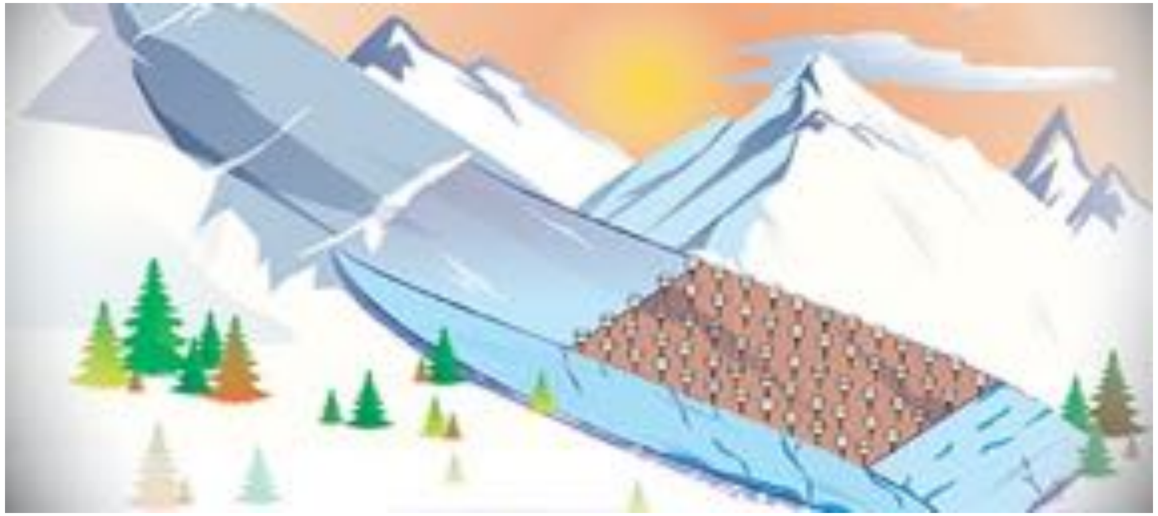
Monitoring glacier dynamics and structure using dense seismic arrays

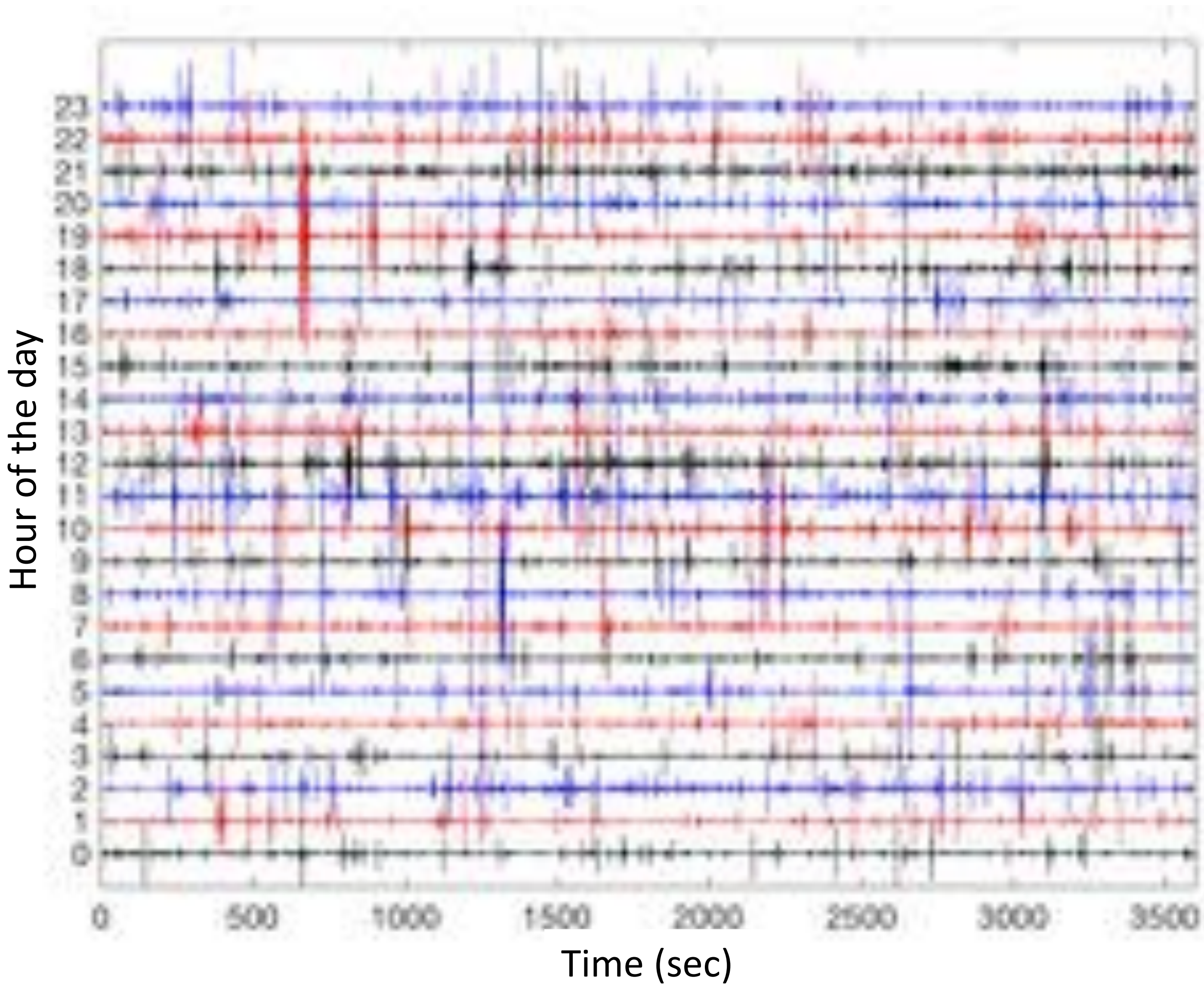


Florent Gimbert

PhDs, Postdocs: Ugo Nanni, Celeste Labedz (Caltech)

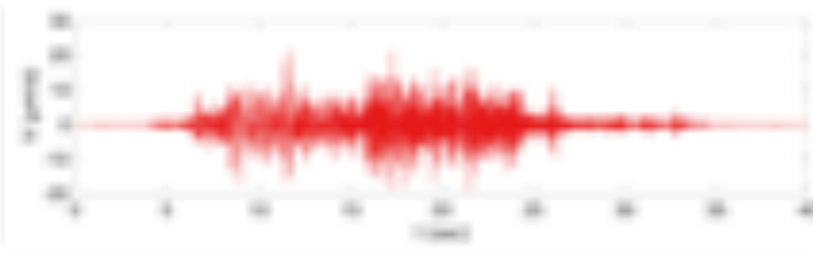
Other collaborators: Philippe Roux (ISTerre, Grenoble), Albanne Lecointre (ISTerre), Victor Tsai (Brown, USA), Timothy Bartholomaus (Univ. Idaho),

1 day on the Argentière Glacier, French Alps

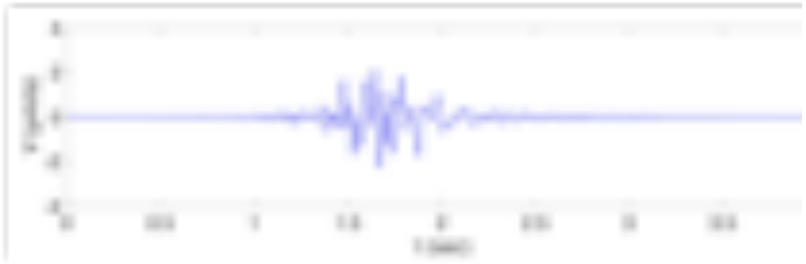


1 day on the Argentière Glacier, French Alps

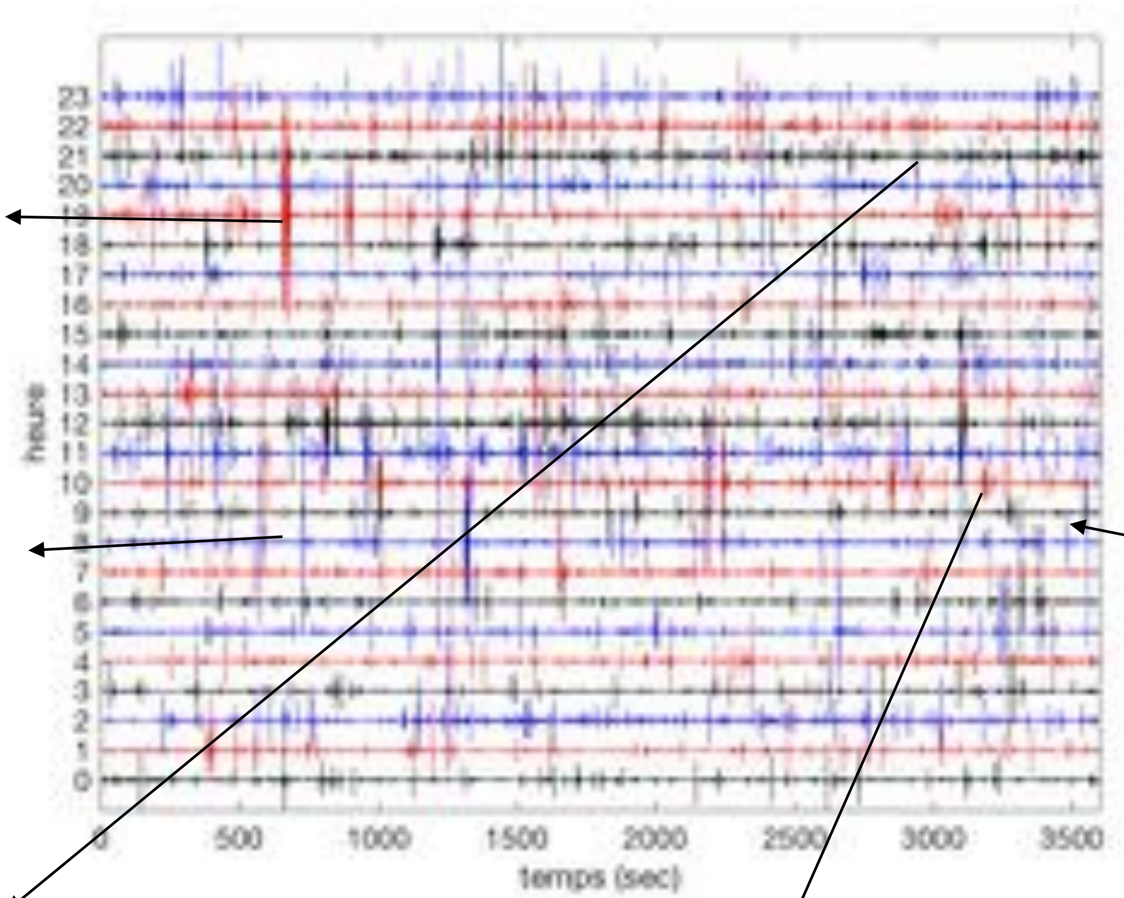
Sérac fall



Crevassing

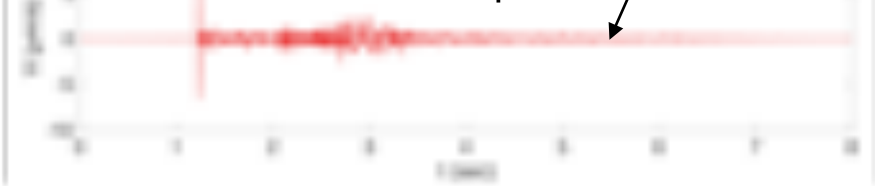


Basal stick-slip



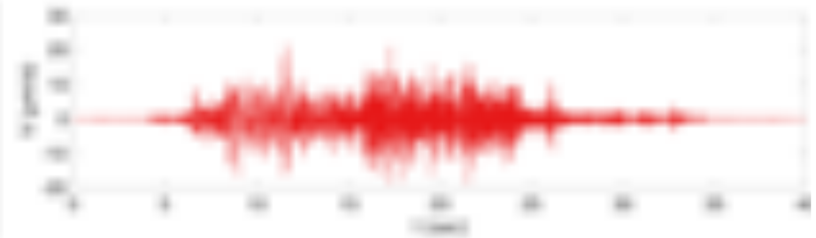
« Tremor »

Distant earthquake

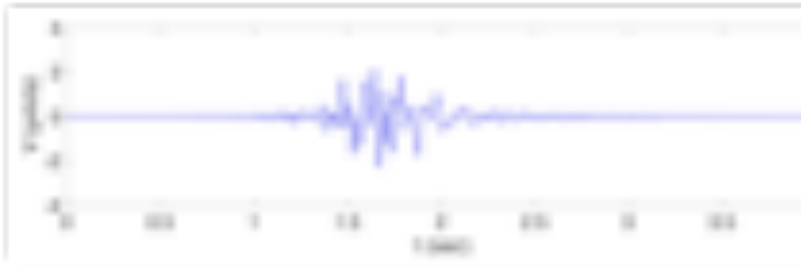


1 day on the Argentière Glacier, French Alps

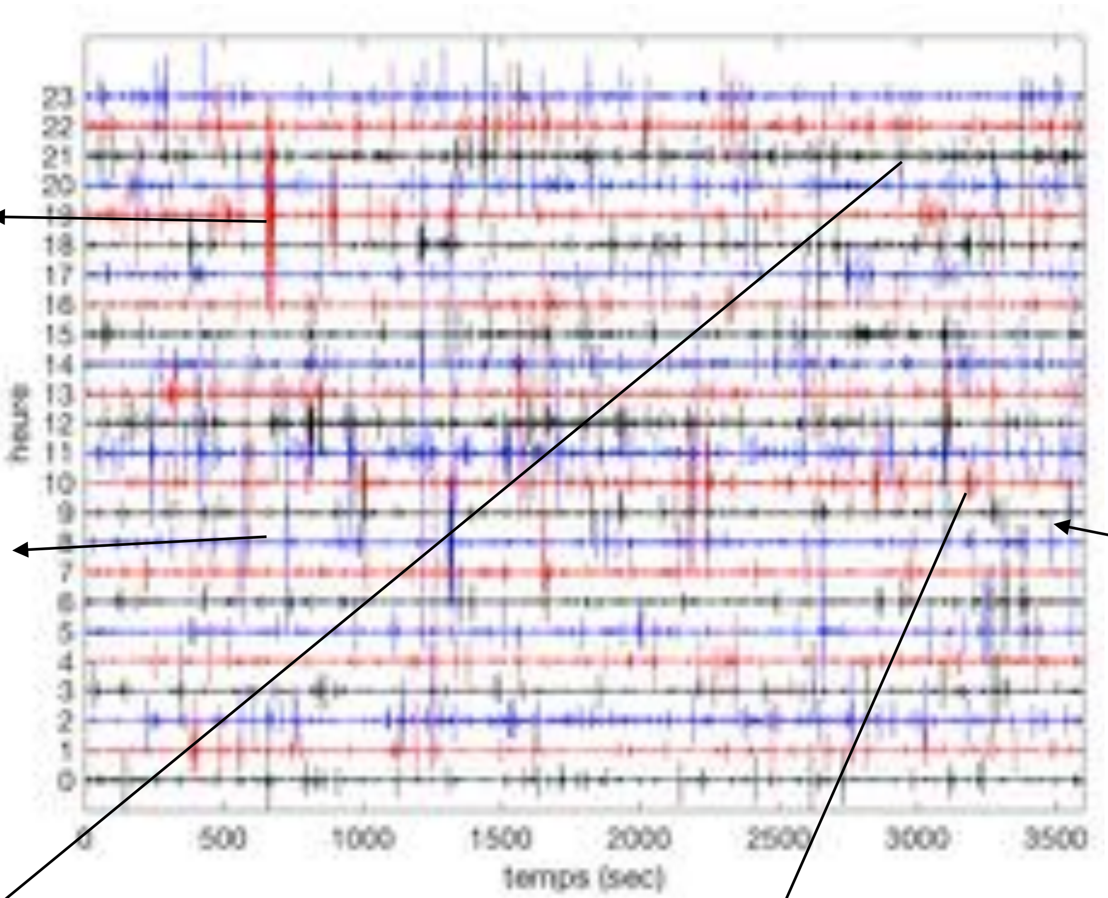
Sérac fall



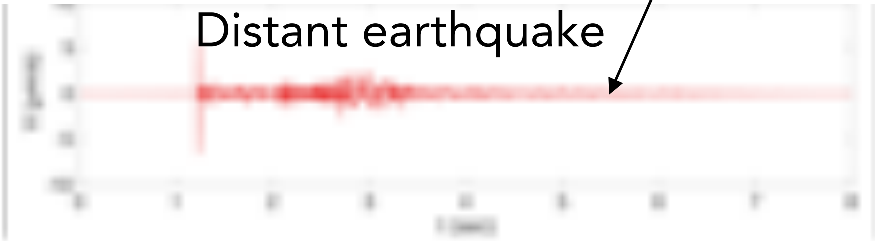
Crevassing



Basal stick-slip

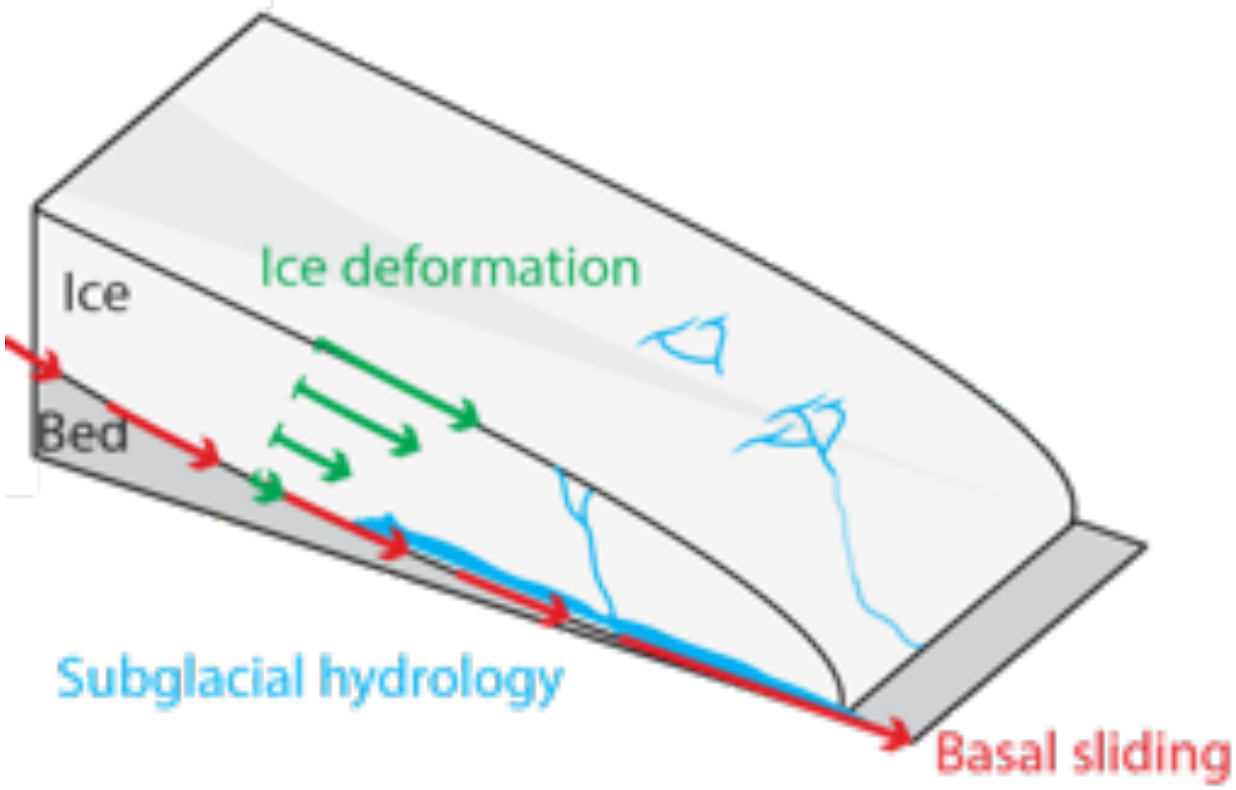


Distant earthquake

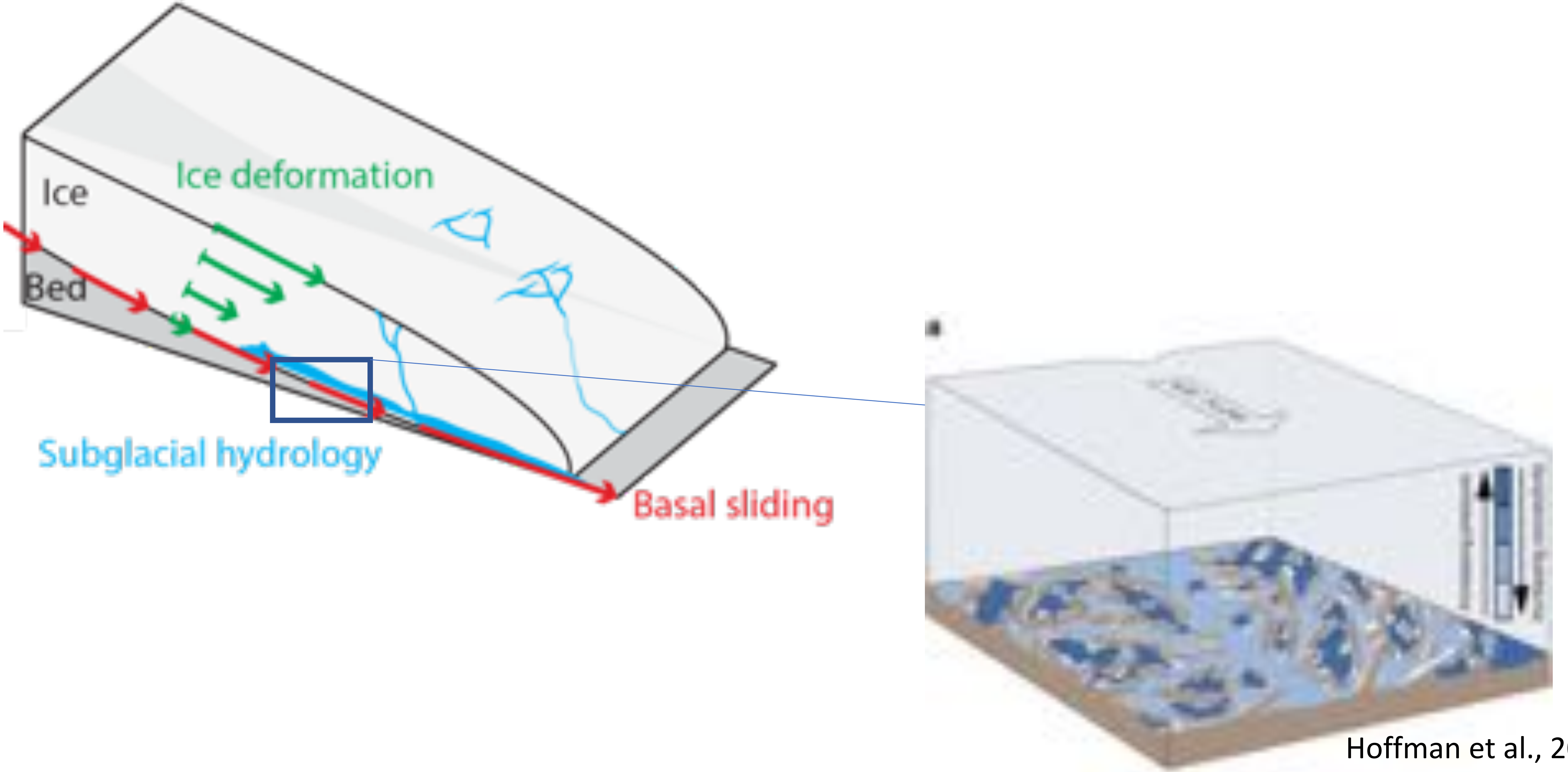


« Tremor »

Subglacial hydrology

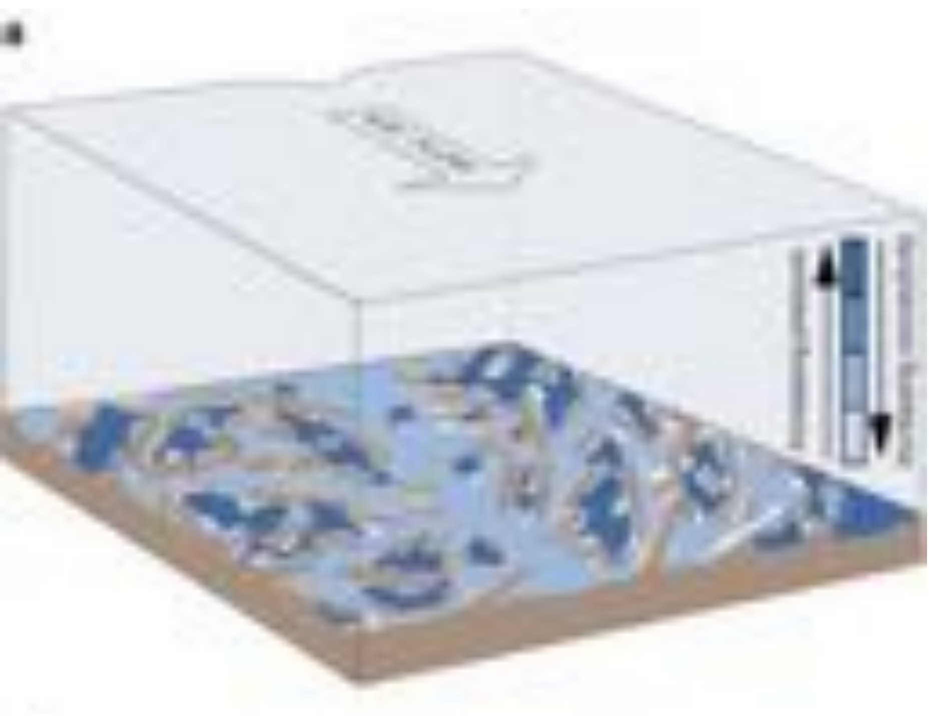


Subglacial hydrology



Hoffman et al., 2016

Subglacial hydrology

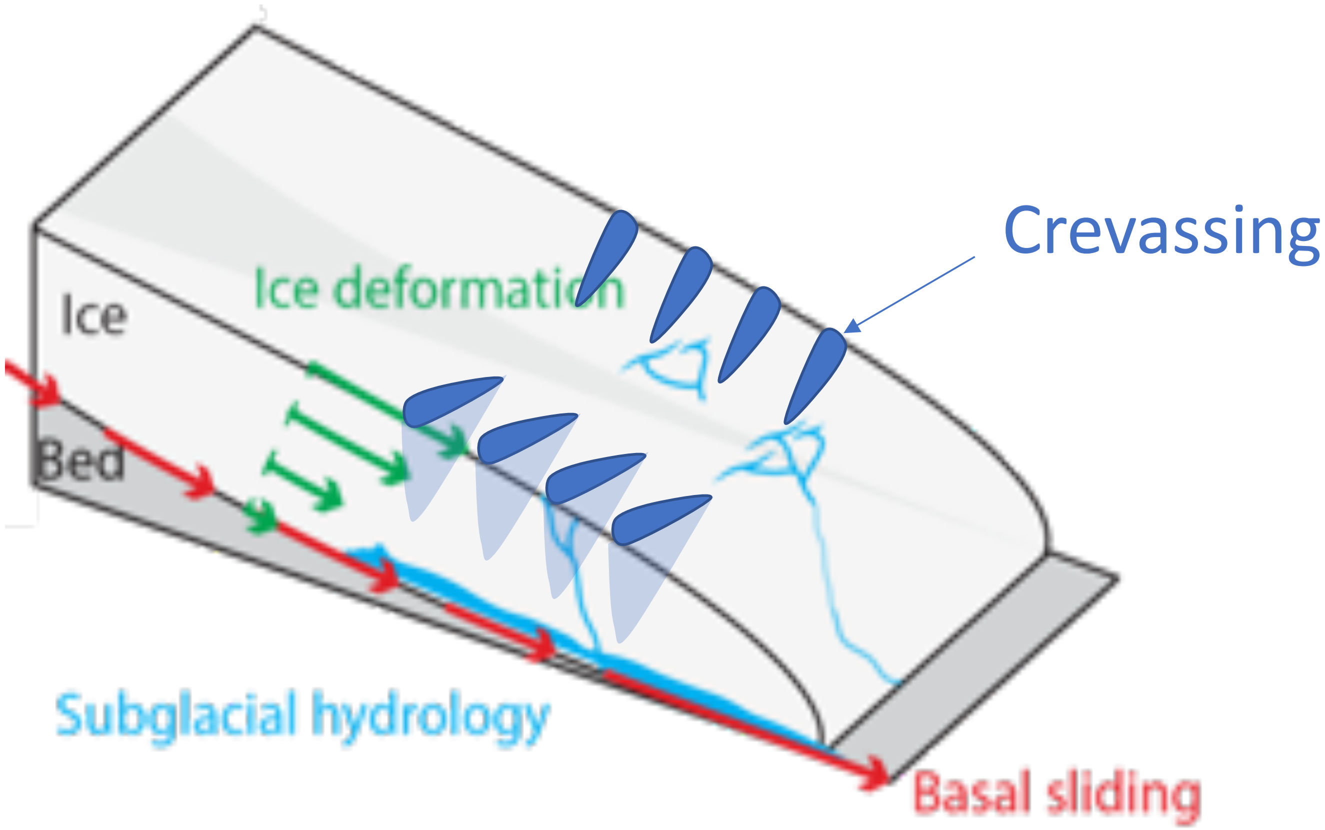


Hoffman et al., 2016

What are the physical characteristics of the subglacial hydrology network (spatial organization, pressure, size)?

How do they evolve with time?

Glacier crevassing



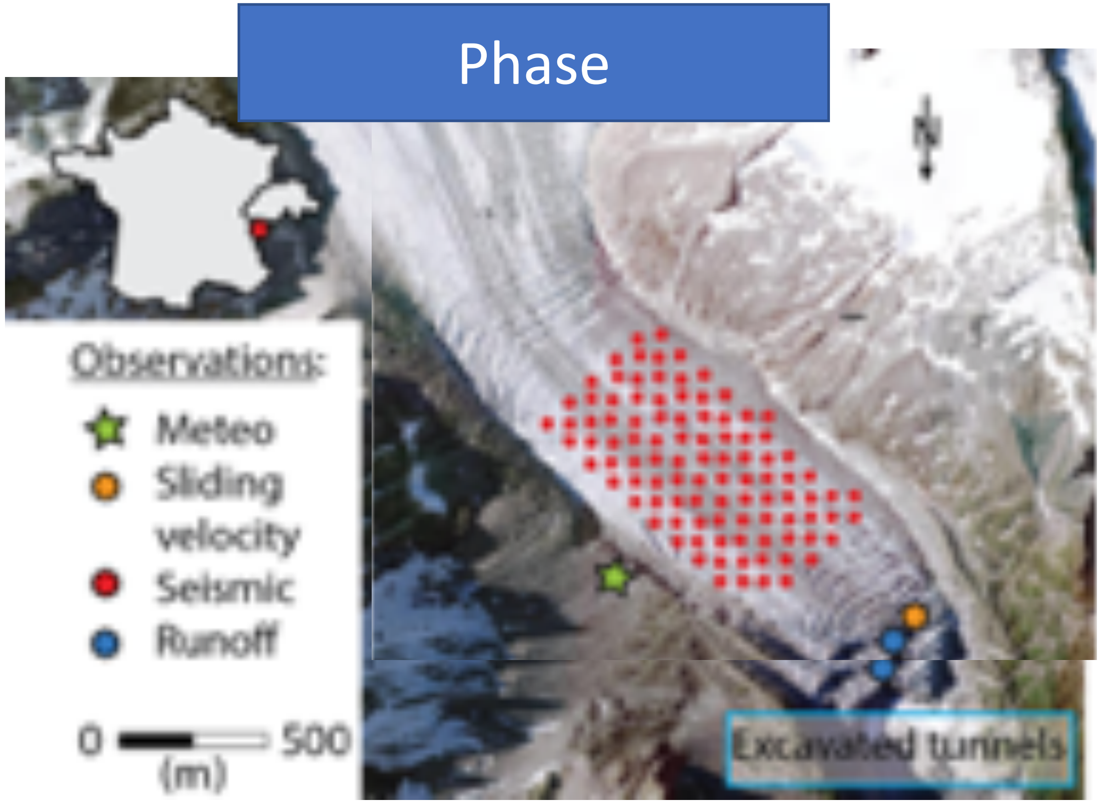
Which physical mechanism controls crevasse propagation?

How deep are crevasses?

Use arrays of sensors for observing spatial and temporal changes

The Argentière Glacier (France)

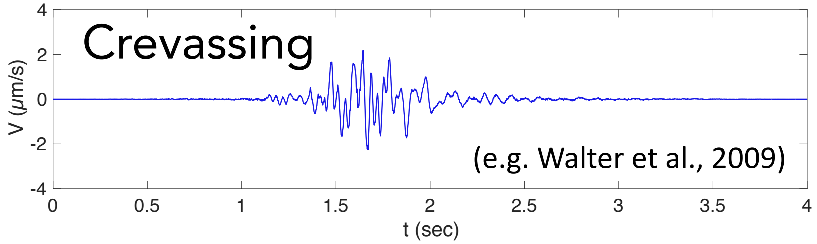
The Lemon Creek Glacier (Alaska)

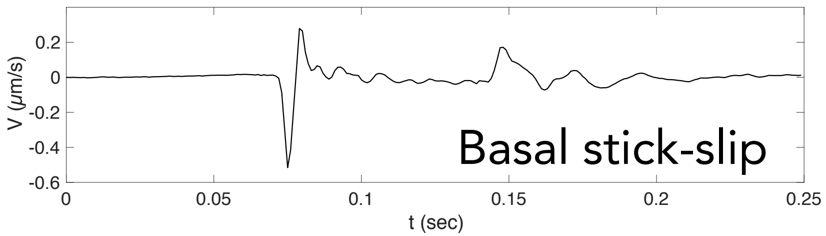


Gimbert et al., SRL, 2021; Nanni et al., PNAS, 2021; Nanni et al., GRL, 2022

Labedz et al., JGR, 2022

Understanding source properties based on signal characteristics





(e.g. Bindschadler et al., 2003; Helmstetter et al., 2015)

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

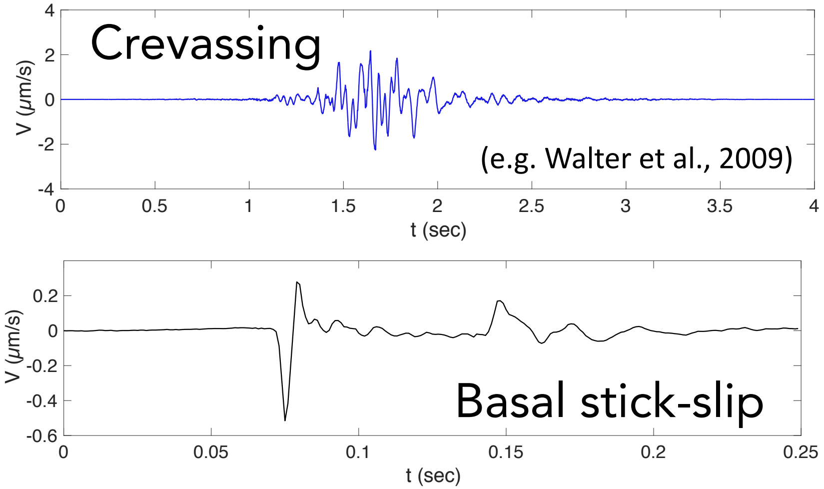
Amplitude Phase

Water flow-induced noise

(e.g. Bartholomaus et al., 2015)

How can we best exploit signal characteristics in order to retrieve the underlying physics ?

Understanding source properties based on signal characteristics



(e.g. Bindschadler et al., 2003; Helmstetter et al., 2015)

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

Amplitude Phase

Water flow-induced noise

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How can we best exploit signal characteristics in order to understand and quantify the underlying physics ?

How can we best exploit signal characteristics in order to understand and quantify the underlying physics ?

As a glaciologist: What physical mechanisms control

- the propagation of crevasses, in particular through depth ?

Van der Veen, 1998; Weiss, 2004; Krug et al., 2014

Astrolabe Glacier, Antarctica

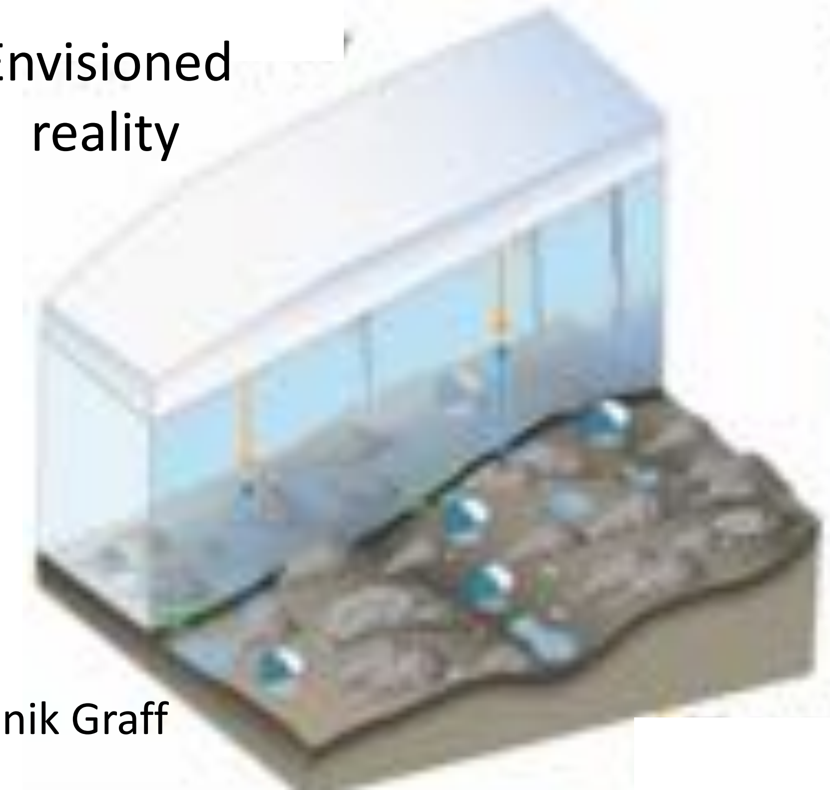
How can we best exploit signal characteristics in order to understand and quantify the underlying physics ?

As a glaciologist: What physical mechanisms control

- the propagation of crevasses, in particular through depth ?

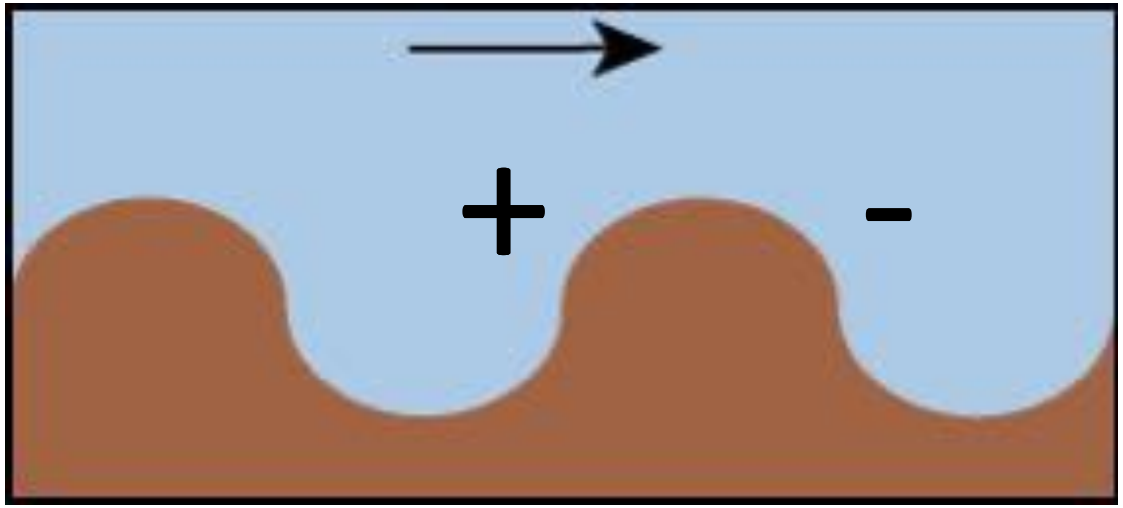
- seismic bed sliding, and does it matter for understanding the overall bed friction ?

Envisioned reality



© Dominik Graff

Theory



Weertman, 1957

How can we best exploit signal characteristics in order to understand and quantify the underlying physics ?

As a glaciologist: What physical mechanisms control

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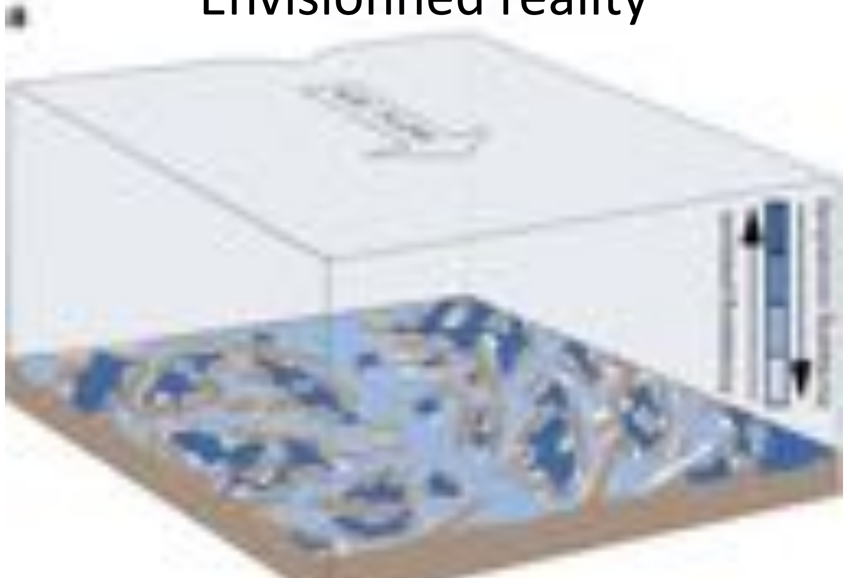
- water flow basal pressure and drainage characteristics ?

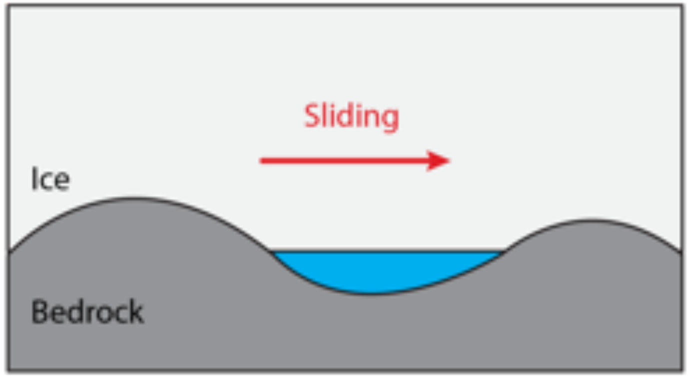
Envisionned reality



Hoffman et al., 2016

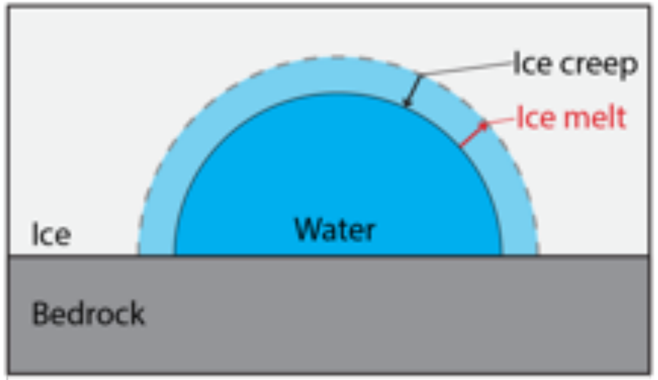
Theory

High pressure cavities



Lliboutry (1958), Kamb (1987)

Low pressure channels



Rothlisberger (1975), Nye (1972)

How can we best exploit signal characteristics in order to understand and quantify the underlying physics ?

As a glaciologist: What physical mechanisms control

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As a seismologist: How can we best use signal characteristics for retrieving and quantifying

- Source physics ?
- Source spatio-temporal dynamics ?

As a seismologist: How can we best use signal characteristics for retrieving and quantifying

- Source physics ?

Crevasse opening
Stick-slip → OK

Water-flow?

Build up of appropriate physical frameworks

- Source spatio-temporal dynamics ?

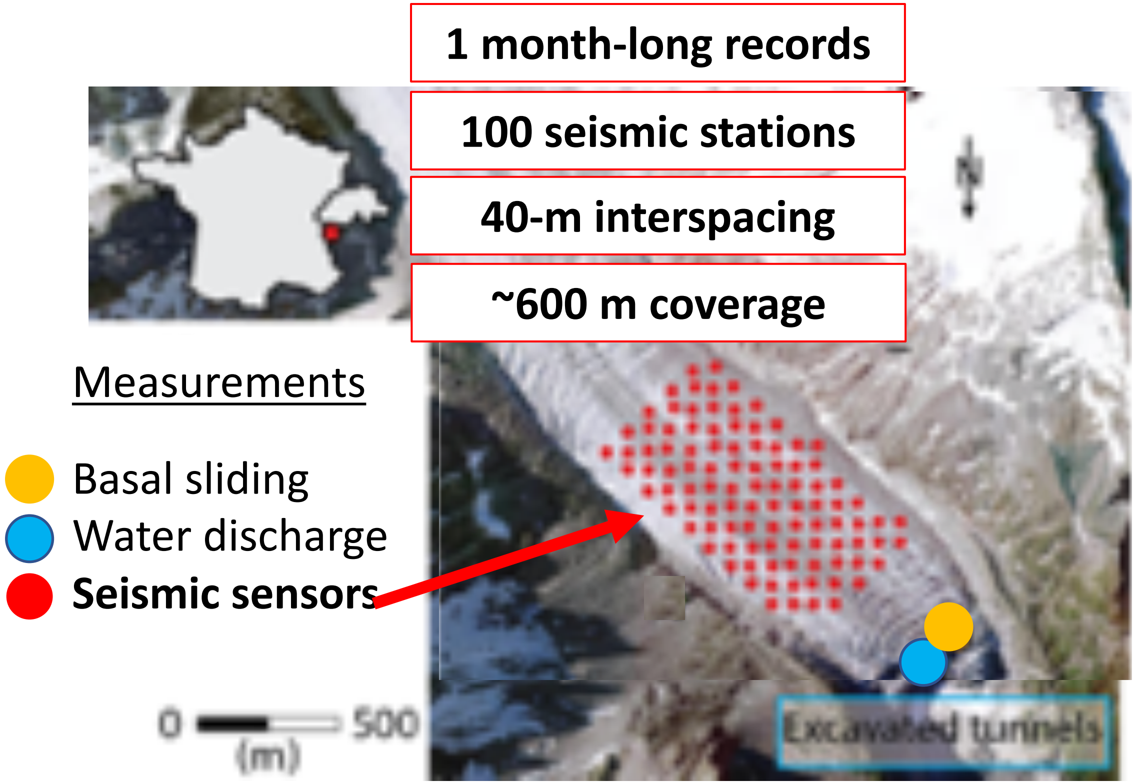
Crevasse opening
Stick-slip

Water-flow

Use of dense seismic arrays

Spatialization using dense seismic arrays

The Argentière Glacier (French Alps)



Gimbert et al., SRL, 2021; Nanni et al., PNAS, 2021;
Nanni et al., GRL, 2022

Spatialization using dense seismic arrays

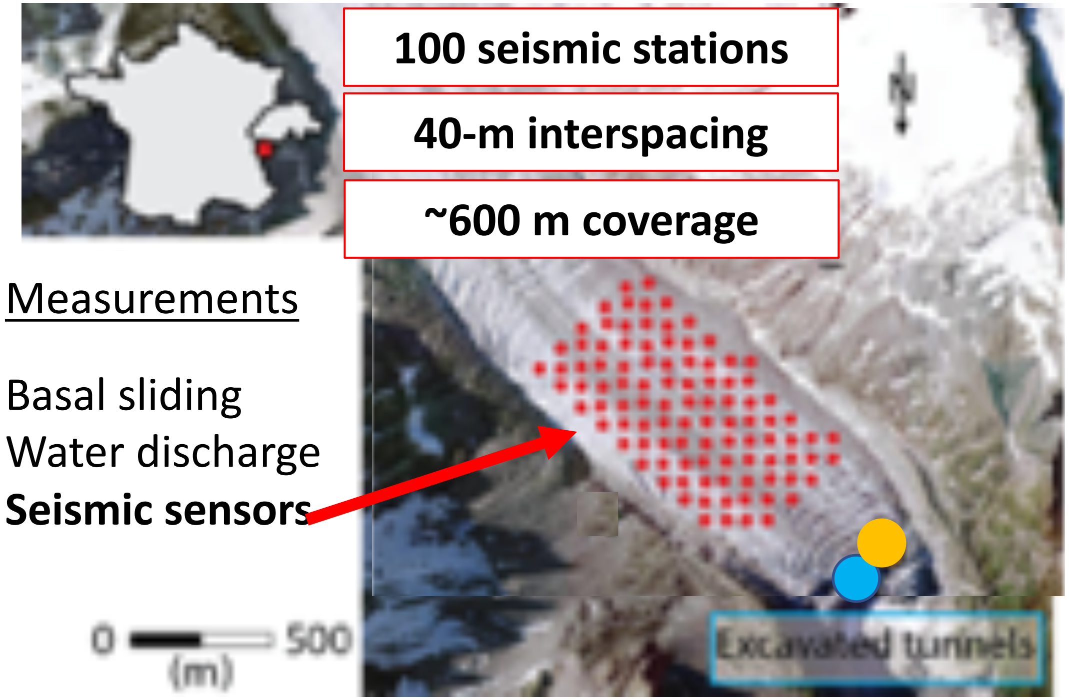
The Argentière Glacier (French Alps)

1 month-long records

100 seismic stations

40-m interspacing

~600 m coverage

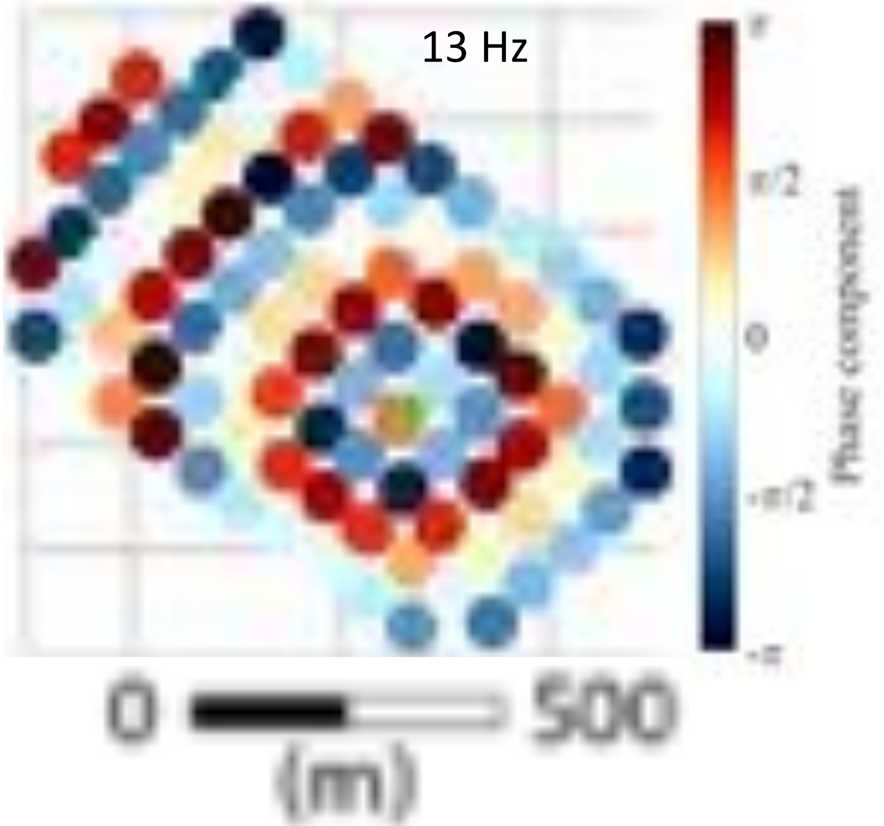


Measurements

- Basal sliding
- Water discharge
- **Seismic sensors**

Gimbert et al., SRL, 2021; Nanni et al., PNAS, 2021; Nanni et al., GRL, 2022

Observed phase field after an icequake

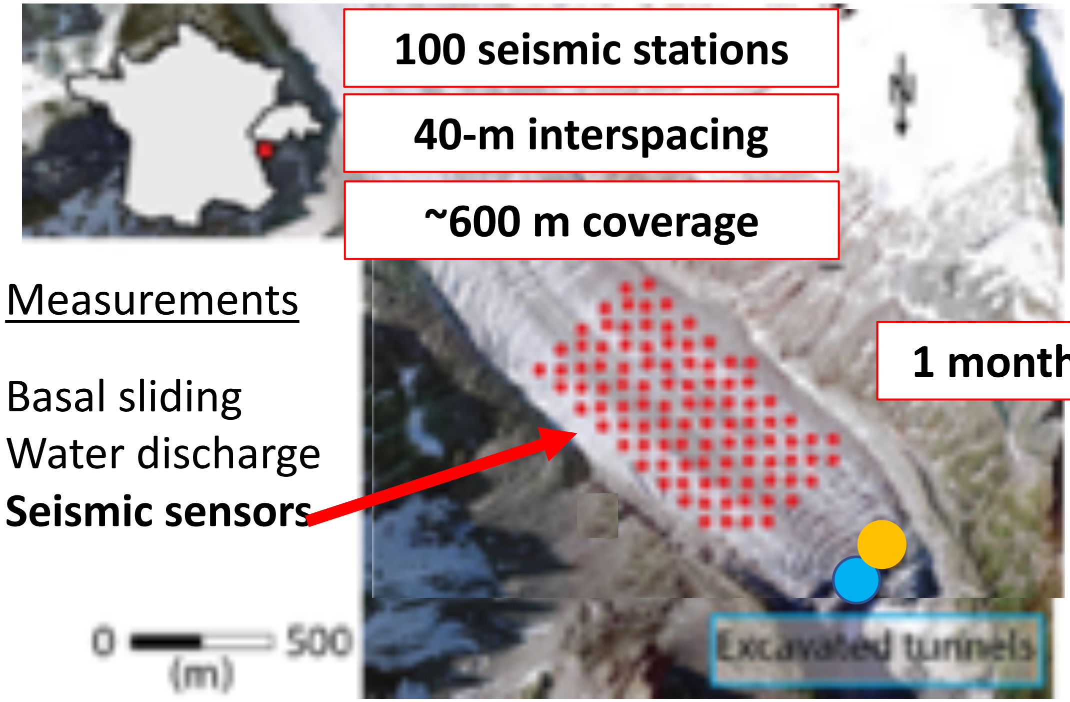


Spatialization using dense seismic arrays

Use sensors as « antennas »

The same sources are detected by several sensors, and thus can be located through array phase delay processing

The Argentière Glacier (French Alps)



100 seismic stations

40-m interspacing

~600 m coverage

1 month-long records

Measurements

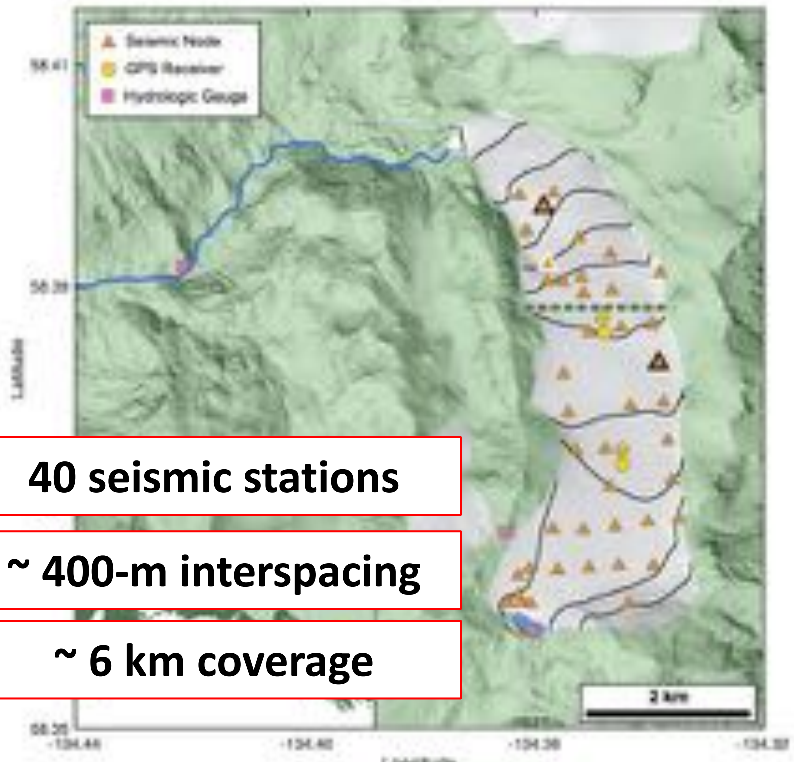
- Basal sliding
- Water discharge
- **Seismic sensors**

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

Use sensors « independantly »

Sensors see distinct enough sources that seismic power at each station pictures local subglacial flow conditions

The Lemon Creek Glacier (Alaska)



40 seismic stations

~ 400-m interspacing

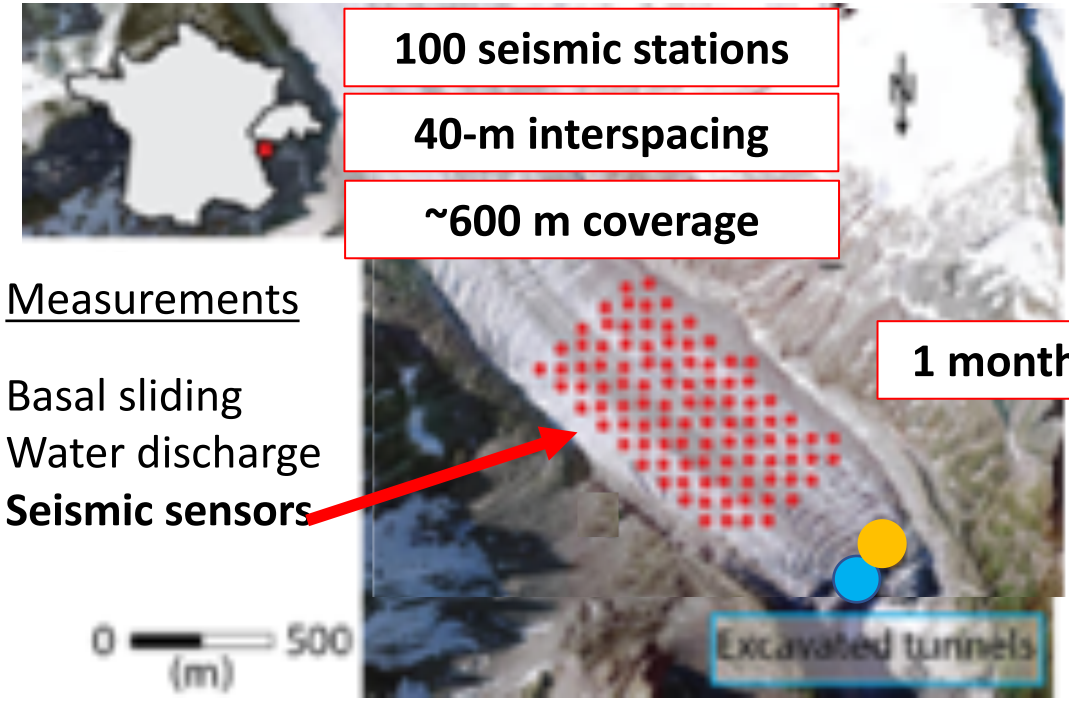
~ 6 km coverage

Labedz et al., 2022

Spatialization using dense seismic arrays

Use sensors as « antennas »

The Argentière Glacier (French Alps)



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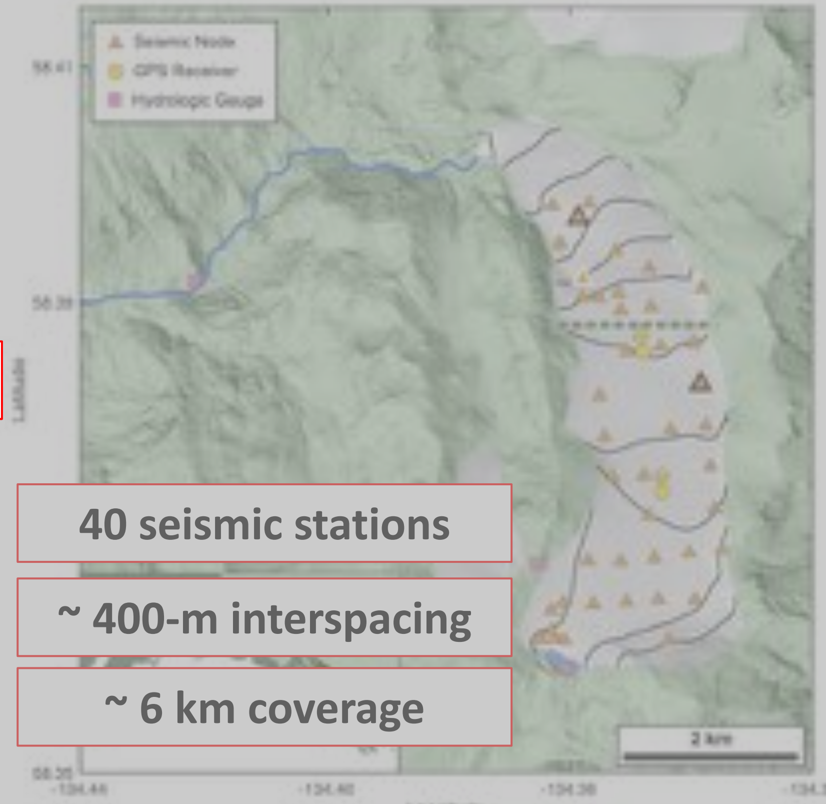


Labedz et al., 2022

Spatialization using array phase analysis

Matched-field-processing (MFP)

- Consider 1 second-long signals
- 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

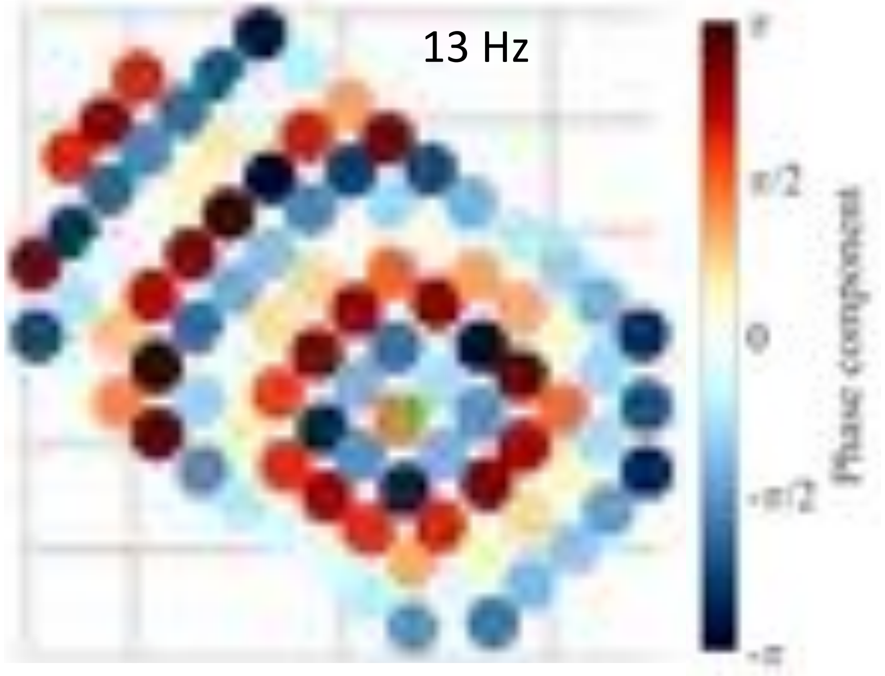
- Evaluate the match between the observed and modelled phases in a 4 dimensional space as

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

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

Observed phase field after an icequake



Nanni et al., 2021; 2022

Spatialization using array phase analysis

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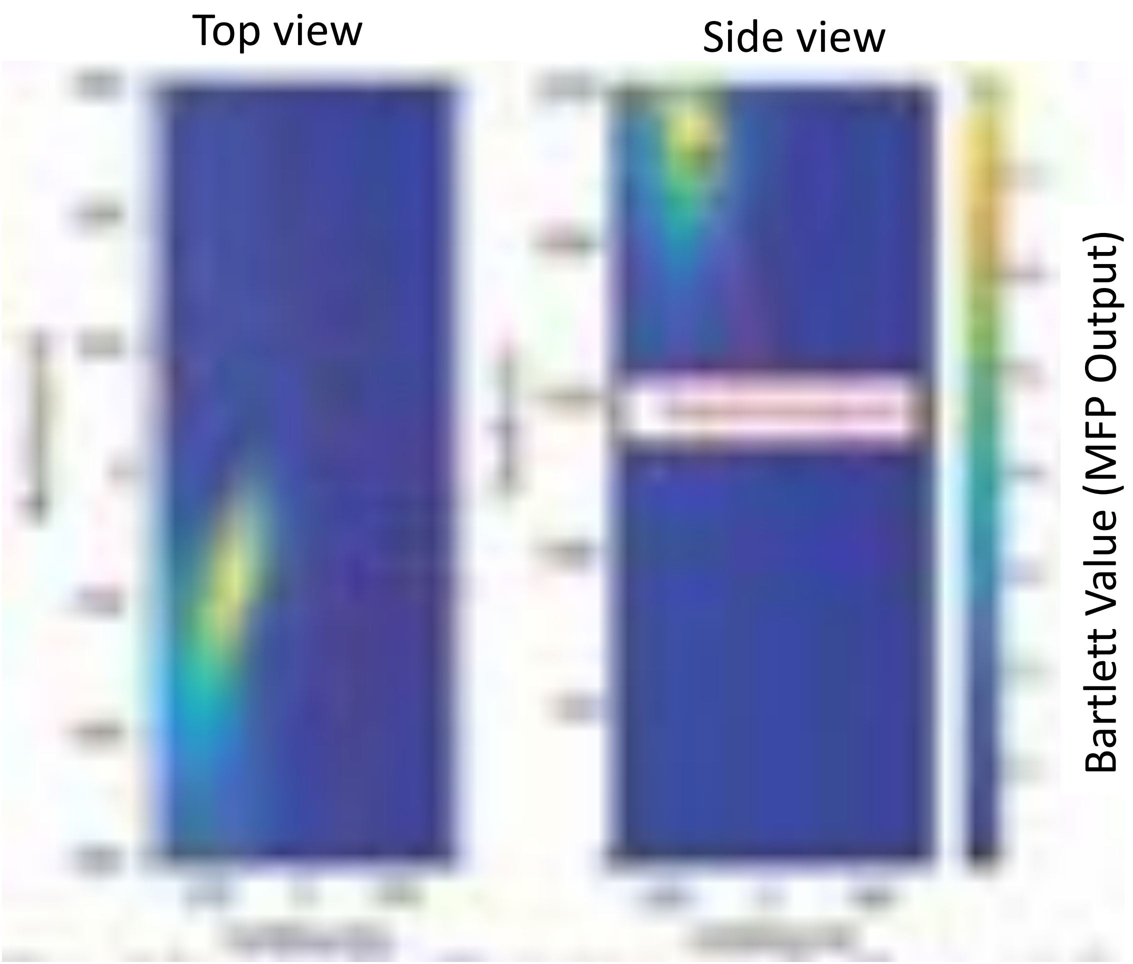
and r_a the distance to the trial source *a*

Example of a well identified icequake



Nanni et al., 2021; 2022

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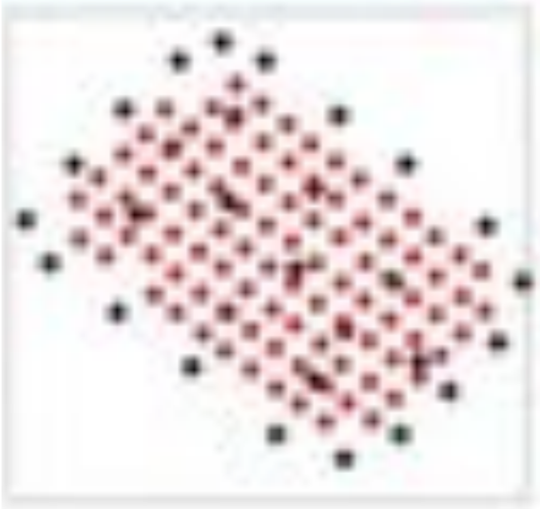
and r_a the distance to the trial source *a*

Scheme for finding maxima

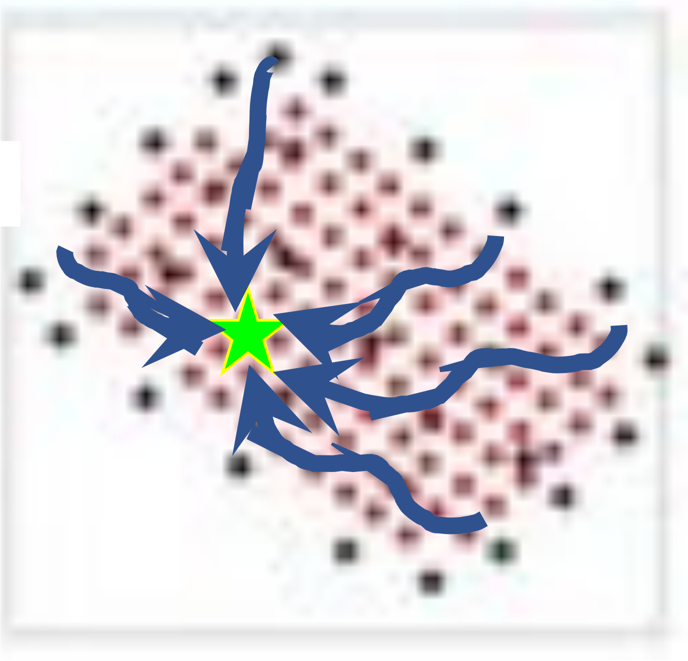
- Use of a gradient-based minimization algorithm (Nelder-Mead optimization)
- Efficiently converge to the best match
- Use 29 starting points to
  - Increase the likelihood that the global best match is found
  - Keep track of local best matches



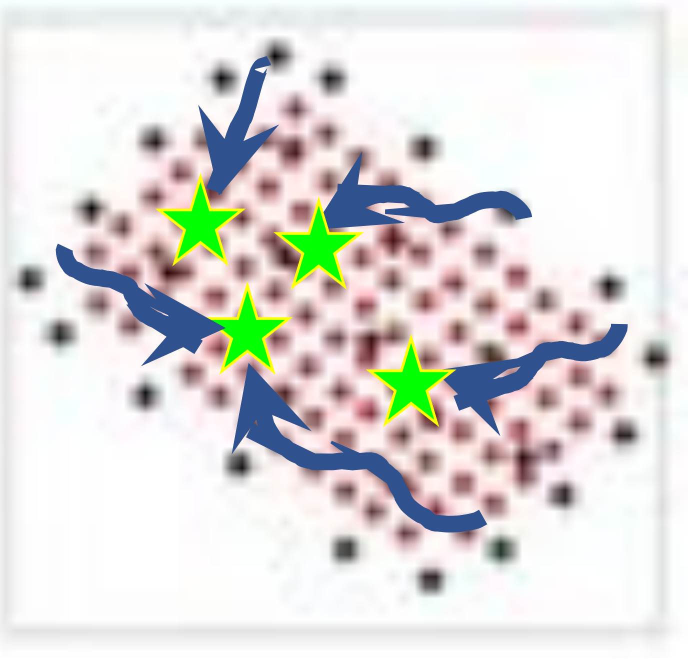
Nanni et al., 2021; 2022

Spatialization using array phase analysis

Coherent wavefield

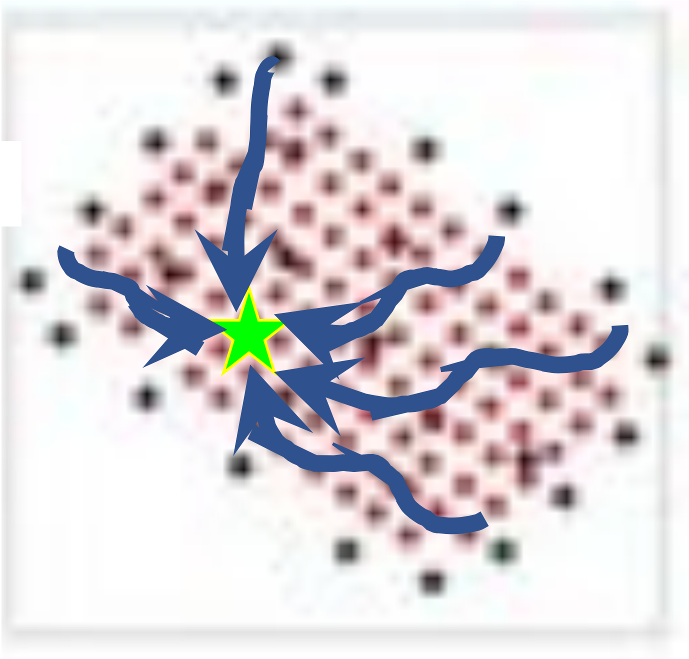


More incoherent wavefield

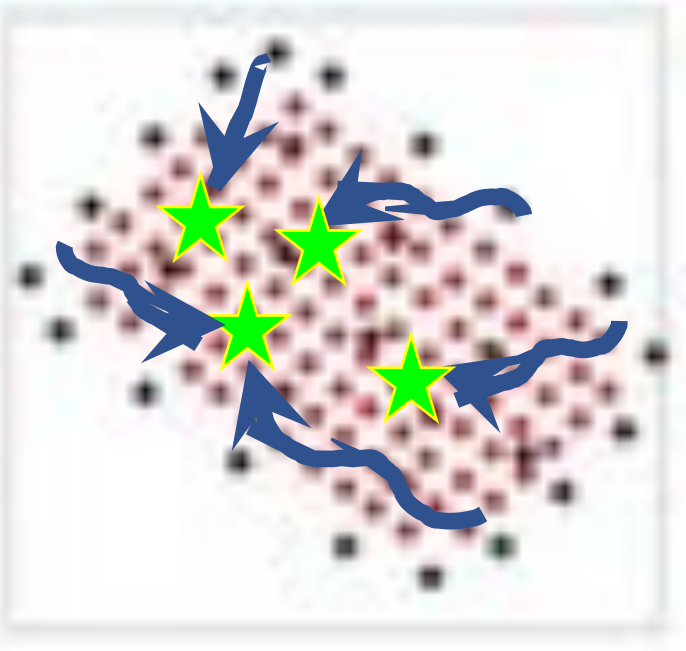


Spatialization using array phase analysis

Coherent wavefield

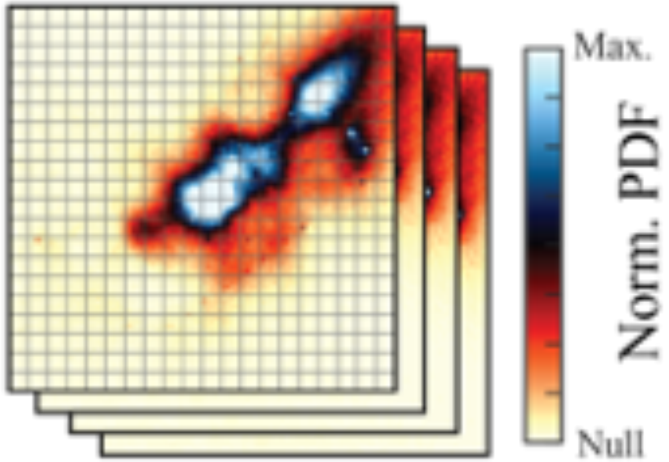


More incoherent wavefield



We save all sources (i.e. up to 29) found every second

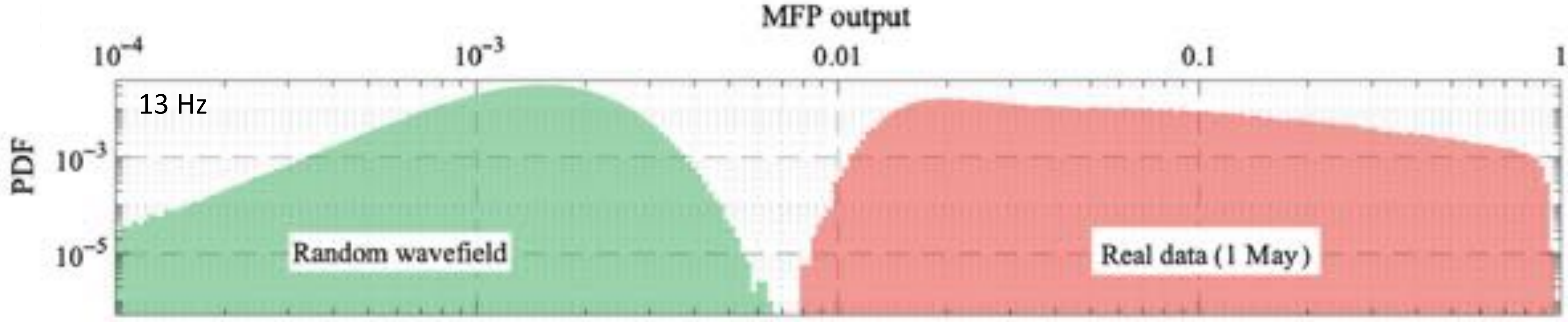
Up to 50+ millions potential locations per day



Using realistic values:

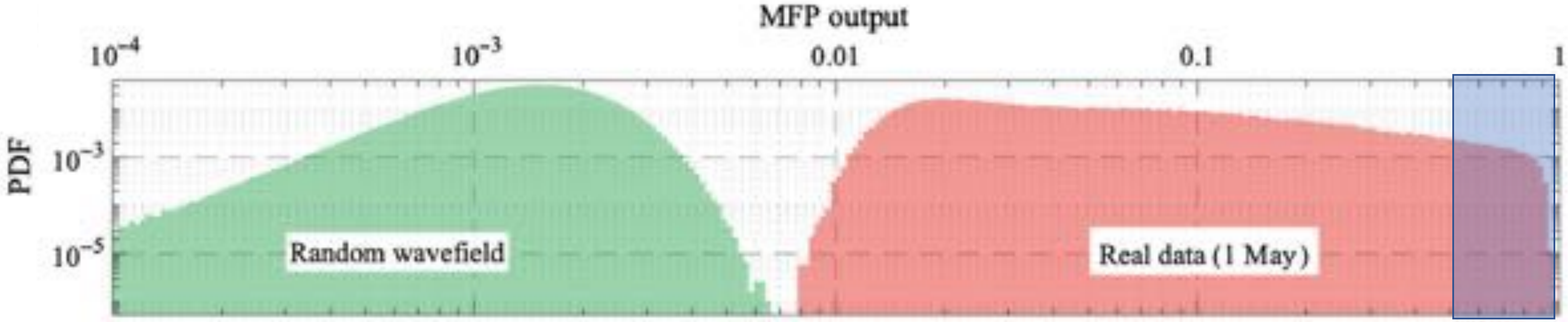
- Phase velocity
  [1500-3600 m.sec^{-1}]
- Source positions
  ± 400m from array center in (x,y,z)

Spatialization using array phase analysis



There is always some degree of coherence in the observed phase field !

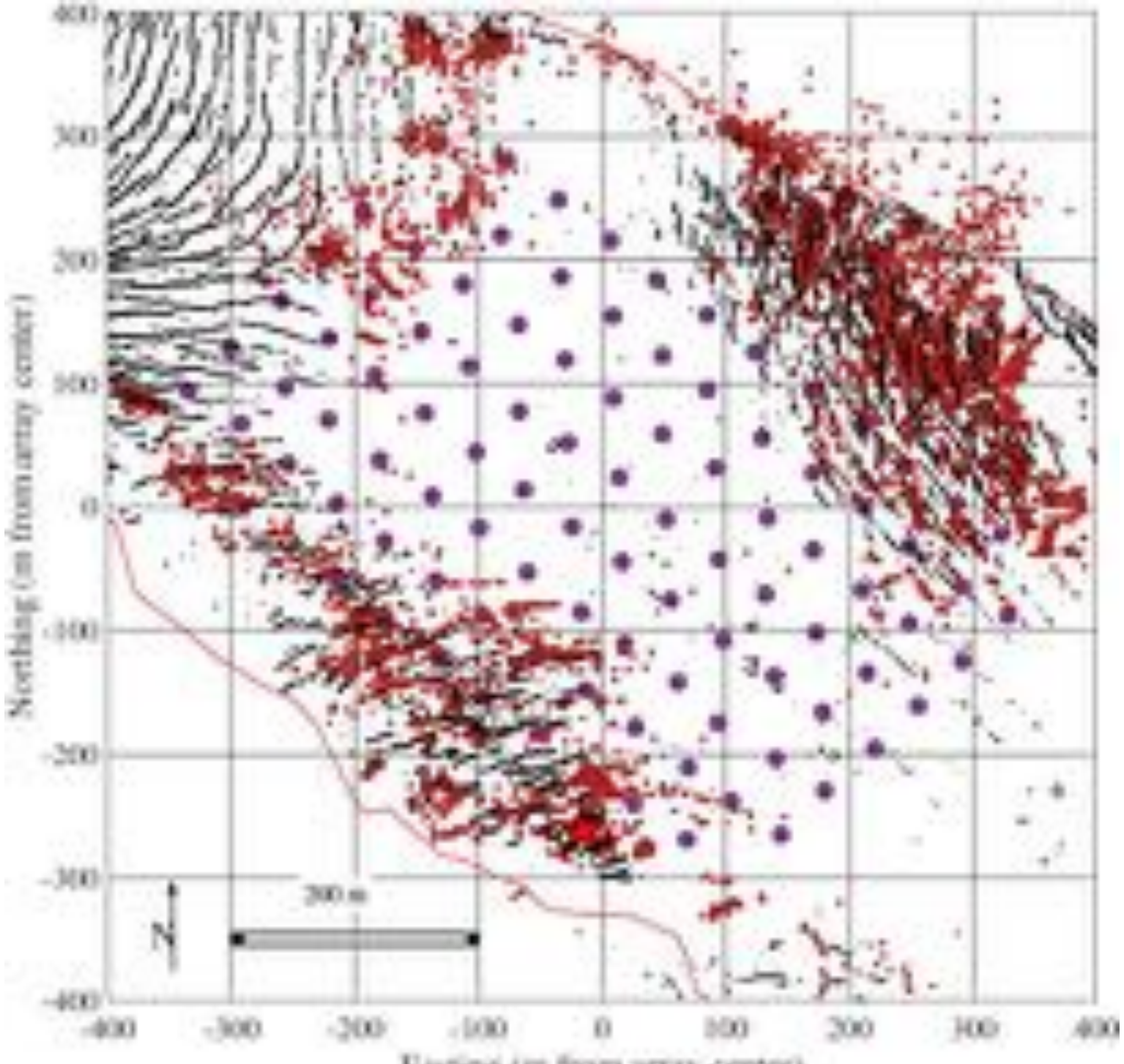
Spatialization using array phase analysis



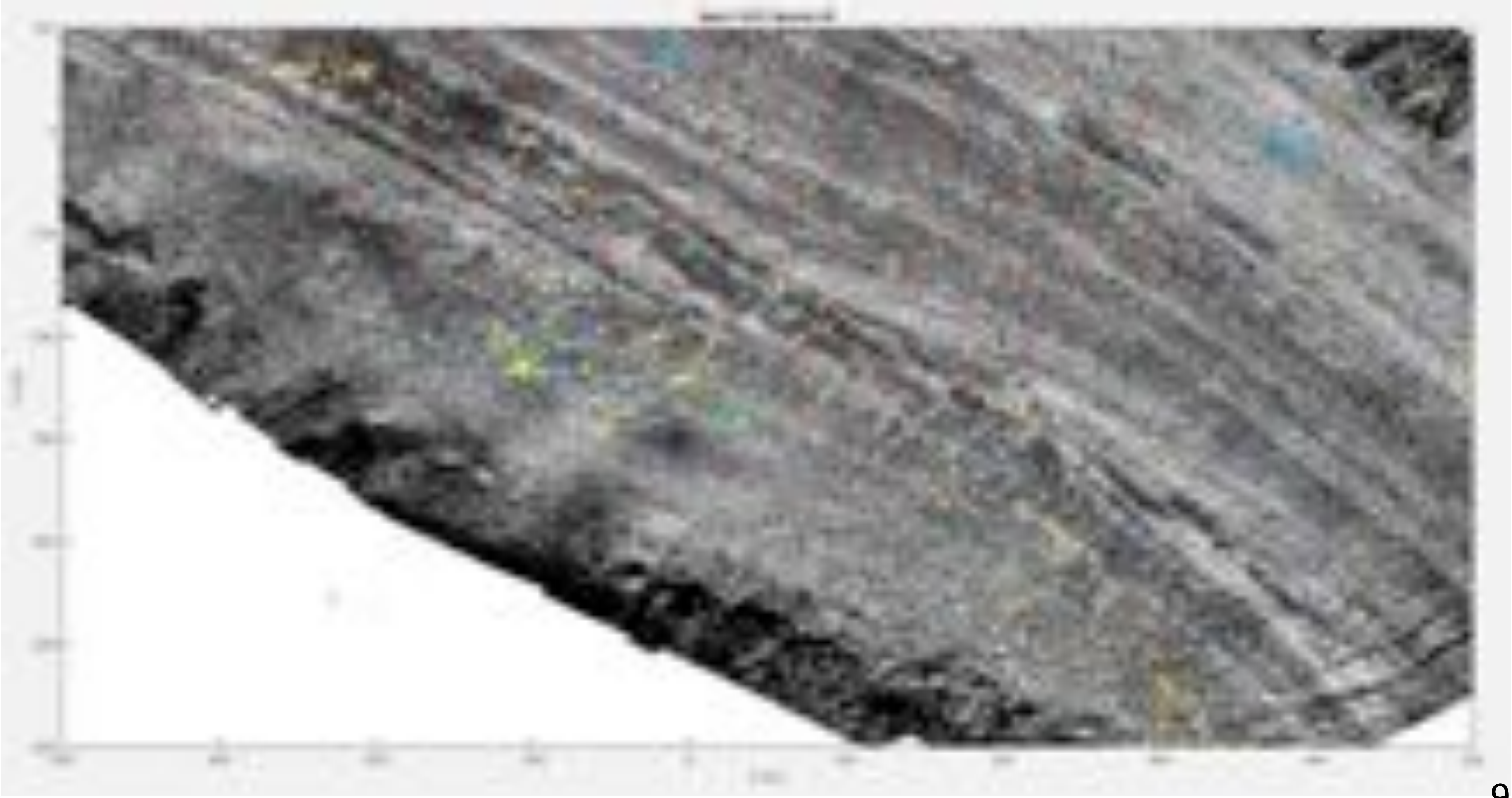
Well located events

Classical use of MFP

Spatialization using array phase analysis



High MFP Outputs
reflect crevasses

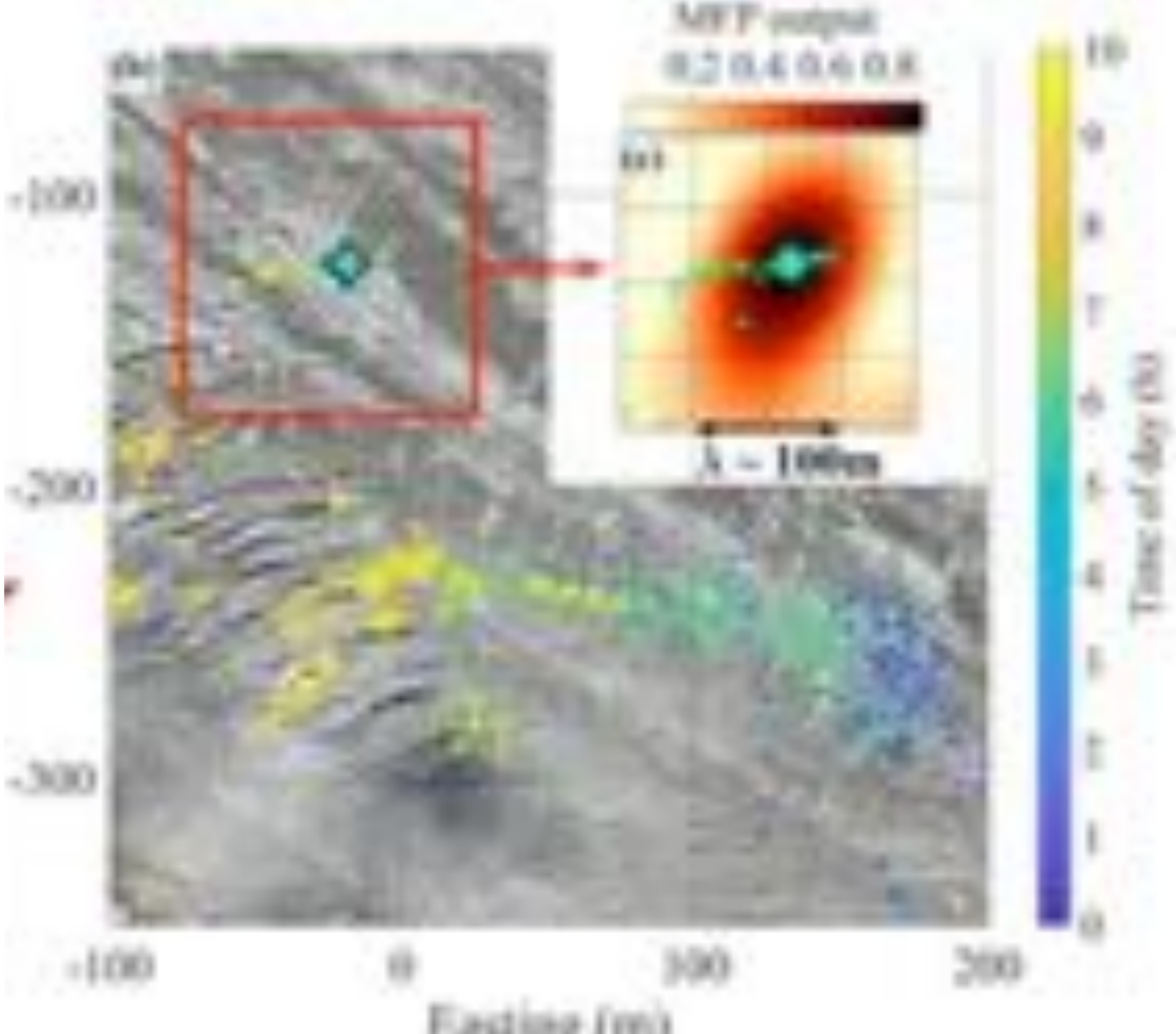


Spatialization using array phase analysis

$f = 17$ Hz

$v_c \approx 1600$ m/s

$\lambda \approx 100$ m



Spatialization using array phase analysis

$f = 17$ Hz

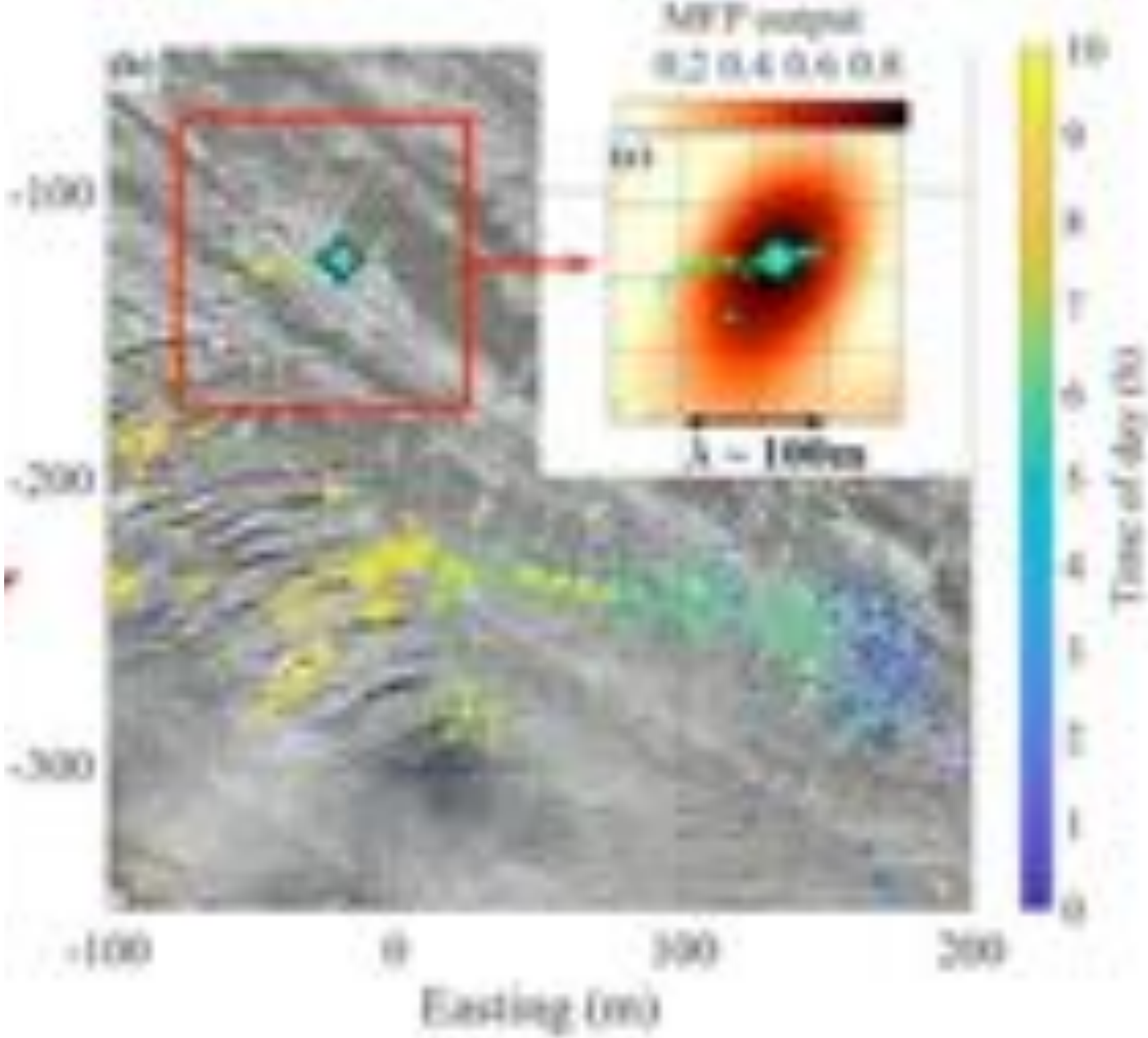
$v_c \approx 1600$ m/s

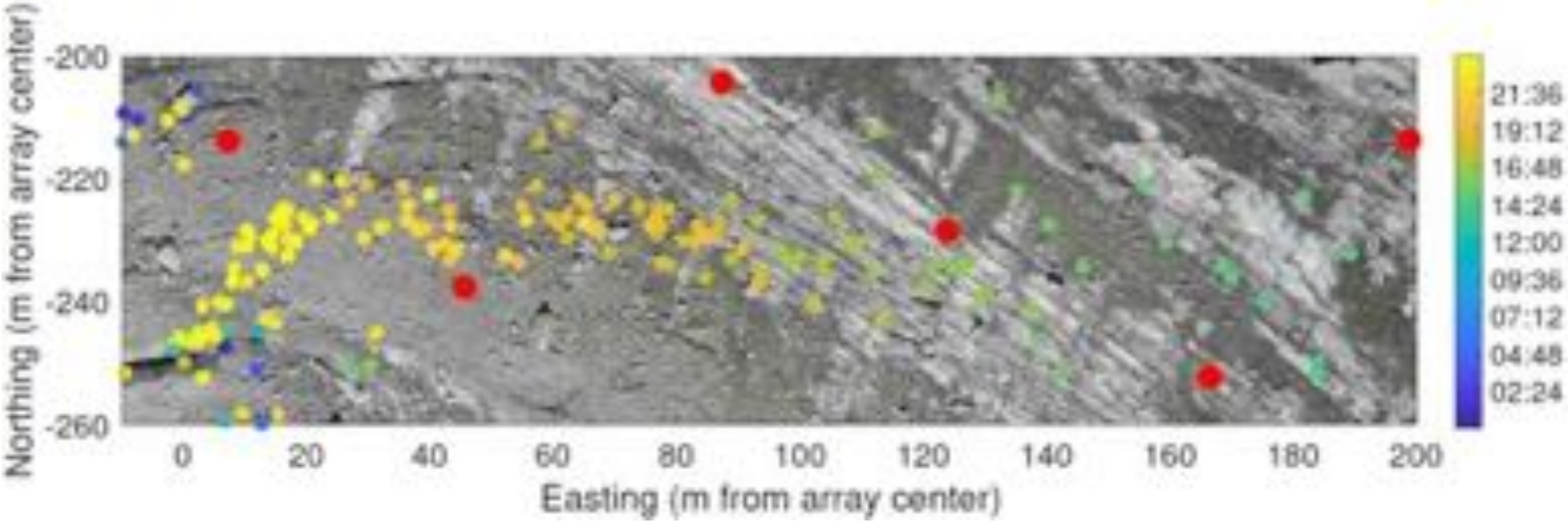
$\lambda \approx 100$ m

Hyper-resolution, i.e. resolution beyond the diffraction limit ?

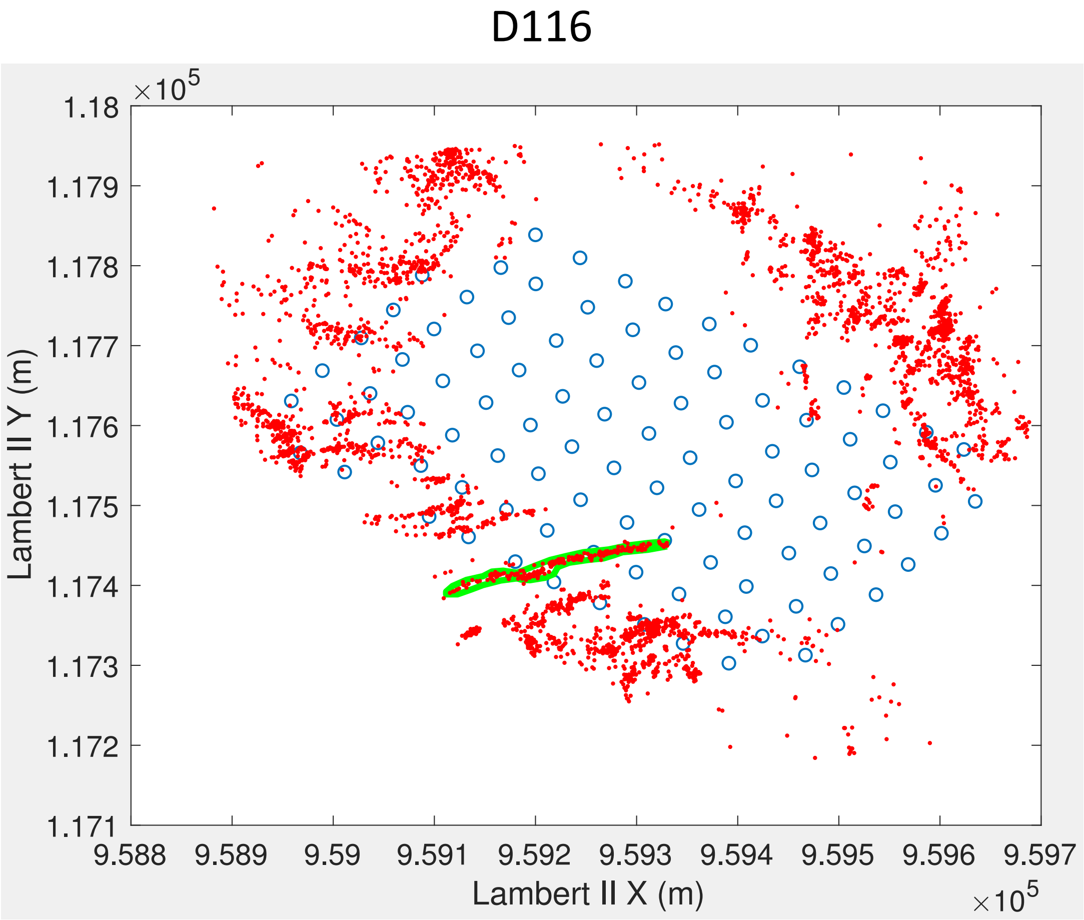
Photo-activated localization microscopy

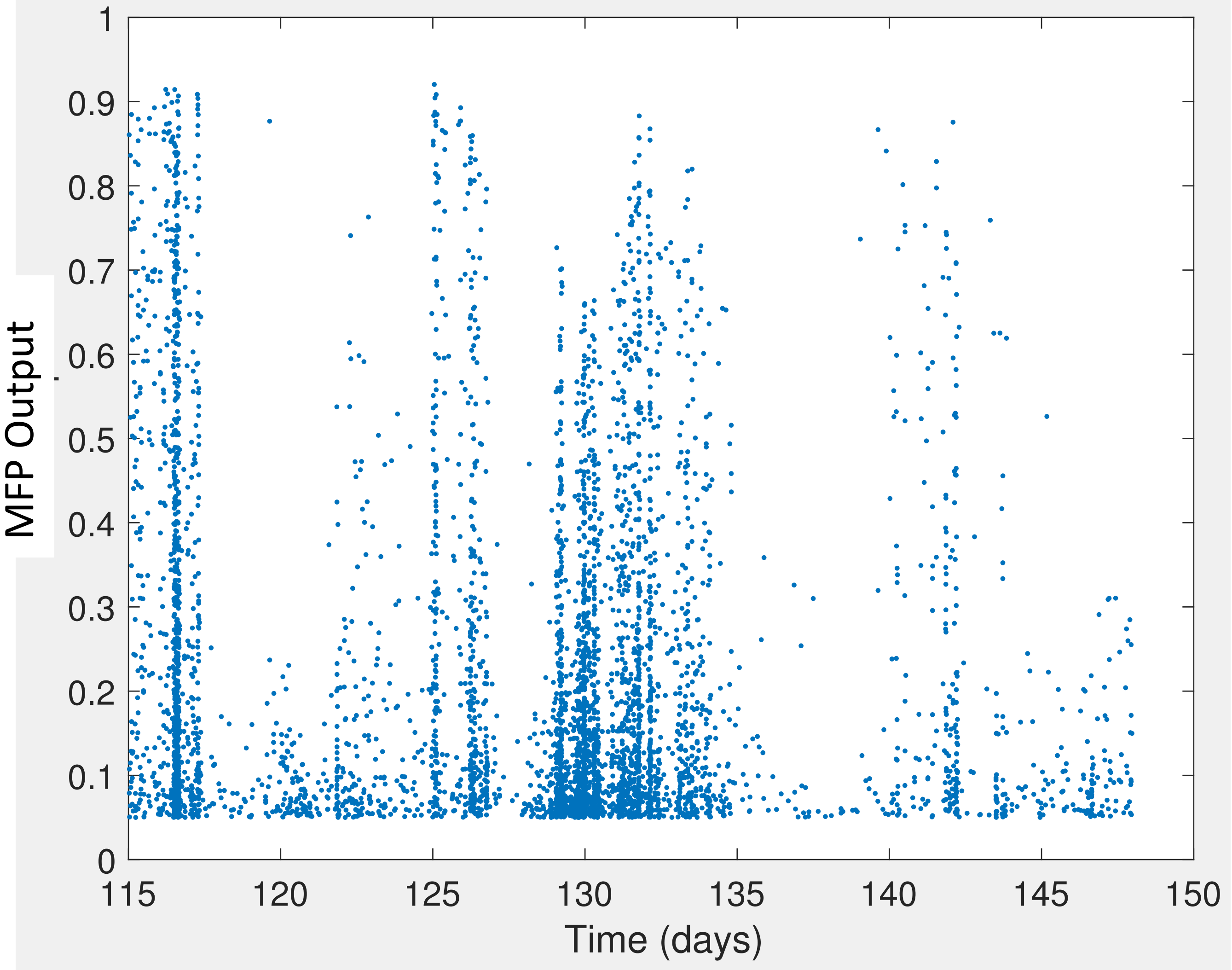
Rust et al., 2006; Betzig et al., 2006




Northing (m from array center)
-200
-220
-240
-260
0
20
40
60
80
100
120
140
160
180
200
Easting (m from array center)
21:36
19:12
16:48
14:24
12:00
09:36
07:12
04:48
02:24

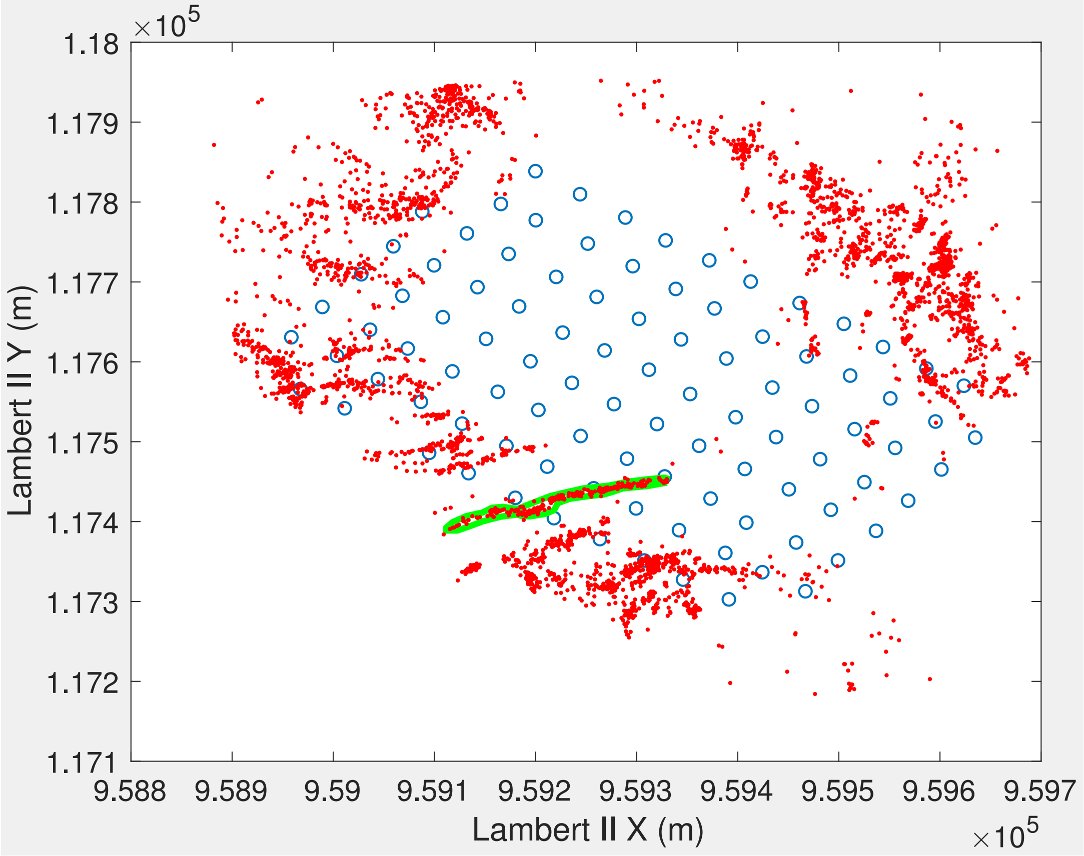
Temporalization using array phase analysis

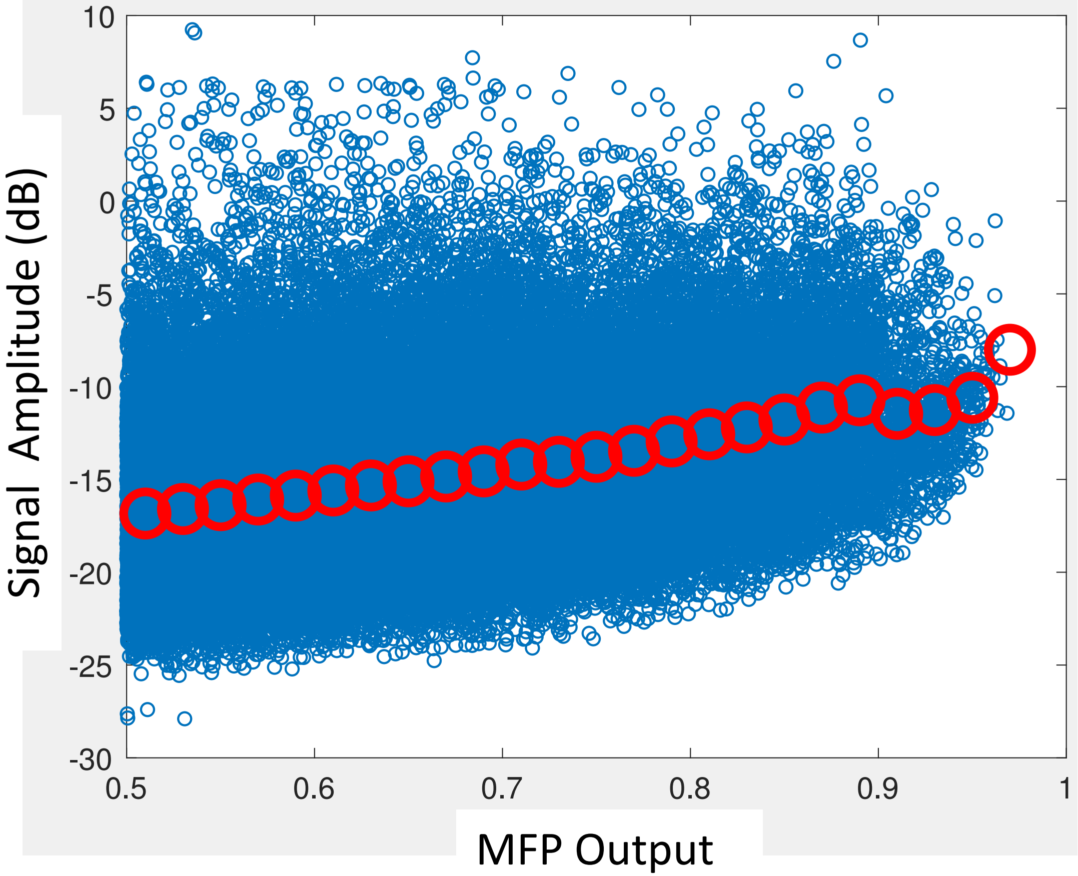




Temporalization using array phase analysis

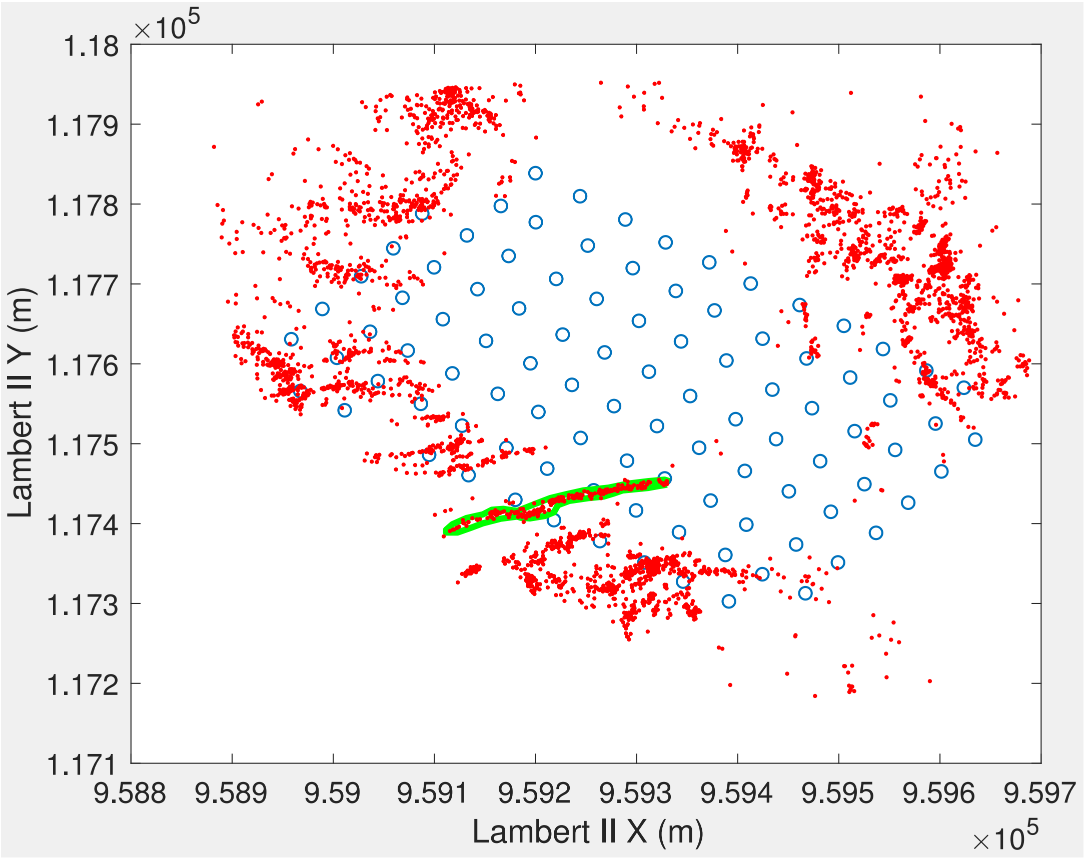
D116

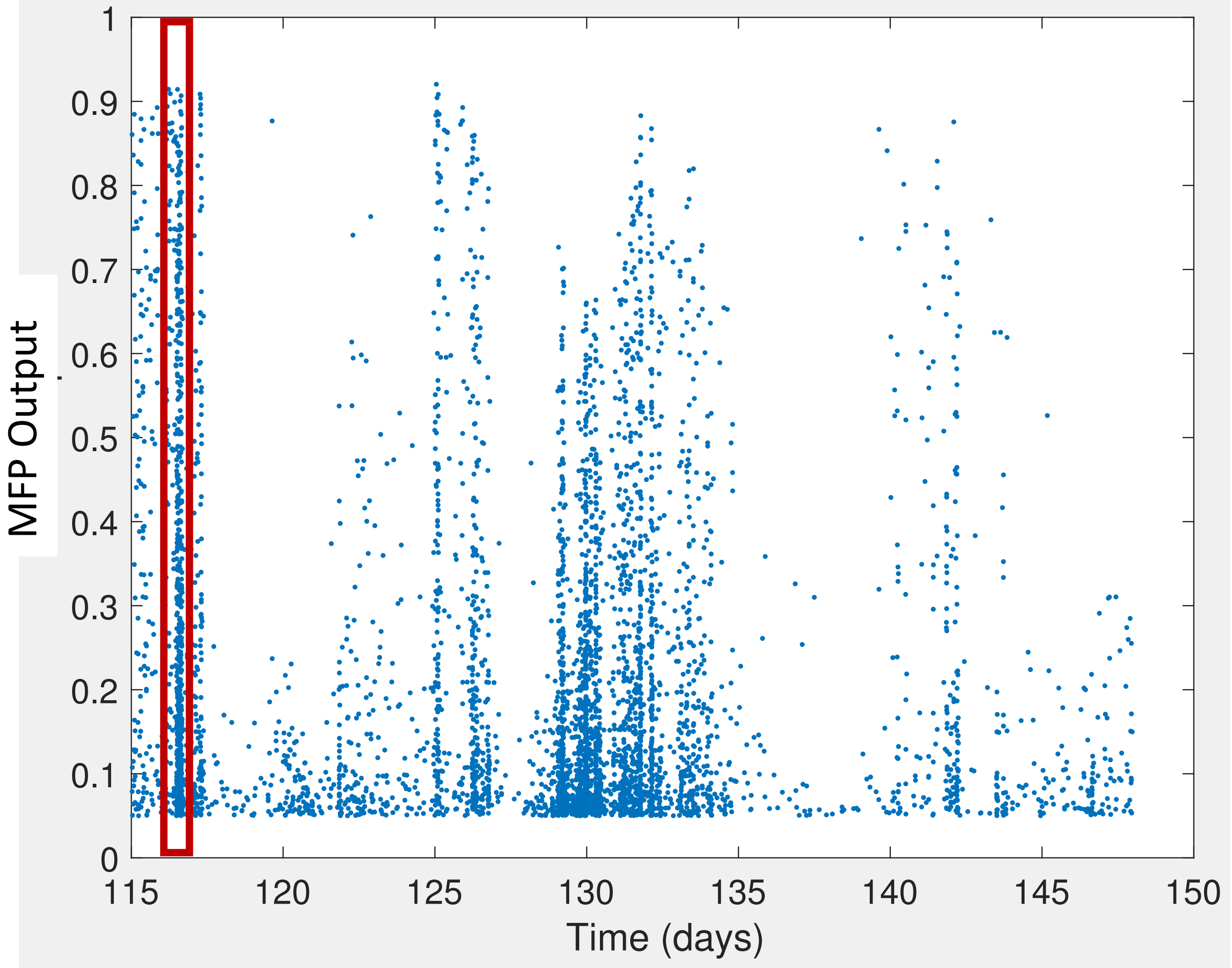




Temporalization using array phase analysis

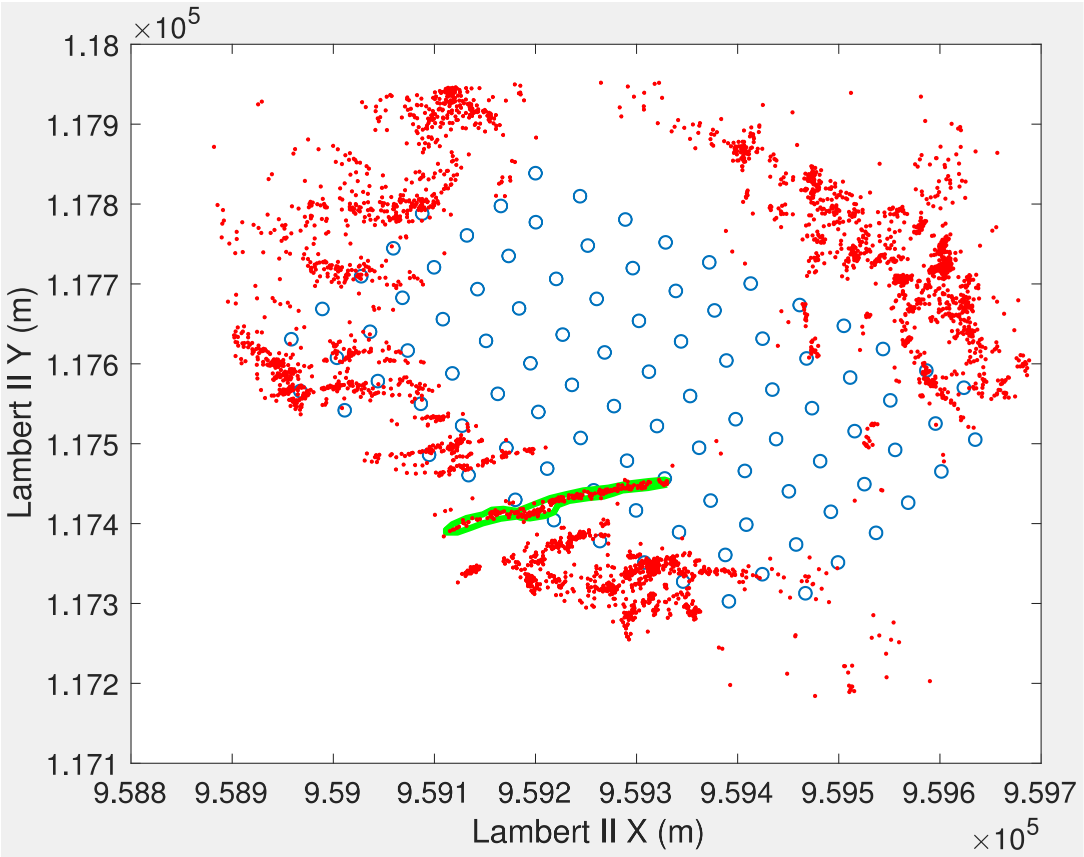
D116

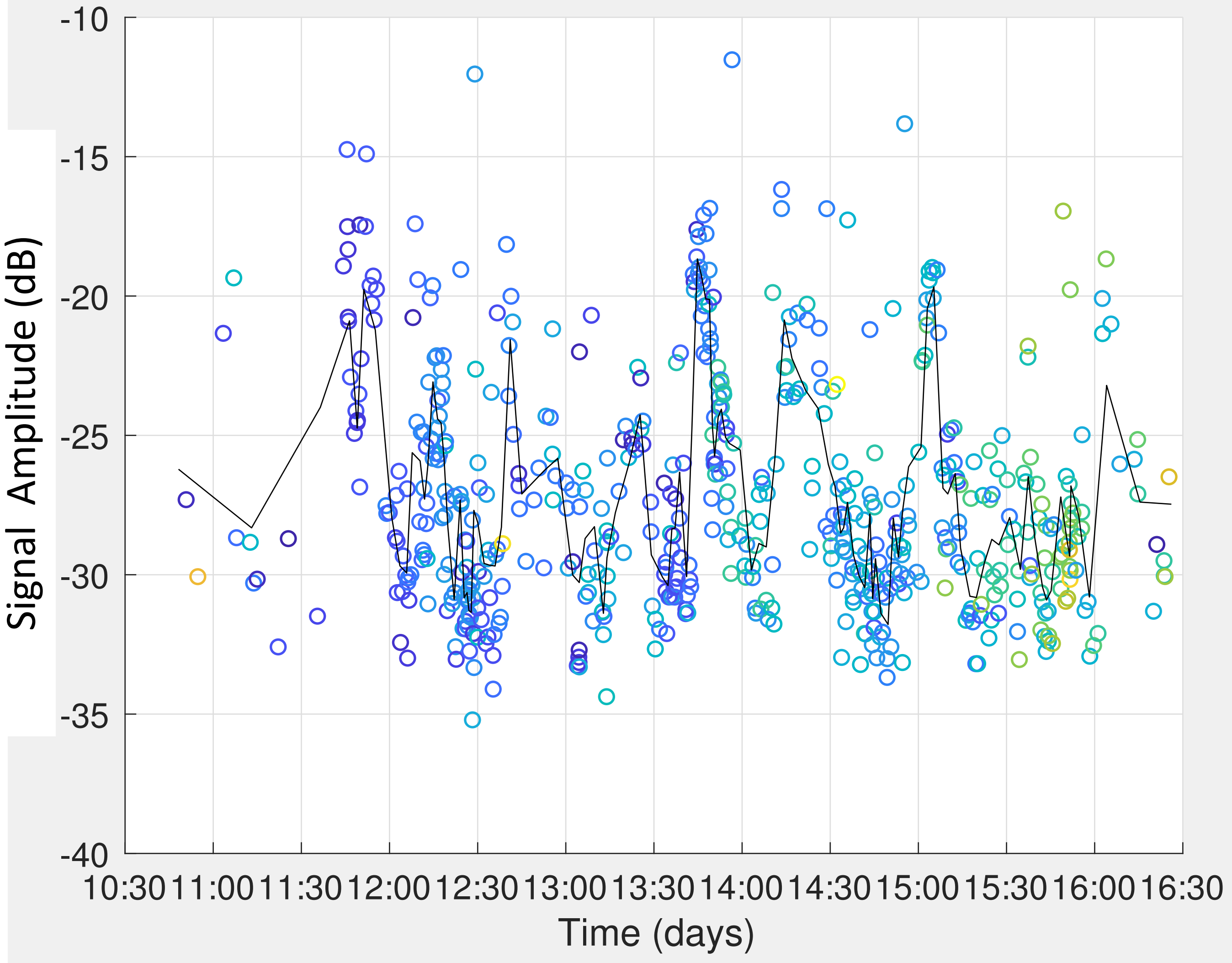




Temporalization using array phase analysis

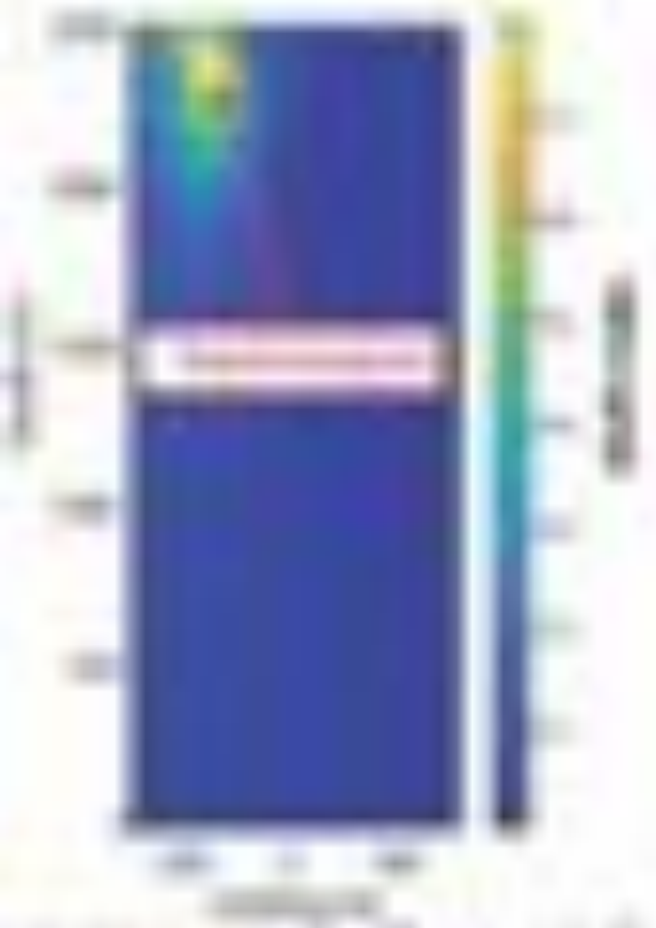
D116





Spatialization using array phase analysis

3D investigation: event depths ?
Difficulty: 2D array, mostly surface waves



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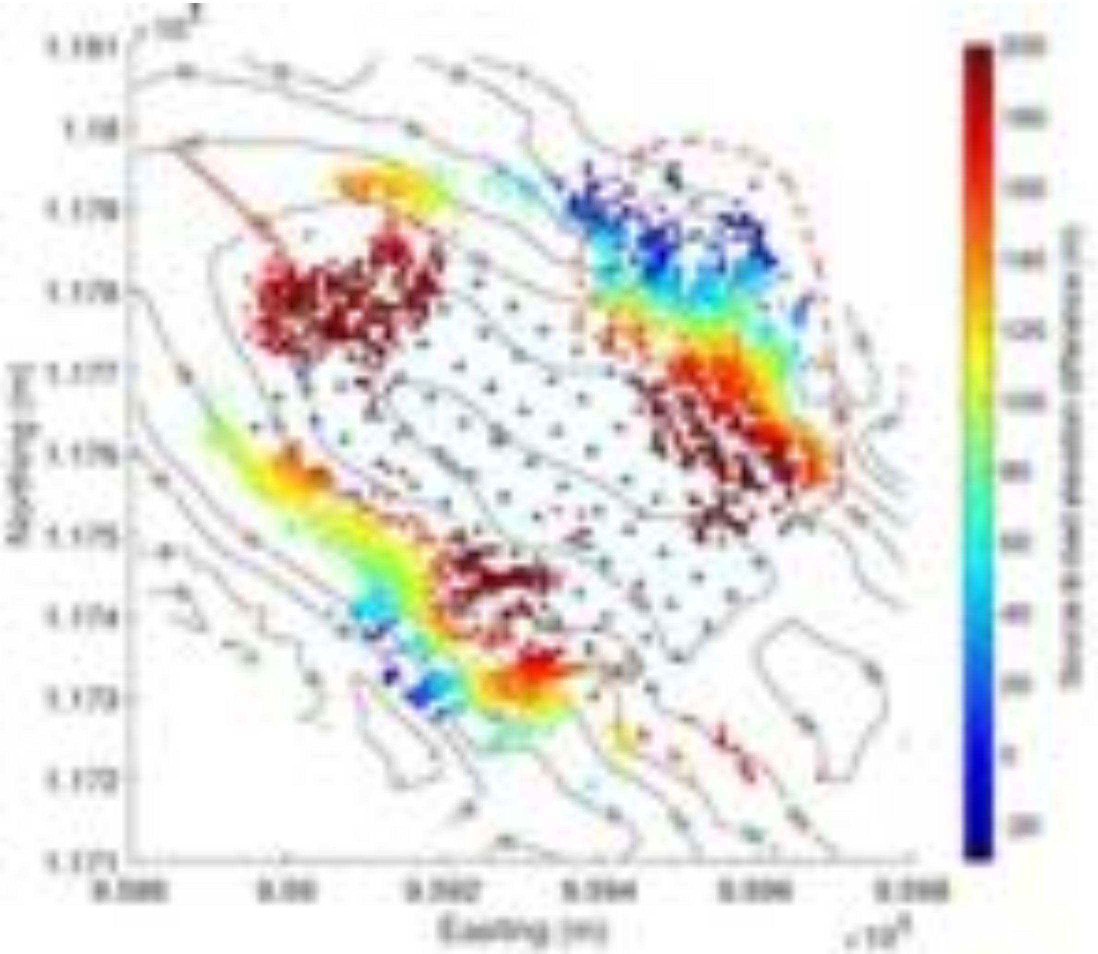
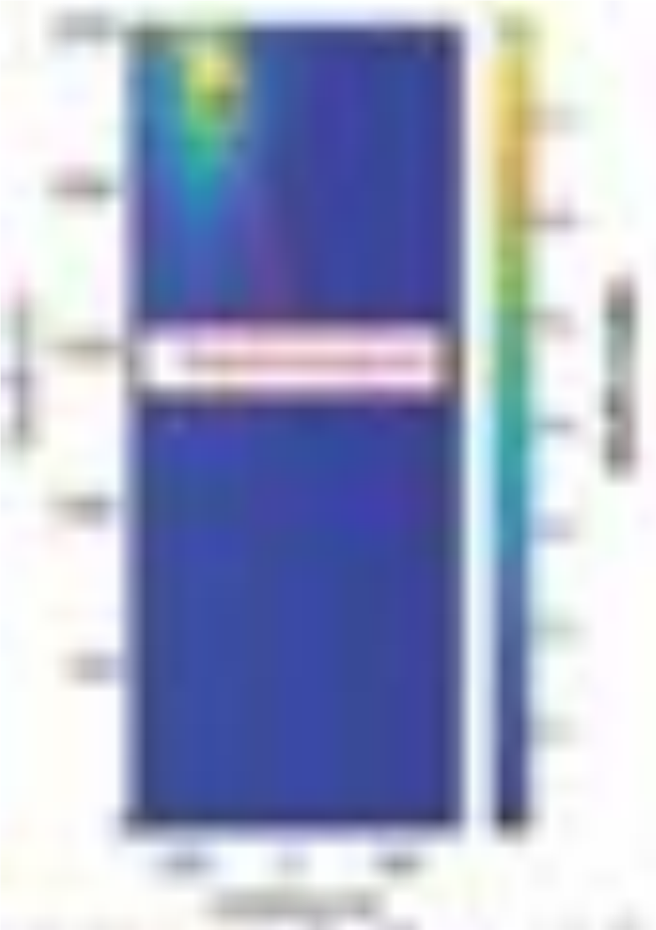
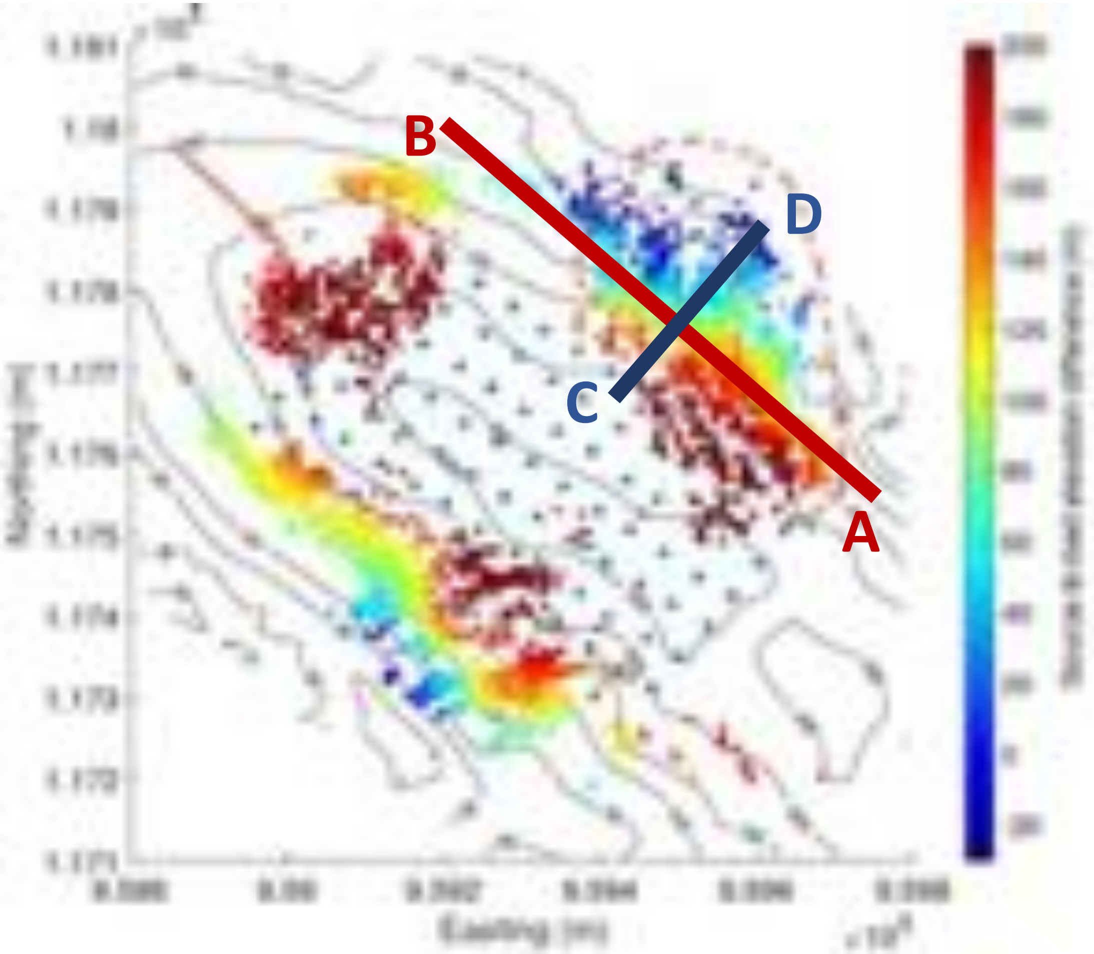


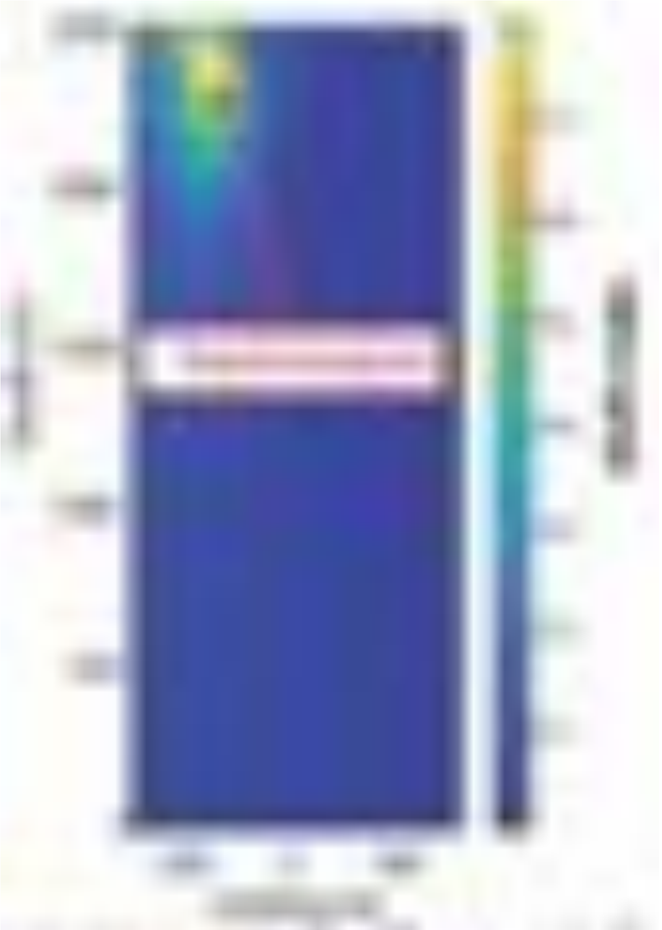


Spatialization using array phase analysis

3D investigation: event depths ?

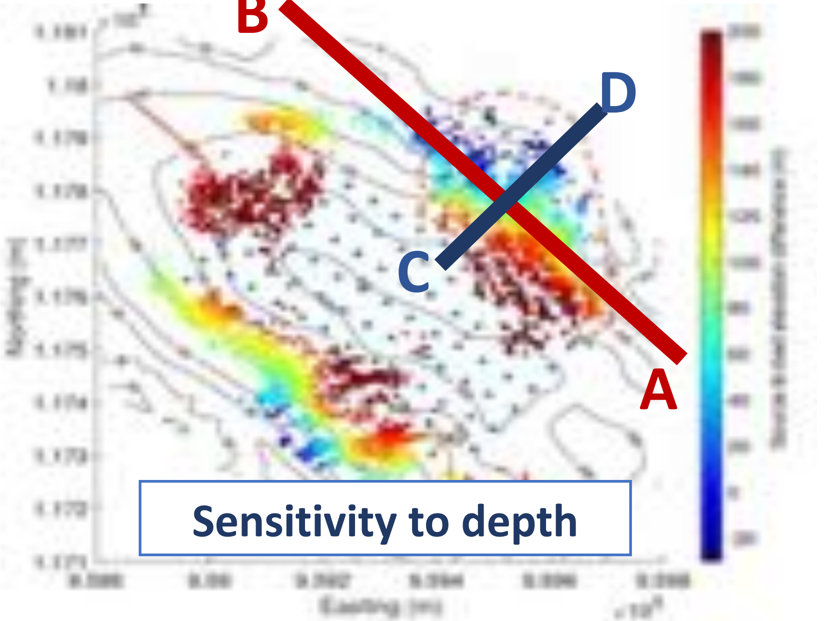
Difficulties: 2D array, mostly surface waves

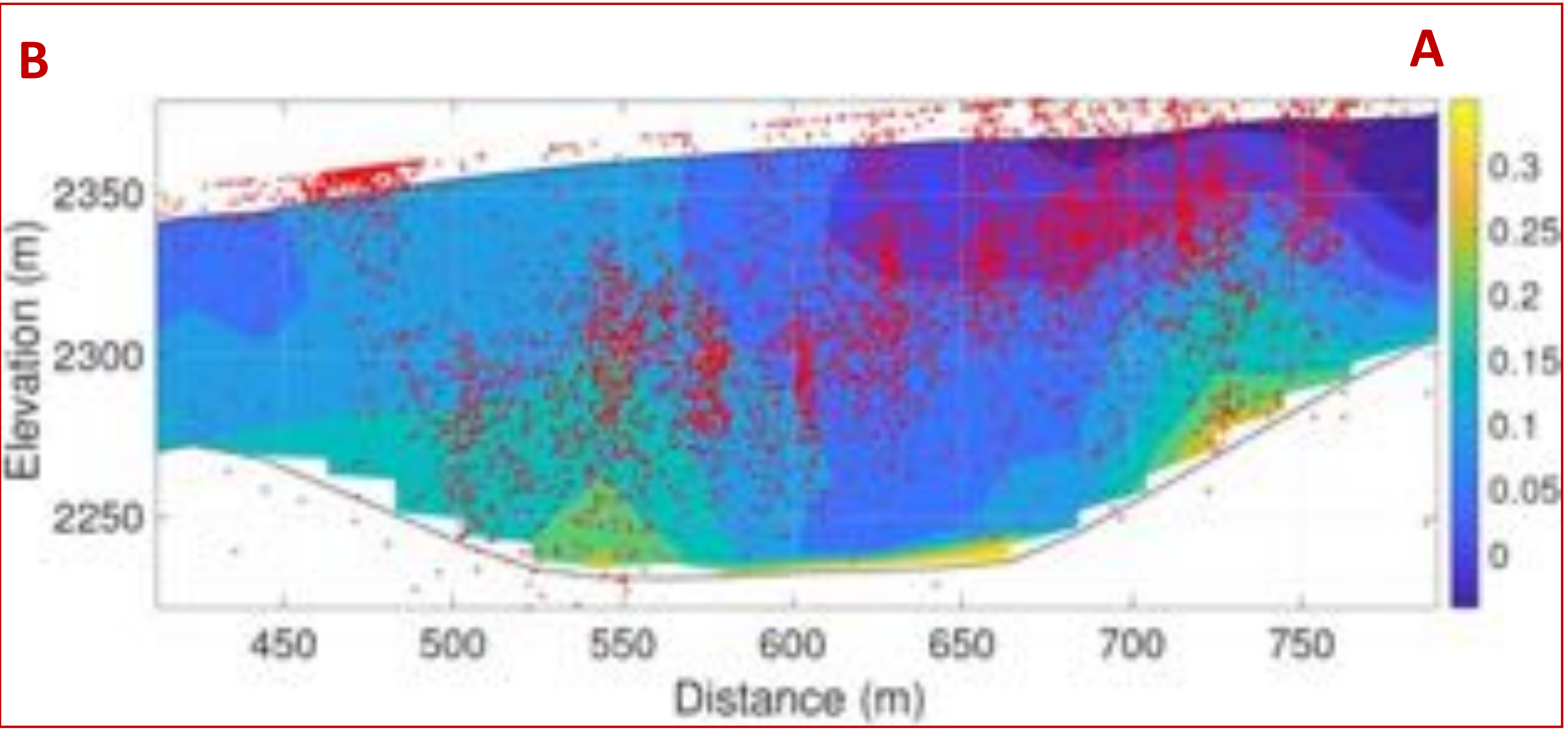


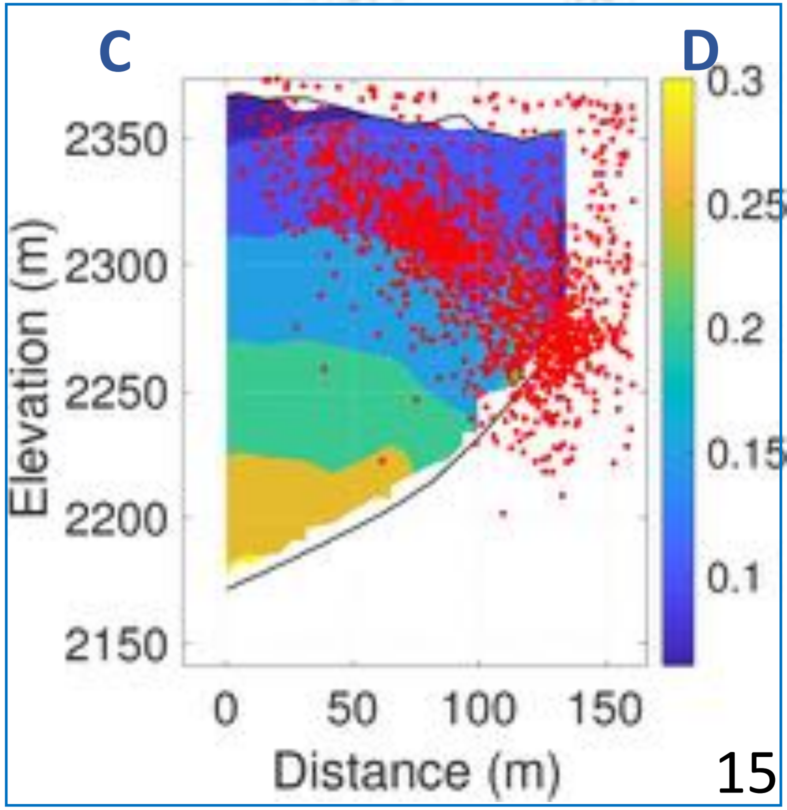


Spatialization using array phase analysis

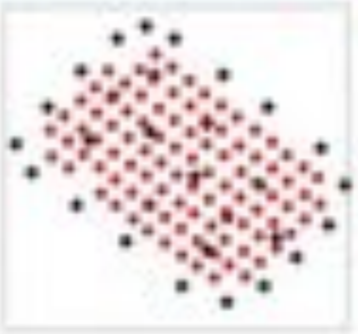
3D investigation: event depths



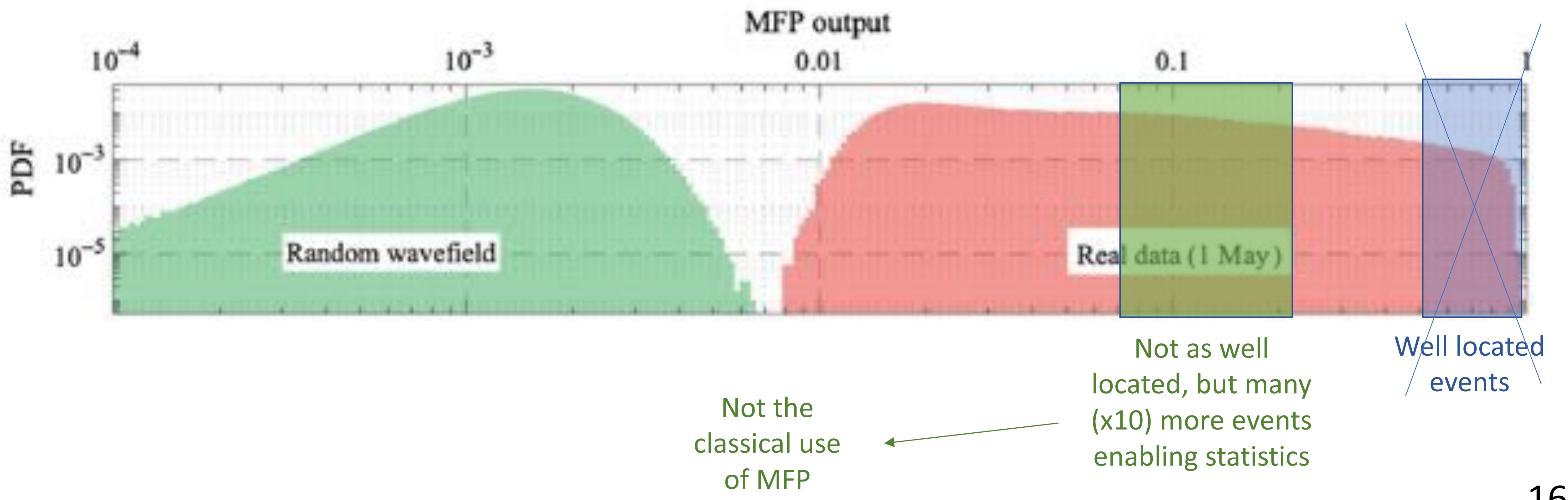




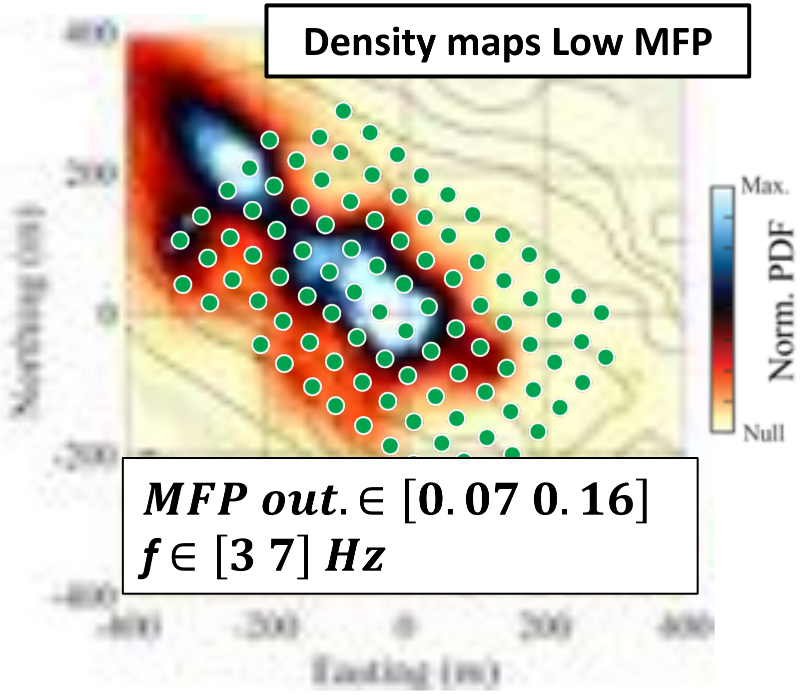
Spatialization using array phase analysis

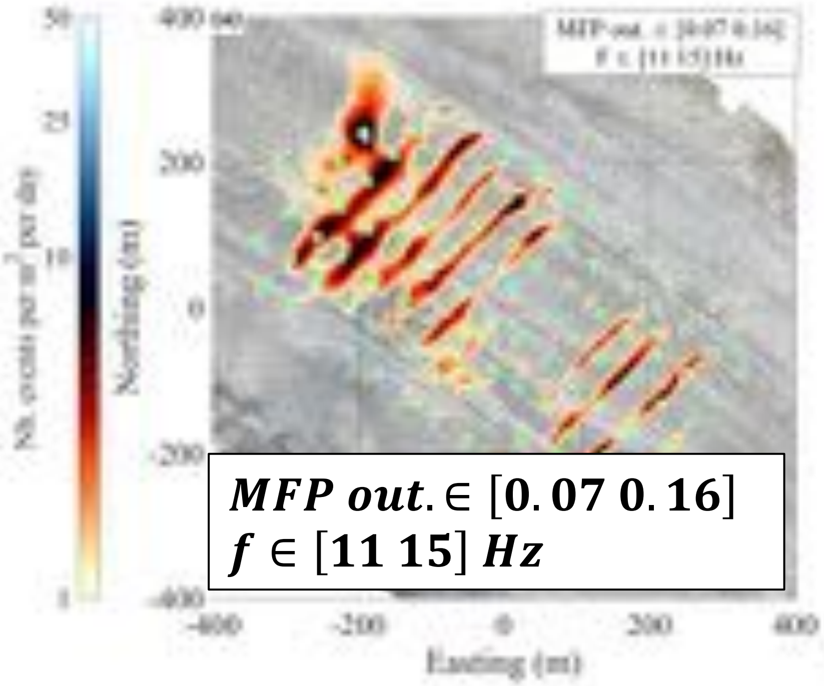


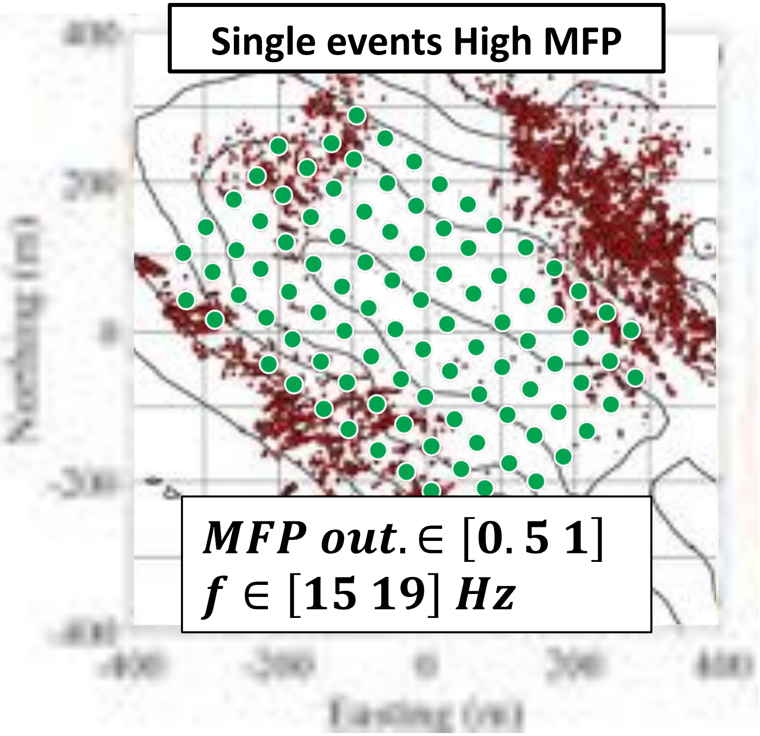
- Use 29 starting points to
  - Increase the likelihood that a global best match is found
  - Allow keeping track of local best matches



Spatialization using array phase analysis

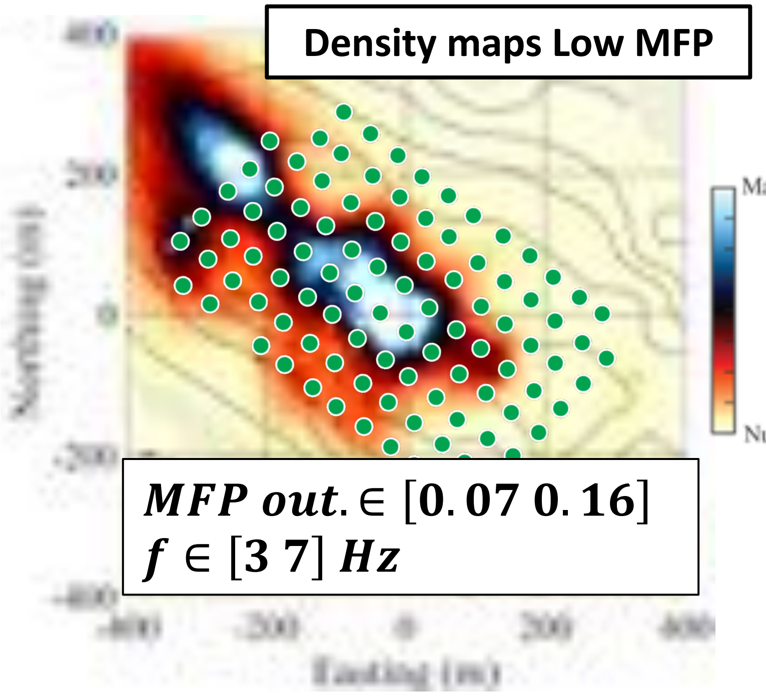


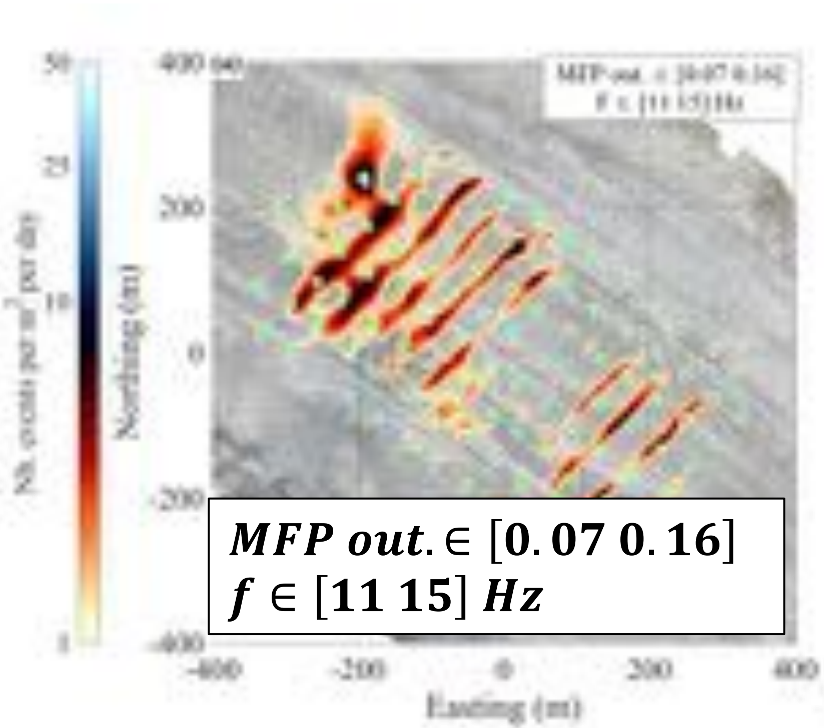


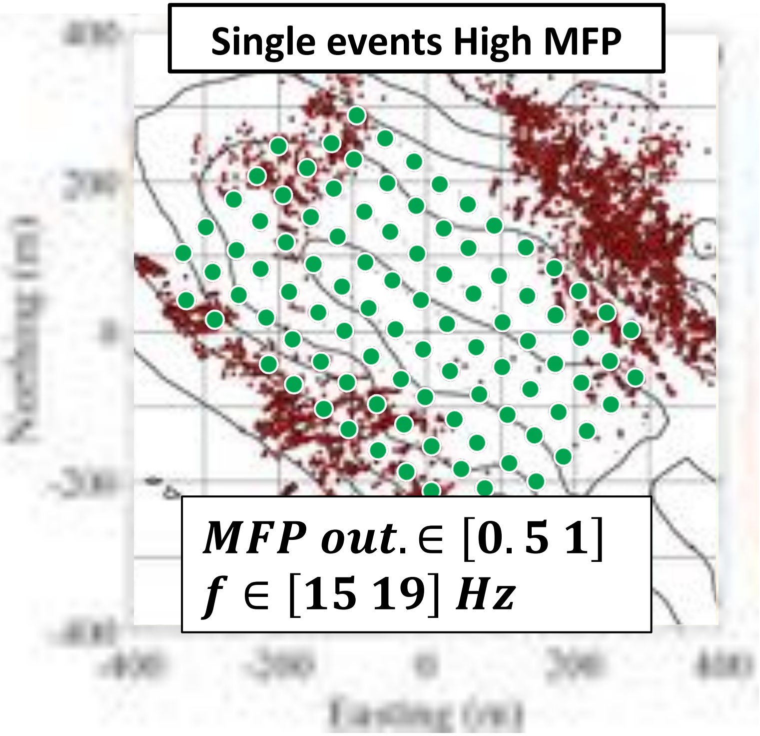


Nanni et al., 2022

Spatialization using array phase analysis







Nanni et al., 2022

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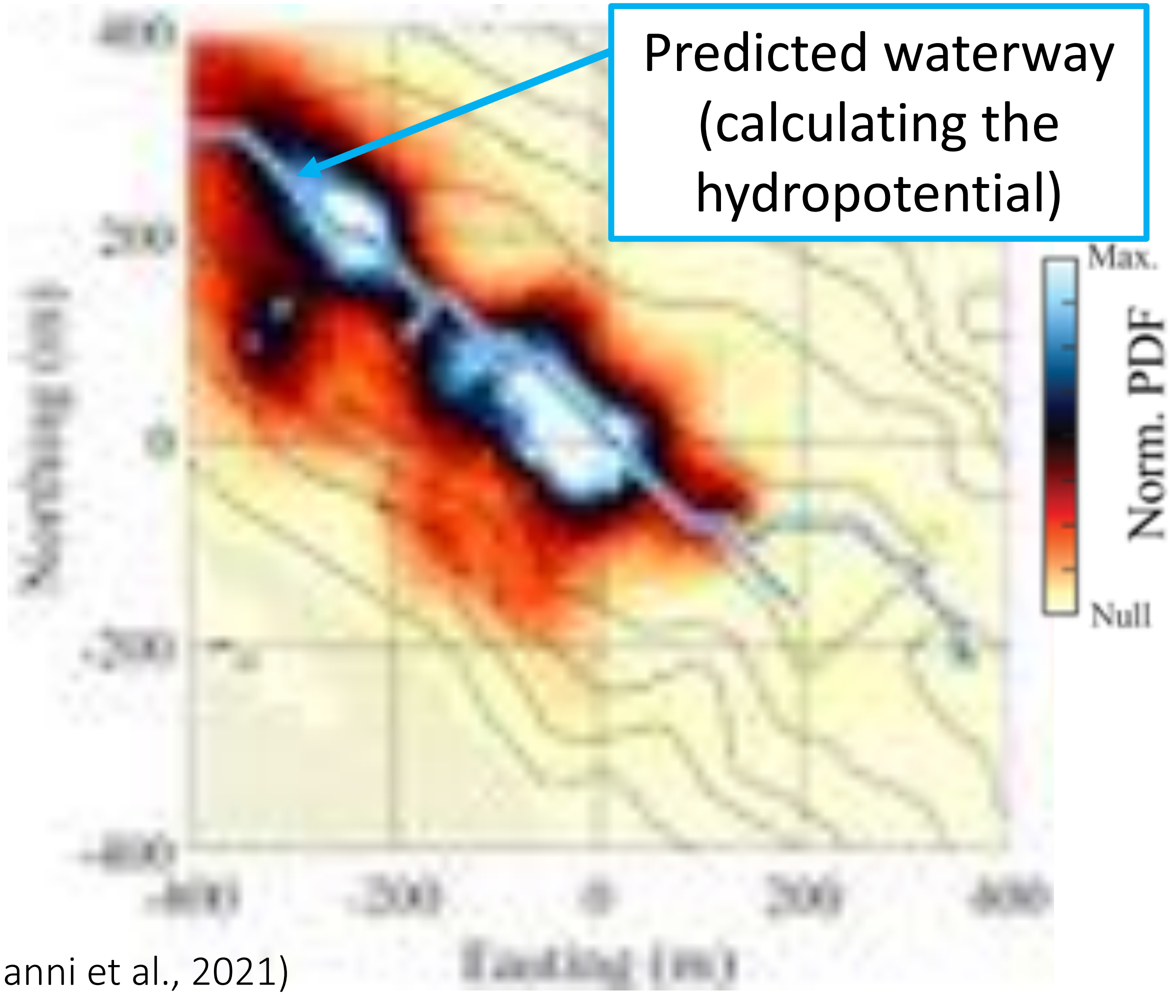


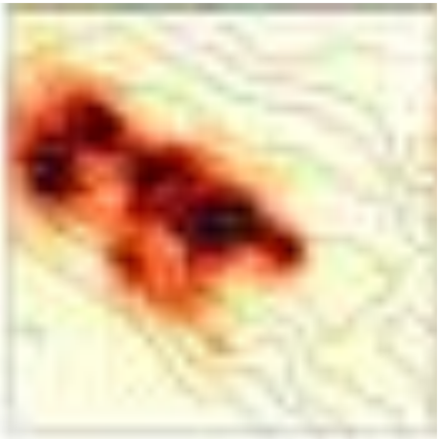
(Nanni et al., 2021)

- Along-flow geometry

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

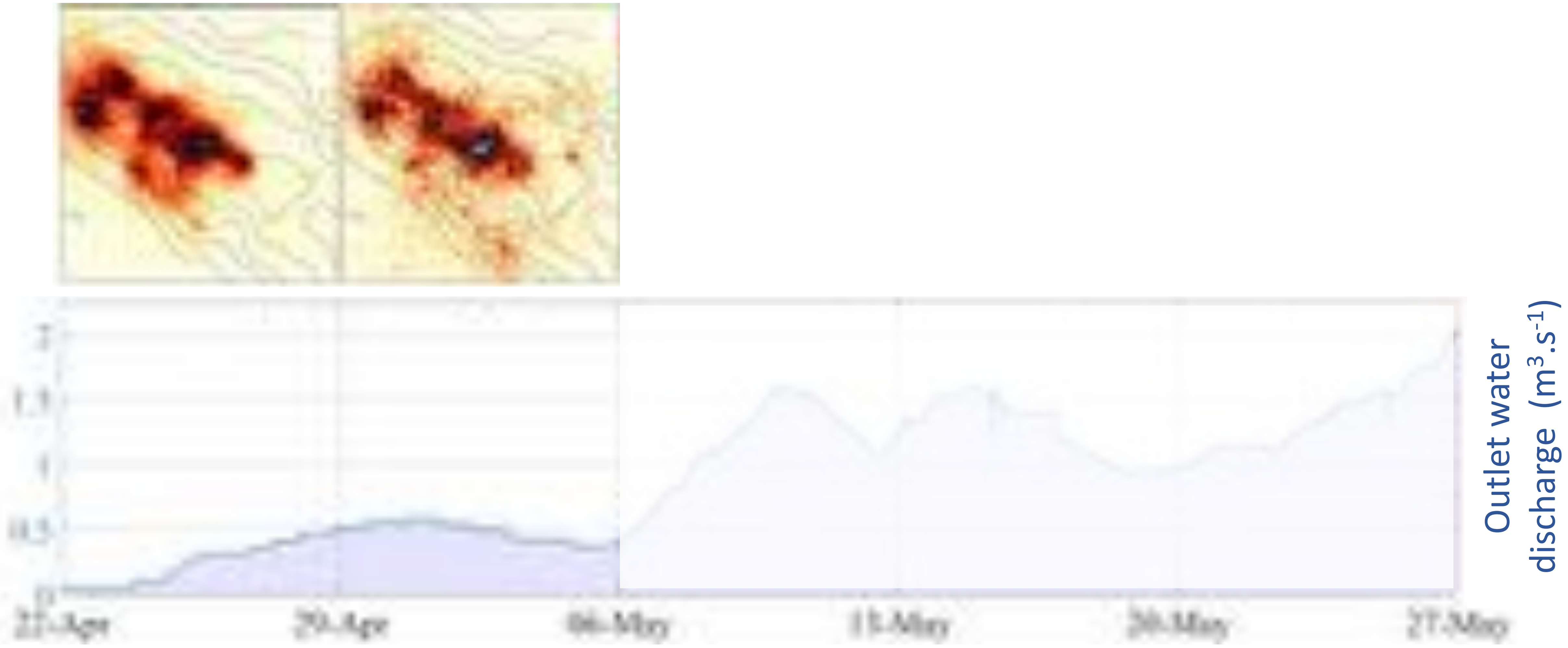
WE ARE ABLE TO LOCATE SUBGLACIAL WATER FLOW

Spatio-temporal dynamics



(Nanni et al., 2021)

From distributed ...



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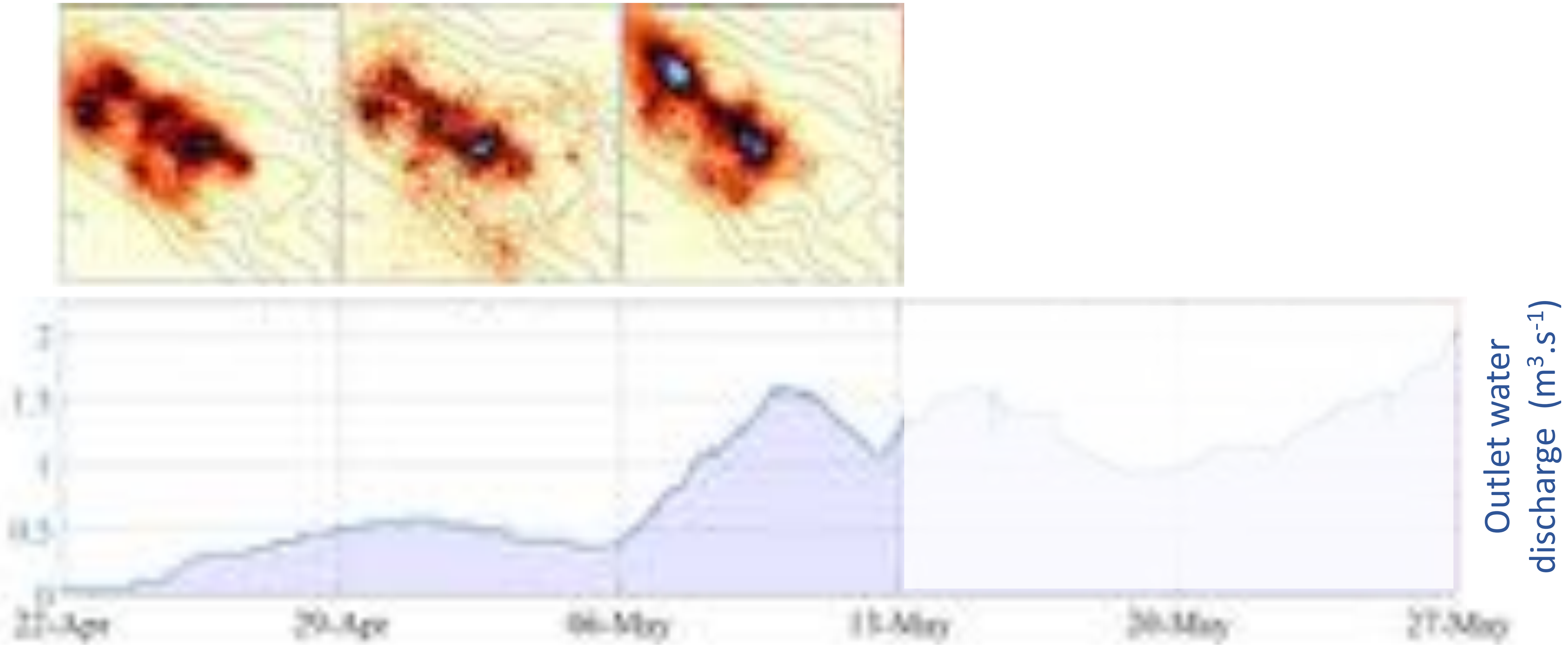
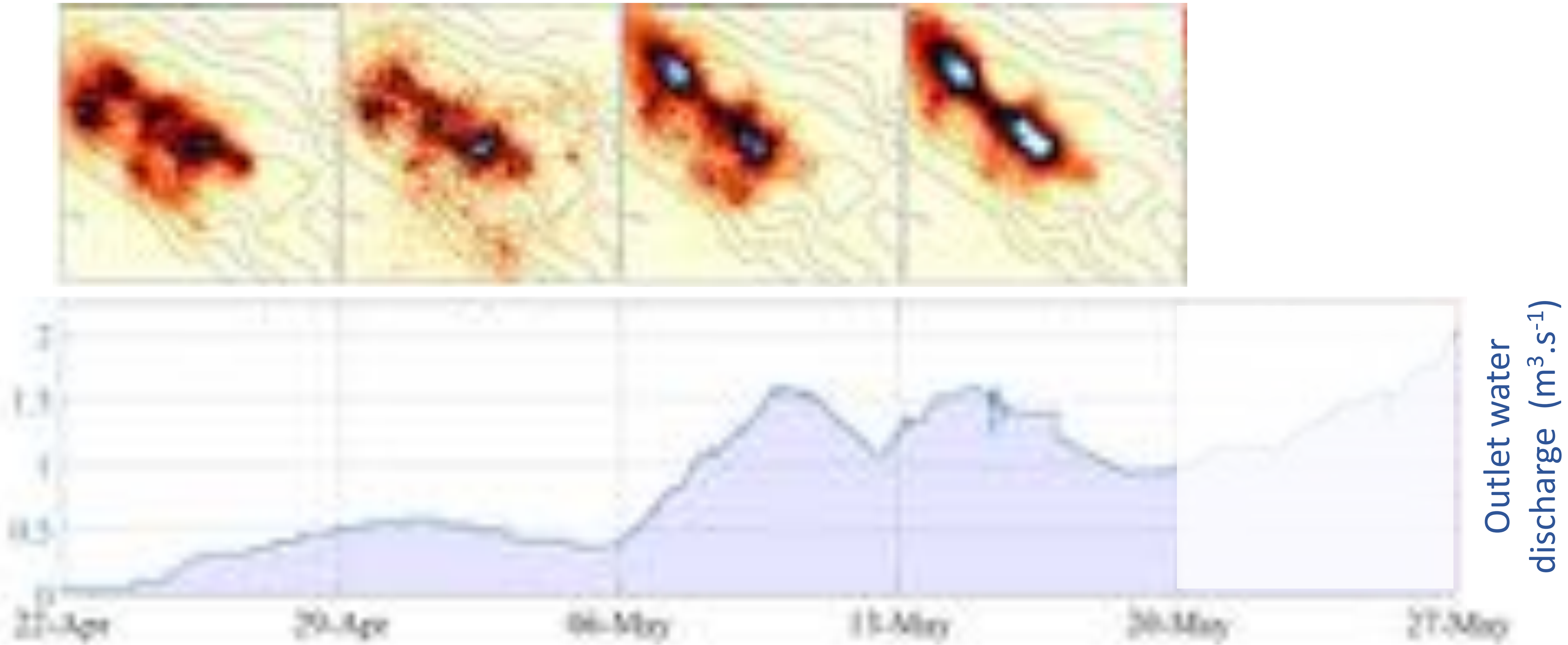


(Nanni et al., 2021)

From distributed … to localized



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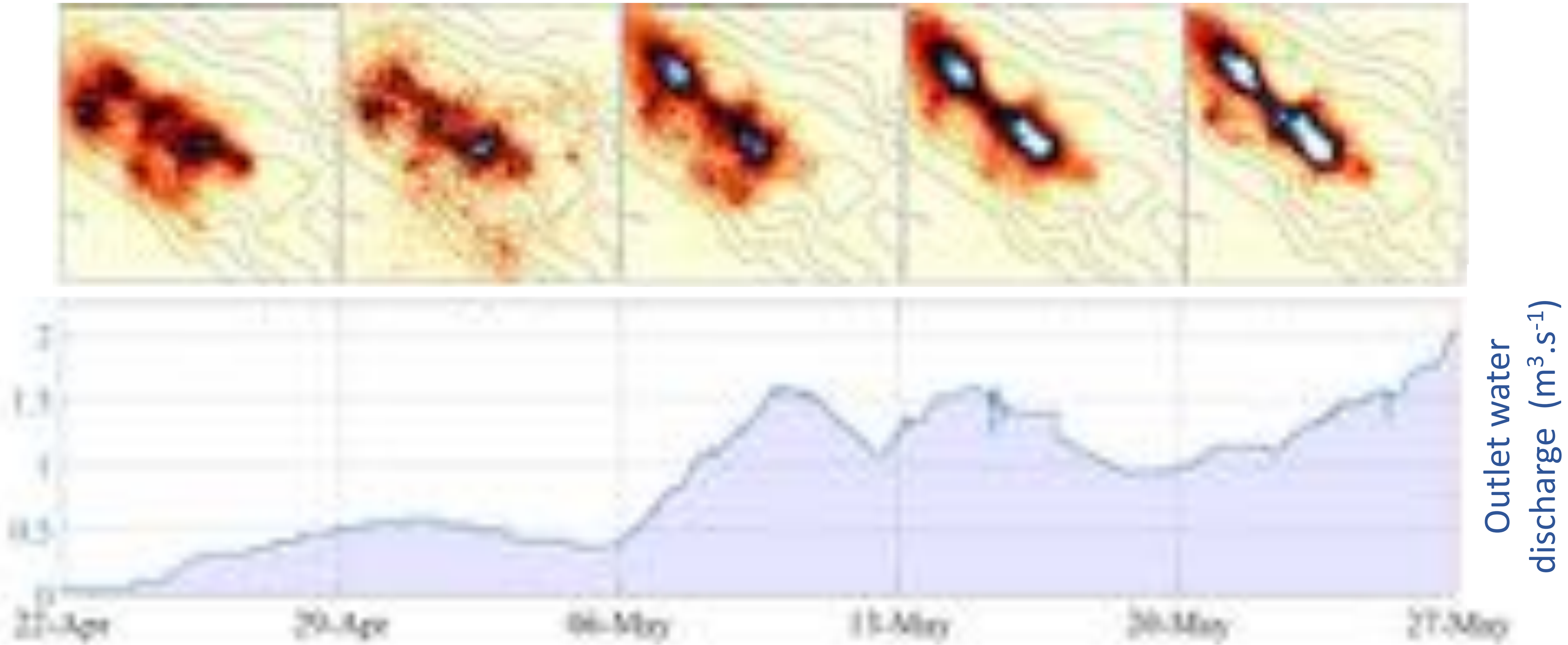
From distributed … to localized



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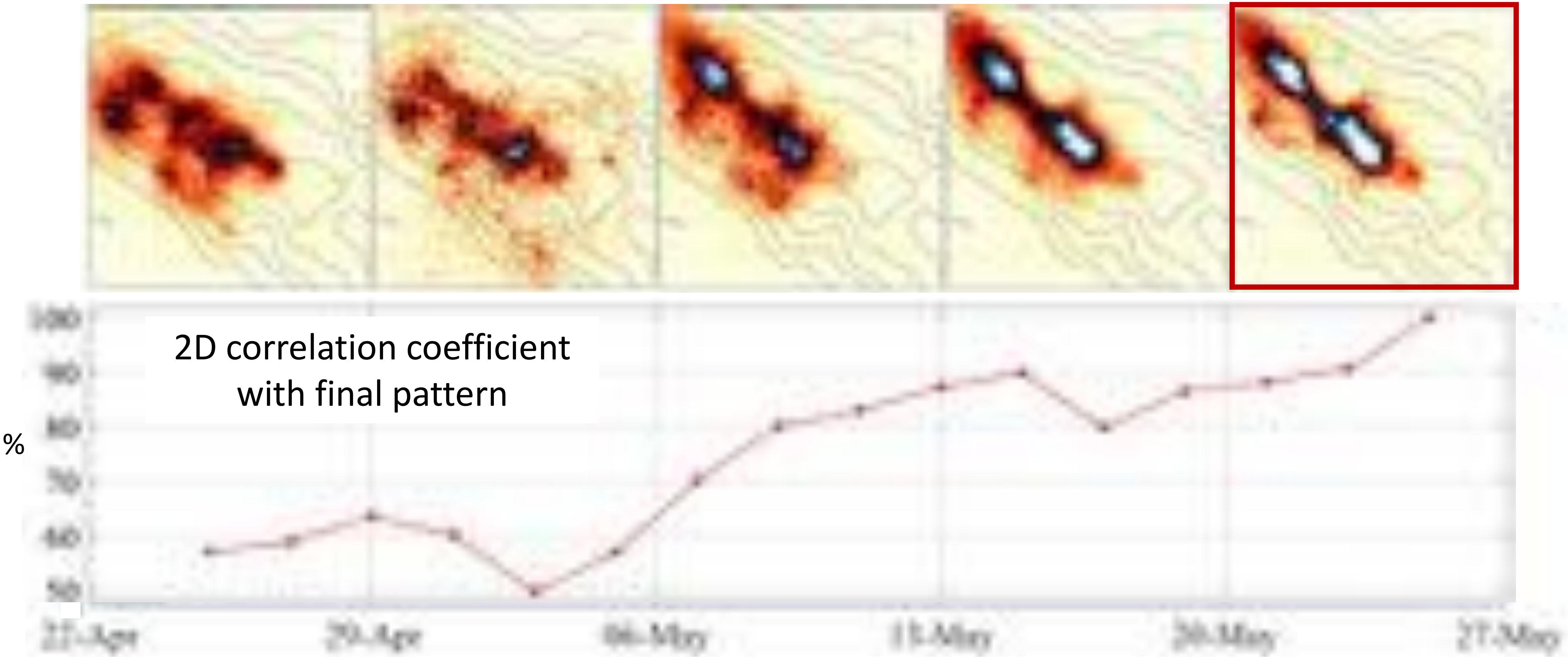
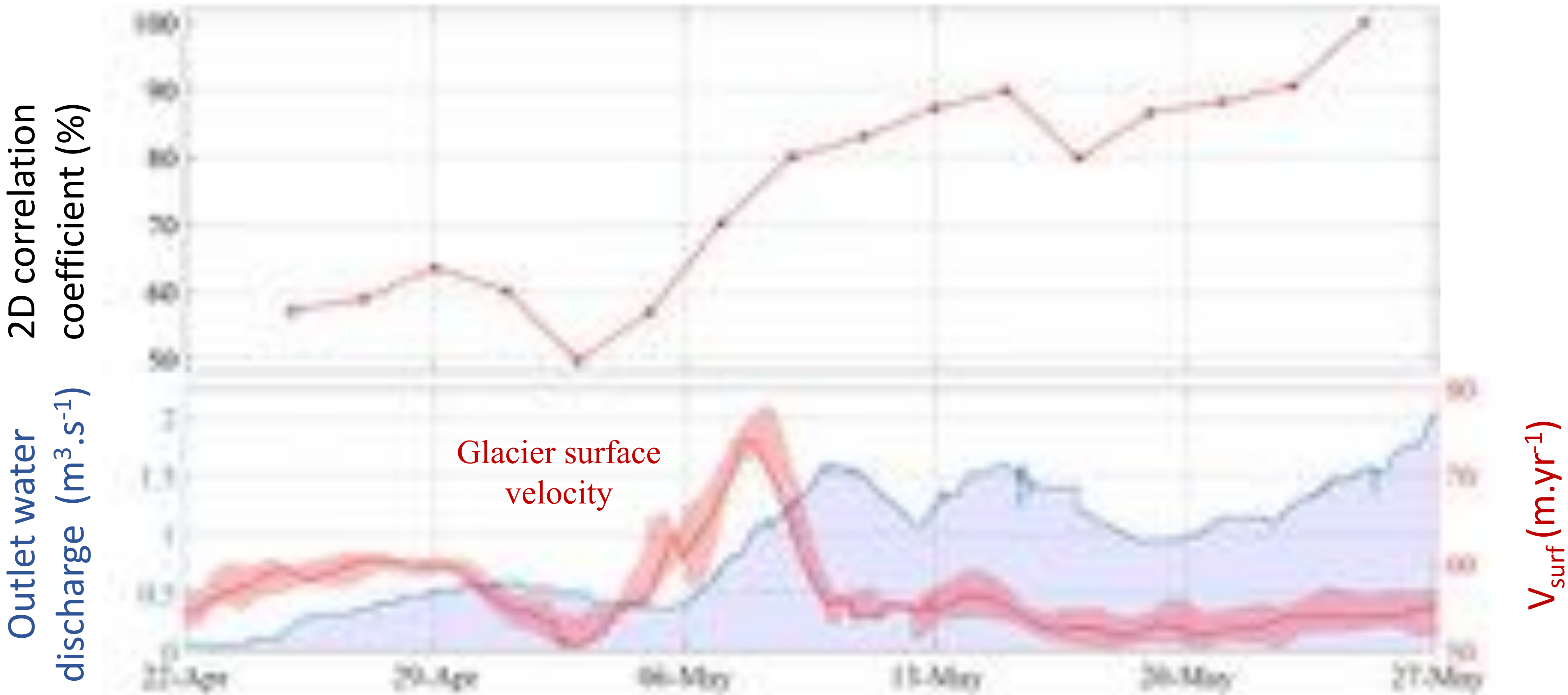


WE ARE CAPABLE OF CAPTURING SUBGLACIAL HYDROLOGY DYNAMICS

Spatial dynamics and hydraulic properties

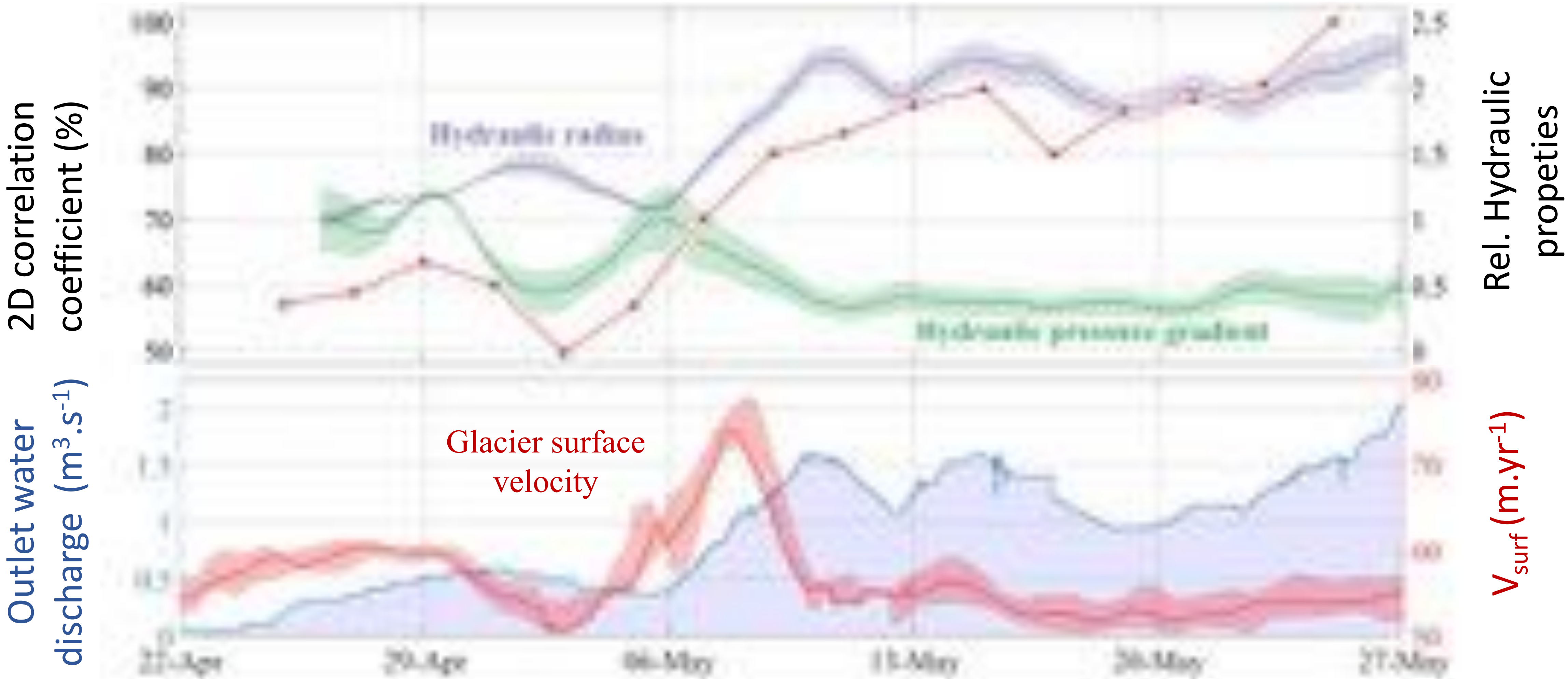
(Nanni et al., 2021)

Spatial dynamics and hydraulic properties



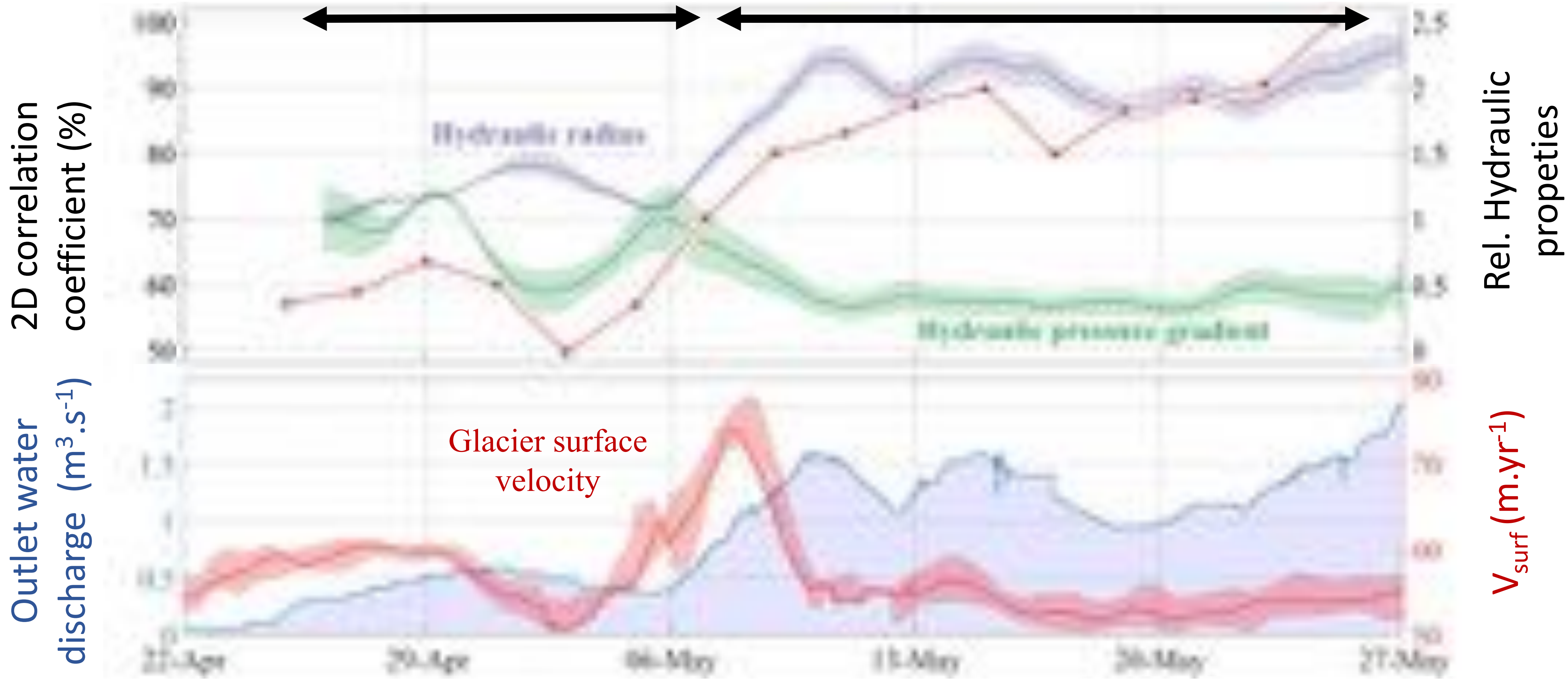
(Nanni et al., 2021)

Spatial dynamics and hydraulic properties



(Nanni et al., 2021)

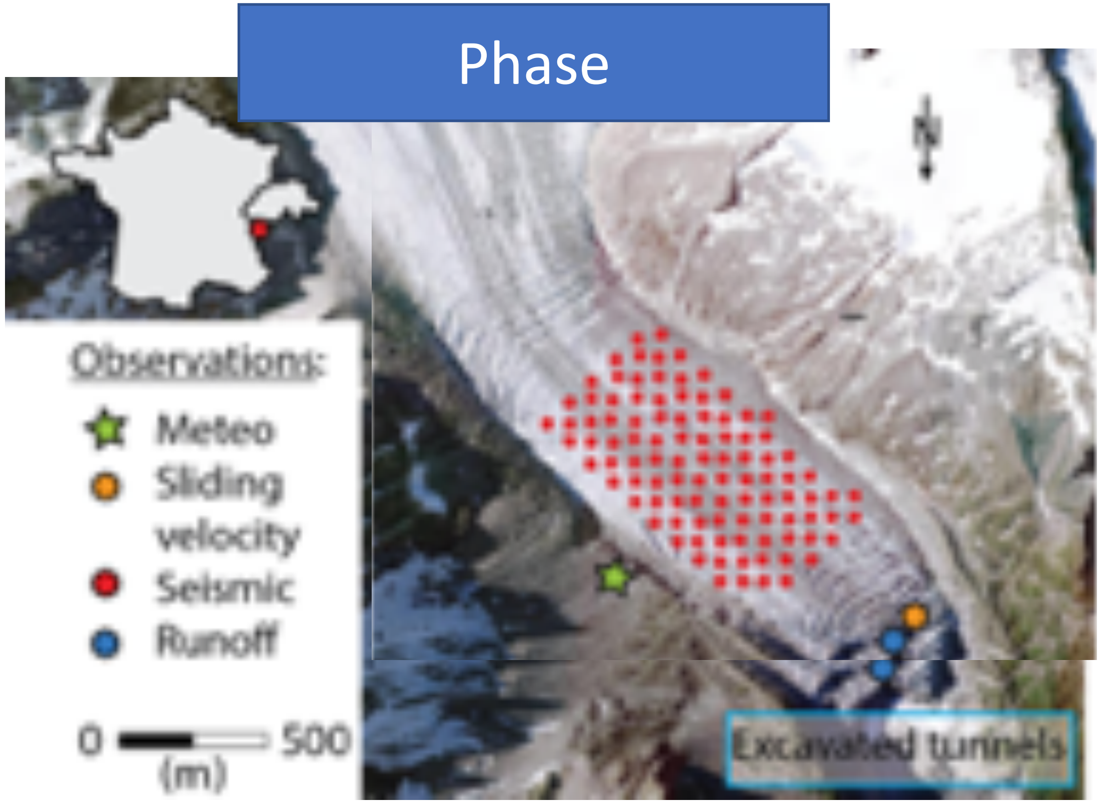
From inefficient to efficient?



(Nanni et al., 2021)

Use arrays of sensors for observing spatial and temporal changes

The Argentière Glacier (France)



Gimbert et al., SRL, 2021; Nanni et al., PNAS, 2021; Nanni et al., GRL, 2022

The Lemon Creek Glacier (Alaska)

Labedz et al., JGR, 2022

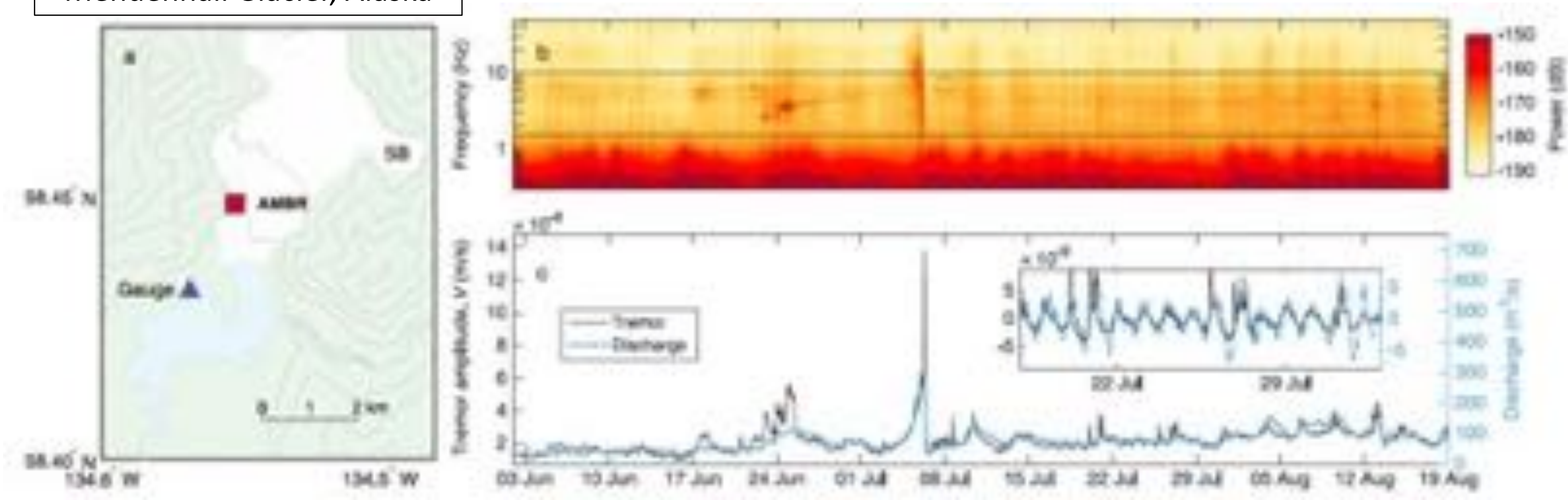
Use arrays of sensors for observing spatial and temporal changes

The Lemon Creek Glacier (Alaska)

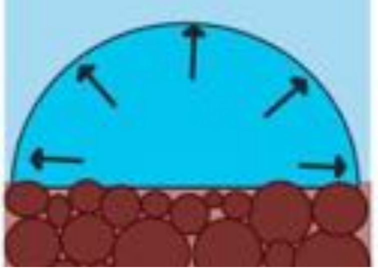
Labedz et al., JGR, 2022

Subglacial hydrology
« Tremors » generated by subglacial water flow

Mendenhall Glacier, Alaska



Bartholomaus et al., 2015



Understanding the physical process behind the « tremor » source

Mendenhall Glacier, Alaska

End-member cases

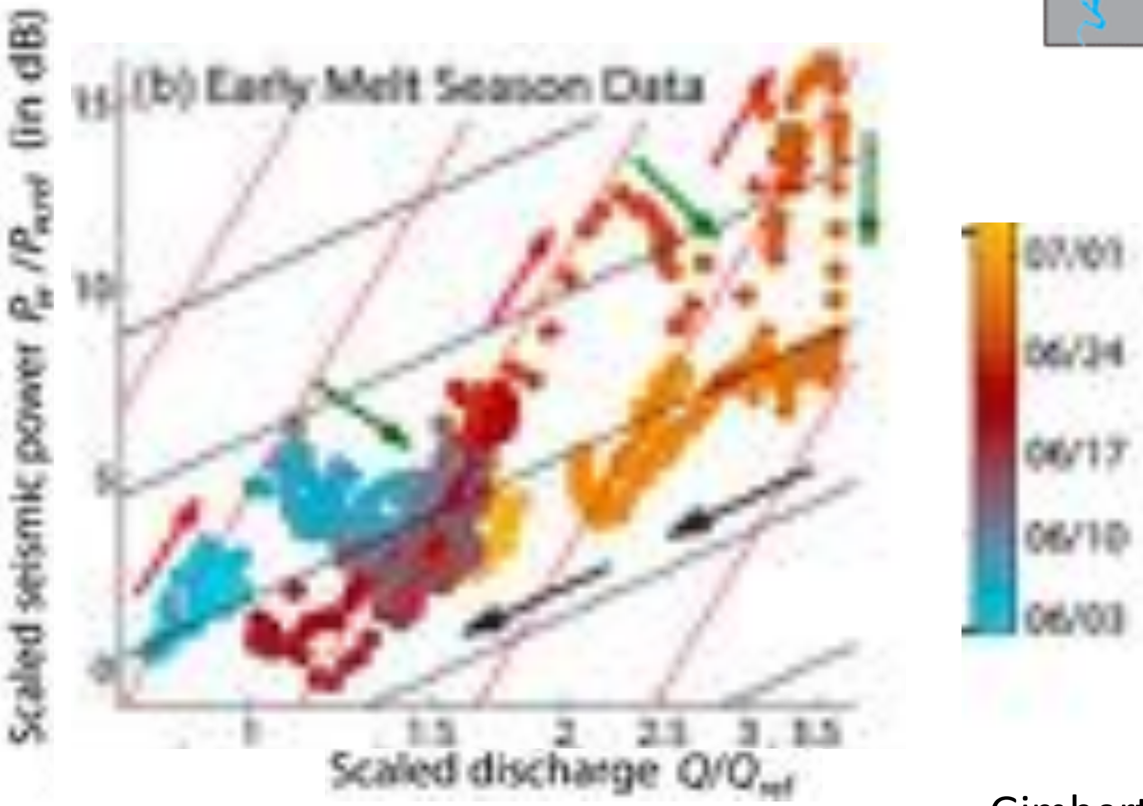
Varying pressure

$P_w \propto Q^{14/3}$ **STRONG scaling**

$\neq$

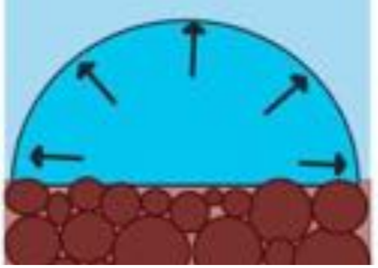
Varying size

$P_w \propto Q^{5/3}$ **WEAK scaling**



Gimbert et al., 2016

Evolution of physical variables like pressure and size can be quantified using seismic and subglacial discharge observations



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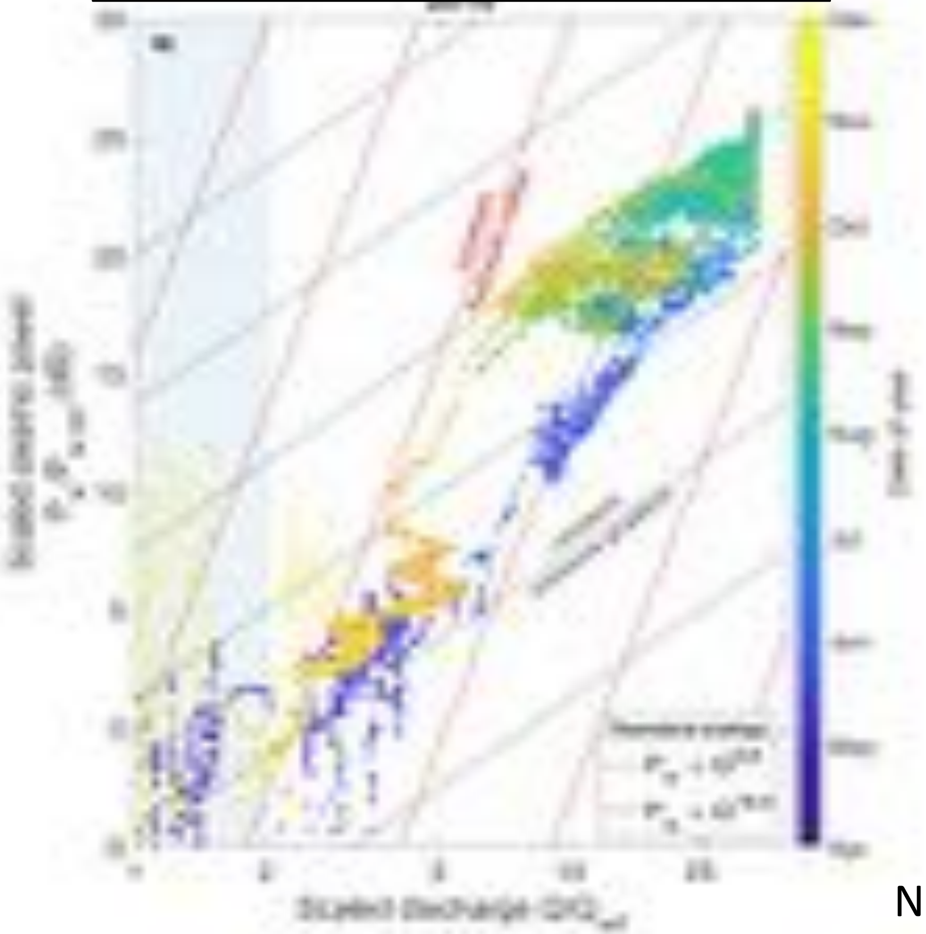

Nanni et al., 2020

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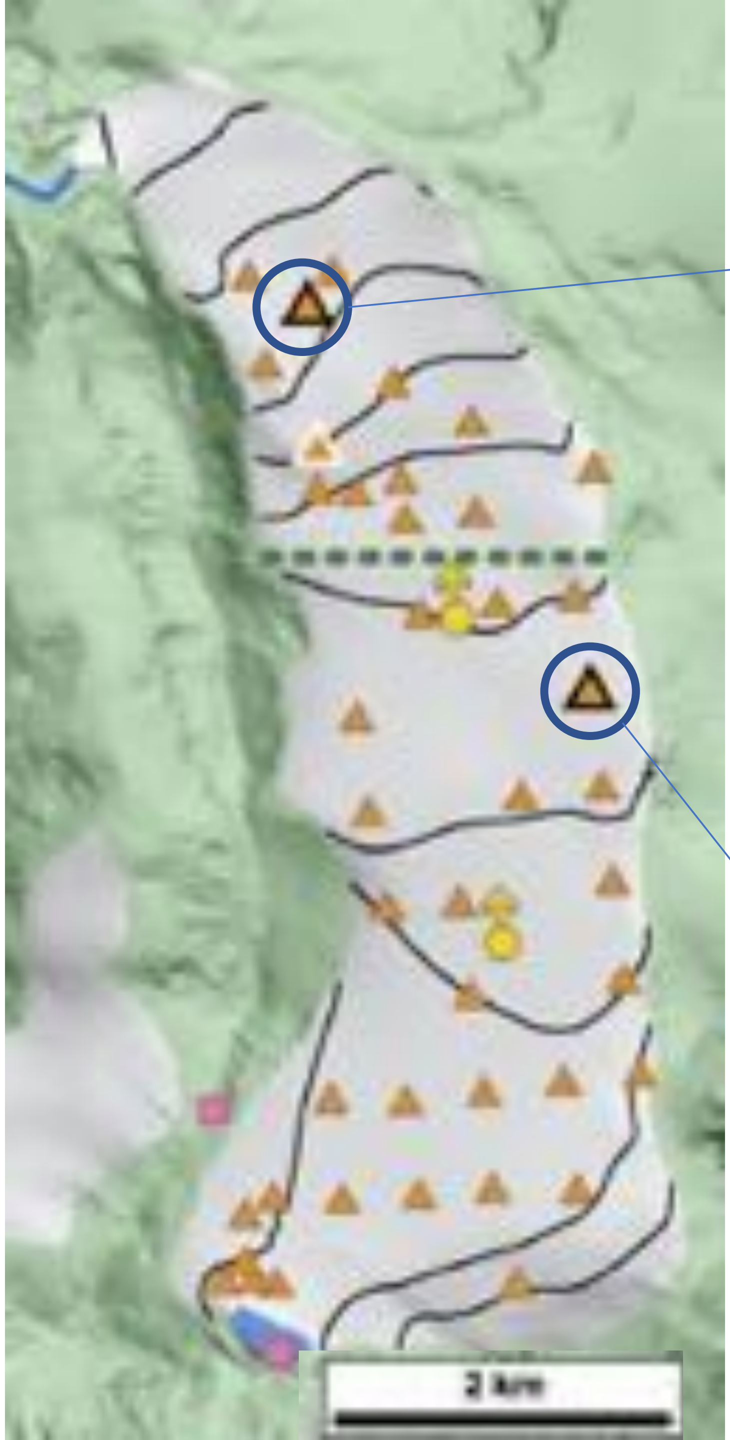
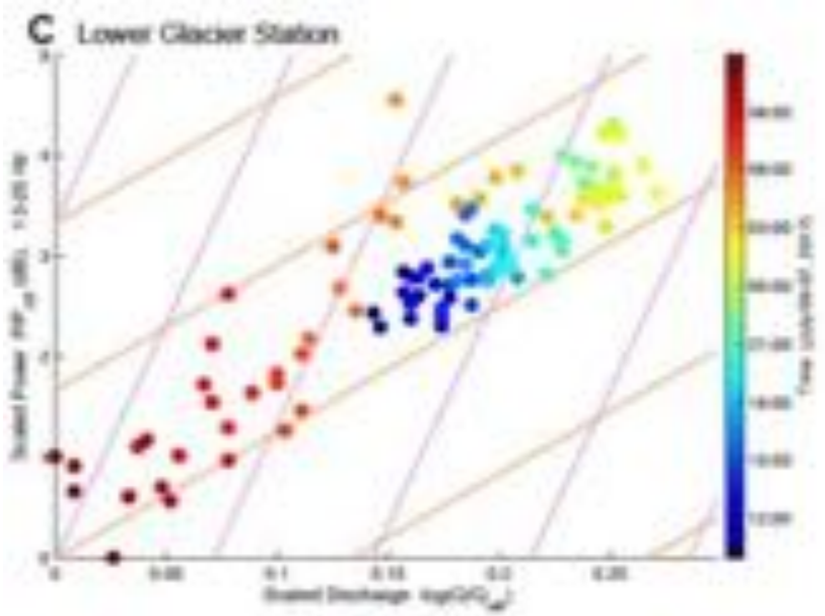
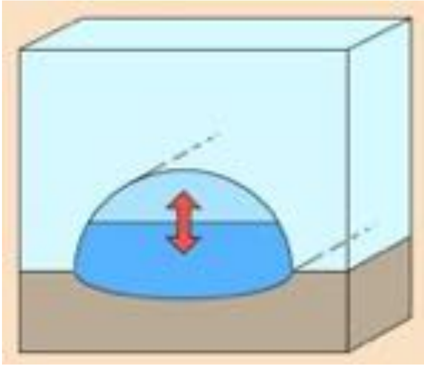
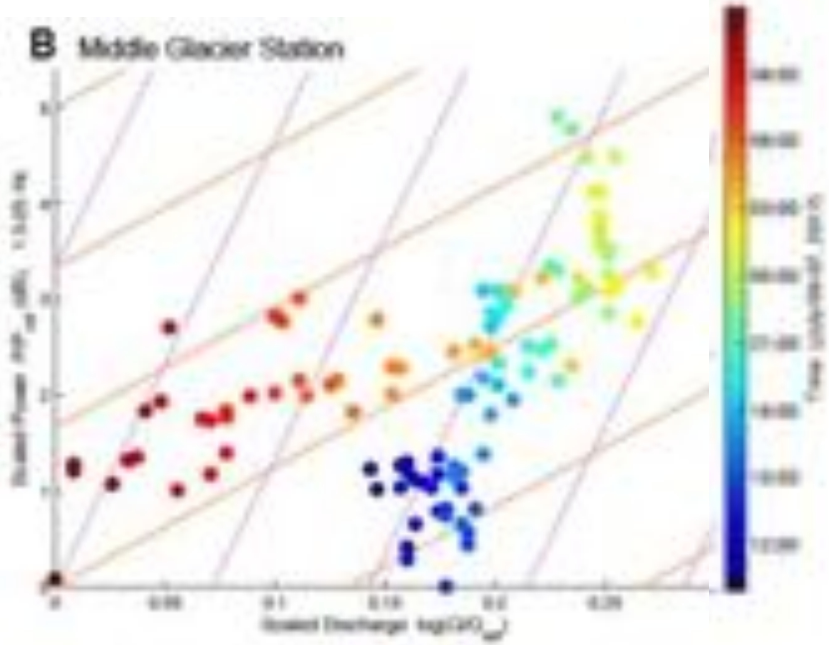


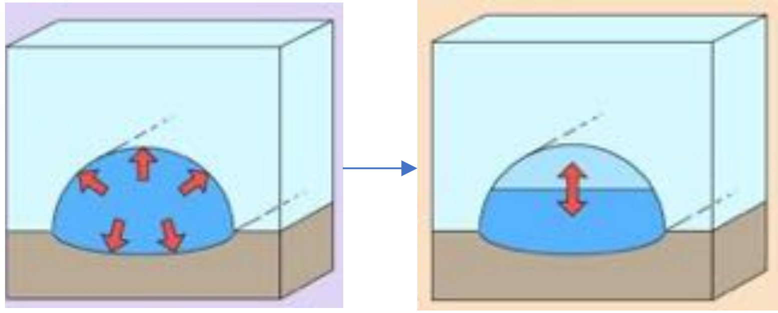


Subglacial conduit flow evolves at constant pressure gradient/varying radius

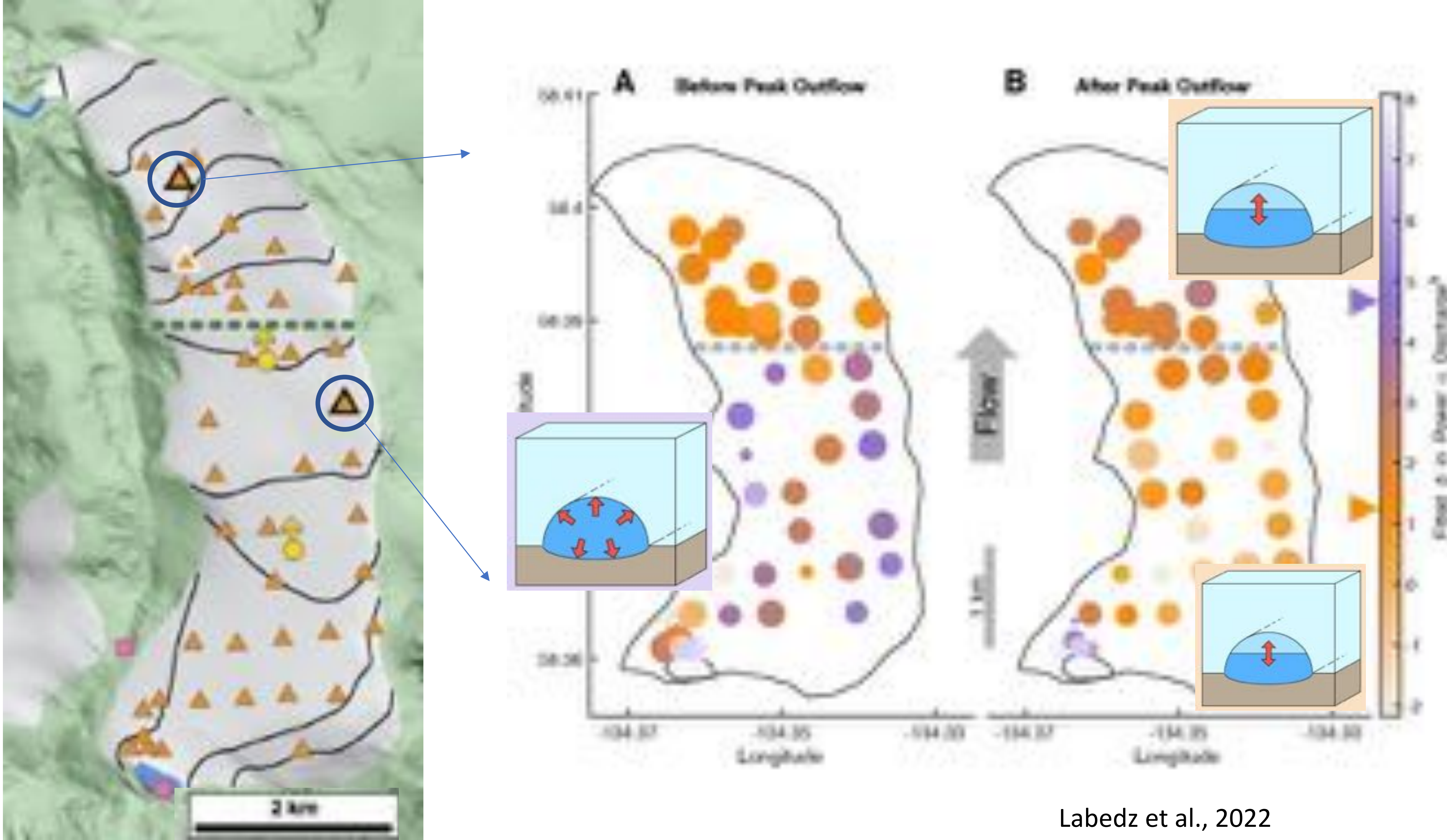




Subglacial conduit flow transitions from varying to constant pressure gradient



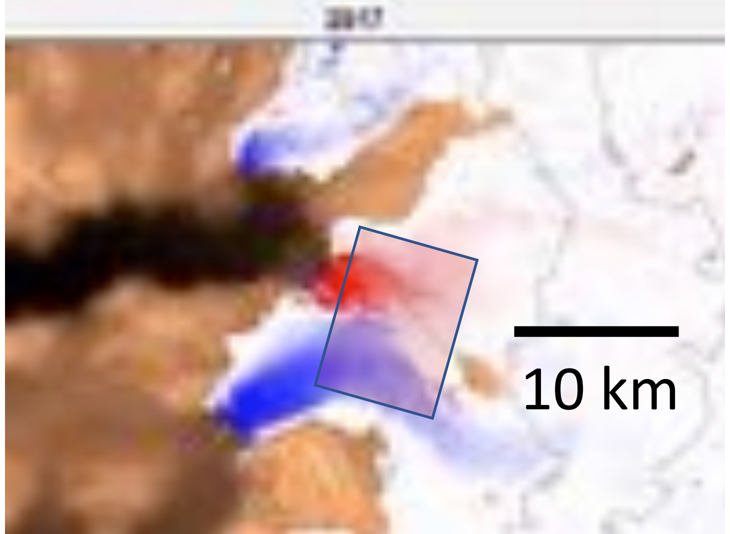
Labedz et al., 2022



Labedz et al., 2022

PERSPECTIVES

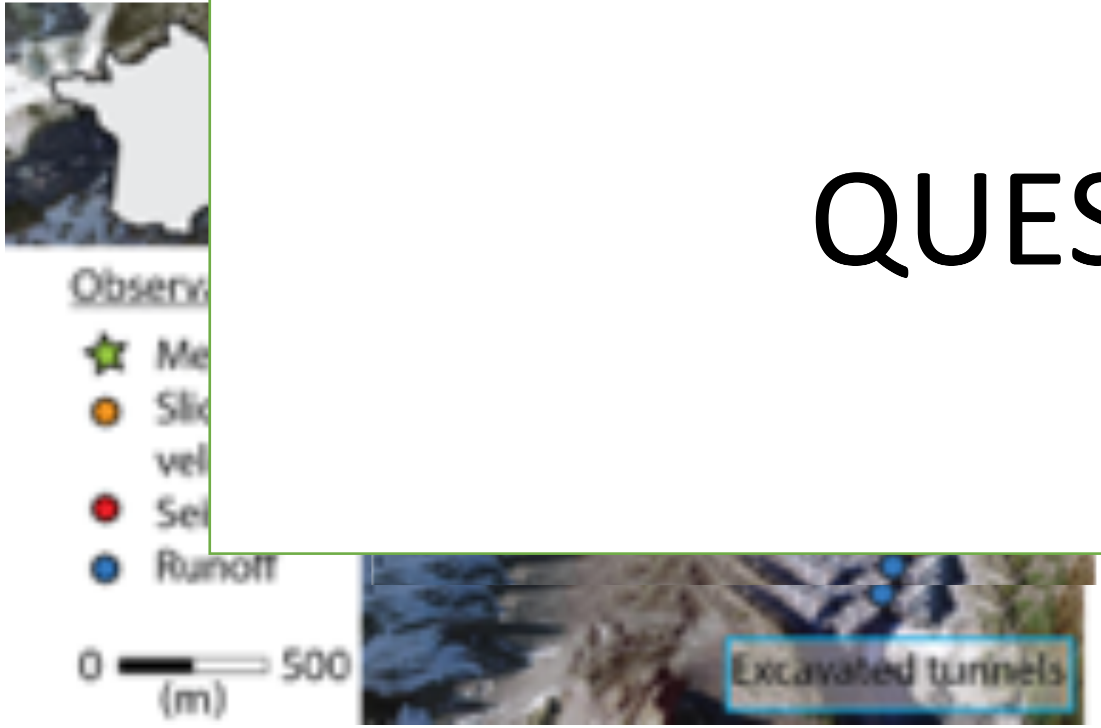
Target representative areas while ensuring imaging capabilities

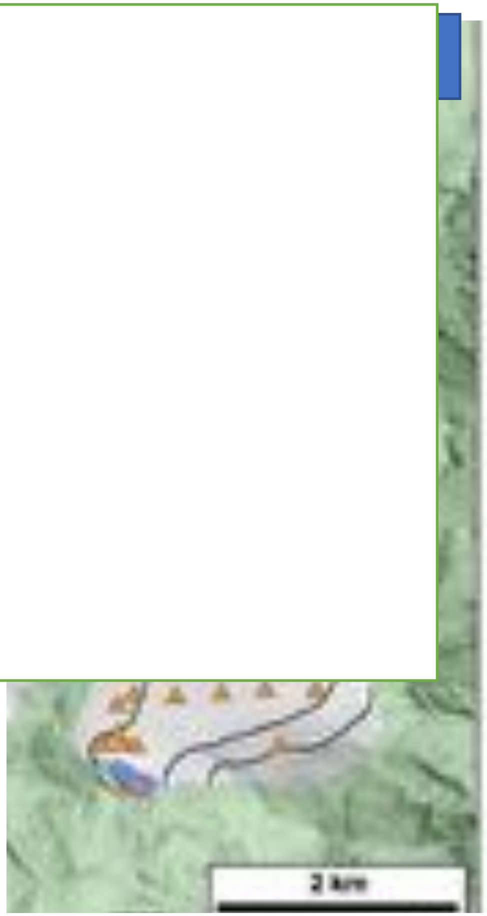


Use arrays of sensors for observing spatial and temporal changes

The Argentière Glacier (France)

The Lemon Creek Glacier (Alaska)





QUESTIONS ?

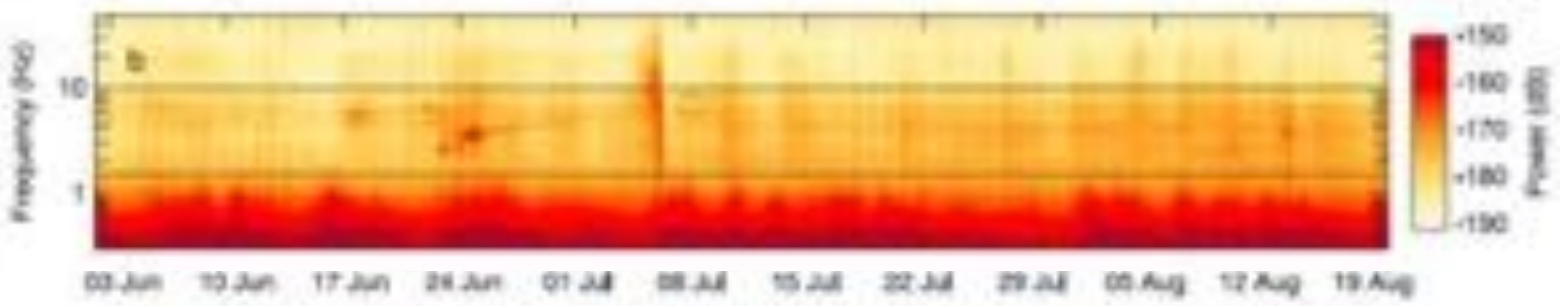
Gimbert et al., SRL, 2021; Nanni et al., PNAS, 2021; Nanni et al., GRL, 2022

Labedz et al., JGR, 2022

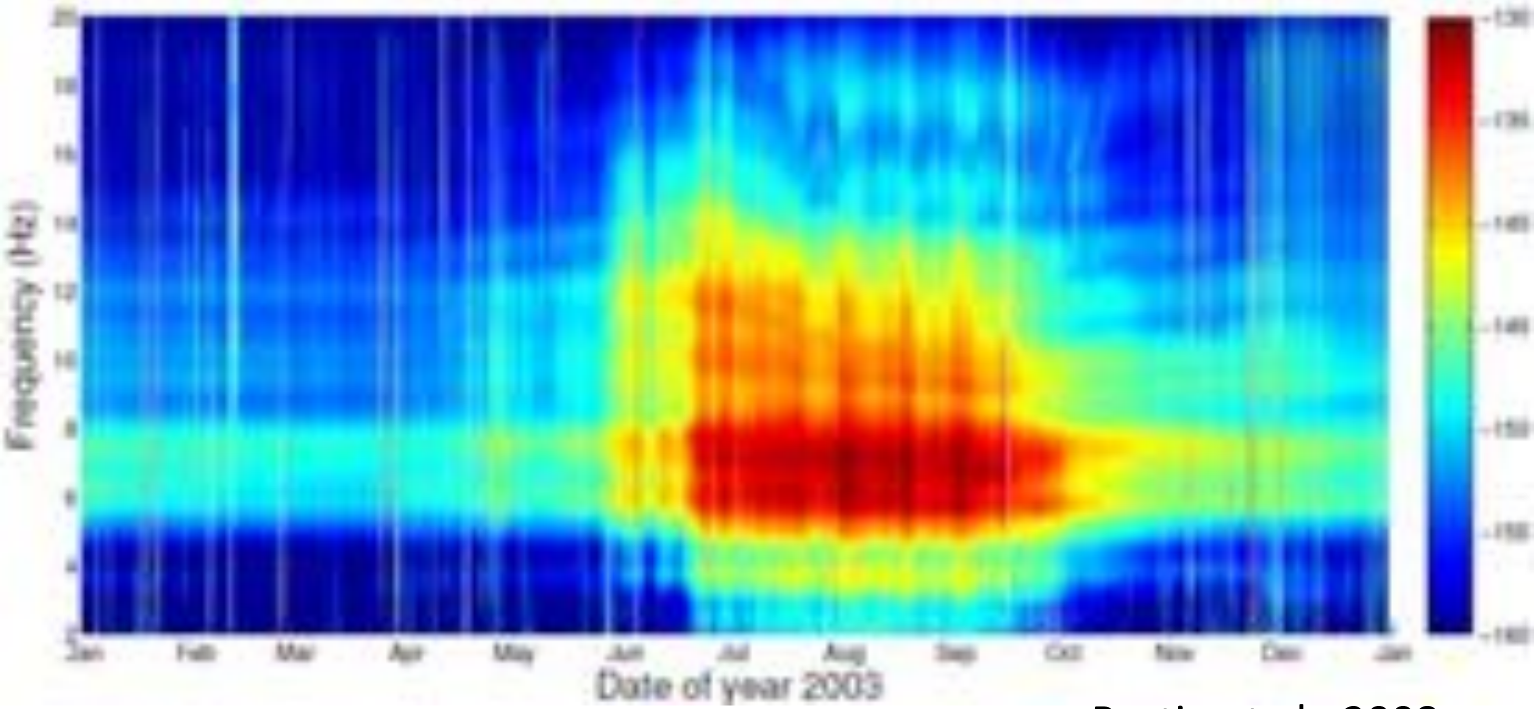
1- Understand the physical process behind the « tremor » source

Glacier

Bartholomaus et al., 2015



River



Burtin et al., 2008

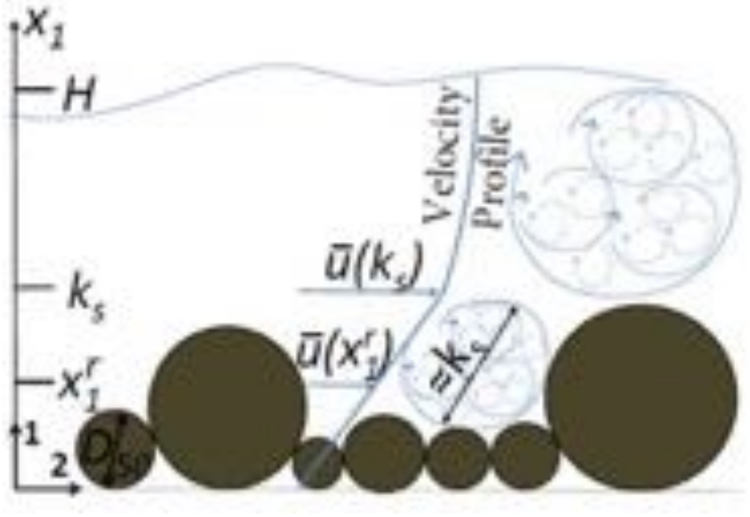
1- Understand the physical process behind the « tremor » source

$$U(f) = F(f) \cdot G(f)$$

Ground velocity Source Green's function

Open surface flow (e.g. river)

Turbulent eddies impinging the rough bed



Gimbert et al., 2014

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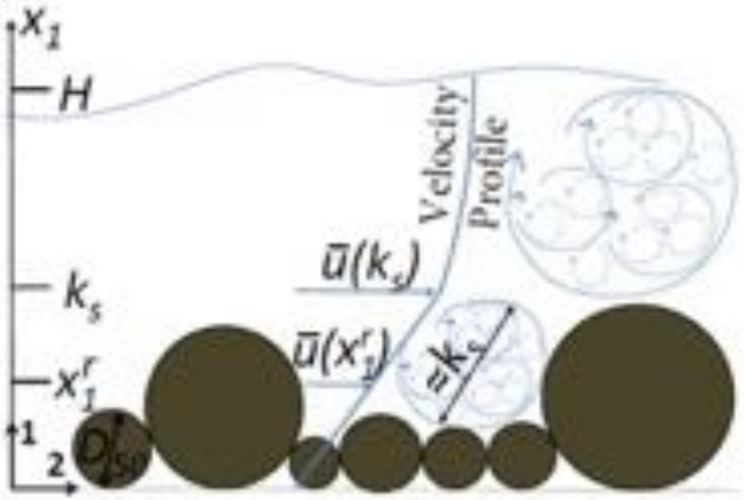
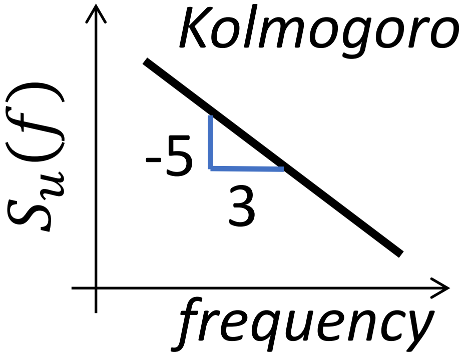


Frequency scaling

Kolmogorov, 1941



Amplitudes of velocities

$$u(t) = u + u'(t)$$

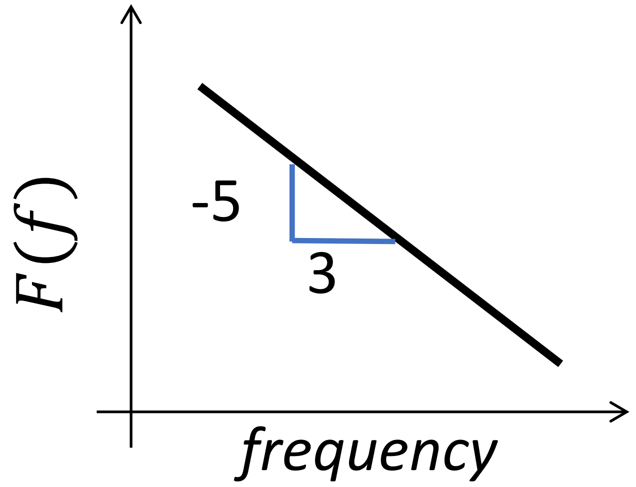
Lamb et al., 2008

$$\begin{cases} \dfrac{\sqrt{\overline{u'(t)^2}}}{u_*} \approx f_1\left(\dfrac{k_s}{H}\right) \\ \dfrac{\bar{u}}{u_*} \approx f_2\left(\dfrac{k_s}{H}\right) \end{cases}$$

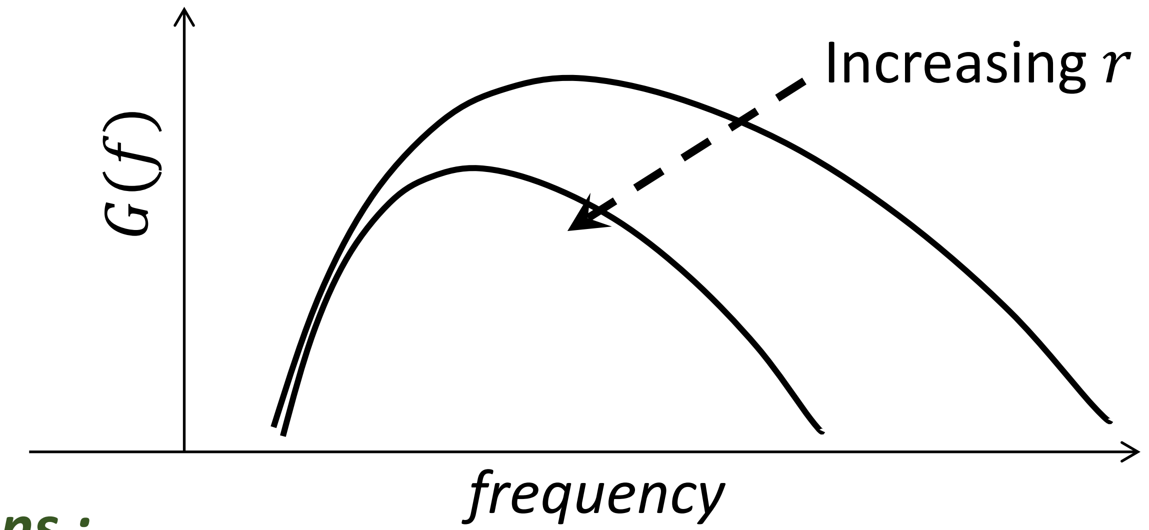
Gimbert et al., 2014

1- Understand the physical process behind the « tremor » source

Open surface flow (e.g. river)



x



$$\boxed{|F(f)| \propto W u_*^{14/3}}$$

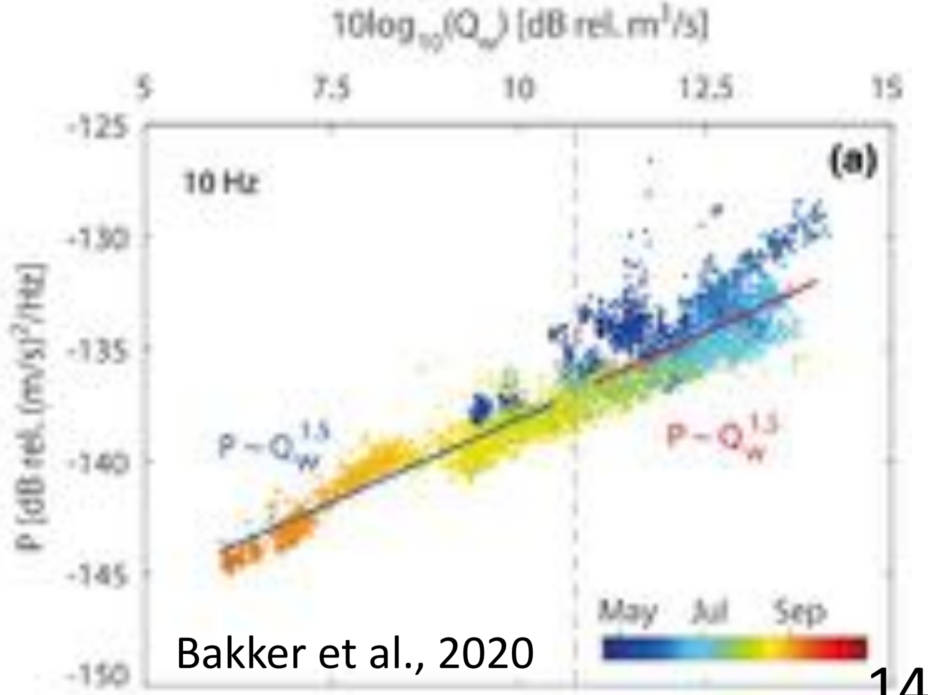
$$P \sim Q^{1.4}$$

Seismic power

Water discharge

Gimbert et al., 2014

Field observations :



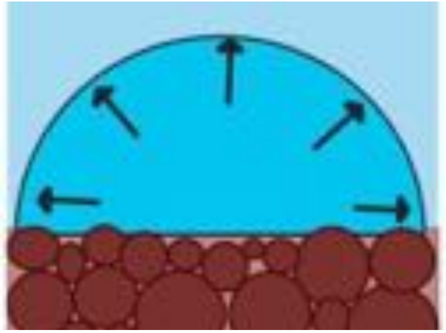
Bakker et al., 2020

1- Understand the physical process behind the « tremor » source

Open surface flow (e.g. river)

$$\boxed{|P(f)| \propto W u_*^{14/3}} \longleftrightarrow \quad P \sim Q^{1.4}$$

Closed conduit (e.g. subglacial channel)



$$P_w \propto \Gamma u_*^{14/3} \quad \text{with} \quad u_* = \sqrt{gRS}$$

$$\boxed{P_w \propto R^{10/3} S^{7/3}}$$

R : hydraulic radius

$$R = A/\Gamma$$

S : hydraulic pressure gradient

$$S = -\frac{1}{\rho g}\frac{\partial p}{\partial x} + \tan\theta$$

1- Understand the physical process behind the « tremor » source

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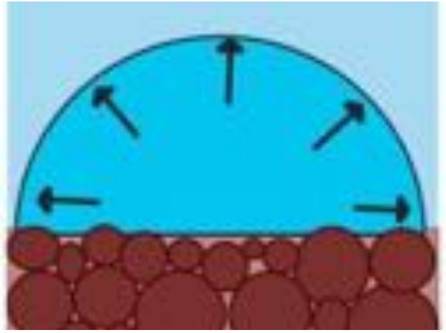

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$$\boxed{P_w \propto R^{10/3} S^{7/3}}$$

$$Q = AU \quad \text{with} \quad U \propto R^{2/3} S^{1/2}$$

Manning, 1891

$$\boxed{Q \propto R^{8/3} S^{1/2}}$$

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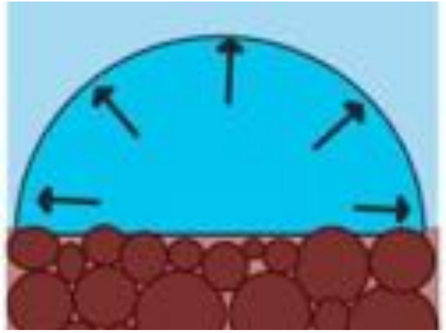

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$$\begin{cases} P_w \propto R^{-82/9} Q^{14/3} \\ P_w \propto S^{41/24} Q^{5/4} \end{cases}$$

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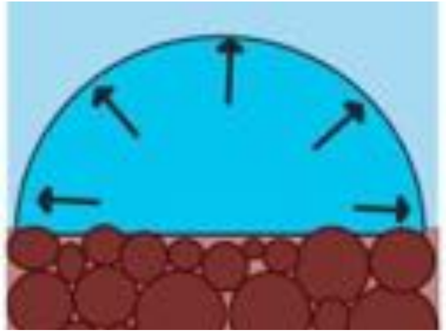

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End-member cases

Varying pressure

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$\neq$

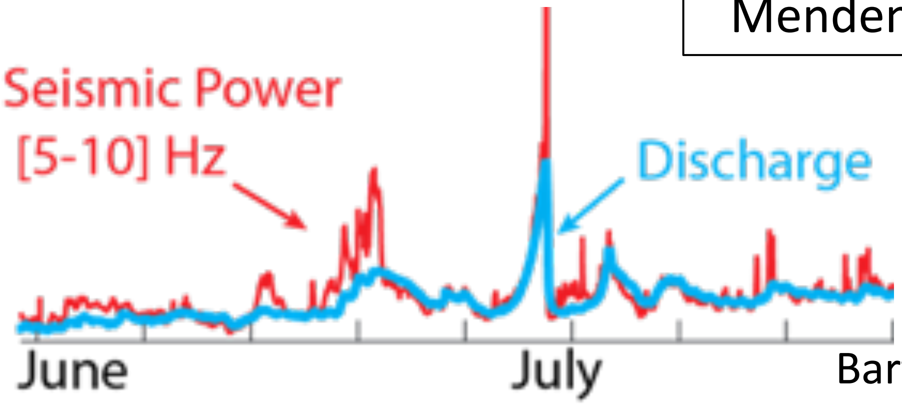
Varying size

$P_w \propto Q^{5/3}$ **WEAK scaling**

Water flow causes ground shaking

Field observations :

Mendenhall Glacier, Alaska



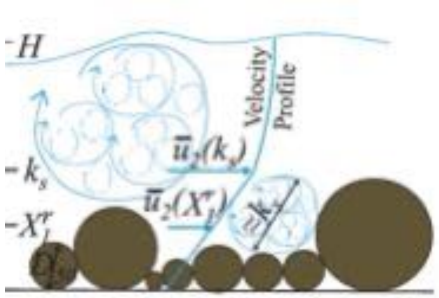
Bartholomaus et al., 2015

Open surface flow (e.g. river)

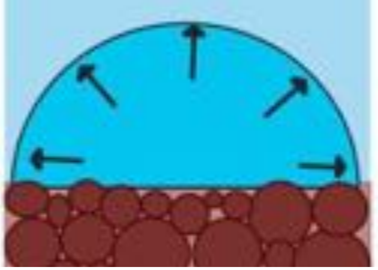
Theory :

$$P \sim Q^{1.4}$$

Seismic power   Discharge



Gimbert et al., 2014



Understanding the physical process behind the « tremor » source

Mendenhall Glacier, Alaska

End-member cases

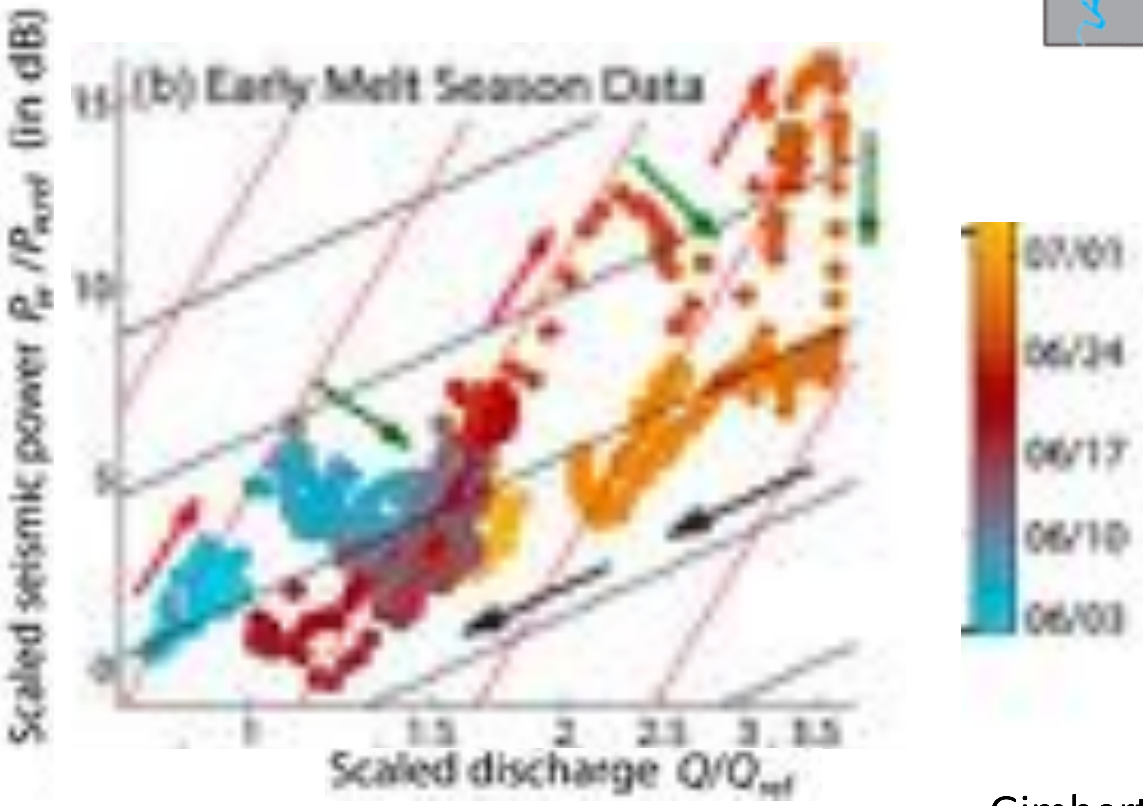
Varying pressure

$P_w \propto Q^{14/3}$ **STRONG scaling**

$\neq$

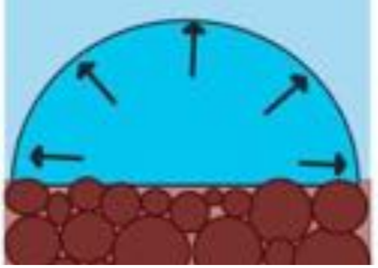
Varying size

$P_w \propto Q^{5/3}$ **WEAK scaling**



Gimbert et al., 2016

Evolution of physical variables like pressure and size can be quantified using seismic and subglacial discharge observations



Understanding the physical process behind the « tremor » source

End-member cases

Varying pressure

$P_w \propto Q^{14/3}$ **STRONG scaling**

$\neq$

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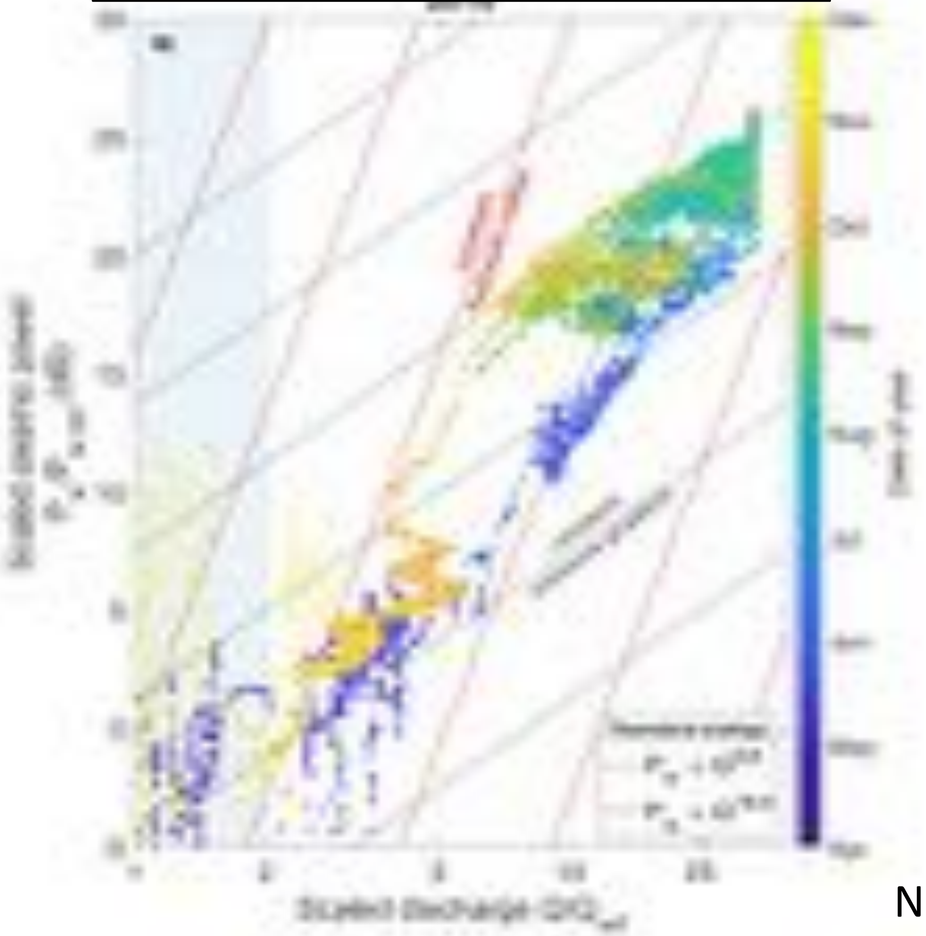
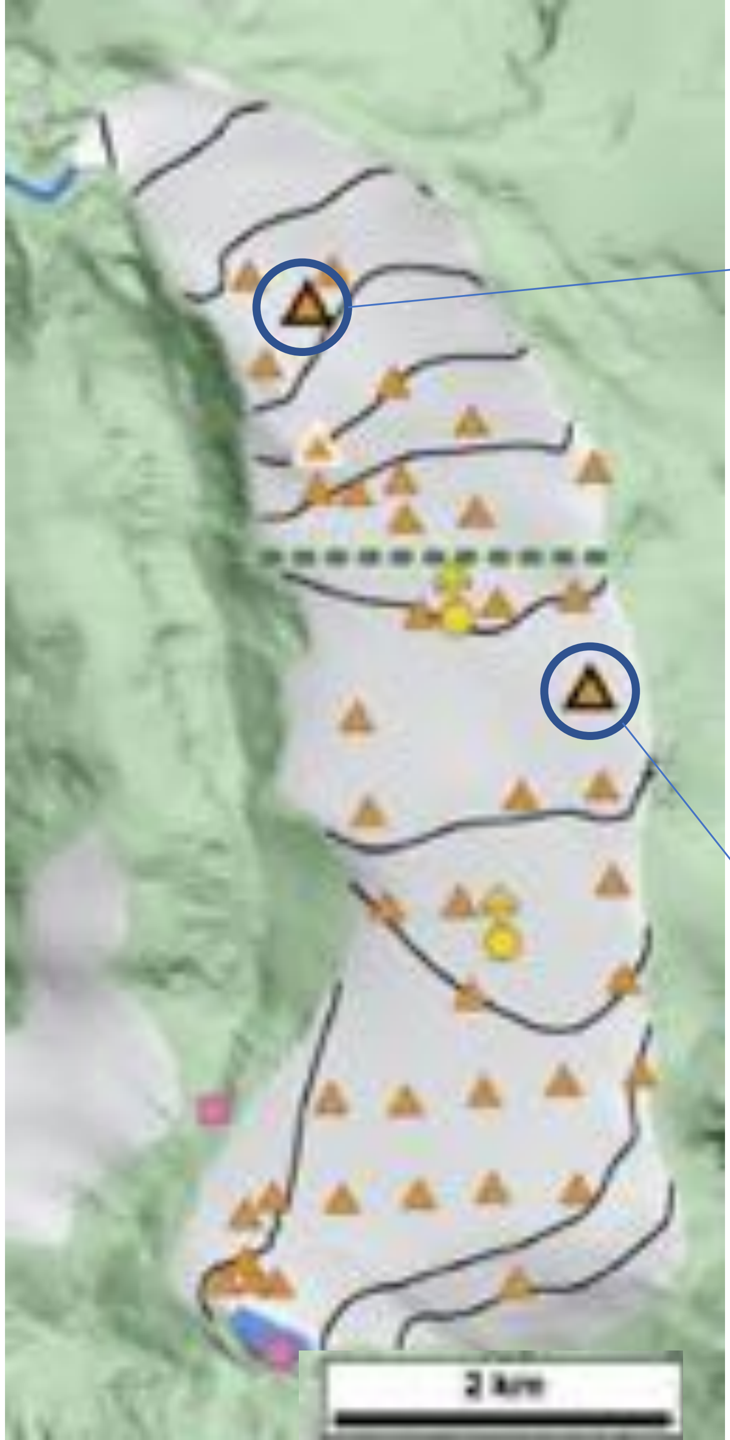
$P_w \propto Q^{5/3}$ **WEAK scaling**

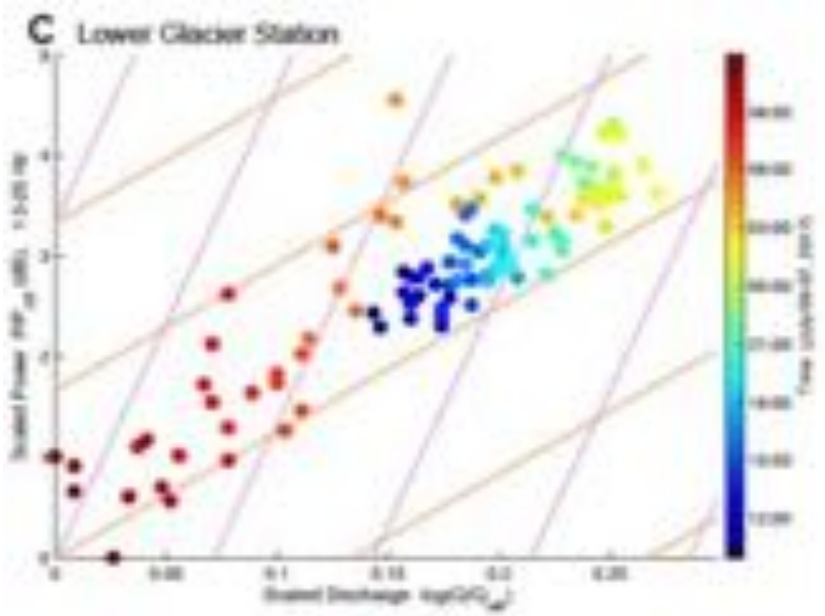
The Argentière Glacier (France)



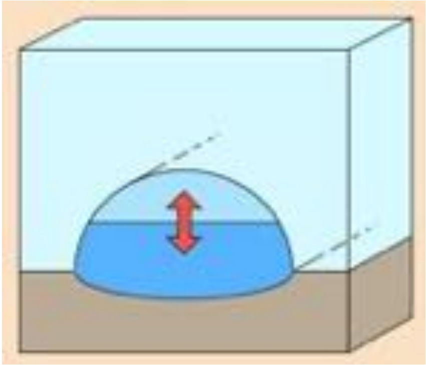
Nanni et al., 2020

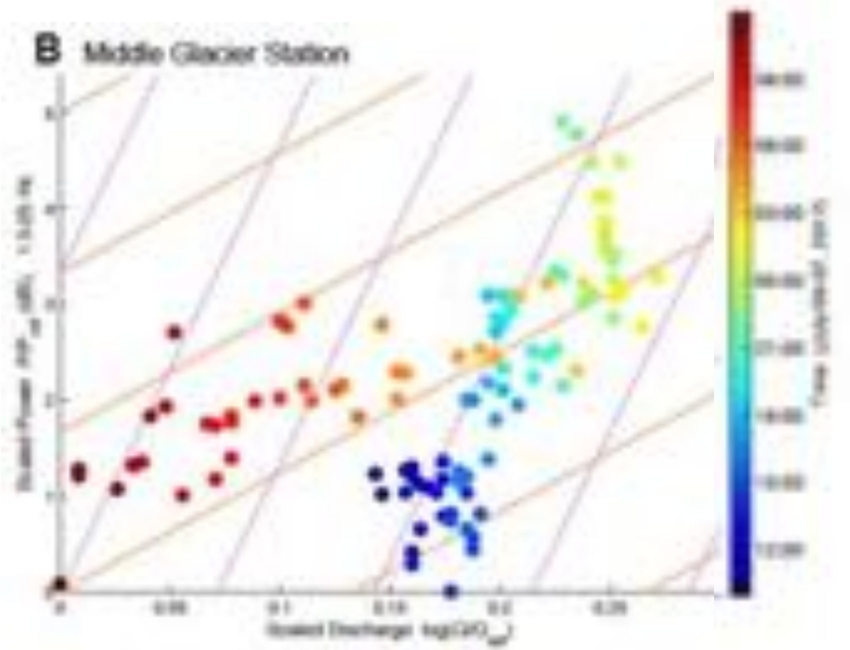
Evolution of physical variables like pressure and size can be quantified using seismic and subglacial discharge observations



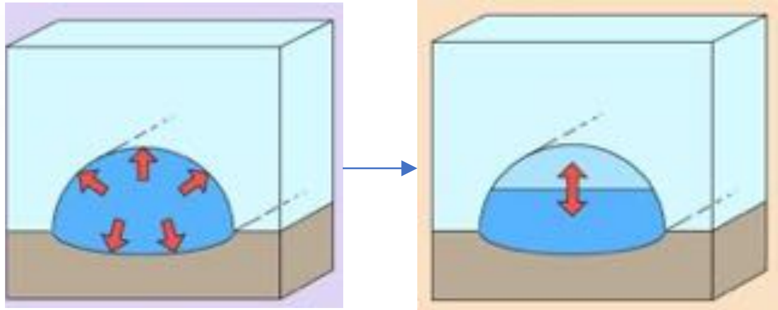


Subglacial conduit flow evolves at constant pressure gradient/varying radius

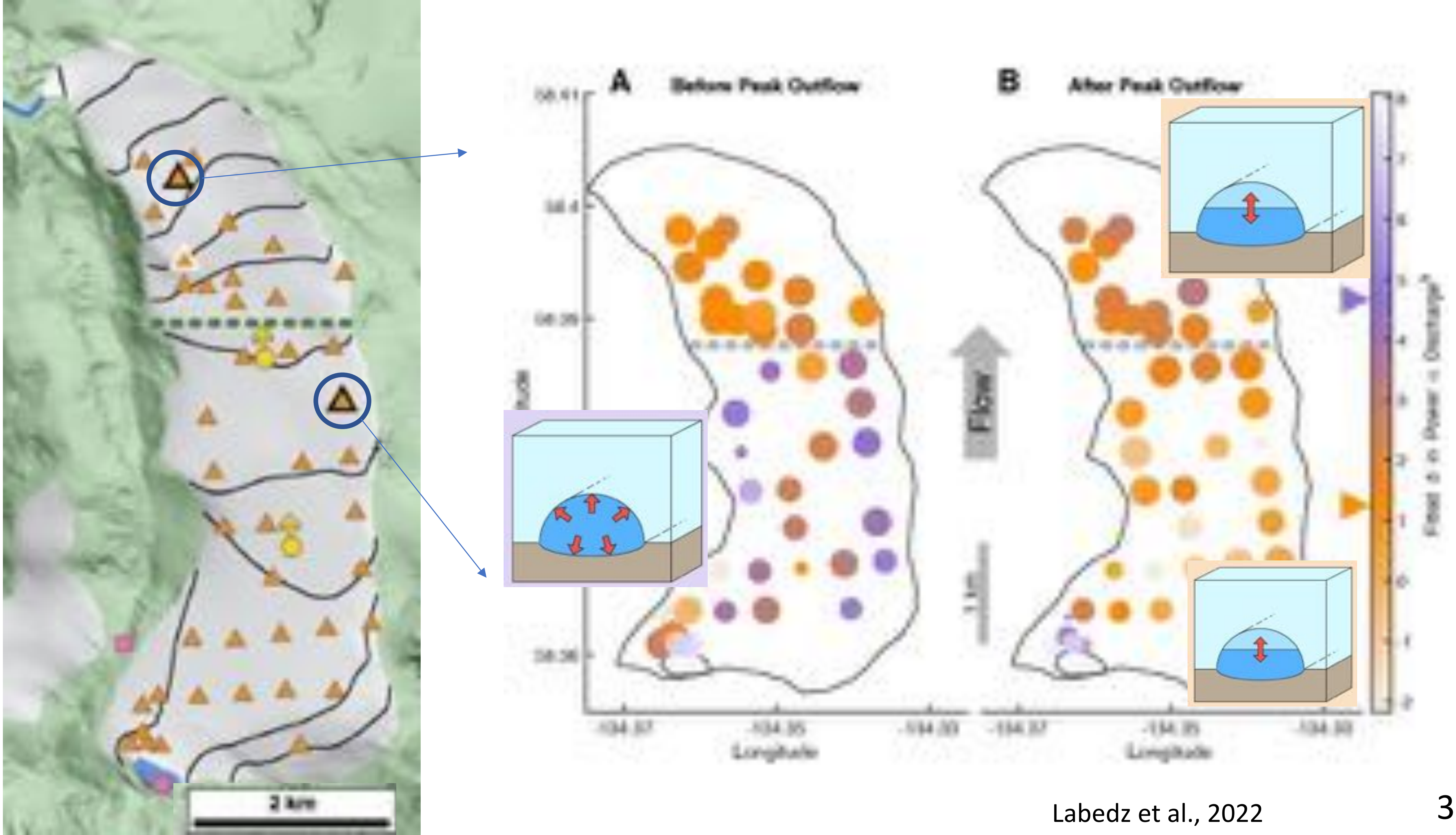




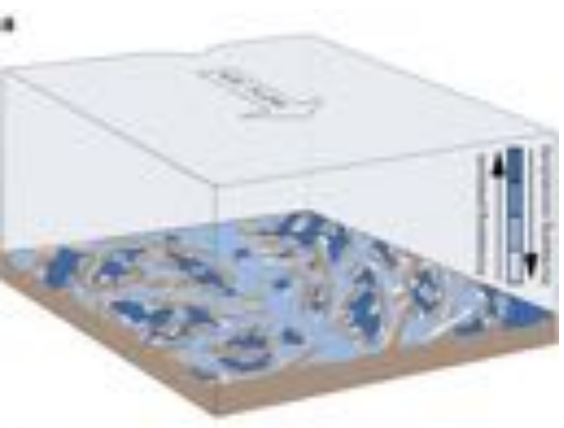
Subglacial conduit flow transitions from varying to constant pressure gradient



Labedz et al., 2022



Labedz et al., 2022



Conclusion

1- Understand the physical process behind the « tremor » source

Turbulent-flow-induced force fluctuations

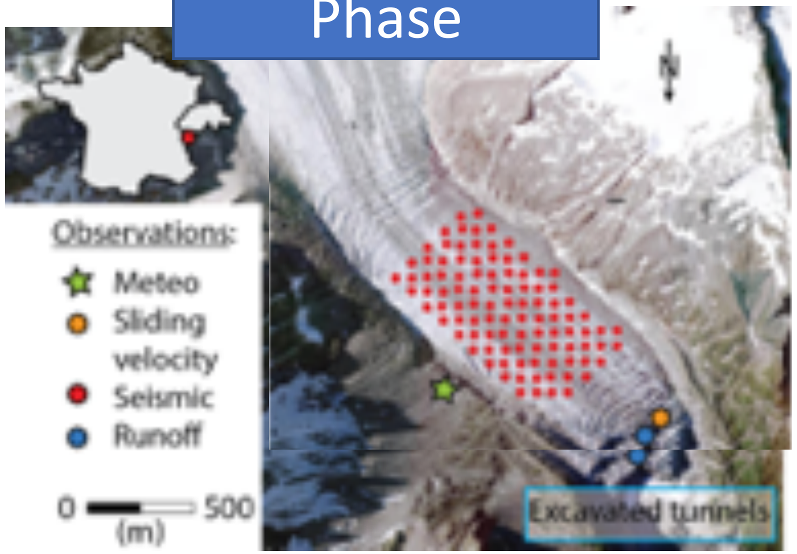
Water pressure and conduit size changes can be inferred from seismic observations

Gimbert et al., 2014; Gimbert et al., 2016; Nanni et al., 2020

2- Use arrays of sensors for observing spatial and temporal changes

Phase

The Argentière Glacier (France)



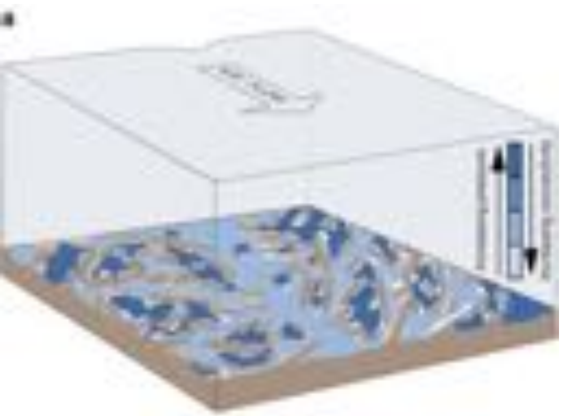
Gimbert et al., 2021; Nanni et al., 2021; Nanni et al., 2022

Amplitude

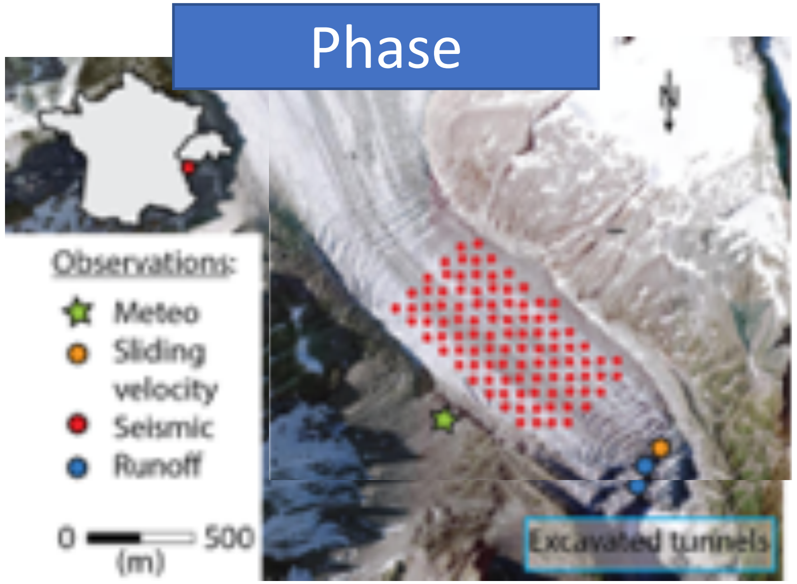
The Lemon Creek Glacier (Alaska)

Labedz et al., 2022

Perspectives

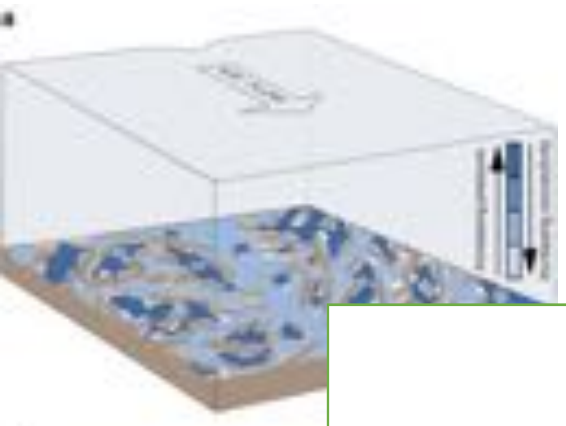


The Argentière Glacier (France)



Can we still image distributed sources with a much coarser array ?

Conclusion



1- Understand the physical process behind the « tremor » source

Turbulent-flow-induced force fluctuations

QUESTIONS ?

t al., 2020

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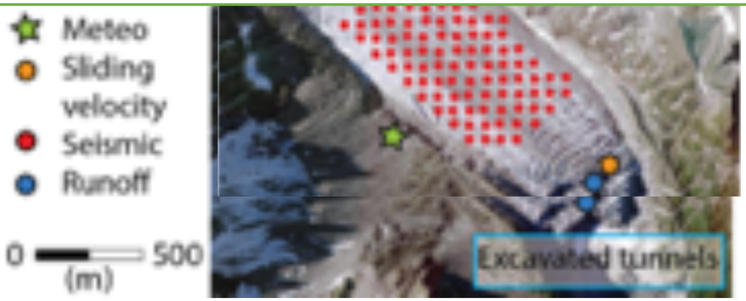
The Argenti

Glacier (France)

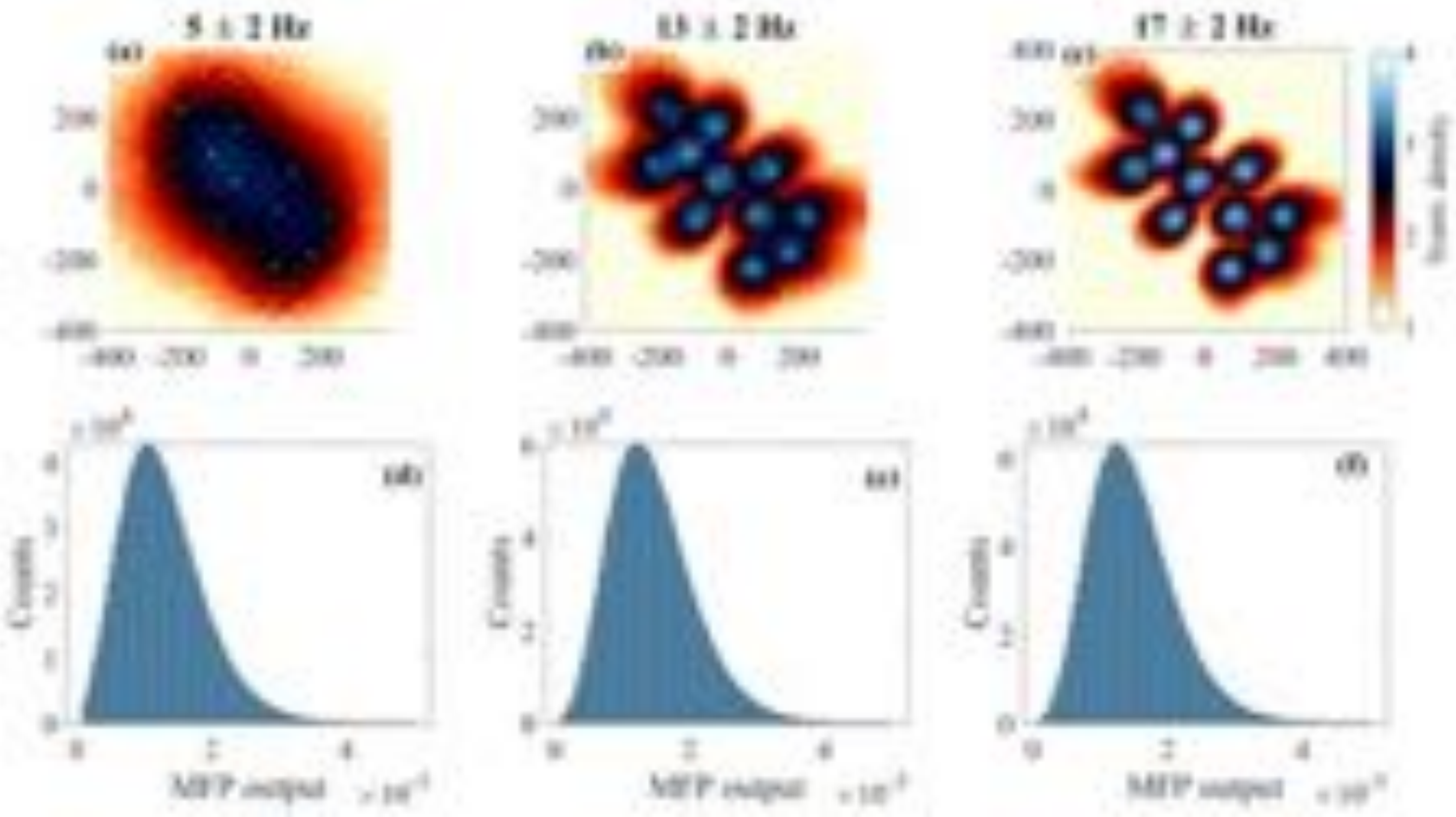


Gimbert et al., 2021; Nanni et al., 2021; Nanni et al., 2022

Glacier (Alaska)

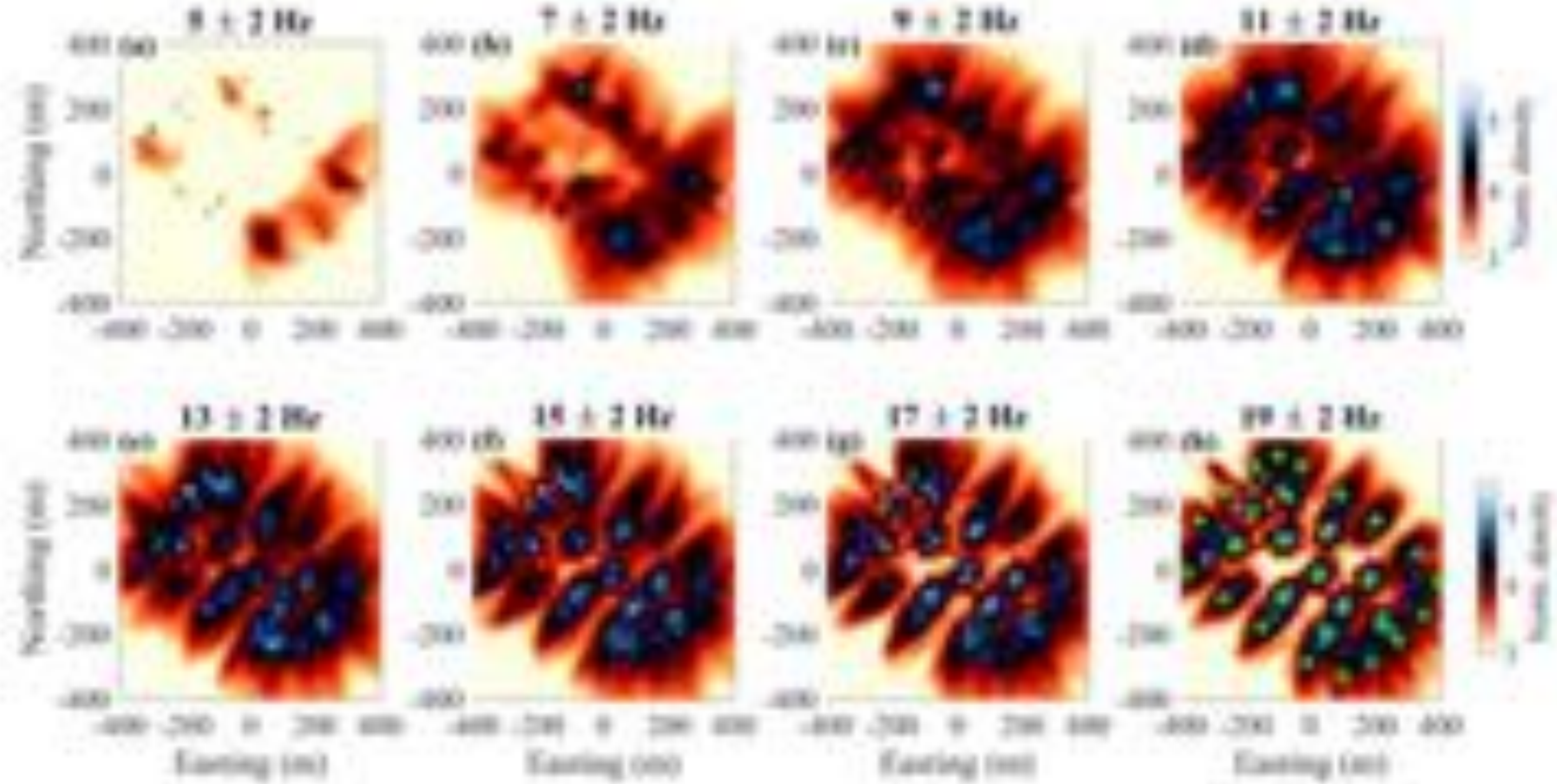
Labedz et al., 2022

Seismic array response with random phases



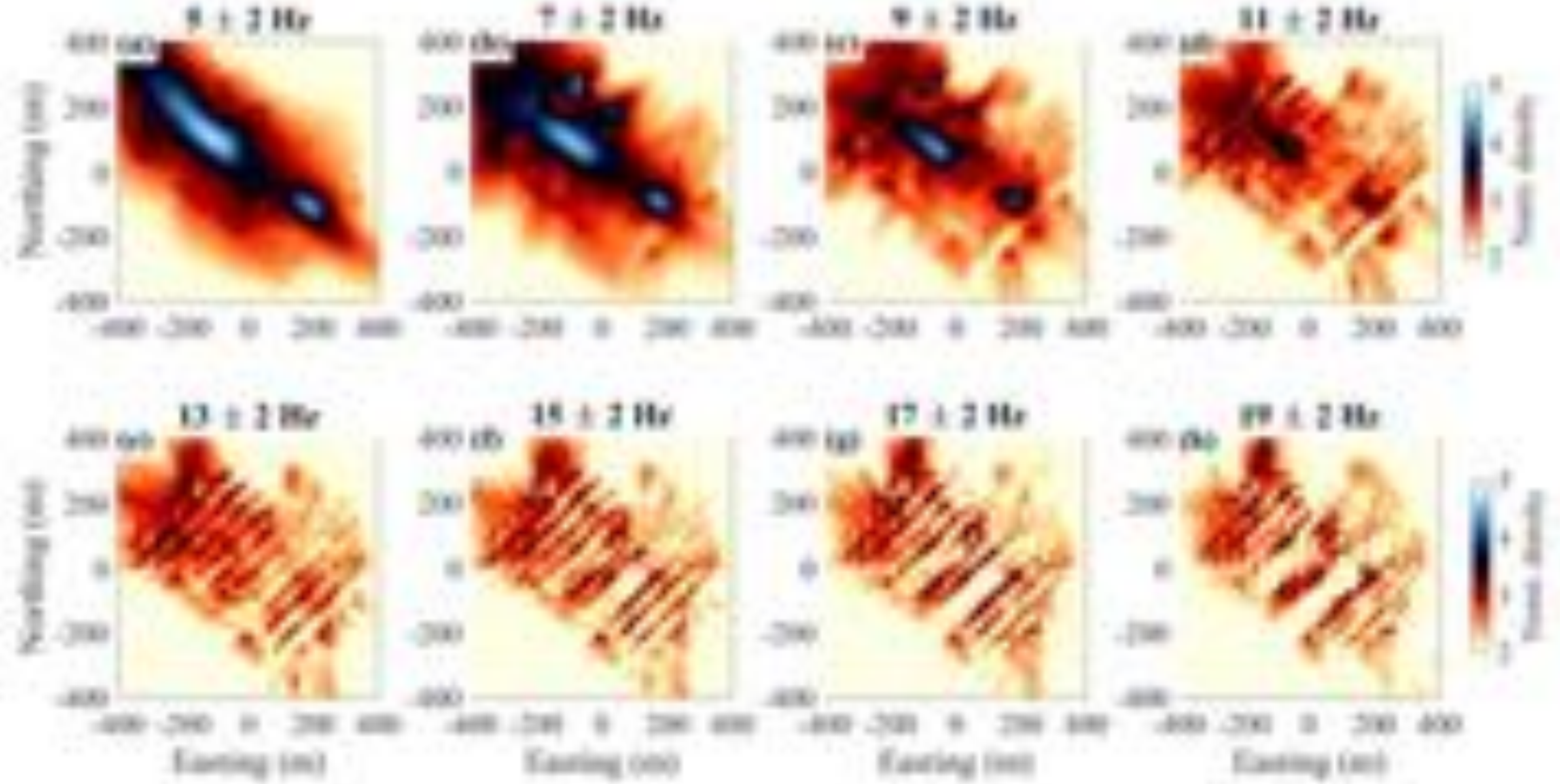
Very low phase coherence: starting points location

$\boldsymbol{MFP\ out.} \in [\mathbf{0\ 0.01}]$



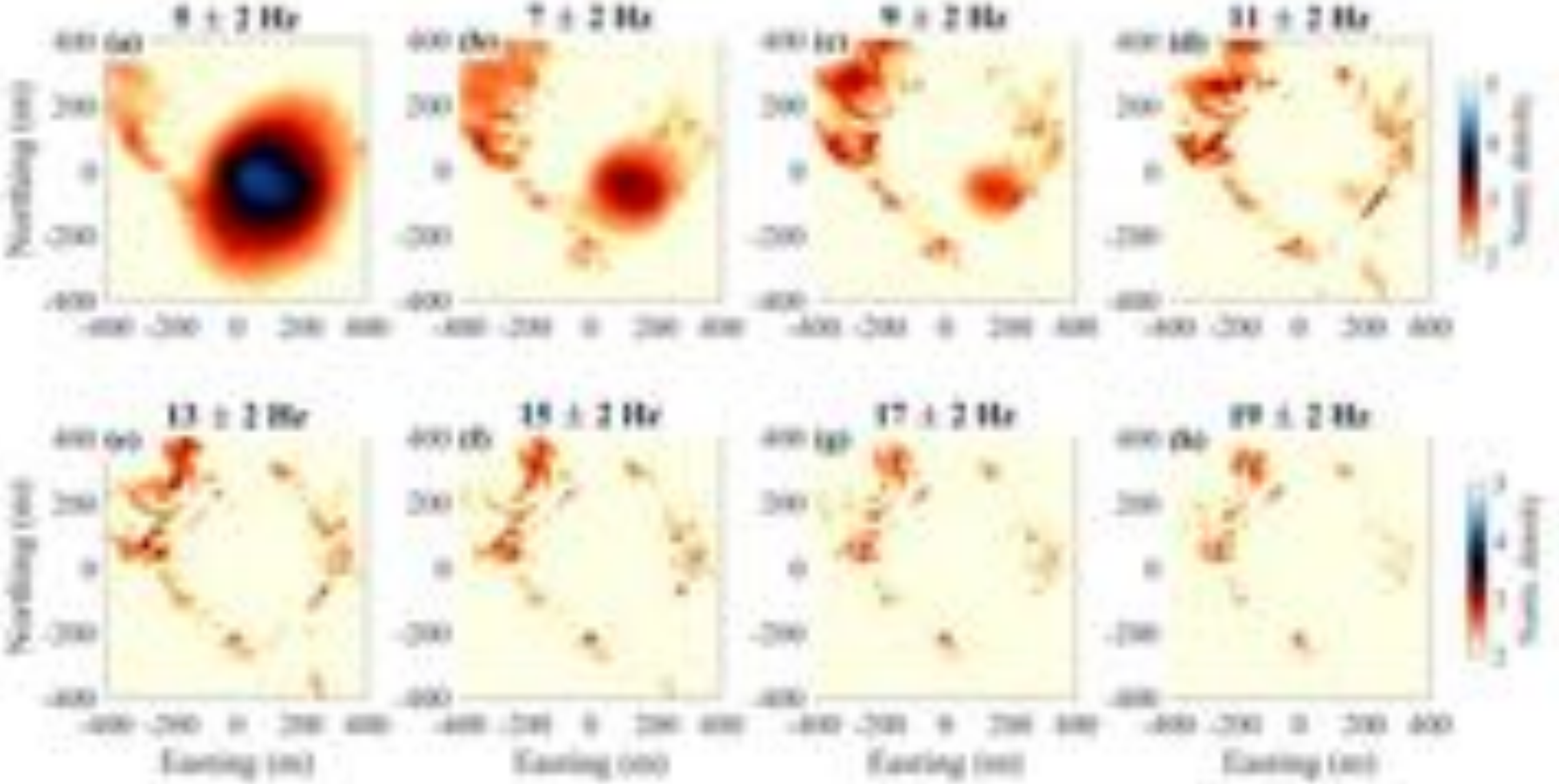
How patterns evolve with frequency

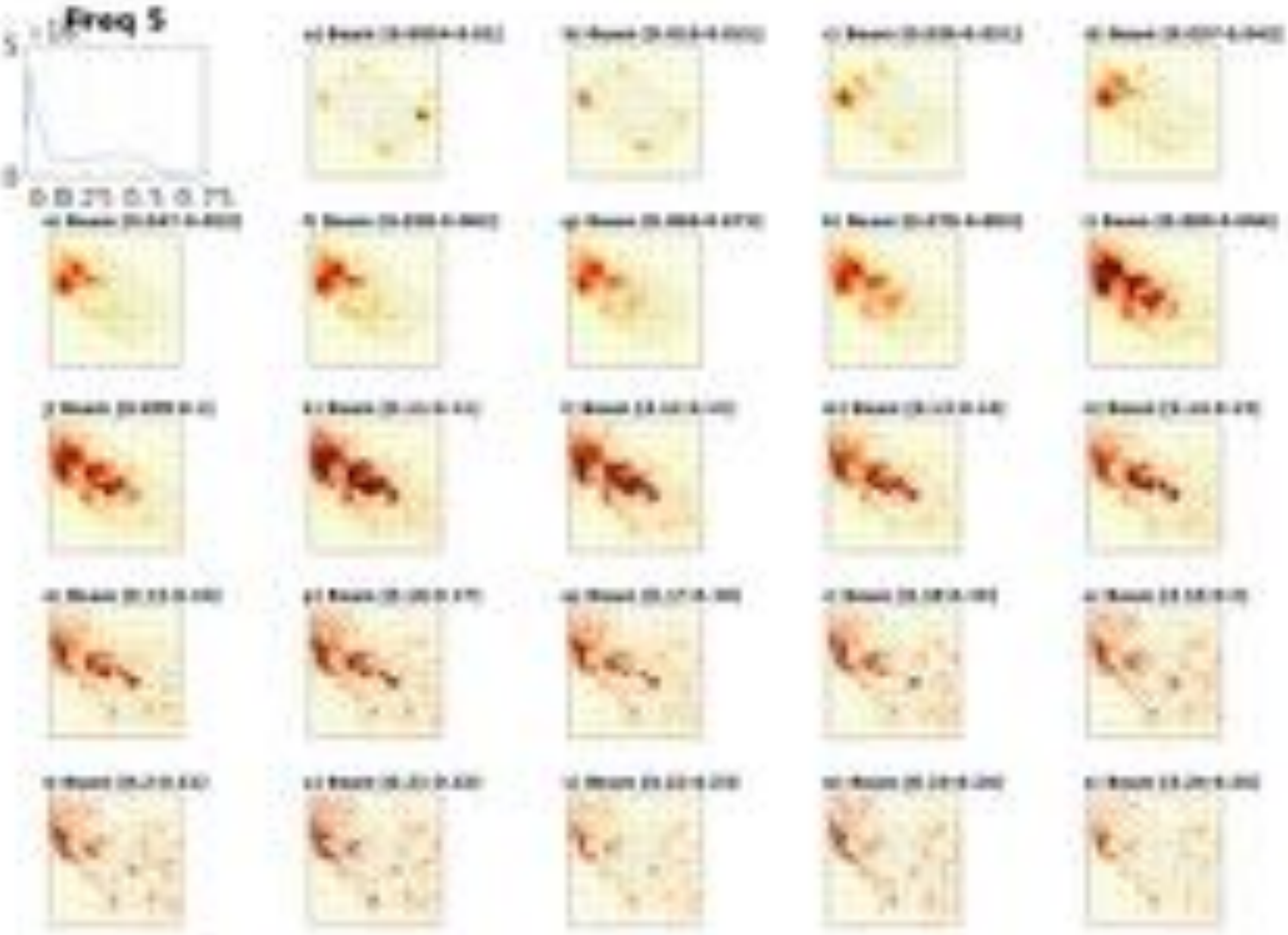
$\boldsymbol{MFP\ out.} \in [\mathbf{0.07\ 0.16}]$



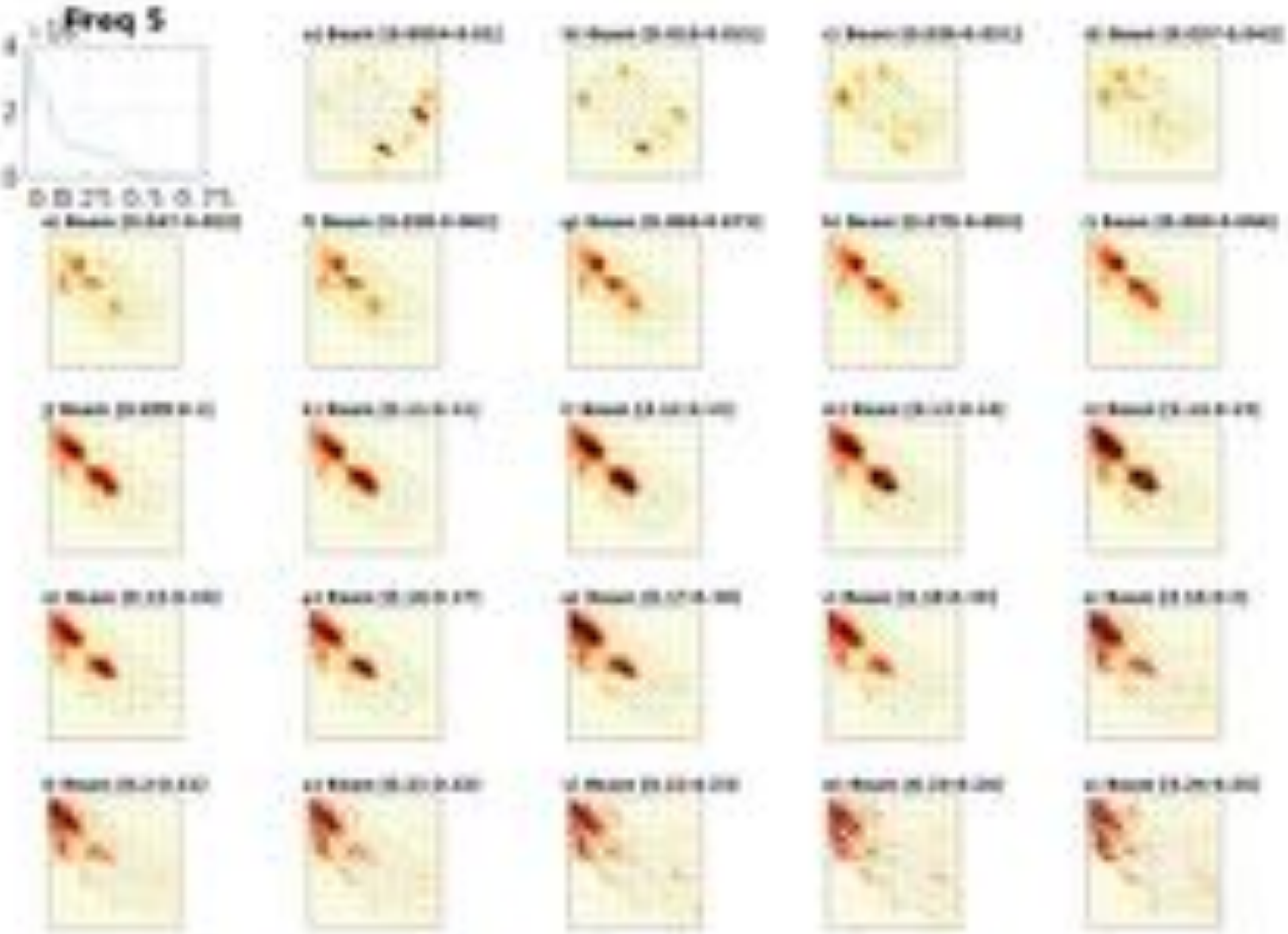
How patterns evolve with frequency

$\boldsymbol{MFP\ out.} \in [\mathbf{0.5\ 1}]$

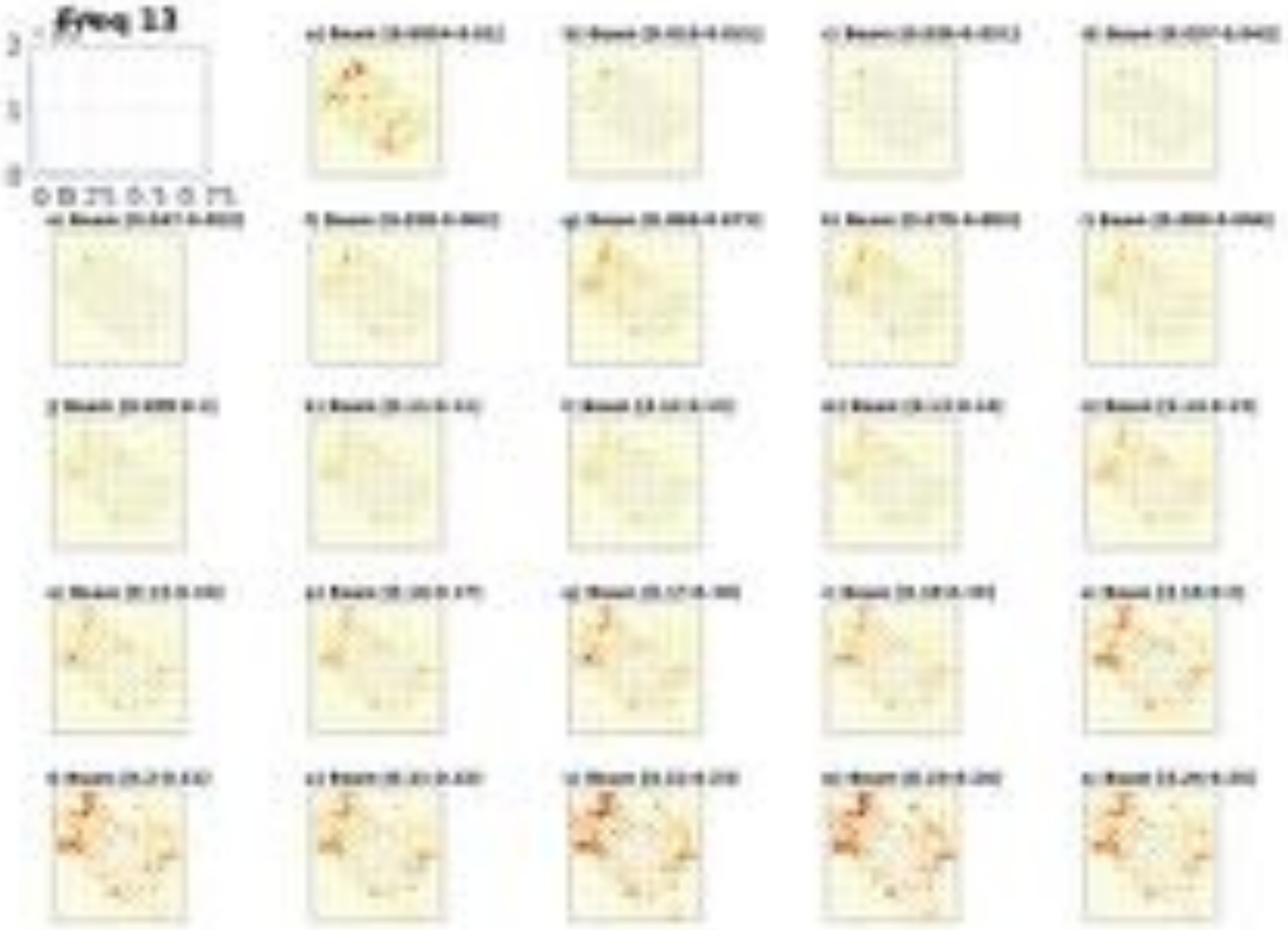




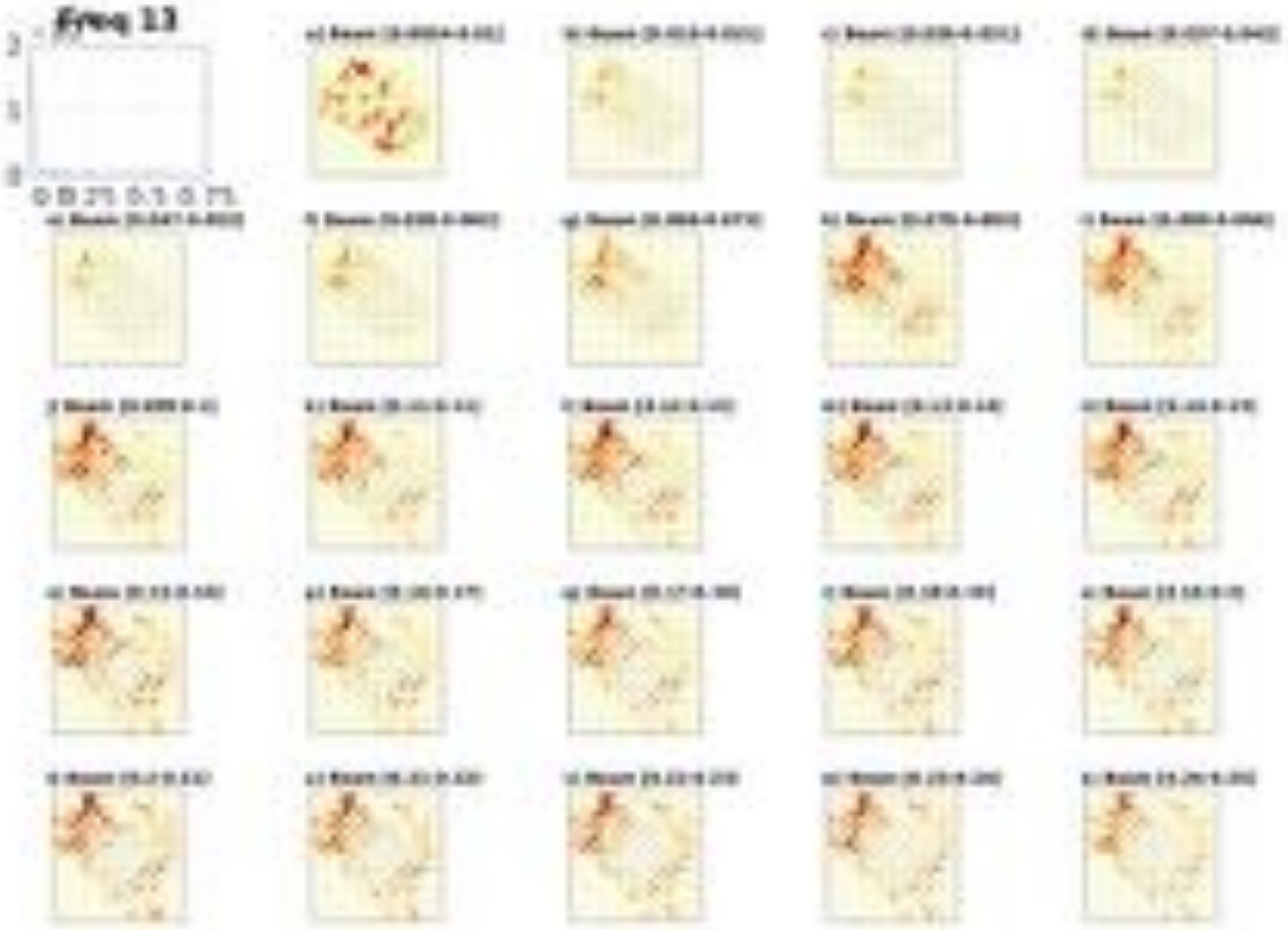
Day 114-124



Day 134-144

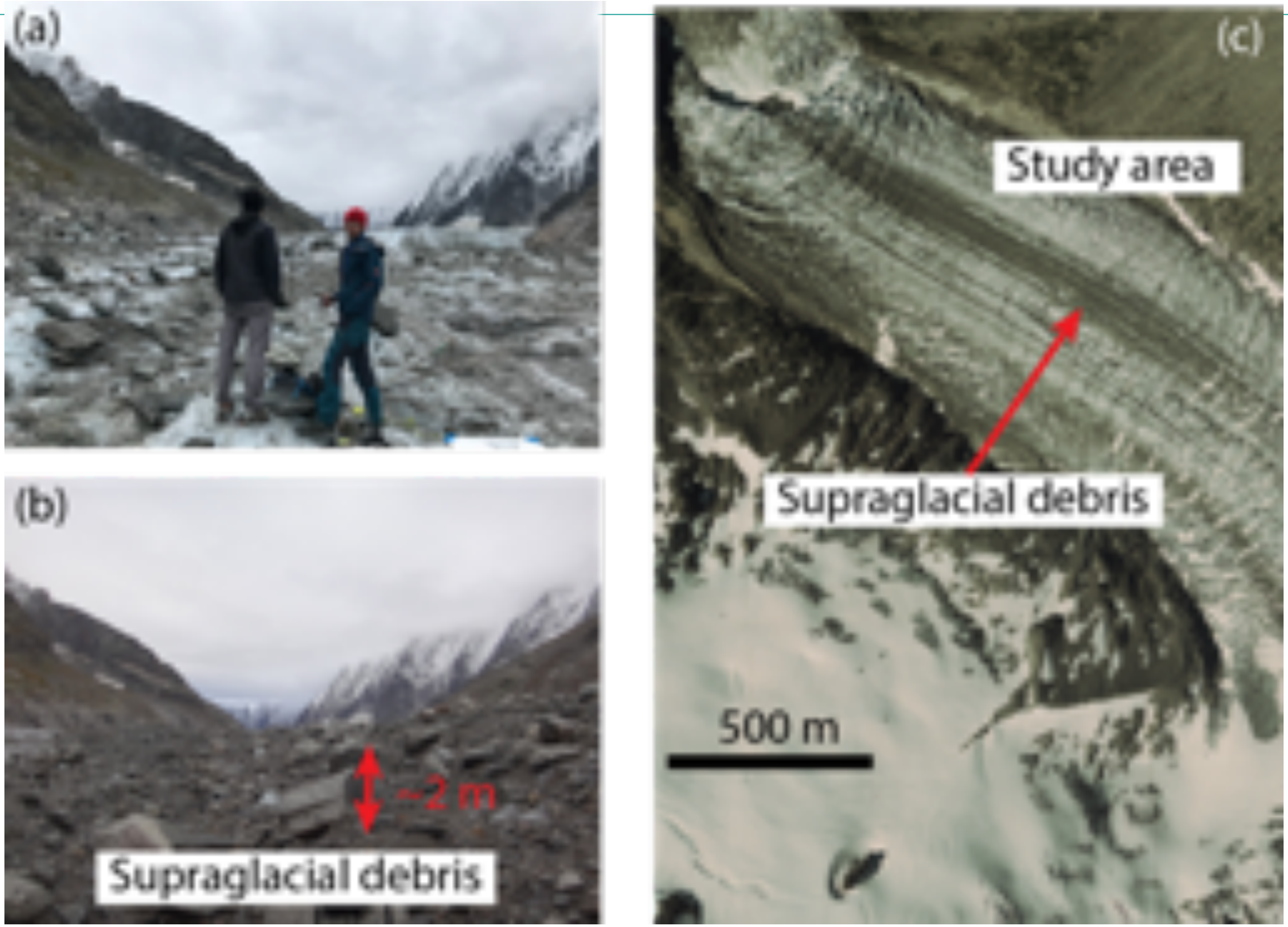


Day 114-124

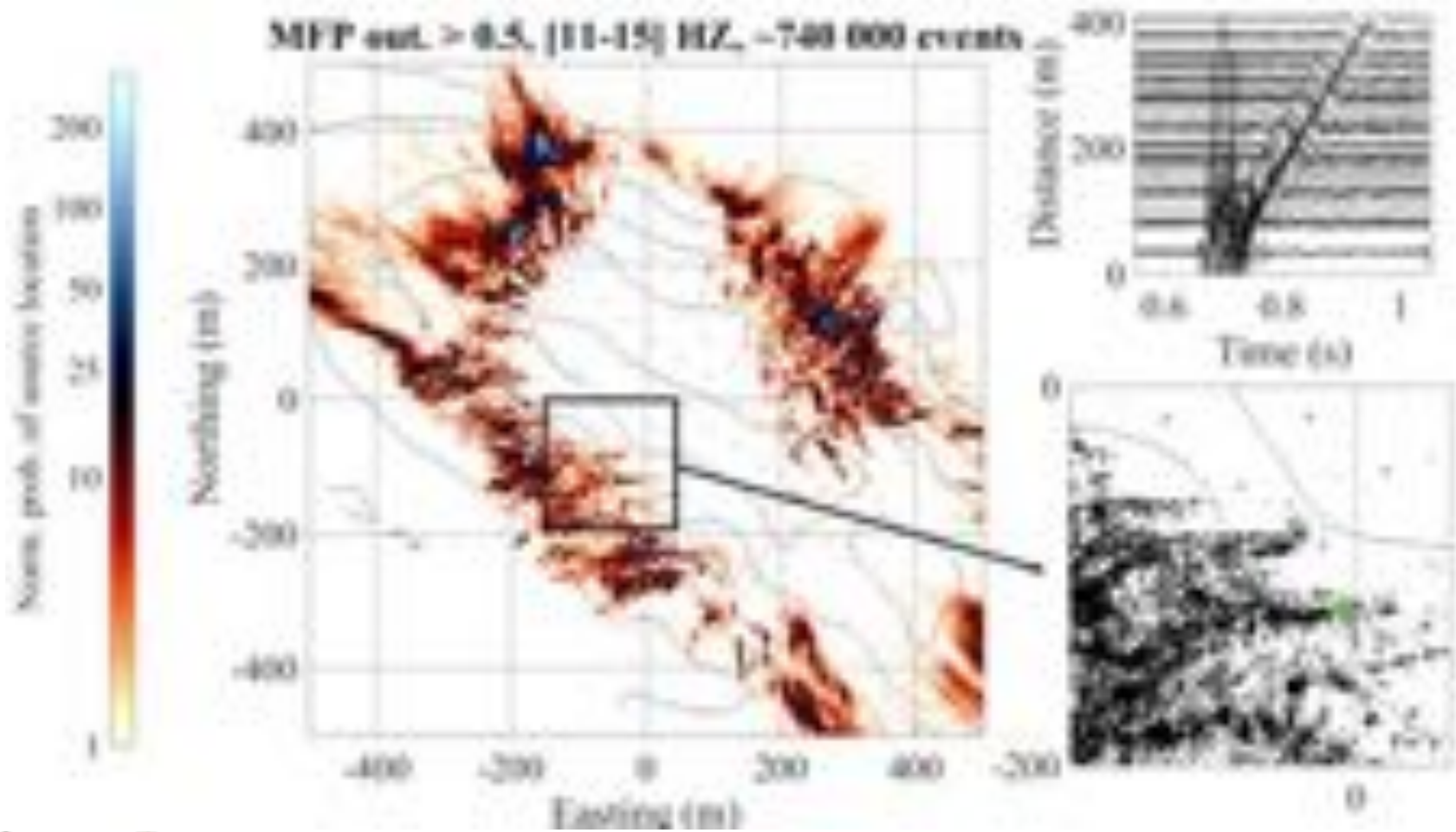


Day 134-144

Evidences for diffracting material

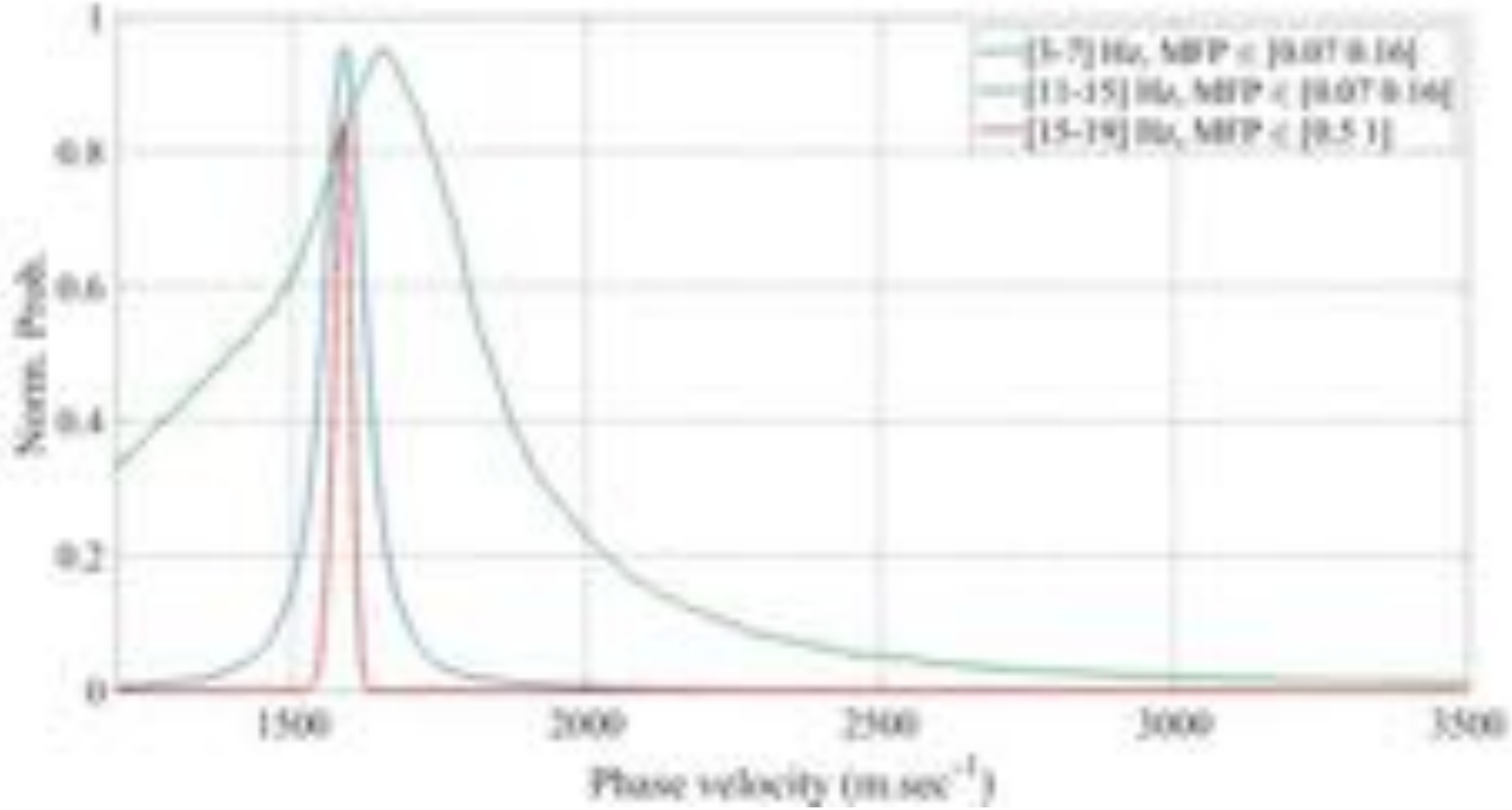


Crevasses

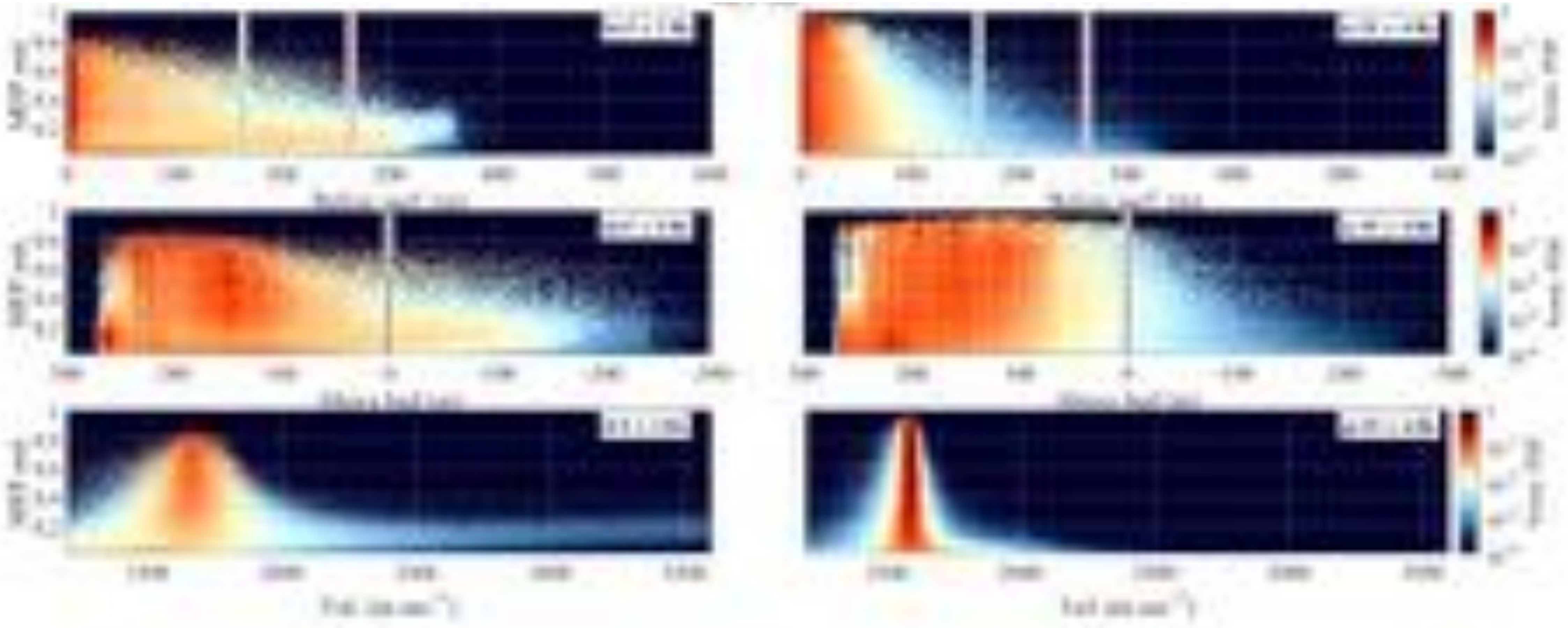


MFP out. > 0.5, [11-15] HZ, ~740 000 events
Norm. prob. of source location
Northing (m)
Easting (m)
Distance (m)
Time (s)

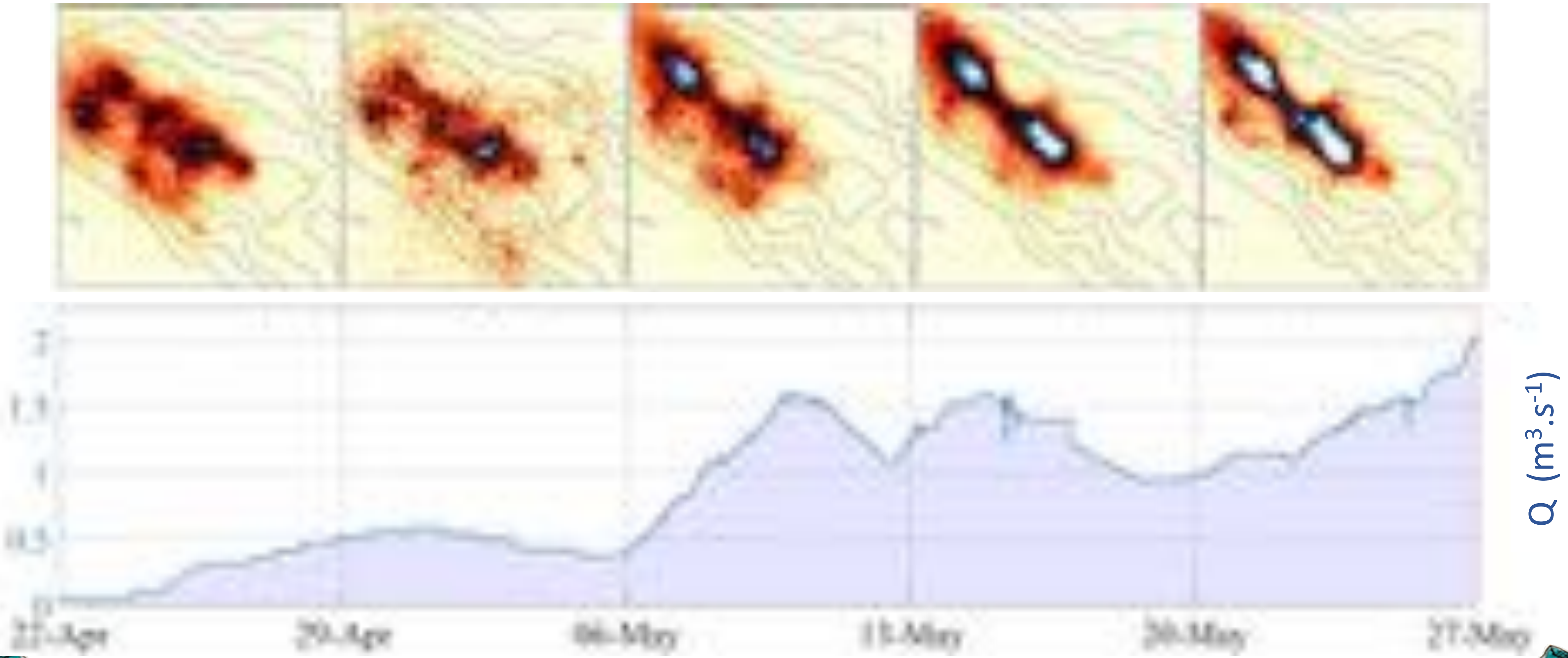
Phase velocity distribution



Phase velocity distribution

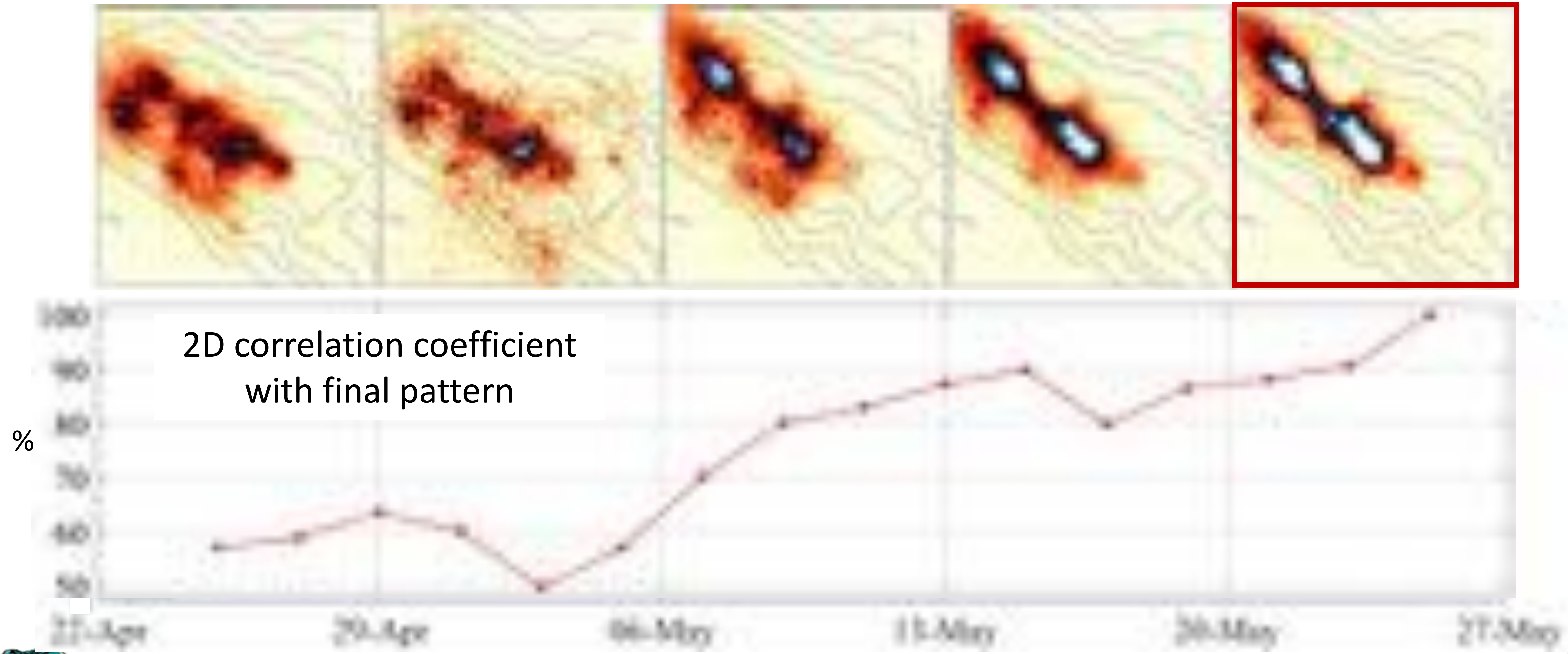


From distributed … to localized

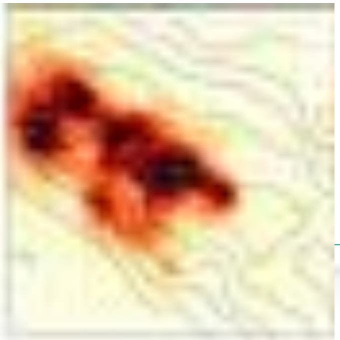


(Nanni et al., 2021 PNAS)

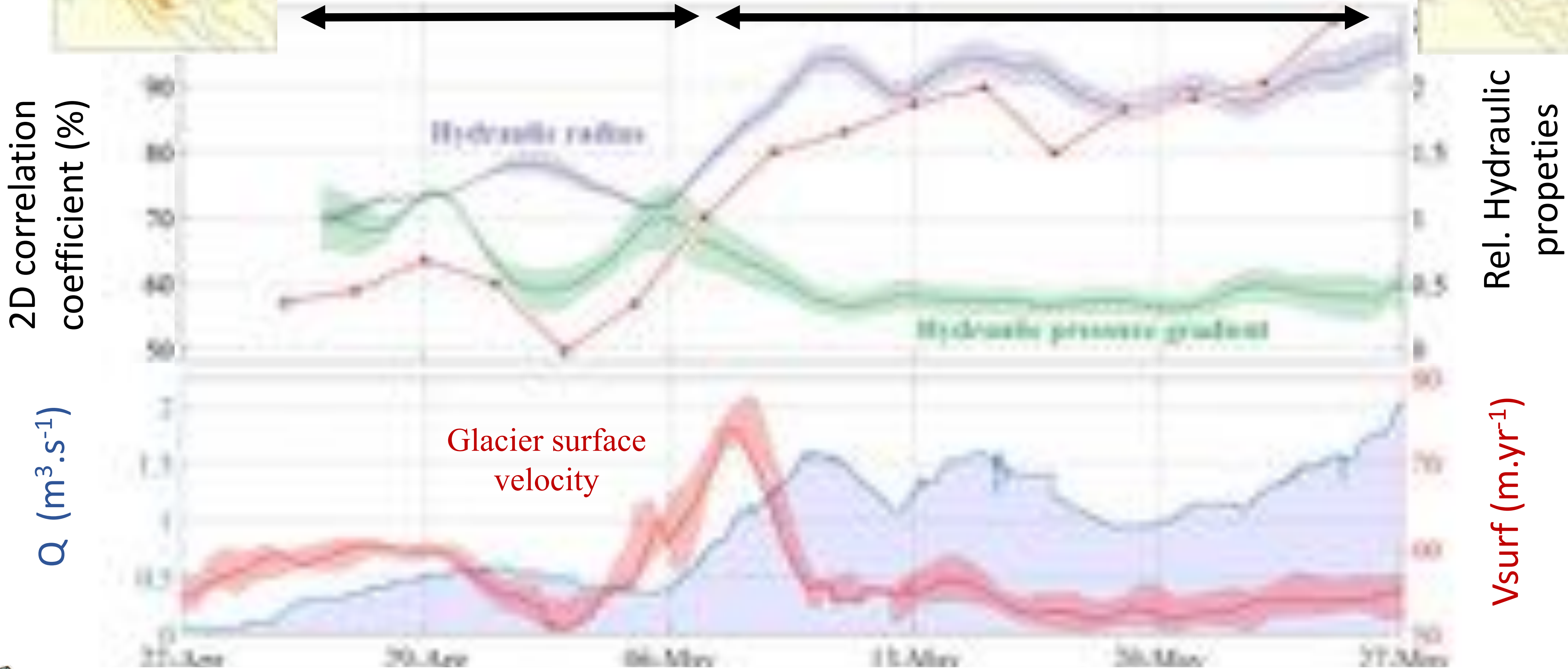
CAPABLE OF CAPTURING SUBGLACIAL HYDROLOGY DYNAMICS



(Nanni et al., 2021 PNAS)

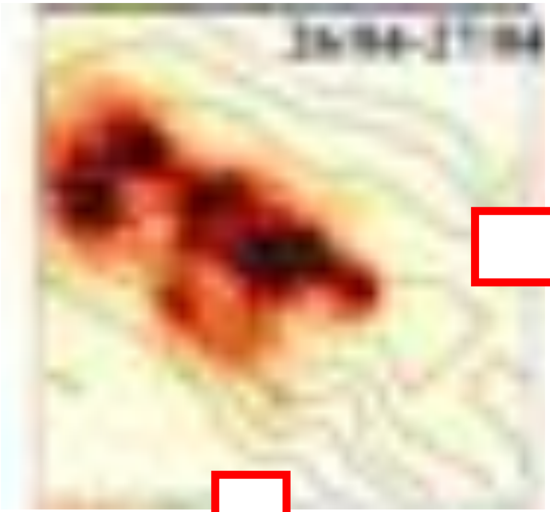


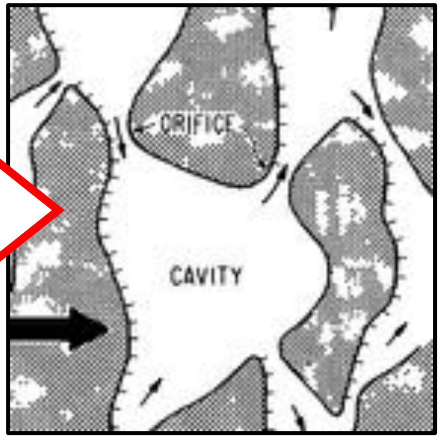
From inefficient to efficient



(Nanni et al., 2021 PNAS)

Observing the inefficient drainage system





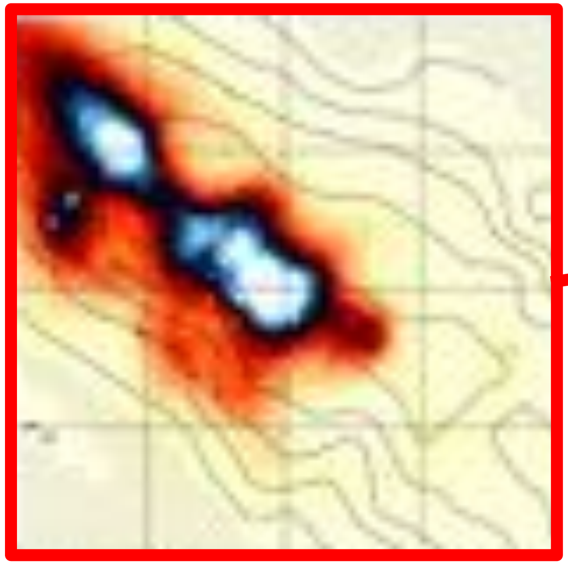
Linked cavity
(Kamb, 1987)

We can observe **<u>distributed</u>** water flow in the cavities with seismology

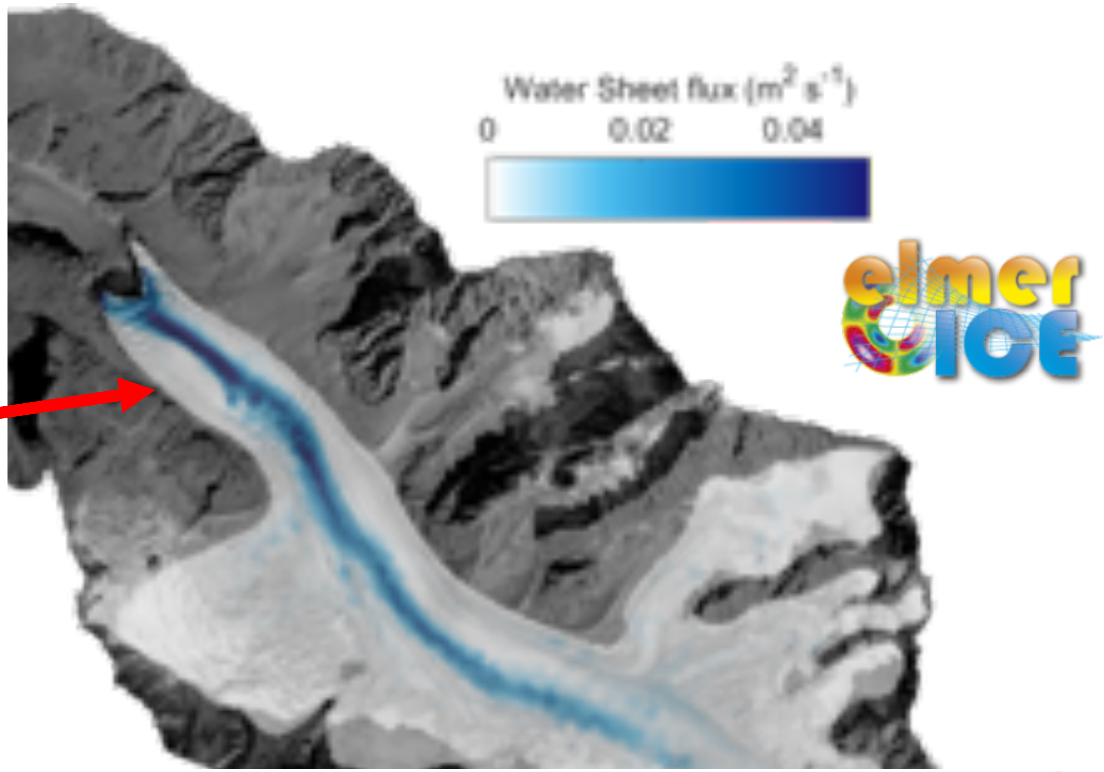
Previously thought to be noise-free

Implication for subglacial hydrology dynamics

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



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



Spectrograms