Resolving subglacial hydrology network dynamics through seismic observations on an Alpine glacier.

A 3-year PhD research defended by **Ugo NANNI** on December 3rd 2020

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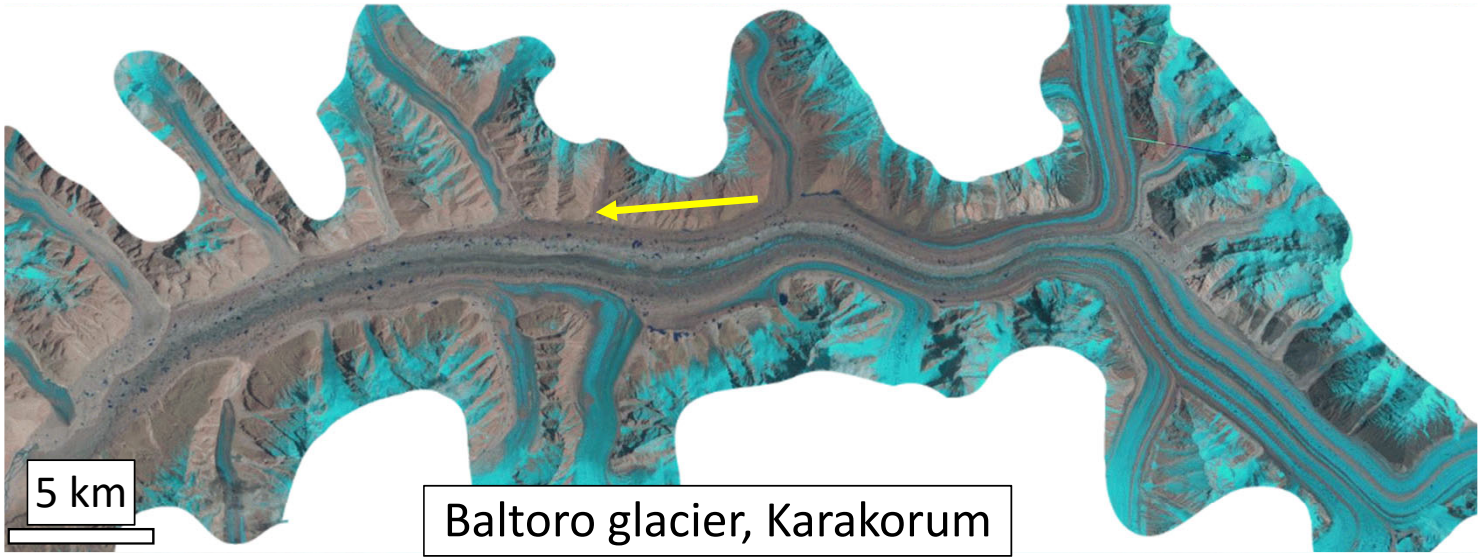
My first step in glaciology

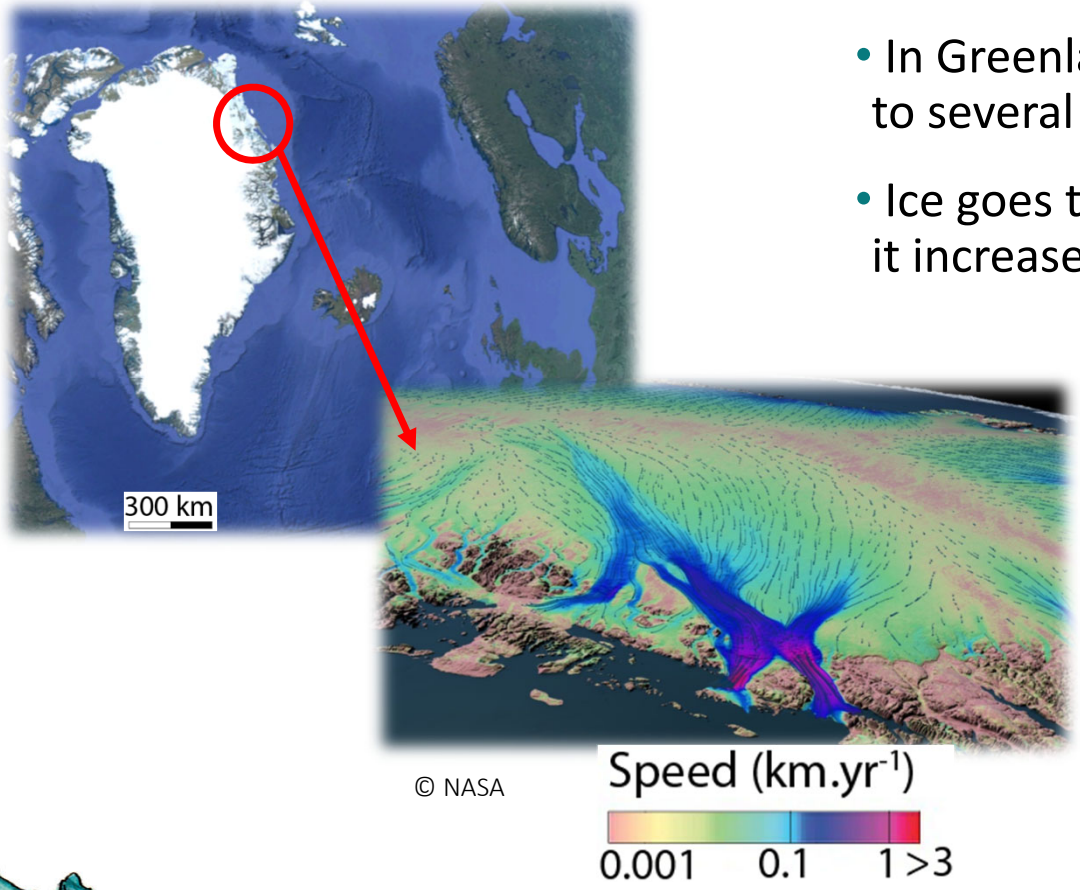
25 years of glaciers movement in one second



Up to 200 m/year

(Paul, 2015; Quincey et al., 2008)

Glaciers and ice sheets drive sea-level-rise



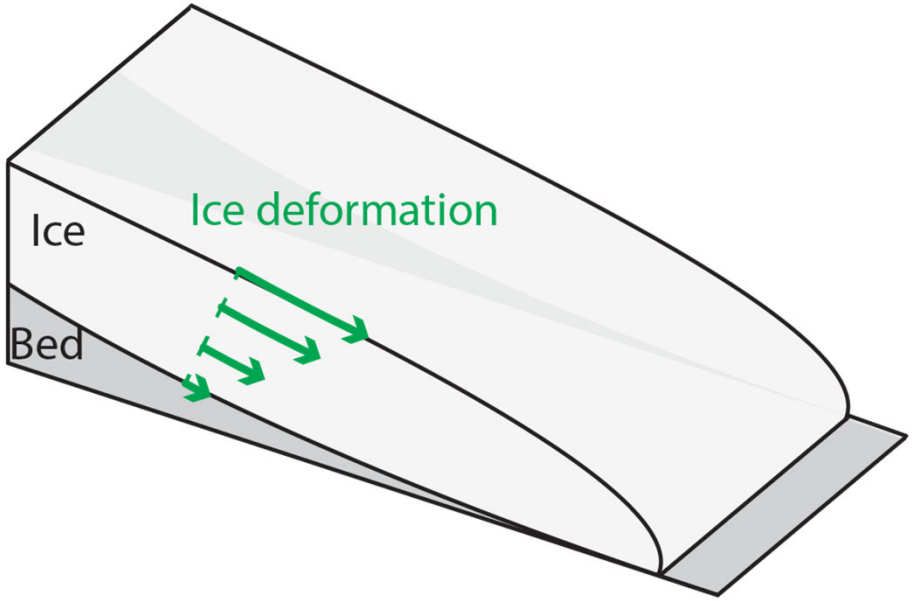
© NASA

- In Greenland glaciers flow up to several kilometer per year!
- Ice goes to the ocean where it increases sea-level rise

A flood in France (2016)

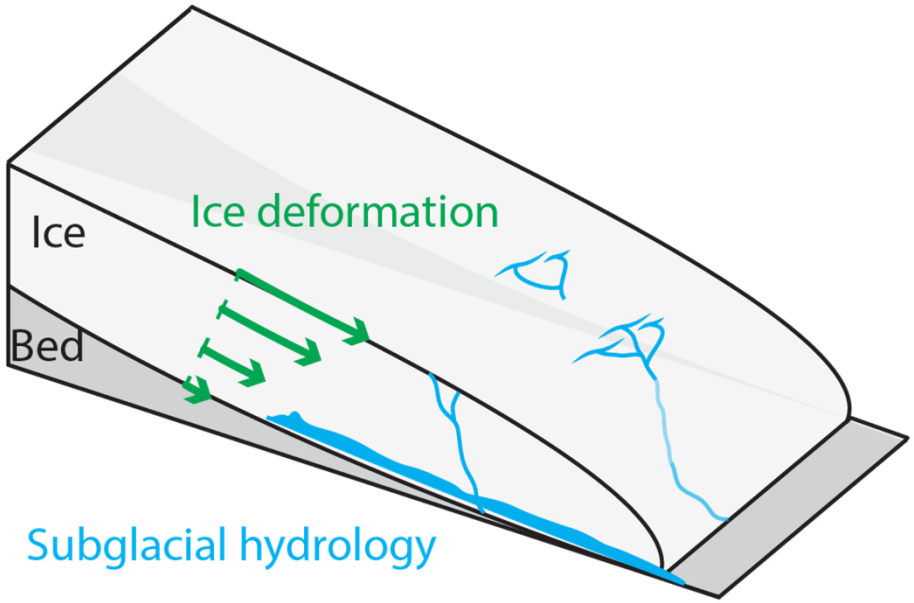
On the dynamics of glaciers

- Glaciers form by snow accumulation
- Ice slowly deforms and flows downhill



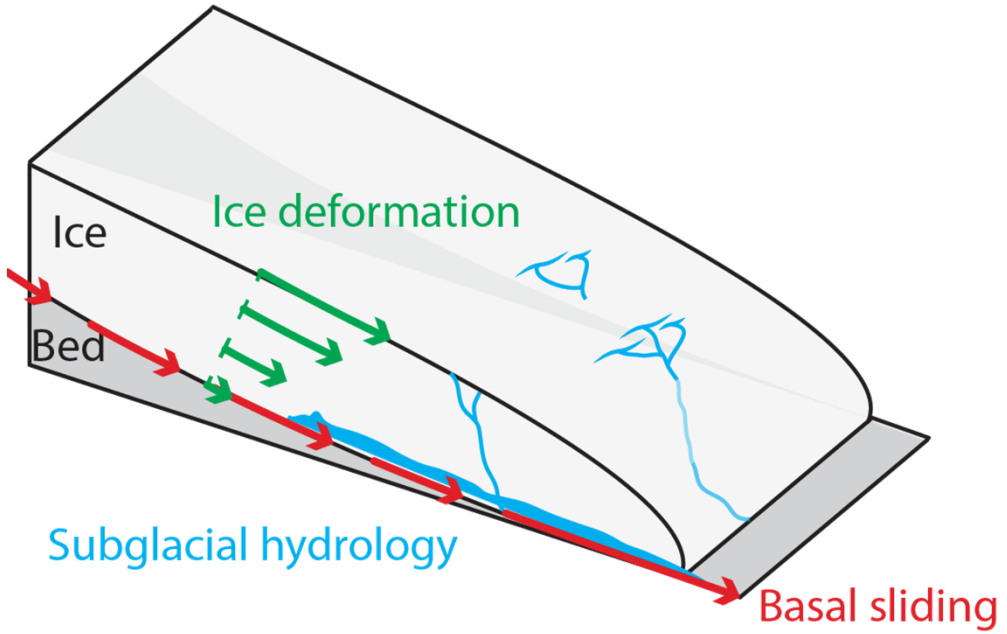
On the dynamics of glaciers

- Glaciers form by snow accumulation
- Ice slowly deforms and flows downhill
- At low altitudes surface melt occurs and meltwater penetrates glaciers



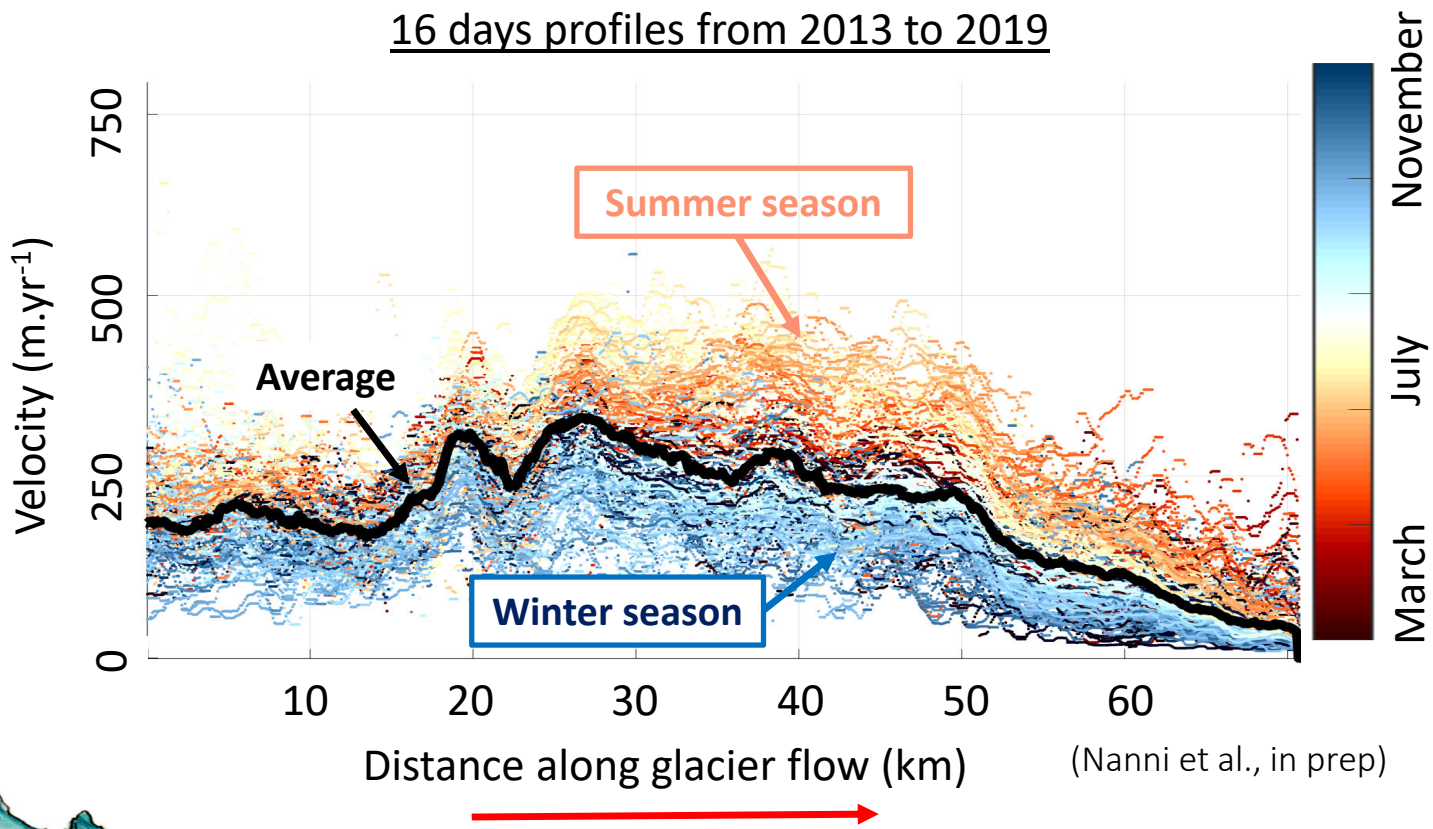
On the dynamics of glaciers

- Glaciers form by snow accumulation
- Ice slowly deforms and flows downhill
- In low altitudes surface melt occurs and meltwater penetrates glaciers
- Subglacial waterflow modulates sliding by lubrication



Up to 50 to 90% of ice flow

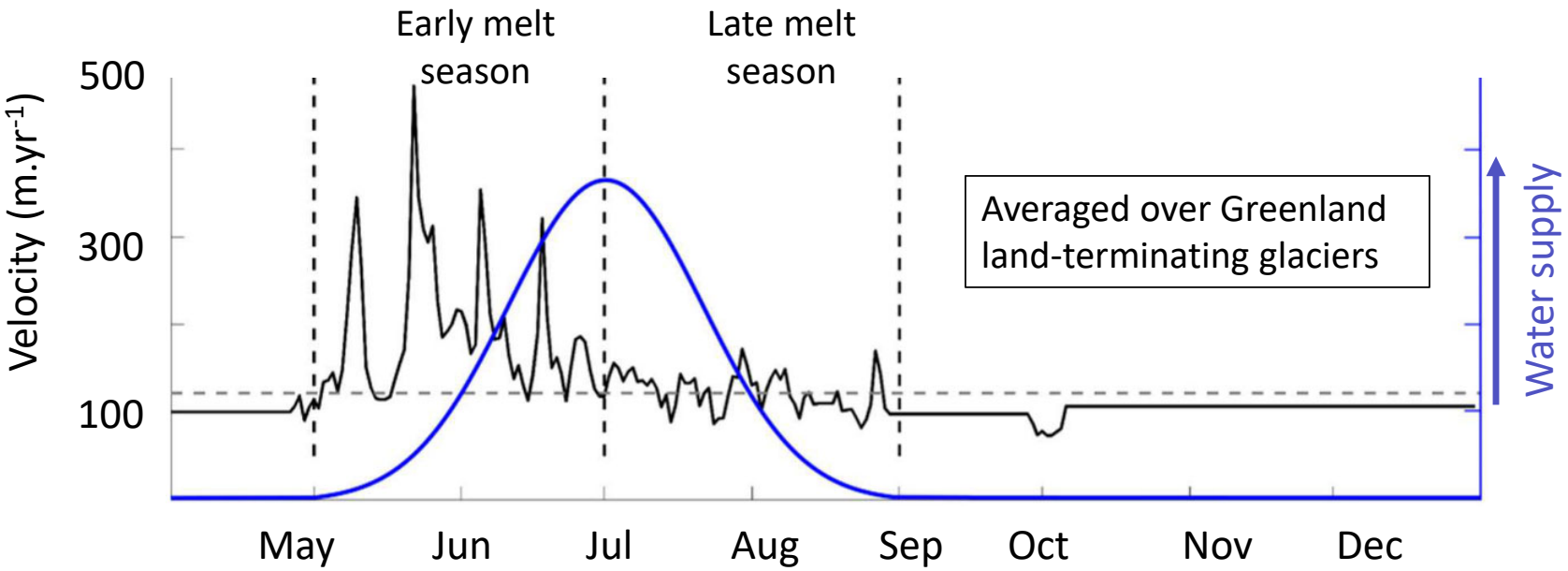
My second step in glaciology



(Nanni et al., in prep)

Fedchenko glacier, Pamir

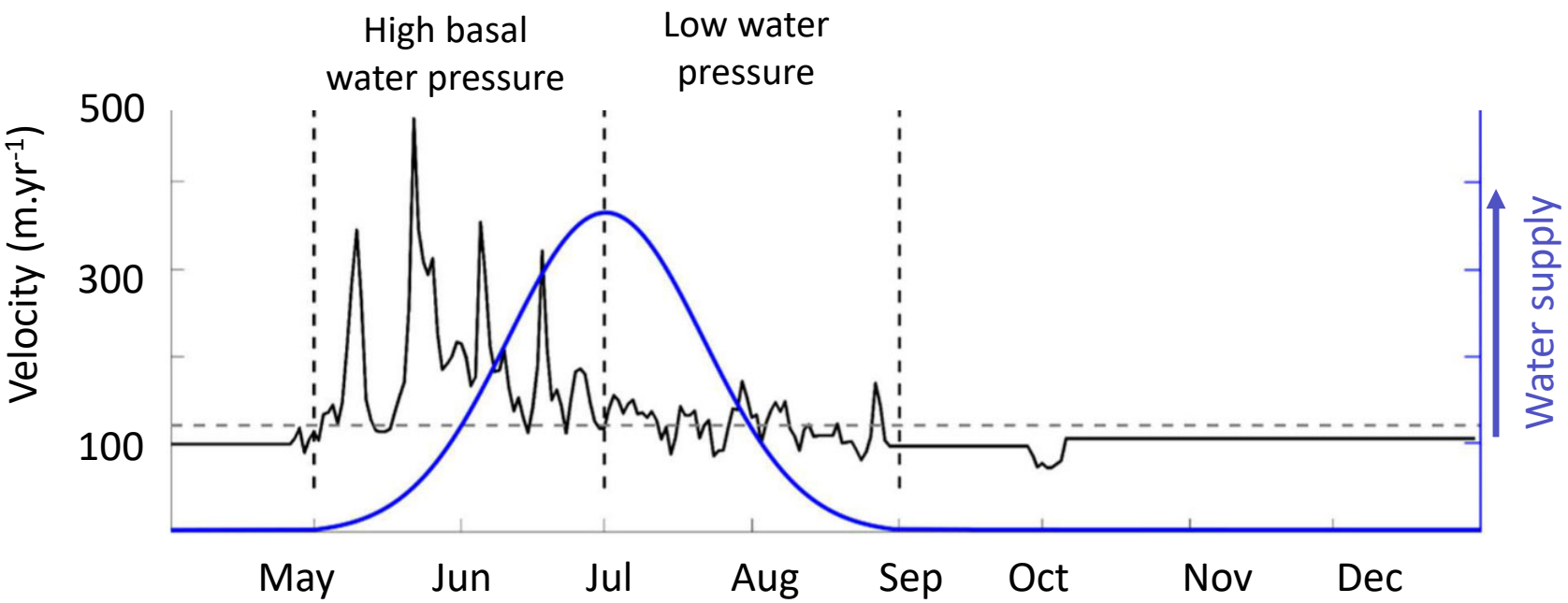
A complex response to water supply



(Davison et al., 2019)

No direct relationship water/sliding

Evolution of the subglacial drainage system

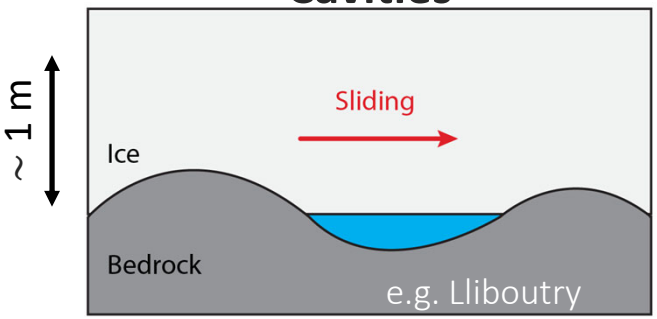


(Davison et al., 2019)

A complex drainage system

Evolution of the subglacial drainage system

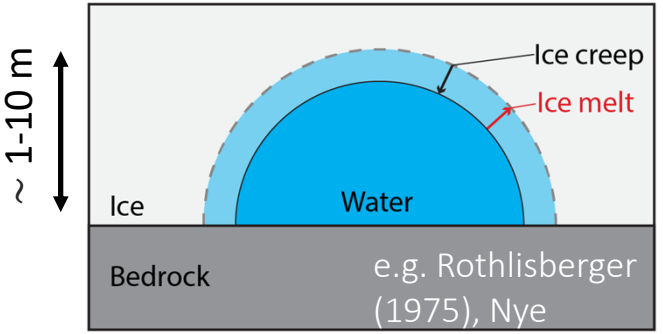
Inefficient and distributed:
Cavities



High basal water pressure

More glacier flow

Efficient and localized :
Channels

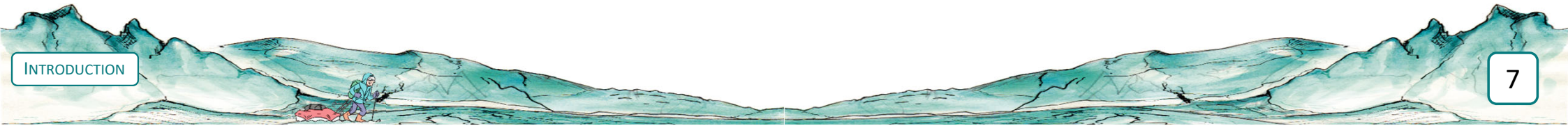


Low basal water pressure

Less glacier flow

Limited measurements

How to measure a system rapidly evolving in time and strongly heterogeneous in space?

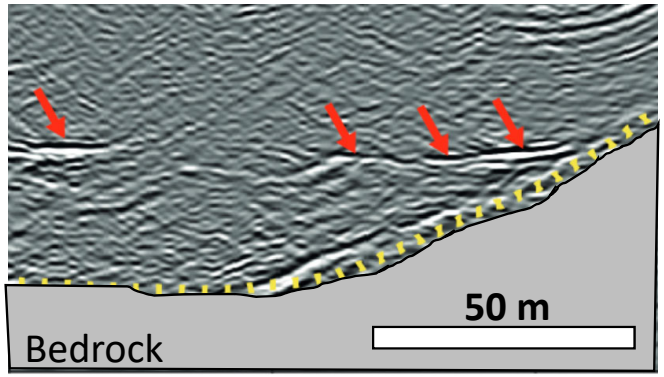


Limited measurements

How to measure a system rapidly evolving in time and strongly heterogeneous in space?

Ground penetrating radar

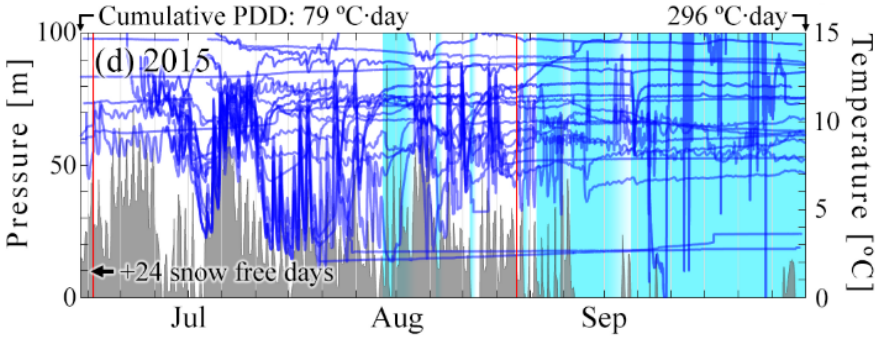
Limited access to physical properties



August 2019, Rhonegletscher
(Church et al., 2020)

Basal water pressure measurements

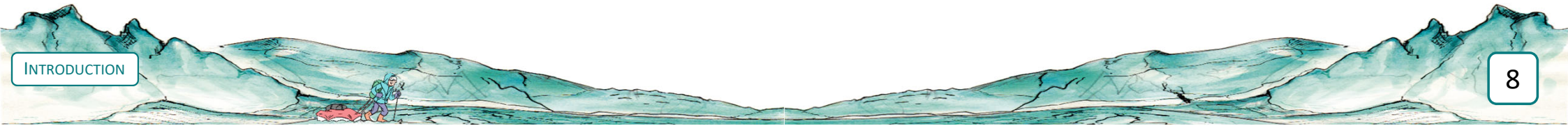
Punctual and highly heterogeneous



Results of 700+ boreholes pressure sensors
(Rada and Schoof, 2018)

Key questions remain

- Where are cavities and channels?
- How do they develop?
- What are their hydraulic properties?



Great uncertainties on the fate of glaciers

Surface Melt–Induced Acceleration of Greenland Ice-Sheet Flow 2002

H. Jay Zwally,[1]* Waleed Abdalati,[2] Tom Herring,[3] Kristine Larson,[4] Jack Saba,[5] Konrad Steffen[6]

Dominant **inefficient** drainage system**?**

ARTICLE 2019

https://doi.org/10.1038/s41467-019-12039-2 OPEN

Rapid accelerations of Antarctic Peninsula outlet glaciers driven by surface melt

Peter A. Tuckett[1], Jeremy C. Ely[1*], Andrew J. Sole[1], Stephen J. Livingstone[1], Benjamin J. Davison[2], J. Melchior van Wessem[3] & Joshua Howard[1]

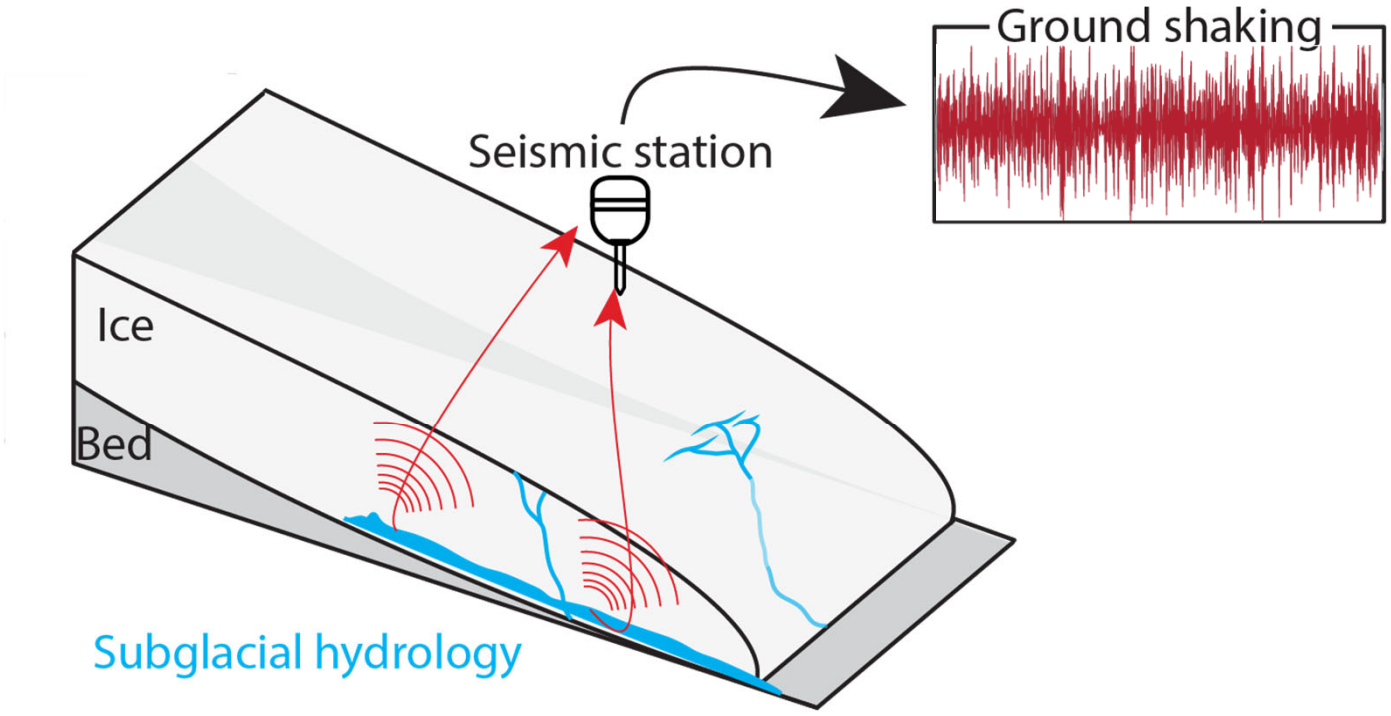
Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet despite warming 2015

Andrew J. Tedstone[1], Peter W. Nienow[1], Noel Gourmelen[1], Amaury Dehecq[1,2], Daniel Goldberg[1] & Edward Hanna[3]

Dominant **efficient** drainage system**?**

Time to find a **new way** to observe subglacial hydrology

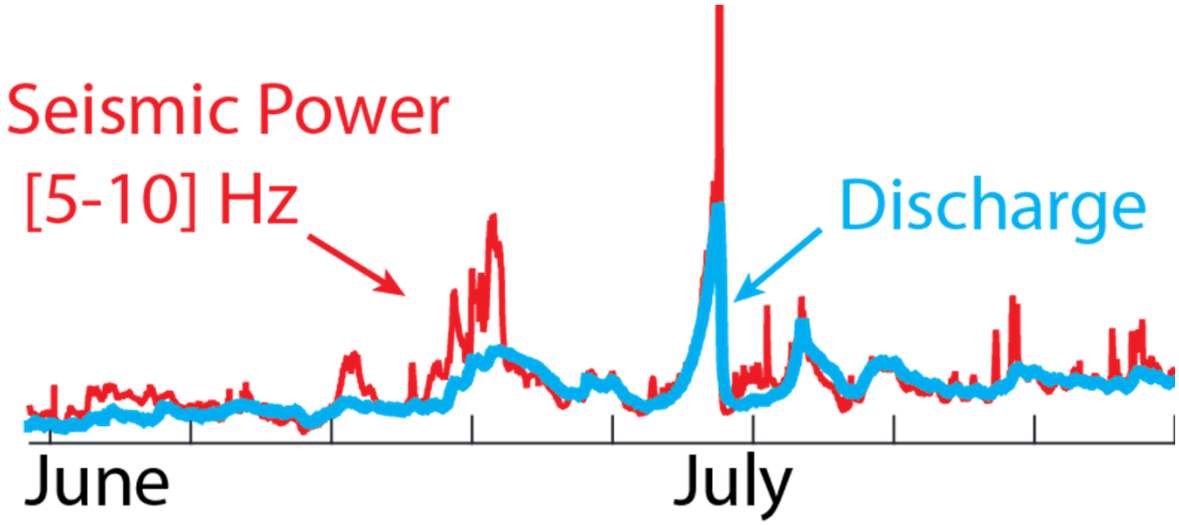
Can seismology help?

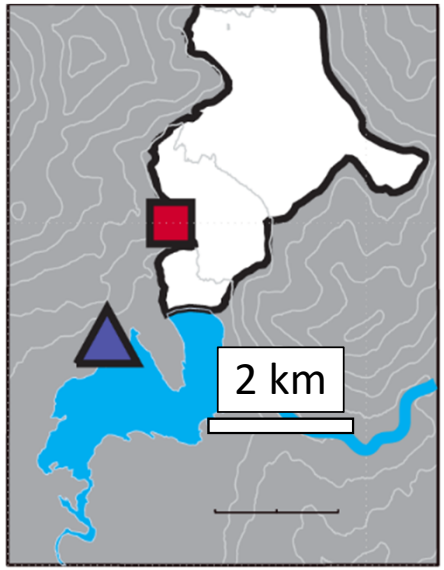


A new-born tool to study subglacial hydrology

Subglacial discharge at tidewater glaciers revealed by seismic tremor 2015

Timothy C. Bartholomaus[1], Jason M. Amundson[2], Jacob I. Walter[1], Shad O'Neel[3], Michael E. West[4] and Christopher F. Larsen[4]



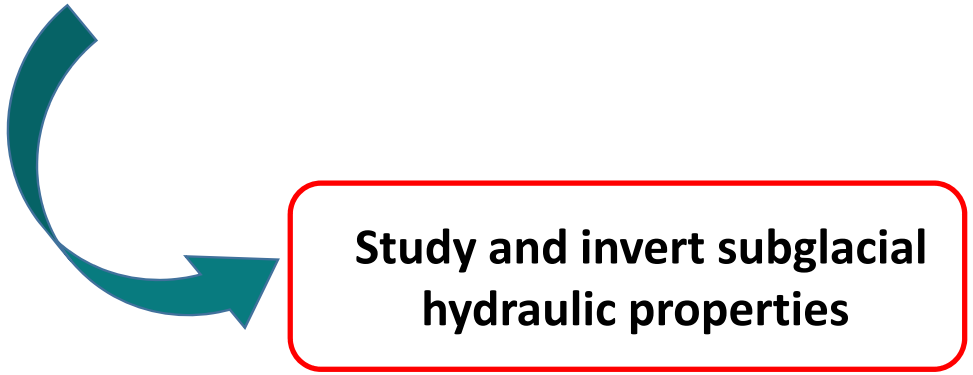


Mendenhall glacier, Alaska

A promising physical framework

Gimbert et al., (2014, 2016):

- Seismic power scales with hydraulic **RADIUS** and hydraulic **PRESSURE** gradient



Study and invert subglacial hydraulic properties

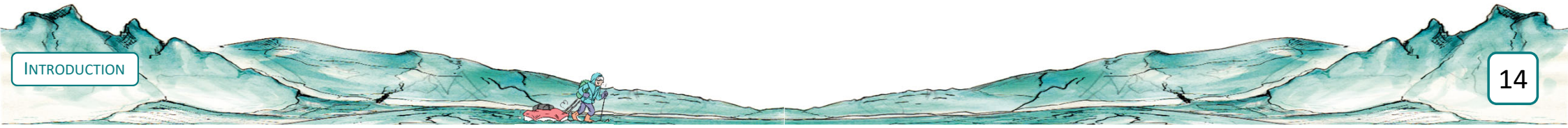
Limitations at the beginning of my PhD

When/where can we apply it

- To other glaciers?
- To complete melt-season? (*at lower discharge?)*

What can we observe?

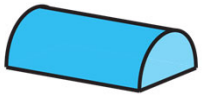
- Only sensitive to channels?
- Spatial information?



My questions

#1 Can we **MEASURE** subglacial-water-flow-induced seismicity over complete melt-seasons?

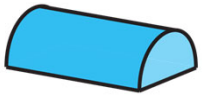
Part I



#2 What is the **TEMPORAL** dynamics of subglacial hydraulic properties over complete melt-seasons?

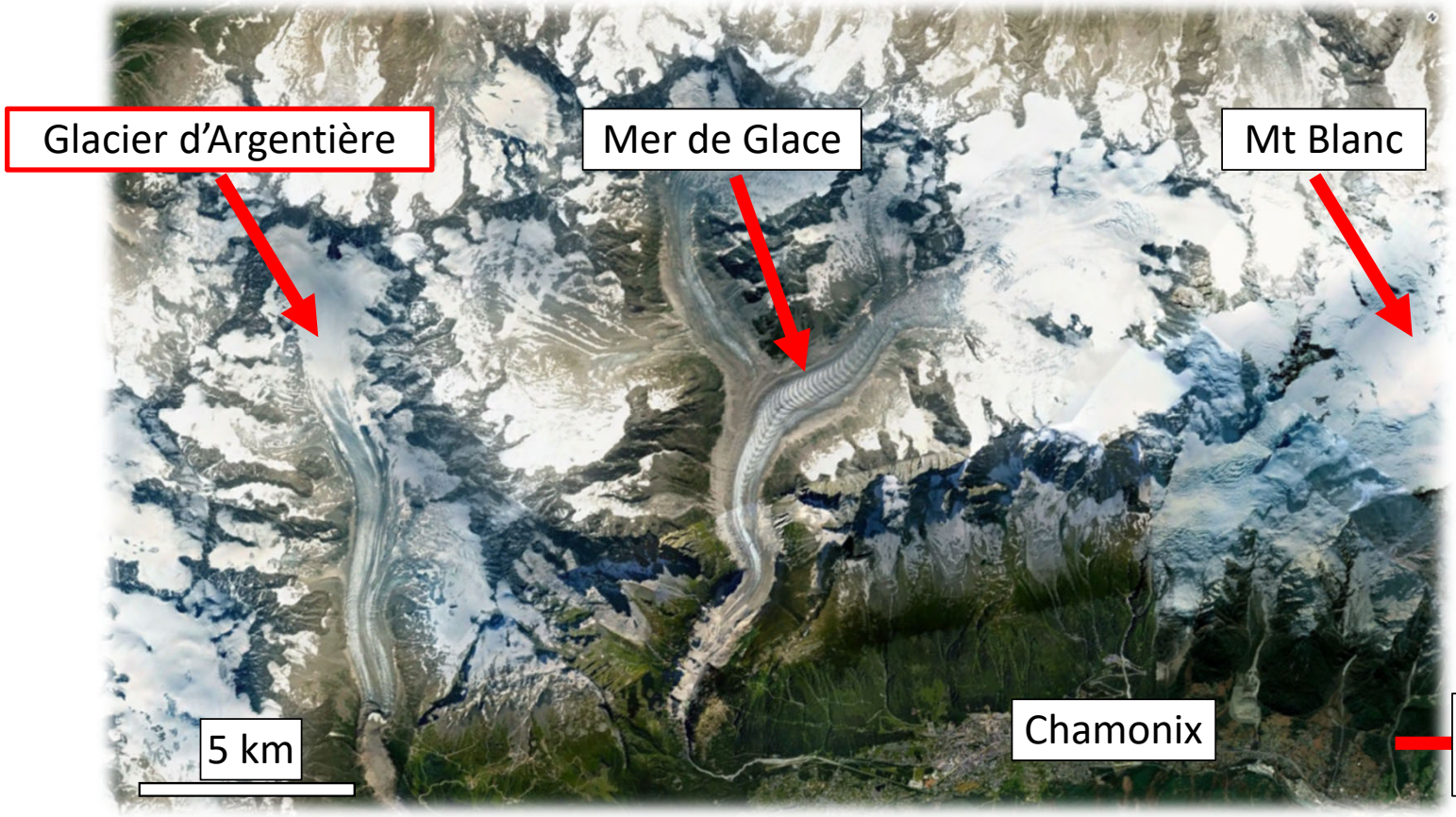
#3 Can we **LOCATE** distributed sources of seismic noise?

Part II



#4 What is the **SPATIAL** dynamics of cavities and channels?

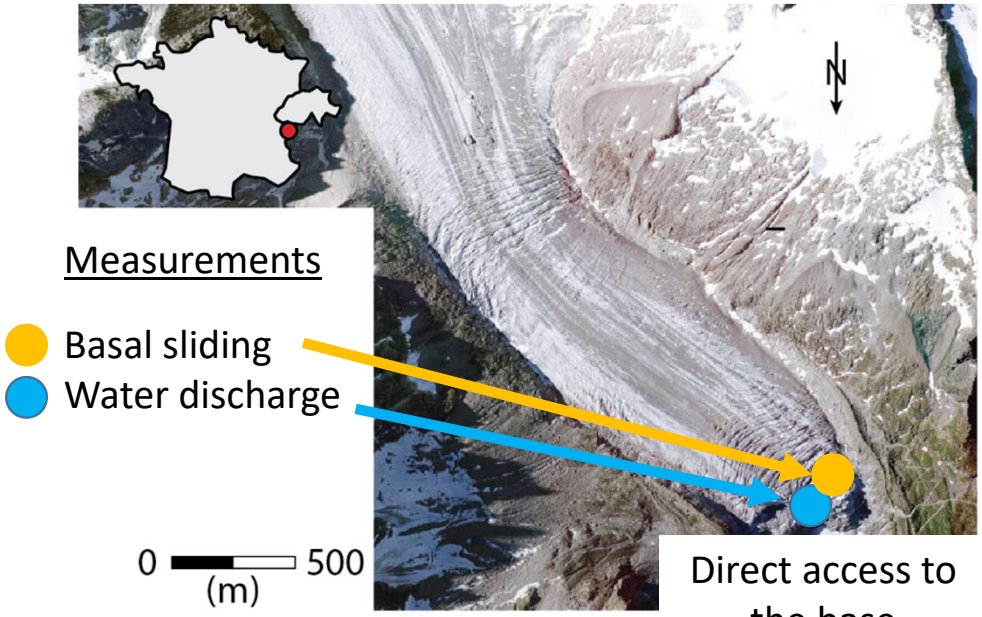
Glacier d'Argentière: a field-scale laboratory



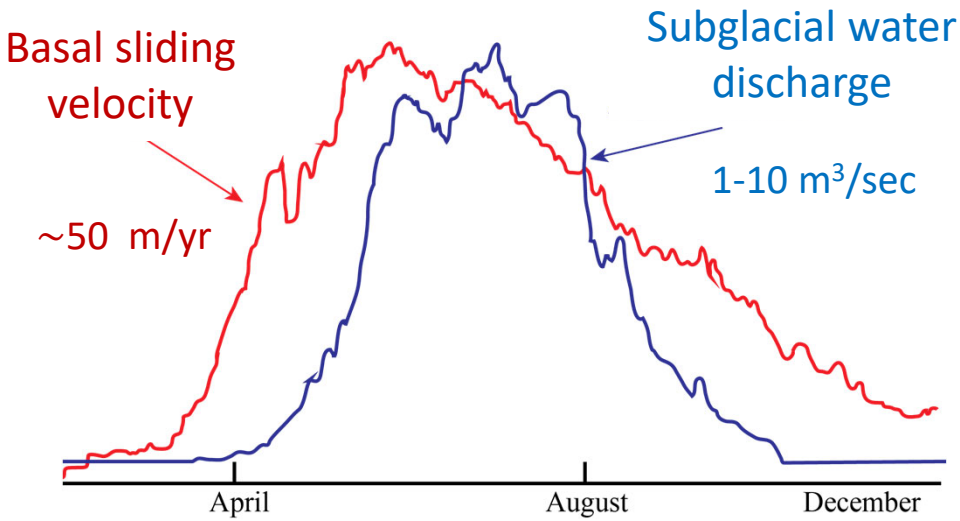
Unique measurements

- 30+ years of measurements of water discharge and **sliding**
- High sensitivity to subglacial water flow

©L. Moreau



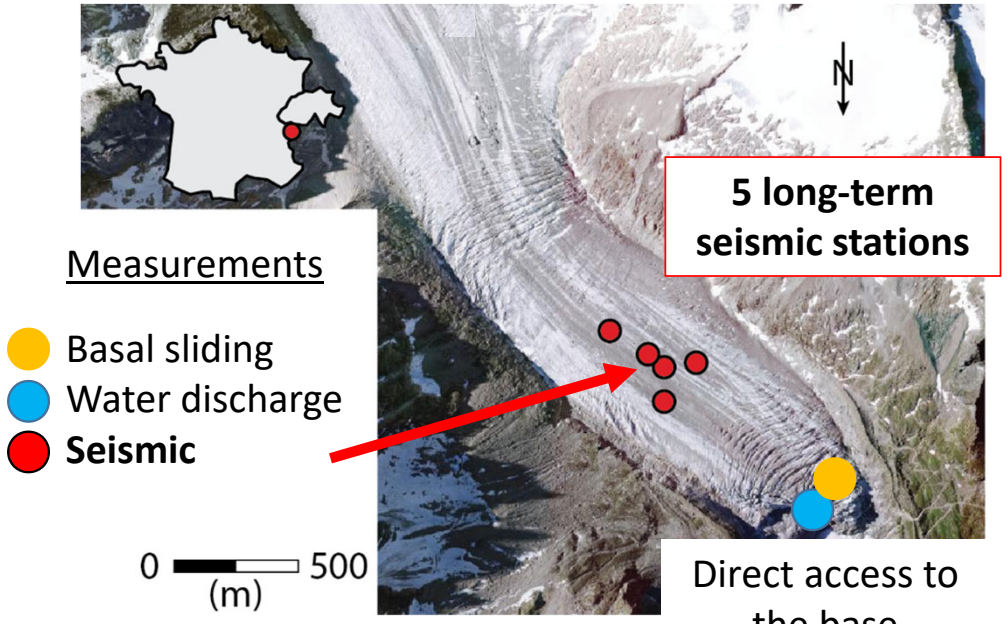
Direct access to the base



2000-2016 average

Seismic measurements: **temporal**

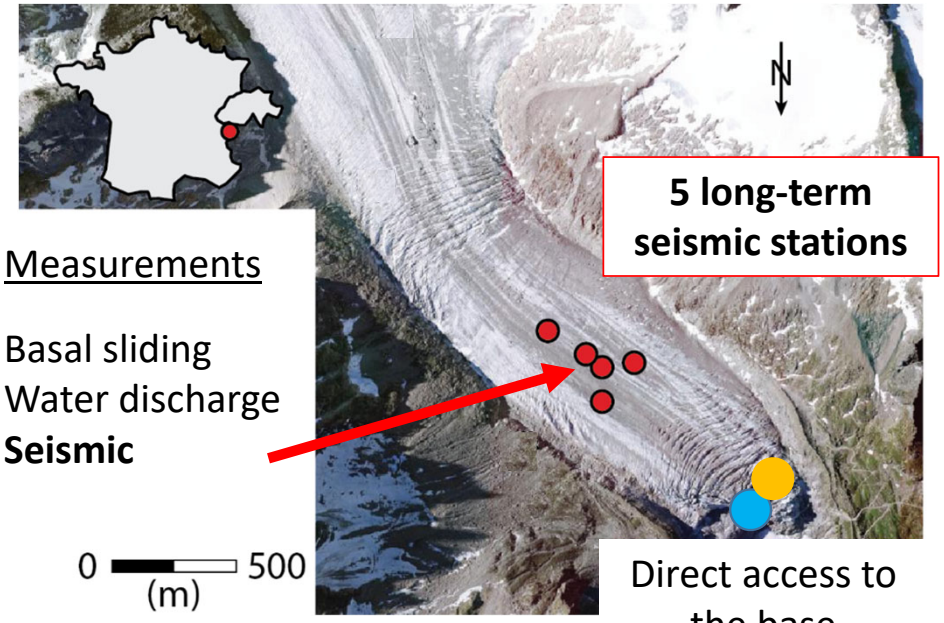
- Up to 7 seismic stations maintained from spring **2016** to winter **2020**
  - Collaboration with Fabian Walter and Dominik Graeff from ETH Zurich



In collaboration with the SAUSSURE project: a multidisciplinary investigation of the subglacial processes on glacier d'Argentière.

Seismic measurements: **temporal**

~ 70 days of maintenance + casing and cabling preparation

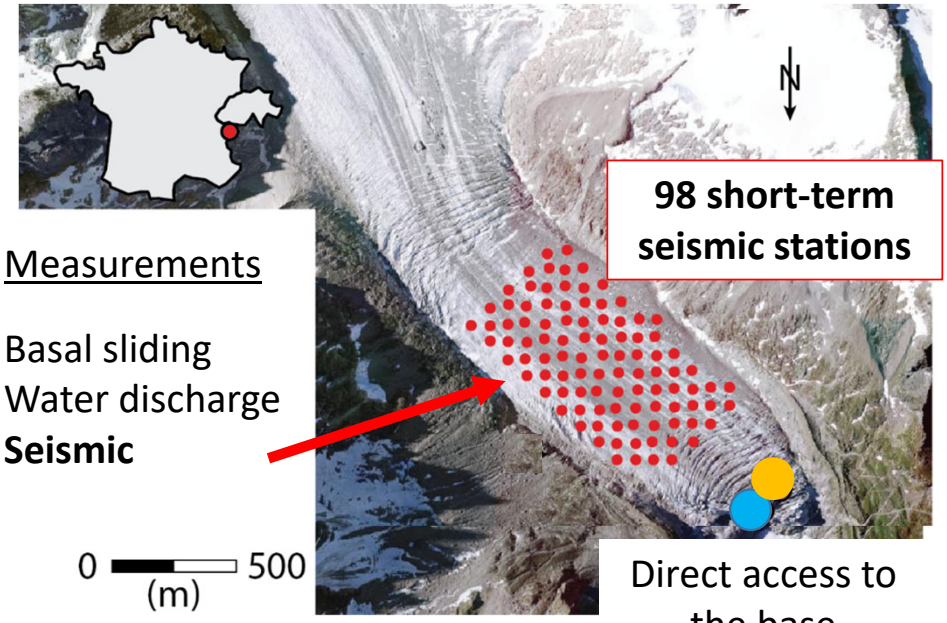


5 long-term seismic stations

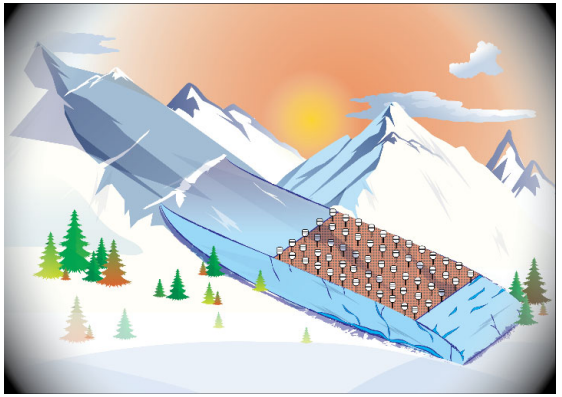
Direct access to the base

Seismic measurements: **spatial**

- 98 seismic stations maitained for one-month in spring 2018
- A cross-disciplinary and cross-institutes collaboration



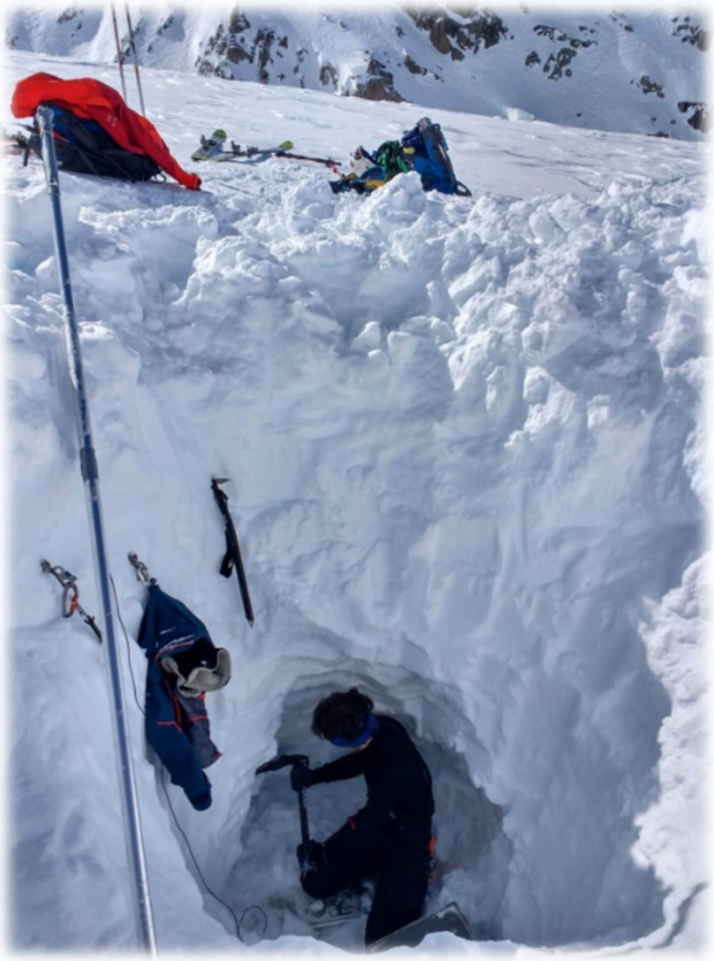
Direct access to the base



ISTerre

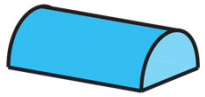
In collaboration with the RESOLVE project: a development of a multi-instrument platform for interdisciplinary research.

So what did I observe?



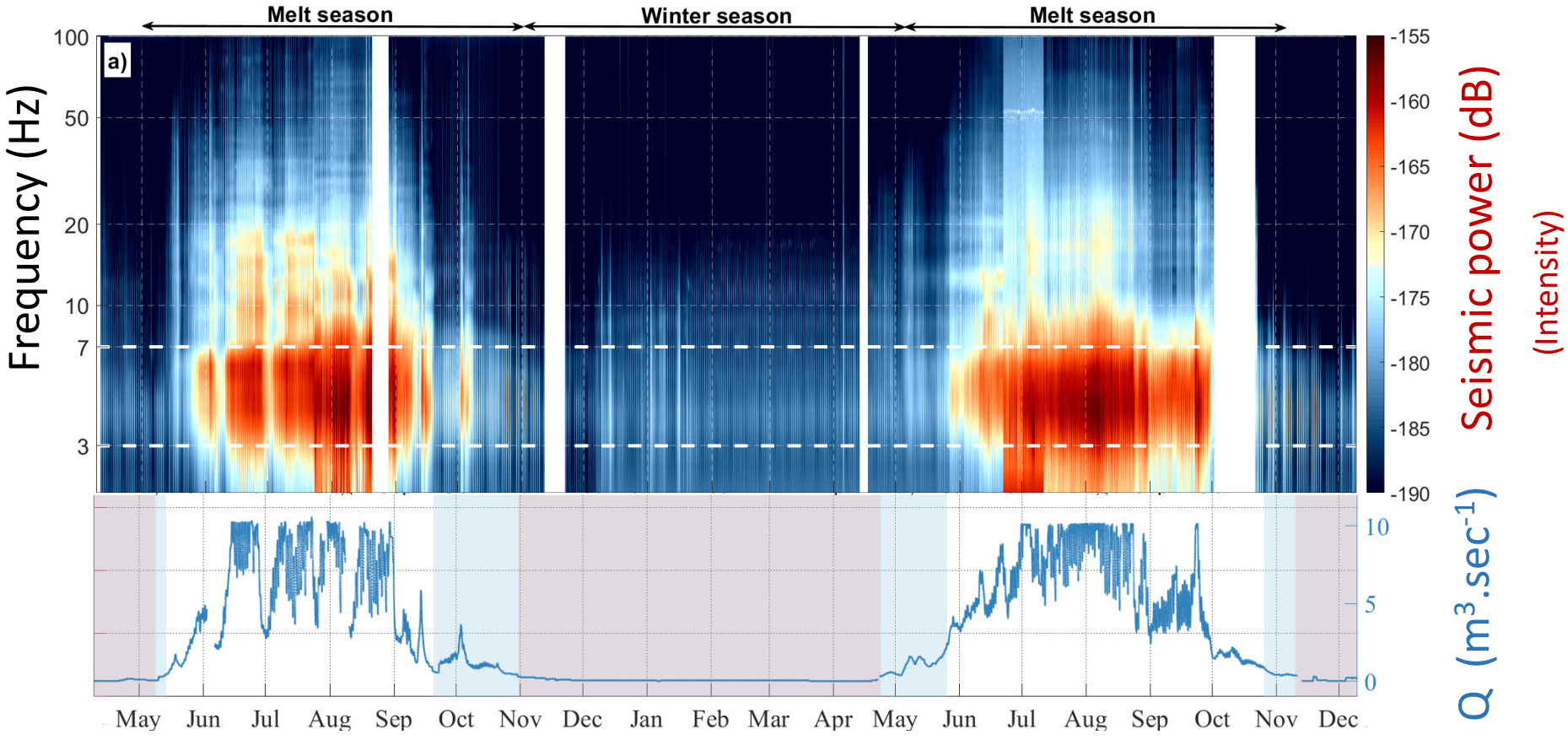
Part I: Temporal investigation of subglacial water flow

#1 Can we **MEASURE** subglacial-water-flow-induced seismicity over complete melt seasons?



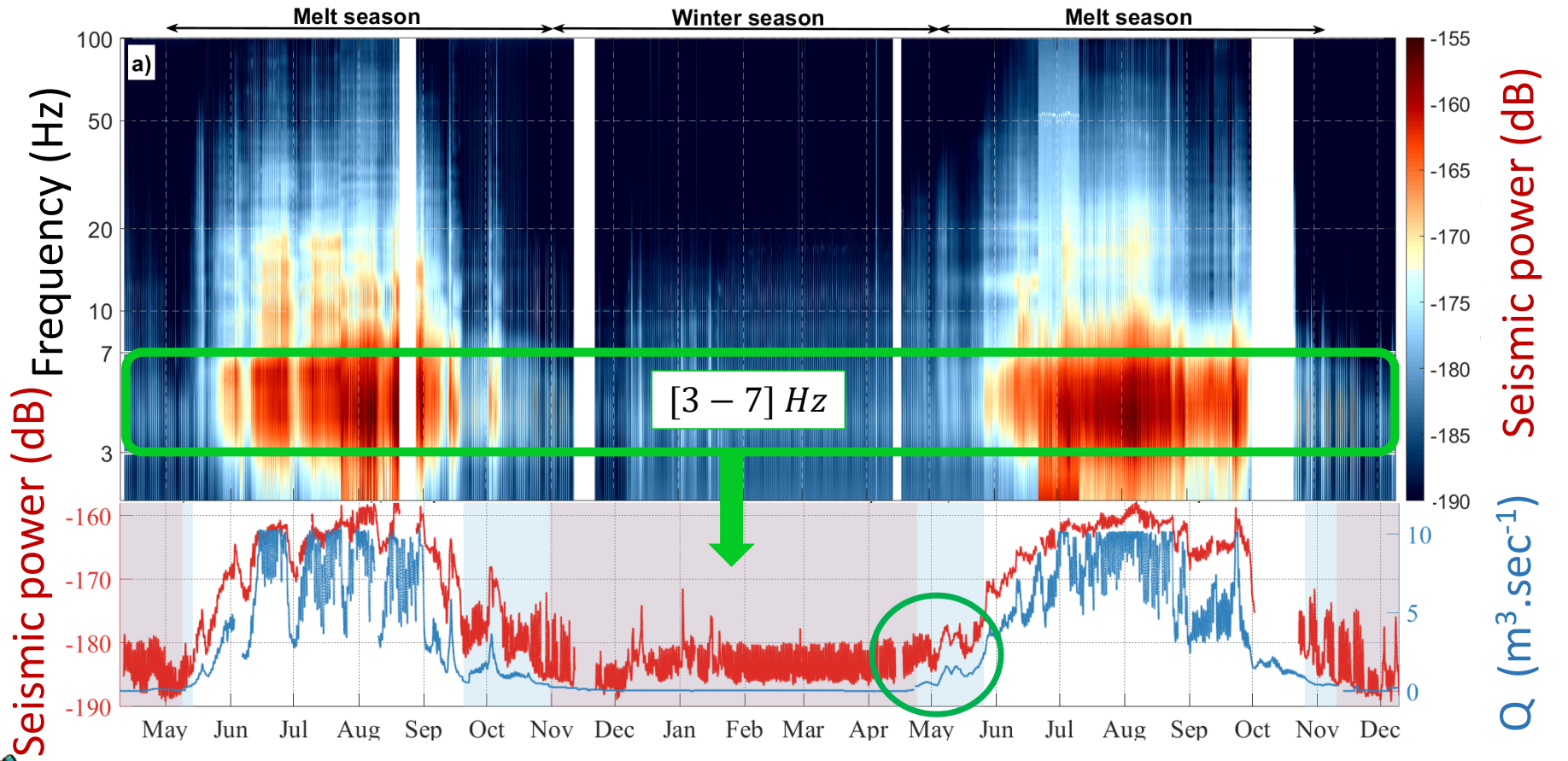
#2 What is the **TEMPORAL** dynamics of subglacial hydraulic properties over complete melt seasons?

Seismic measurements



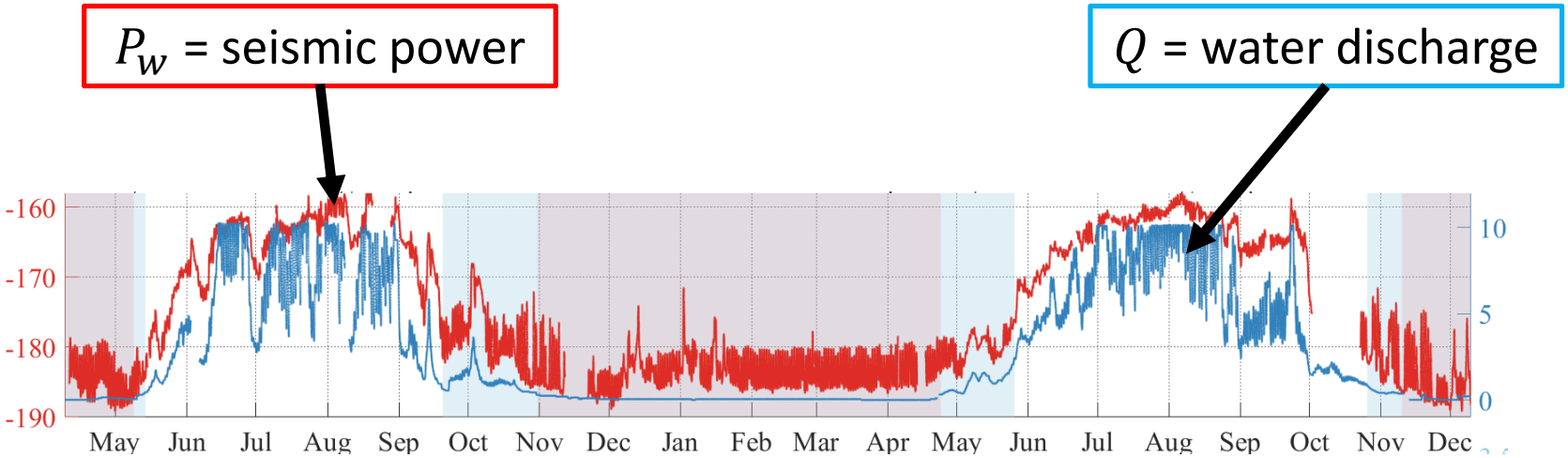
(Nanni et al., 2020)

Seismic measurements



(Nanni et al., 2020)

Notations

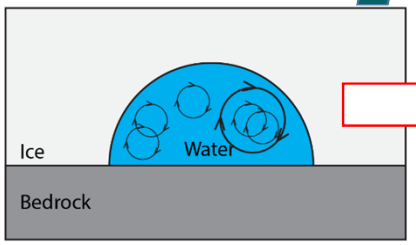


(Nanni et al., 2020)

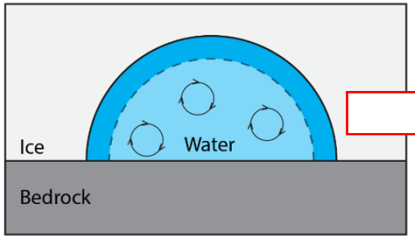
Theoretical end-members

(Gimbert et al., 2016)

2 predicted responses

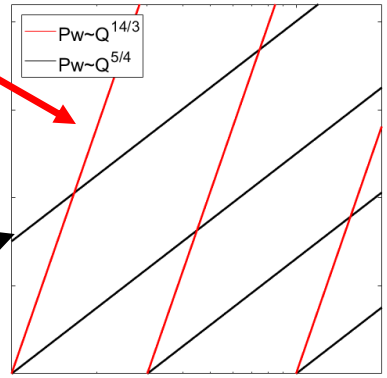


Only **Pressure gradient S** varies → $P_w \propto Q^{14/3}$

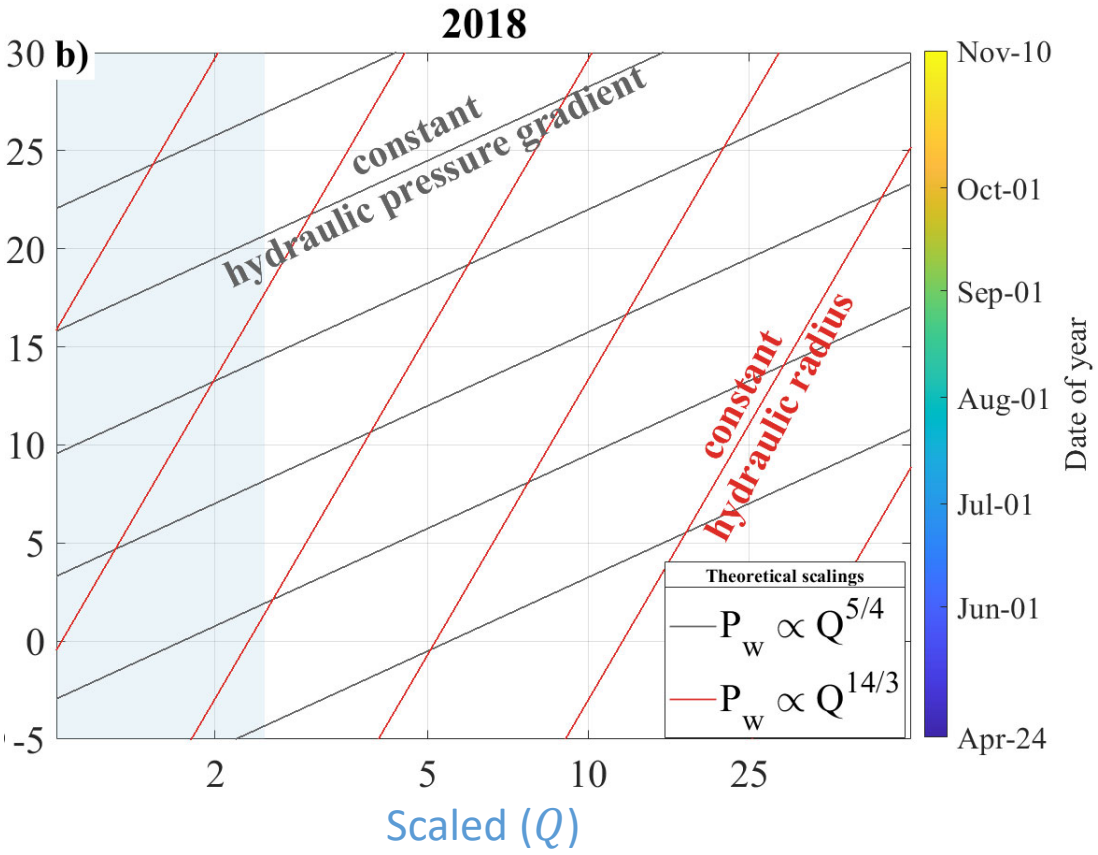


Only **Hydraulic radius R** varies → $P_w \propto Q^{5/4}$

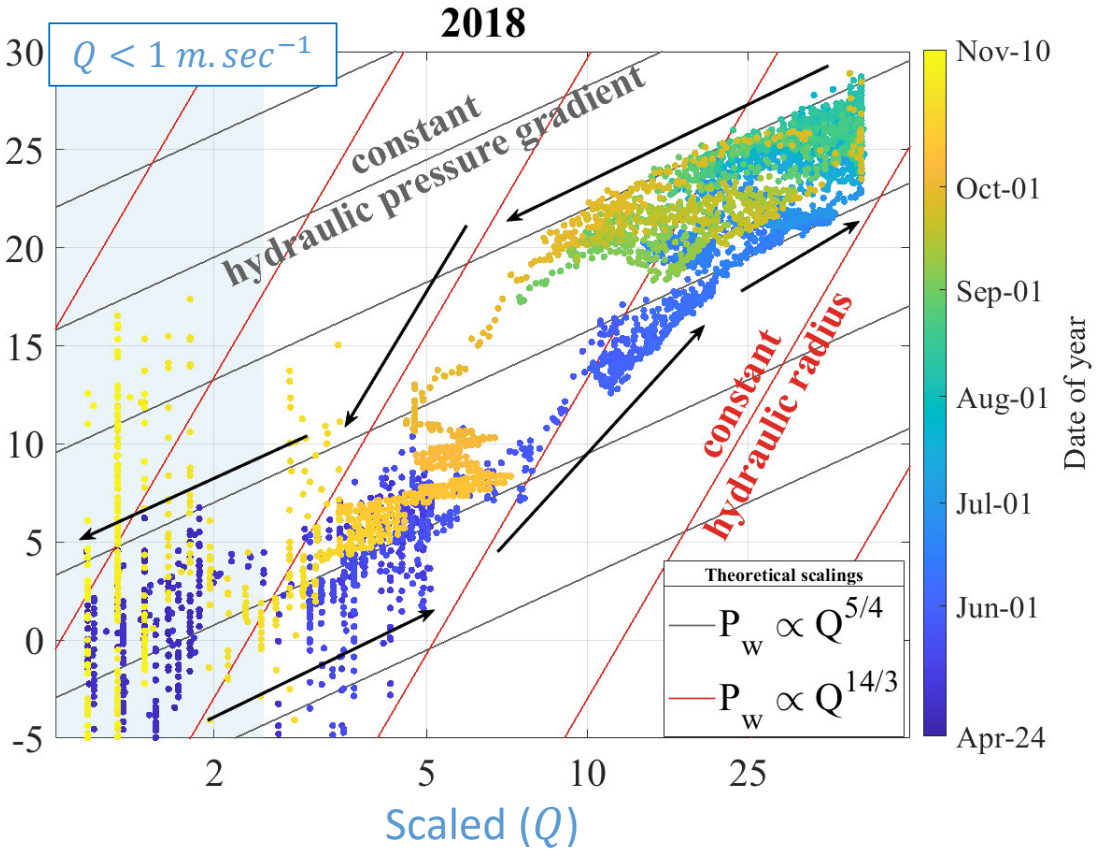
Log-Log representation



Trends at seasonal scales



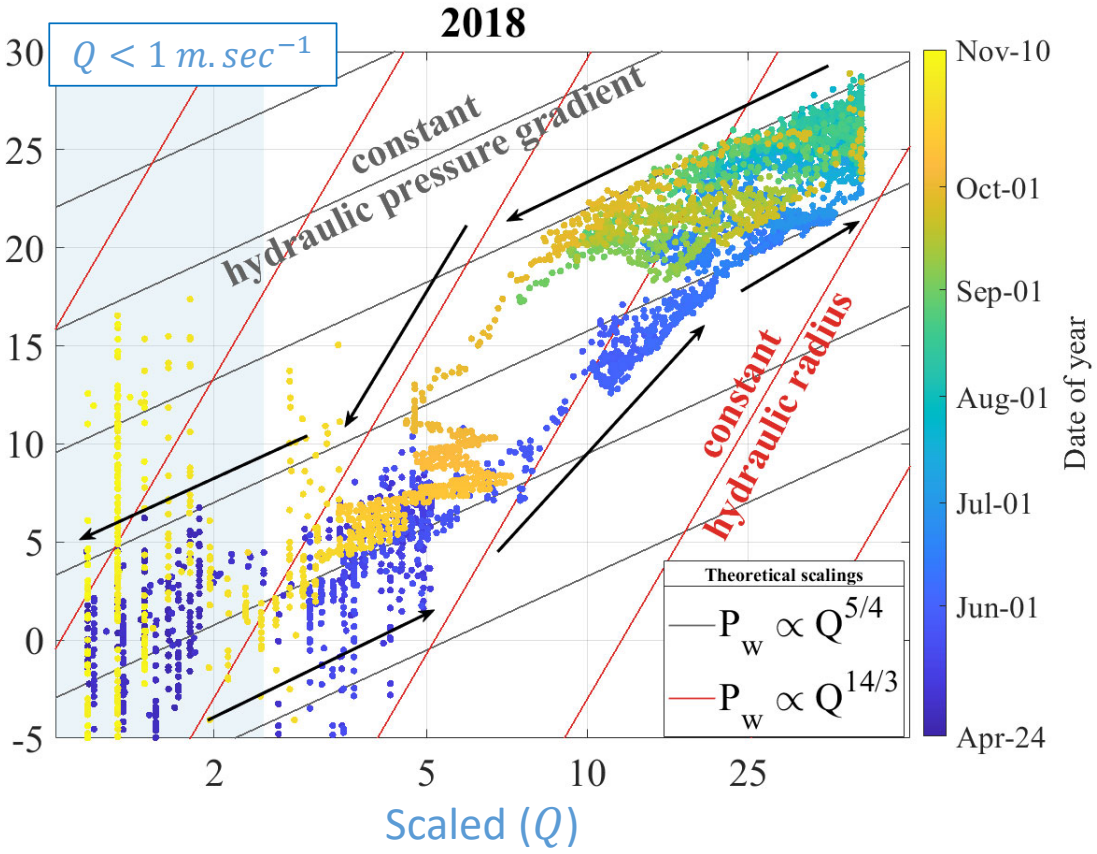
Trends at seasonal scales



- Consistency between observations and predictions

(Nanni et al., 2020)

#1 I USED SEISMOLOGY TO STUDY COMPLETE MELT SEASON



- Consistency between observations and predictions

Now invert hydraulic properties S and R

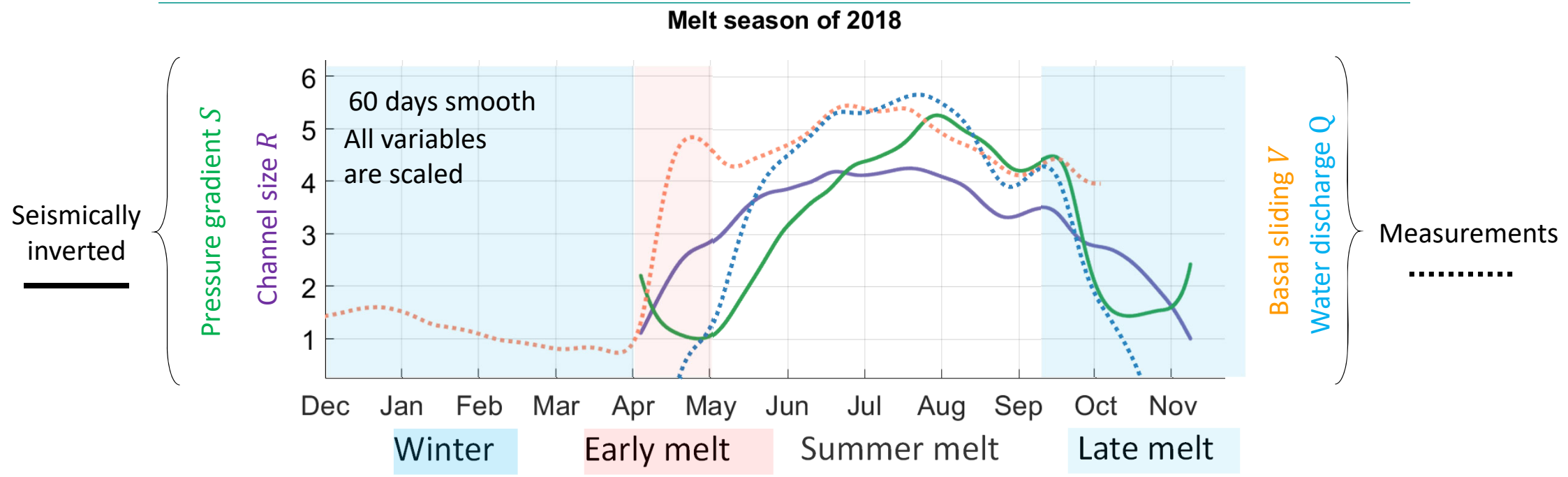
$$Q \sim R^{2/3} S^{1/2}$$

$$P_w \sim R^{7/3} S^{7/3}$$

(Gimbert et al., 2016)

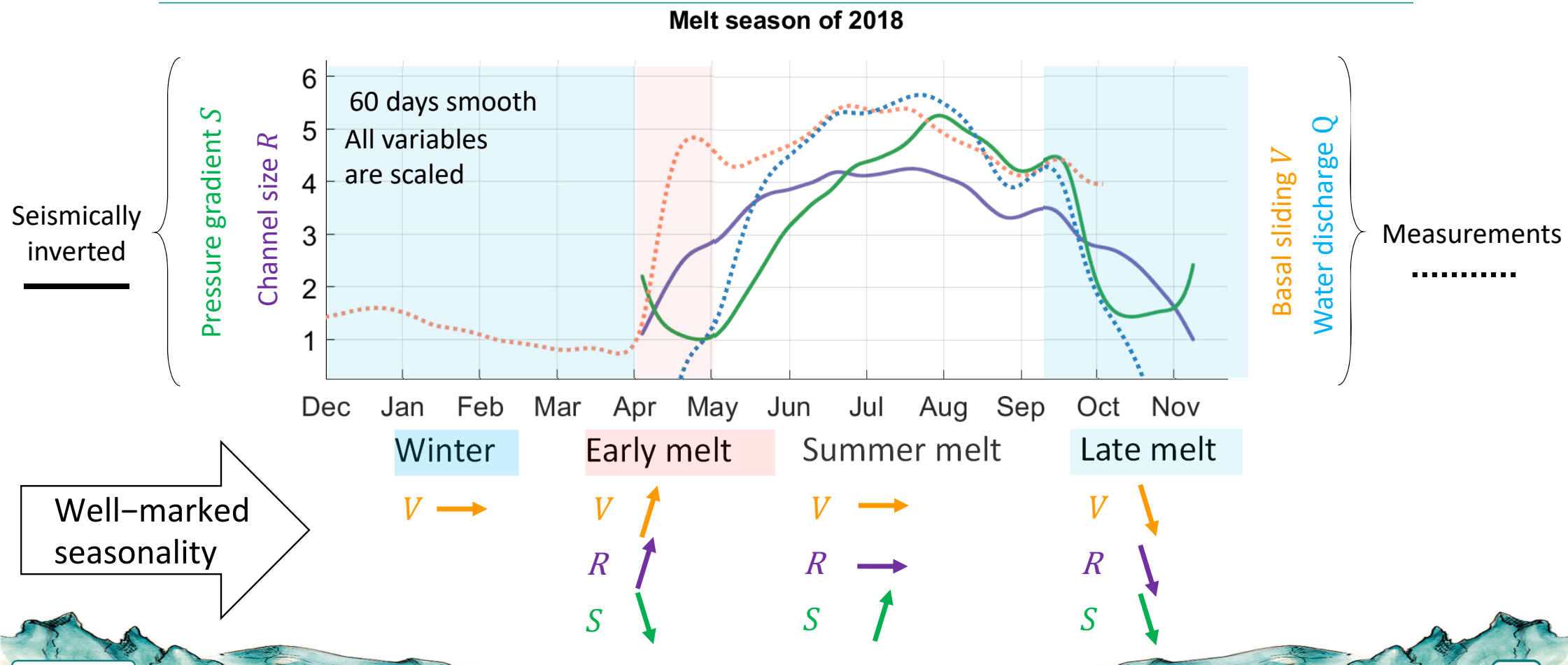
(Nanni et al., 2020)

Inversion of hydraulic properties



(Nanni et al., 2020)

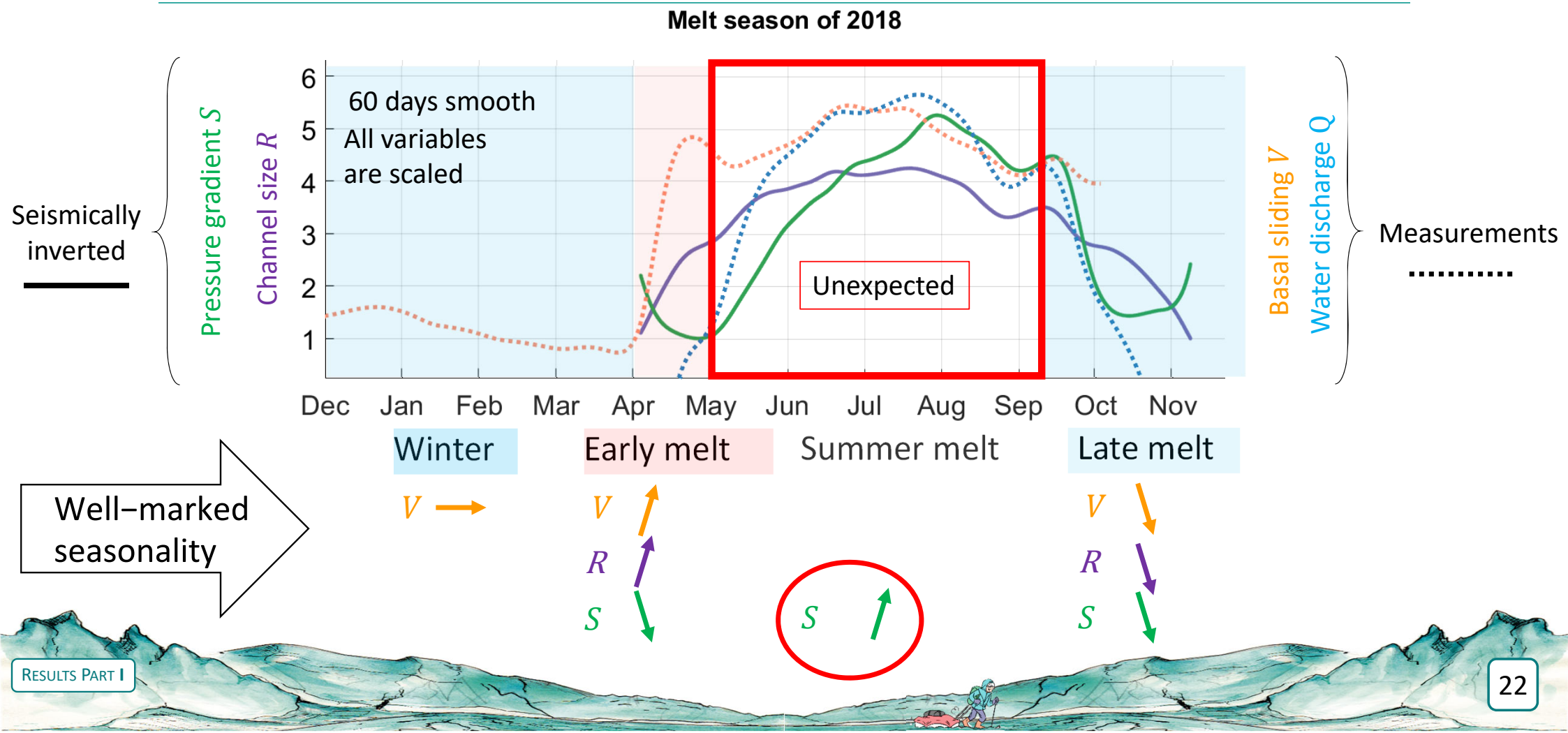
Inversion of hydraulic properties



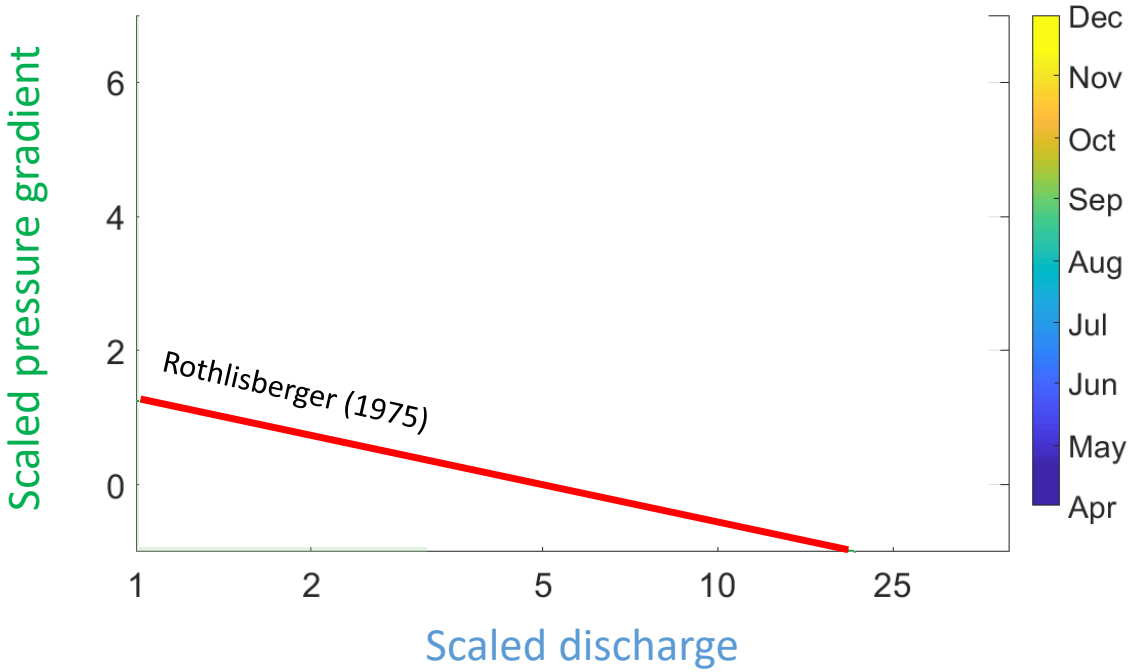
Well–marked seasonality

(Nanni et al., 2020)

#2 I SUCCESSFULLY INVERTED HYDRAULIC PROPERTIES

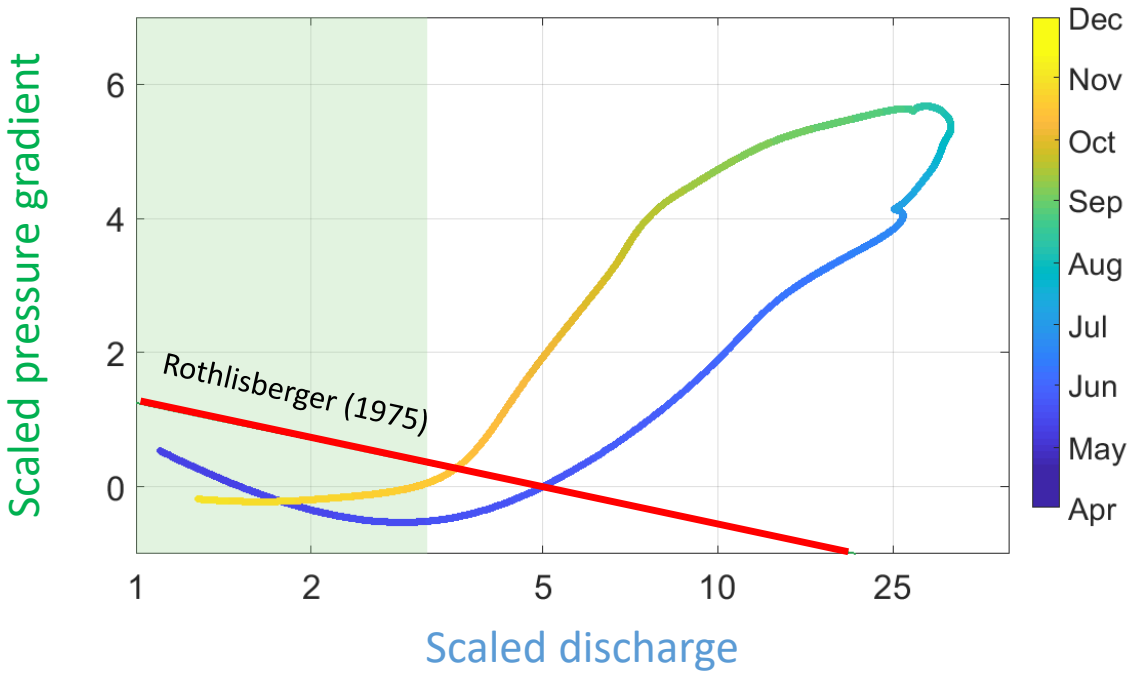


Channel dynamics: theory



- Steady-state and equilibirum prediction for channel dynamics by Rothlisberger (1975)

Channel dynamics: theory VS observation



- Steady-state and equilibirum prediction for channel dynamics by Rothlisberger (1975)
- Out of equilibrium and **pressurized** at high discharge

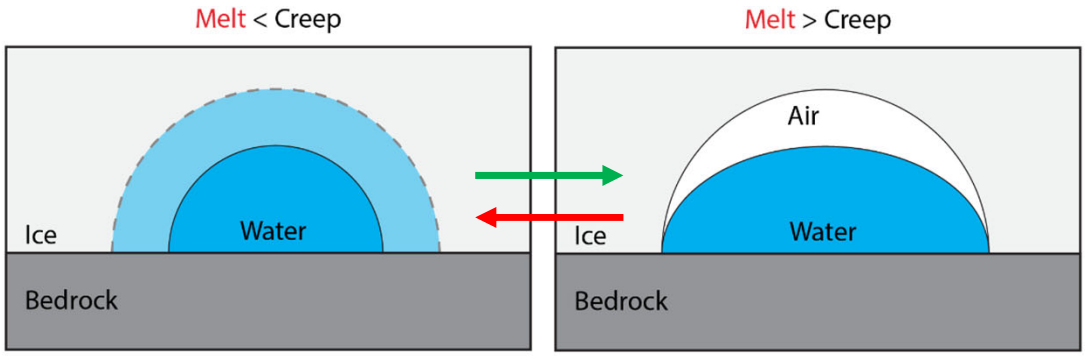
(Nanni et al., 2020)

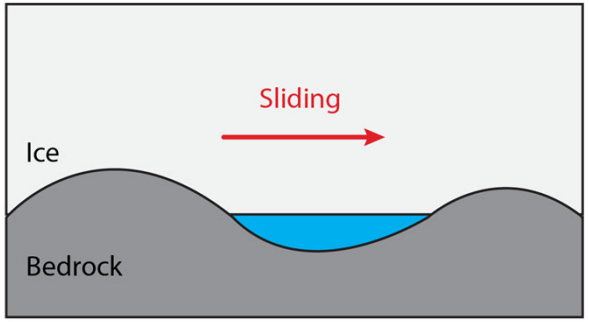
Potential cause(s) for high pressure in summer

Short term water input = Transient state

or/and

Cavities dominate the seismic power ?





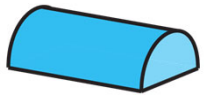
Kinetics of water supply > channel's response time

Cavities might be pressurized

Previously thought to be noise-free

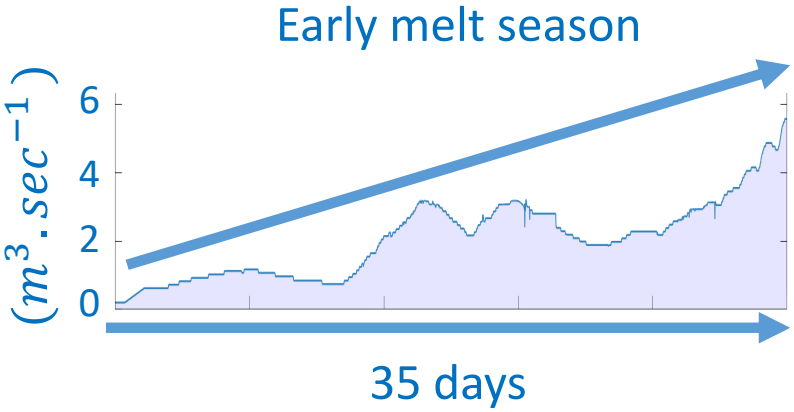
Part II: Spatial investigation of subglacial water flow

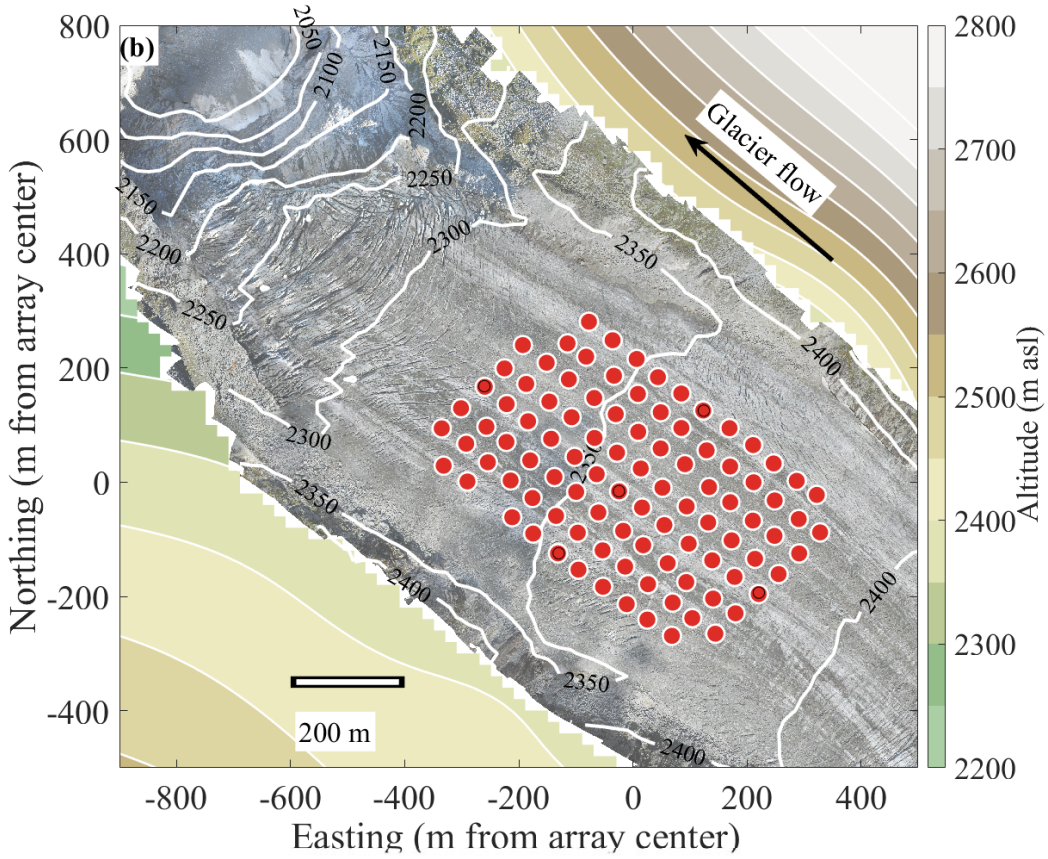
#3 Can we **LOCATE** distributed sources of seismic noise?



#4 What is the **SPATIAL** dynamics of cavities and channels?

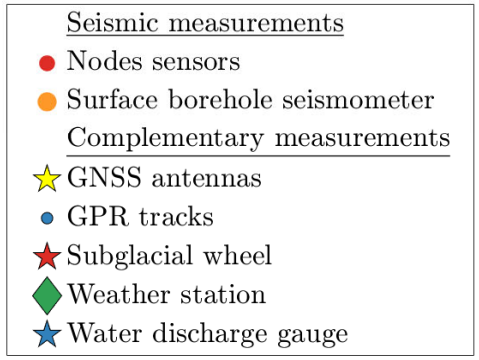
Measurements: 98 seismic sensors

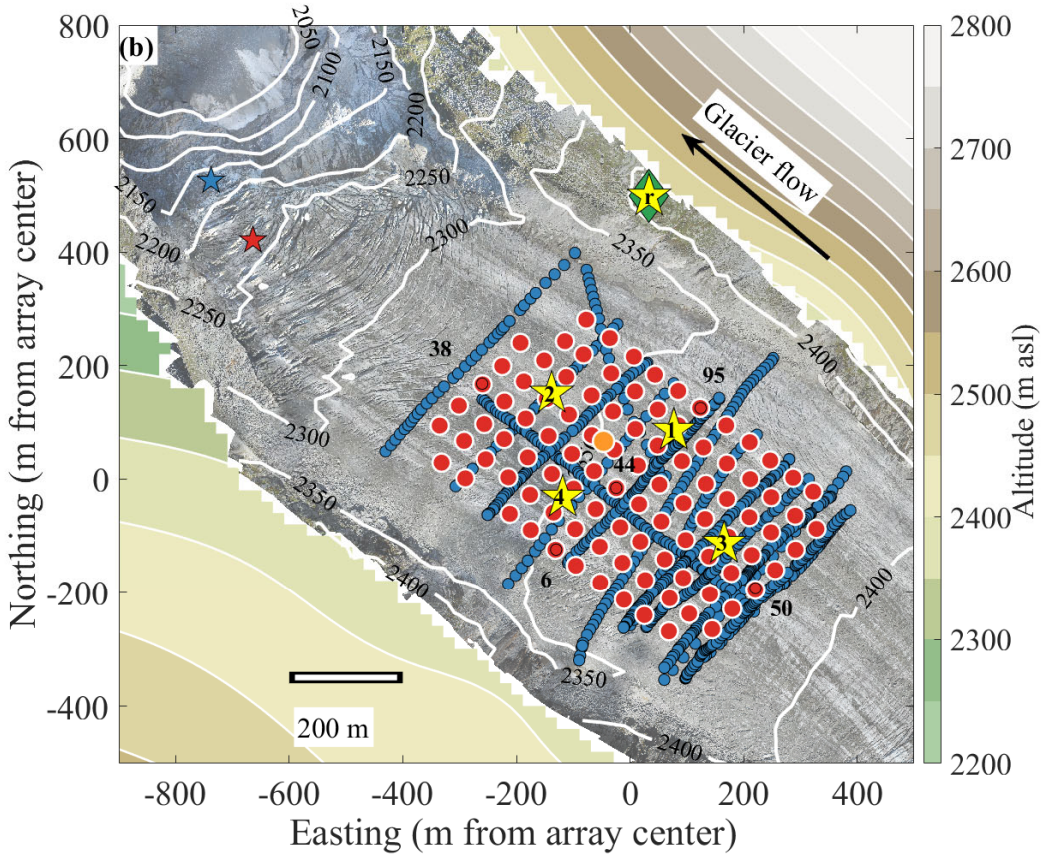




(Gimbert, **Nanni**, Roux et al., 2020)

The RESOLVE-Argentière project

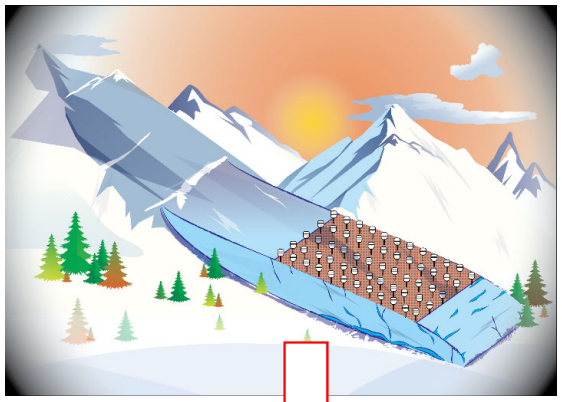




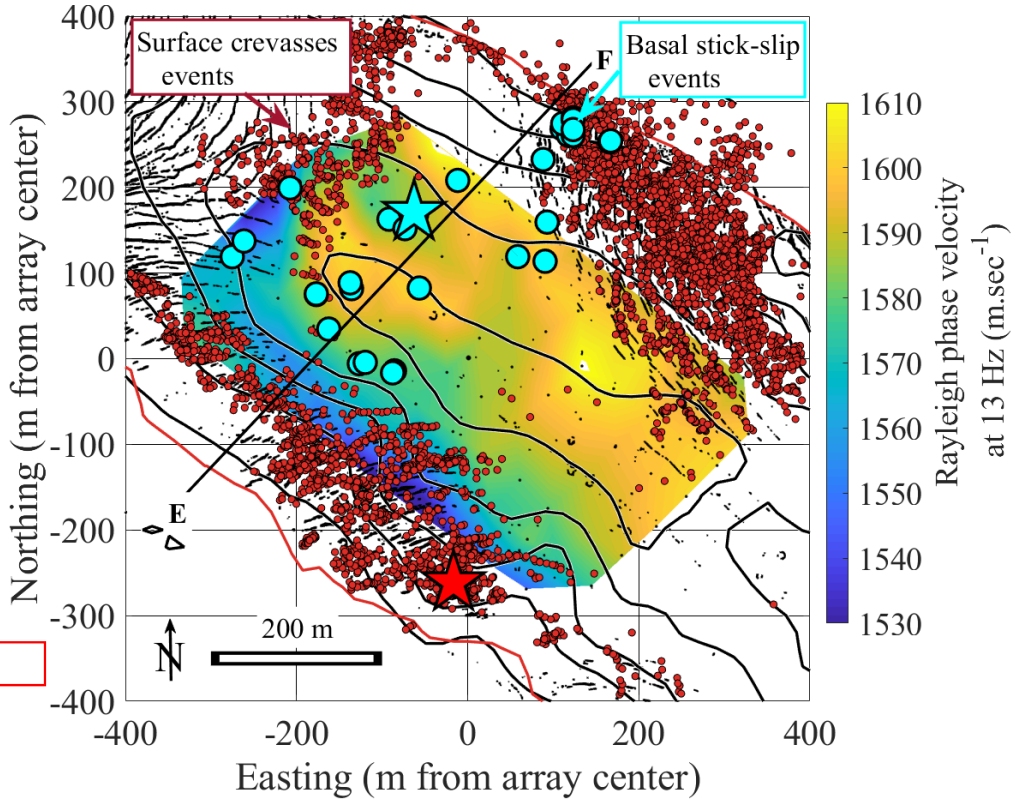
Add RESOLVE paper

(Gimbert, **Nanni**, Roux et al., 2020)

The RESOLVE-Argentière project

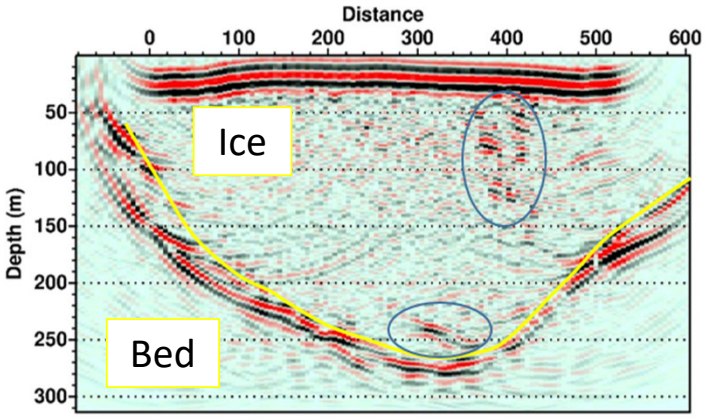


A wide range of **seismic analysis** presented in our community paper.

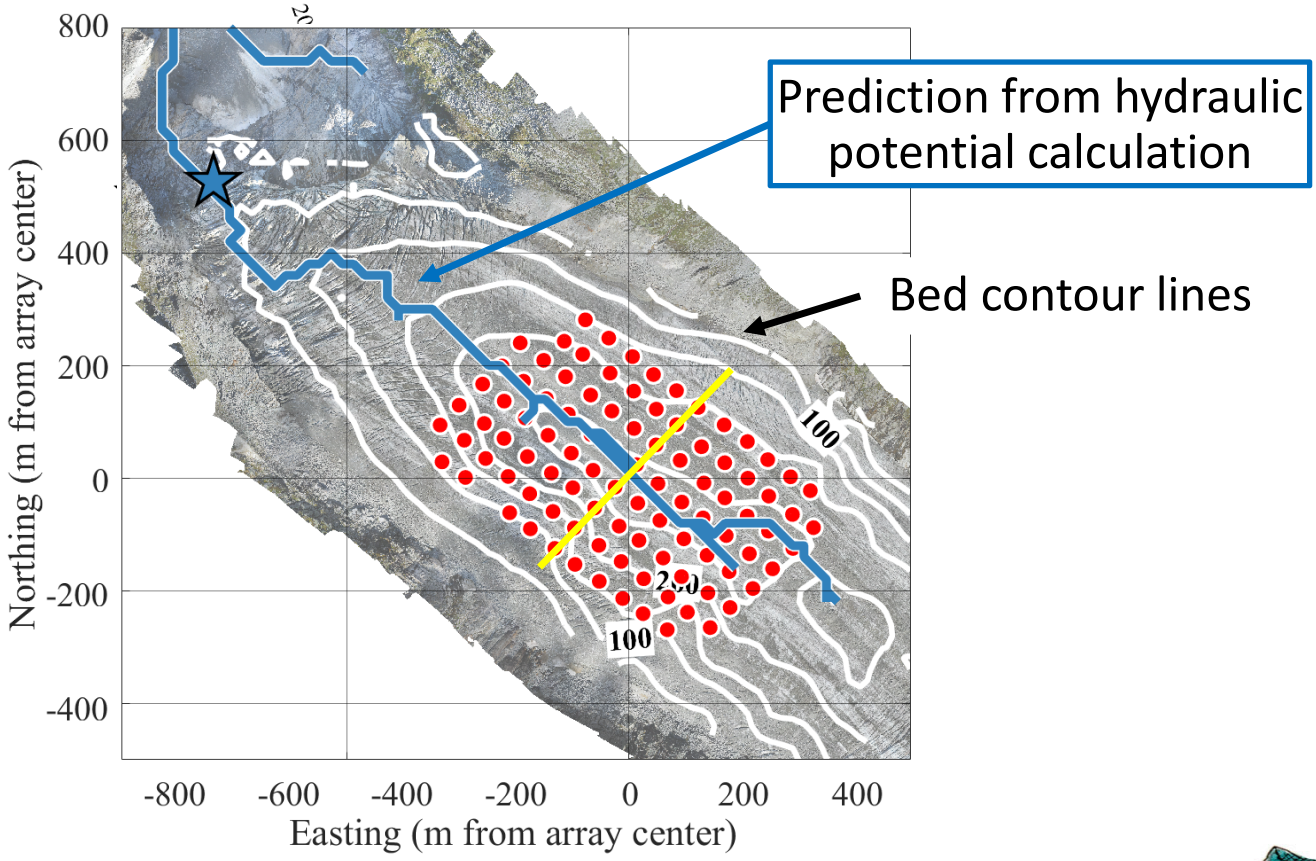


(Gimbert, **Nanni**, Roux et al., 2020)

Glacier geometry and waterways



GPR imaging results



(Gimbert, **Nanni**, Roux et al., 2020)

How to locate **distributed** noise sources ?

Very few studies …

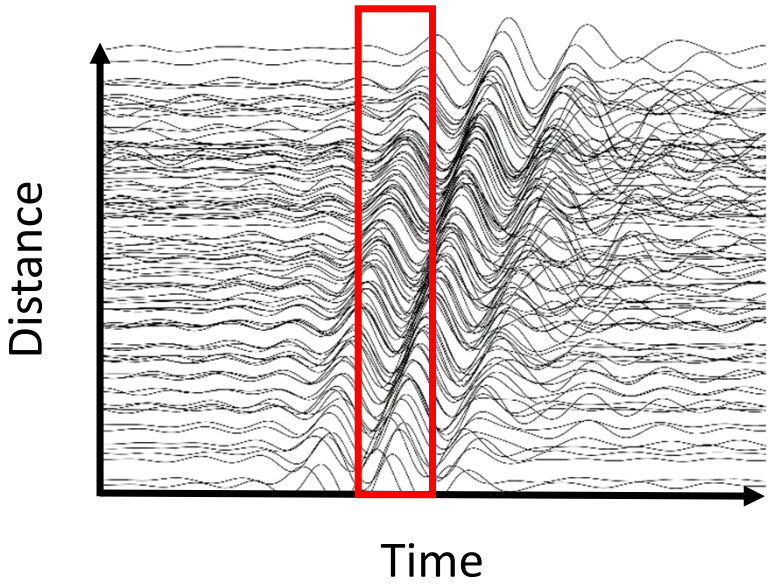
Venkatesh et al., 2003; Stehly et al., 2006; Burtin et al., 2010; Corciulo et al., 2013; Chmiel et al., 2019

How to locate **punctual** sources ?

$$u(t) = Ae^{i\omega t}$$

Amplitude — **Phase**

Phase differences ~ time delays



Phase coherence for a punctual source

Wavefront when throwing
a stone in a lake

Phase coherence for a punctual source

Wavefront when throwing
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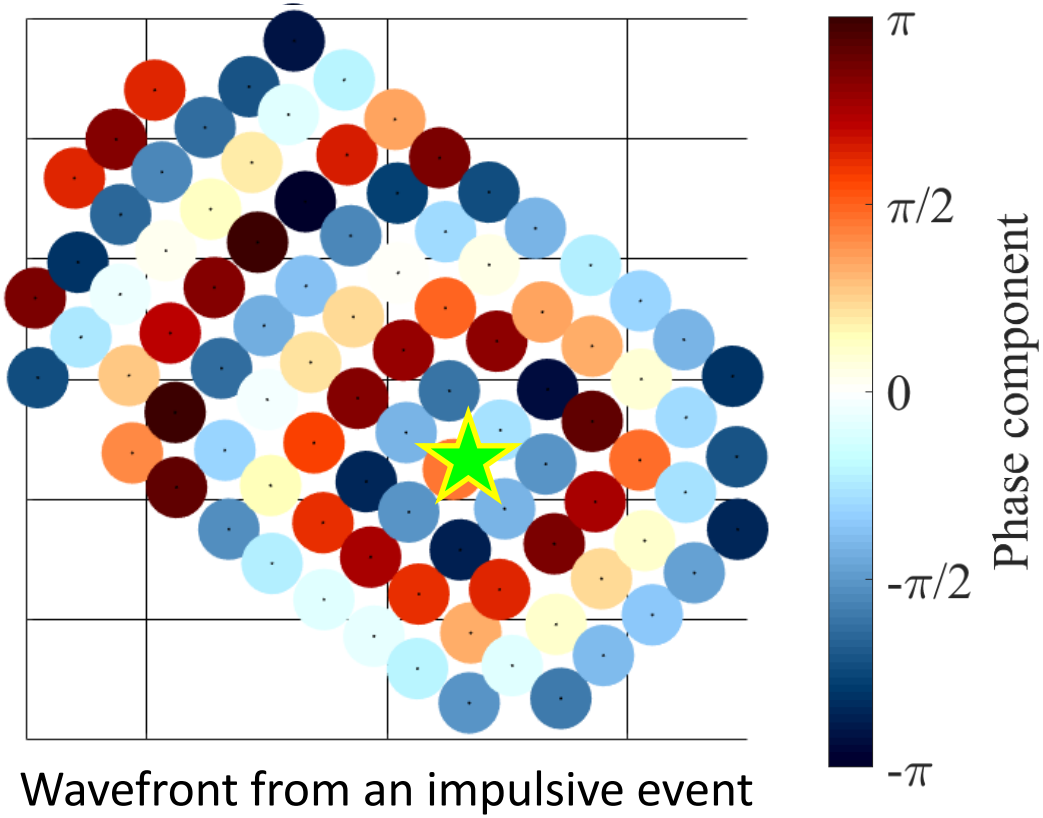
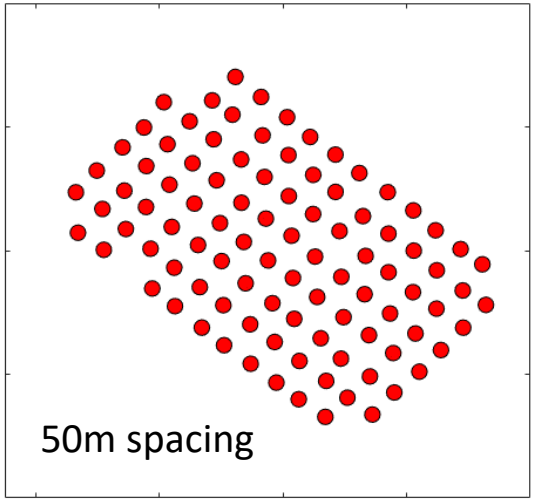


Wavefront from an impulsive event

MFP: the Match-field-processing method

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)

Seismic array



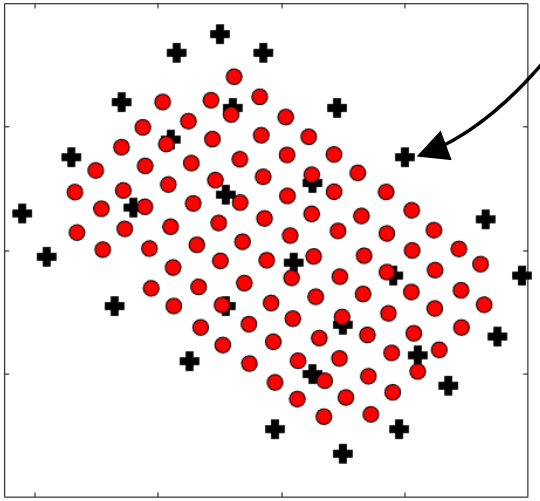
(e.g. Kuperman et al., 1997; Corciulo et al., 2013; Chmiel et al., 2019)

MFP: the Match-field-processing method

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)

Find local and global minima

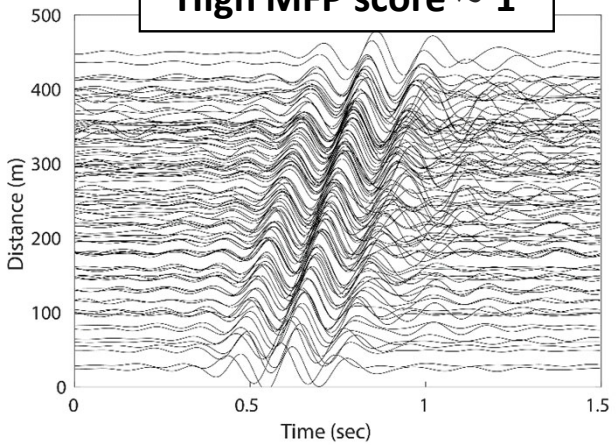
29 starting points



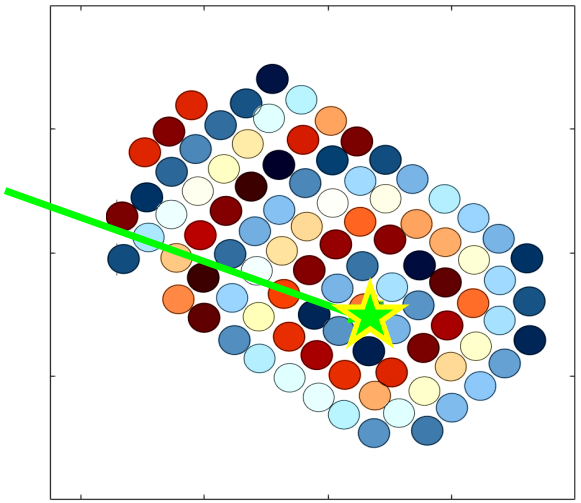
Punctual source: easy

- Assume a unique source over 1 second-signal
- Minimize misfit $|\mathrm{Phase}_{\mathrm{model}} - \mathrm{Phase}_{\mathrm{observed}}|$ (*gradient-based minimization*)
- MFP score $\propto$ phase coherency over the array

Impulsional signal:
High MFP score ~ 1



Unique location



Distributed sources: tricky

- Assume a unique source over 1 second-signal
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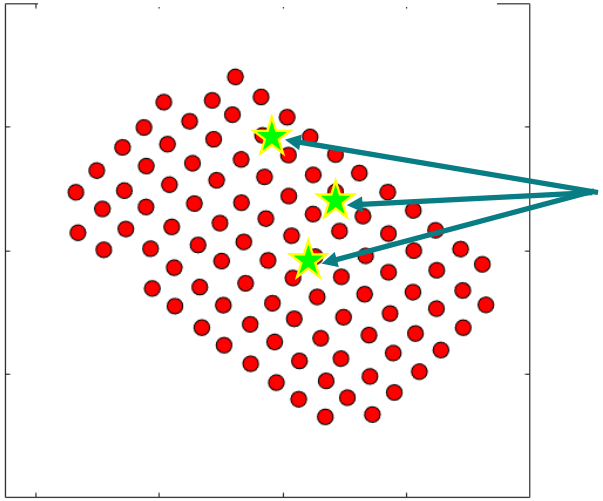
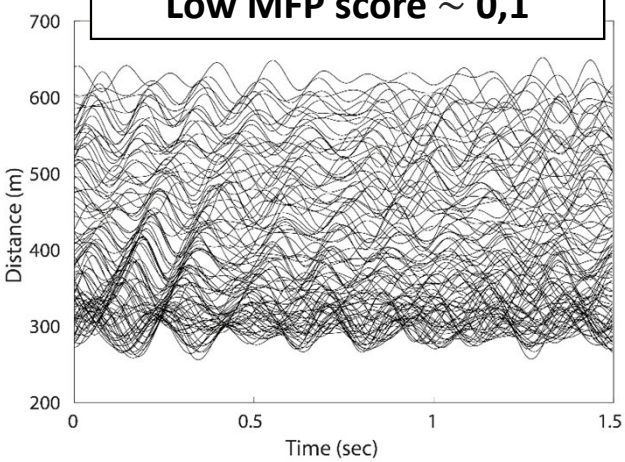
- MFP score $\propto$ phase coherency over the array

Multiple locations



Noisy signal:
Low MFP score ~ 0,1



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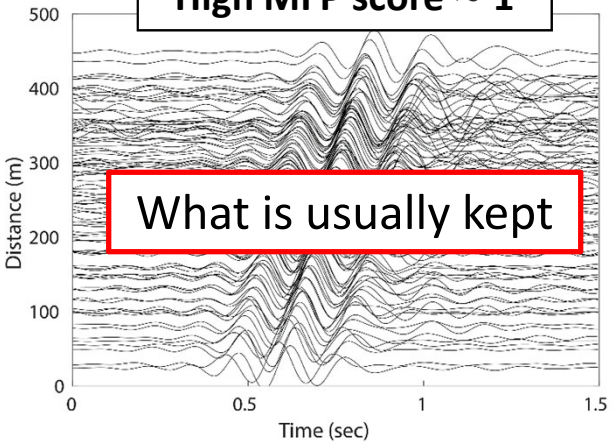
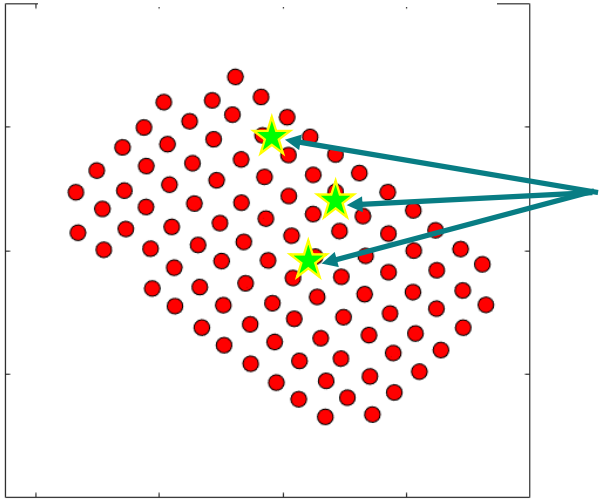


Multiple locations



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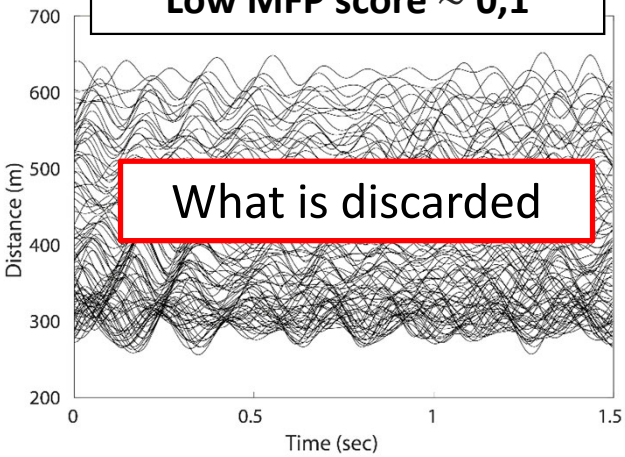

A CONCEPTUAL ADVANCE!

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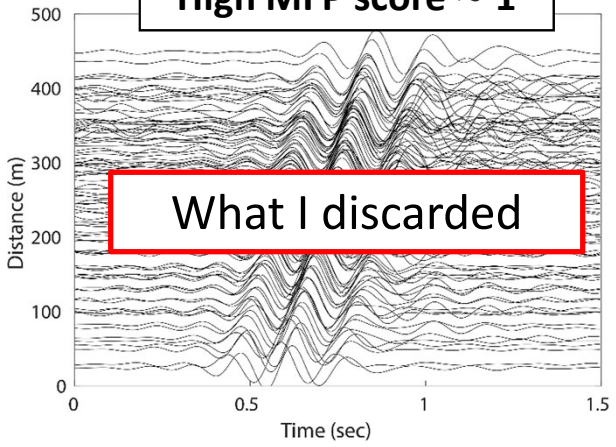
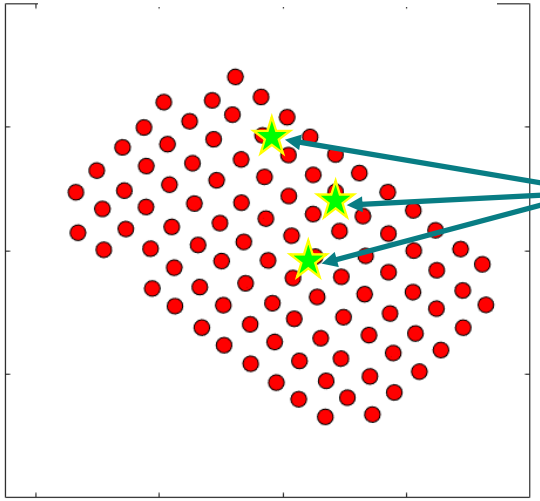
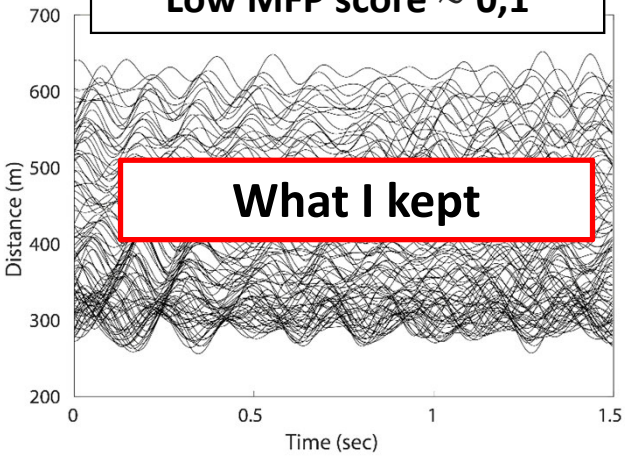


Multiple locations

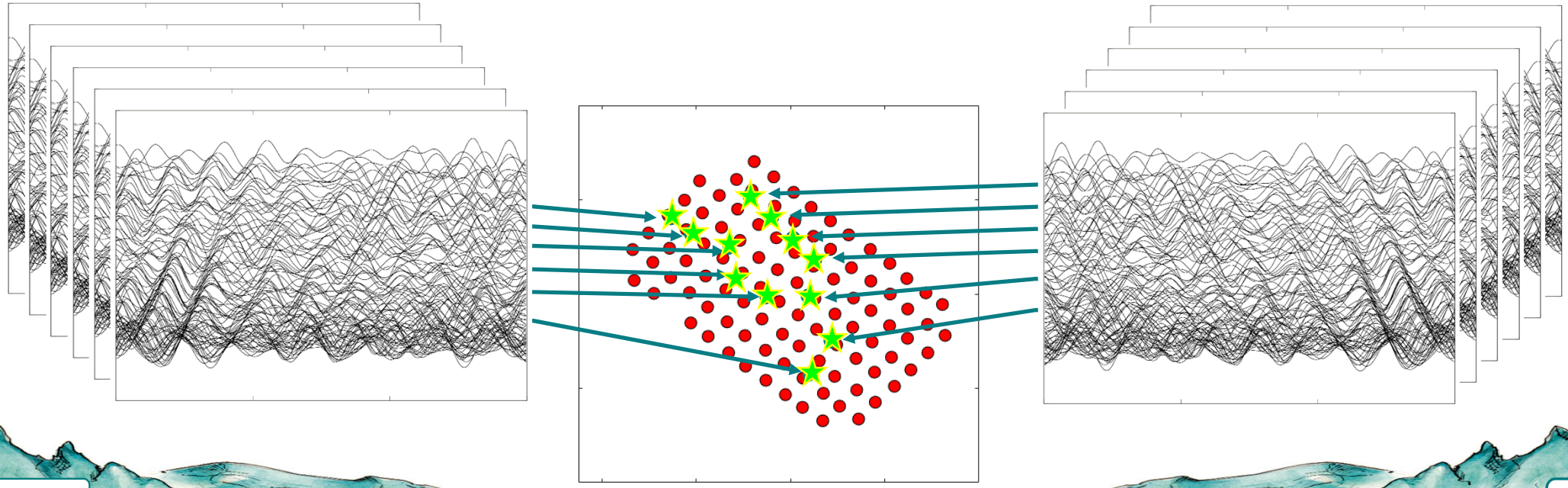


Noisy signal:
Low MFP score ~ 0,1

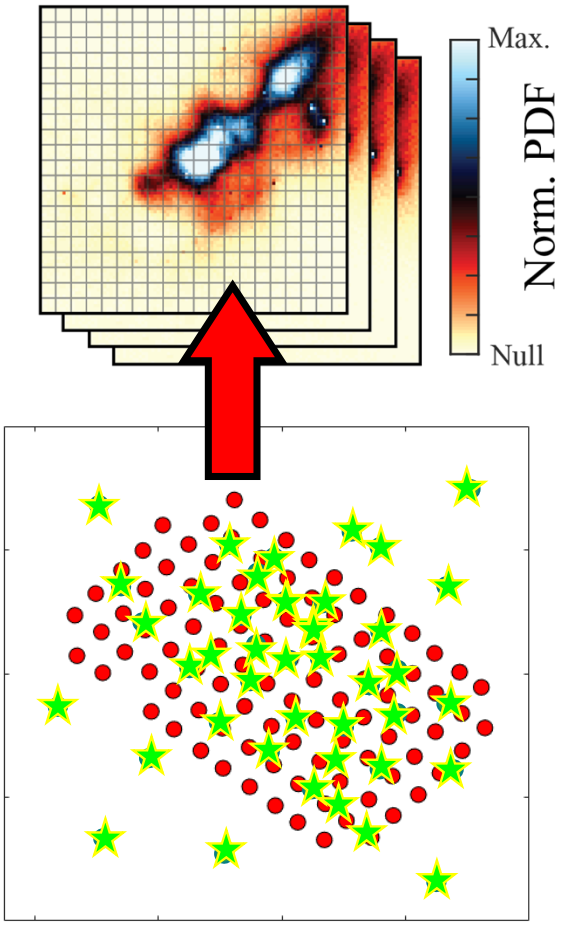


A CONCEPTUAL ADVANCE!

- Subglacial water flow: **low MFP** score (several sources are active simultaneously)
- I stack each 1 second-location over long time periods (~ days)



Making density probability maps

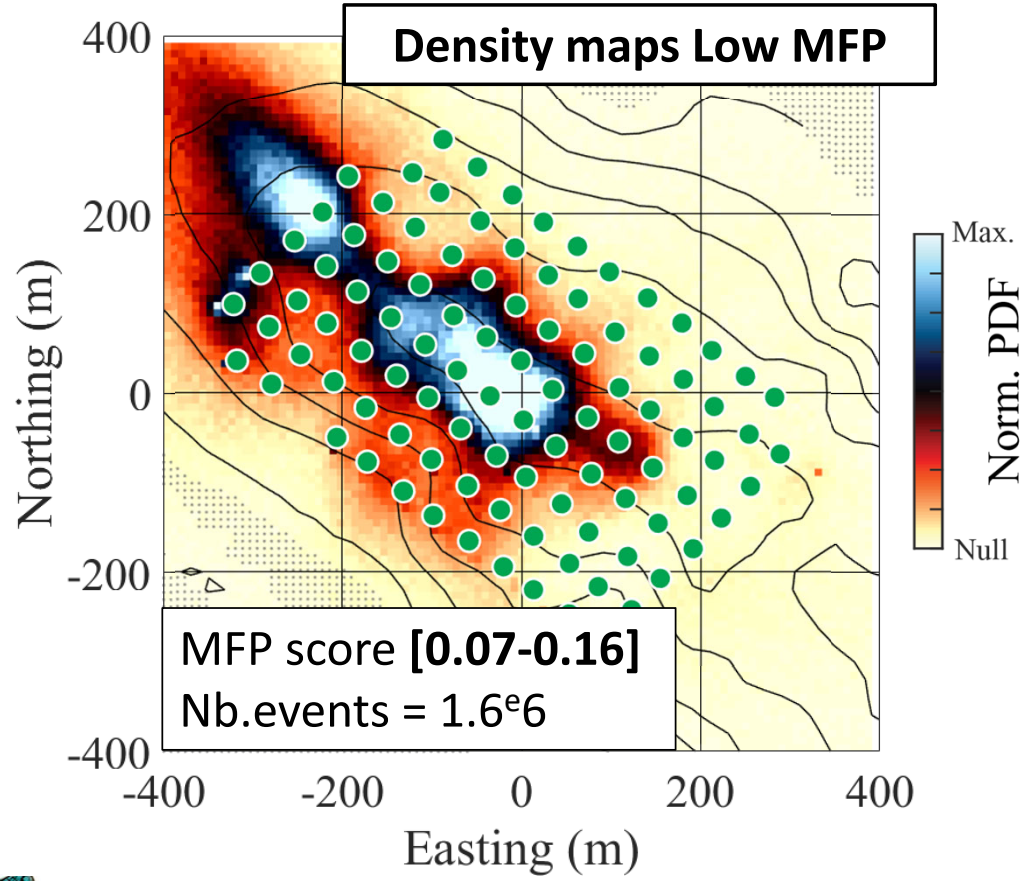


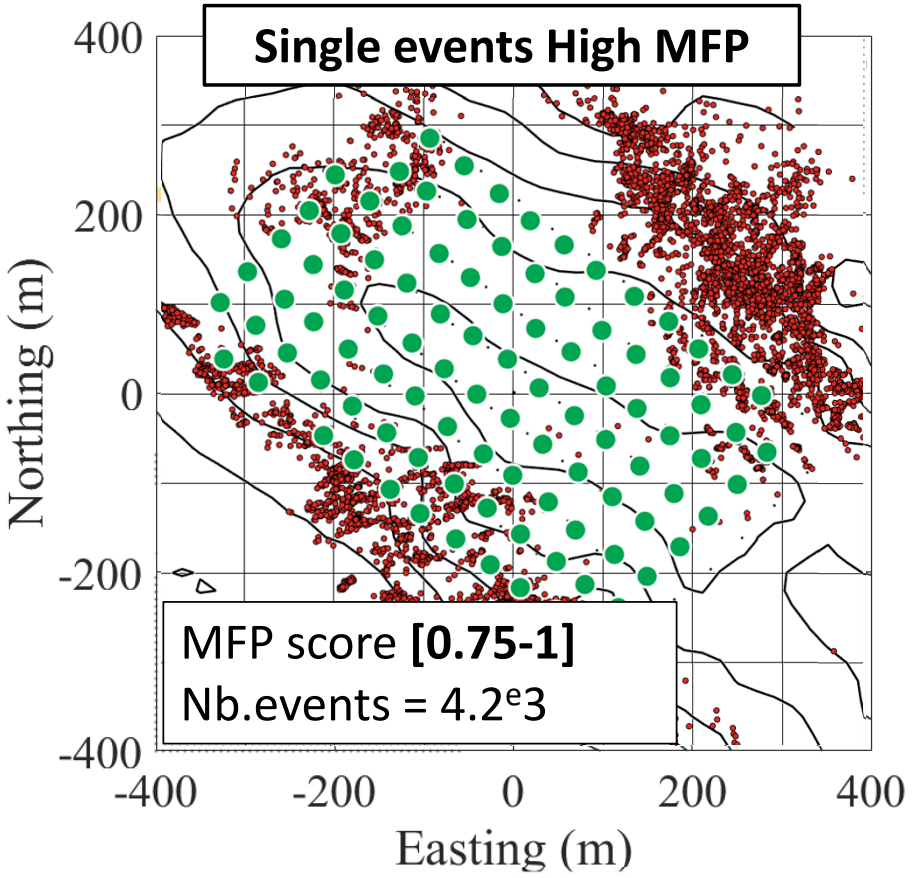
Up to 50+ millions potential locations per day

I selected realistic values:

- Phase velocity
  [1500-3600 m.sec^{-1}]
- Source positions
  ± 400m from array center in (x,y,z)

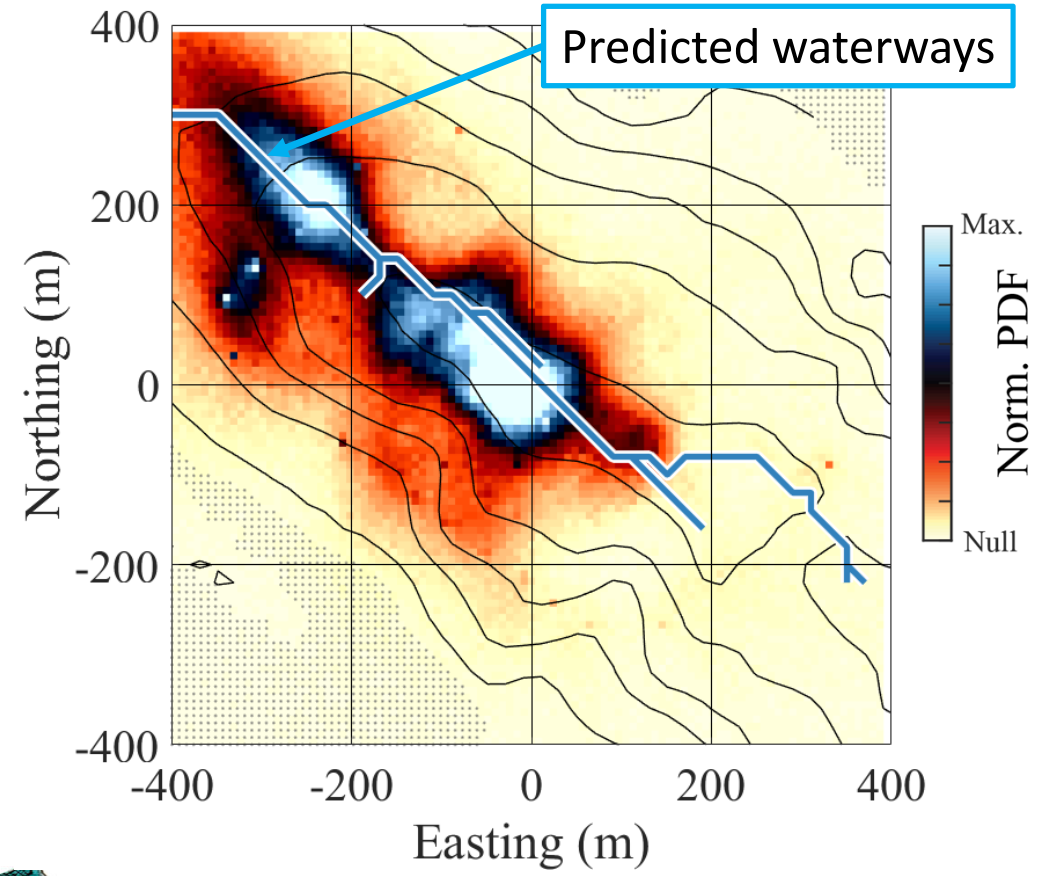
Patterns of noise and punctual sources

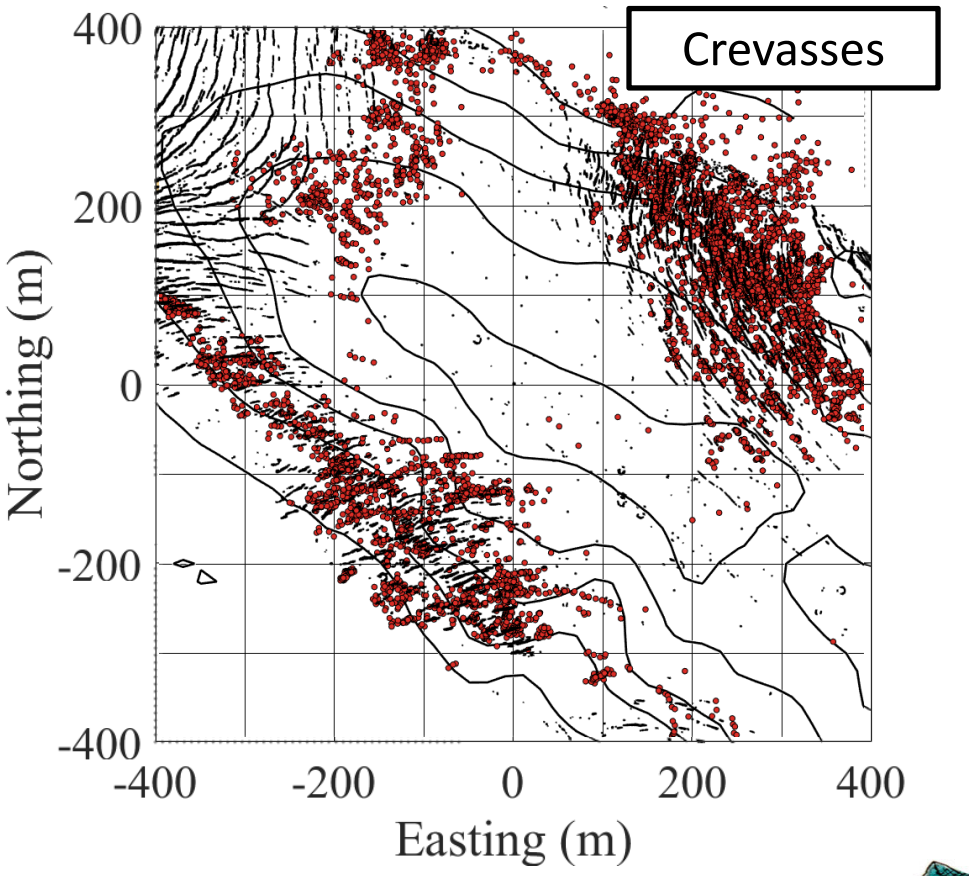




(Nanni et al., subm.)

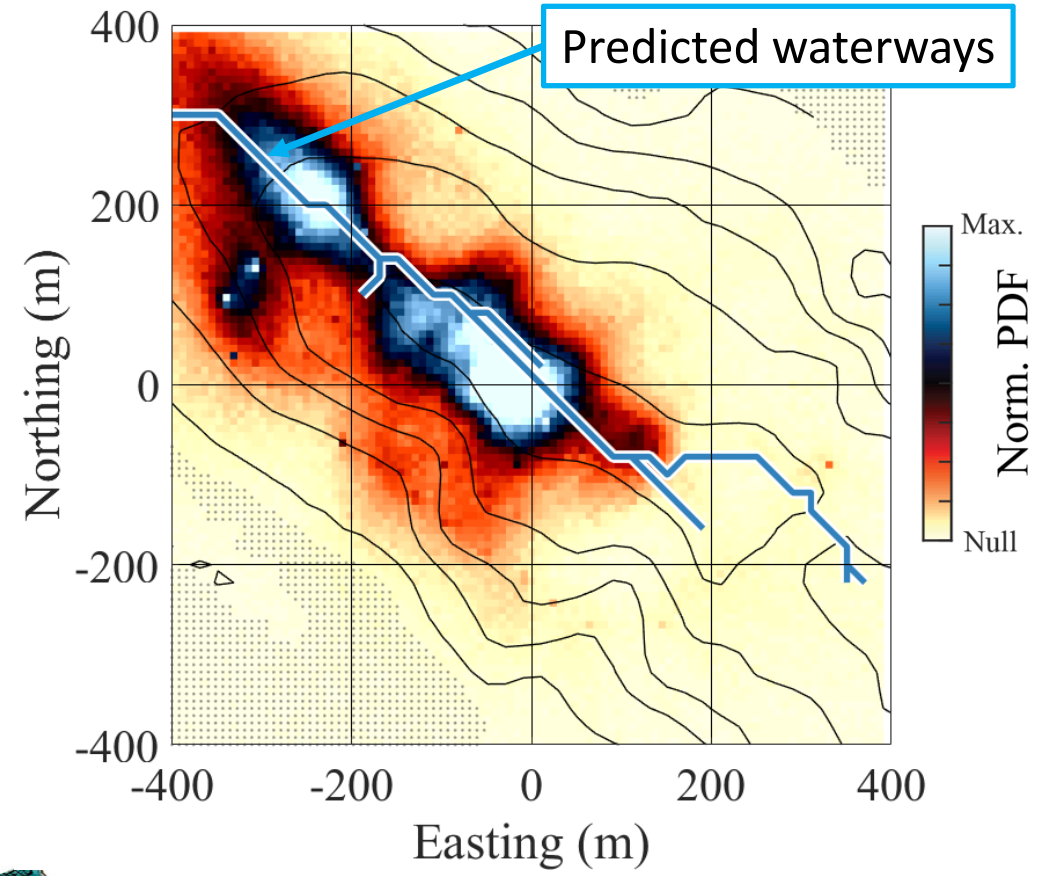
Patterns of noise and punctual sources





(Nanni et al., subm.)

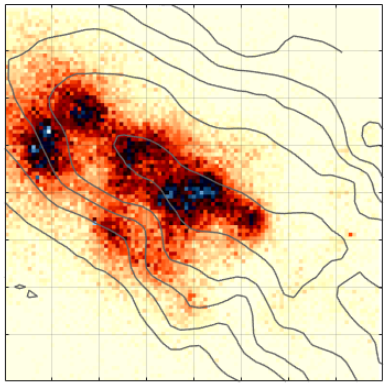
#3 I AM CAPABLE OF LOCATING SUBGLACIAL WATER FLOW

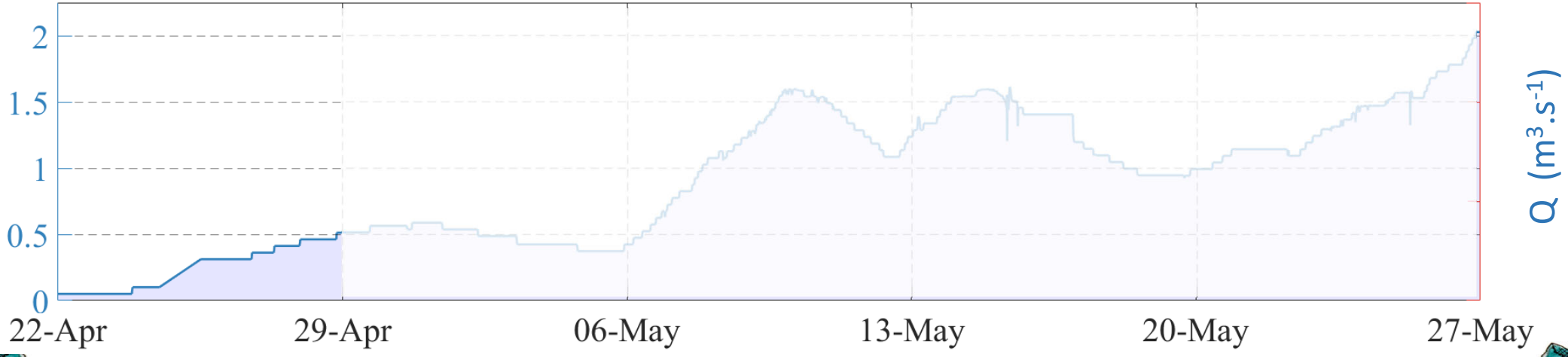


- Along-flow geometry
- ~ 50m width of source location
  - Due to seismic wavelength? (300m at 5Hz)
  - Spread sources?

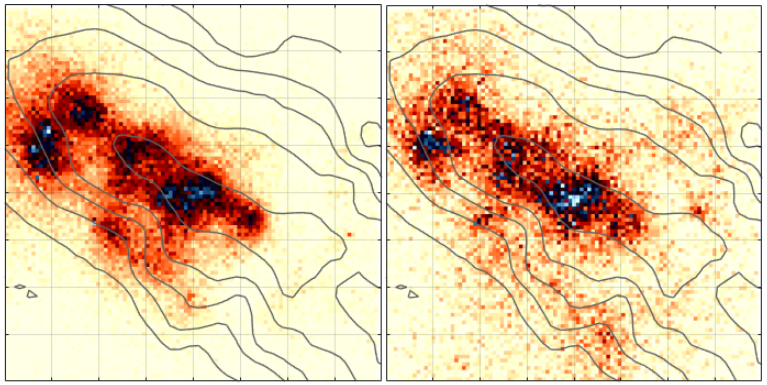
(Nanni et al., subm.)

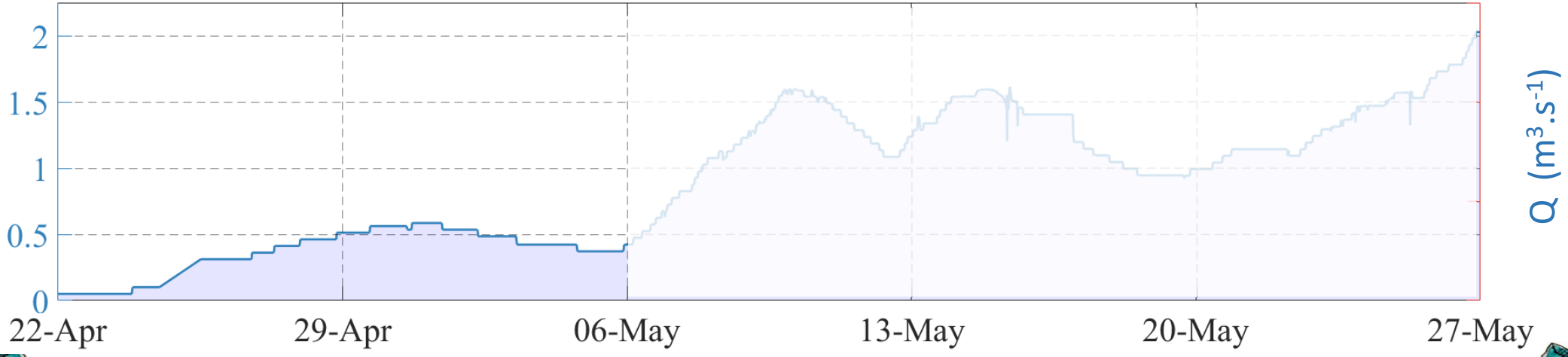
Spatio-temporal dynamics



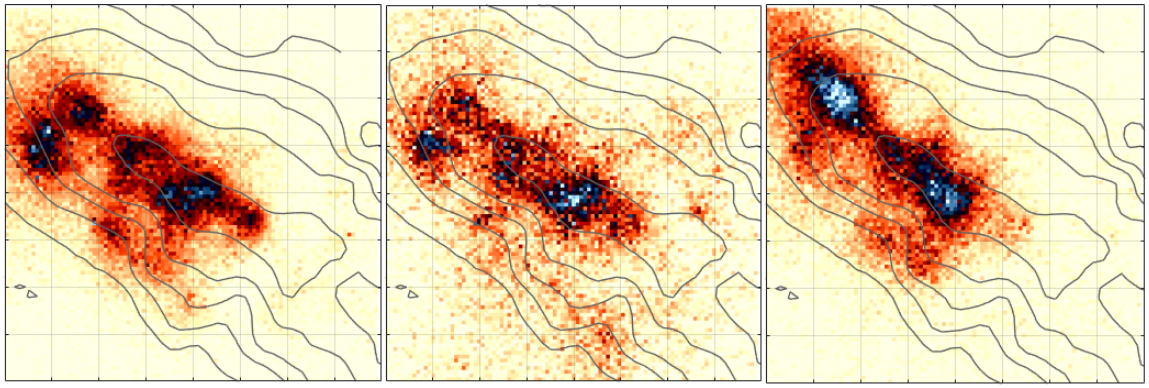


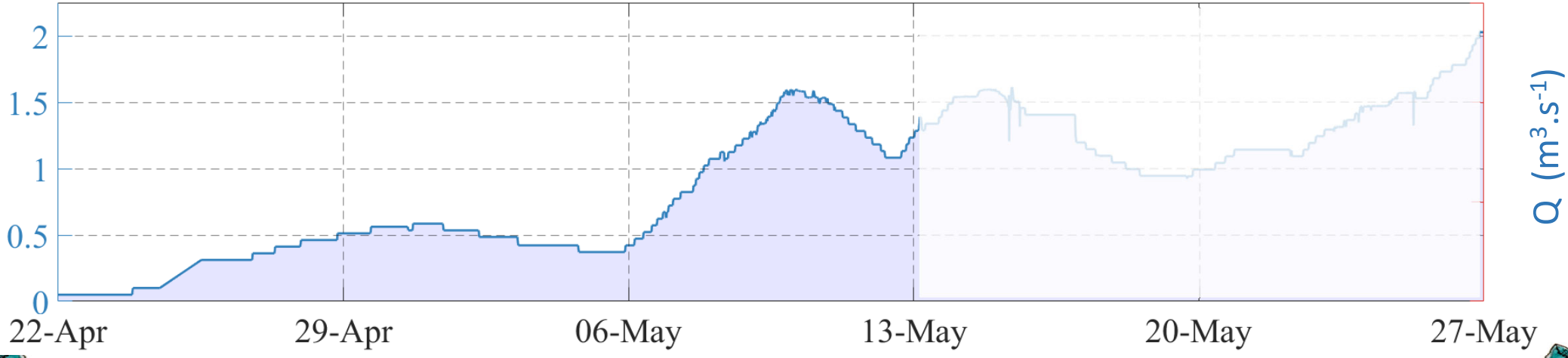
From distributed …



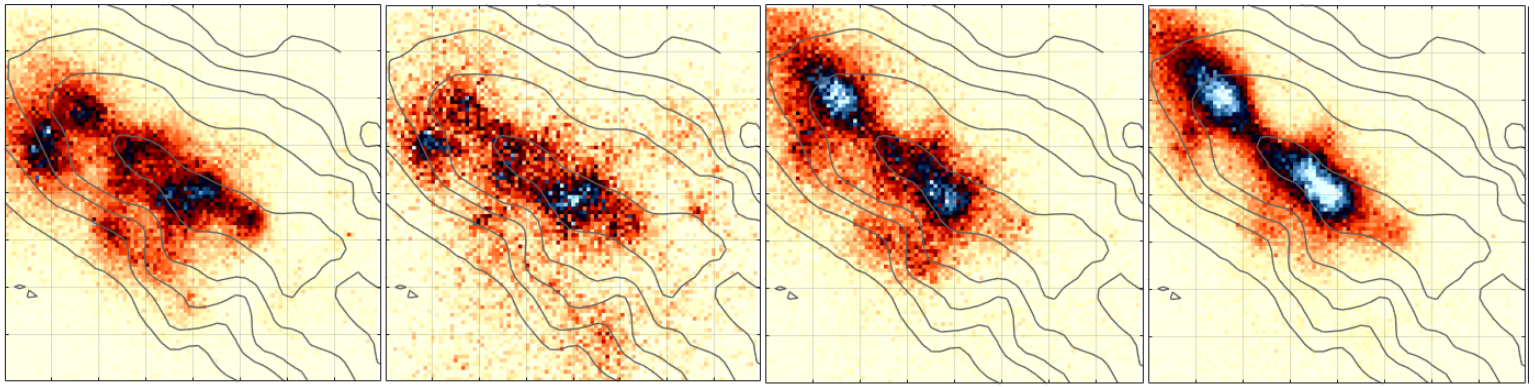


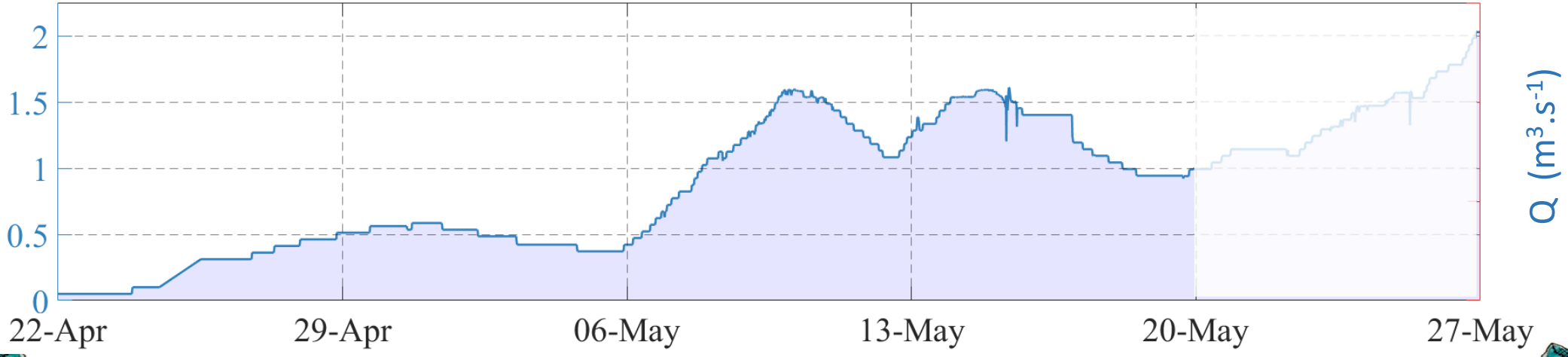
From distributed …



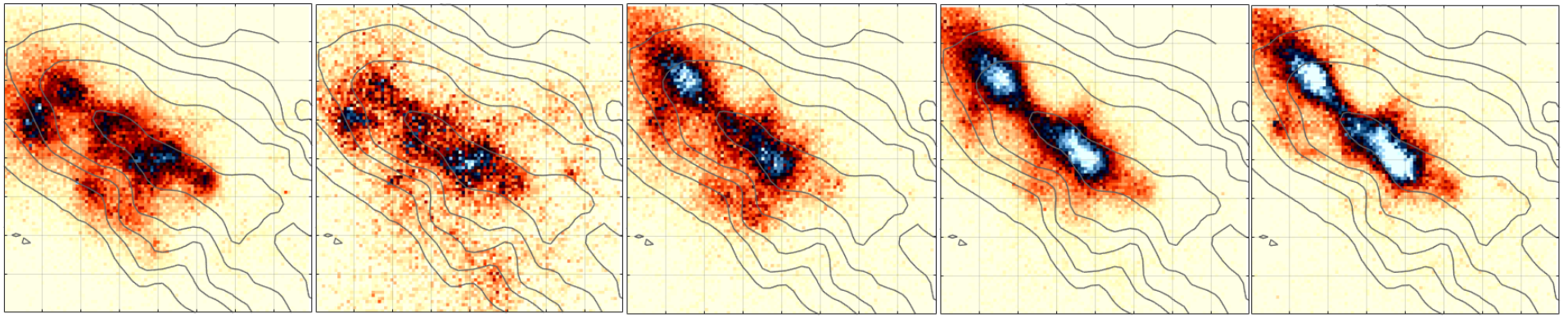


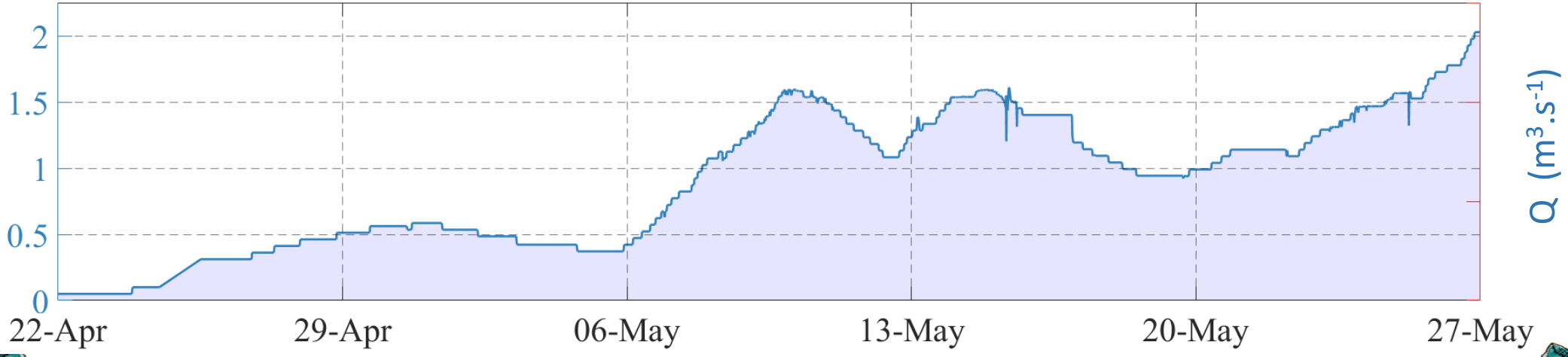
From distributed … to localized



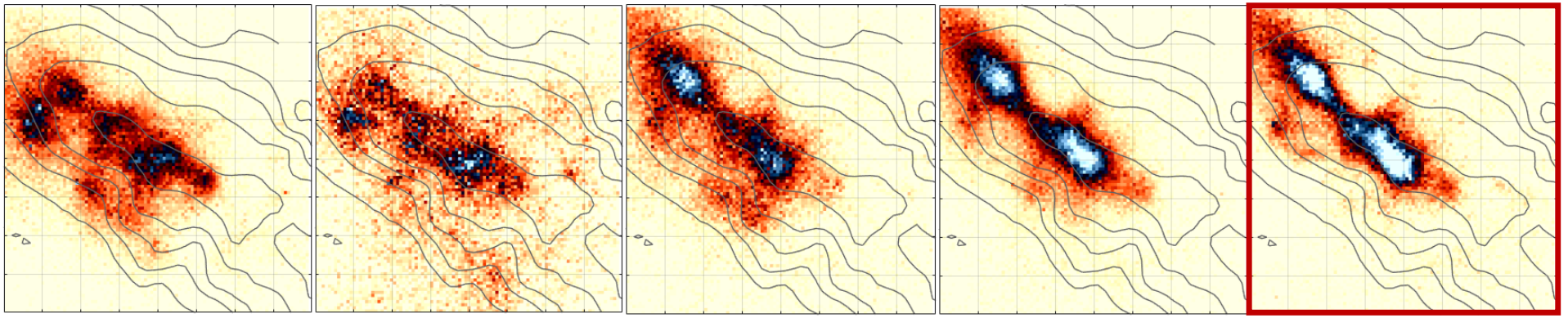


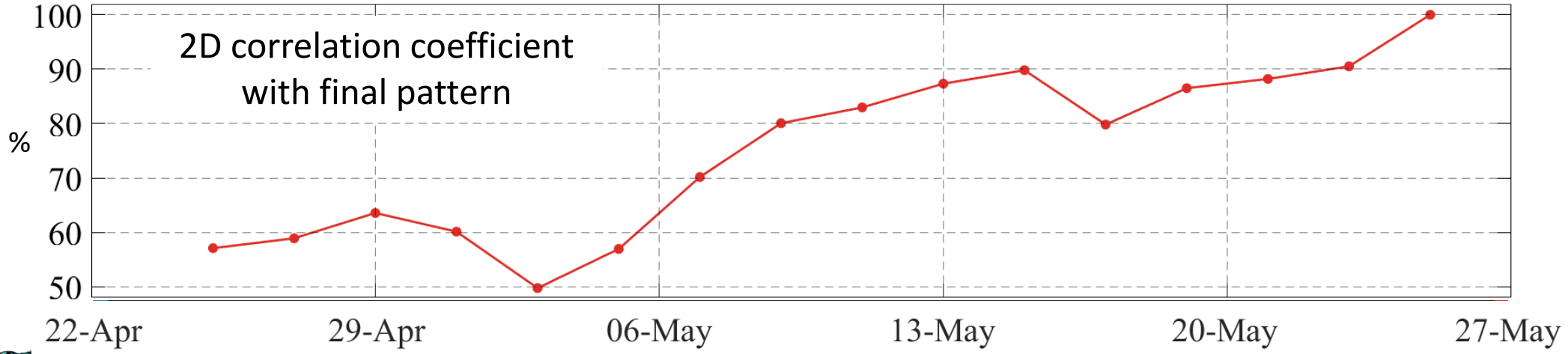
From distributed … to localized



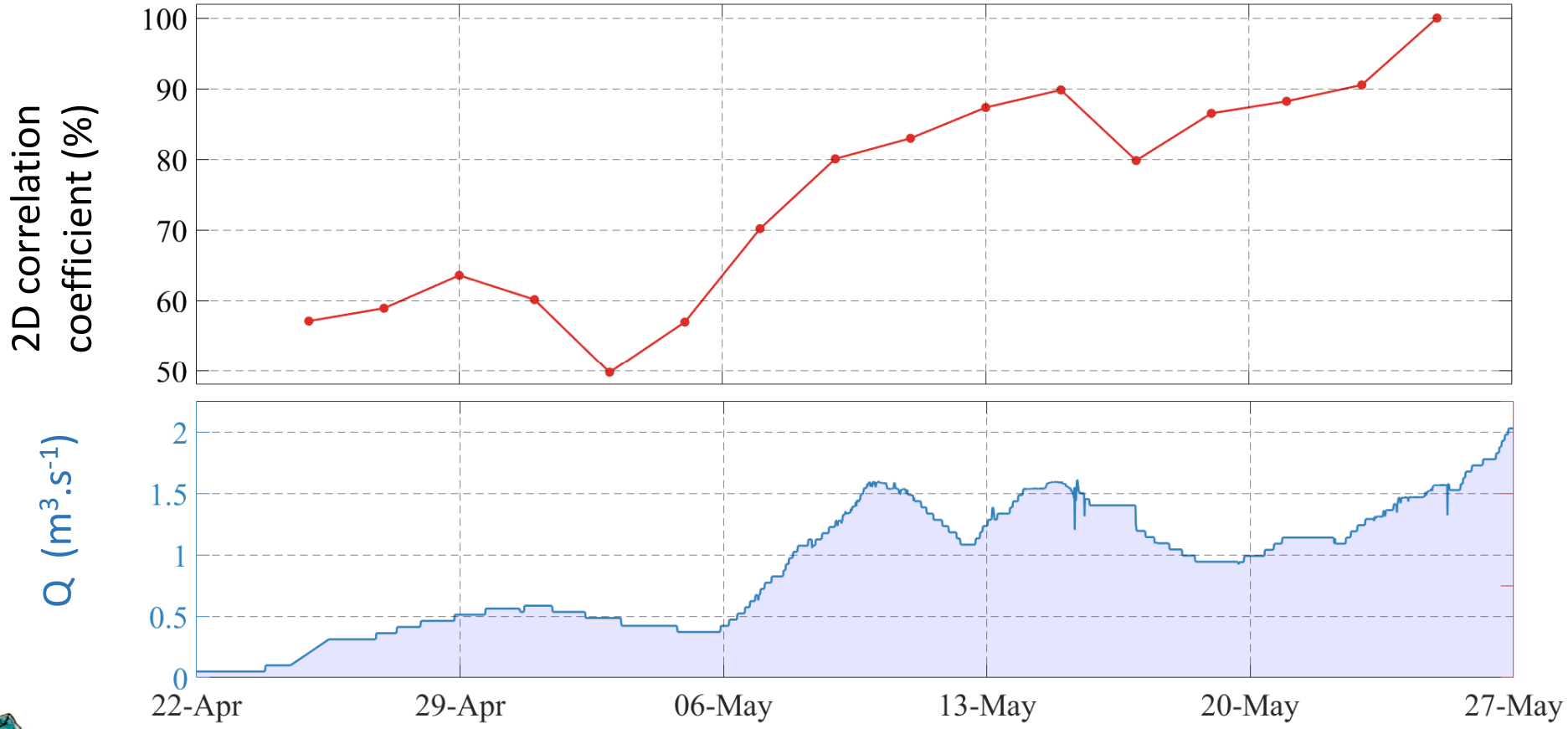


#4 I AM CAPABLE OF CAPTURING SUBGLACIAL HYDROLOGY DYNAMICS



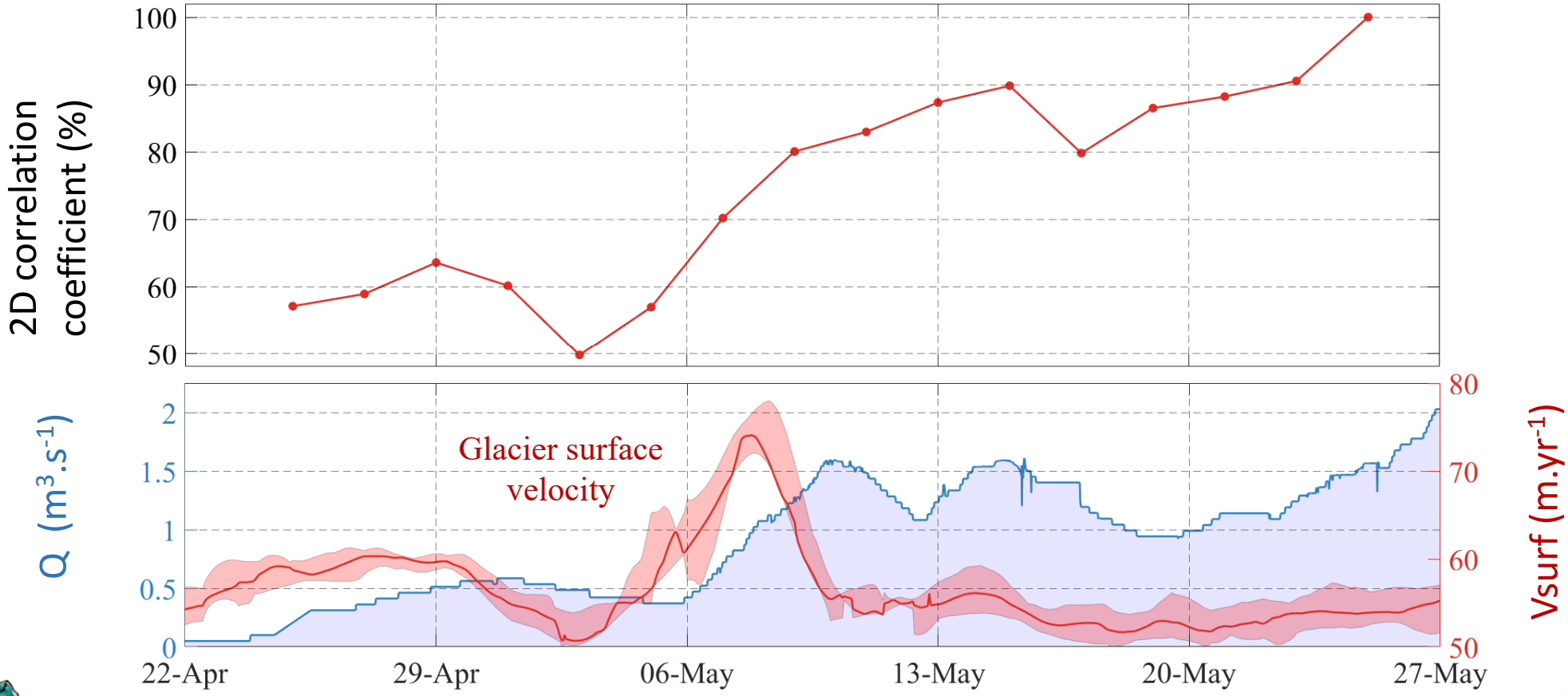


Spatial dynamics and hydraulic properties



(Nanni et al., subm.)

Spatial dynamics and hydraulic properties



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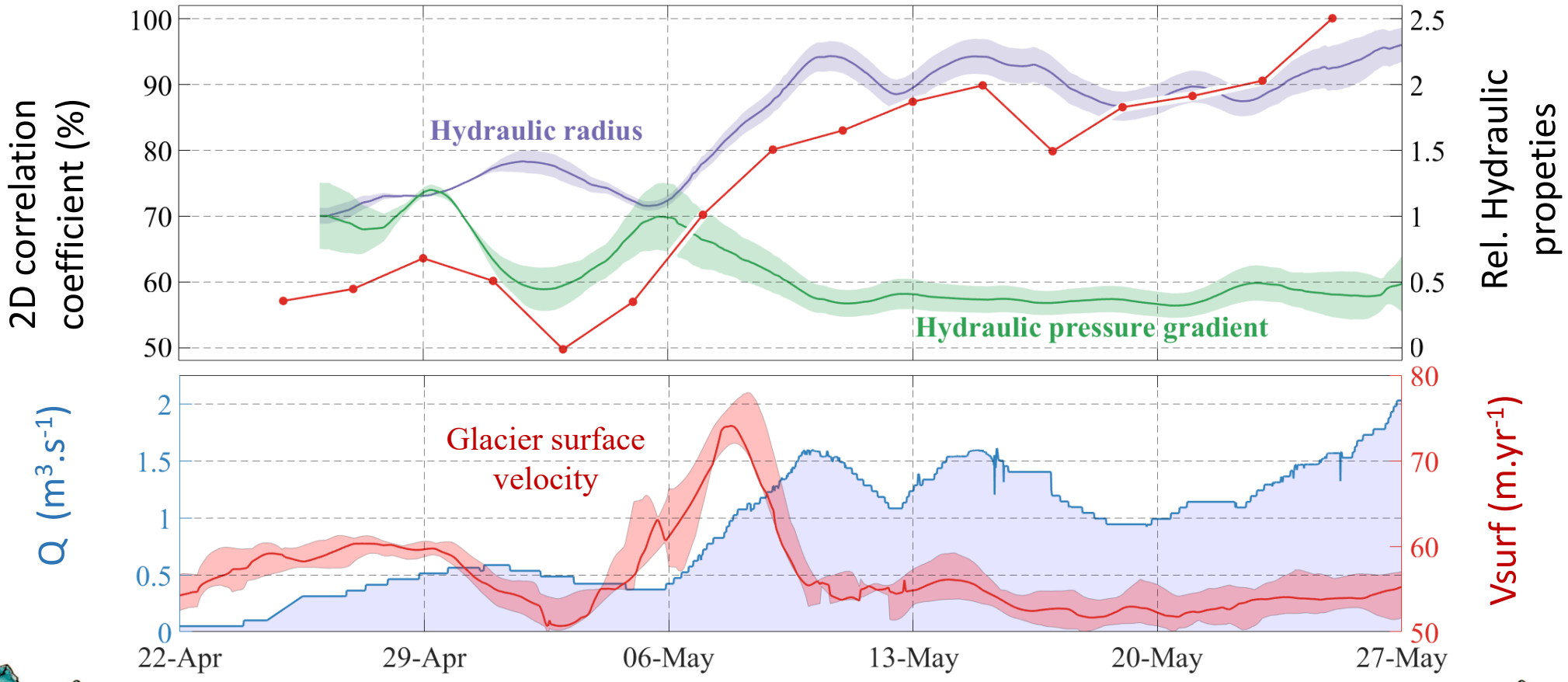
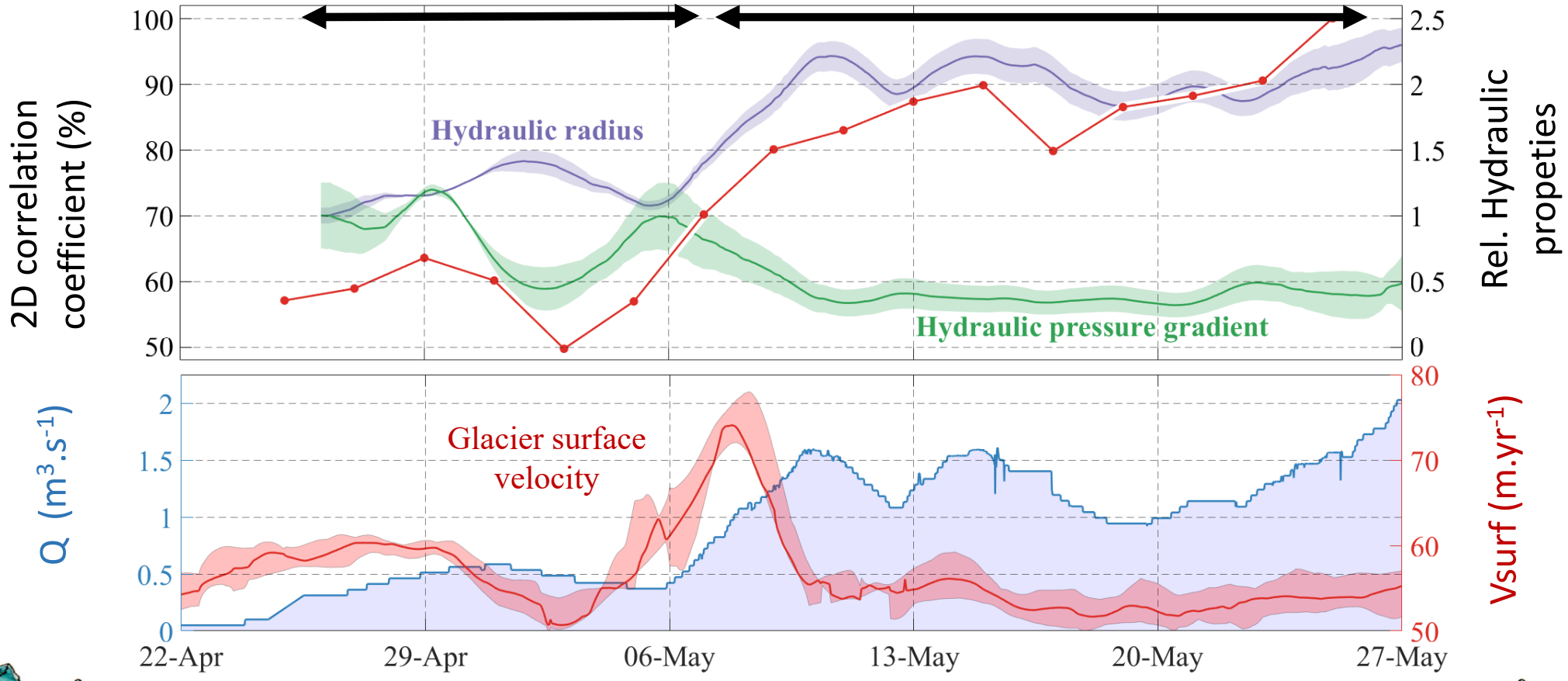
Spatial dynamics and hydraulic properties



(Nanni et al., subm.)

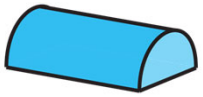
From inefficient to efficient?



(Nanni et al., subm.)

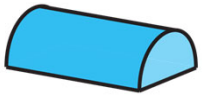
My questions on the methodology

#1 Can we MEASURE subglacial-water-flow-induced seismicity over complete melt-seasons?



#2 What is the TEMPORAL dynamics of subglacial hydraulic properties over complete melt-seasons?

#3 Can we LOCATE distributed sources of seismic noise?



#4 What is the SPATIAL dynamics of cavities and channels?

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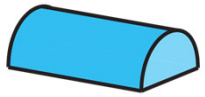

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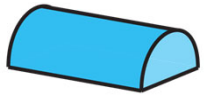
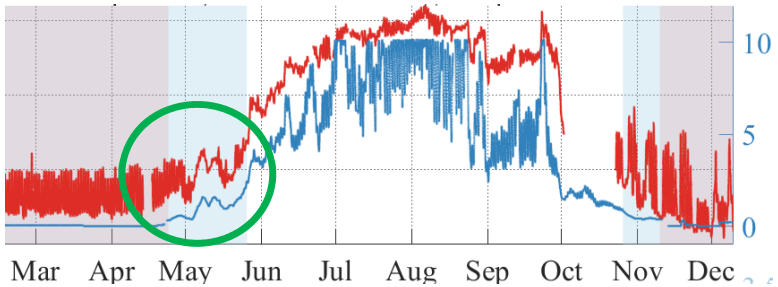


#4 What is the **SPATIAL** dynamics of cavities and channels?

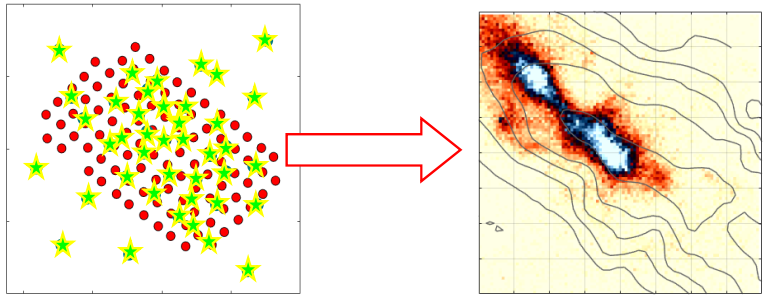
My conclusions on methodological aspects

I USED SEISMOLOGY TO STUDY COMPLETE MELT-SEASON

I WAS CAPABLE OF SPATIALLY LOCATING SUBGLACIAL WATER FLOW



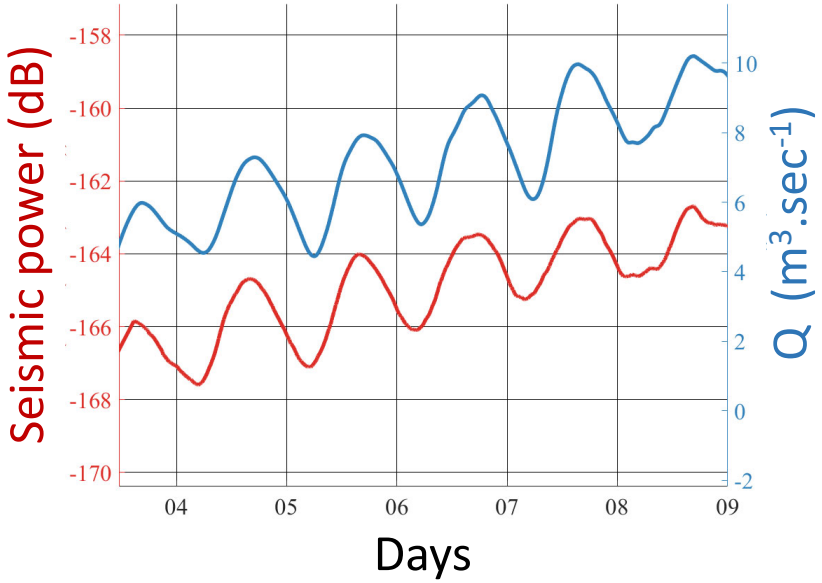
Published in The Cryosphere



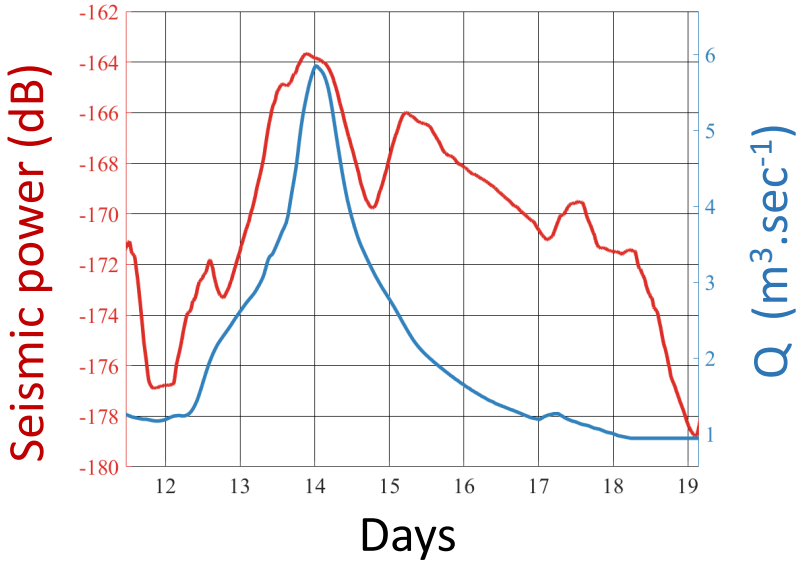
Submitted to PNAS + published in SRL

Perspectives: different timescales

Daily variations



Storm event



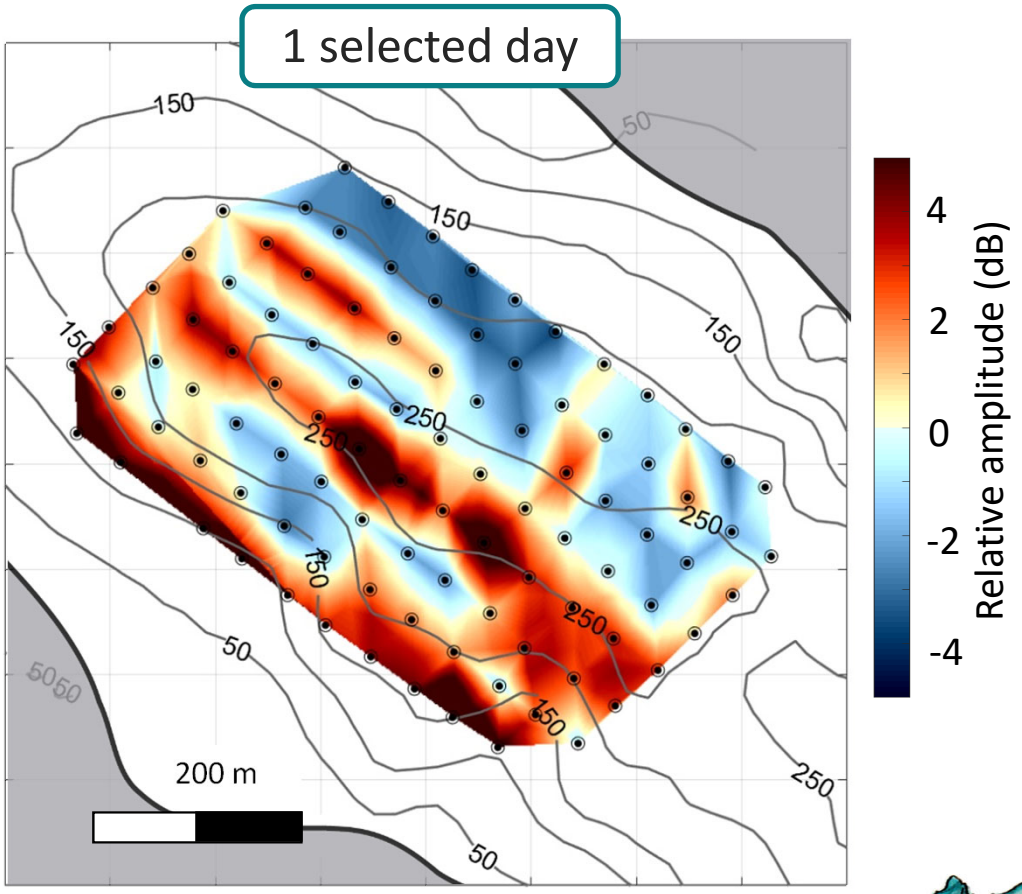
Investigate kinetic effect and transient states

Perspectives: spatial variations of amplitudes

$$u(t) = Ae^{i\omega t}$$

Amplitude Phase

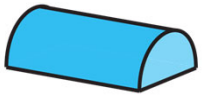
- Might allow to spatialized hydraulic properties
- Complex effect of attenuation/amplification



(Nanni et al., in prep.)

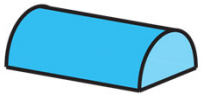
My questions on the studied processes

#1 Can we MEASURE subglacial-water-flow-induced seismicity over complete melt-seasons?



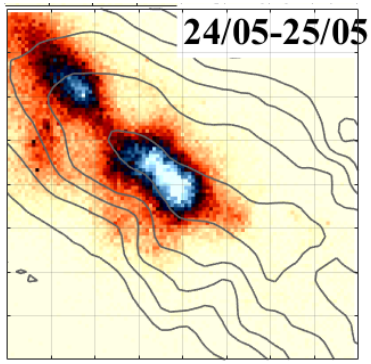
#2 **What is the TEMPORAL dynamics of subglacial hydraulic properties over complete melt-seasons?**

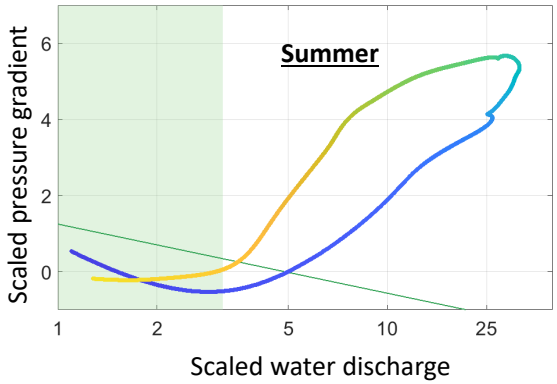
#3 Can we LOCATE distributed sources of seismic noise?



#4 **What is the SPATIAL dynamics of cavities and channels?**

My conclusions on the studied processes

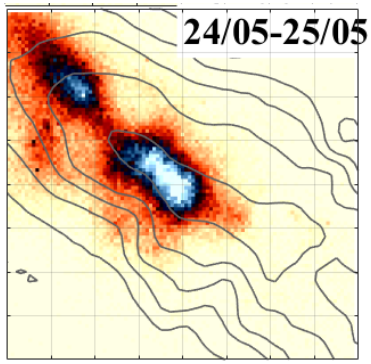




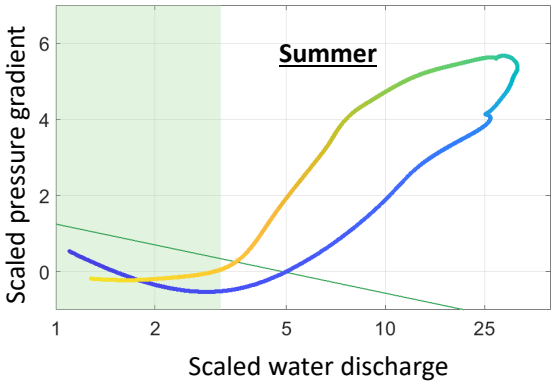
Localized water flow

High pressure gradient in summer!

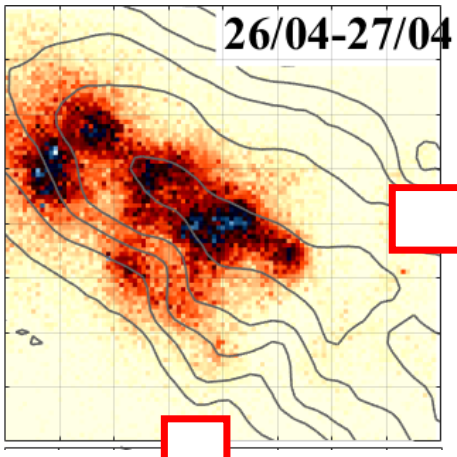
My conclusions on the studied processes

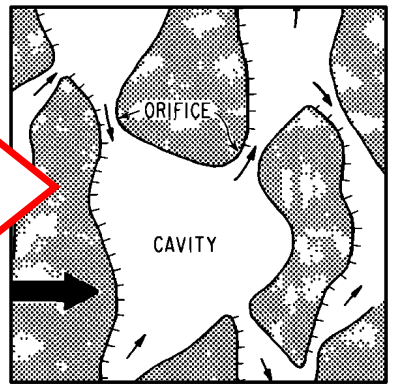


Localized water flow



High pressure gradient in summer!



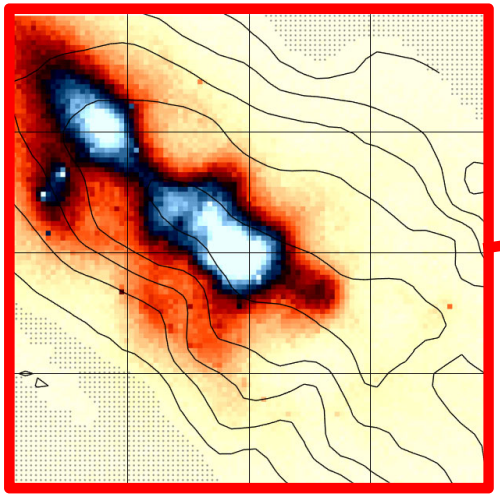


Linked cavity
(Kamb, 1987)

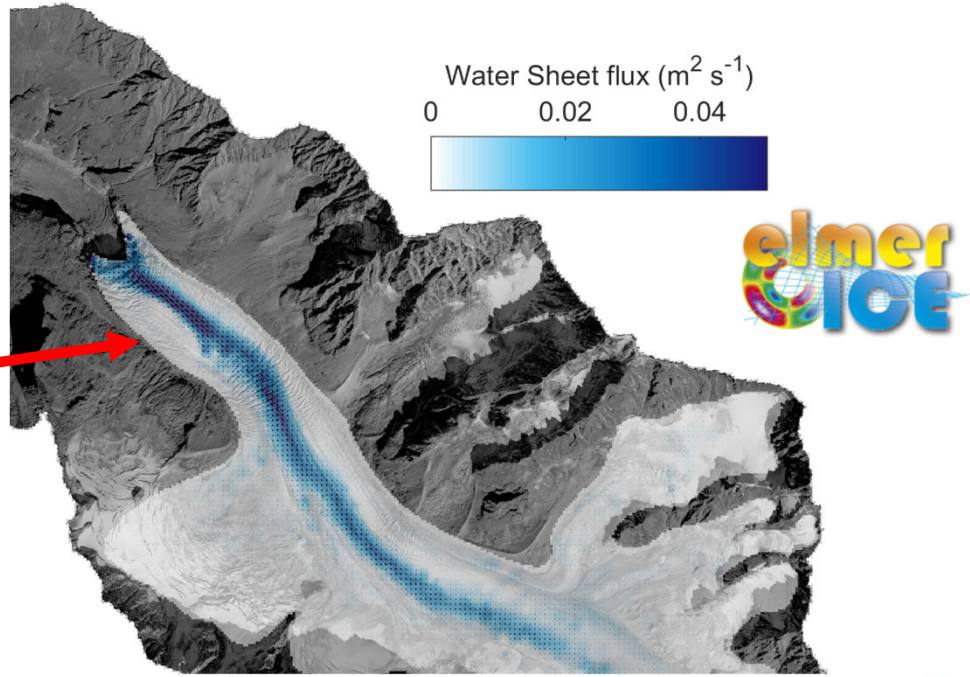
I can observe **distributed** water flow in the cavities with seismology

Implication for subglacial hydrology dynamics

- Do we observe cavities only?
- Do cavities domiantes the drainage system?



Modelling subglacial hydrology with Elmer/Ice-GlaDS coupling by A. Gilbert



Perspectives: we need to study other settings

Current (or soon) dense seismic experiments

Subglacial lakes in Greenland
(S. Livingstone, A. Booth and others - **UK**)

My post-doc?

Soft-bedded glaciers and surges in Spitzberg
(T. Schuler, A. Kholer, and others - **Norway**) *My post-doc?*

My PhD

Subglacial hydrology and stick-slips in Canada
(N. Stevens, L. Zoet and others - **USA**)

Grounding line dynamics and subglacial hydrology in Antarctica – 1,000 sensors
(The International Thwaites Glacier collaboration)

Perspectives: continue sharing beyond academia

An artistic collaboration with EdZ

Making comics with 12 other PhD students

Presenting my works during the « Week of science»

A collaboration during the Grenoble Scientific Game Jam


THANK YOU ALL
AND COLLEAGUES, LAB MEMBERS, FAMILY ...