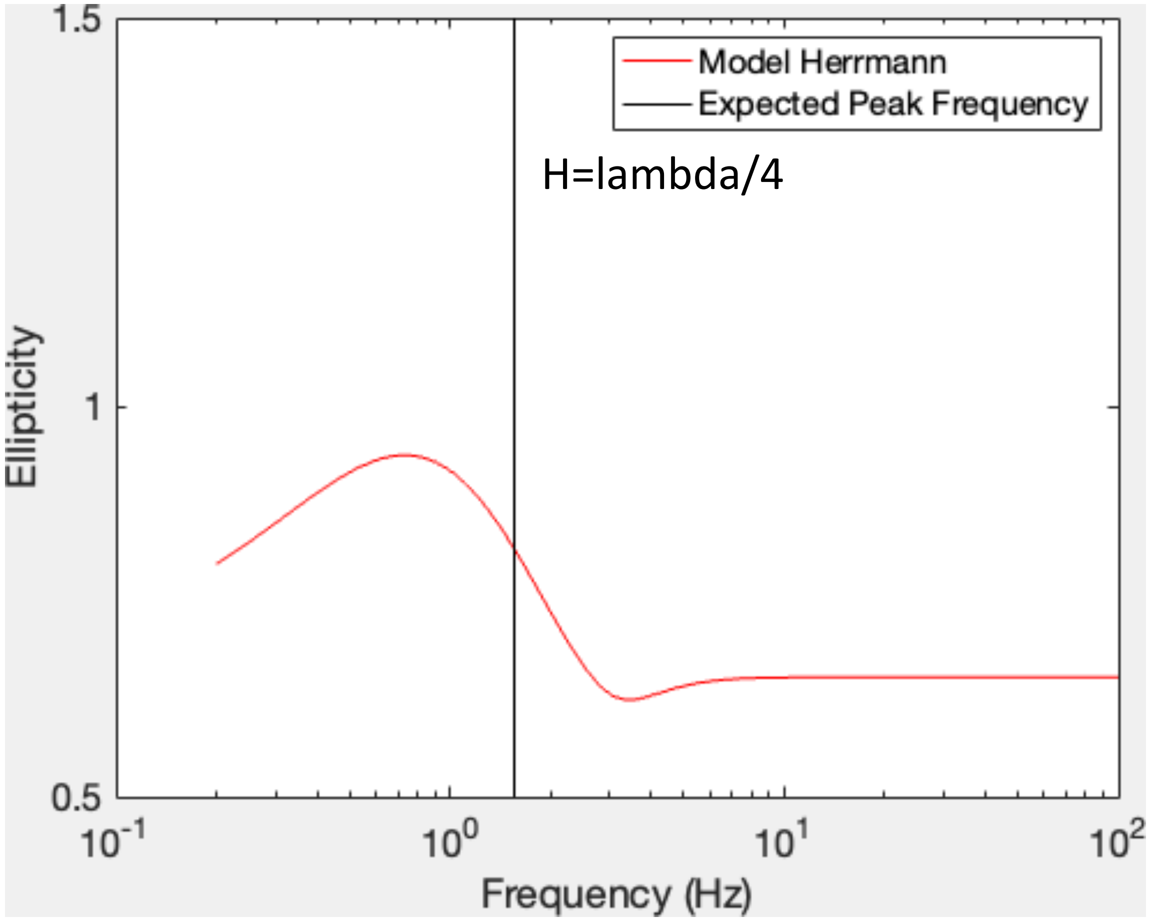


SYNTHETICS

Using Herrmann, R. B. (2013) Computer programs in seismology: An evolving tool for instruction and research, *Seism. Res. Lettr.* **84**, 1081-1088, doi:10.1785/0220110096





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Glacier thickness

Project 4: use noise interferommetry and H/V ratio analysis to retrieve bed thickness maps - compare with radar – pRes.

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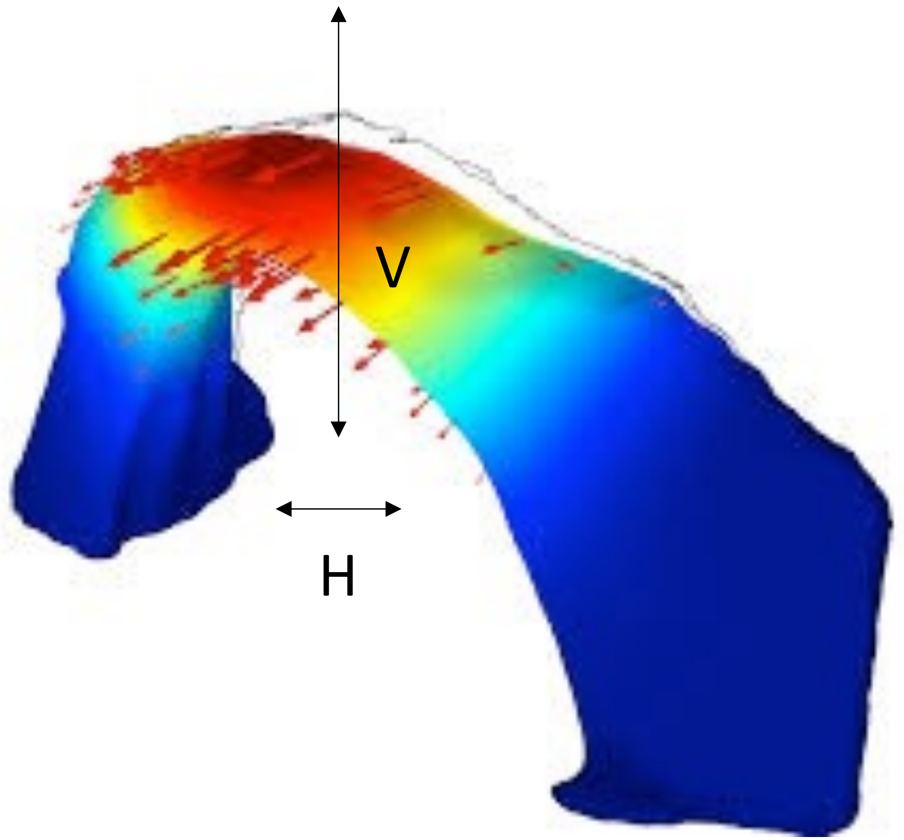
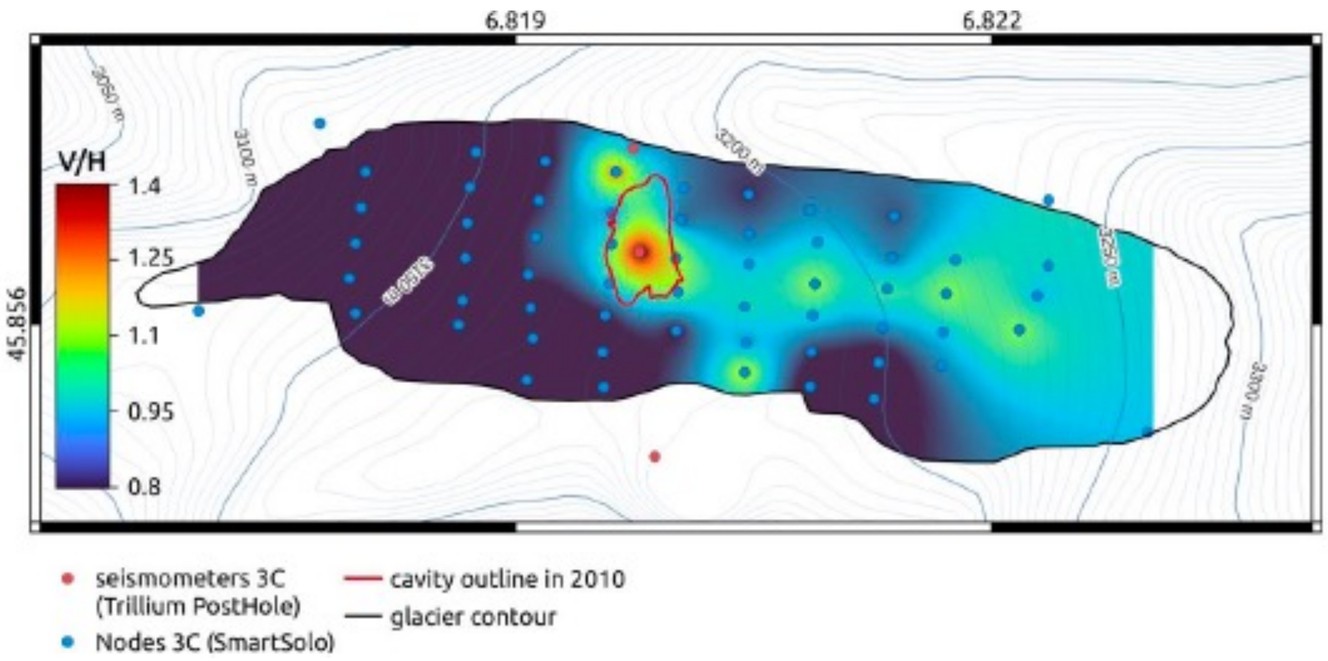
What can we do with seismics ?



V/H



Guillemot et al., in review

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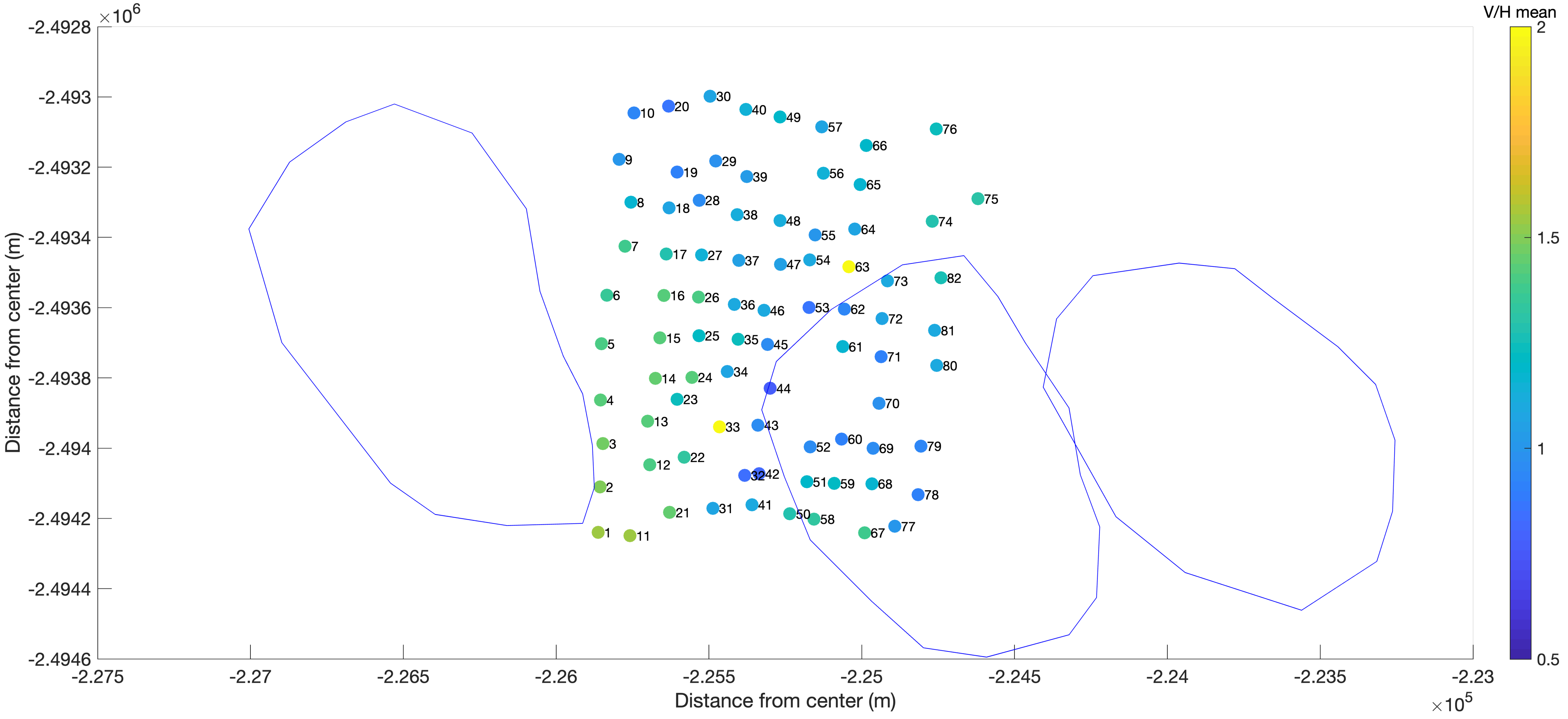

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Subglacial storage

Project 5: use V/H analysis and/or other techniques to retrieve lake locations/loss of friction

Coming field experiment

Strategy – Optic fibre – etc ?