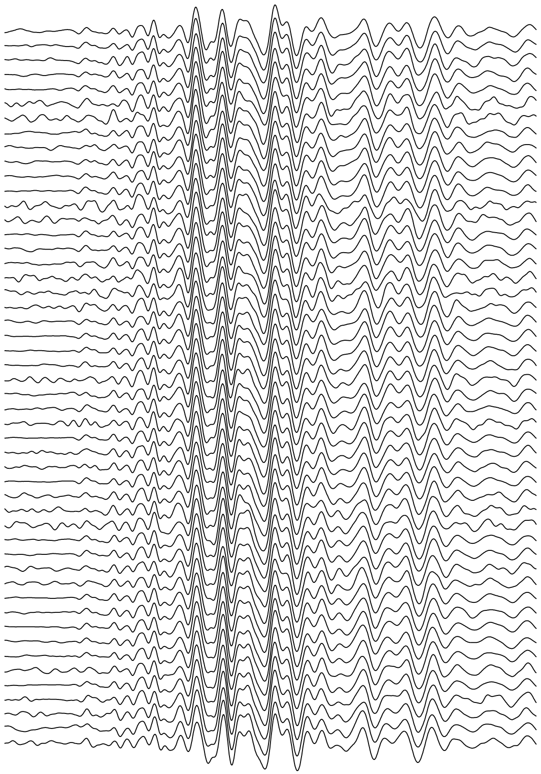
Repeating icequakes and landquakes



Agnès Helmstetter

ISTerre, Université Grenoble-Alpes

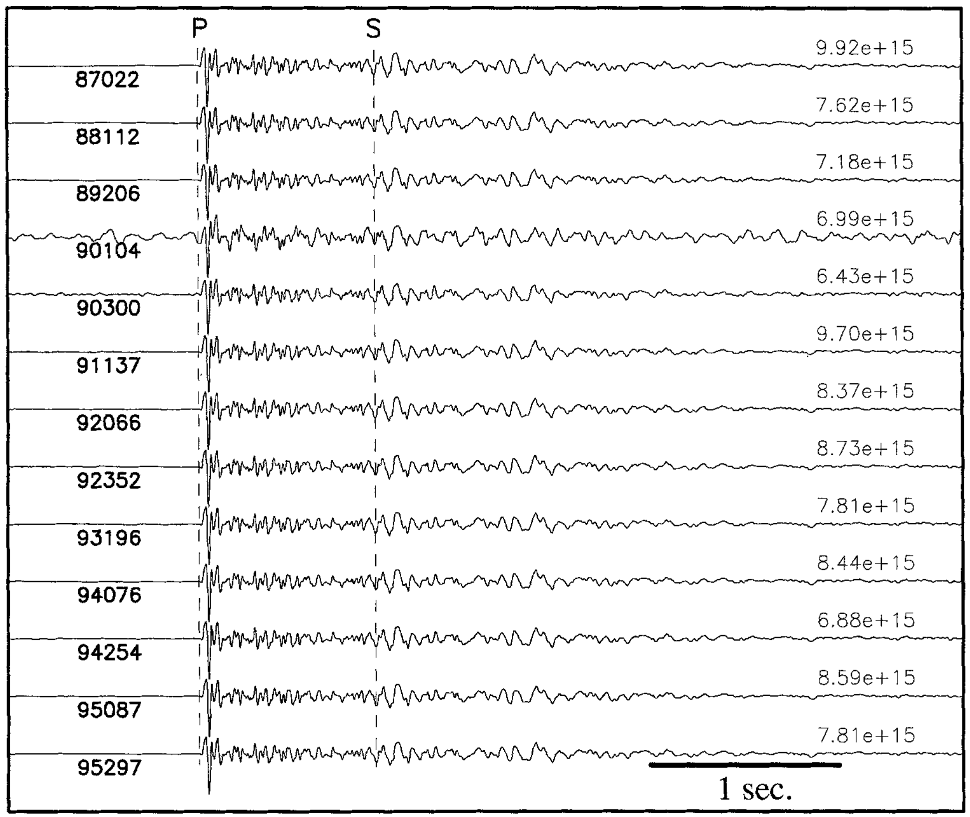
Collaboration with Eric Larose, Laurent Baillet, Raphaël Mayoraz, Claudia Röösli, Fabian Walter, Barbara Nicolas, Michel Gay, Pierre Common

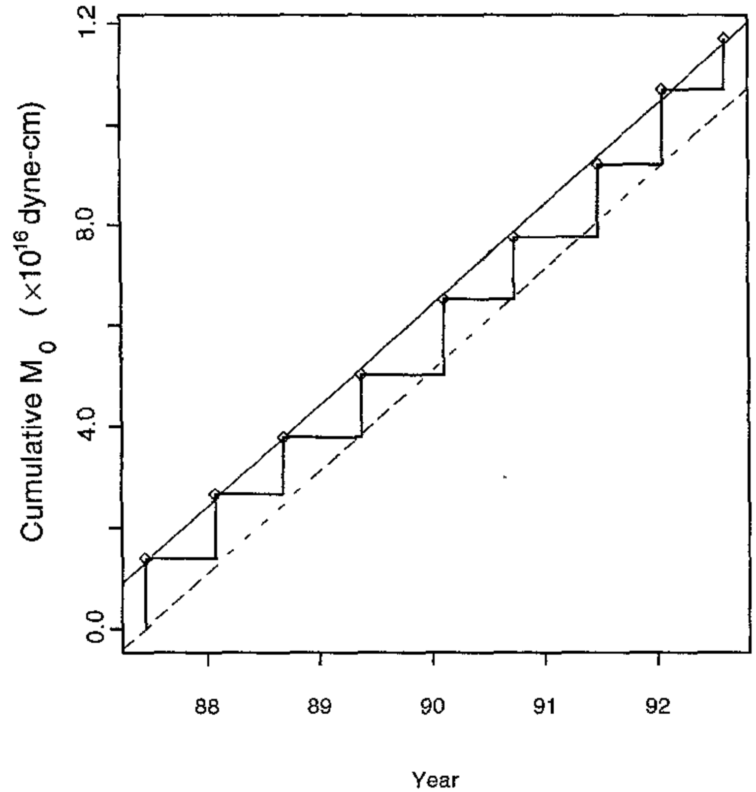
ISTerre

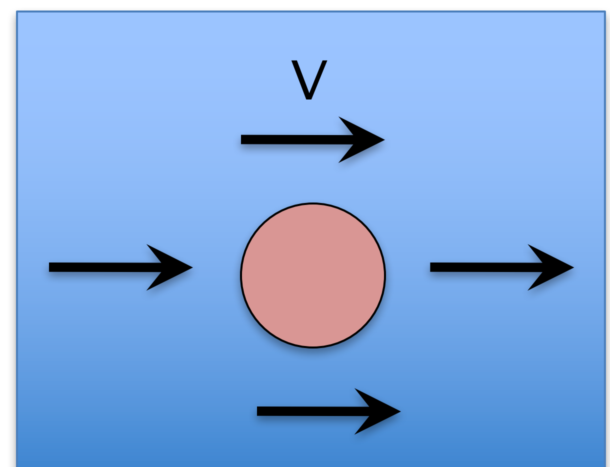
Institut des Sciences de la Terre

Repeating earthquakes

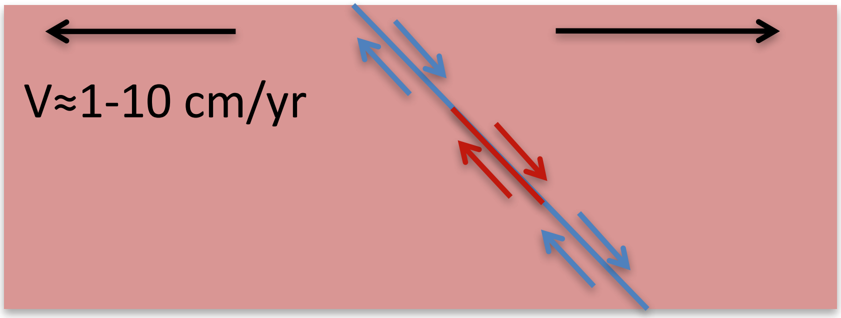
Parkfield, California
(Nadeau and Johnson, 1998)







Repeating earth/ice/land-quakes

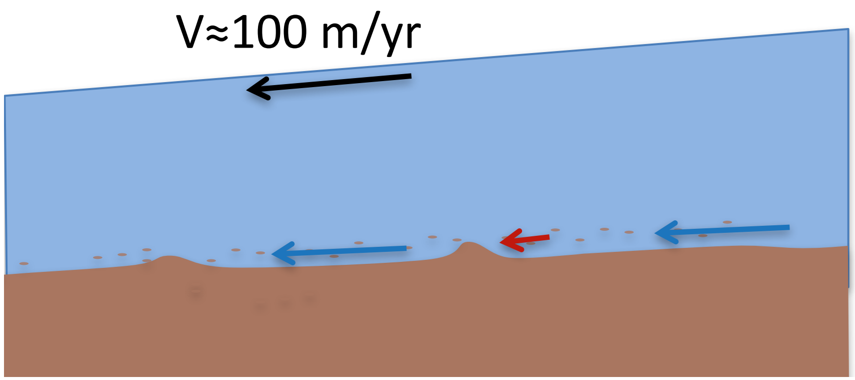


Repeating earthquakes

Tectonic loading

Asperities on the fault surrounded by creeping zones

(# friction parameters?)

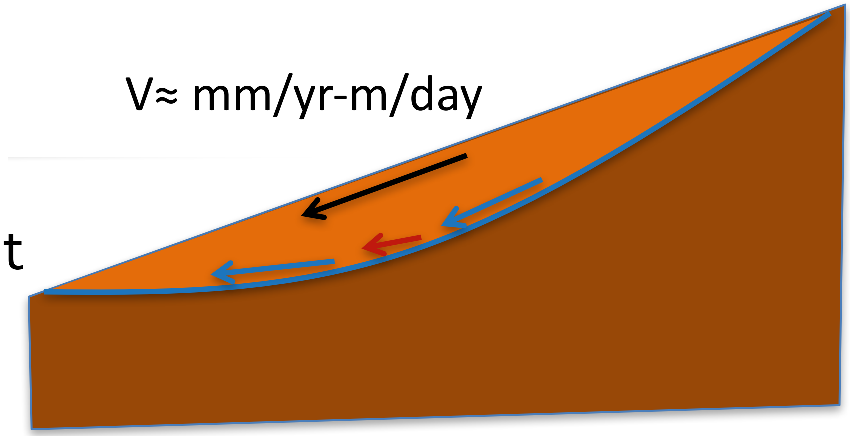


Repeating icequakes

Slip at the ice/bed interface

Loading by glacier movement

"sticky spots" ; rock debris? Bumps?



Repeating landquakes

Loading = gravity + rockslide movement

asperities : interface rugosity?

Motivations

> Proxy for aseismic slip?

> Reproducible source
>
> => can be used to detect small changes in the medium?

> Precursor of a large rupture?

Why landslides and glaciers?

Faster displacement, (usually) smaller size

$\Rightarrow$ longer time series

Shallower

$\Rightarrow$ easier to detect seismic events and to measure aseismic slip

Time dependent loading and forcings

$\Rightarrow$ analyze the influence of loading and forcings

$\Rightarrow$ more complex!

- daily and seasonal variations of velocity by a factor > 2
- increase in water pressure
- ice : near melting point $\Rightarrow$ change in rheology

Outline

> Icequakes

Antarctica, Greenland, Alpine glacier

> Landslides

Rausu (Japan) and Aletsch (Switzerland)

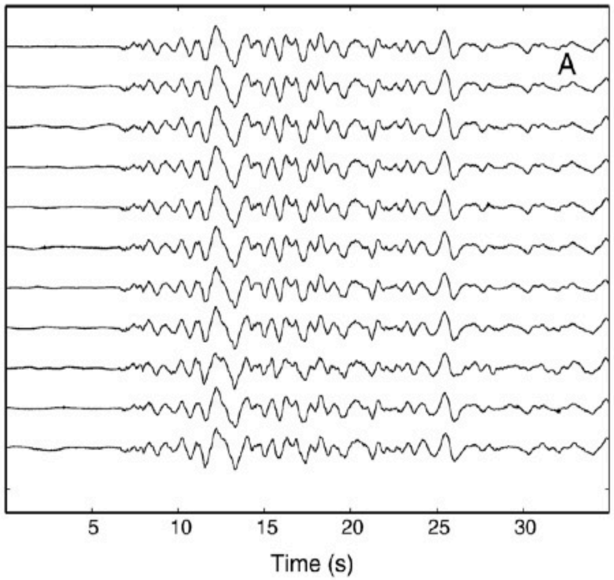
> Rock-glacier

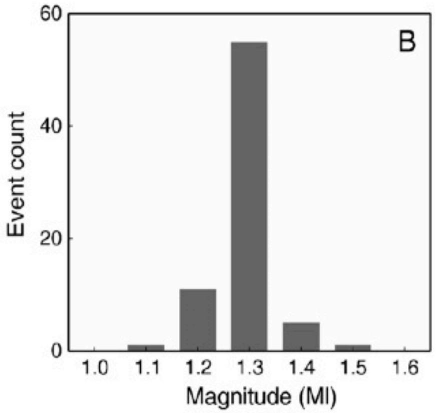
Gugla (Switzerland) and comparison with Mount Rainier (US)

Repeating icequakes in Antarctica

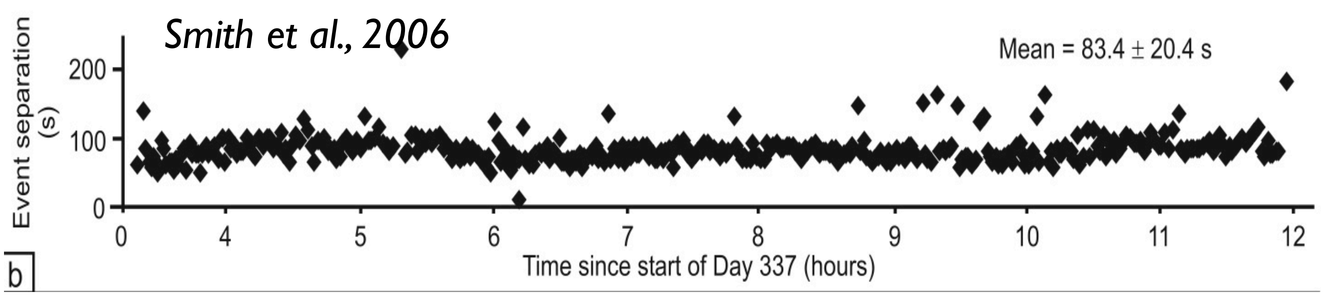
- first observed by Anandakrishnan *(1993)*
- different scales in magnitude, space and time
  - M=-1.8, dt=83 sc (*Smith et al 2006*)
  - M=1.8, dt=25 mn (*Zoet et al, 2012*)
  - M_w=7, L=200 km, slip=50 cm, dt=12 hr (*Wiens et al 2008*)

Danesi, 2007





Smith et al., 2006

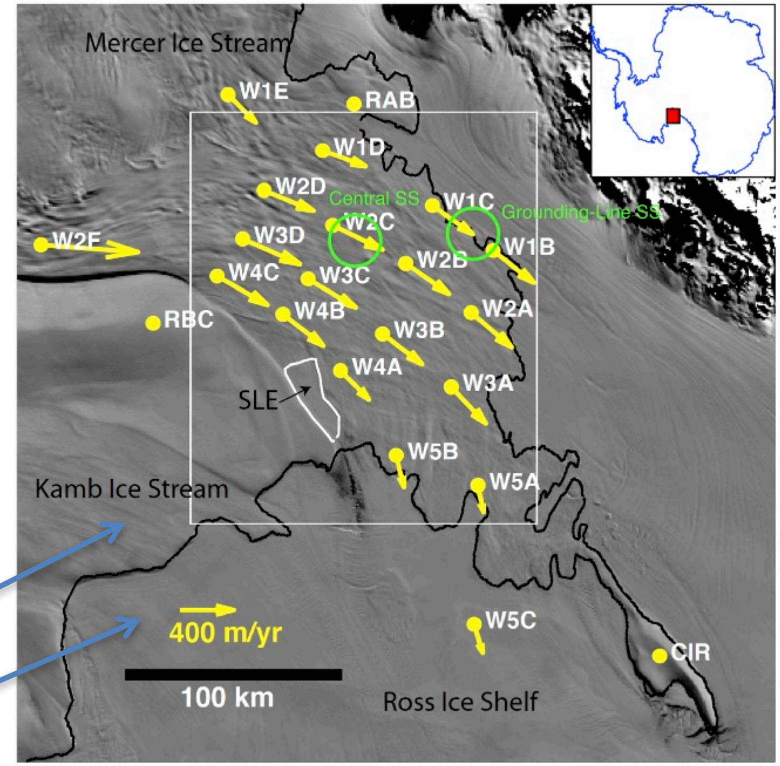


Whillans Ice Stream

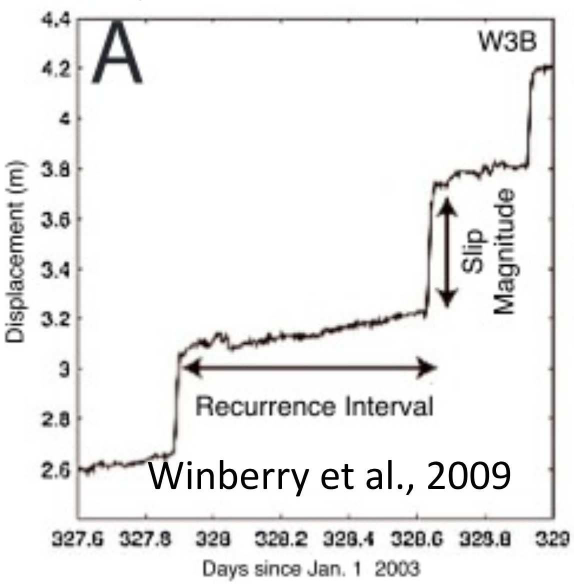
- 2 events/day at high and low tides
- rupture length ≈ 200 km
- slip ≈ 50 cm, M_w=7
- duration 30 mn
- rupture propagation 150 m/s
- slip velocity ≈ mm/s

Grounded ice

Floating ice

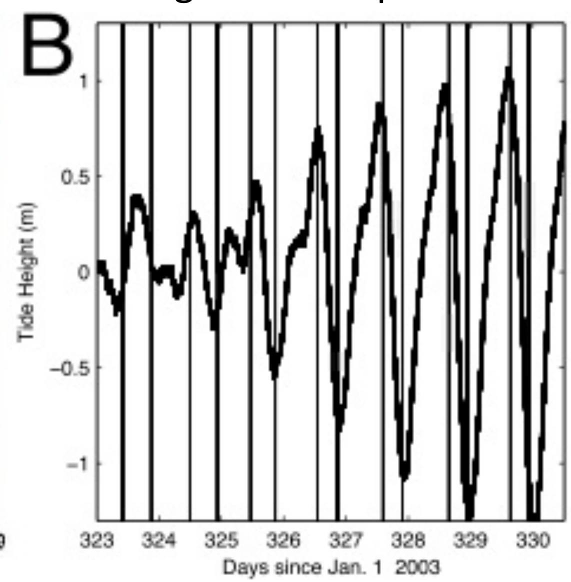


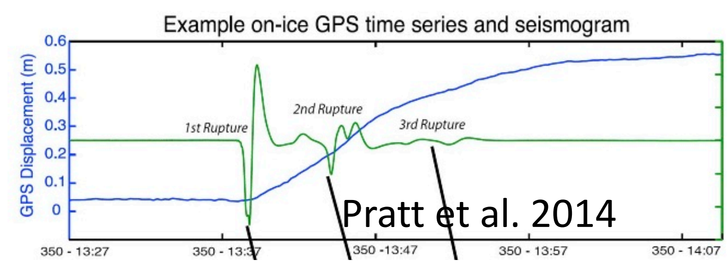
Displacement (GPS)



Winberry et al., 2009

Tidal height and icequakes





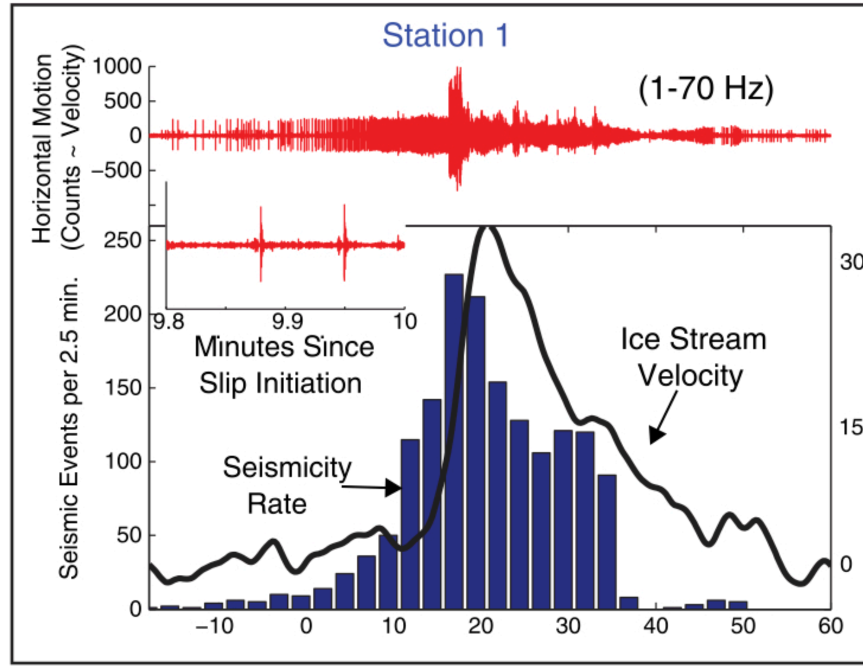
Pratt et al. 2014

Small repeaters occurring during rupture!

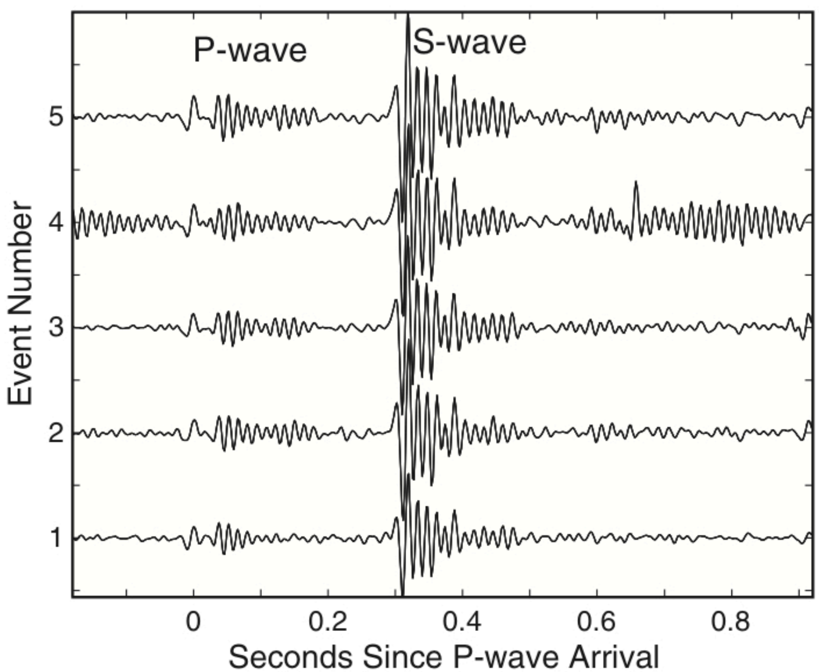
(*Winberry et al, GRL 2013*)

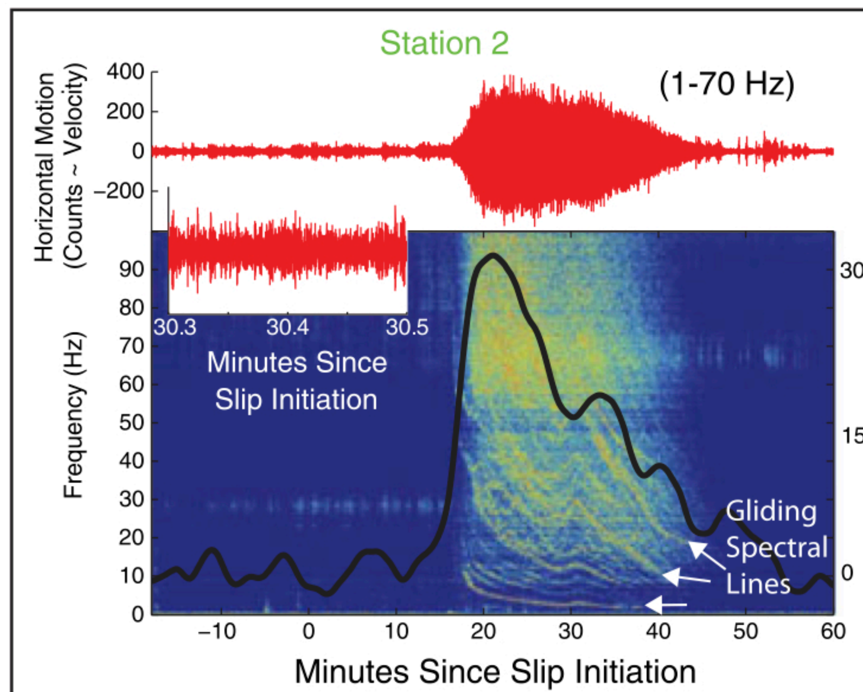
> 2 # behaviors at # stations

- repeating small icequakes dt=5s, with rate   slip rate
- or gliding tremor, with f_0 = 1/ recurrence time



Micoearthquake Family Recored at Station 1

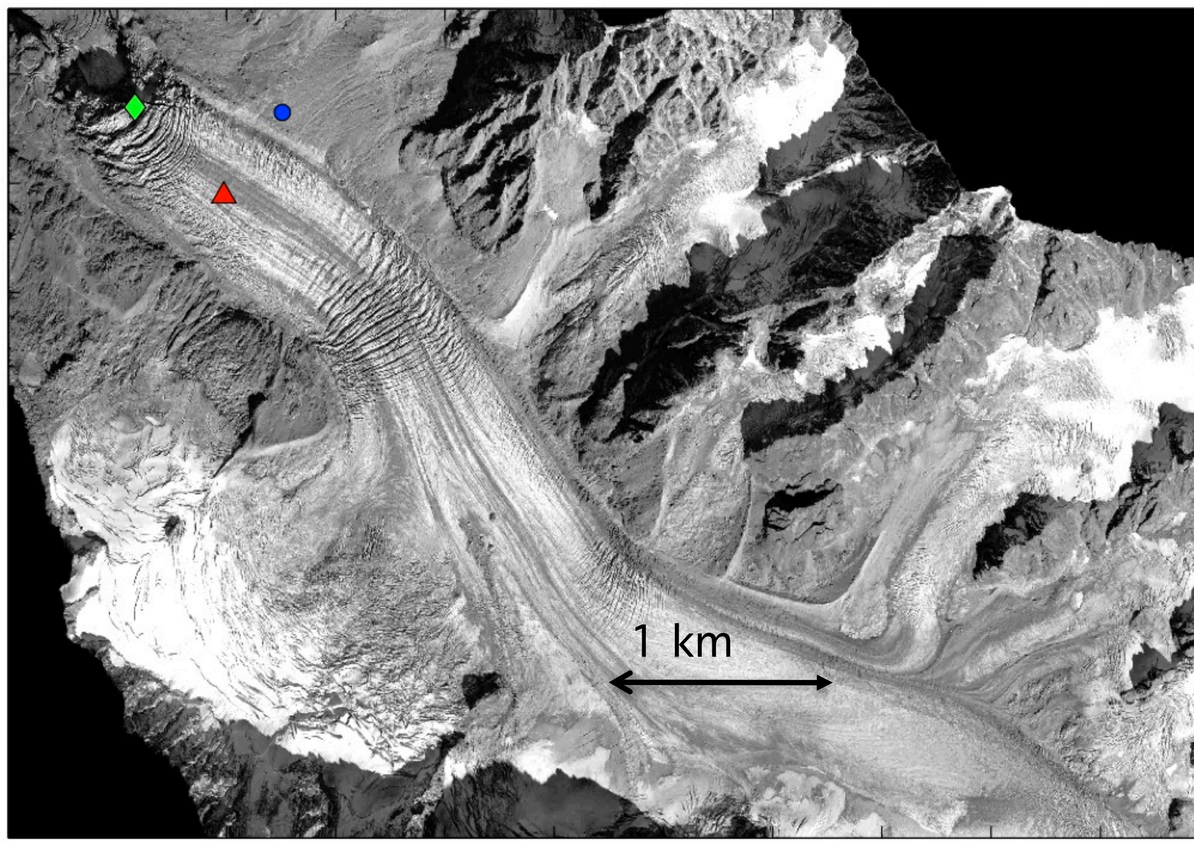




Repeating icequakes, Glacier d'Argentière

Mont-Blanc massif
Temperate glacier (T=0°C)
3400-1600 m elevation
10 km in length
Velocity ≈ 80 m/yr
Thickness ≈ 200 m
(*Helmstetter et al, 2015*)

One 3C accelerometer
Sampling rate 1000 Hz



Repeating icequakes, Glacier d'Argentière

> similar waveforms

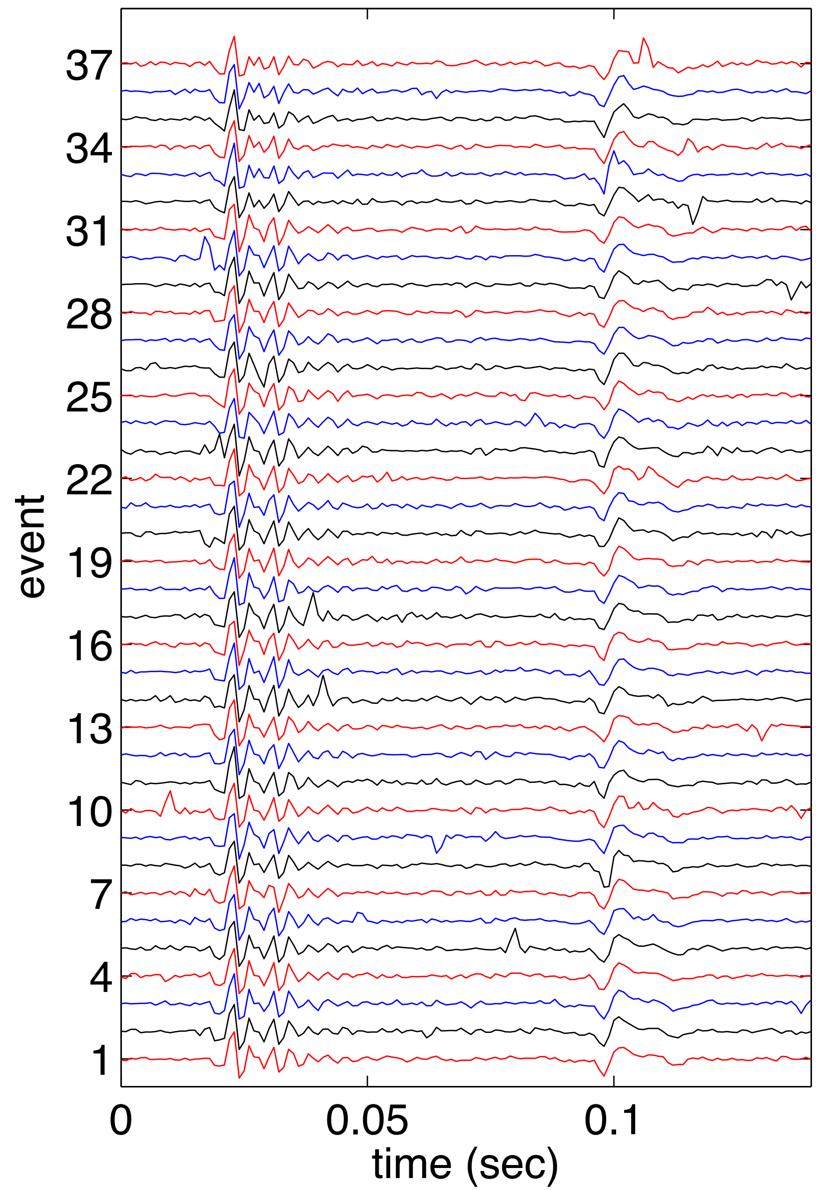
> high-frequency ≈200 Hz

> distinct P and S waves ⇒ deep source

>18 # clusters with 10-884 events

> identification of template waveforms by STA/LTA

> identification of similar events by template matching

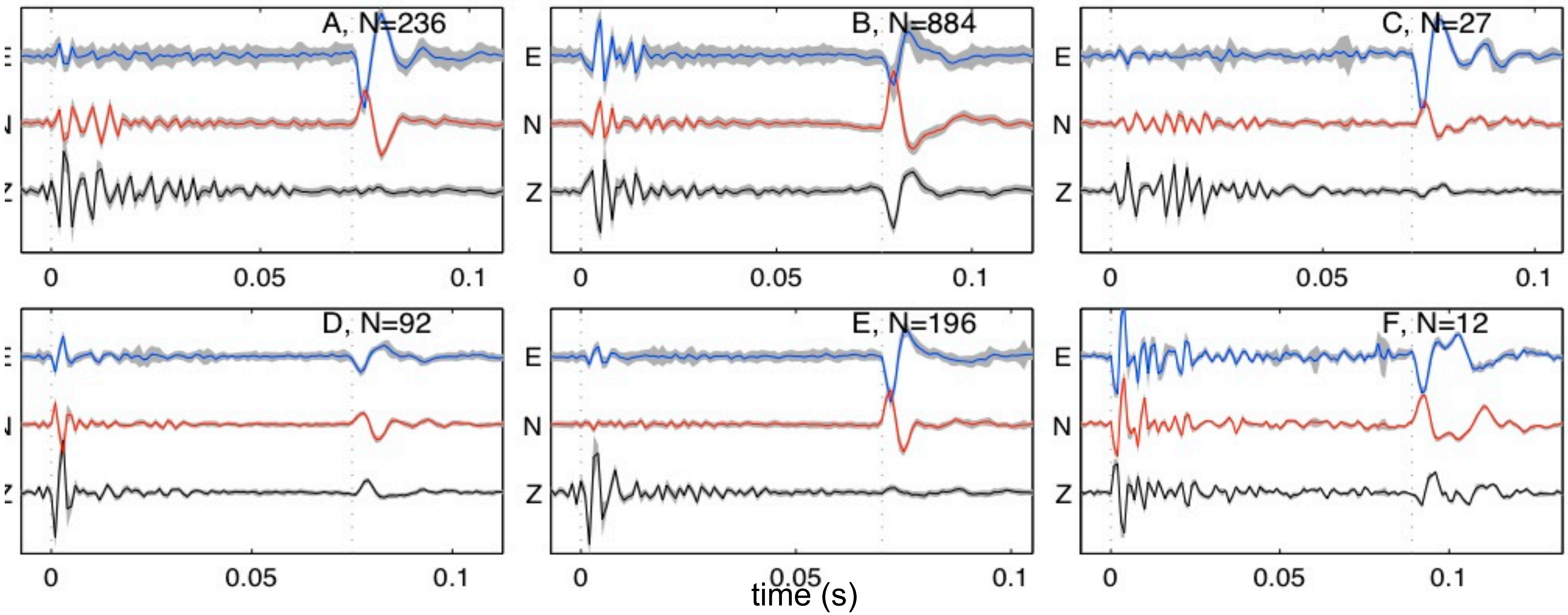


Repeating icequakes, Glacier d’Argentière

Seismograms 3C (acceleration)

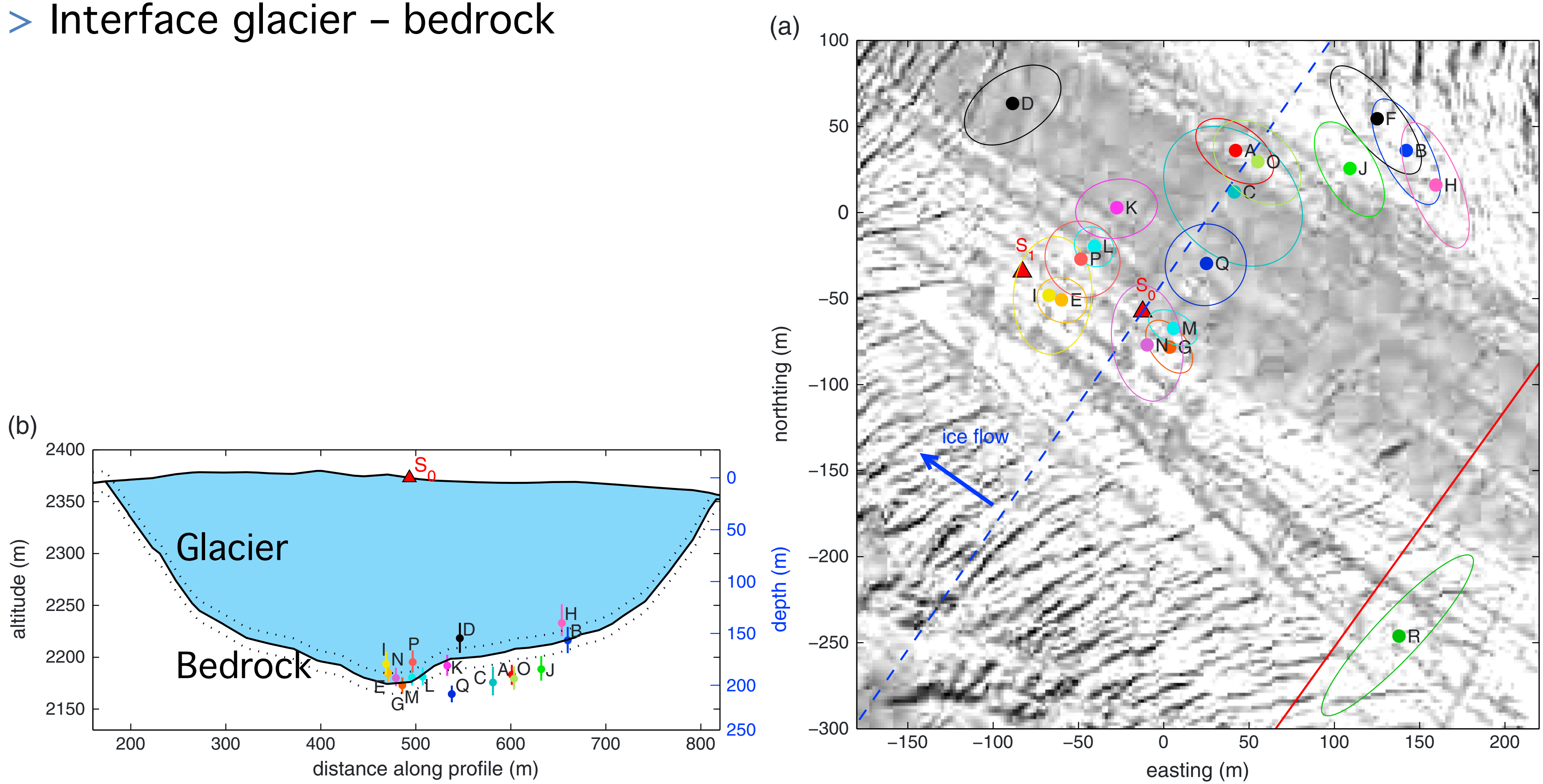
Stack of signals after normalization and alignment

Grey line : standard deviation among all events



Location of repeating icequakes

- > Location with a single 3C sensor from P wave polarization and P-S time delay
- > Interface glacier – bedrock

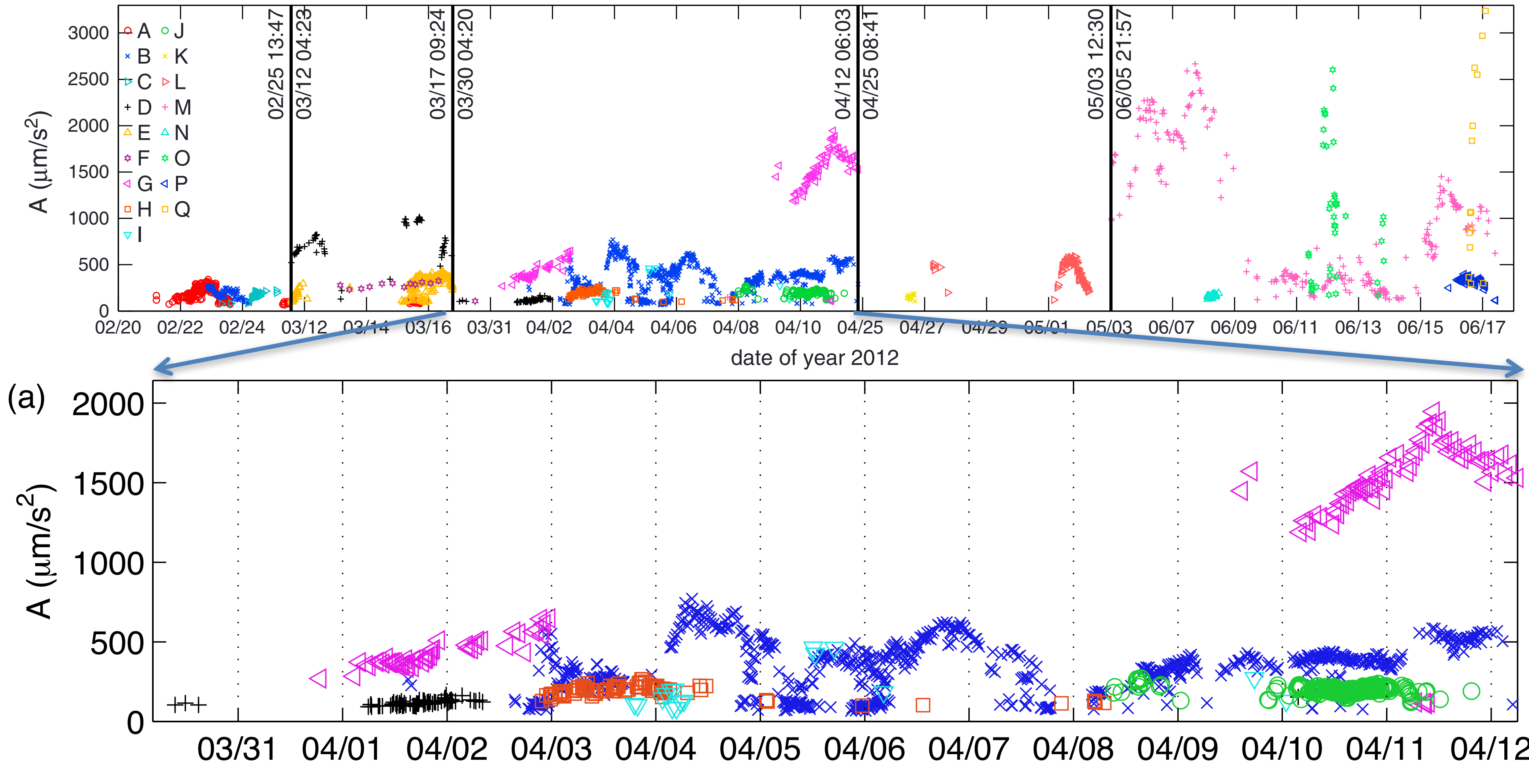


Time series of icequakes amplitudes

February – June 2012 with large gaps (vertical lines)

Succession of active and quiet periods

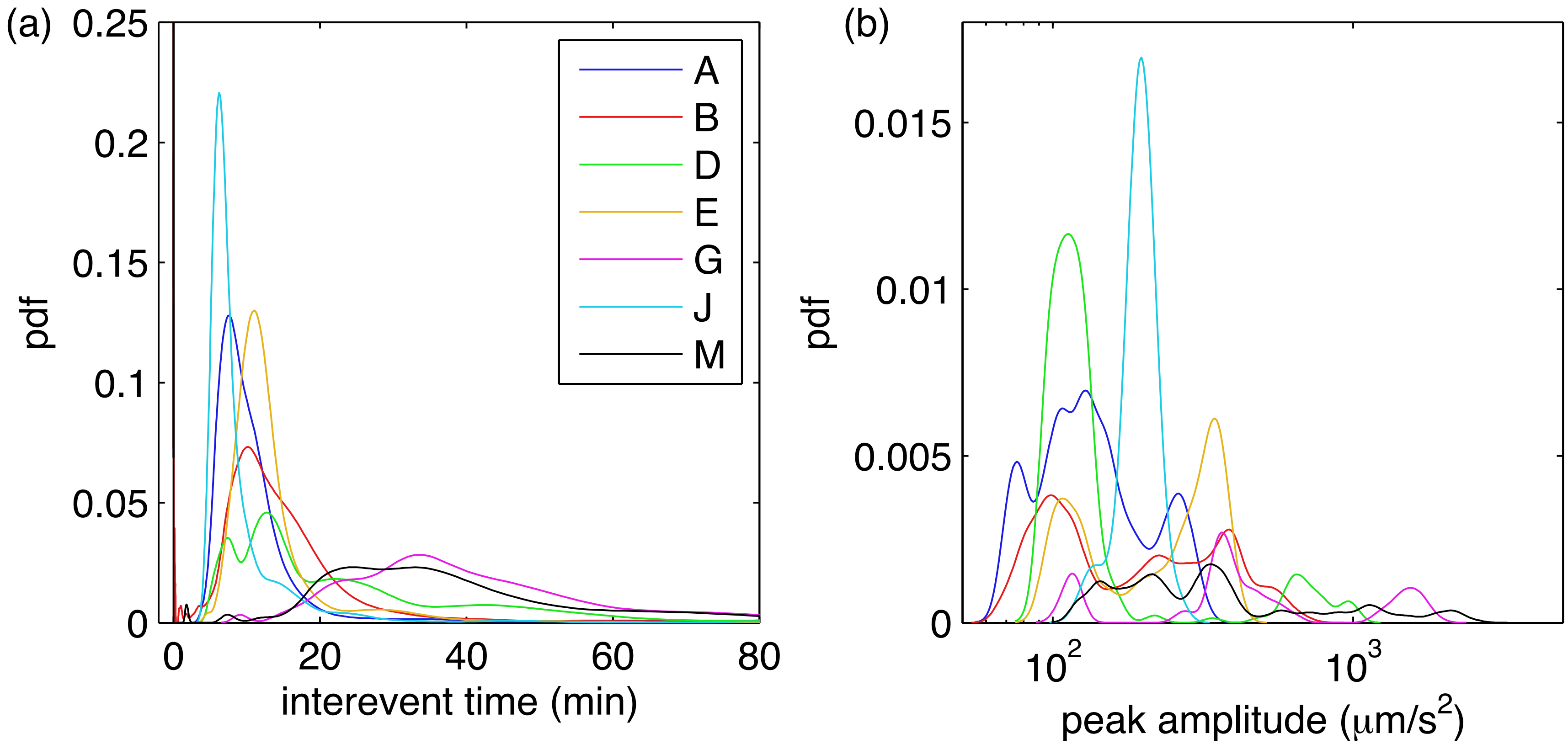
Progressive evolution of amplitude and recurrence times



Distribution of inter-ev. times and amplitudes

> Distribution of inter-ev.times: quasi periodic <dt>≈10 mn

> Distribution of amplitudes: much narrower than GR law



Distribution of inter-ev. times and amplitudes

> distribution of inter-ev.times: quasi periodic <dt>≈10 mn

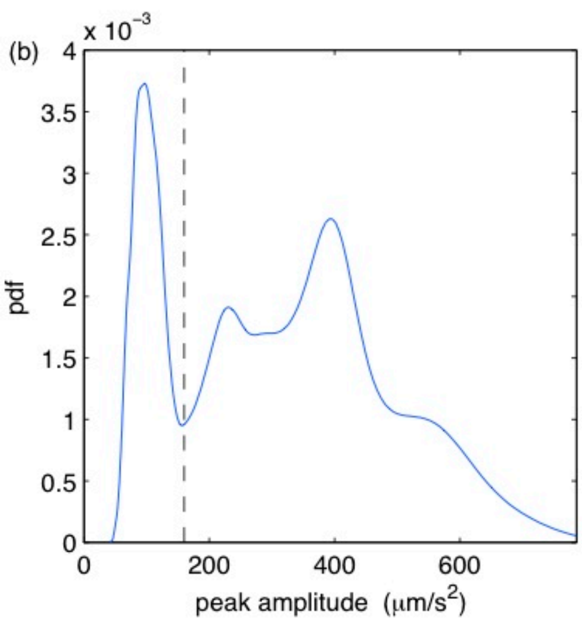
> and clustering for short dt and small A with power–law pdf(dt)

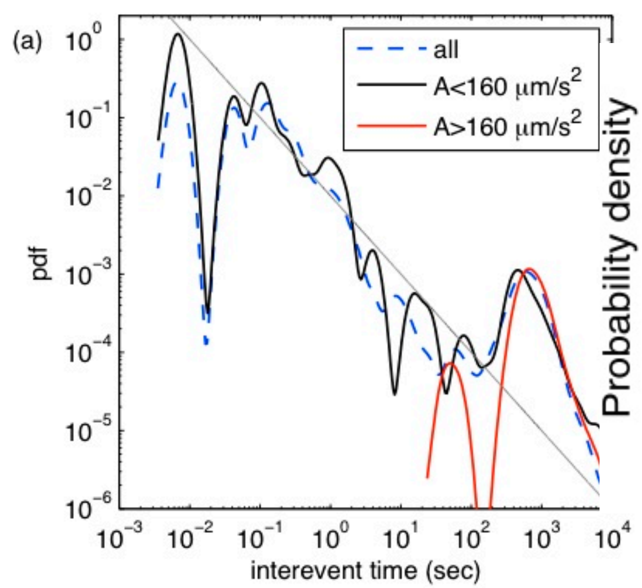
> ... same as repeating earthquakes in Parkfield (*Lengliné et al; 2008*)

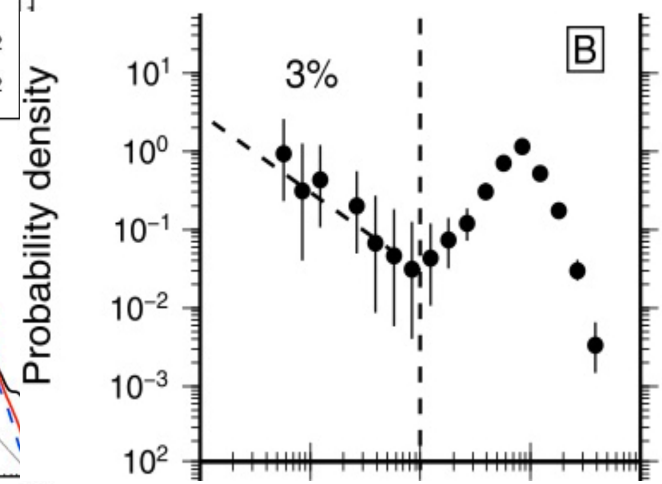
pdf(amplitude) Argentière

pdf(inter-ev.times) Argentière

pdf(inter-ev.time) Parkfield







(Lengliné et al, 2008)

Greenland

> 3 July -15 August

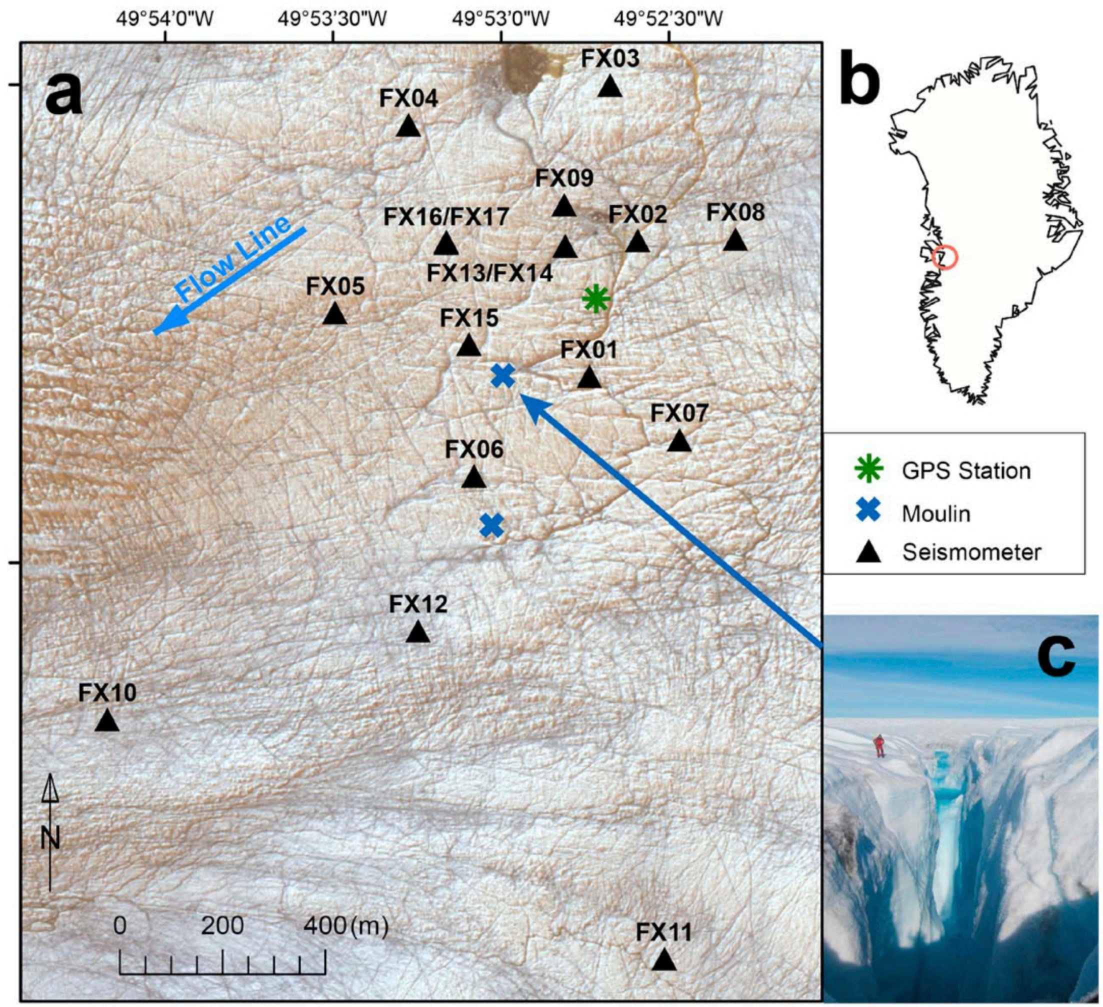
>17 3C seismometers at the surface and in boreholes

> Measurements of displacement, water level and water pressure in a moulin

> Ice thickness ≈ 650 m

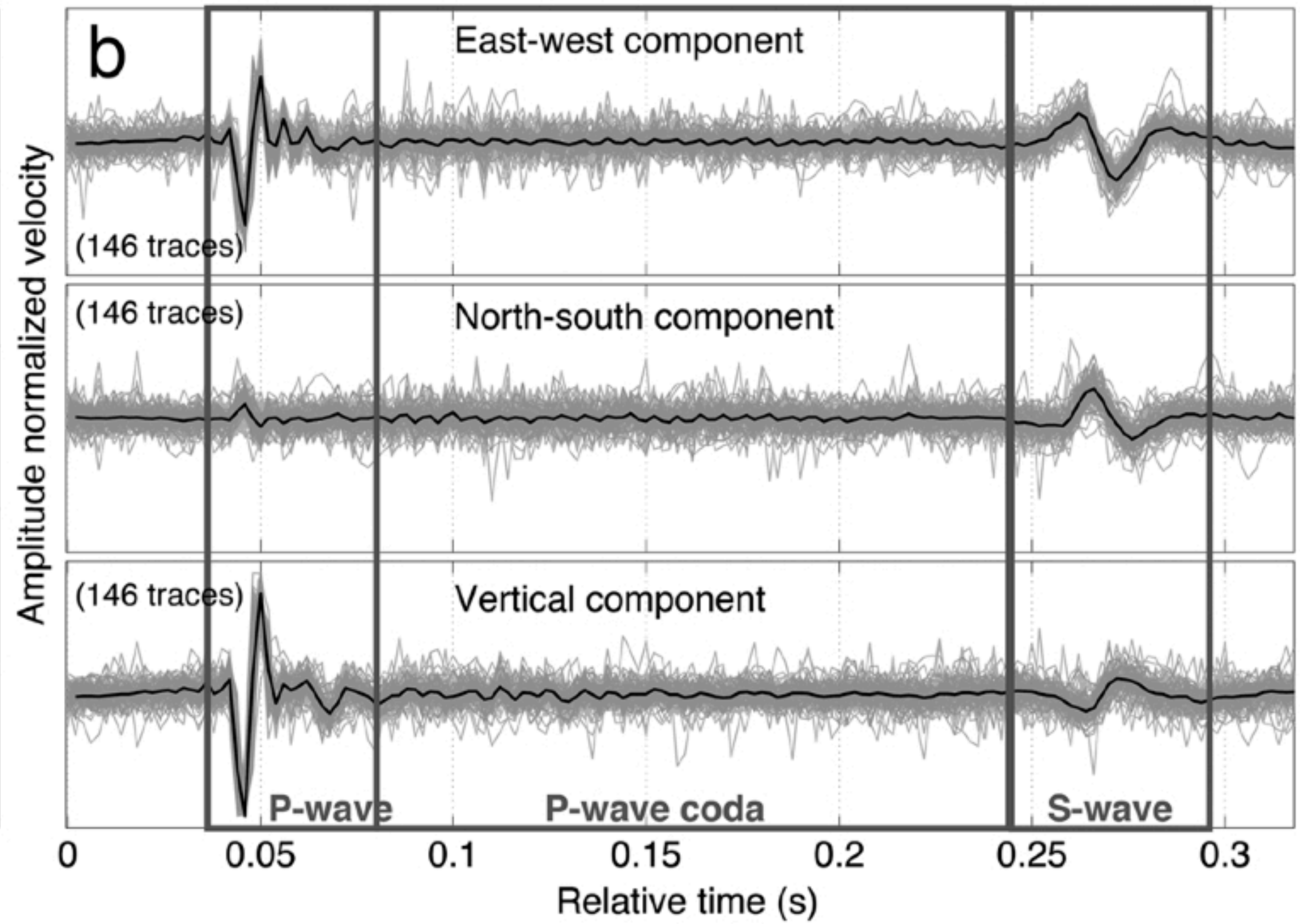
> velocity ≈ 27 cm/day

(Röösli et al, JGR 2016)

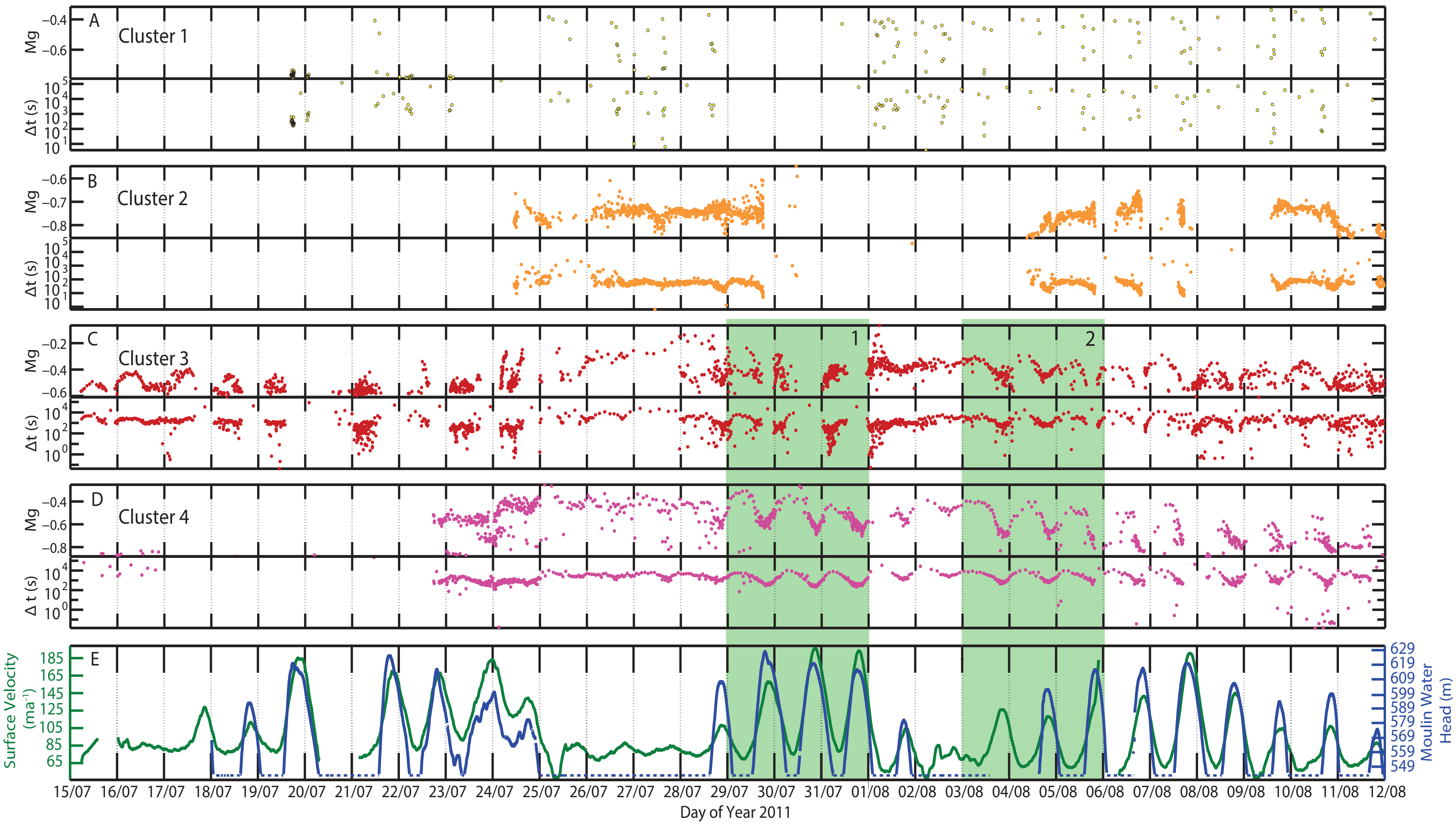


Repeating icequakes in Greenland

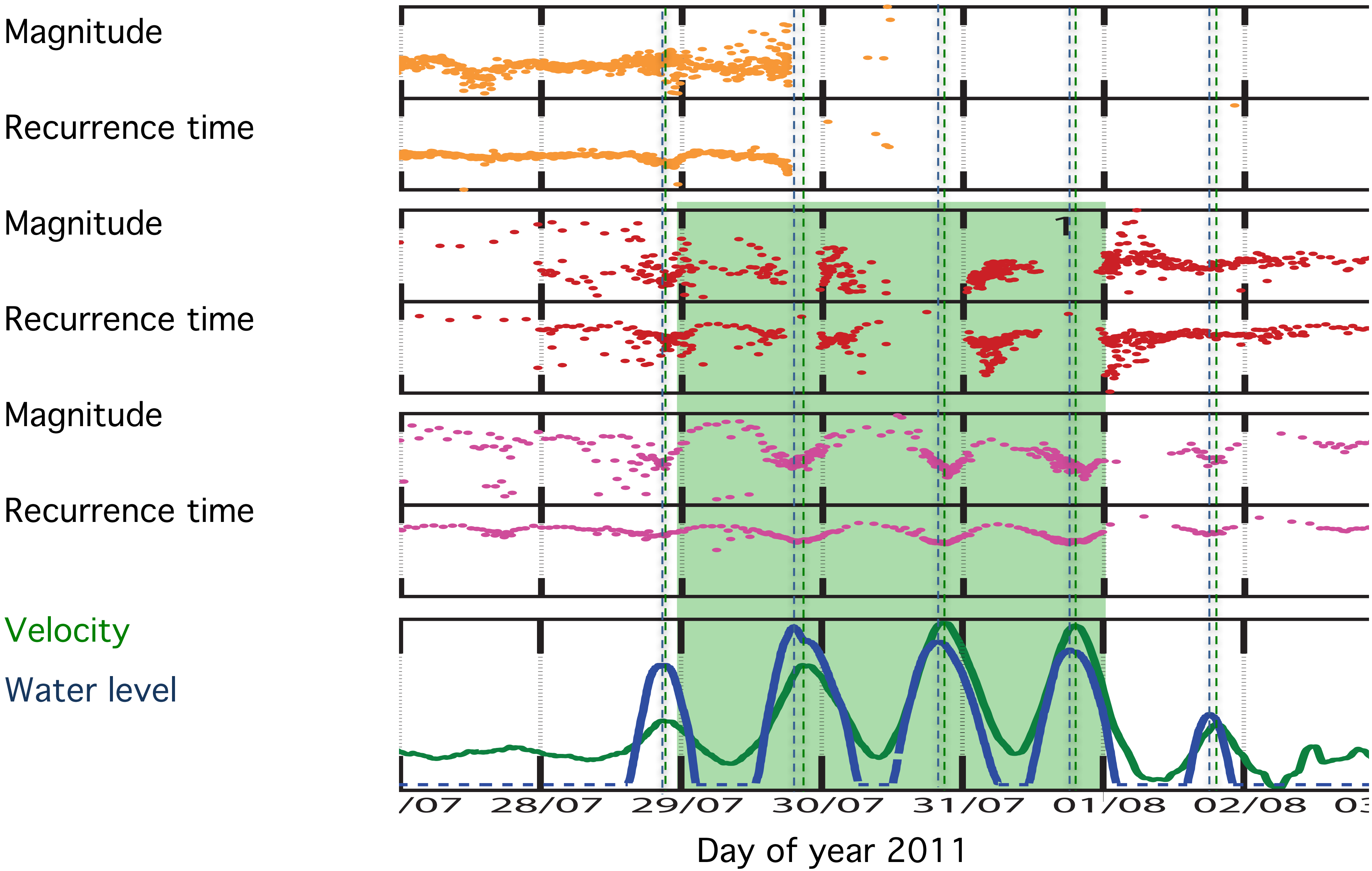
More than 11,000 basal icequakes detected, grouped into > 100 clusters *(Roosli et al, JGR 2016)*



Time series of icequakes magnitude, inter-event times, displacement and water level



Time series ... zoom



Time series : seismic and aseismic slip

> seismic slip ~ signal amplitude, cumulated over time bins of 0.1 day

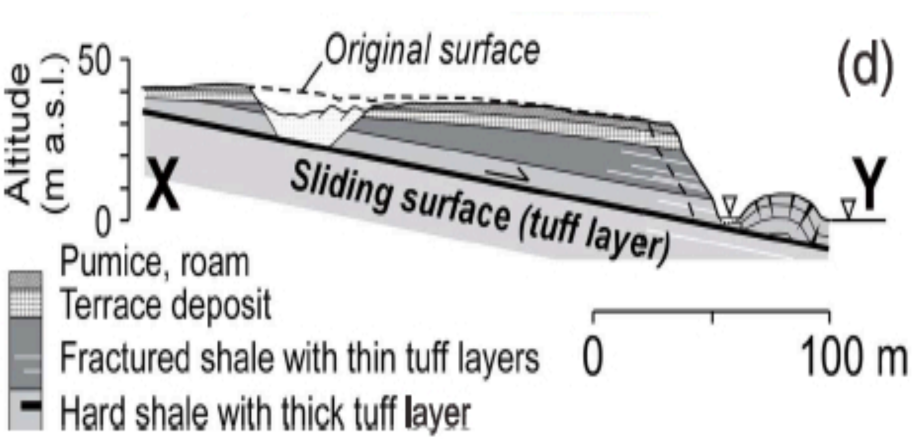
Geophysical Research Letters

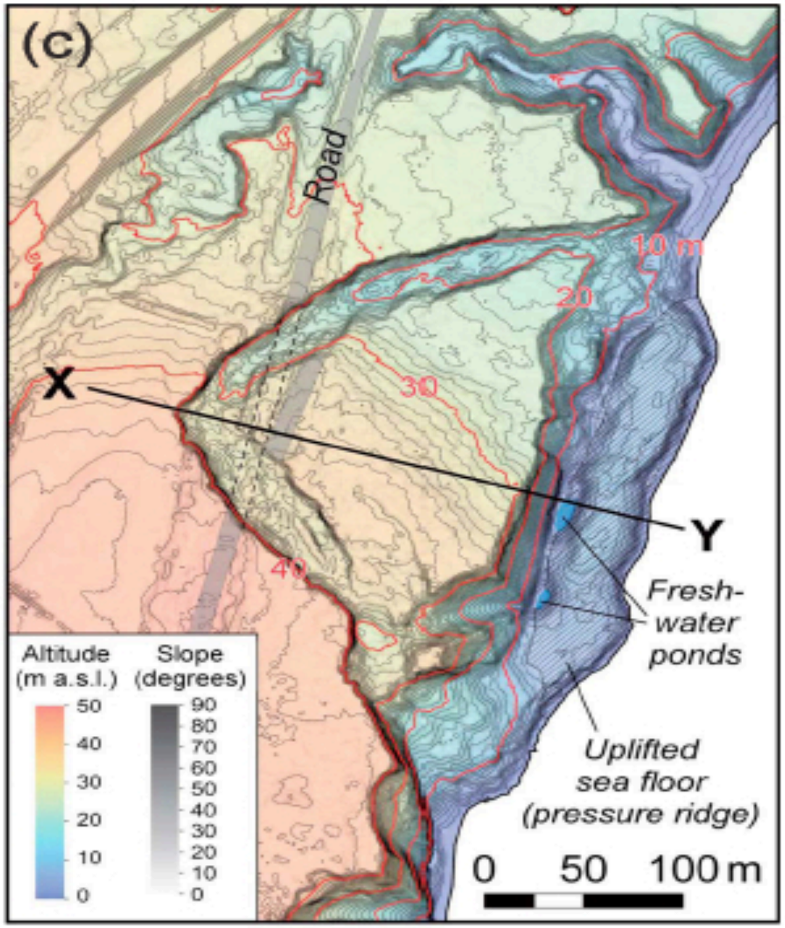
RESEARCH LETTER
10.1002/2016GL069288

Possible stick-slip behavior before the Rausu landslide inferred from repeating seismic events

Masumi Yamada[1], Jim Mori[1], and Yuki Matsushi[1]

Key Points:
- We found tiny repeating earthquakes





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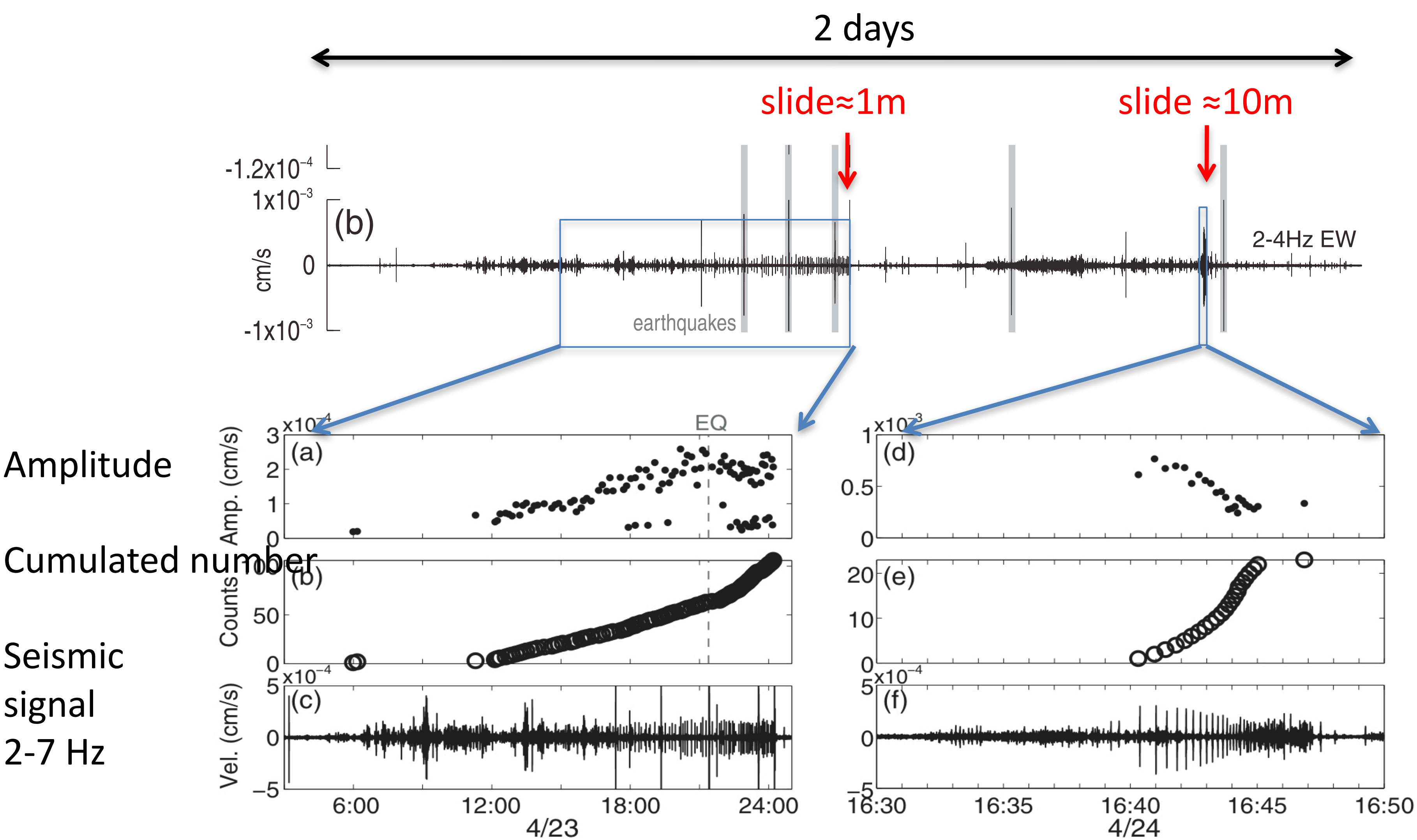


Aletsch

Valais, Switzerland

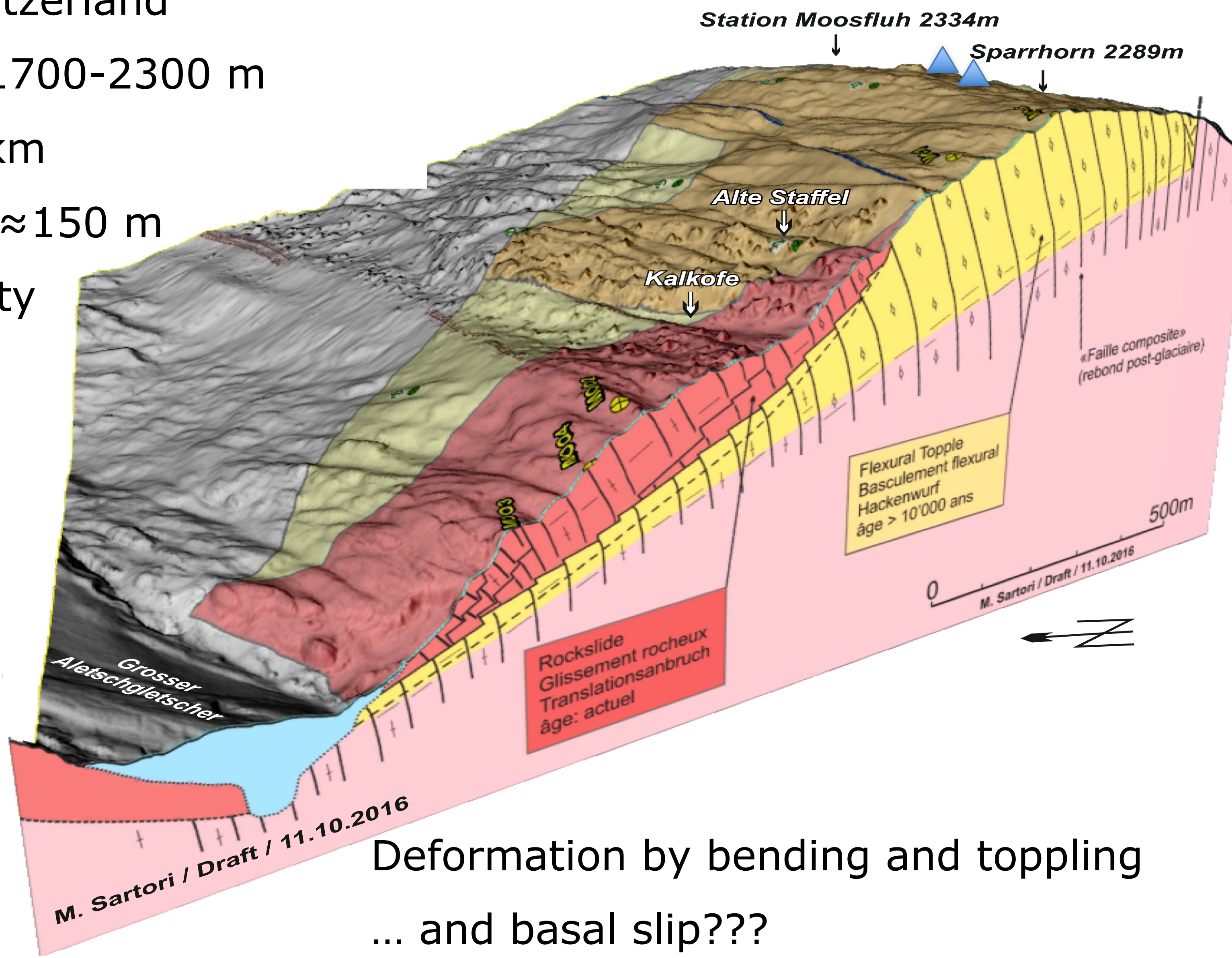
Elevation 1700-2300 m

Length≈1km

Thickness ≈150 m

Max velocity

≈1 m/day

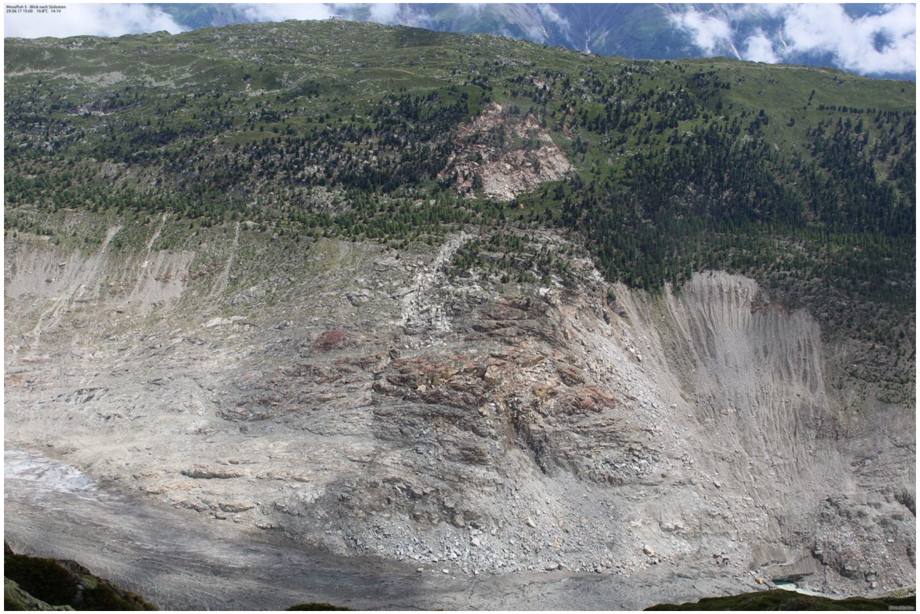


Deformation by bending and toppling

… and basal slip???

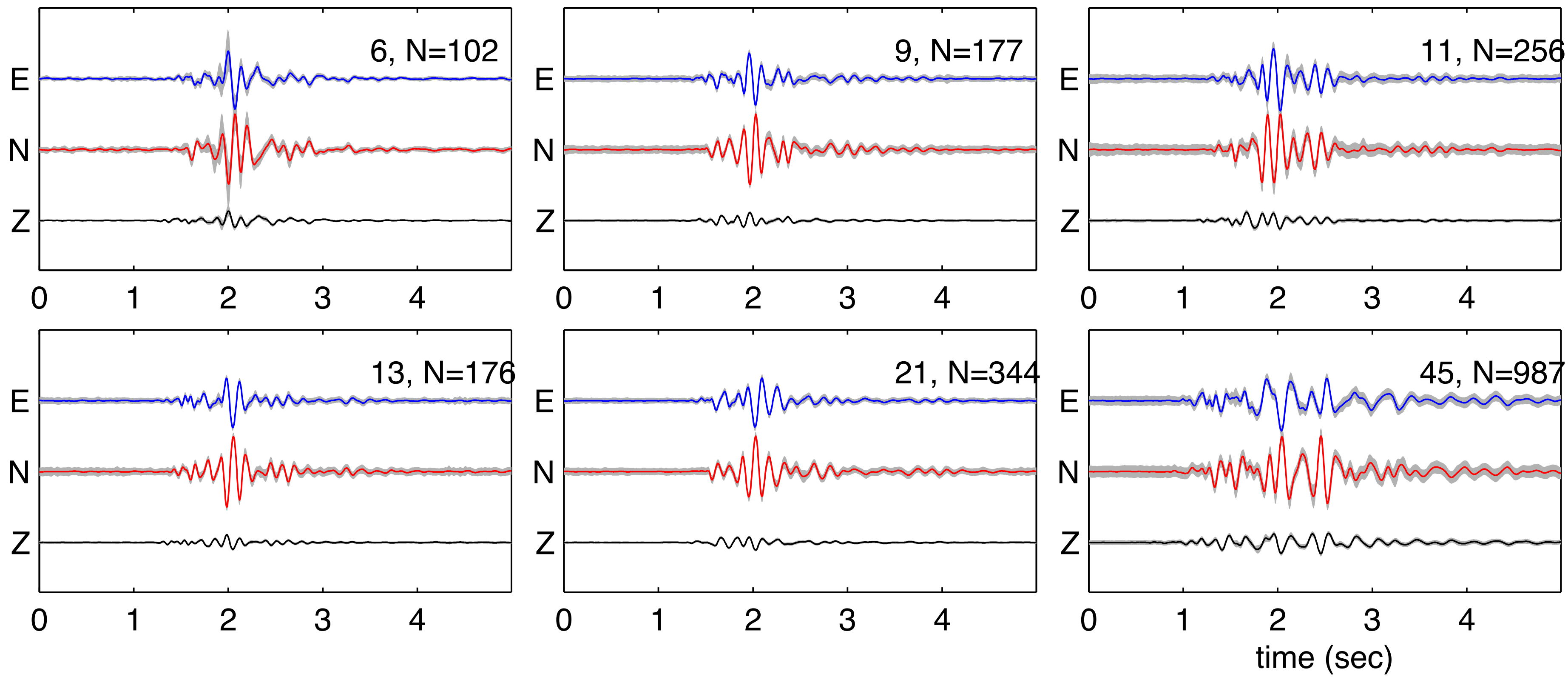
Aletsch

1 image / month
march-september 2017



Seismic signals

- Duration ≈2 s, frequency ≈5 Hz
- 30000 events detected by template-matching since 2016/10/3
- 640 clusters with up to 1474 events



Seismic activity and displacement rate

Selection of «repeaters»

Regular in time and size

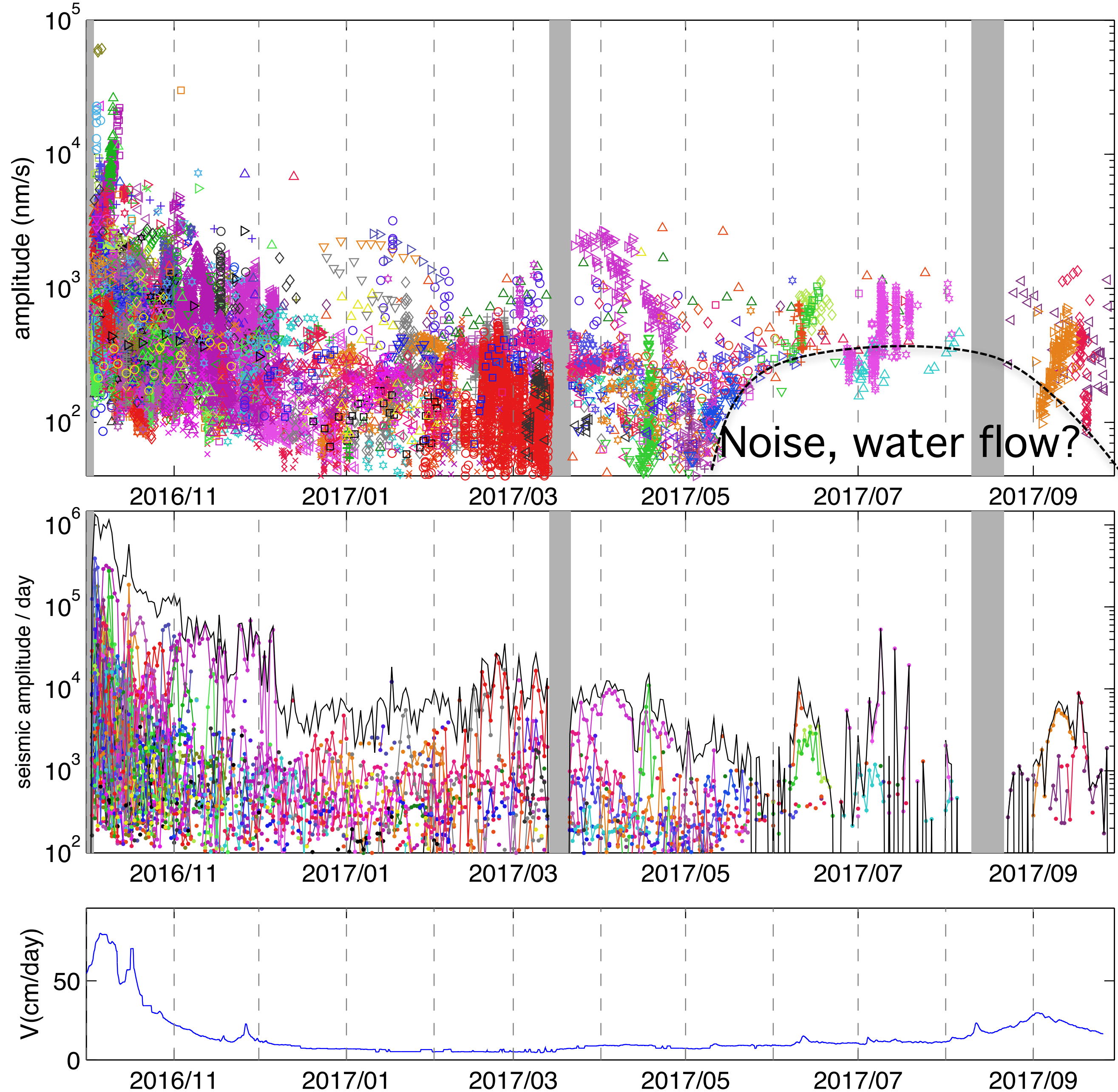
symbol for each cluster

Cumulated

amplitude/day

Rockslide velocity

(GPS data ETHZ)

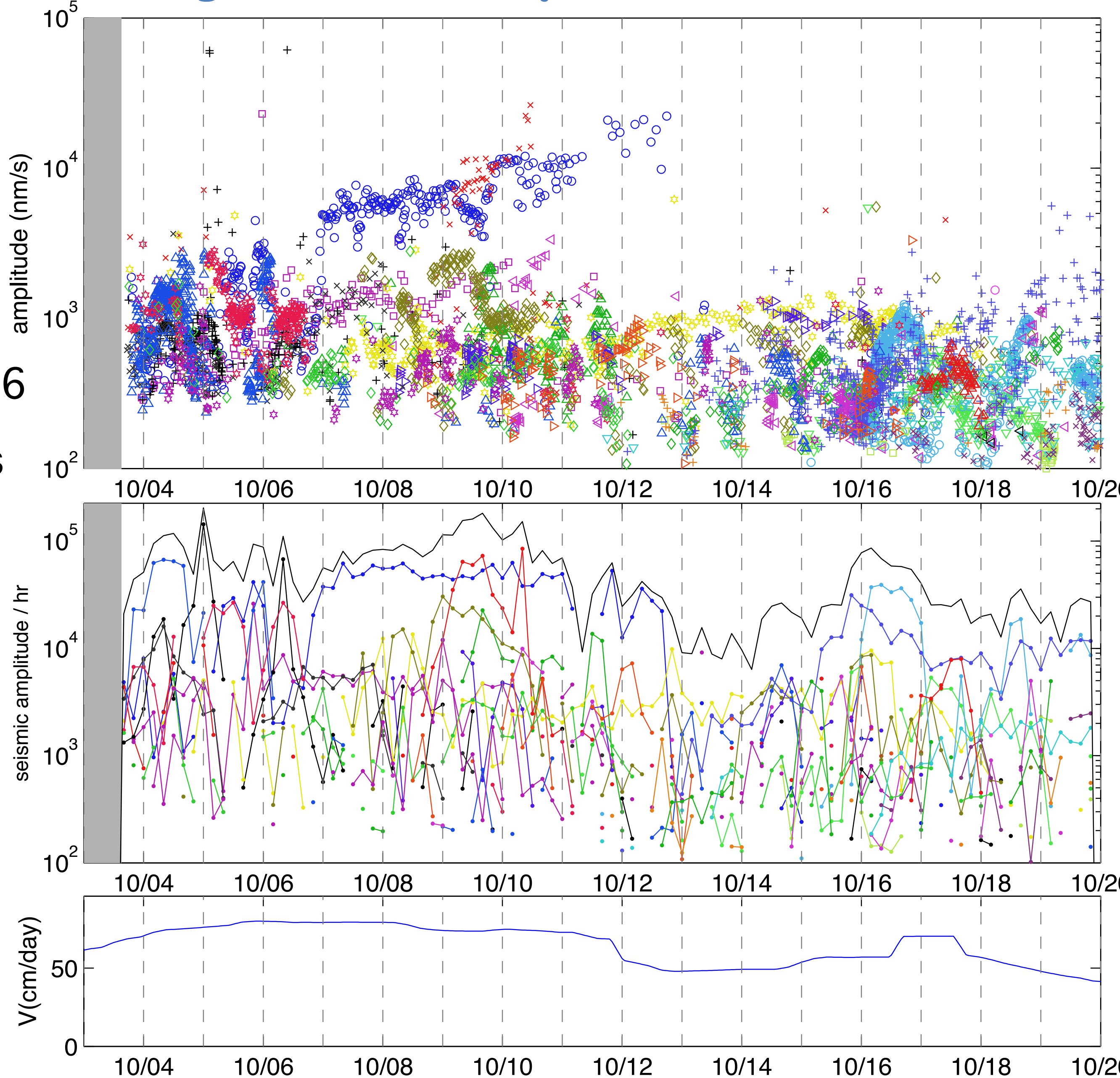


Seismic activity and displacement rate

Zoom

3-20 October 2016

Largest sequences

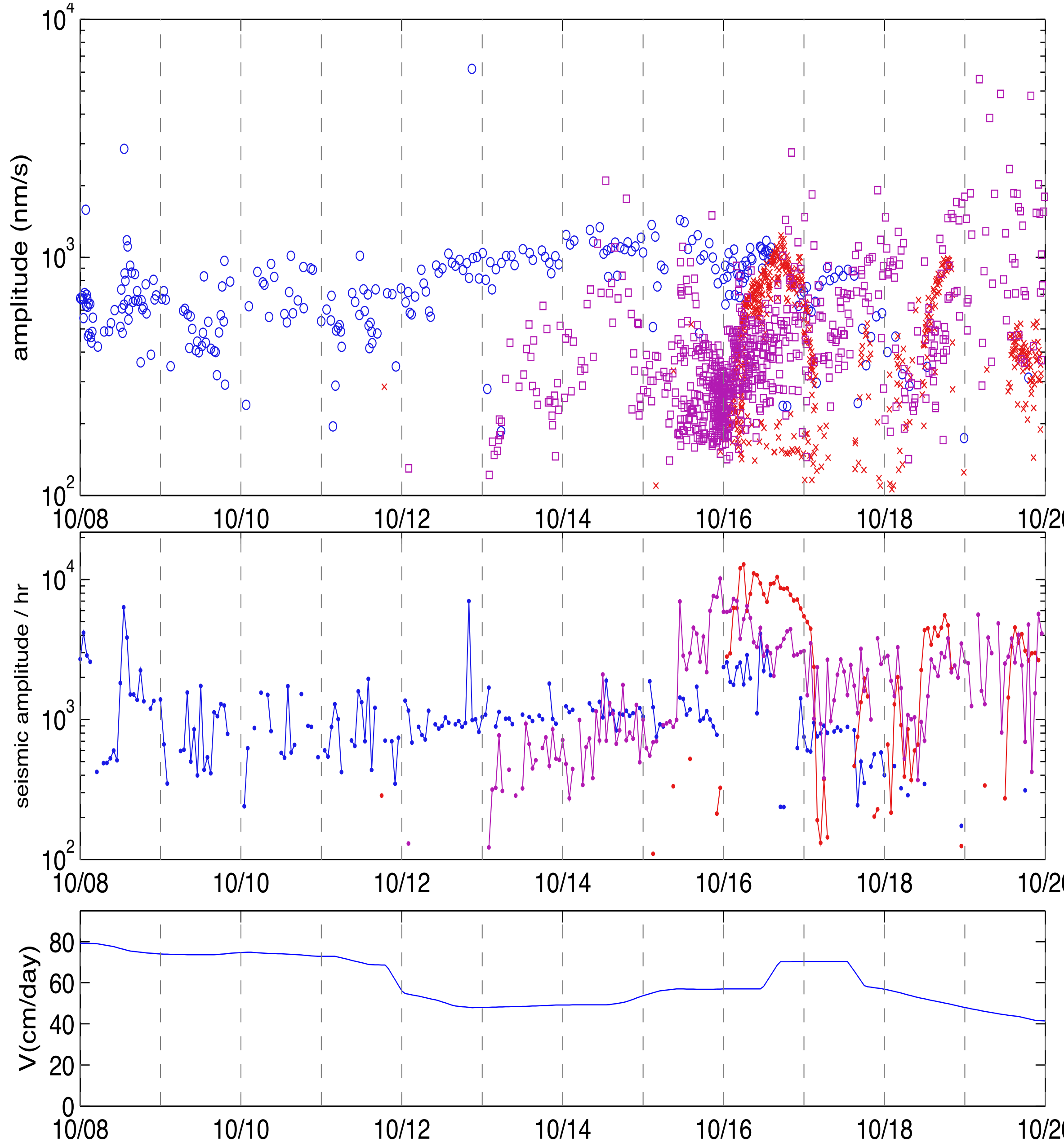


Seismic activity and displacement rate

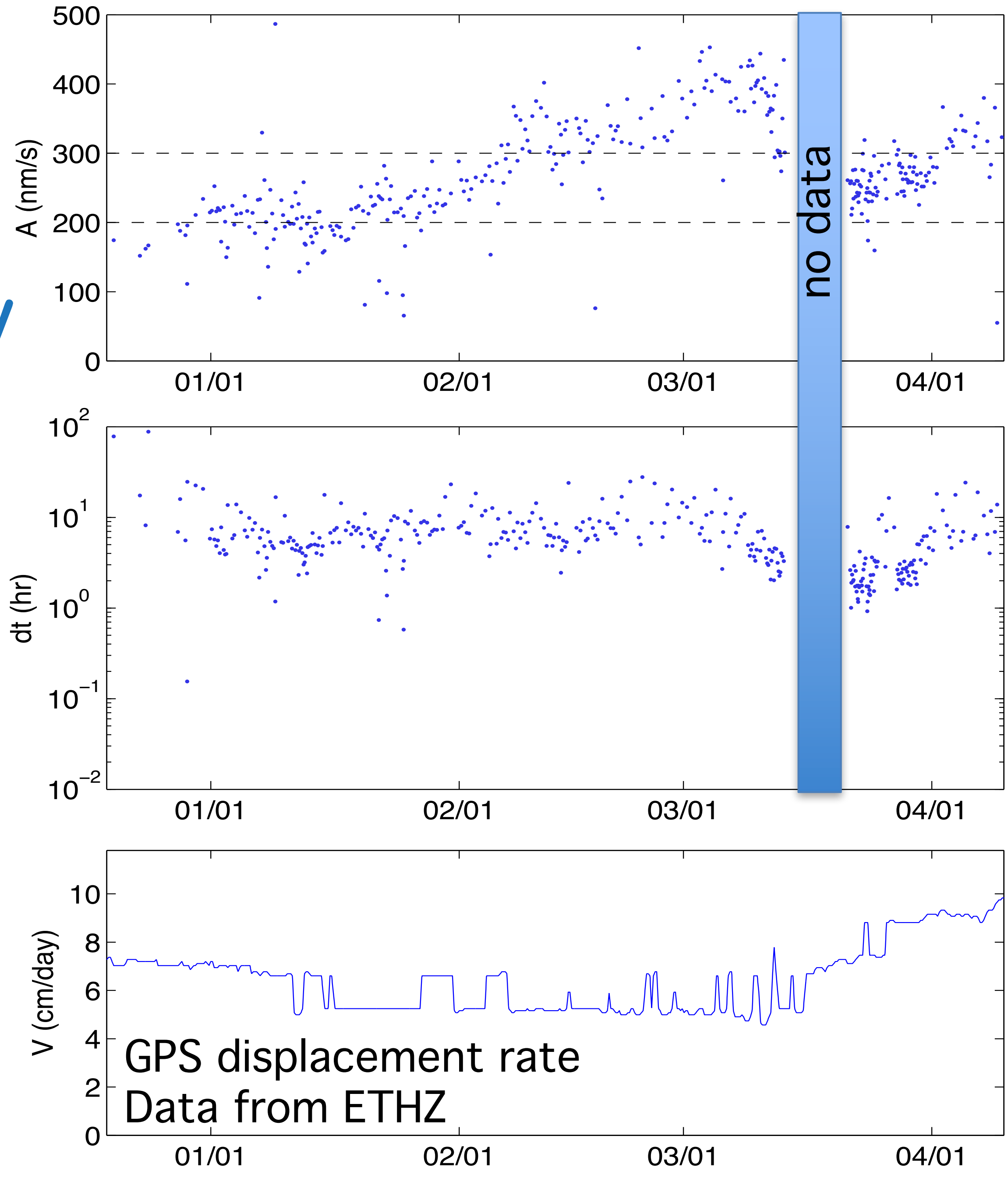
Zoom

10-20 October 2016

3 sequences



Relation between peak amplitude, recurrence time and sliding velocity



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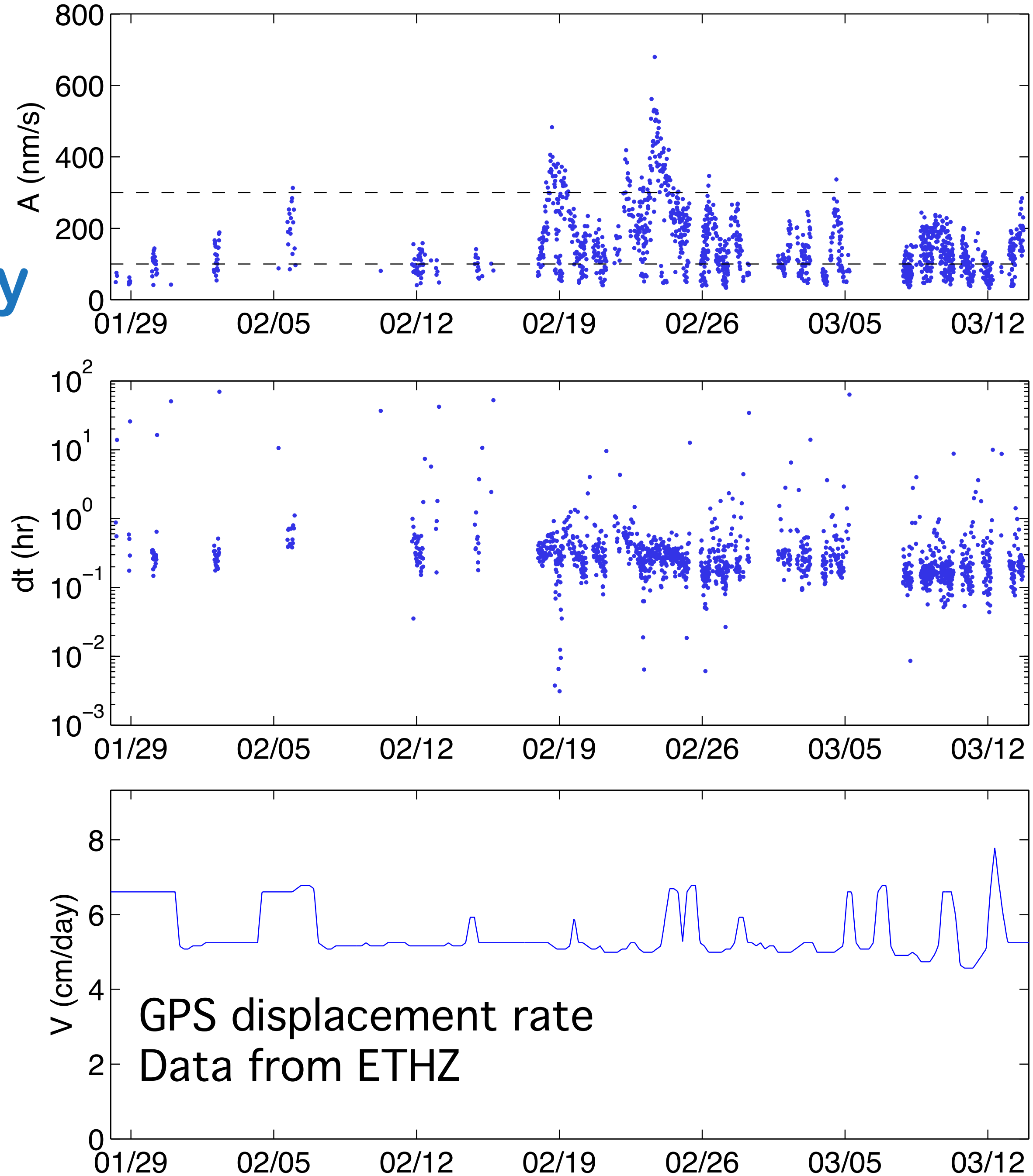


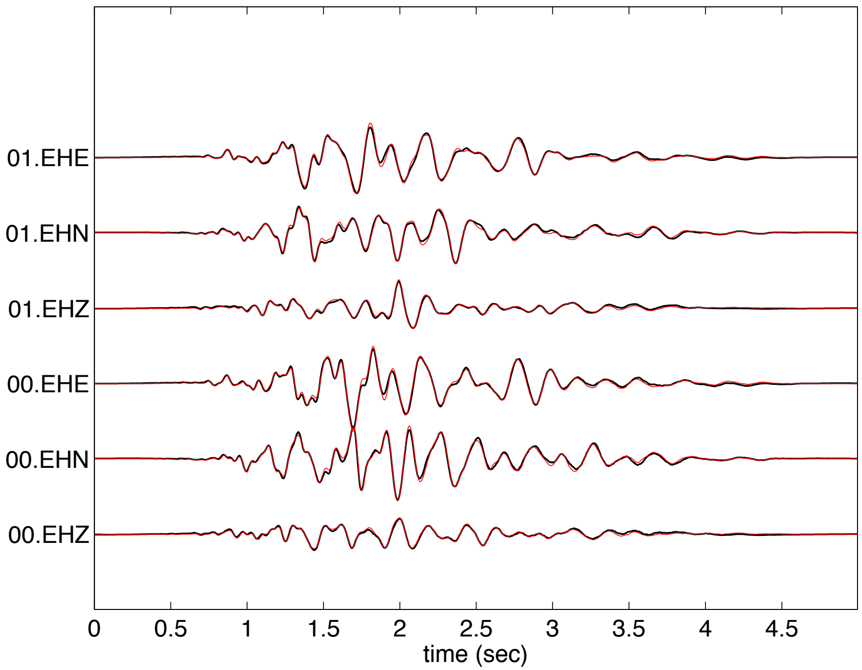
Waveforms of small and large events

Black : stack of small events, A < 100 nm/s and <A>= 71 nm/s

Red : stack of large events, A > 300 nm/s and <A>= 378 nm/s

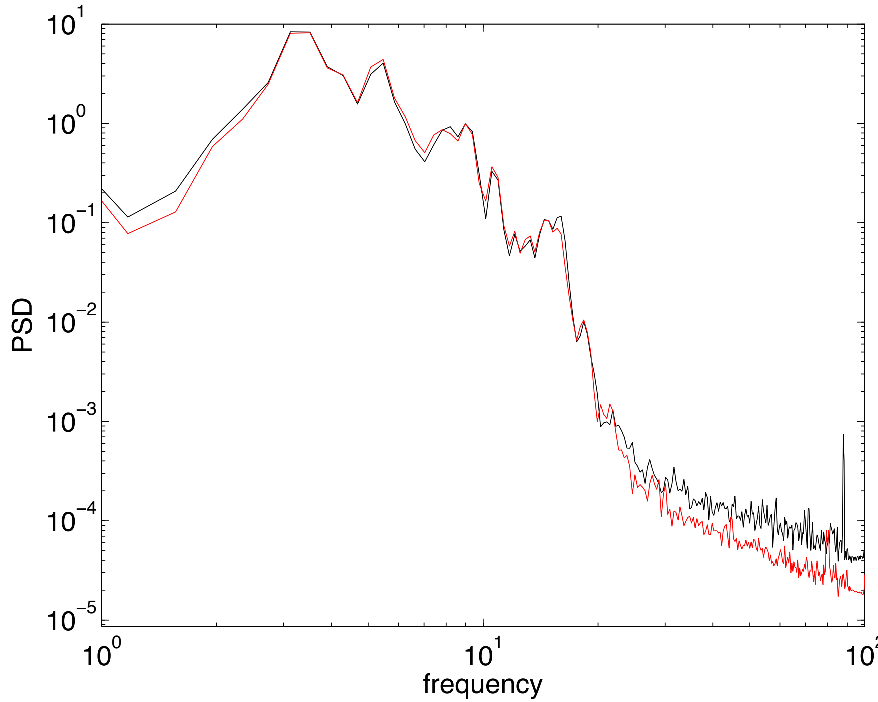
Magnitude ? <0 ? Corner frequency > 1000 Hz?

Stacked waveforms, normalized by peak amplitude A, no filter



Normalized spectrum

Smaller events have relatively more energy for f>20Hz



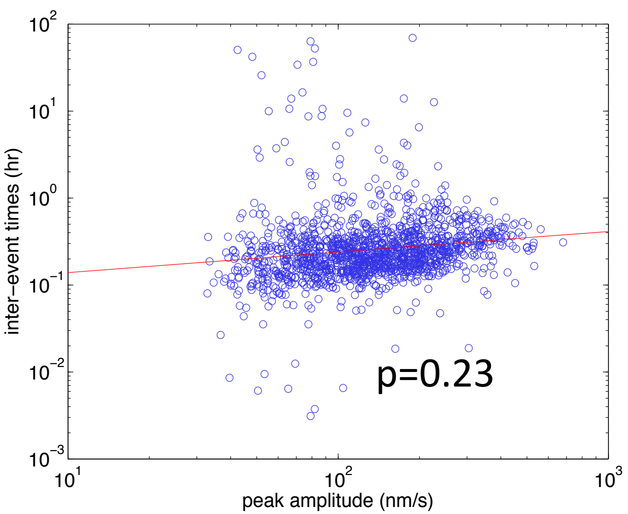
Relation between size and recurrence time

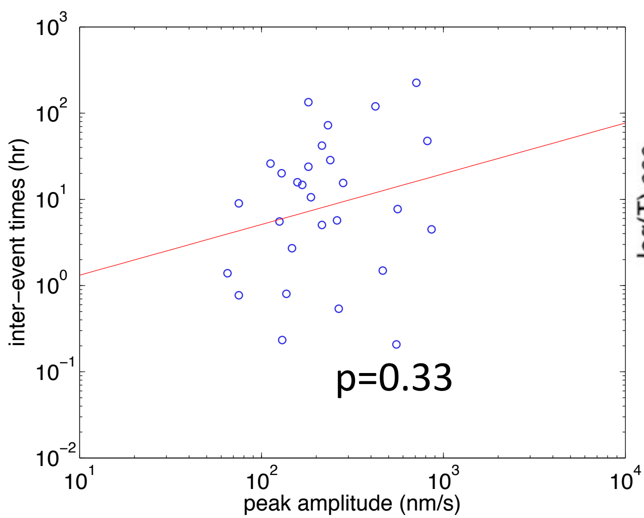
Interevent times as a function of amplitude for :

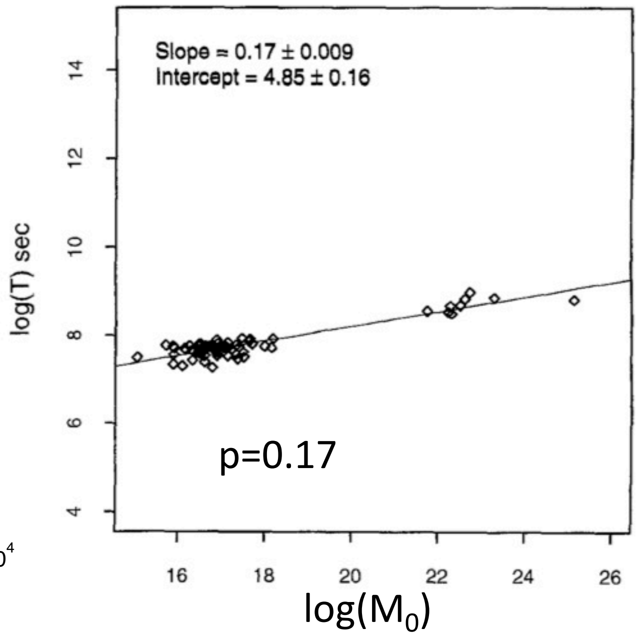
> 1 sequence of repeaters in Aletsch

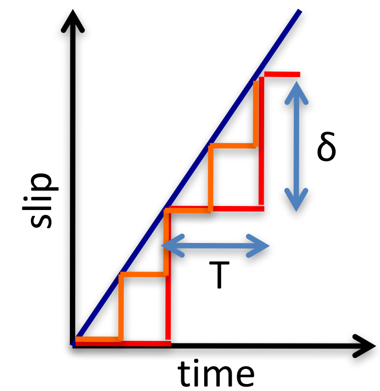
> Average values for the 28 most regular sequences with times between 2016/12/1 and 2017/9/1

> Average for 62 sequences in Parkfield (p=0.17; Nadeau and Johnston, 1998)









$T \sim M_0$

Constant L (Lengliné et al 2014)

No interseismic slip

Constant loading =>$T \sim \delta$

$M_0 \sim \delta L^2 \sim \delta \sim T$

$T \sim M_0^{1/3}$

Constant stress drop $L \sim \delta$

No interseismic slip

$M_0 \sim \delta L^2 \sim \delta^3 \sim T^3$

$T \sim M_0^{1/6}$

> Nadeau and Johnson (1998)

no interseismic slip =>$T \sim \delta$

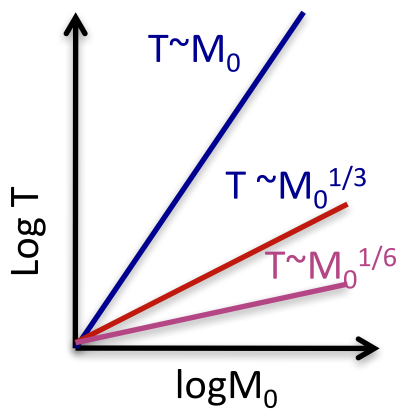
stress drop decreases with M_0

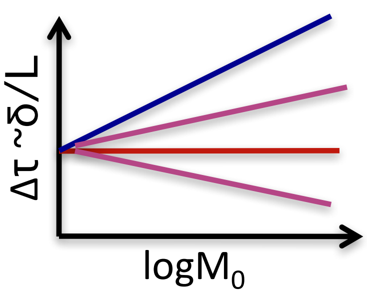
$M_0 \sim \delta^6 \sim T^6$

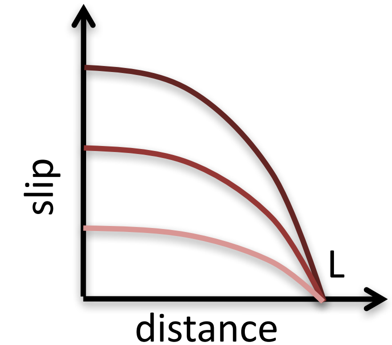
> Cattania (2017)

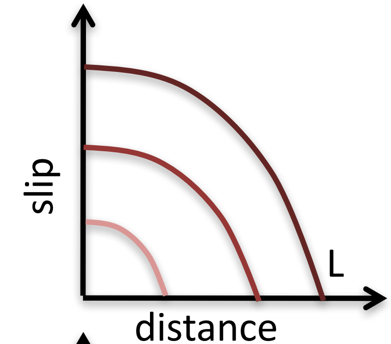
interseismic slip =>$T \sim L$

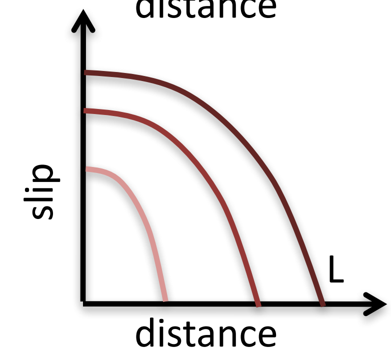
stress drop increases with M_0

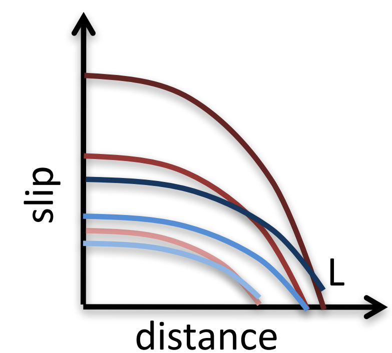








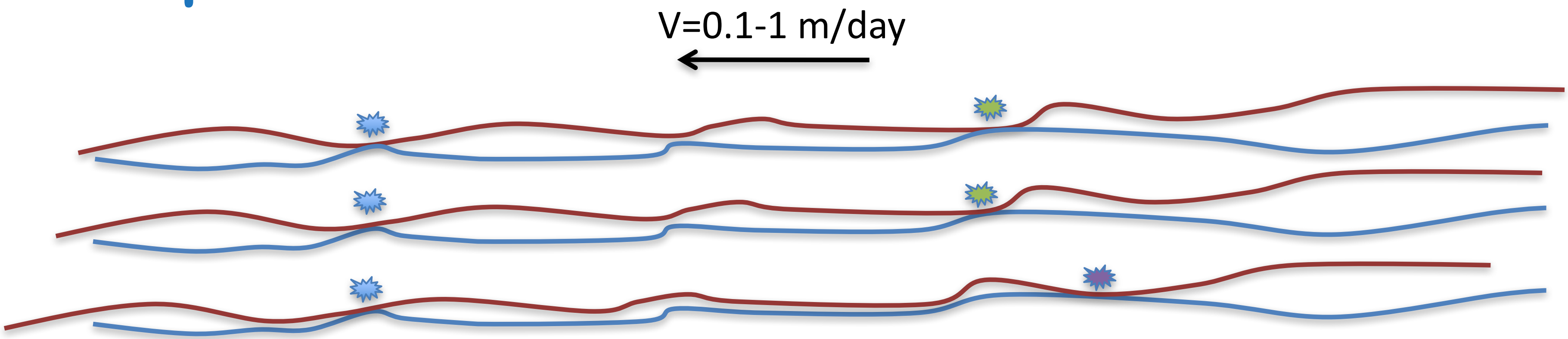




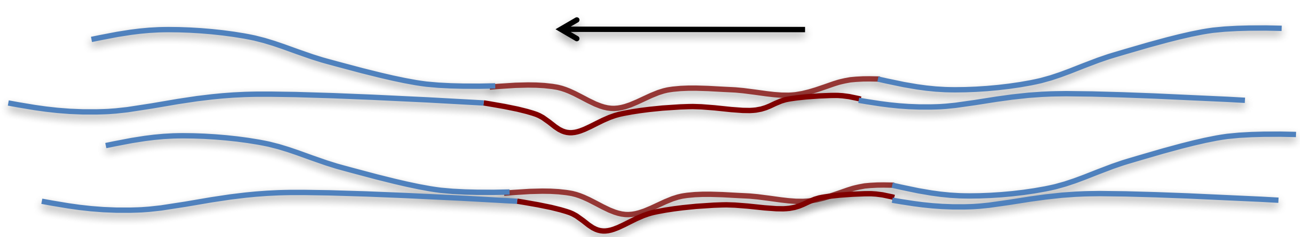
Temporal variation of amplitude and recurrence times within each cluster

- No correlation between # clusters
- No correlation with precipitations, snow or temperature
- No correlation with rockslide velocity
- Variations dues to local properties of the interface?

Asperities ...



At large scale, appearance and destructions of asperities with slip



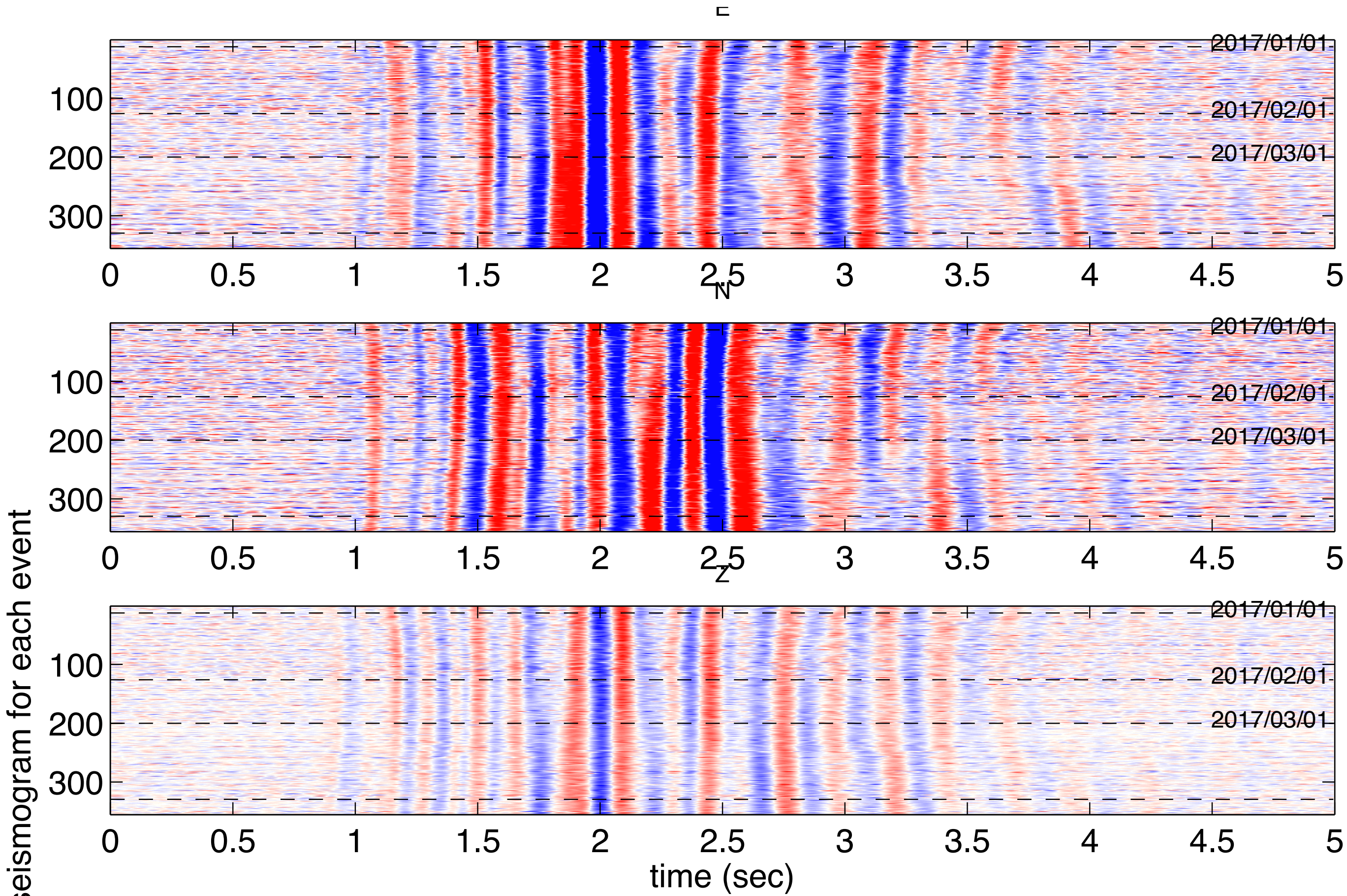
At the scale of one asperity (≈1m?),

a small slip can change the contact area and the stress on the interface

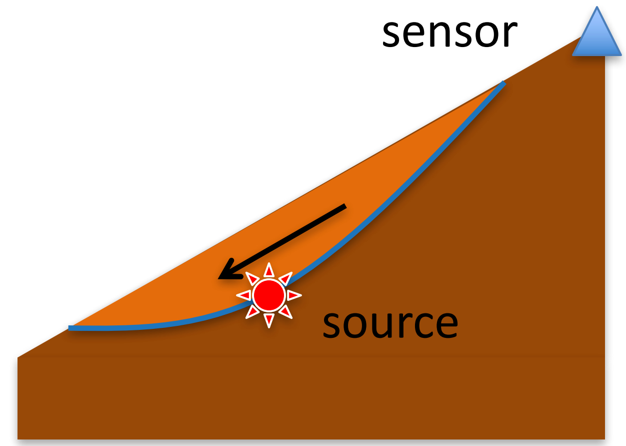
yielding a change in amplitude and recurrence time?

Temporal changes in seismic waveforms

- One sequence of repeaters with 355 events in 4 months
- 1 line = 1 event, color ~ seismic ground velocity
- 1 plot for each trace (Z,N,E)
- Source moving or change in the medium?



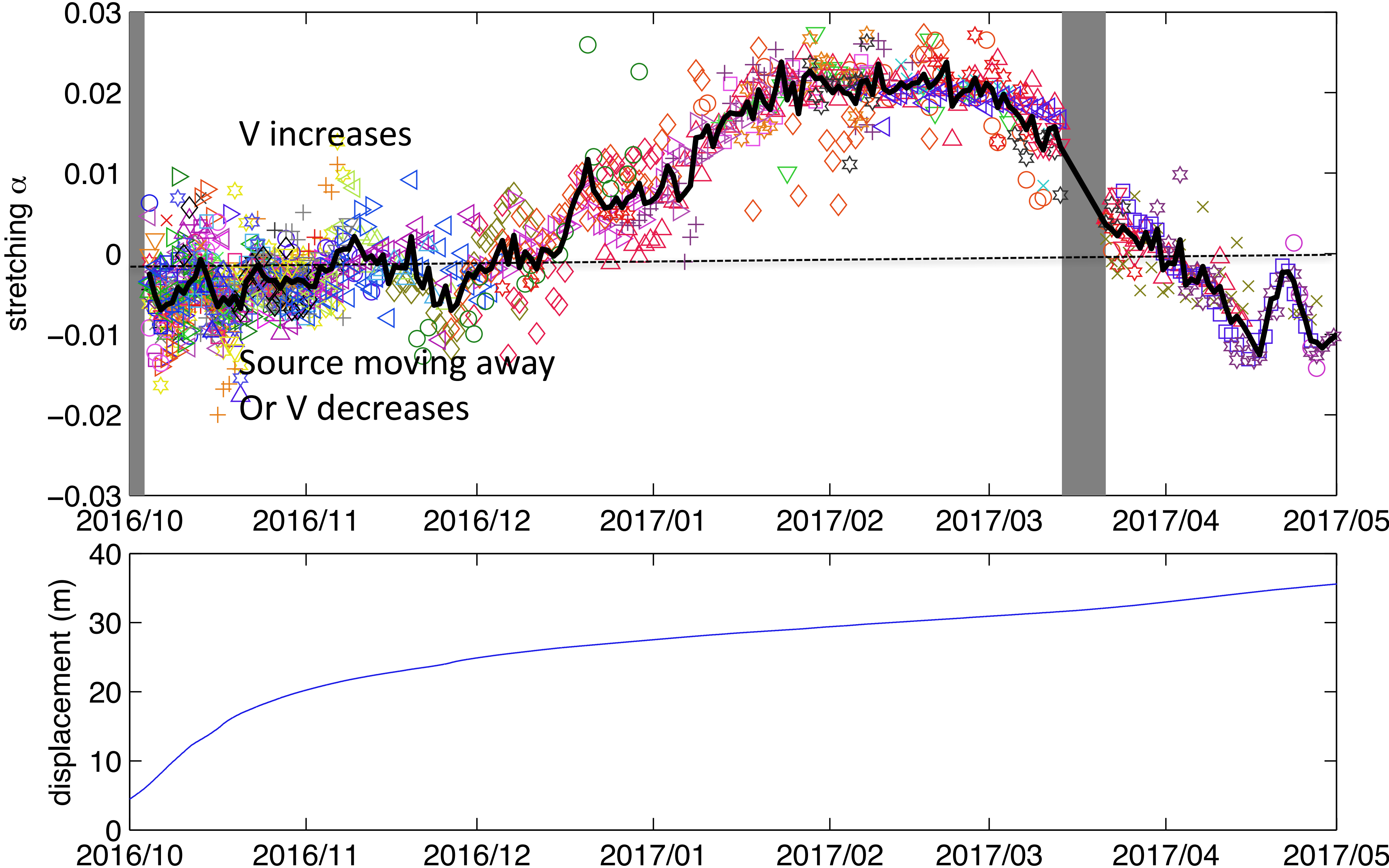
Temporal variation of waveforms



- Selection of « repeating » events
- Shifting and stretching of signals
- Average over 1 day => waveform $y_i(t)$
- Correlation with the stack of all events y_t
- Find dt_i and $\boldsymbol{\alpha}_i$ that maximize the correlation between

  $y_i((t+dt_i)*(1+\boldsymbol{\alpha}_i))$ and y_t
- Fixed source => $\boldsymbol{\alpha}$=dV/V : variation of seismic wave velocities
- Source moving with rockslide => $\boldsymbol{\alpha}$ ~displacement and $\boldsymbol{\alpha}<0$
- Align all curves for # clusters by minimizing residuals and average

Temporal variation of waveforms



Gugla

Rock-glacier

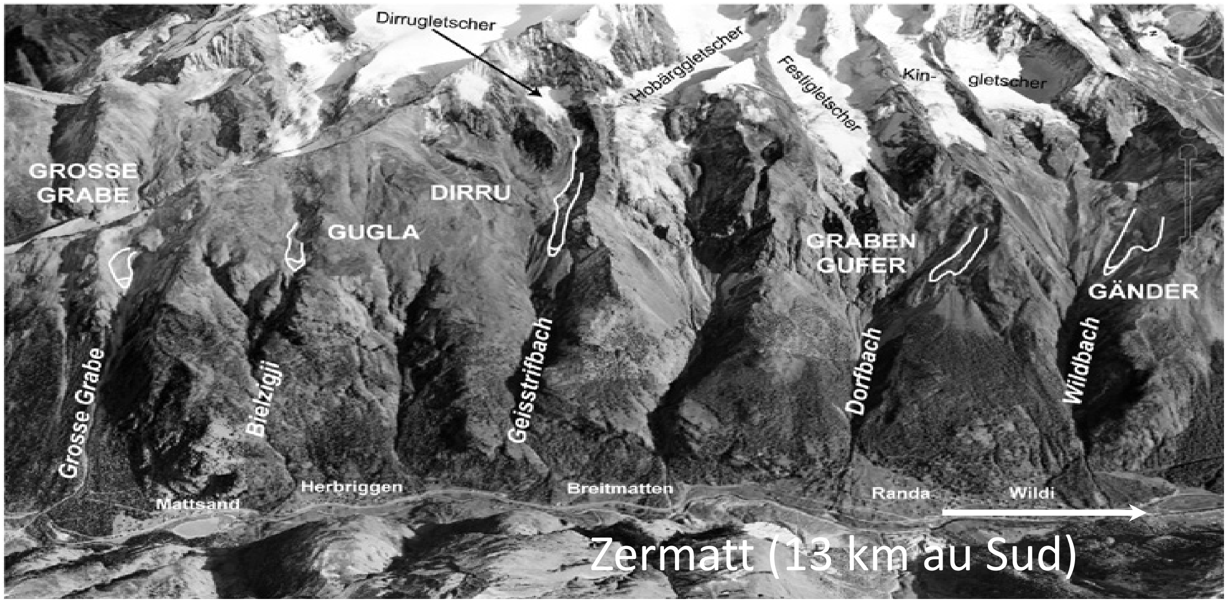
in Switzerland

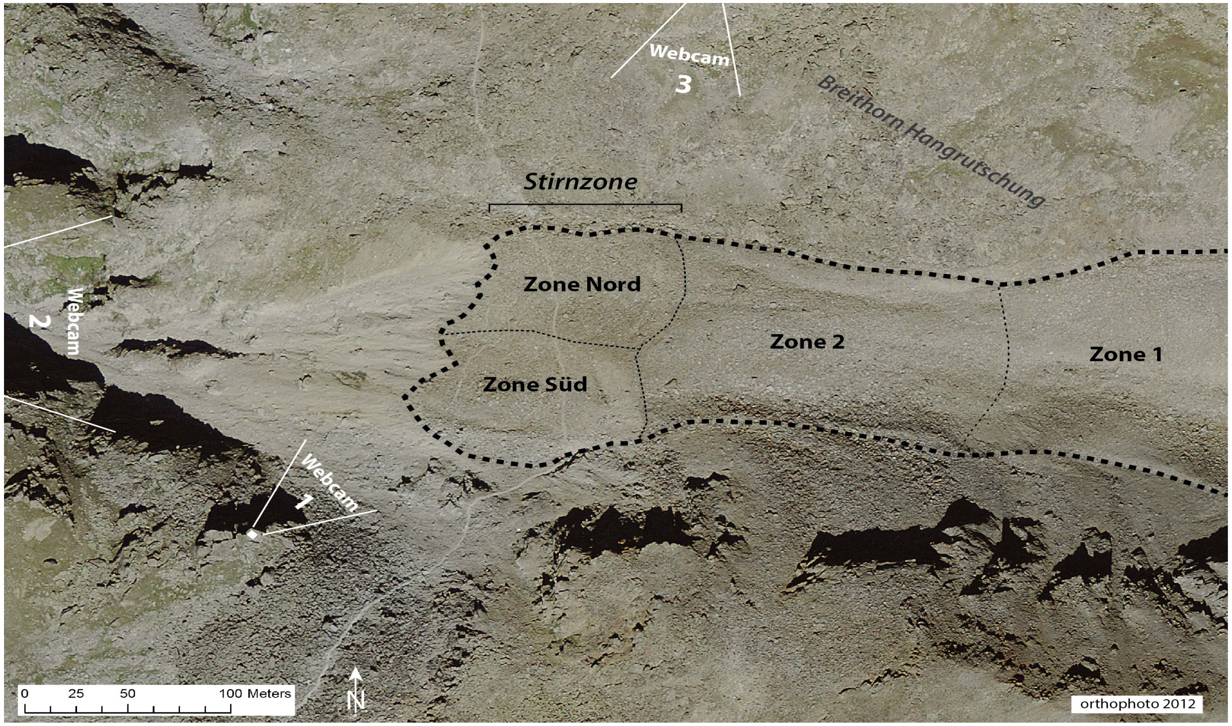
(Valais near Zermatt)

Elevation 2600-3000 m

length ~600 m

Width 130 m





Gugla - Instrumentation

Seismology (ISTerre)

◇ 6 1C 2Hz seismometers

⊡ digitizer (continuous 200 Hz)

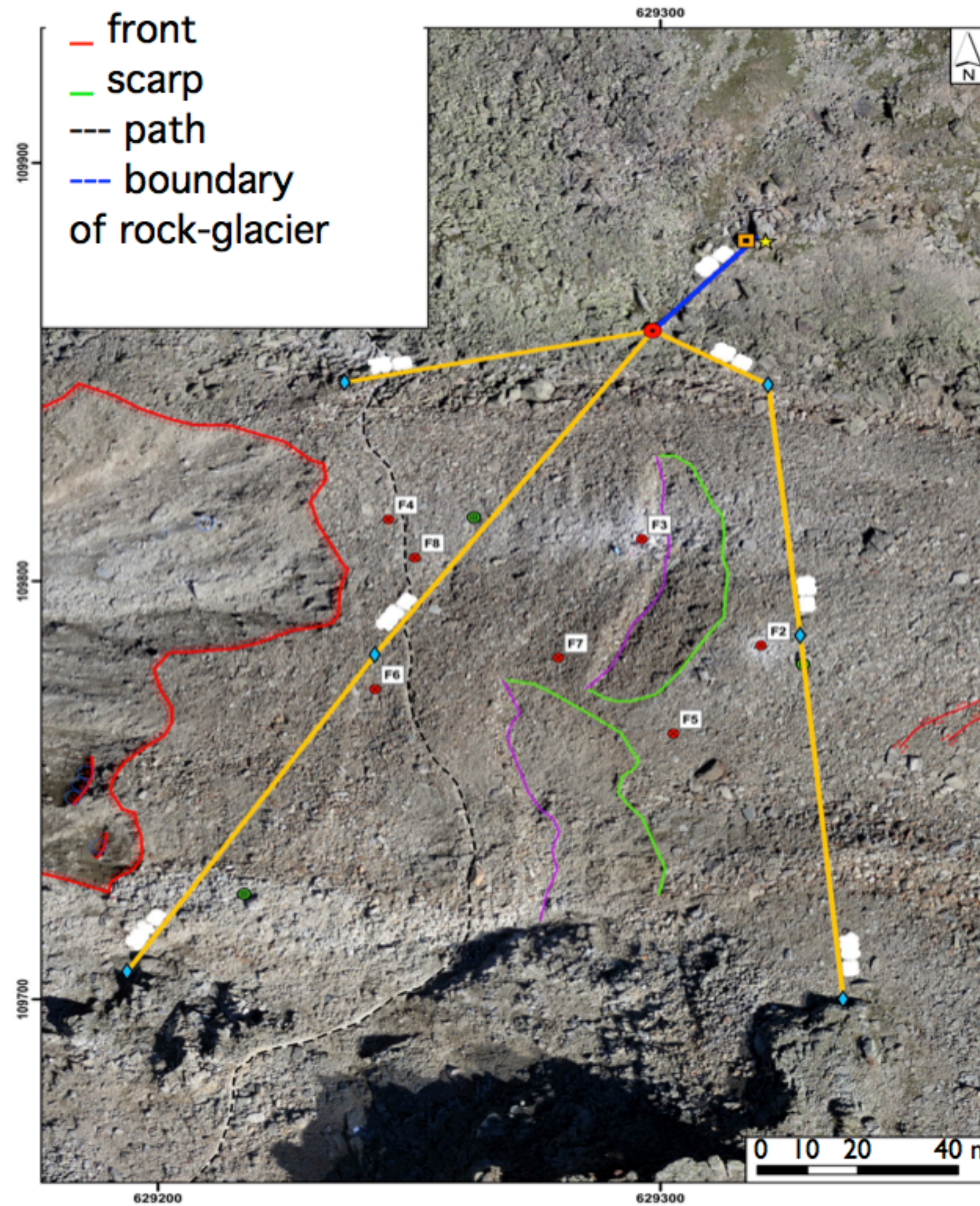
installed Oct 2015

Displacement (Univ. Fribourg and ETHZ):

◎ GPS : 60 points measured (twice) every yr1 continuous GPS since 2007

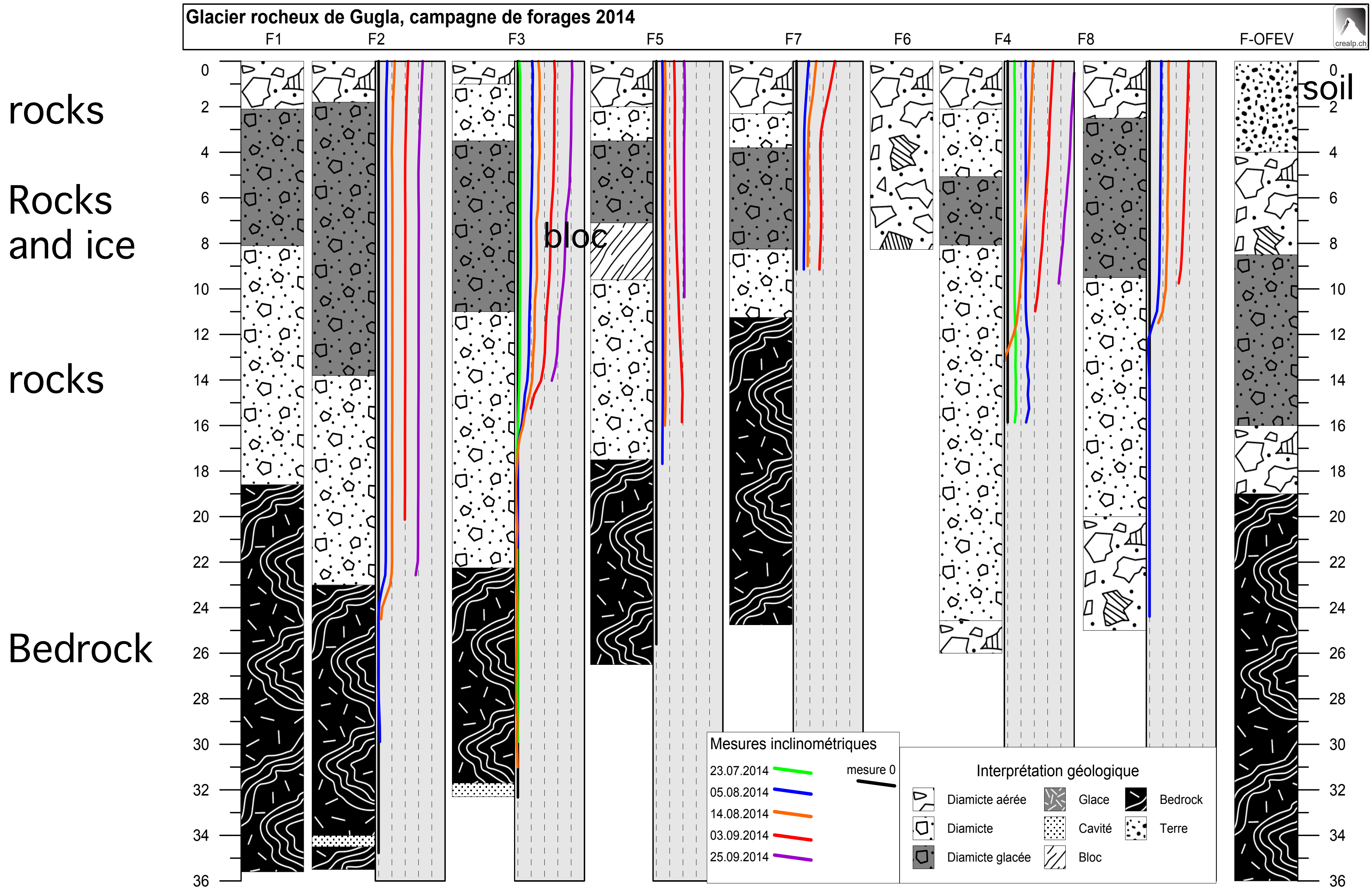
⊗ 7 **boreholes** drilled in 2014 by CREALP with inclinometers and temperature

2 **webcams**



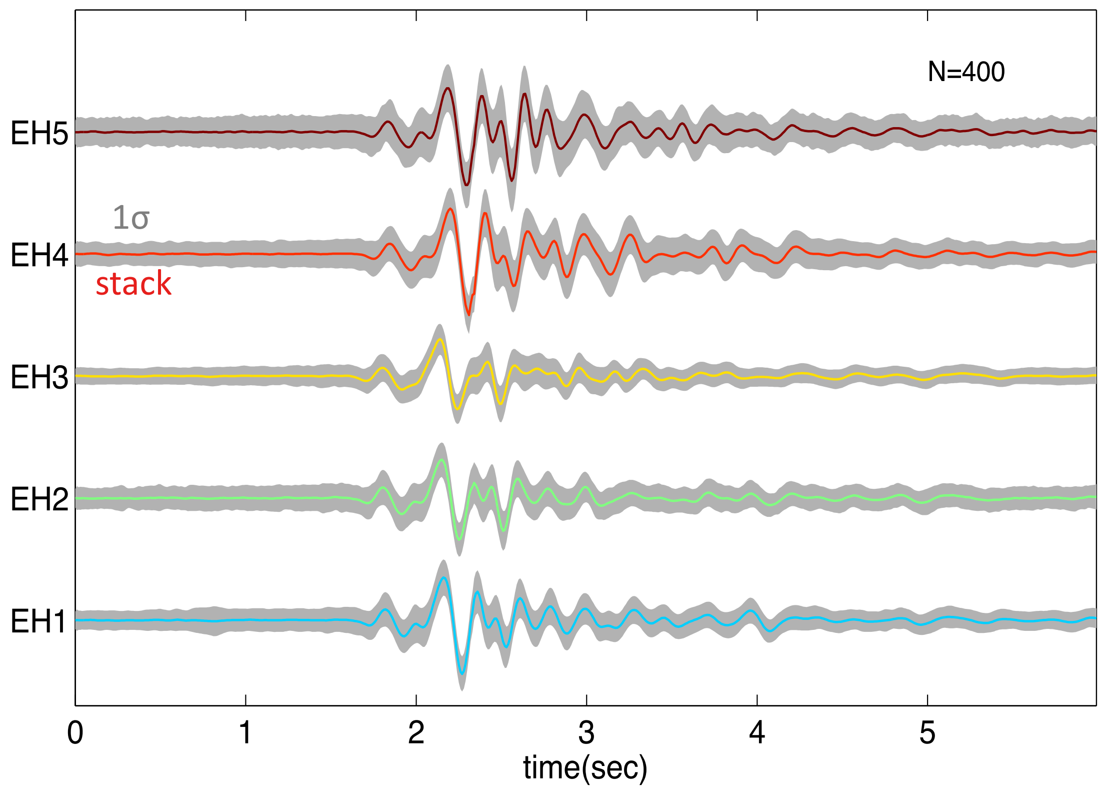
Gugla – Boreholes and inclinometric data

Data from CREALP and OFEV

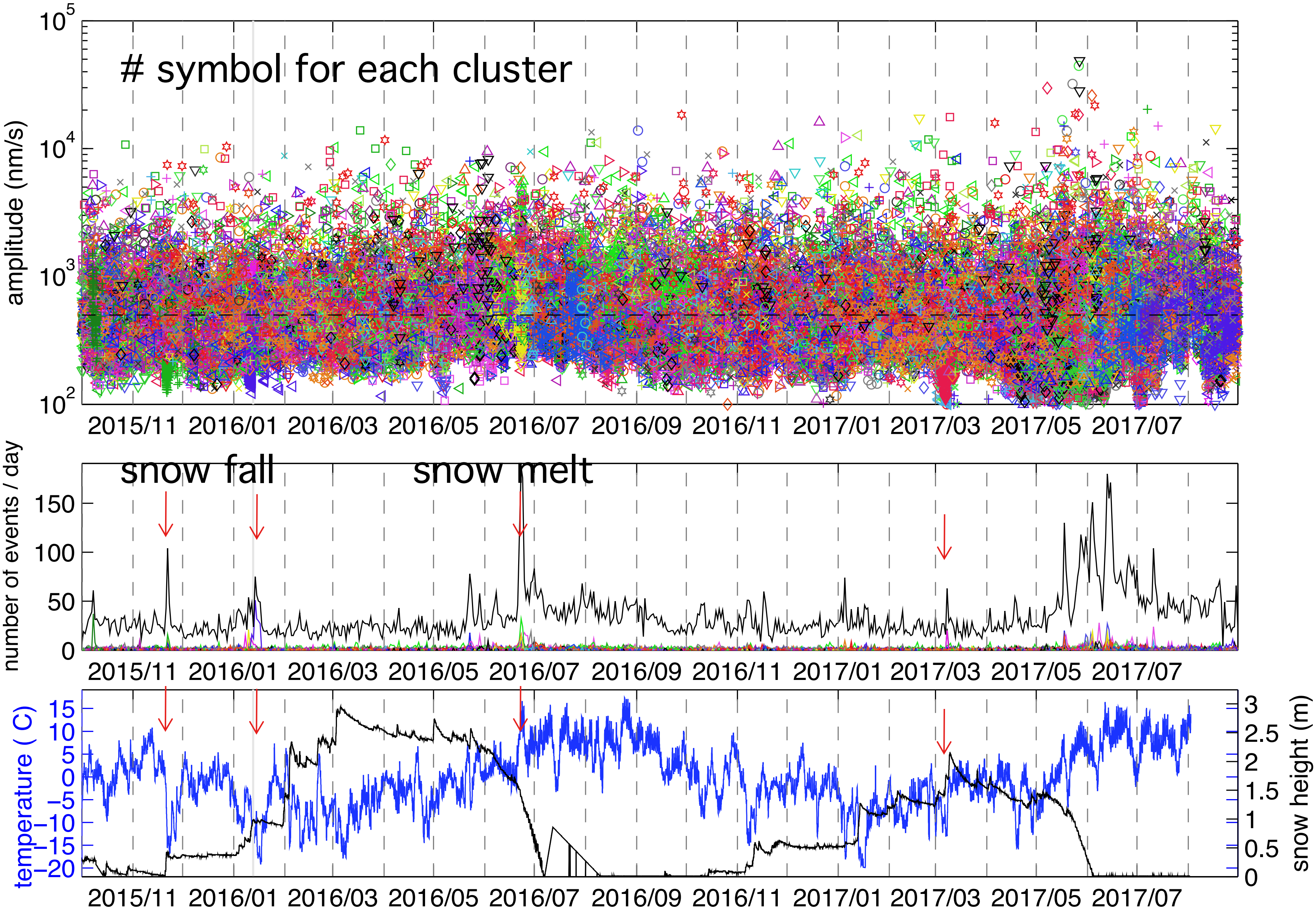


Detection and classification of events

- selection of short (~5s) and low frequency events (~5Hz)
- detection by template-matching
- ≈ 257 clusters with up to 1100 events since 2015/10/1
- good correlation between sensors and between events



Seismic activity



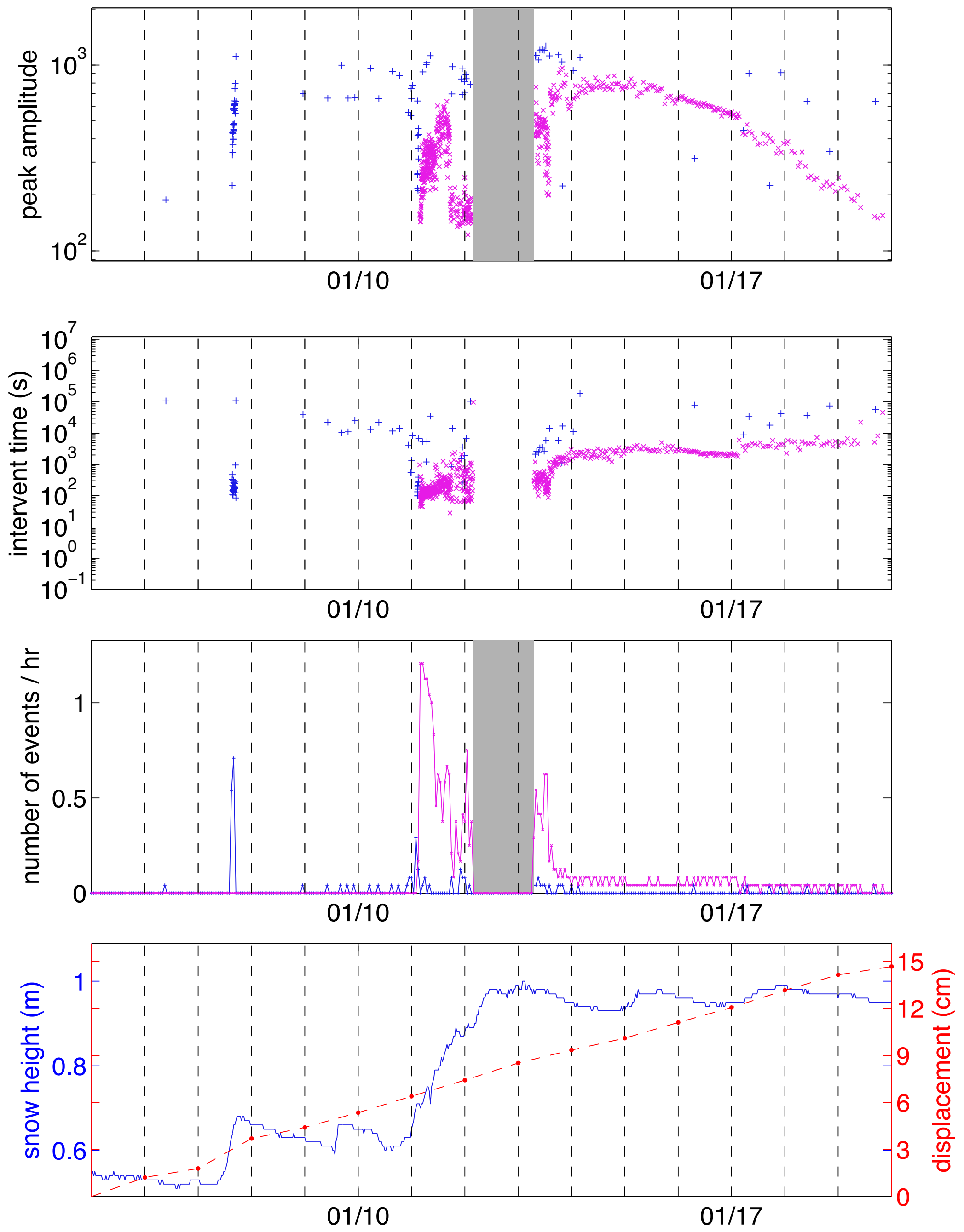
Repeaters triggered by snow falls

Example for January 2016

Progressive change of amplitude and recurrence times

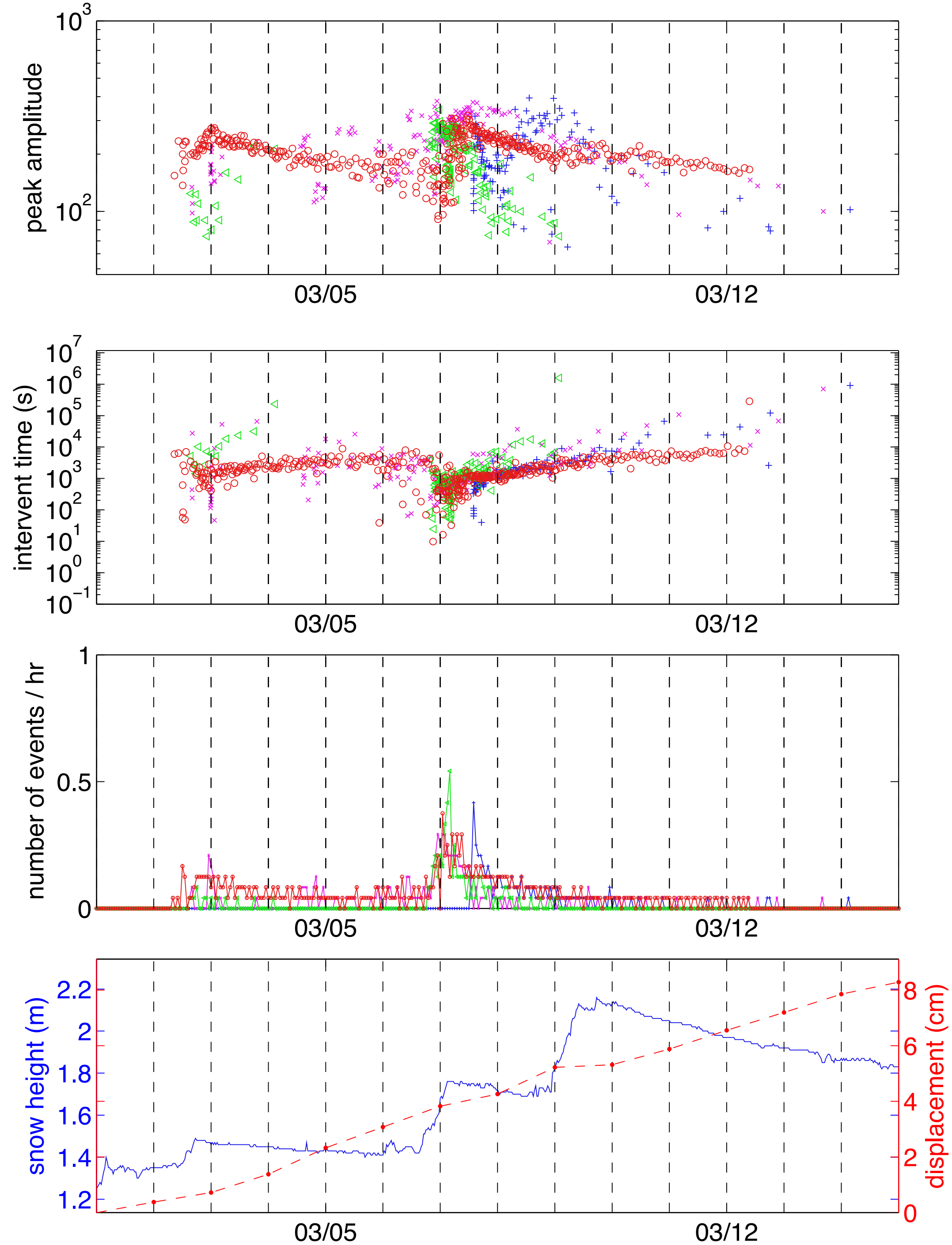
2 clusters activated

Almost no delay between snowfall and seismicity



Repeaters triggered by snow falls

Example for March 2017



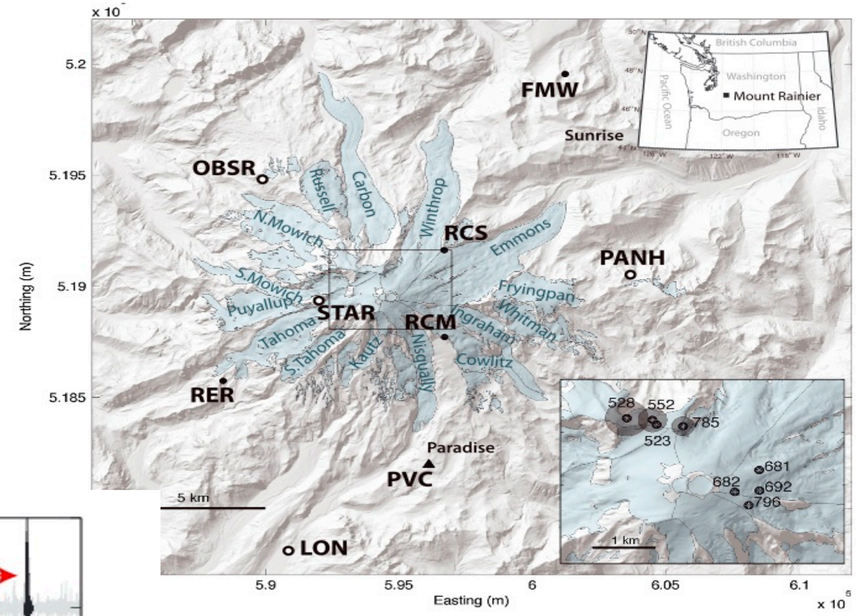
Comparaison : Mount Rainier

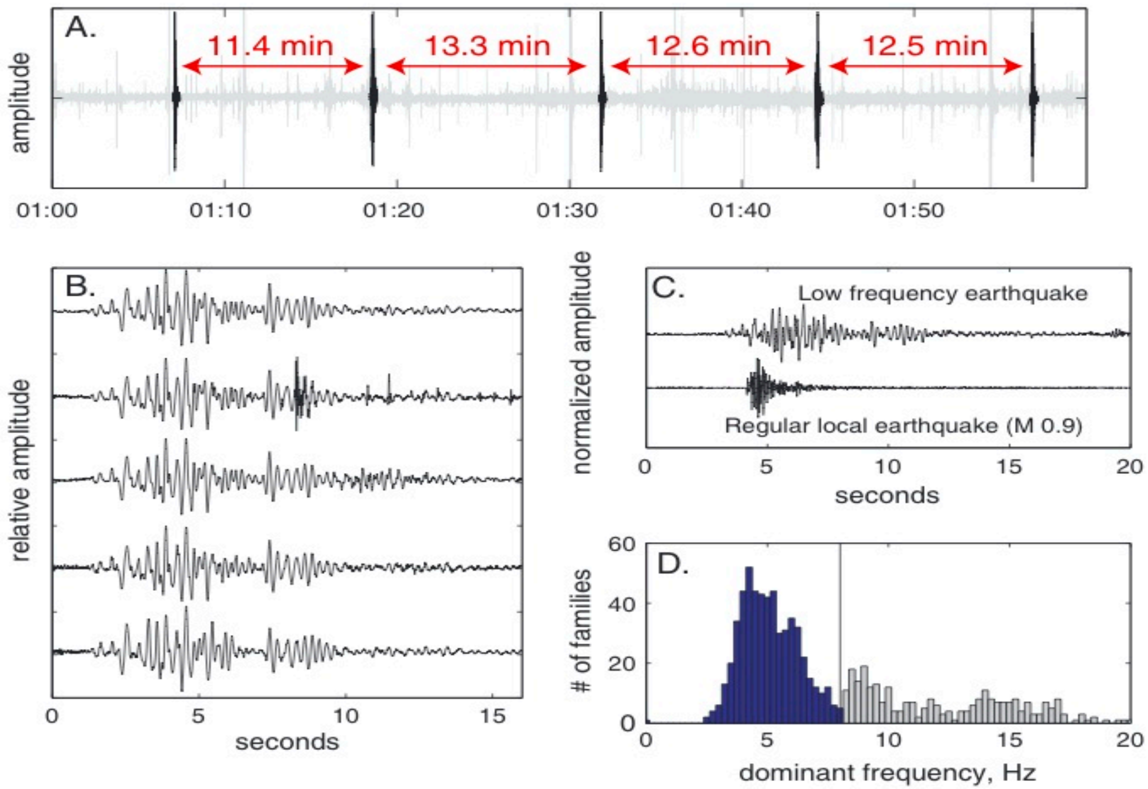
Glacier-covered volcano

Multiplets of low frequency events(≈5 Hz)

repeating every ≈10 mn

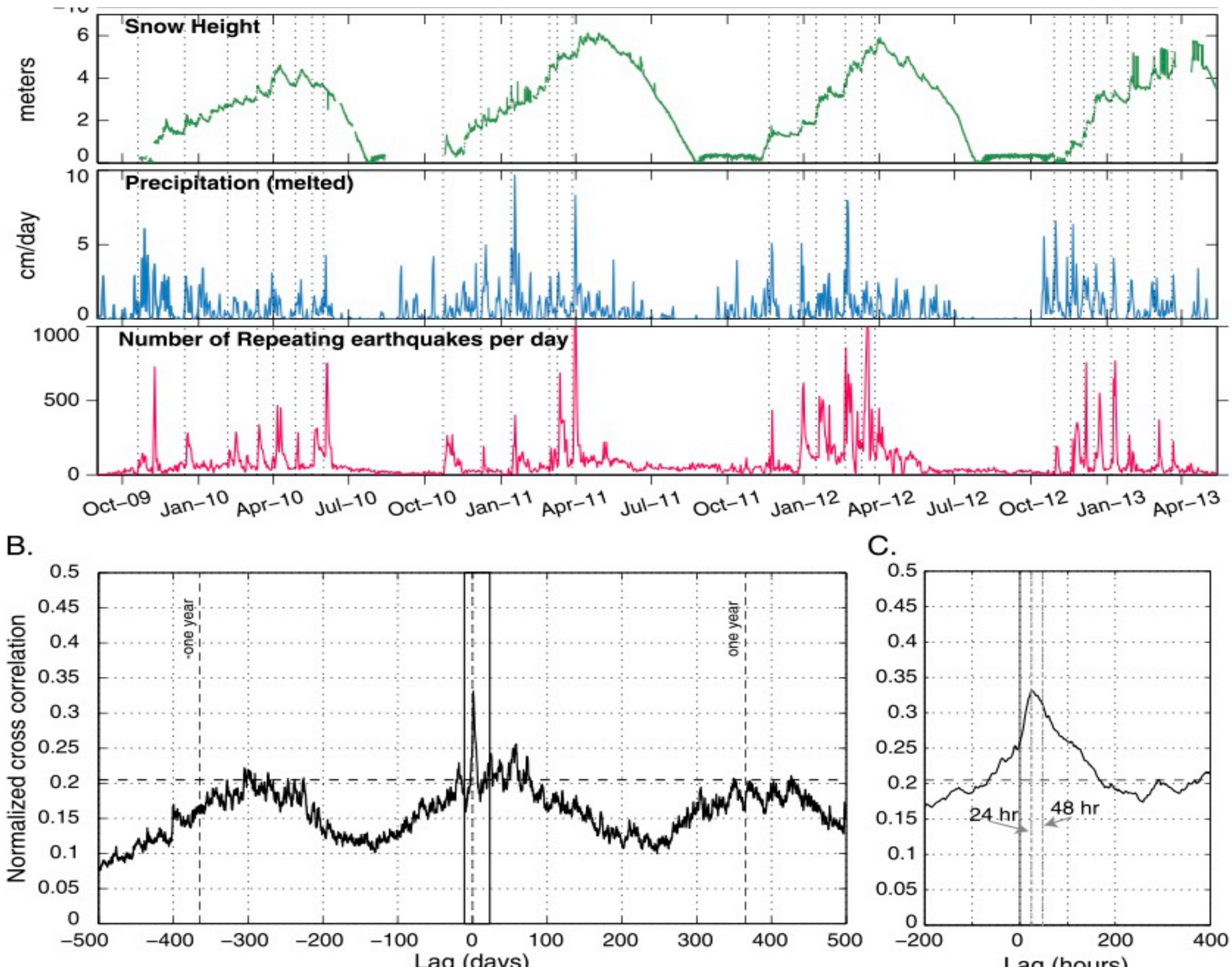
(Thelen et al 2013, Alstadt et al 2014)





Comparison : Mount Rainier (US)

Alstadt et al 2014

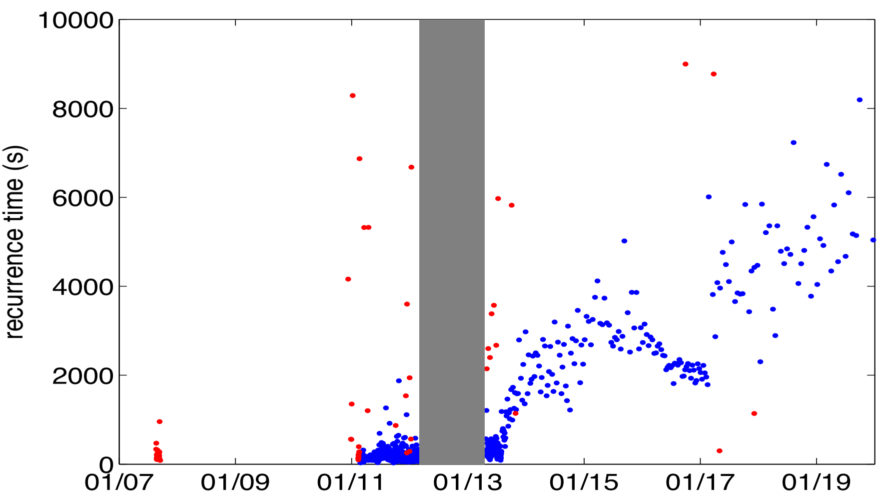


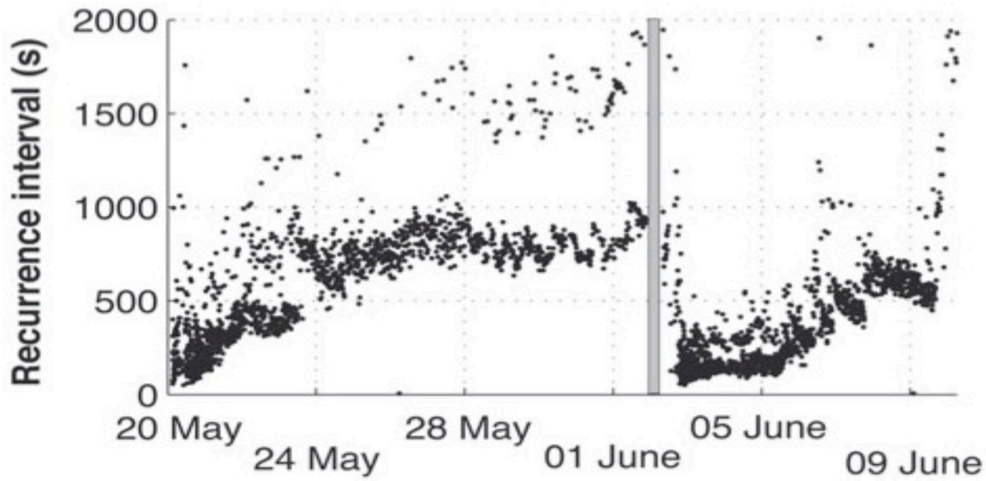
Gugla / Mount Rainier

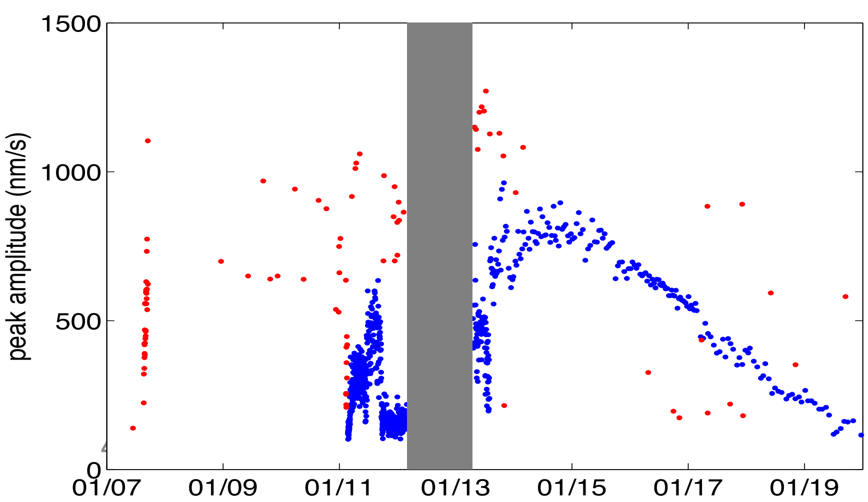
Progressive variations of amplitude and recurrence time

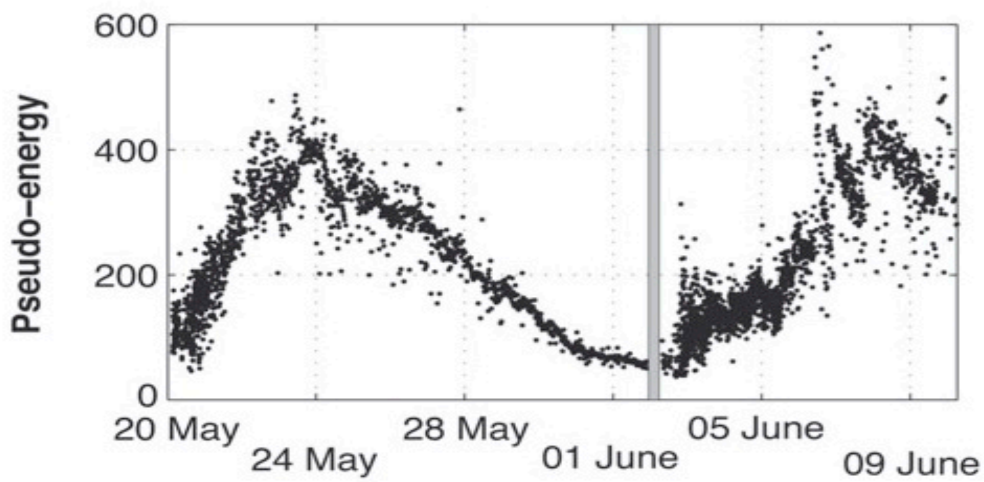
Gugla, January 2016

Mount Rainier (Allstadt et al 2014)









Triggering mechanism

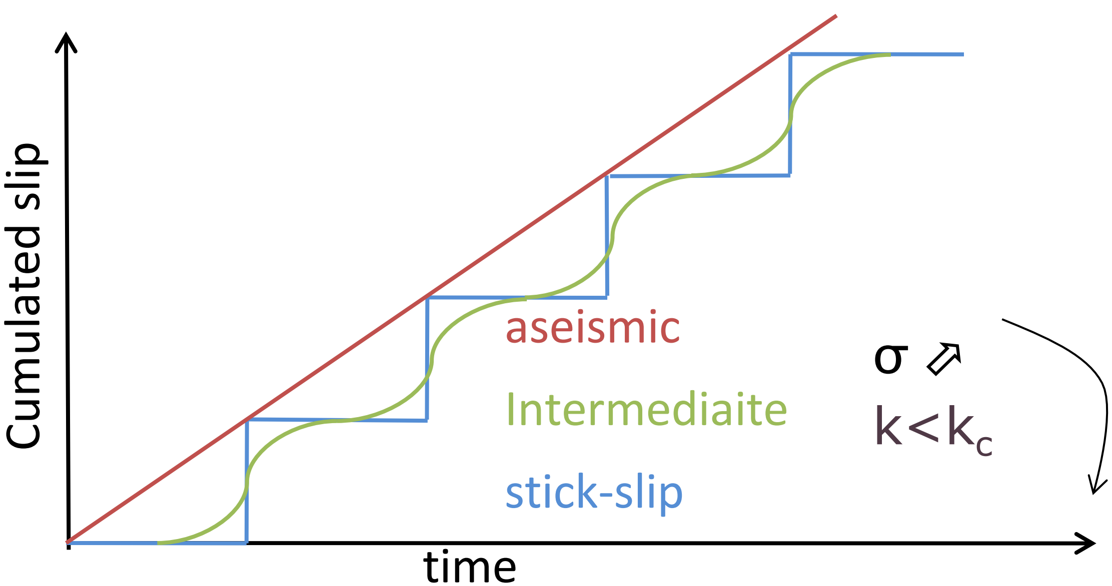
Allstadt et al (2014) : increase of normal stress due to snow weight~0.1%

+ redistribution, pressurisation of water in sub-glacial cavities => lubrification and slip acceleration

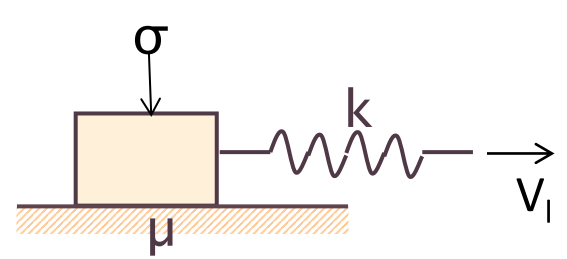
In summer : drainage network more developped => no over-pressure

In Gugla : very cold => no melt and no acceleration

Ttransition aseismic ⇒ seismic induced by increased normal stress?



σ ⬀ $k<k_c$



Conclusions (1/2)

≈ regular sequences of repeating icequakes and landquakes

But most events are random or clustered

Progressive variations of amplitude and recurrence times

No (systematic) correlation with sliding rate

No correlation and no interaction between # sequences

Weak correlation between recurrence time and size

Conclusions (2/2)

⇒ Viscous deformation of ice or creep within the asperity

⇒ Variability mostly due to local changes of the interface

⇒ Landquakes are not (always) precursors of failure

Progressive changes in waveforms, mostly influenced by changes in the medium

Triggering by snowfall (Gugla, Rainier) : transition aseismic => seismic slip due to increased in normal stress?

Perspectives

- Observations :
  - add more seismometers in Alestch and Gugla in order to better locate and characterize repeaters
- Numerical modeling and laboratory experiments
  - Triggering by an increase in normal stress
  - Temporal variations in seismic moment and recurrence rate
  - Transition seismic ⇔ aseismic
  - Transition random ⇔ regular
  - Scaling laws of slip, rupture length and recurrence times

Aletsch instability

[M Sartori, October 2016]