THE EARTH SURFACE PLAYGROUND

Investigating the processes that shape the Earth – from the past and from the modern perspective

ENVIRONMENTAL SEISMOLOGY

GRAIN-SIZE DATA MODELLING

LUMINESCENCE FRAMEWORK

SUBITOP PROJECT MANAGEMENT

Environmental seismology

Using ground motion data to quantify Earth surface dynamics

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This is the Covid19 field, containing text that explains the content of the slide in case audio connection breaks down.

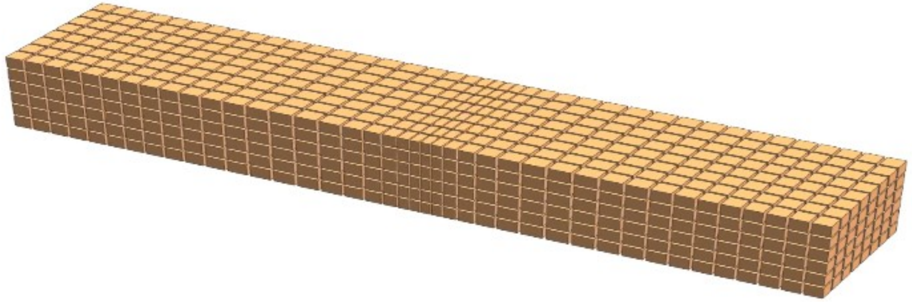
So what do we do today?

- Brief introduction to environmental seismology
- A gentle example on signals and interpretation
- Mass wasting on hillslopes
- Sediment and water transport in rivers
- Probing water and damage in the ground
- Wrapping up the batch of information

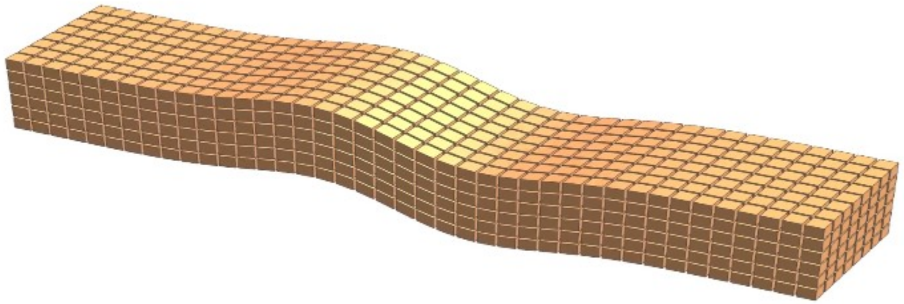
Types of seismic waves

Body waves

P wave

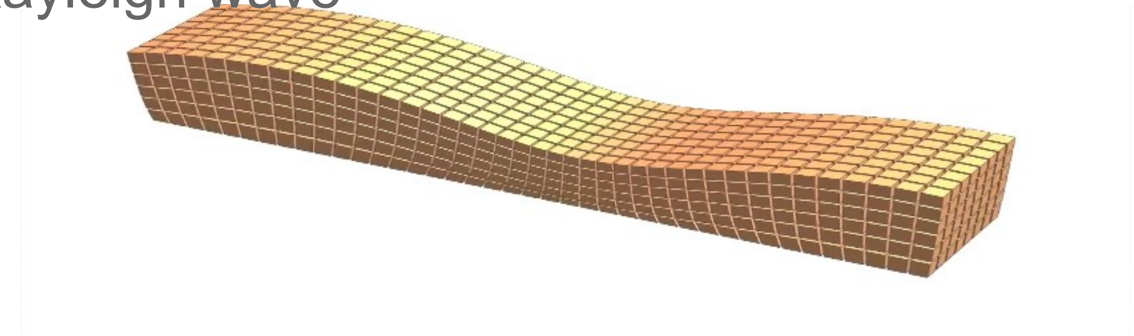


S wave

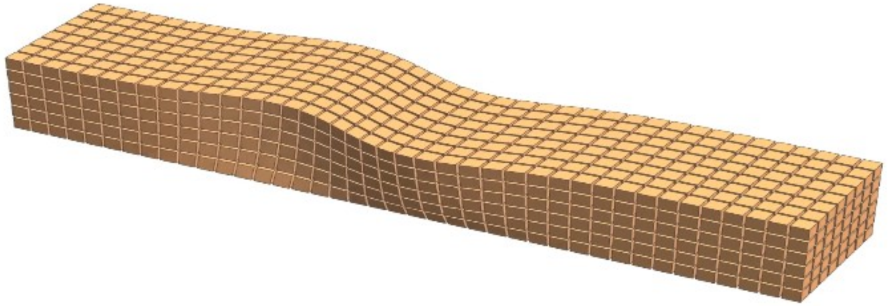


Surface waves

Rayleigh wave

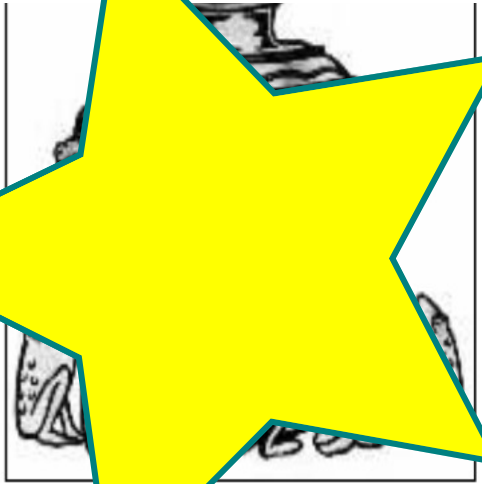


Love wave

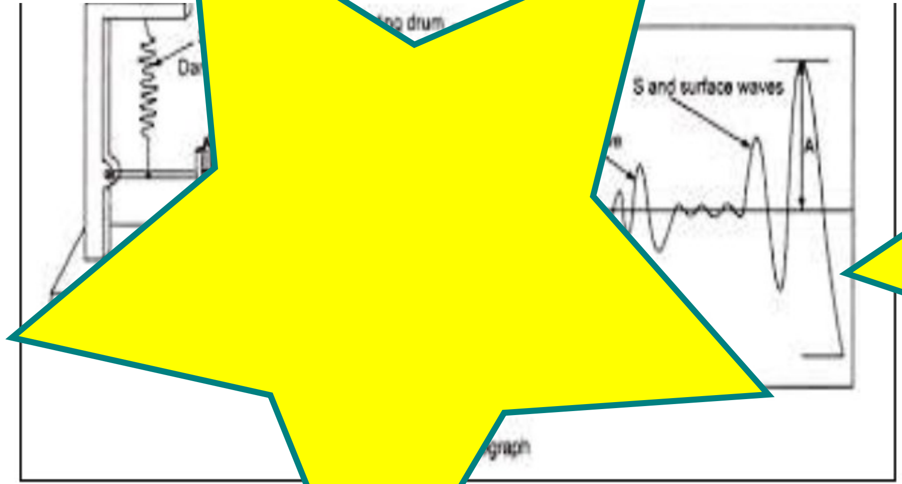


There are two basic types of waves, those within solid media (body waves) and those at the boundary between two media (surface waves). For body waves there are P and S waves, for surface waves there are Rayleigh and Love waves. Environmental seismology mainly faces surface waves.

How to measure seismic waves?



AD



19th century

Now on the way to Mars

That is basically it. Modern geophone sensors directly use this principle (plus a dampening resistor to suppress endless swinging). The analogue voltage signal is sampled and digitised by a data logger, at sampling frequencies of 100 Hz and higher.

What does a seismic station look like?

Seismic stations consist of sensor and digitiser/logger. In the simplest case, the geophone is pushed into the ground and the logger is placed next to it, equipped with batteries allowing for many days of continuous recording.

What does a seismic station look like?

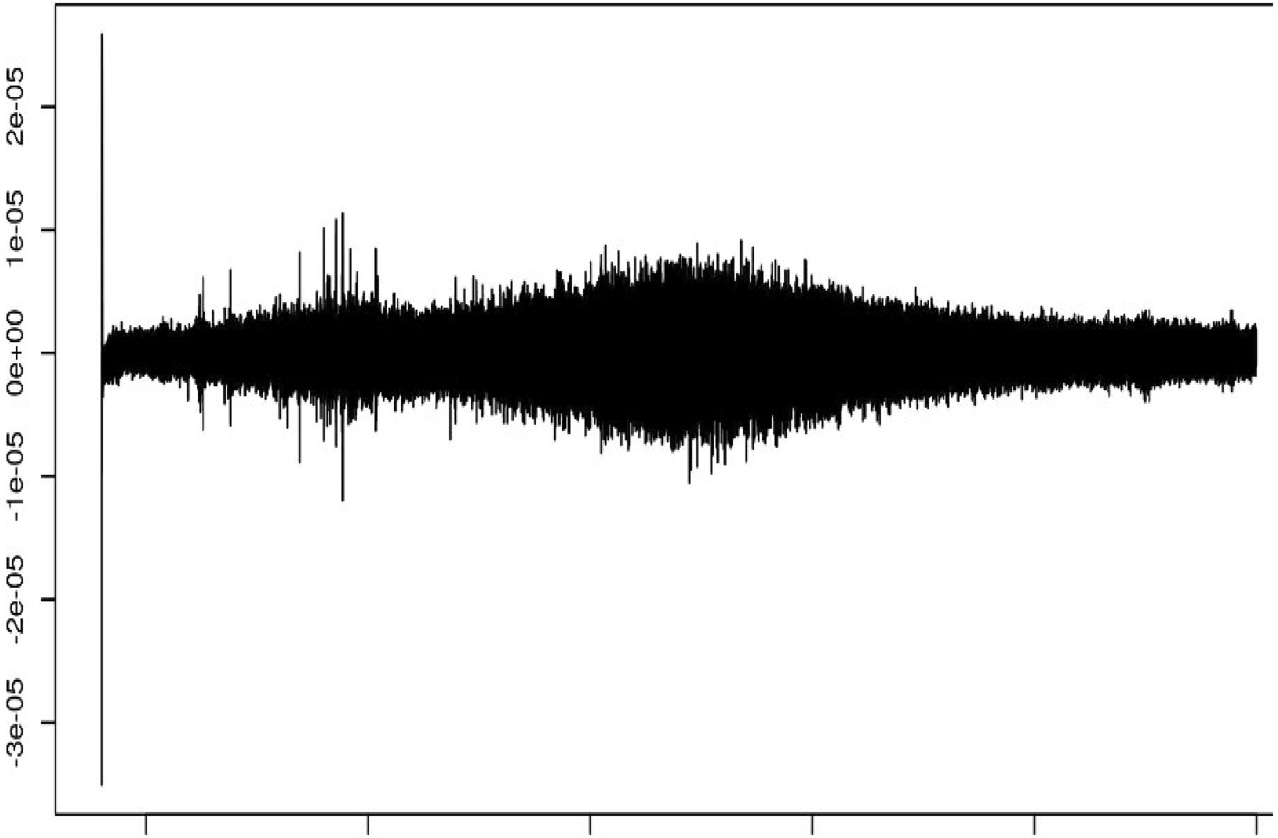
Broadband sensors (pale green device) contain more advanced electronics and can resolve seismic waves with periods of two minutes and more. A proper environmental seismic station requires burying the sensor, and packing logger and large battery safely in isolated boxes.

What does a seismic station look like?

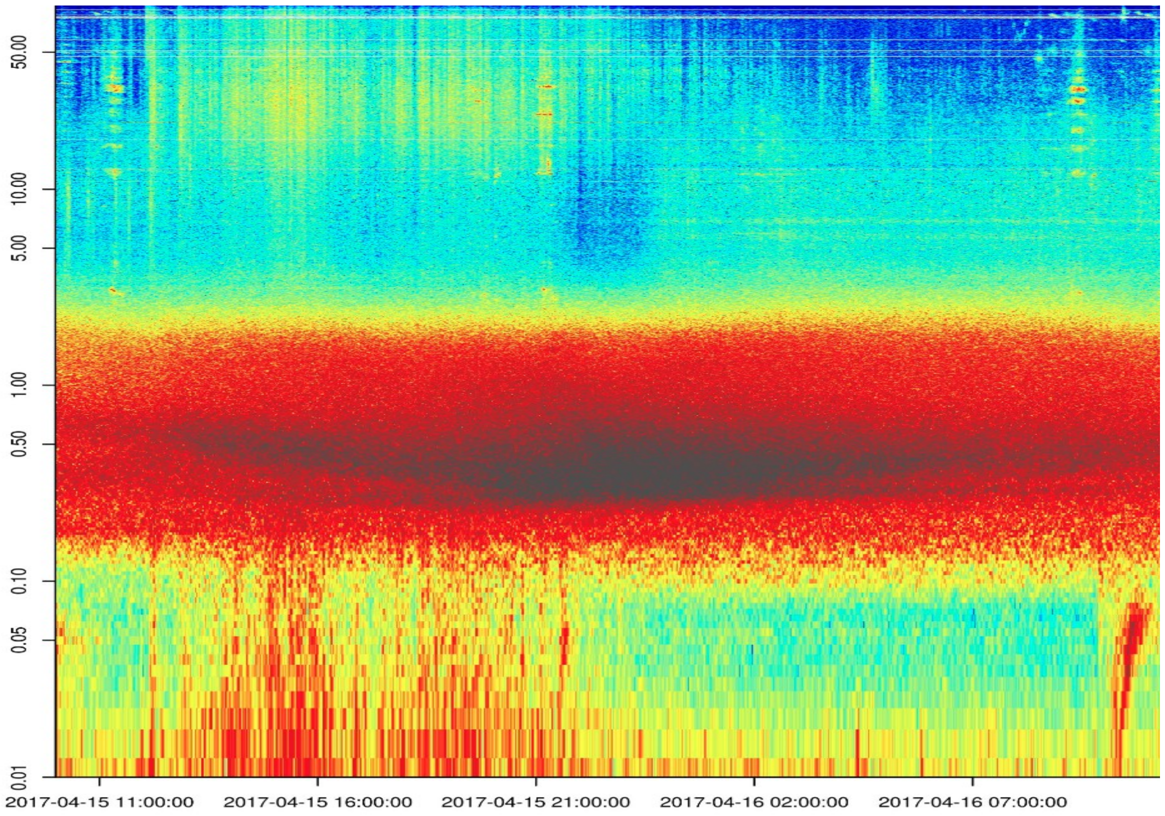
Seismic stations can get even more complex, including live data telemetry, additional sensors (meteorological, ground moisture,…) and multiple seismic sensors installed as “small aperture array”.

What do the measured data look like?

A time series (time domain, wave form)



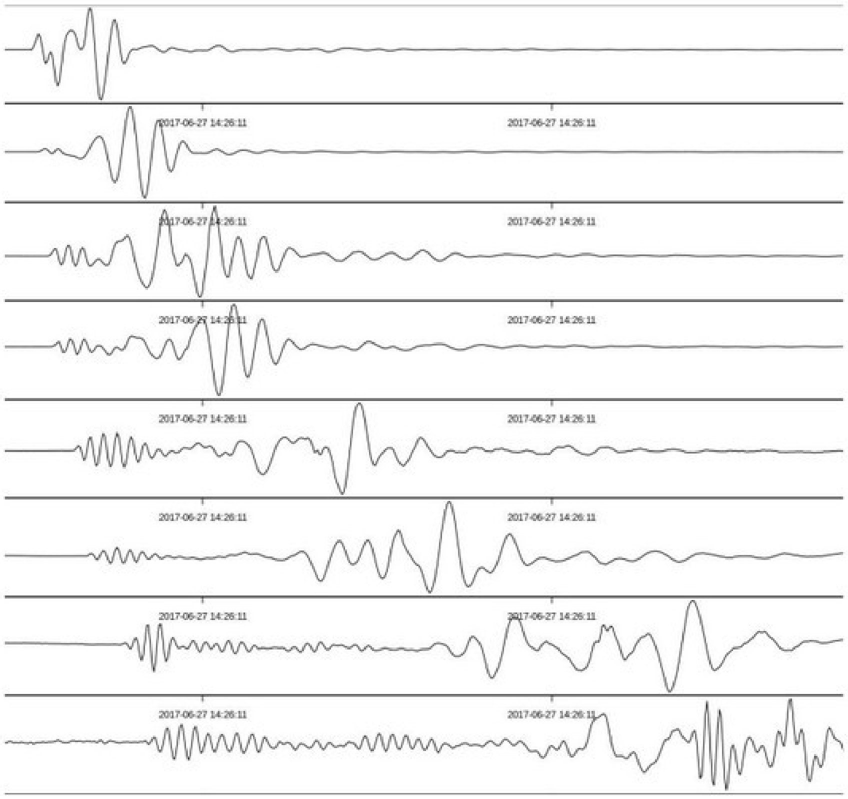
A spectrogram (frequency domain)



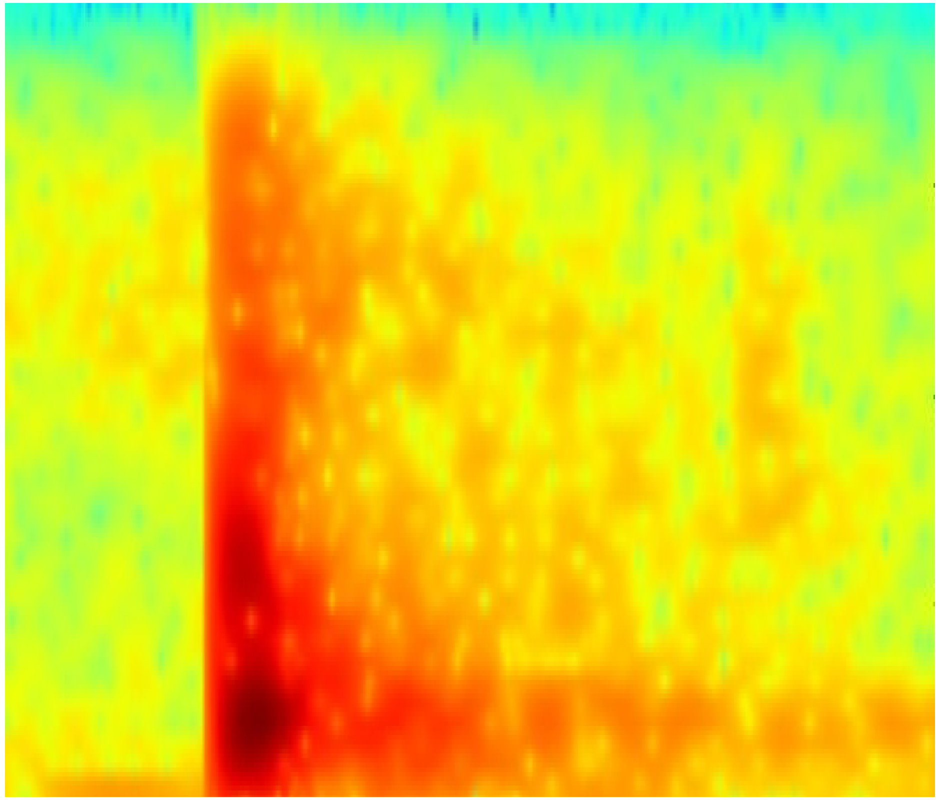
There are two principal ways to look at the data at first instance. A) inspecting the time series of ground velocity values (m/s) and B) converting that time series into spectra (Fourier transform), allowing for information about the frequency content of a signal.

What do the measured data look like?

A time series (time domain, wave form)



A spectrogram (frequency domain)



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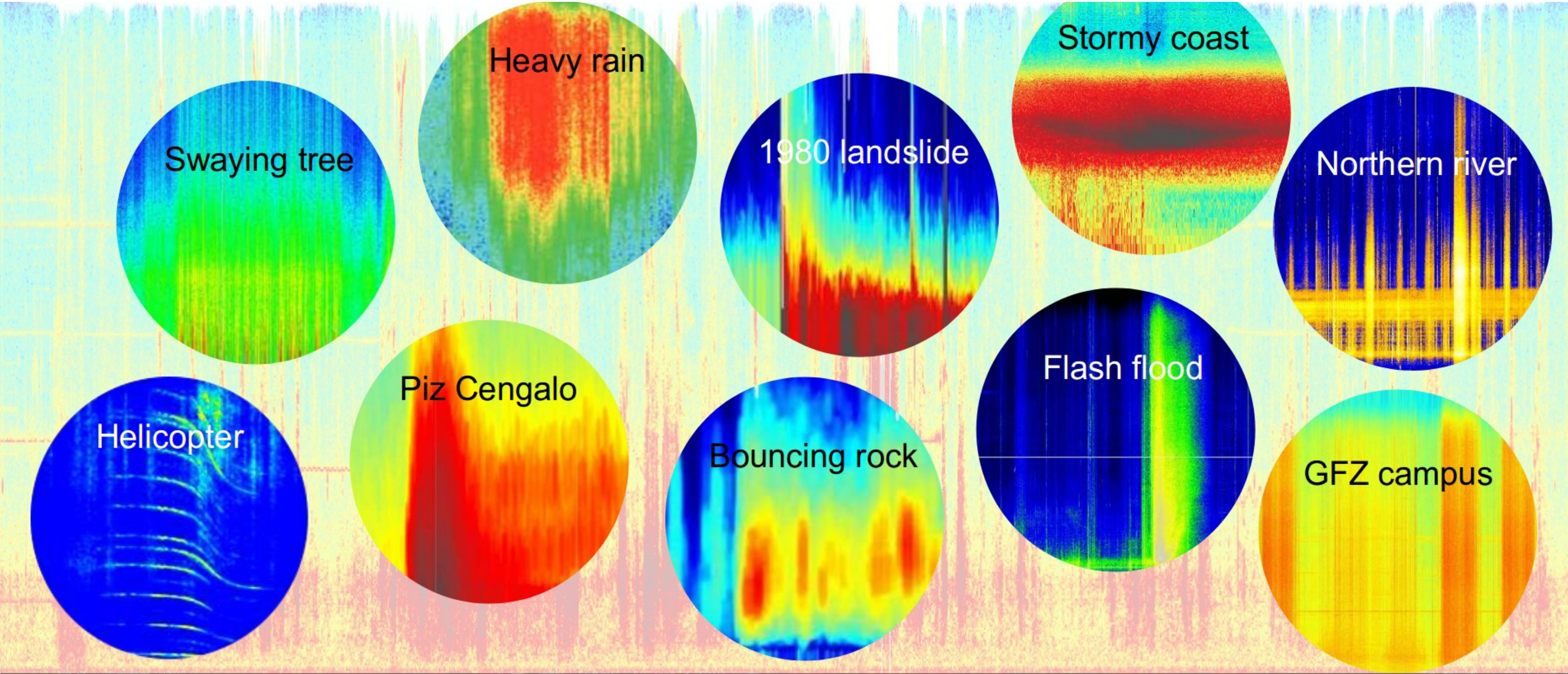
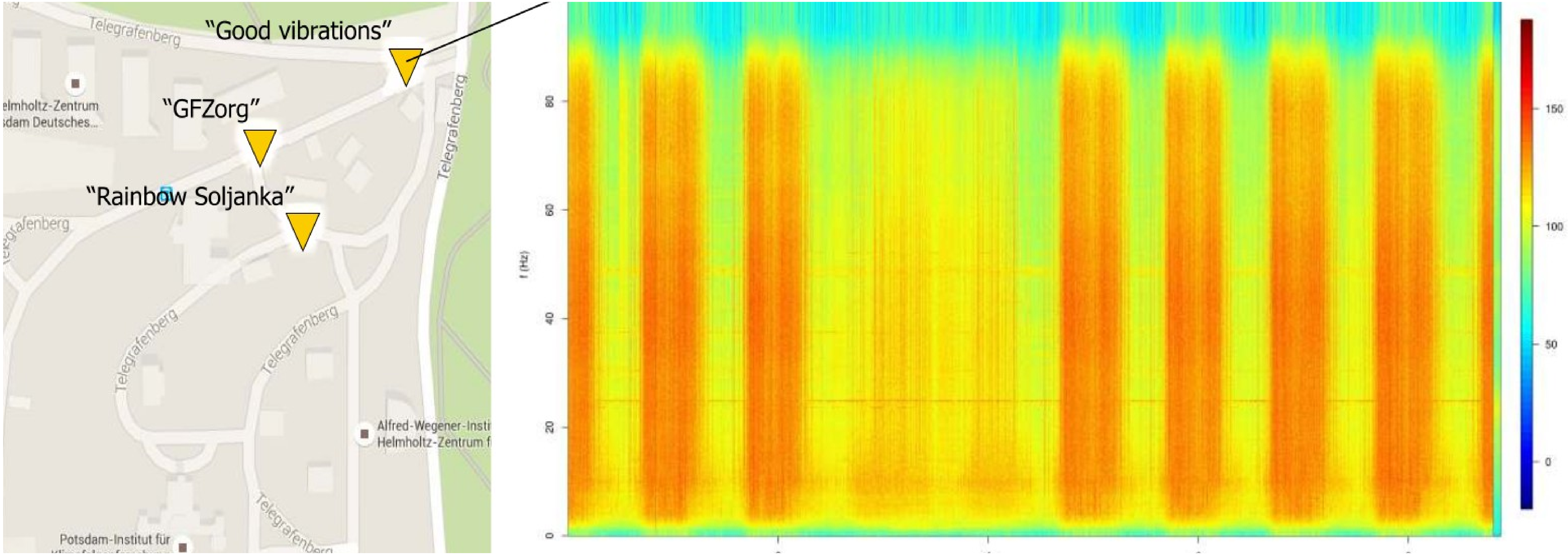
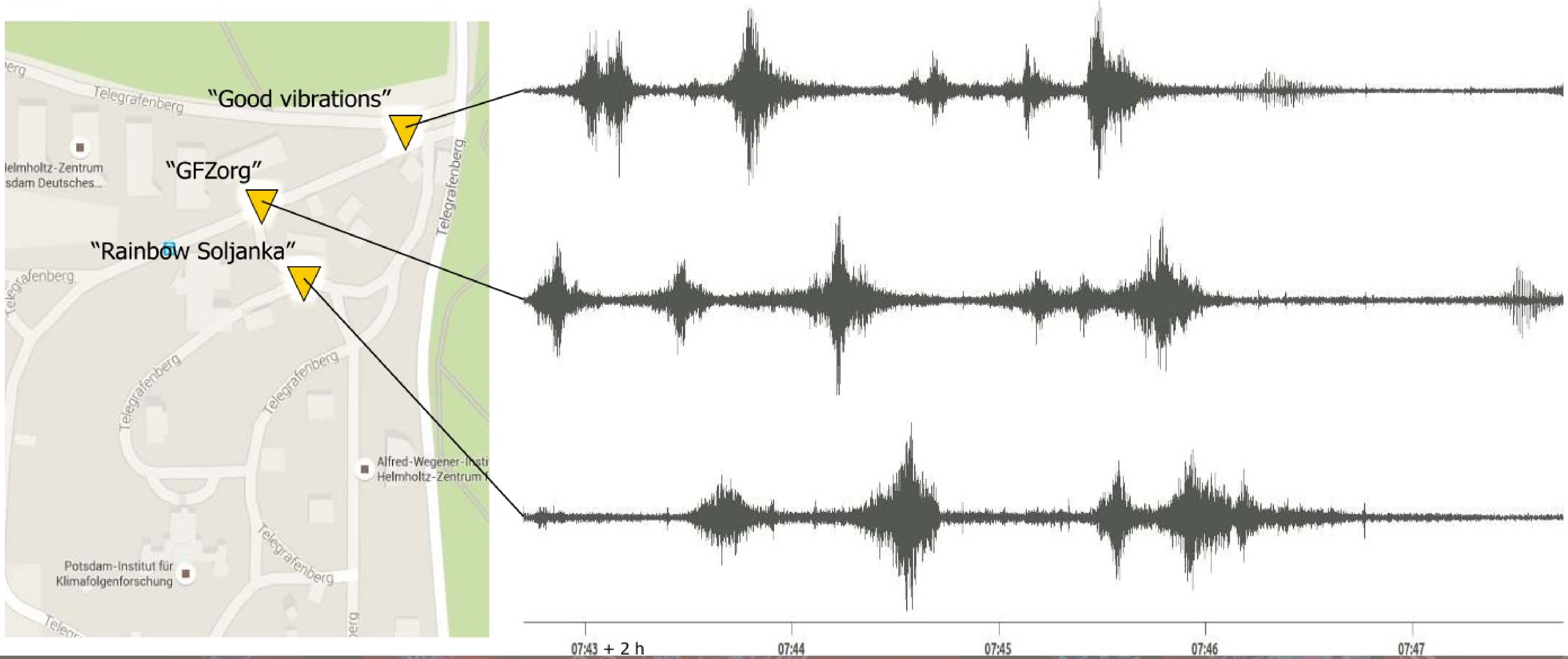


A gentle application example – the GFZ campus in Potsdam



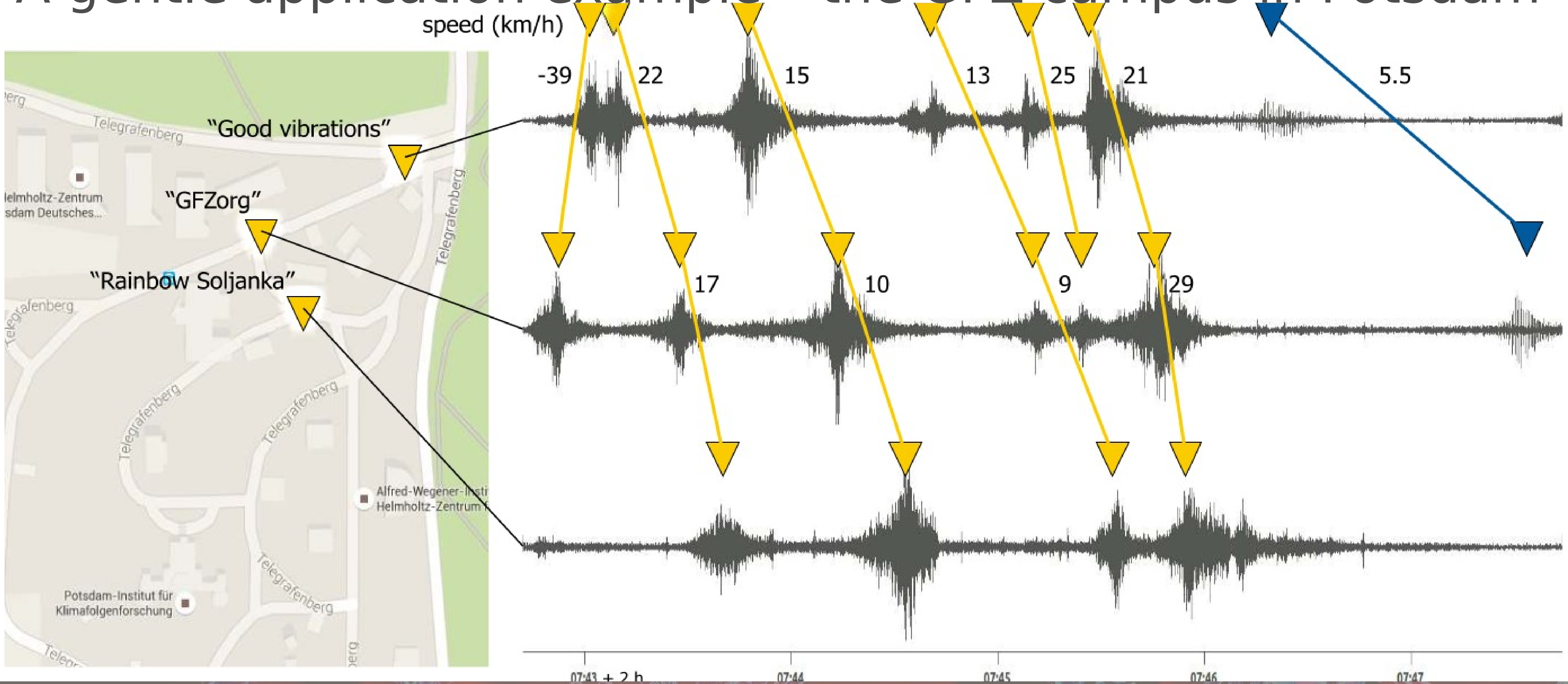
A small network of three geophone stations on the GFZ campus. The one at the entrance and its spectrogram shows… signatures of activity controlled by week day, day time, and lunch time. Note also the 50 Hz constant signal.

A gentle application example – the GFZ campus in Potsdam



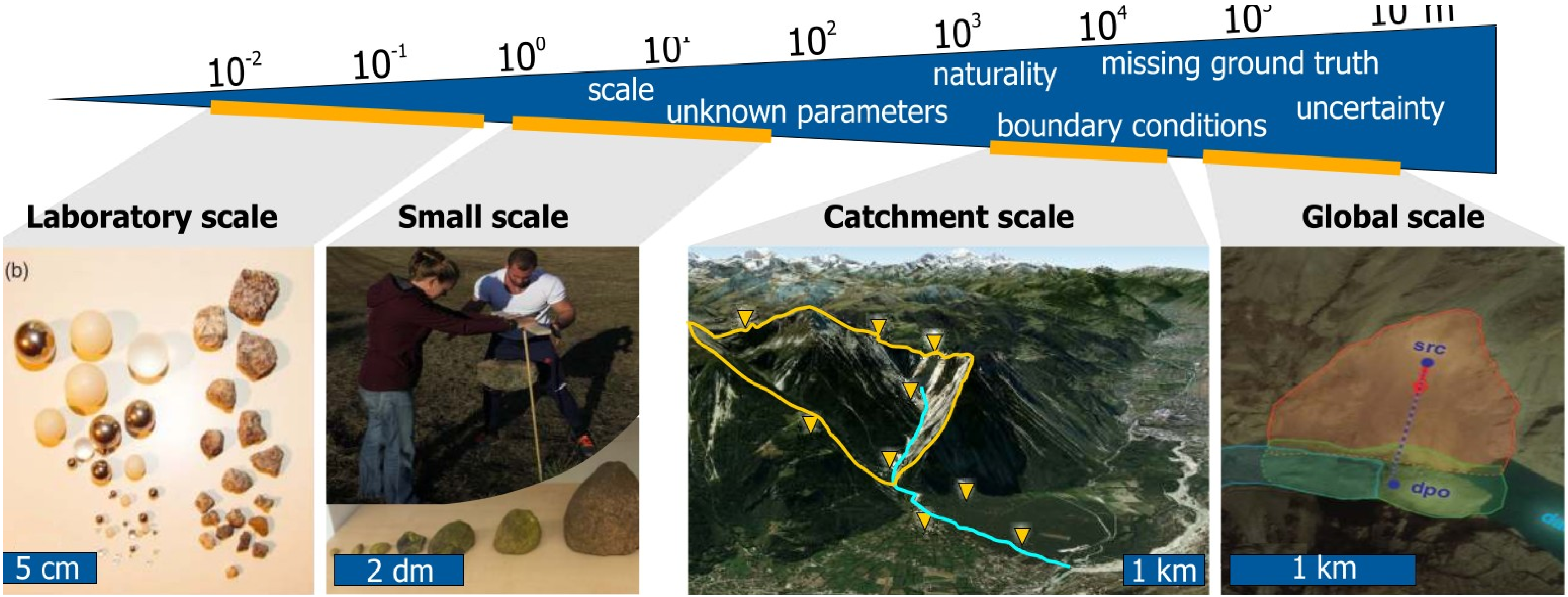
Seismic wave forms as recorded by all three stations...

A gentle application example – the GFZ campus in Potsdam



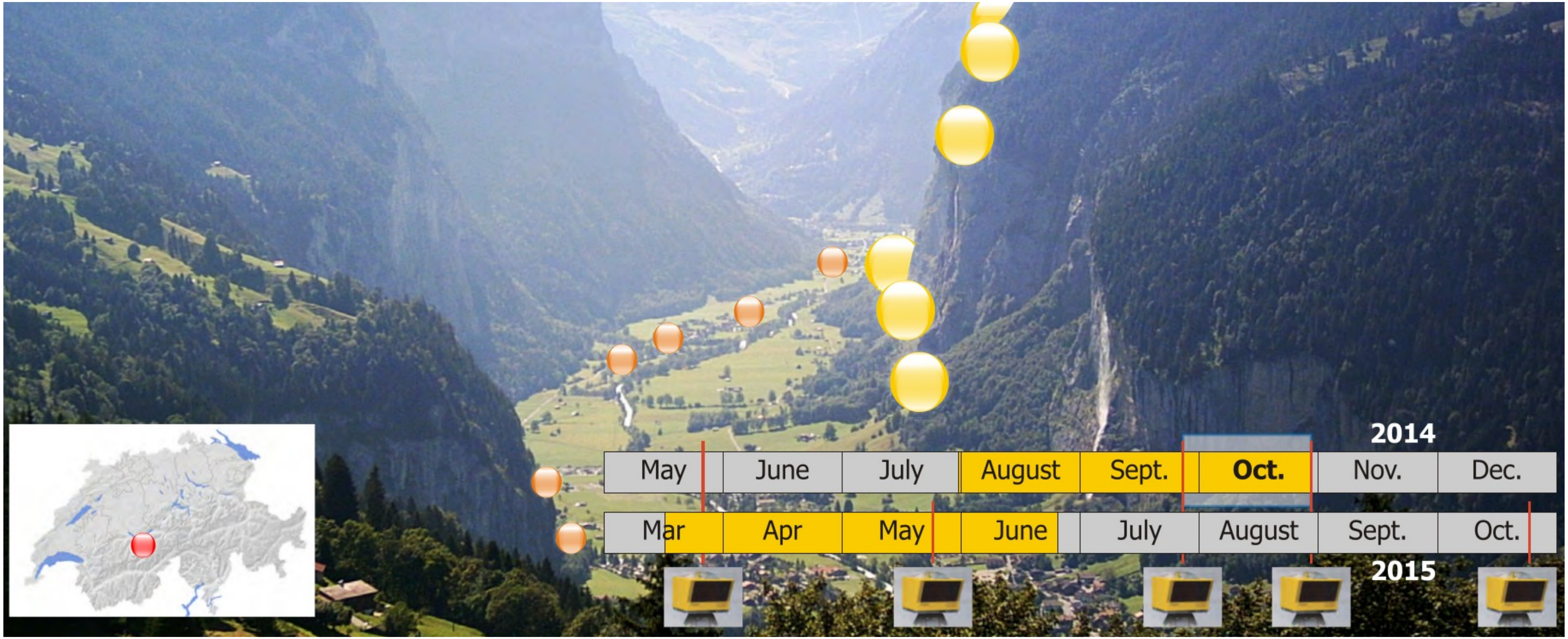
Seismic wave forms as recorded by all three stations… allow detecting and quantifying vehicle mobility on the campus, and the detection of a strange, slow moving signal source…

Application I – mass wasting processes in mountain landscapes



Information is available at the small scale (details about seismic wave generation and relation to particle properties), but at very large scales we have to assume a lot to relate seismic signal characteristics to physical properties of processes and the materials they affect.

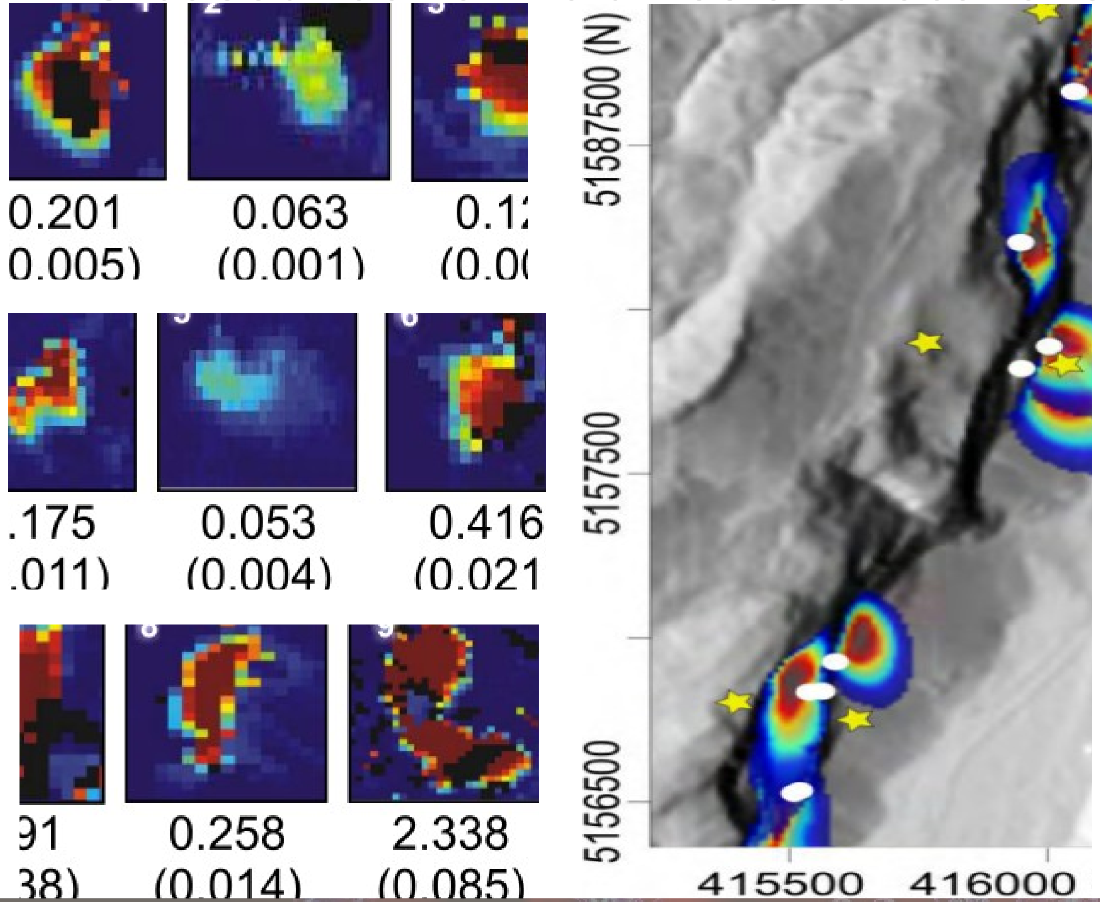
Application I – mass wasting processes in mountain landscapes



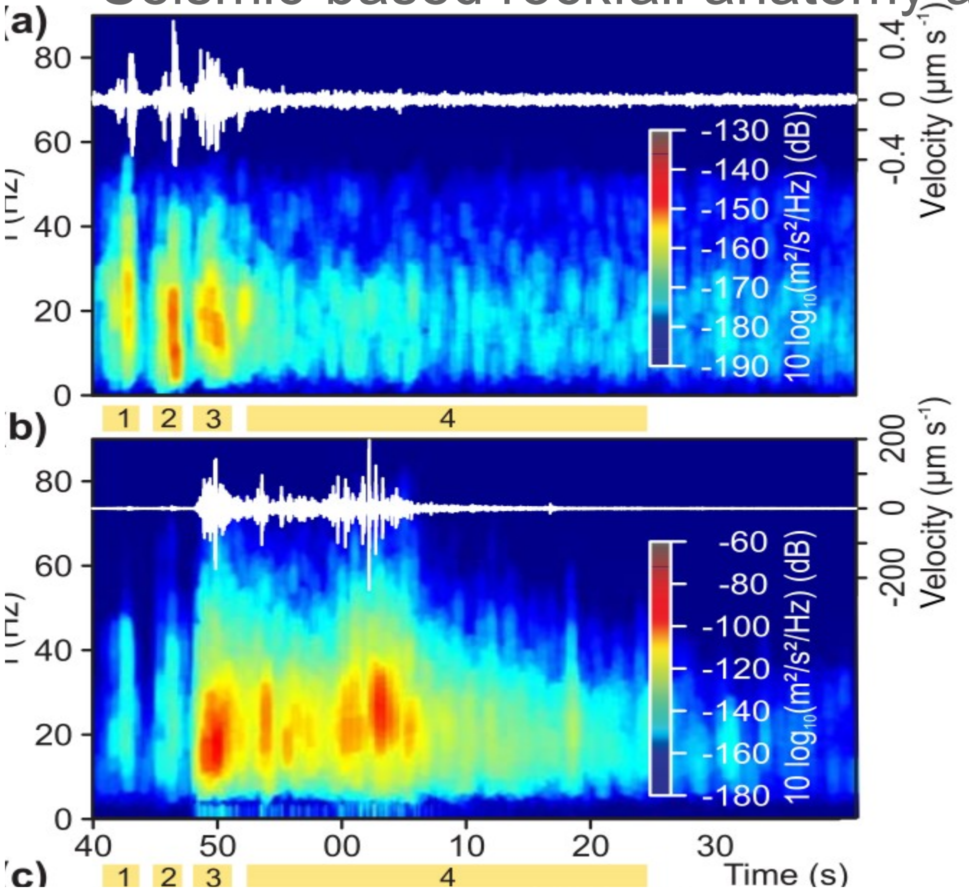
To expand the scale of information: welcome to the heart of Switzerland, the Lauterbrunnen Valley, where alpine skiing was developed, James Bond hung up, and base jumpers have fun, now. We instrumented a 700 m cliff with six seismometers and scanned the wall by TLS over two years.

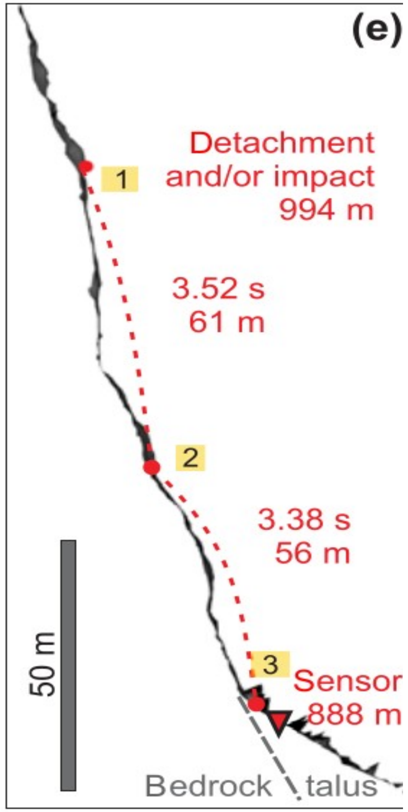
Application I – mass wasting processes in mountain landscapes

TLS-based rockfall volumes and locations



Seismic-based rockfall anatomy and kinetics





TLS provides precise information about location and volume of rock fall material (ten rockfalls in one month, from 0.05 m³ to 2.3 m³, white dots in hillshade map). Seismology provides location (~80 m error) and detailed insight to events: impacts, free fall times, talus slope activity.

Application II – mass wasting processes on clif coasts

Location
Timing
Duration
Mode of failure
Volume
Anatomy

Inform authorities
Close beach parts
(precursor signals)

Patterns

Spatial activity
Temporal activity
Magnitude-freq.
Coastline evolution

Triggers

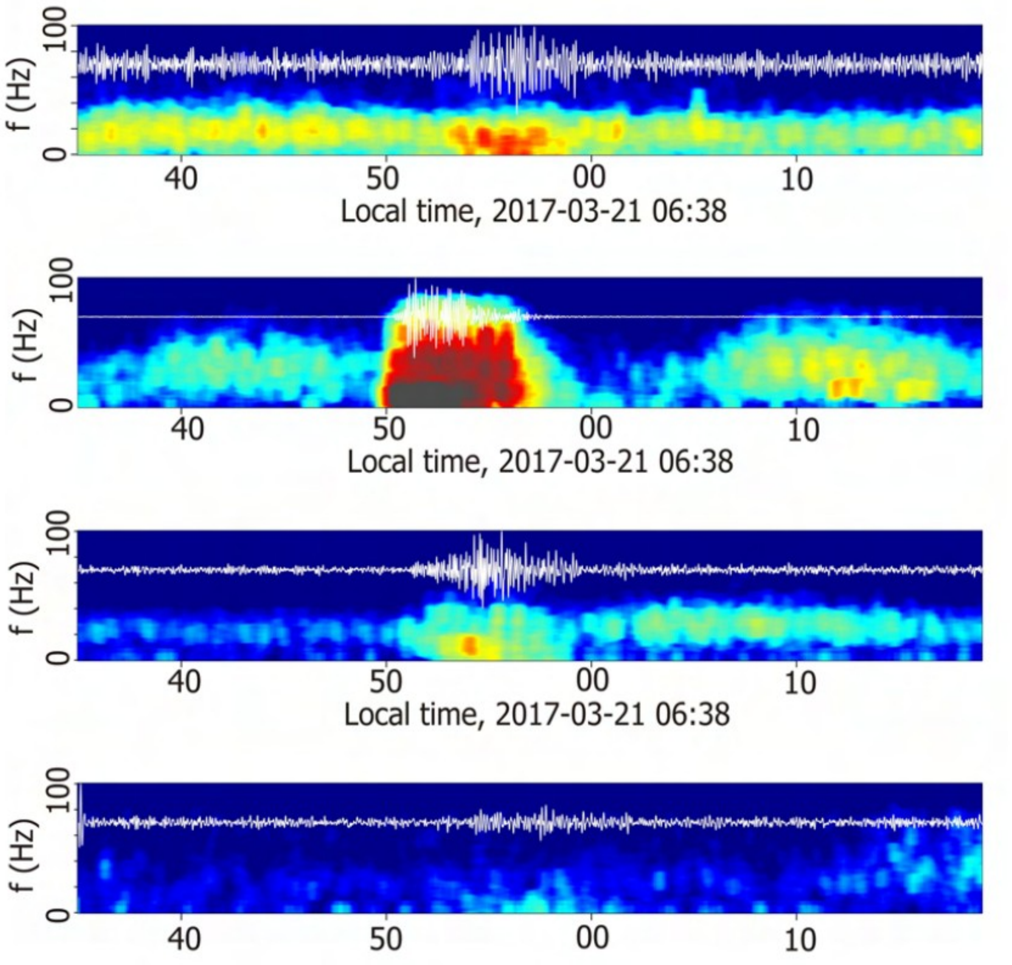
Time lags
Intensity
Duration
Long time series

We survey cliff activity since 2017, using 4 seismometers, a 6-sensor antenna, and drone imagery. We ask and answer a series of questions, which can only be tackled with continuous, high resolution information on episodic cliff failure events.

Application II – mass wasting processes on cliff coasts

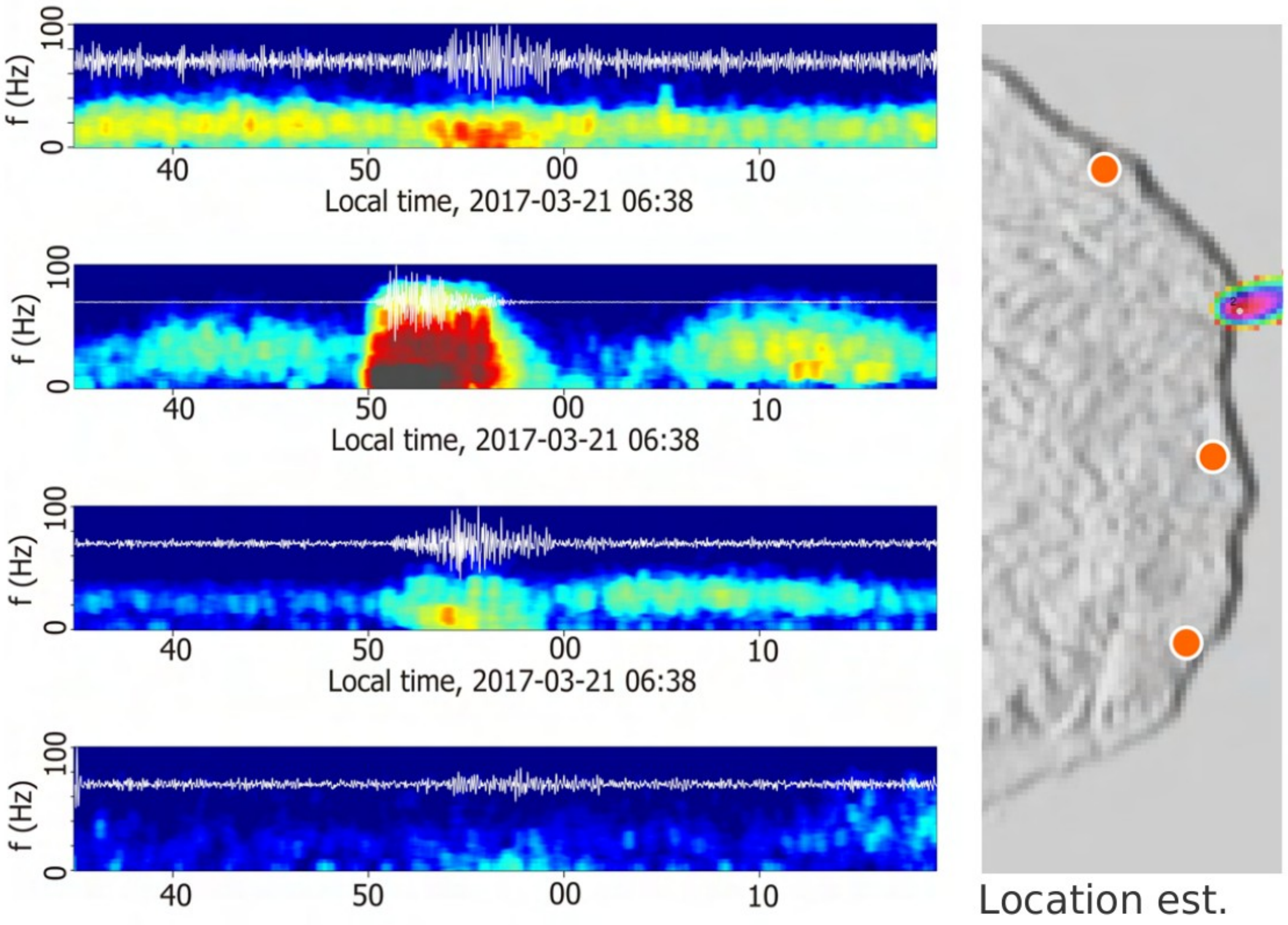
High resolution 3D information on cliff wall evolution and eroded volumes are provided by drone surveys. Kristen Cook will provide more details on that topic, later during this semester.

The anatomy of a cliff failure event



Spectrogram and seismograms of one example cliff failure. Which properties can you spot? Where did the event happen with respect to the four seismic stations, arranged from North to South with about 1 km station spacing?

The anatomy of a cliff failure event



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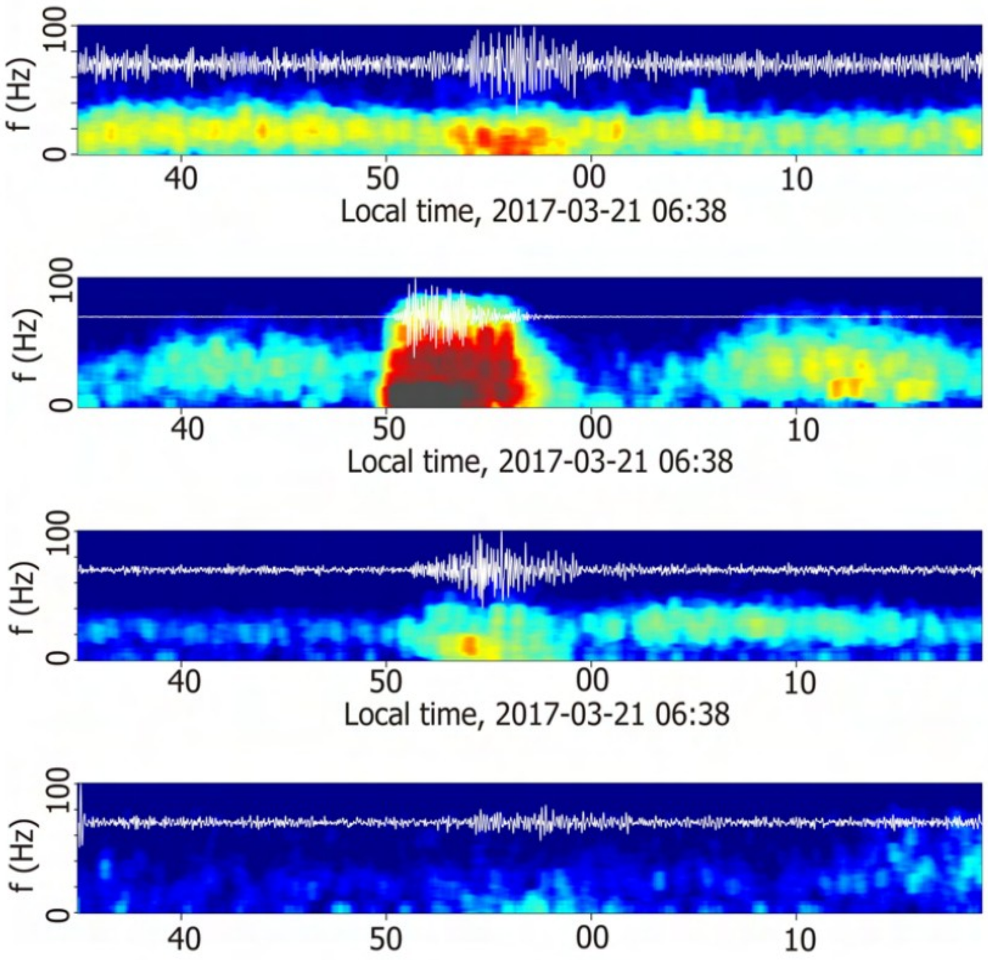
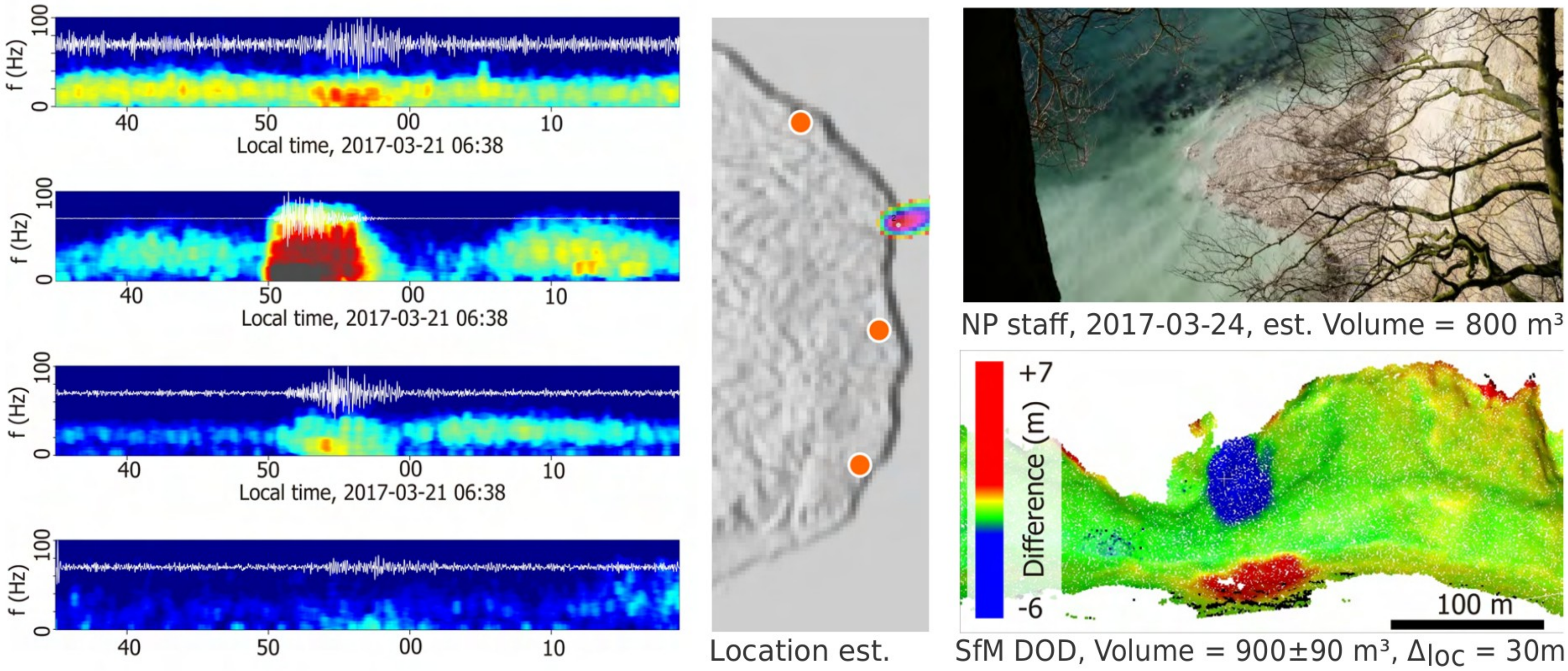


Location est.

NP staff, 2017-03-24, est. Volume = 800 m³

Spectrogram and seismograms of one example cliff failure. Which properties can you spot? Where did the event happen with respect to the four seismic stations, arranged from North to South with about 1 km station spacing?

The anatomy of a cliff failure event



Spectrogram and seismograms of one example cliff failure. Which properties can you spot? Where did the event happen with respect to the four seismic stations, arranged from North to South with about 1 km station spacing?

From a single event to seasons of events

So, the seismic approach provides:

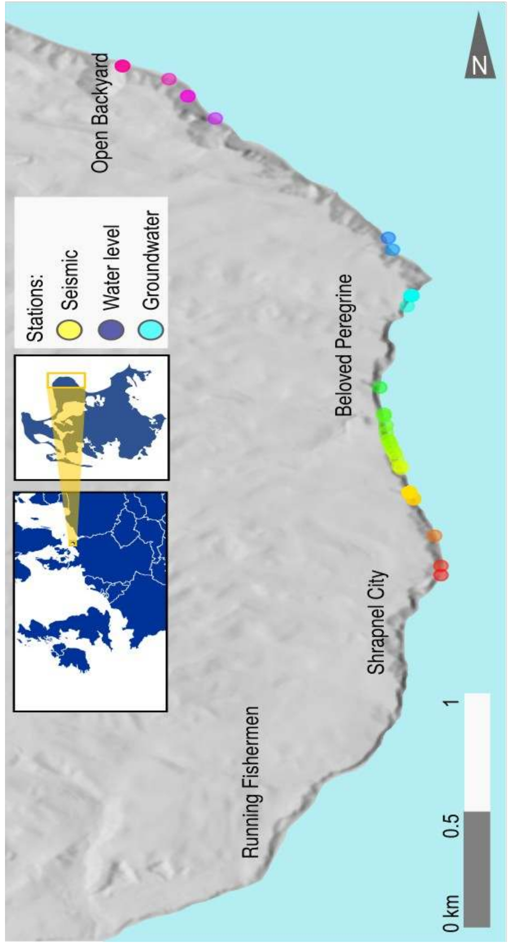
- continuous, high resolution first order information on:

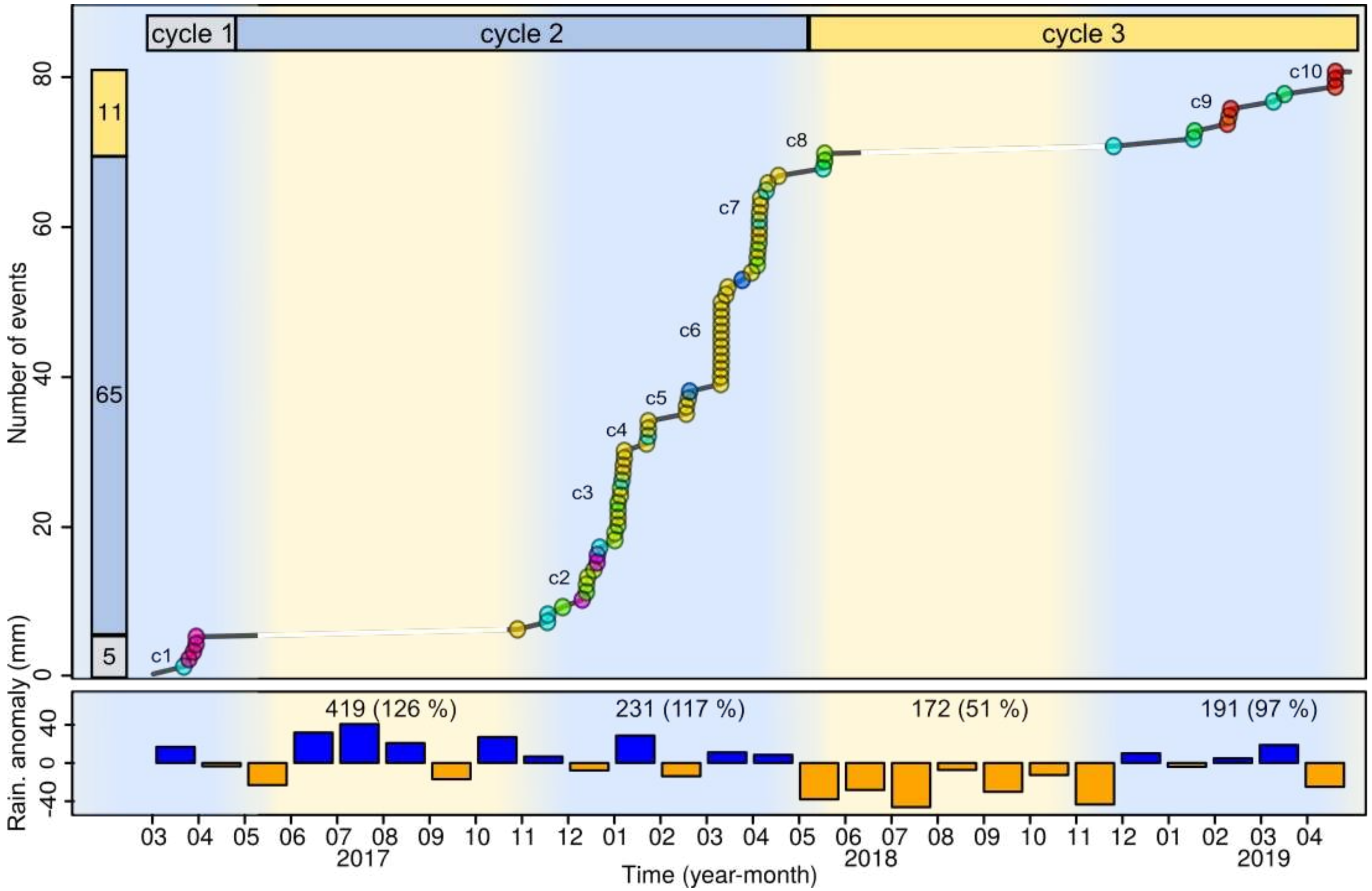
- event start and duration,
- event location (and volume)

This opens the door to inspect (independently recorded data on) drivers and triggers

Beyond anatomies of single events, the seismic approach allows studying multi-seasonal time series of event onsets, durations and locations. This allows inspecting responsible mechanisms. What are drivers and triggers? What is the difference between them?

From a single event to seasons of events – the drivers





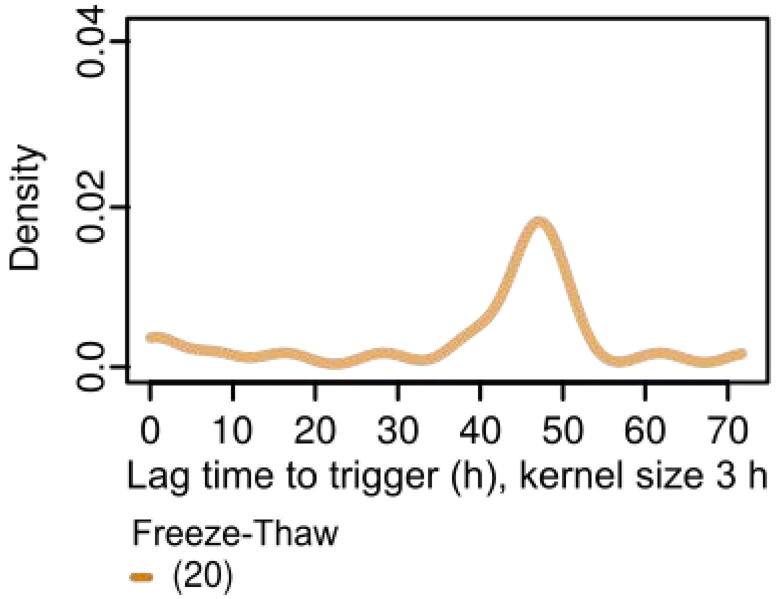
Failures are clustered spatially and seasonally.

Wetter years result in more failures compared to drier than average years.

Failures occur as day-long clusters.

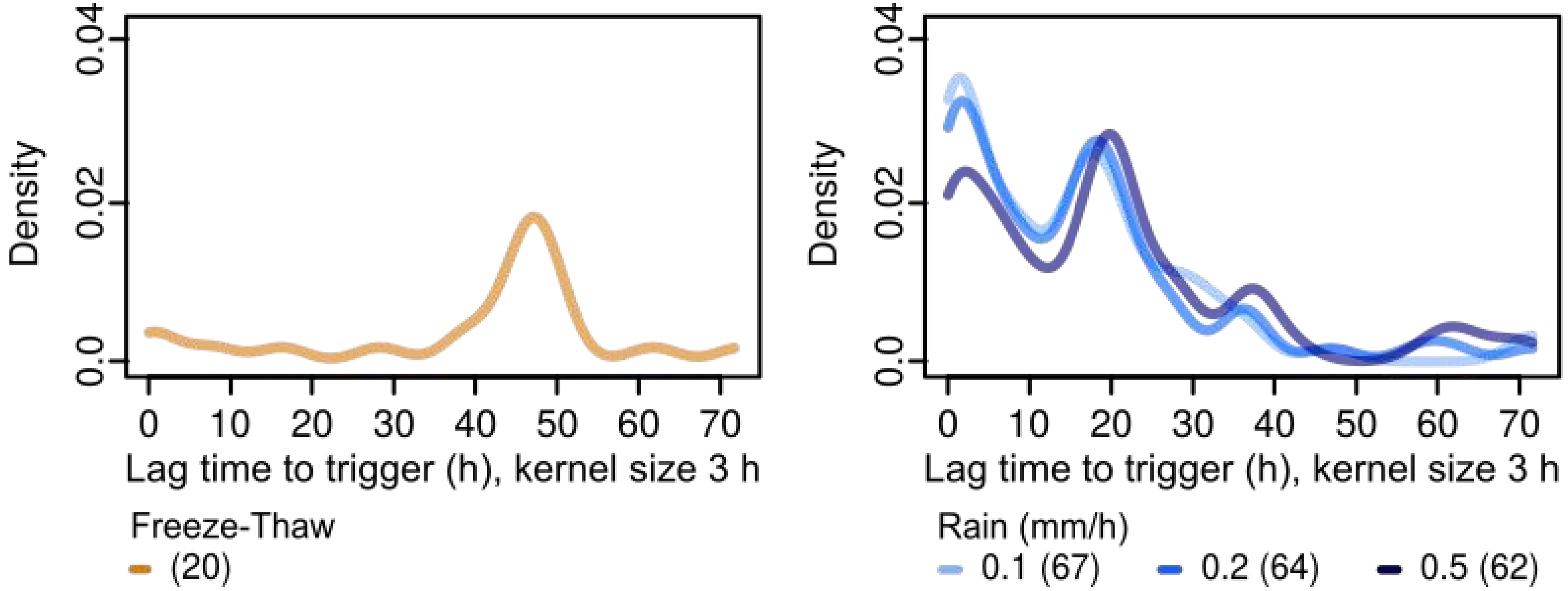
Inspect the spatial clusters of cliff failures. What could be reasons? Inspect the temporal clustering, at seasonal, multi-seasonal, and at event scale What could be reasons?

From a single event to seasons of events – the triggers



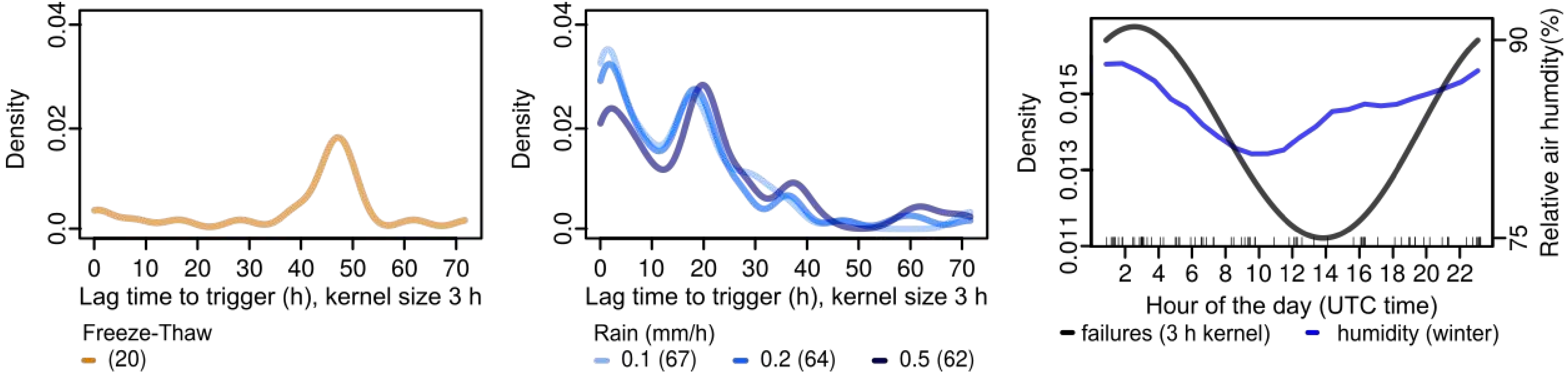
The plots show the time between the occurrence of a trigger process (e.g., freez-thaw transition) and a cliff failure. The line is a kernel density estimate, similar to a histogram. It implies that after a freeze-thaw transition, it takes about two days until a failure happens. Does this make sense?

From a single event to seasons of events – the triggers



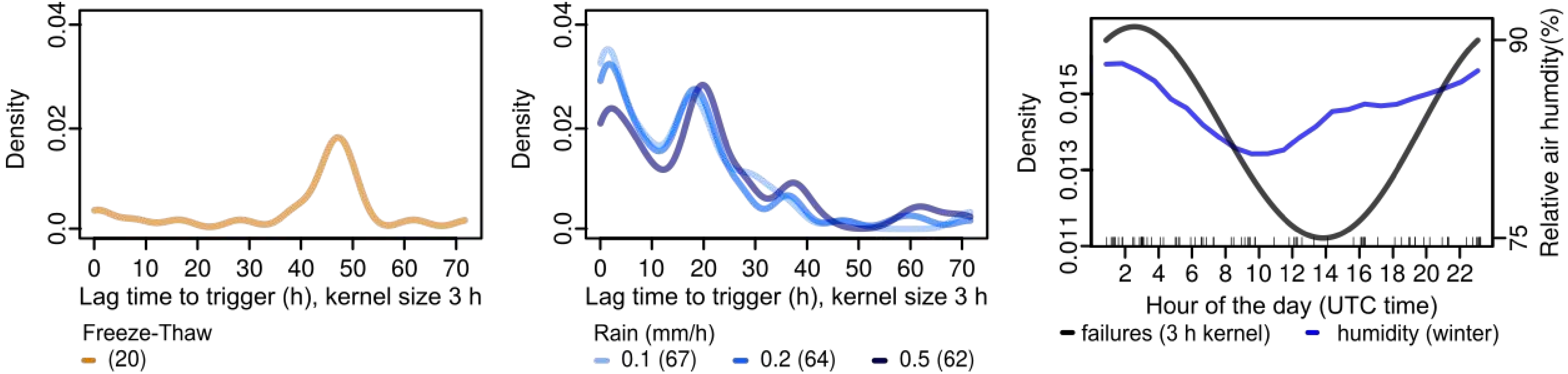
What about lag times to rain events? Why do we have two clusters of “reaction times” to rain events? What could be reasons?

From a single event to seasons of events – the triggers



Note the diurnal pattern of cliff failure occurrence. Why are there more events at night than at day? What could drive/trigger this pattern?

From a single event to seasons of events – the triggers



Failures are predominantly triggered by water/moisture, at the event-scale and and the diurnal scale. Mechanisms appear to be: i) direct rain on cliff (0–2 h time lag), ii) water flow below the surface (16–25 h time lag), and iii) condensation on the cliff surface.

Ever been to Hiddensee? And/or looking for BA or MA topic?

The next complex cliff coast is not far away. Hiddensee has a marvellous and highly active clif, which is instrumented, as well. If you are interested in the topic, fell free to ask for a BA/MA or internship project.

Wrapping up hillslope mass wasting as application seismology

Seismic station networks can
- detect (and track), date and locate discrete mass wasting events
- provide continuous (near real time) coverage of entire catchments

We are able to study
- the anatomy of single events at high detail
- span temporal scales, from event to multiple years
- investigate preparation phase, drivers and triggers of failures

We are drowning in data from sites around the world, so assistance is very welcome.

Let’s look at the continuous part of seismic signals

So far, we have touched signals of discrete events (rockfalls, cliff failures). Now, we want to focus on continuous signals.

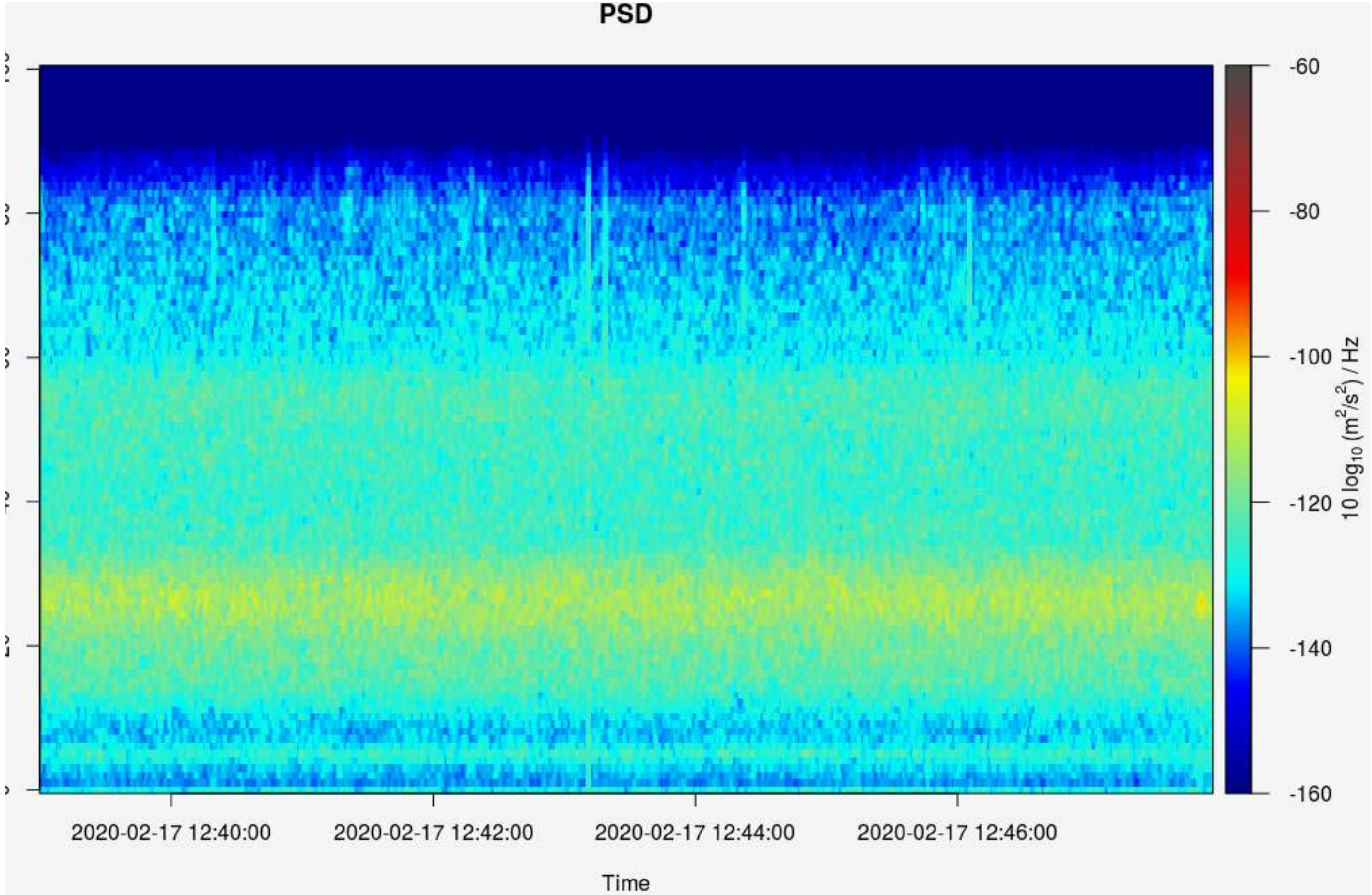
Welcome to Scotland’s Highlands – the Feshie River

One of the last field trips before the Covid dictated period.

Welcome to Scotland’s Highlands – the Feshie River

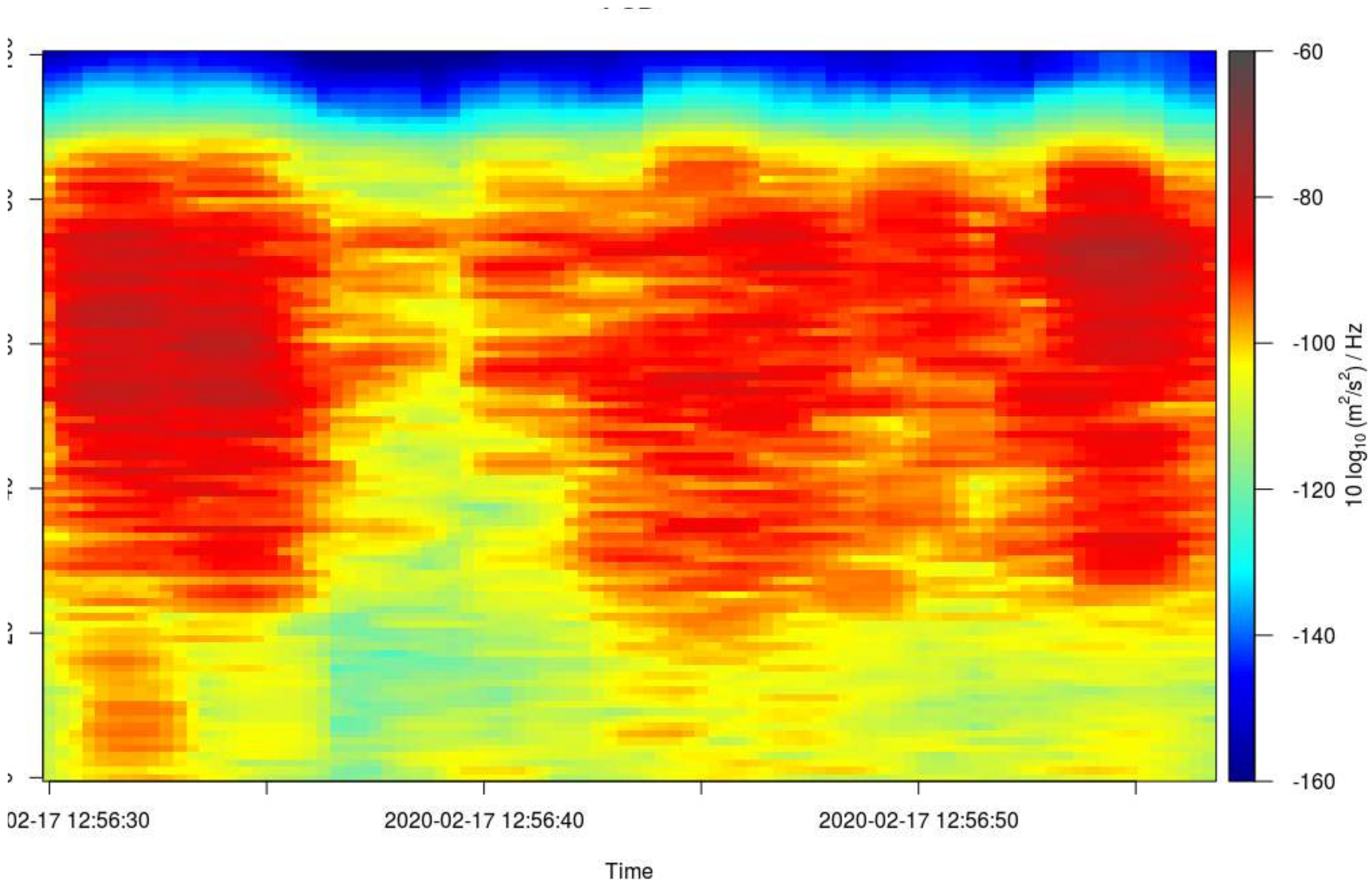
A glacially determined valley, with the braided stream excavating unknown volumes of cobbles and gravel.

The seismic signal of a river under turbulent flow conditions



The seismic spectrogram recorded by a station next to the bank of the Feshie. Note the signal only due to turbulent flowing water, as a horizontal pattern with peak energy around 20–30 Hz. By the way: river width 10–15m, gradient 0.02 m/m, flow depth 0.6–0.9 m, sensor about 4–6 m away.

The seismic signal of a river and bedload flux

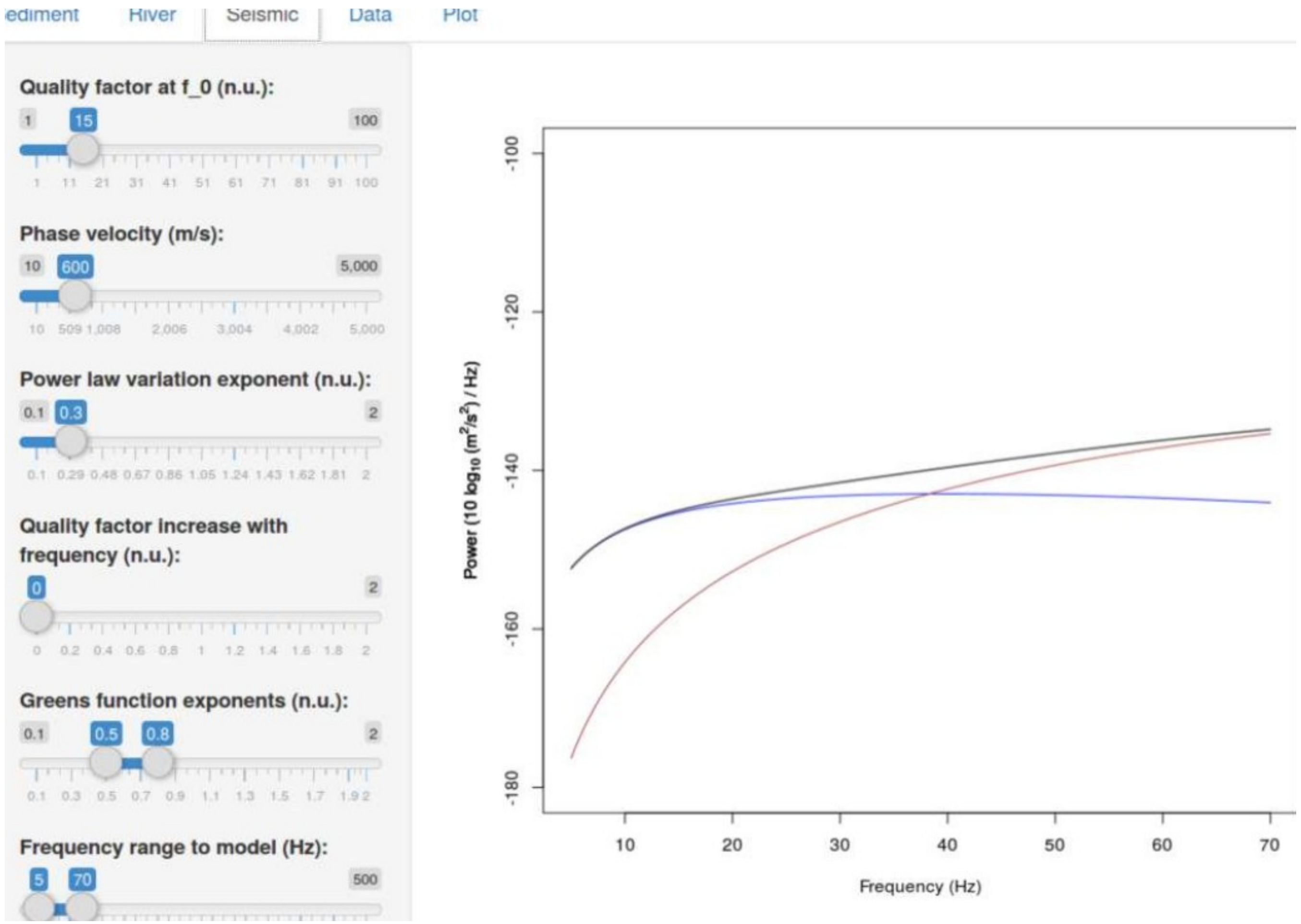


Here, a spectrogram which exposes the signature of a person mimicking bedload movement. The gravel is pushed “gently” down stream. Note the much higher seismic energy and at frequencies of 30–90 Hz.

The seismic sources active under these conditions

What are the mechanisms that create seismic signals of rivers?

Mechanistic models to predict spectra due to water and bedload



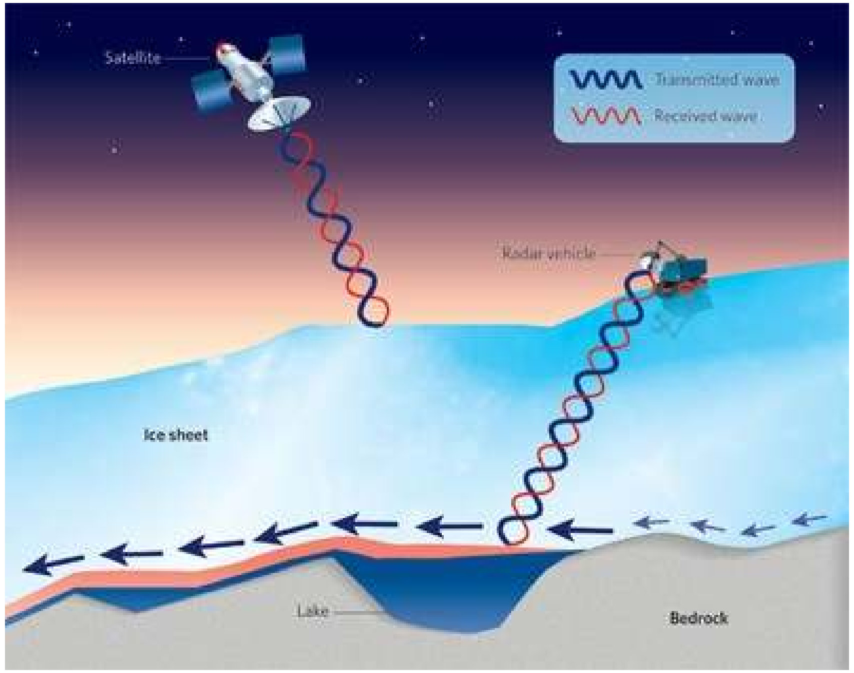

```
## calculate spectrum (Tsai et al., 20
p_bedload <- model_bedload(d_s = 0.7,
                           s_s = 0.1,
                           r_s = 2650,
                           q_s = 0.001,
                           h_w = 4,
                           w_w = 50,
                           a_w = 0.005,
                           f = c(0.1, 2
                           r_0 = 600,
                           f_0 = 1,
                           q_0 = 20,
                           e_0 = 0,
                           v_0 = 1295,
                           x_0 = 0.374,
                           n_0 = 1,
                           res = 100,
                           eseis = TRUE
```

These models were written into the R package ‘eseis’ and can either be used to predict seismic properties, or to invert seismic signals (spectra) for unknown parameters, such as water level or bedload flux.

Dietze (2018), Dietze et al. (2019)

Mechanistic models to predict spectra due to water and bedload

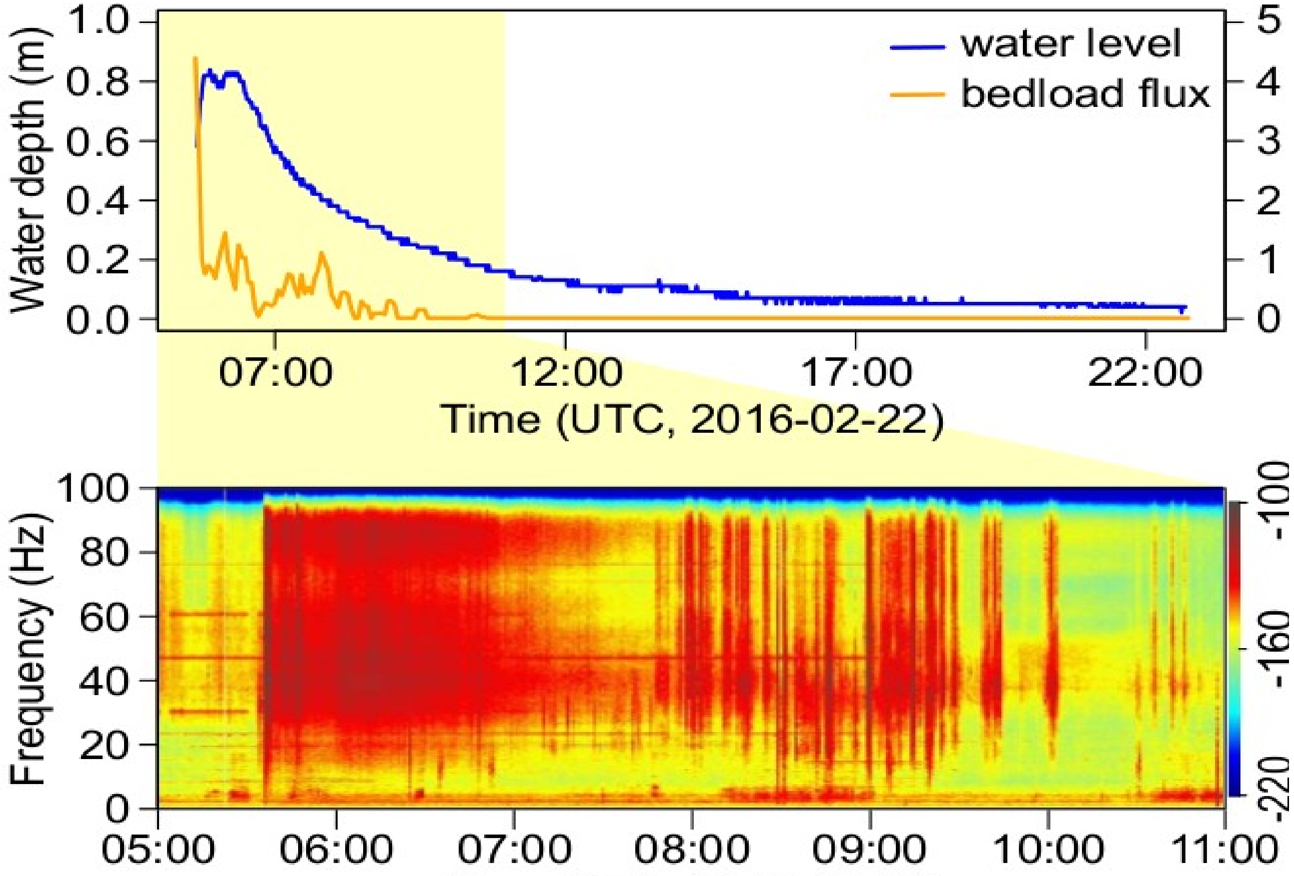
So what is this good for? For an inverse approach: predicting bedload flux from seismic data!



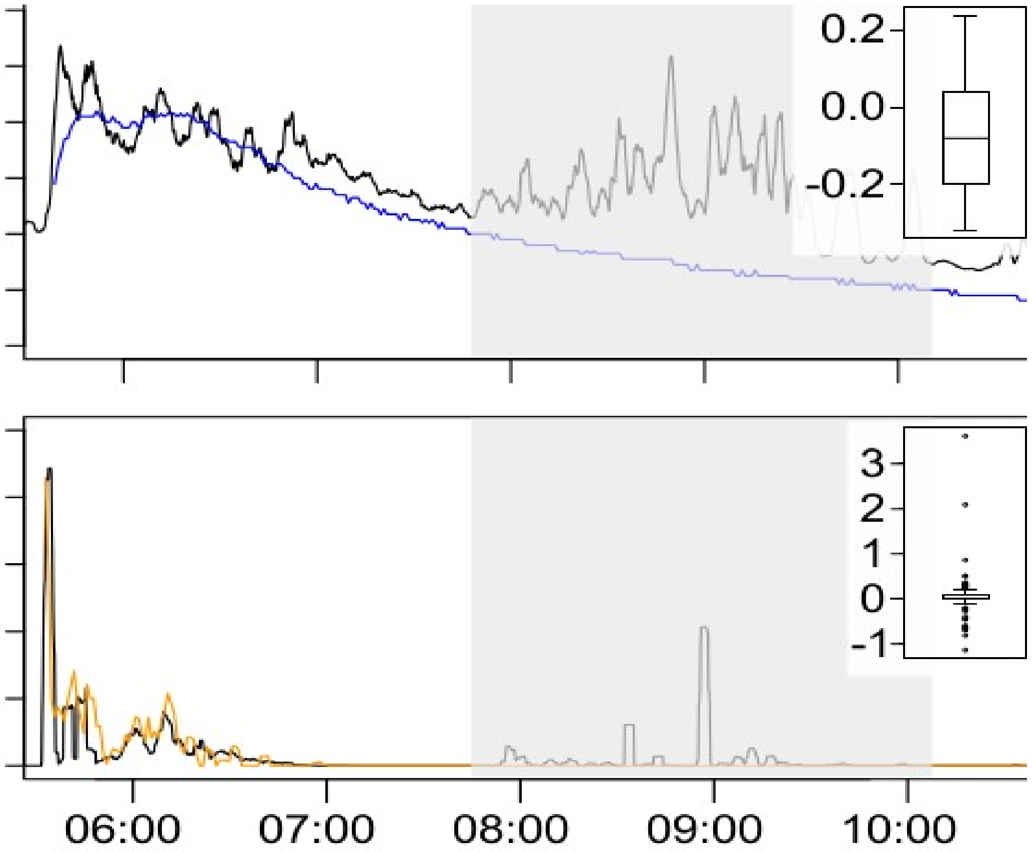
Potential applications of seismically sensed bedload flux, most useful in places where direct measurements are hostile or simply not possible.

Testing the approach – The Nahal Eshtemoa, Negev Desert, Israel

Independent measurement data



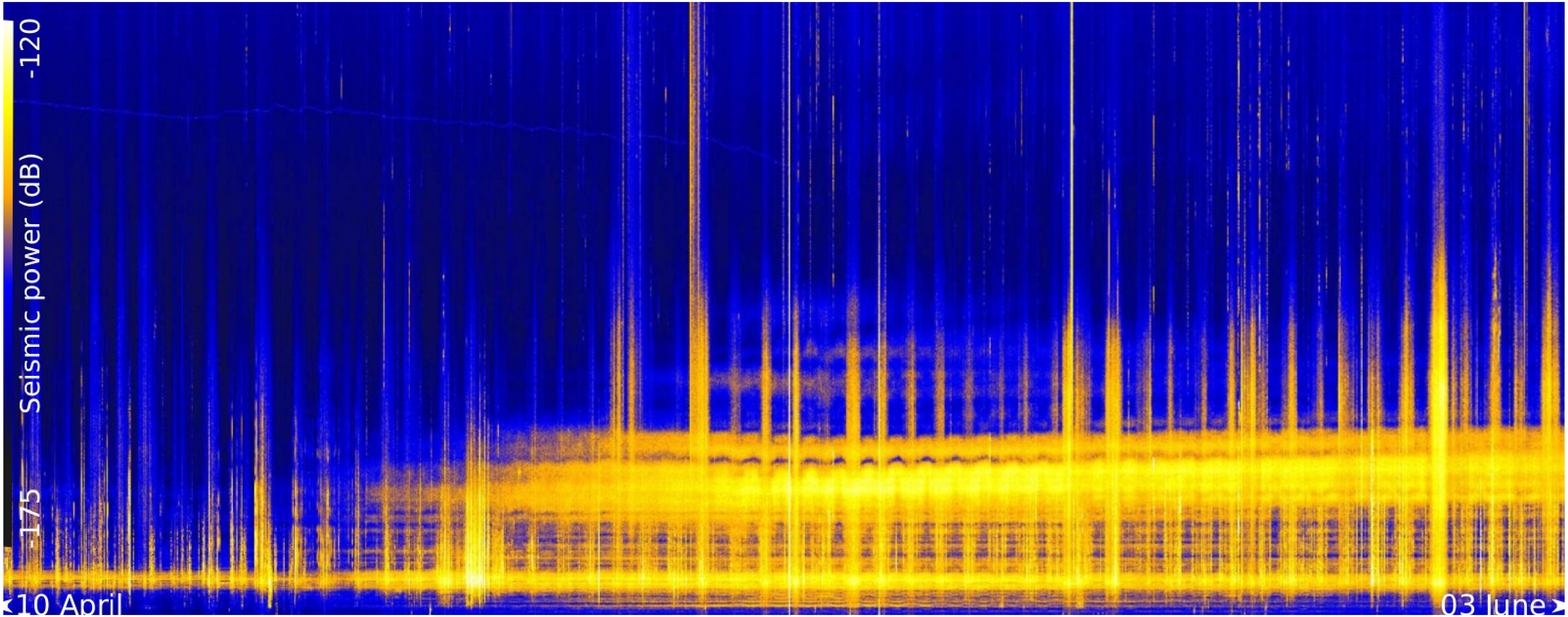
Seismic inversion model (black)



The flash flood hit the site rapidly and lasted for a few hours. Its seismic imprint is a broad band energy rise. Note the sharp energy spikes after 8 am, which are due to people maintaining the observatory. The model approach reproduces both the water level and bedload time series.

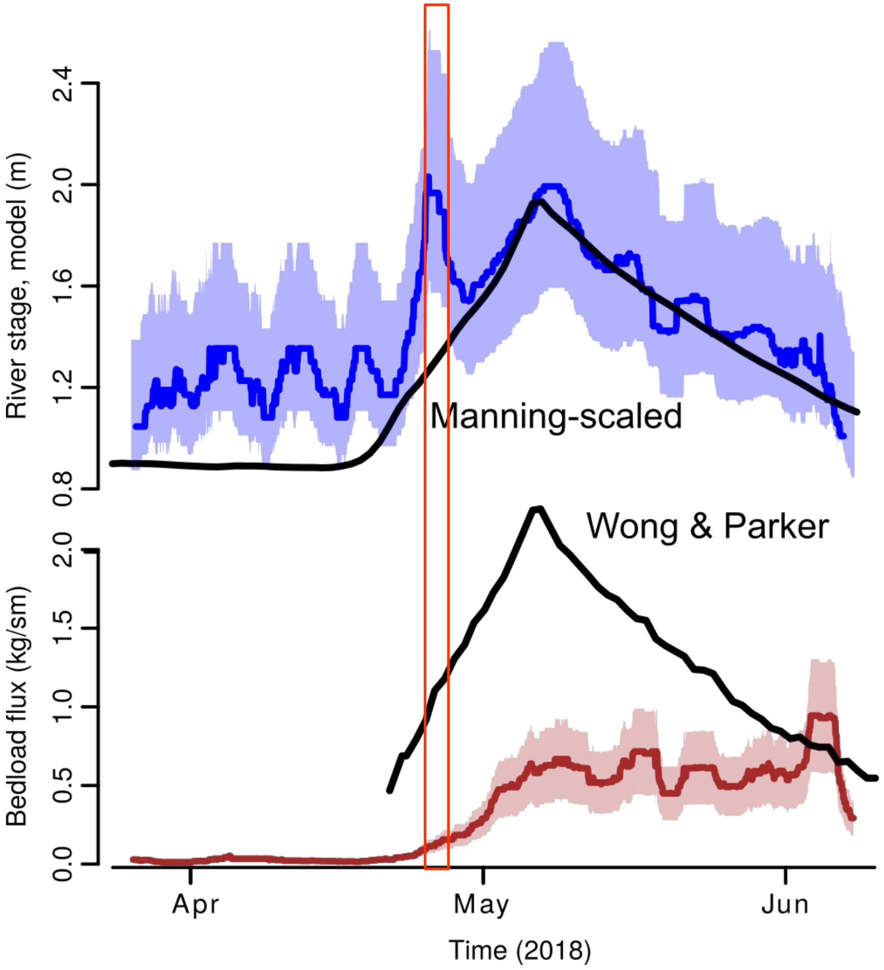
Applying the approach – in the Arctic during winter time

The seismic footprint of the Saevaron from winter to spring flood



The spectrogram shows a continuous signal around 8 Hz due to the river, and a broadband signal 10–30 Hz starting around ice break-up during spring. Note the diurnal patterns of sediment transport during the first weeks in spring (diurnal snow melt signal) that vanishes in summer.

Model inversion results for water level and bedload flux



Wrapping up:

Seismic sensors can also record continuous signals, caused by environmental dynamics, such as flowing water and the sediment it transports.

They allow probing hydraulic and sediment transport data at safe distance, integrating over tens of metres.

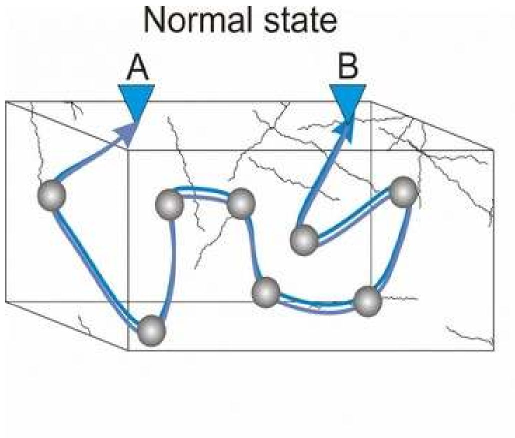
Physically based models and their inversion deliver (almost) real time data, given the parameters can be constrained sufficiently robust.

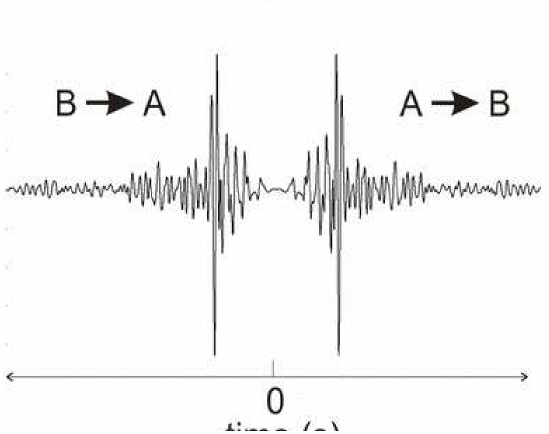
Model inversion results show a strong deviation of bedload flux from the water discharge/level evolution, which cannot be picked up by typical flow-related bedload transport equations.

Let’s look at the continuous “noise” part of seismic signals

Welcome to the Hochvogel, a 2700 m high peak with a crack that can fit a bus.

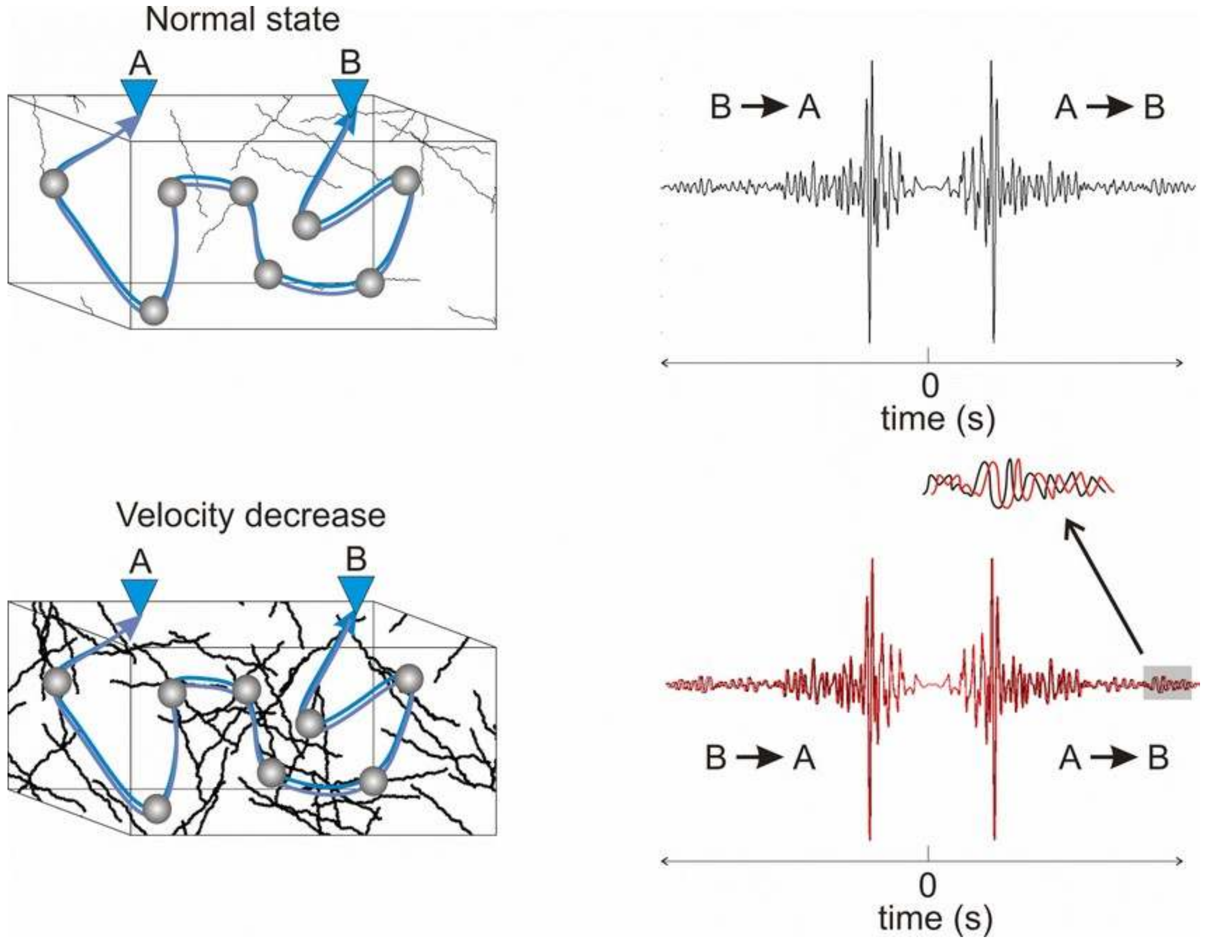
Signals from noise?





The concept of coda wave interferometry or noise cross correlation: seismic waves become scattered on their way through a solid medium. Their cross-correlation reveals a given time lag, depending on the amount of damage within the solid.

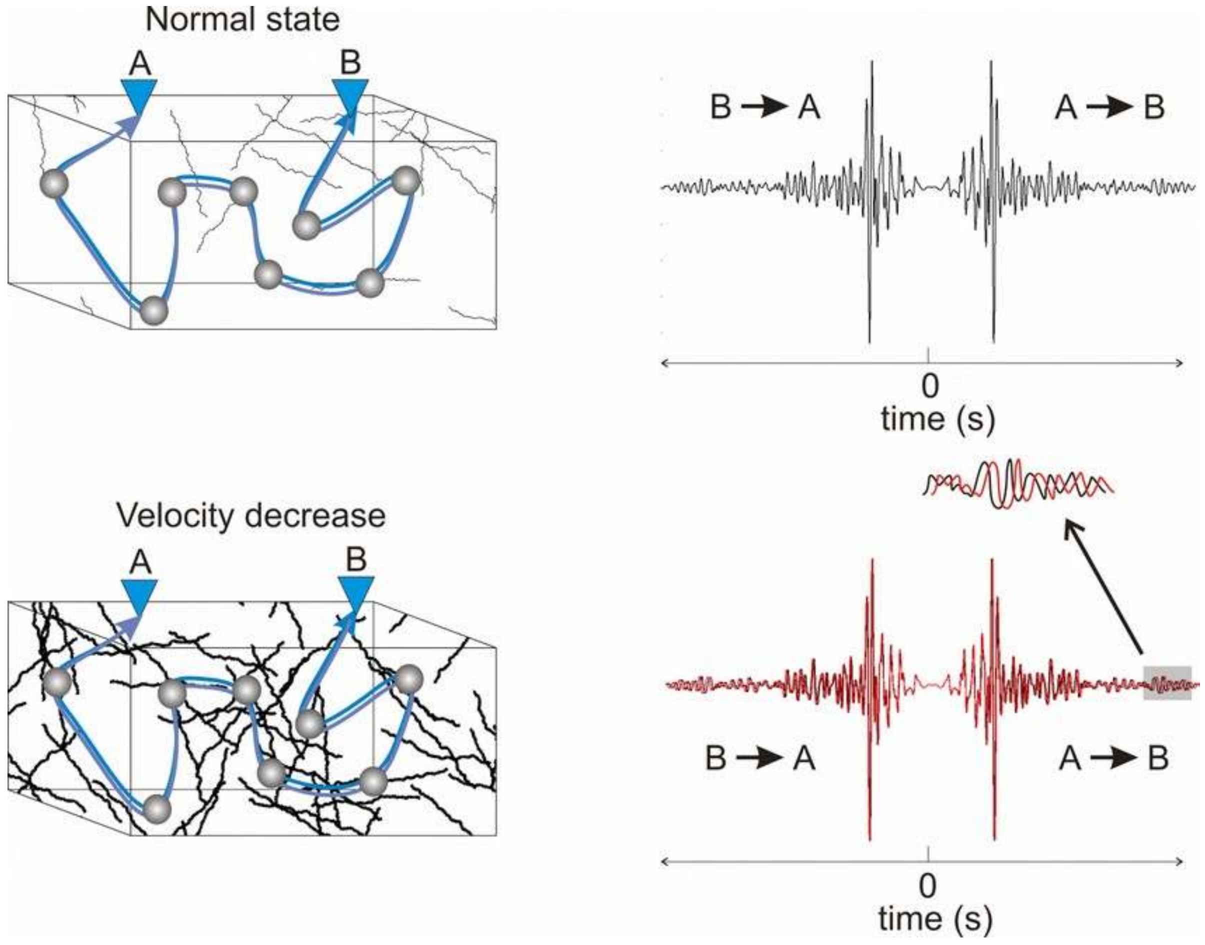
Signals from noise?

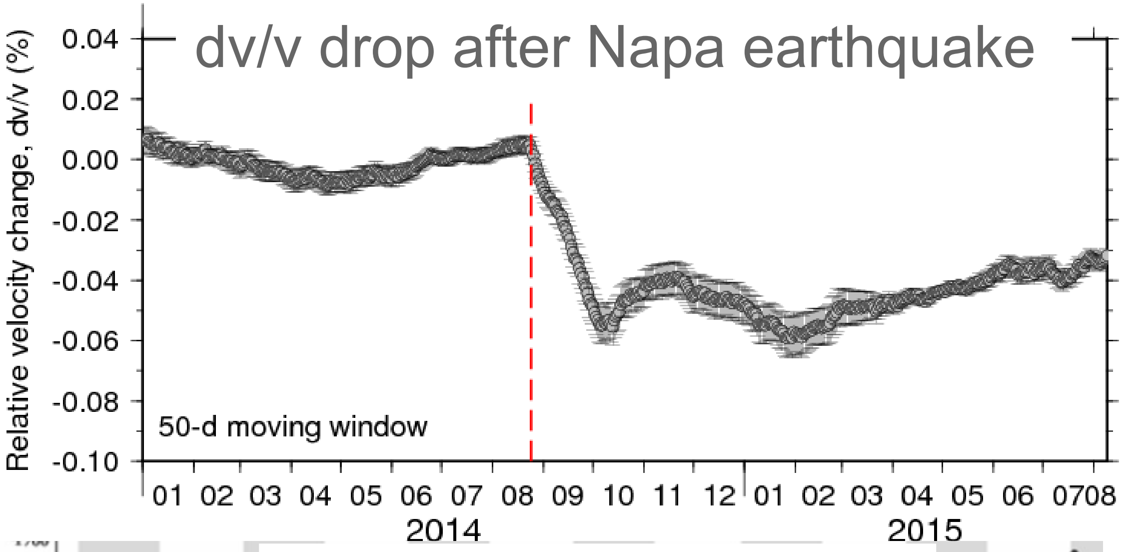


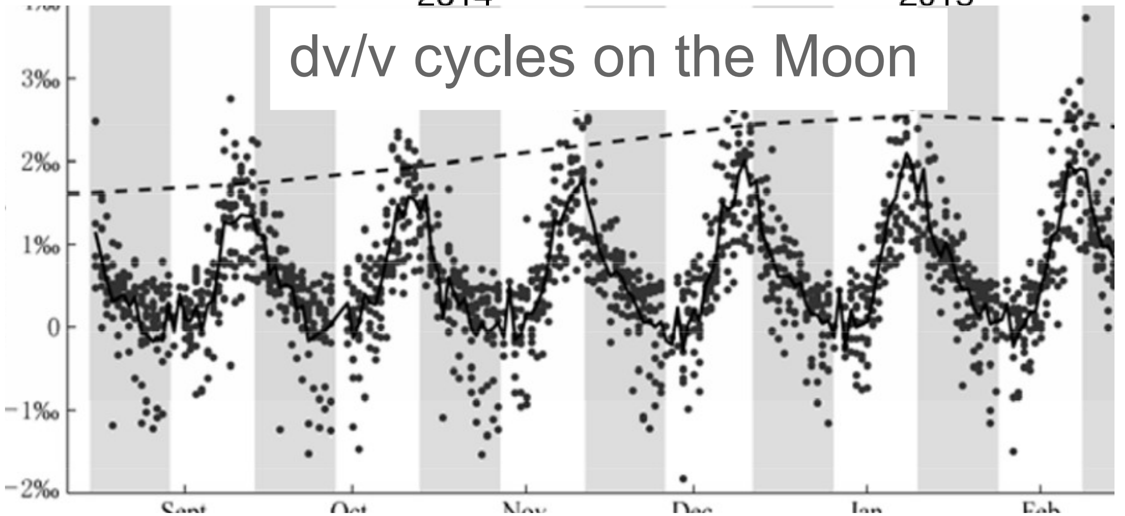
When the damaging increases, the scattering becomes more intense and hence the cross-correlation shows a larger time lag. Hence, the time lag (or relative seismic wave velocity) can be seen as a proxy for damage – or other changes to the soild medium.

Brenguier et al. (2016)

Signals from noise!

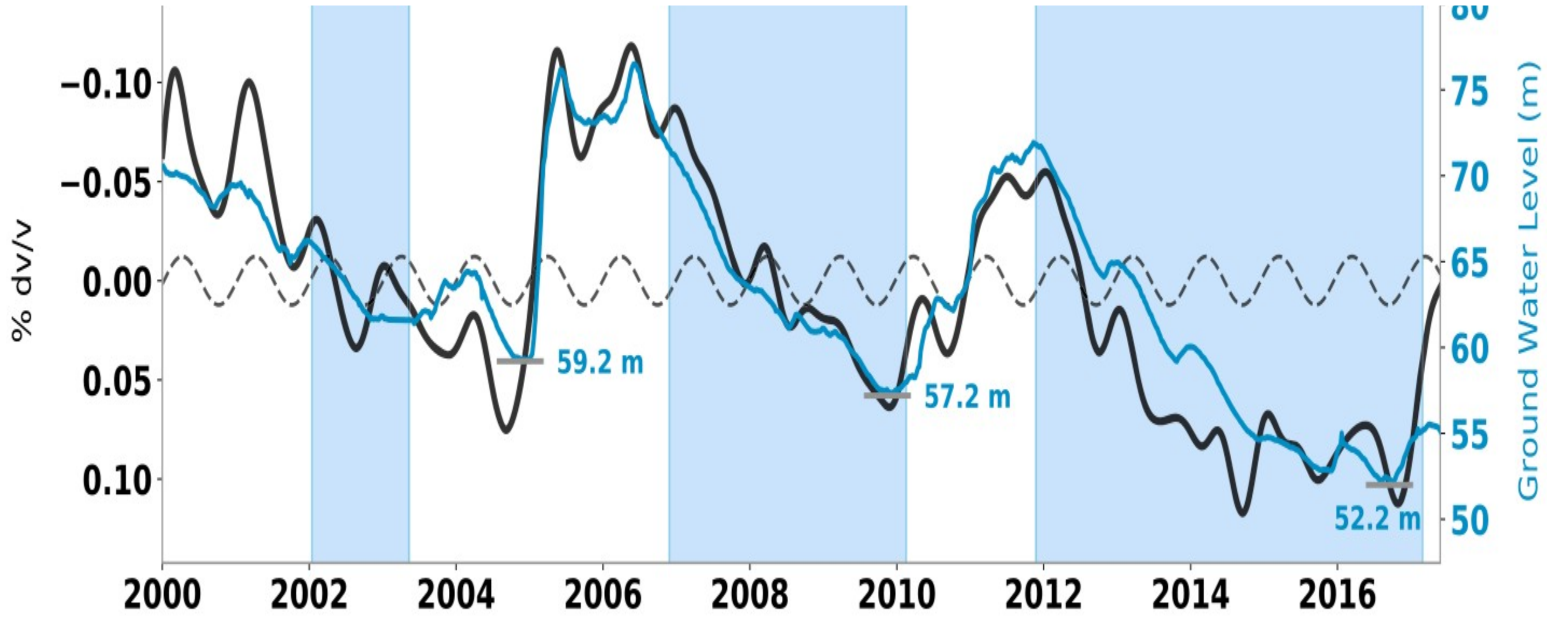


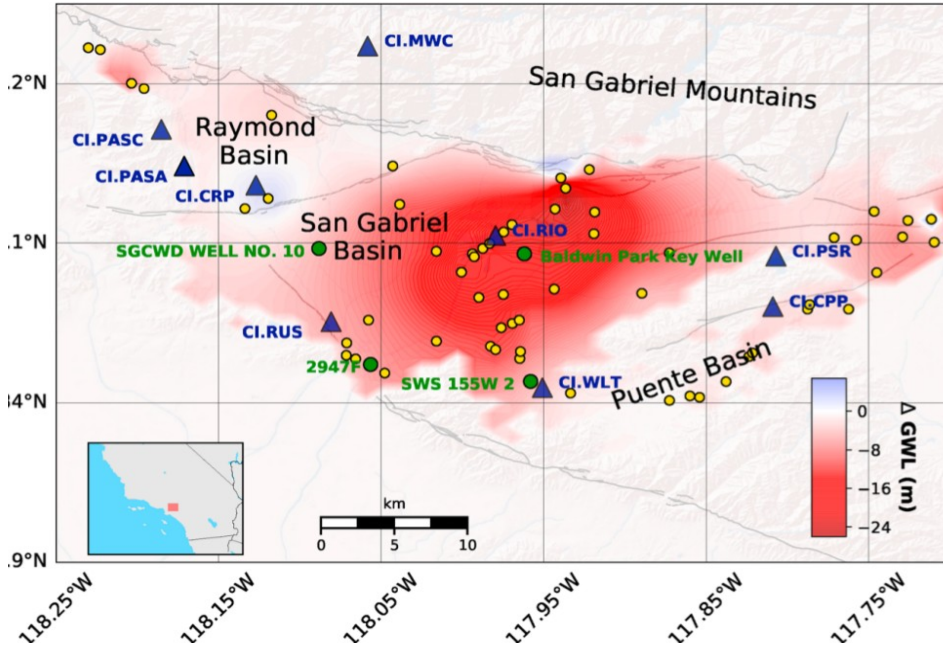




This relationship has been observed after large earthquakes (healing of the ground takes some years) but also on the Moon where the sun heats up The Moon and increases stress in the rock and thus the relative wave velocity.

Signals from noise! – Probing groundwater levels





Groundwater affects seismic wave velocity across entire geological basins.

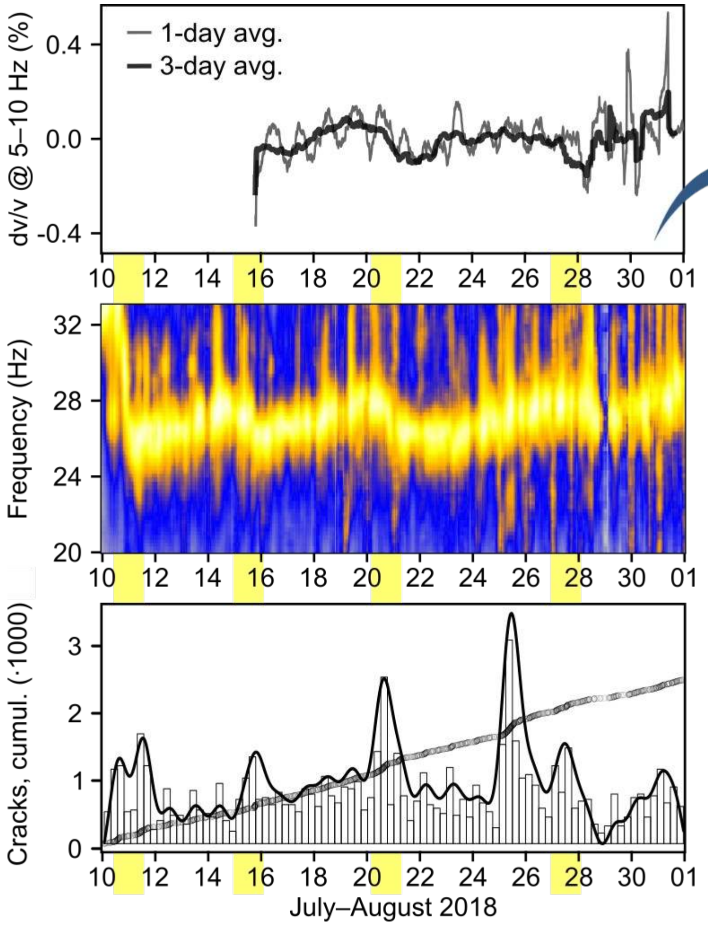
The proxy can also be used to study basin-wide ground water levels over years to decades.

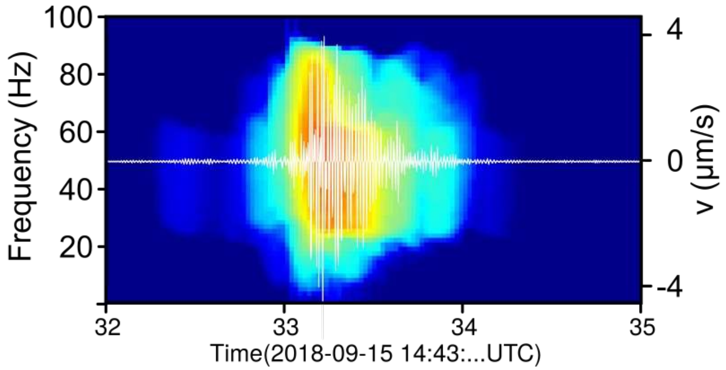
Clements & Denolle (2018)

The Hochvogel: a peak falling apart

Back to the Hochvogel, can we use seismic wave velocity change as proxy for stress evolution inside the rock mass? Here, we use data from seven geophones installed around the peak. We explore dv/v, the peak’s resonance frequency, and discrete crack signals to explore this question.

Signals from noise! – Probing rock stress from the surface





Wave velocity (dv/v) shows a diurnal cycle, driven by insolation/temperature, but also a multi-day cycle of slow rise and rapid drop.

The same cycles are visible in the peak's resonance frequency, and the emission of crack signals.

The seismic data show cyclic increase and decrease of wave velocity and resonance frequency – both proxies of stress evolution inside the rock. Simultaneously with drop in stress there is enhanced emission of crack signals. This points at a early stage of stick-slip motion.

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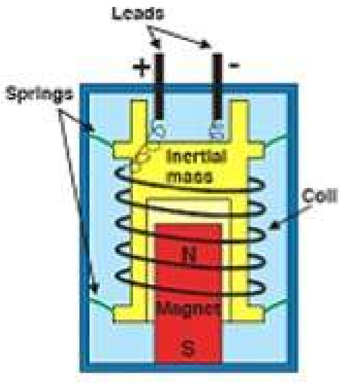
That was it – a quick race through environmental seismology

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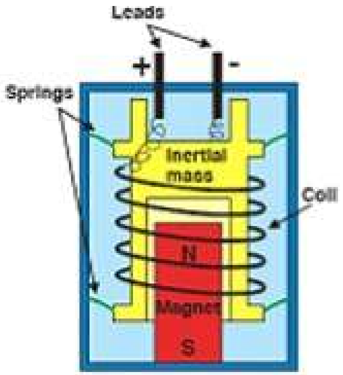

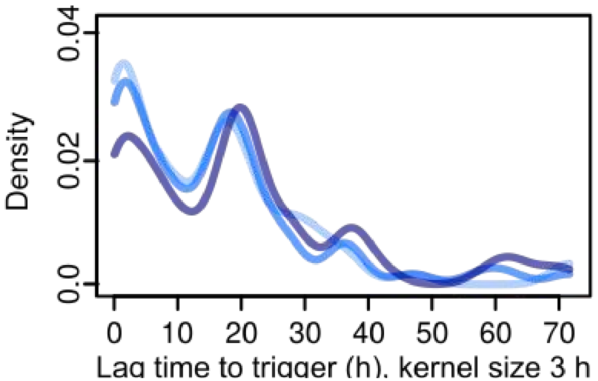

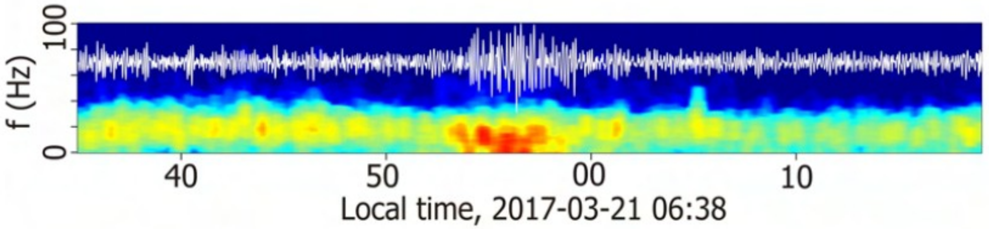

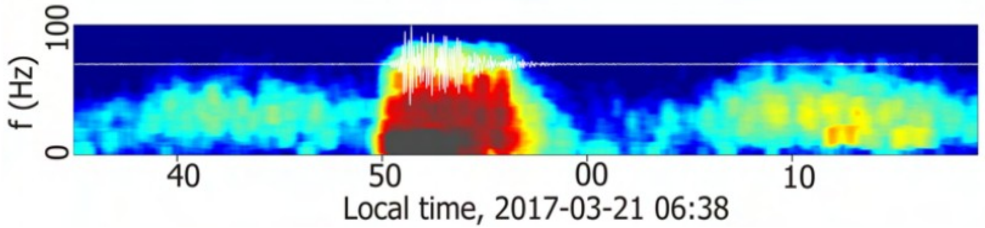

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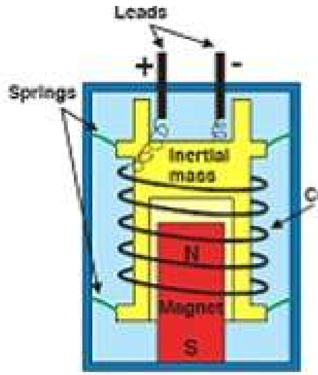

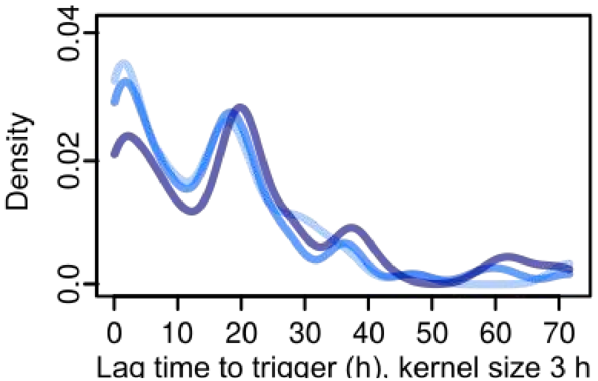

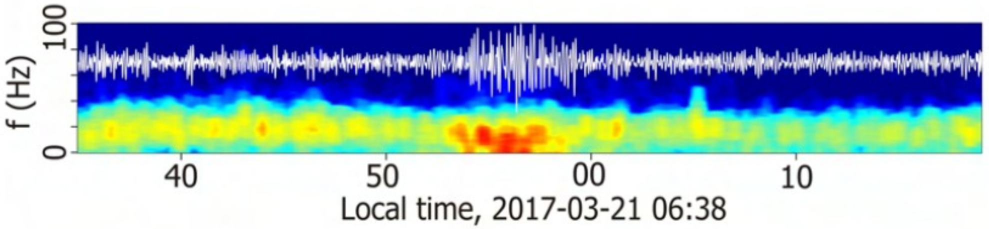

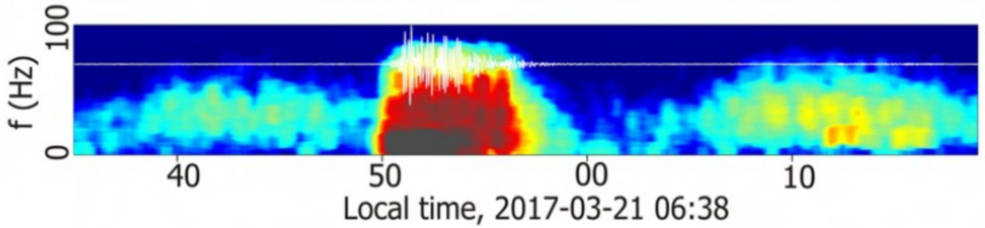

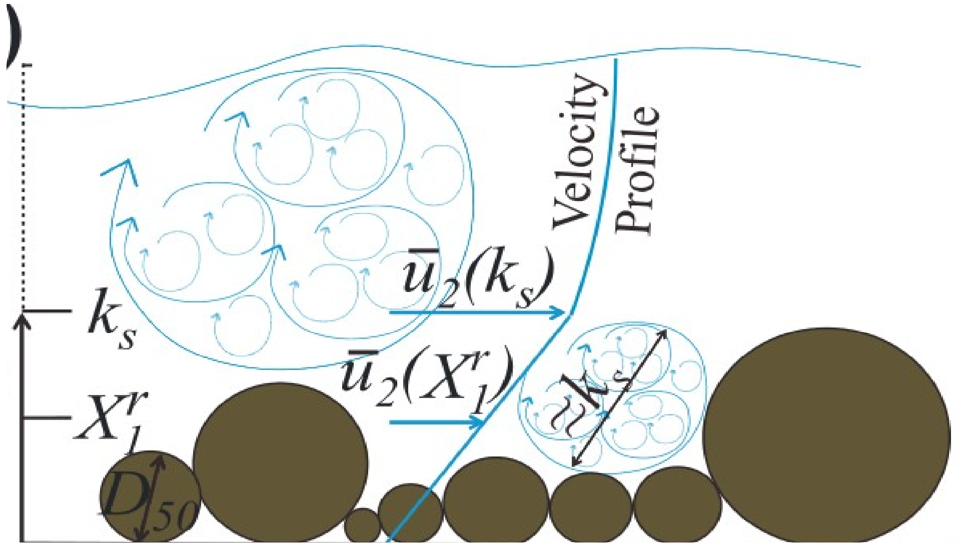

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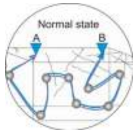

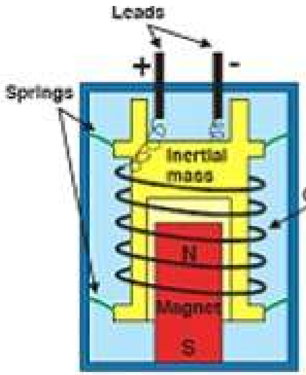

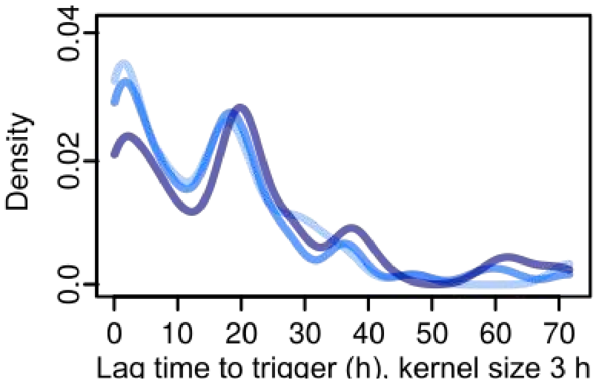

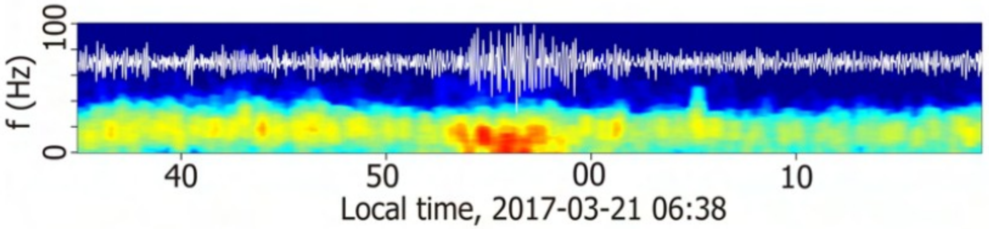

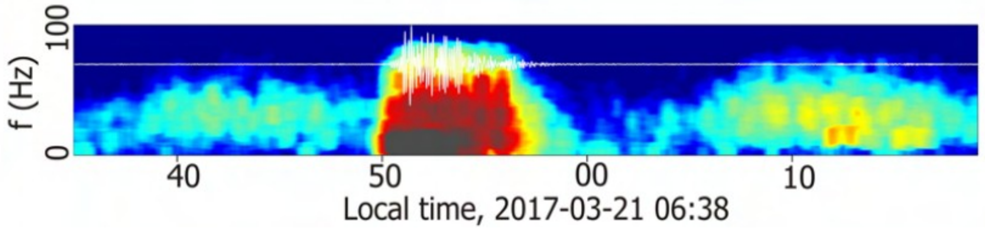

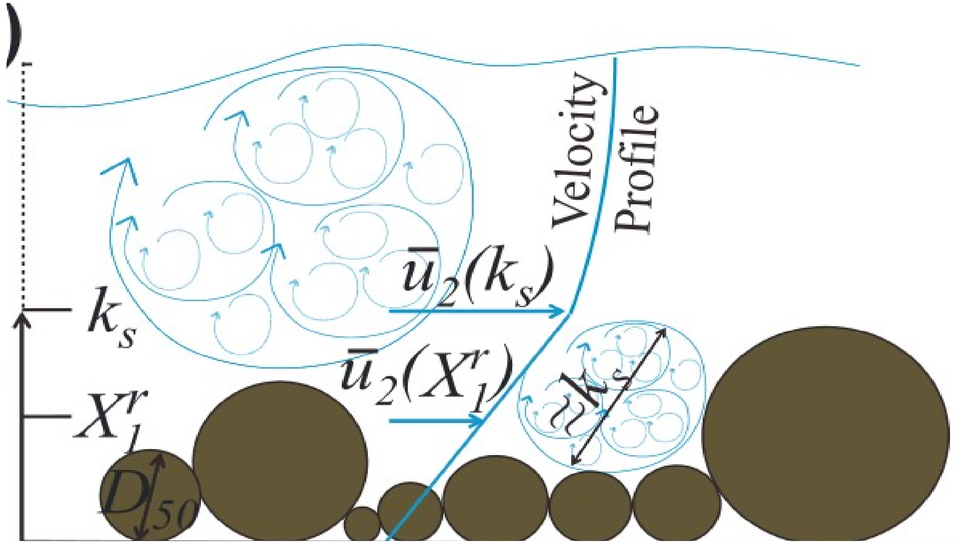

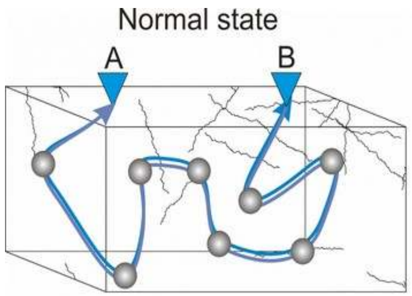

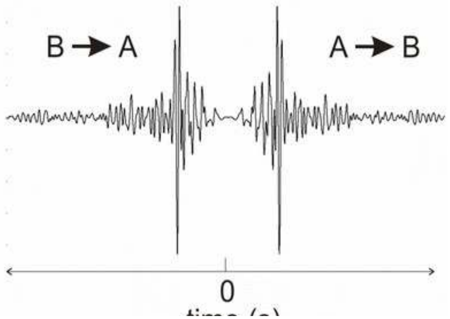

Vielen Dank!

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