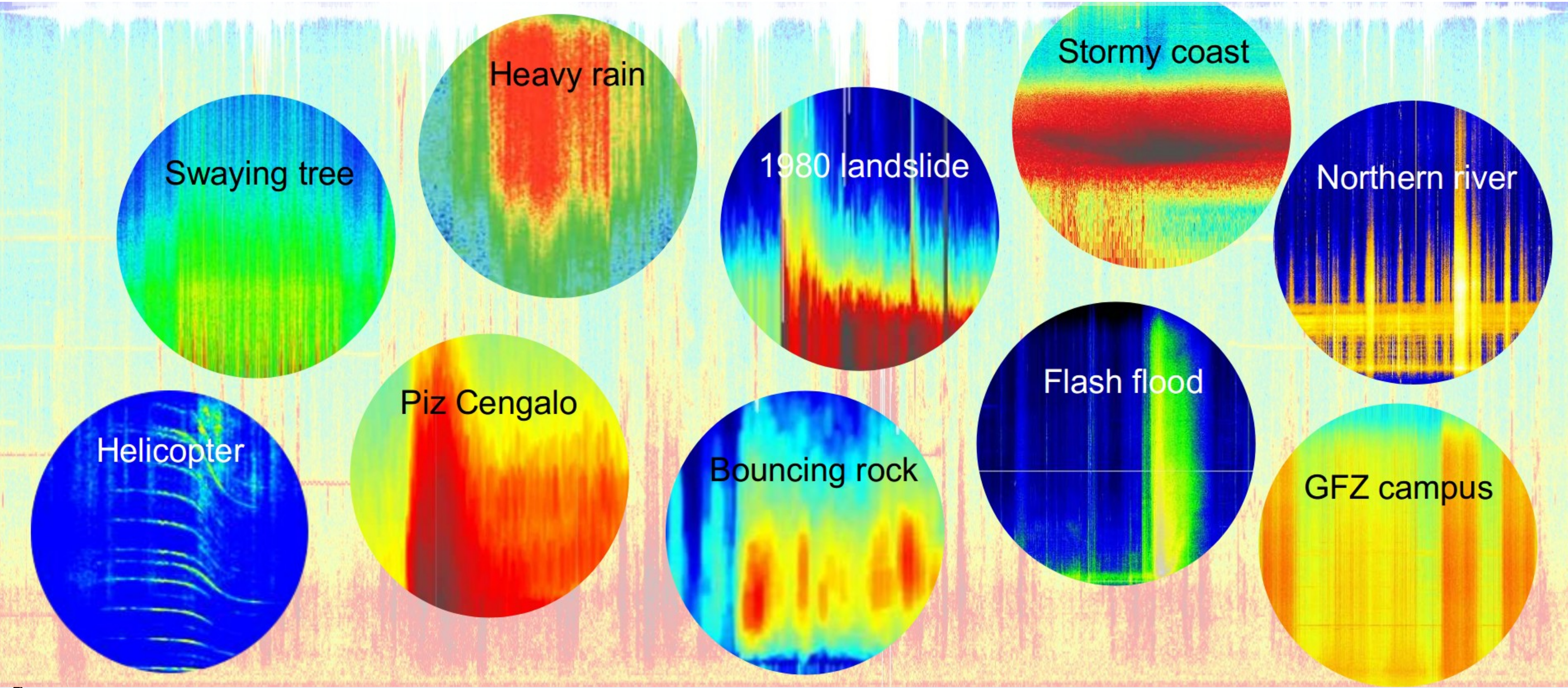
We need more models!

How geomorphology in seismic models leverages our understanding of landscape dynamics

Michael Dietze
RWTH Aachen

A kaleidoscope of seismic signals as spectrograms of episodes of Earth surface activity



A textbook collection of geomorphic processes

weathering	**mass wasting**	**rivers & water**	**atmosphere**	**glacial**
frost	rockfall et al.	river flow	air pressure	cracking
thermal	landslide et al.	bedload	wind action	deformation
salt	dry granular	turbudity current	rainfall	calving
clay expansion	debris flow	overland flow	hail & snow	subglacial flow
debutressing	creep & slide	groundwater	saltation, repat.	
chemical	avalanches	suspension		
biological	rock glaciers	karst		

A textbook collection of geomorphic processes

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~~chemical~~	avalanches	~~suspension~~		
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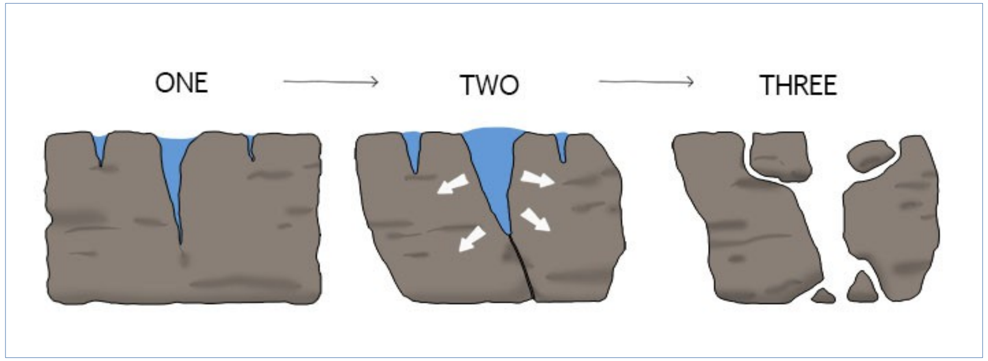
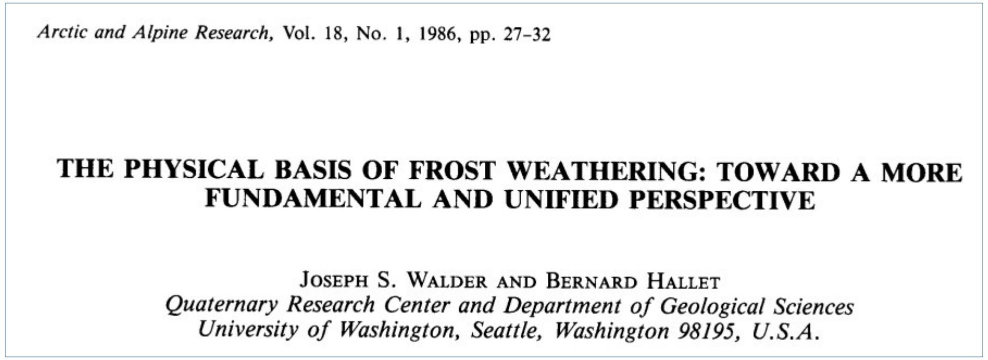
What do we know?
Can we model physically?

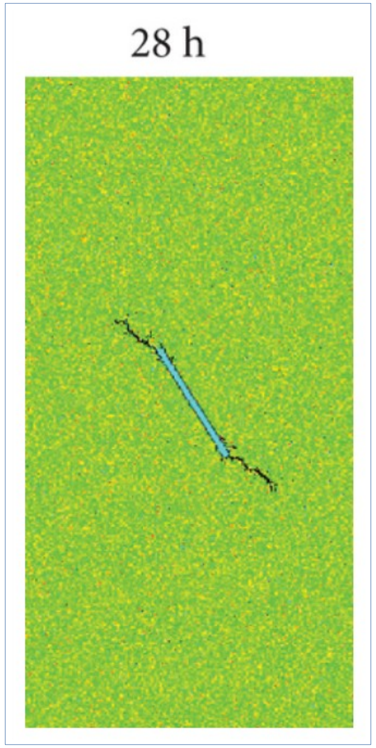
The action of frost on rock



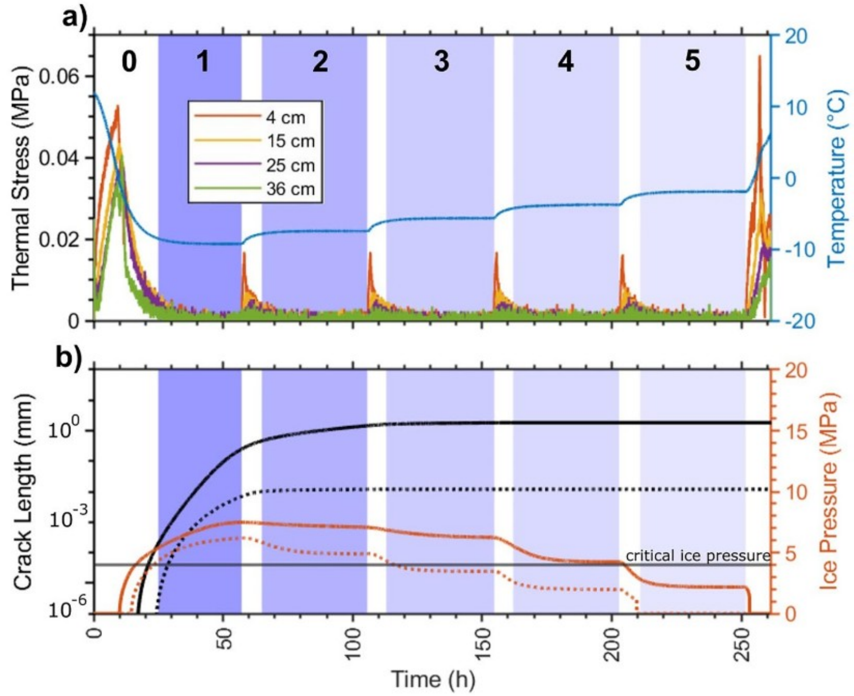

Arctic and Alpine Research, Vol. 18, No. 1, 1986, pp. 27–32

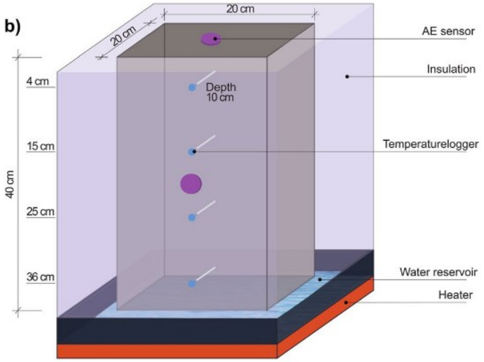
THE PHYSICAL BASIS OF FROST WEATHERING: TOWARD A MORE FUNDAMENTAL AND UNIFIED PERSPECTIVE

JOSEPH S. WALDER AND BERNARD HALLET
Quaternary Research Center and Department of Geological Sciences
University of Washington, Seattle, Washington 98195, U.S.A.

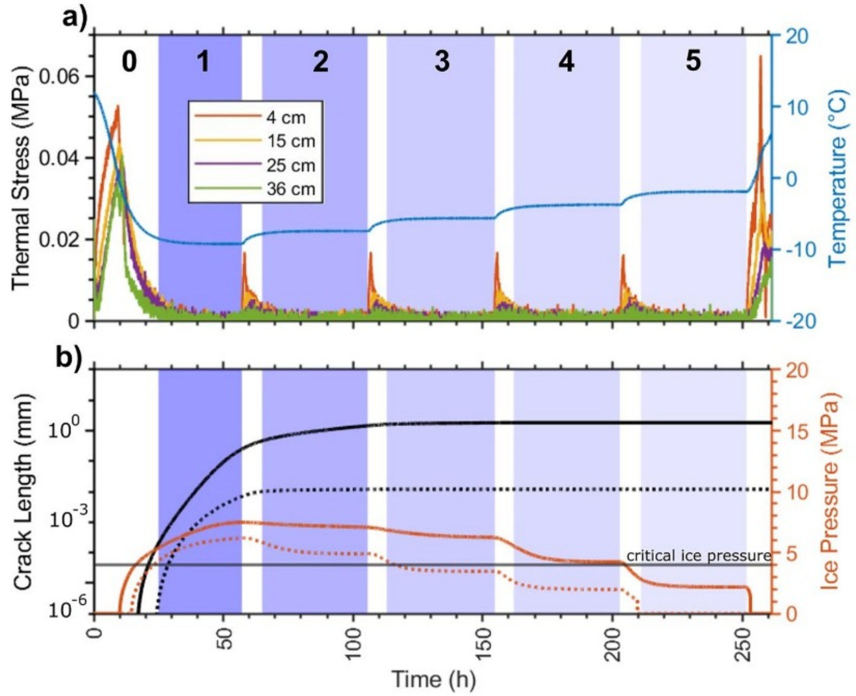


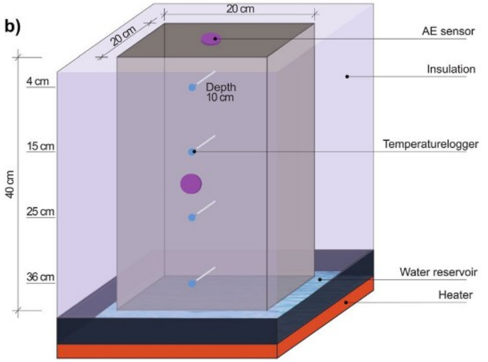
The action of frost on rock





The action of frost on rock

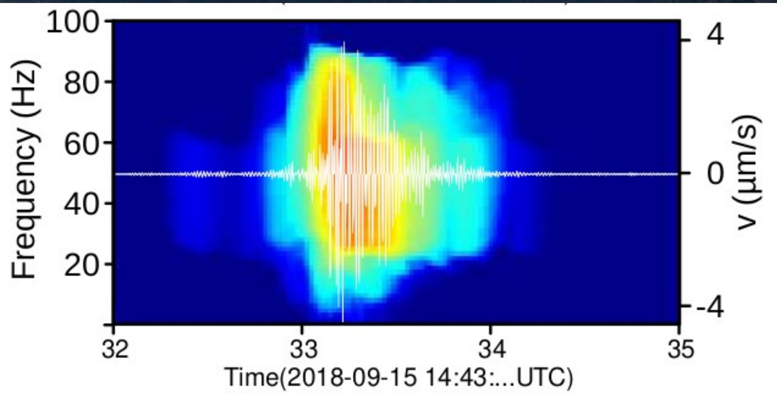




What
Where
When
(Why)

But: no model

Or the other way around: the reaction of rock to stress

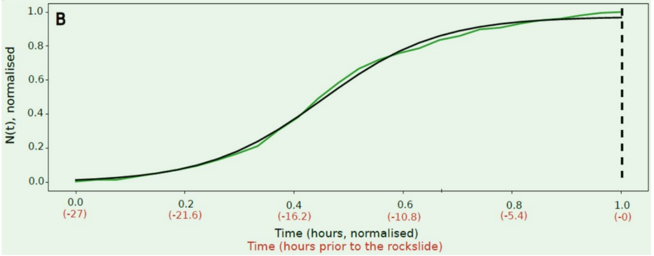


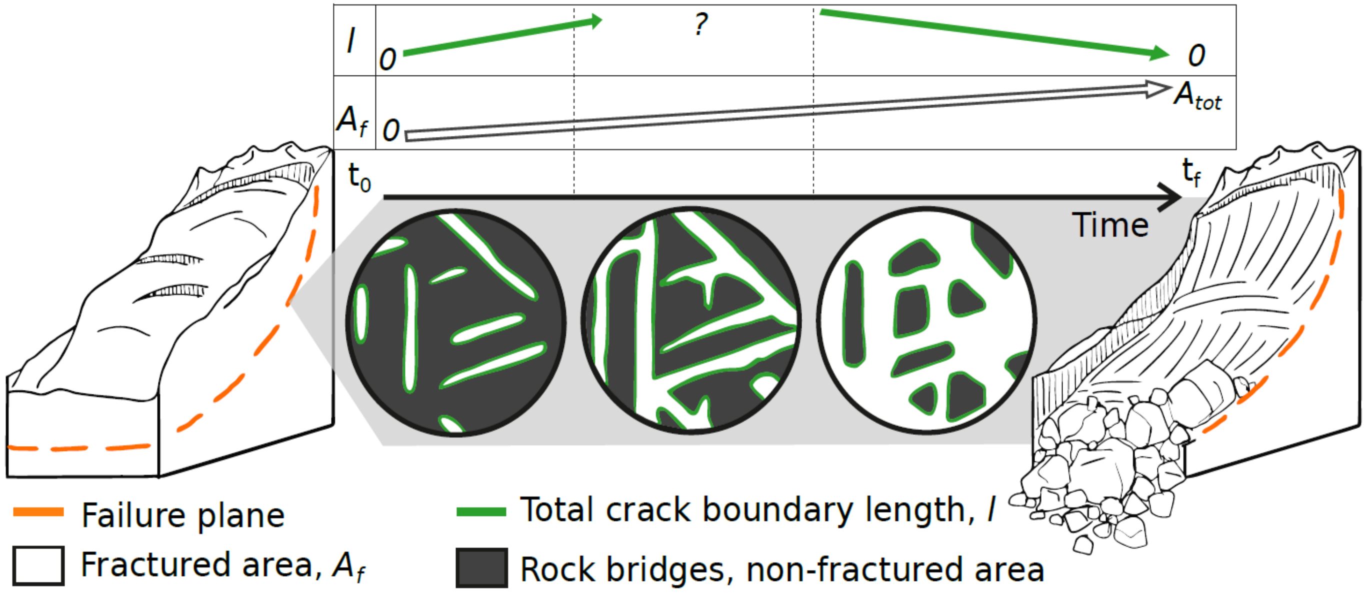
What
Where
When
(Why)

But: no model

Or the other way around: the reaction of rock to stress

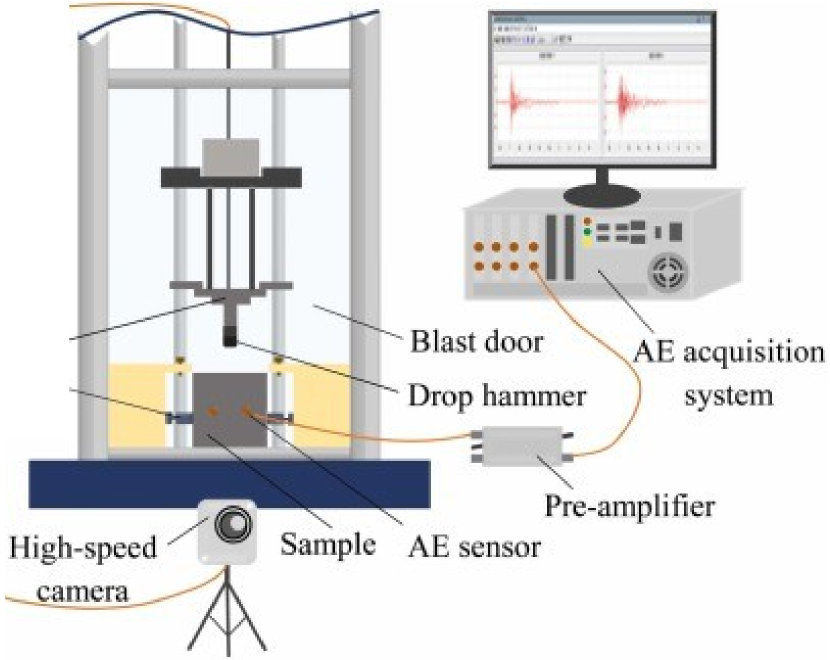
$$N(t) \quad \frac{A_{tot}}{1+\exp\left(\frac{-t}{\tau}+b\right)}$$

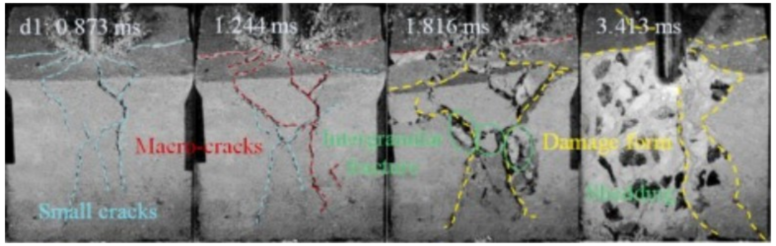




What
Where
When
Why

But: no model





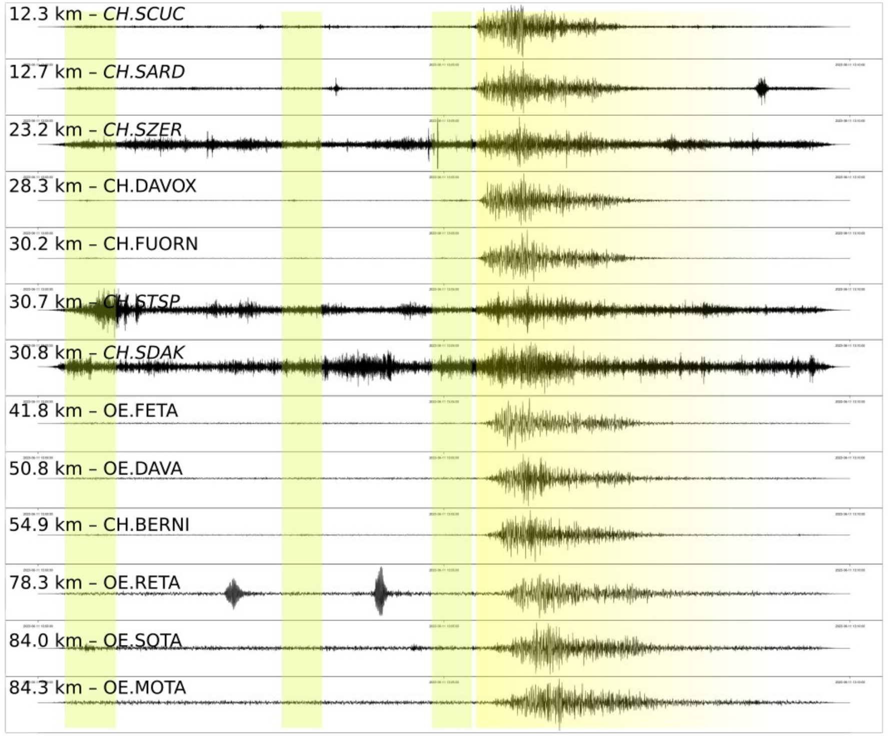
The action of gravity... Example A: large volume mass wasting events

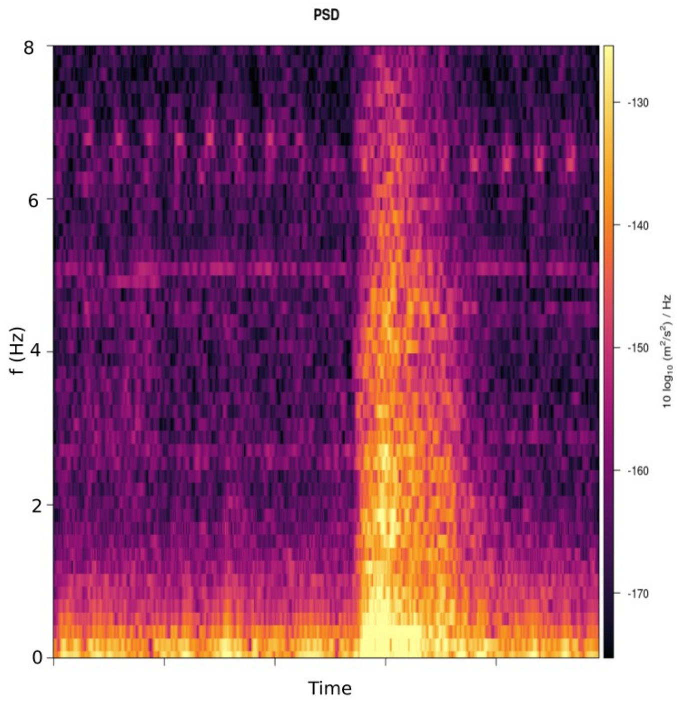
11.06.23
15:05:17
144 s
10^6 m³ rock

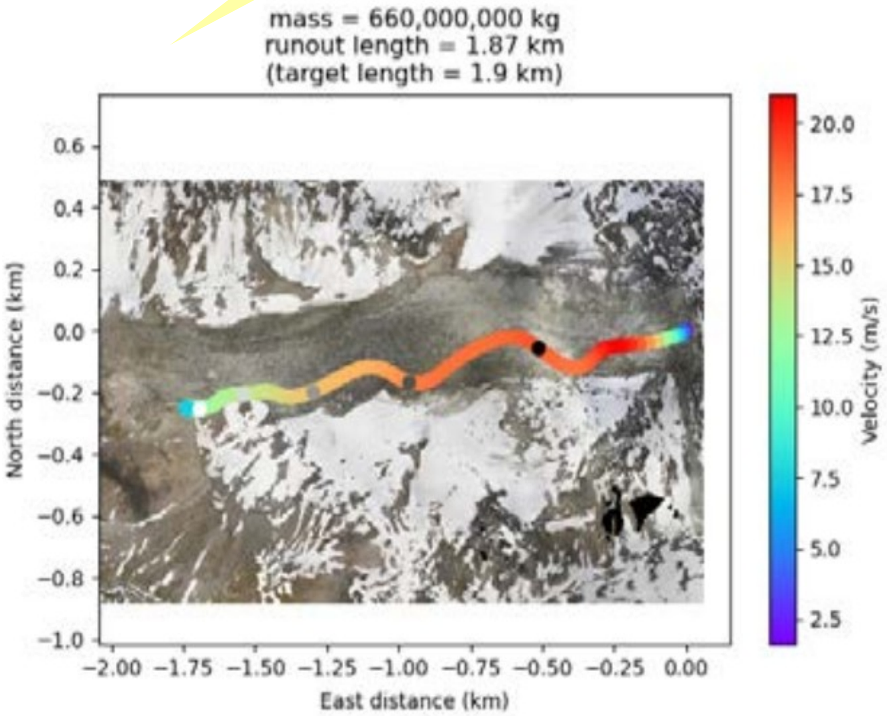
www.meinbezirk.at/landeck/c-lokales/

The action of gravity… Example A: large volume mass wasting events

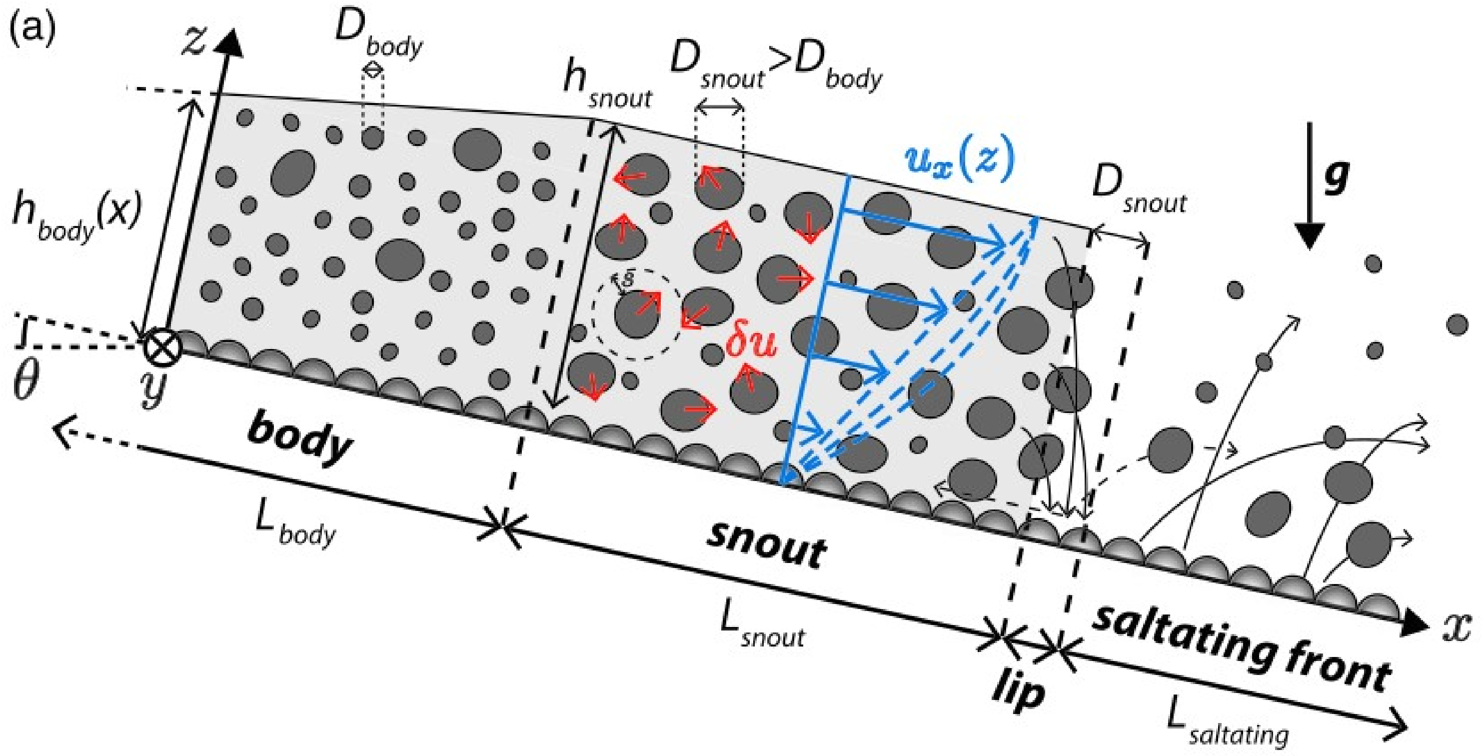
Time-force vector, i.e.:
- How much mass
- Along which trajectory
- With which velocity

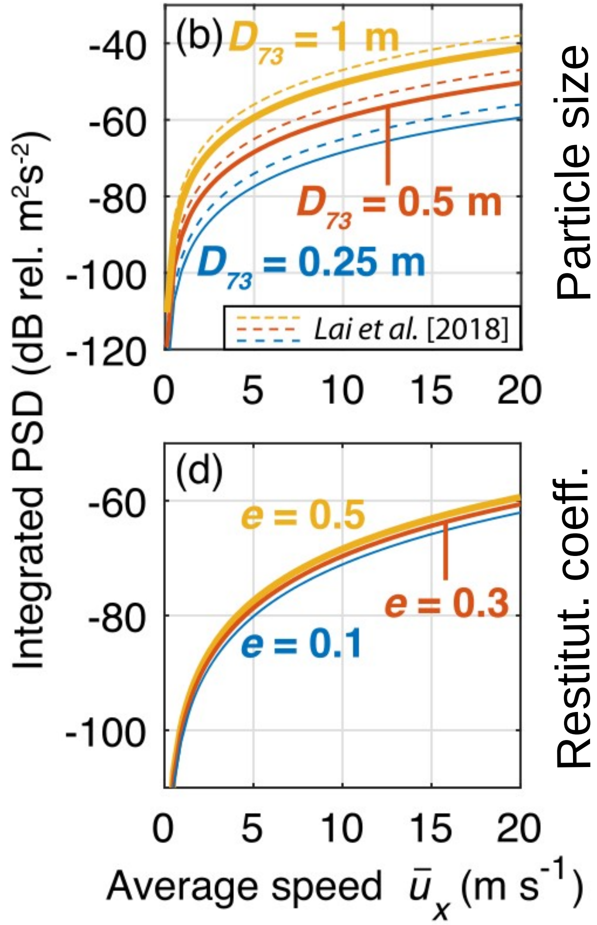






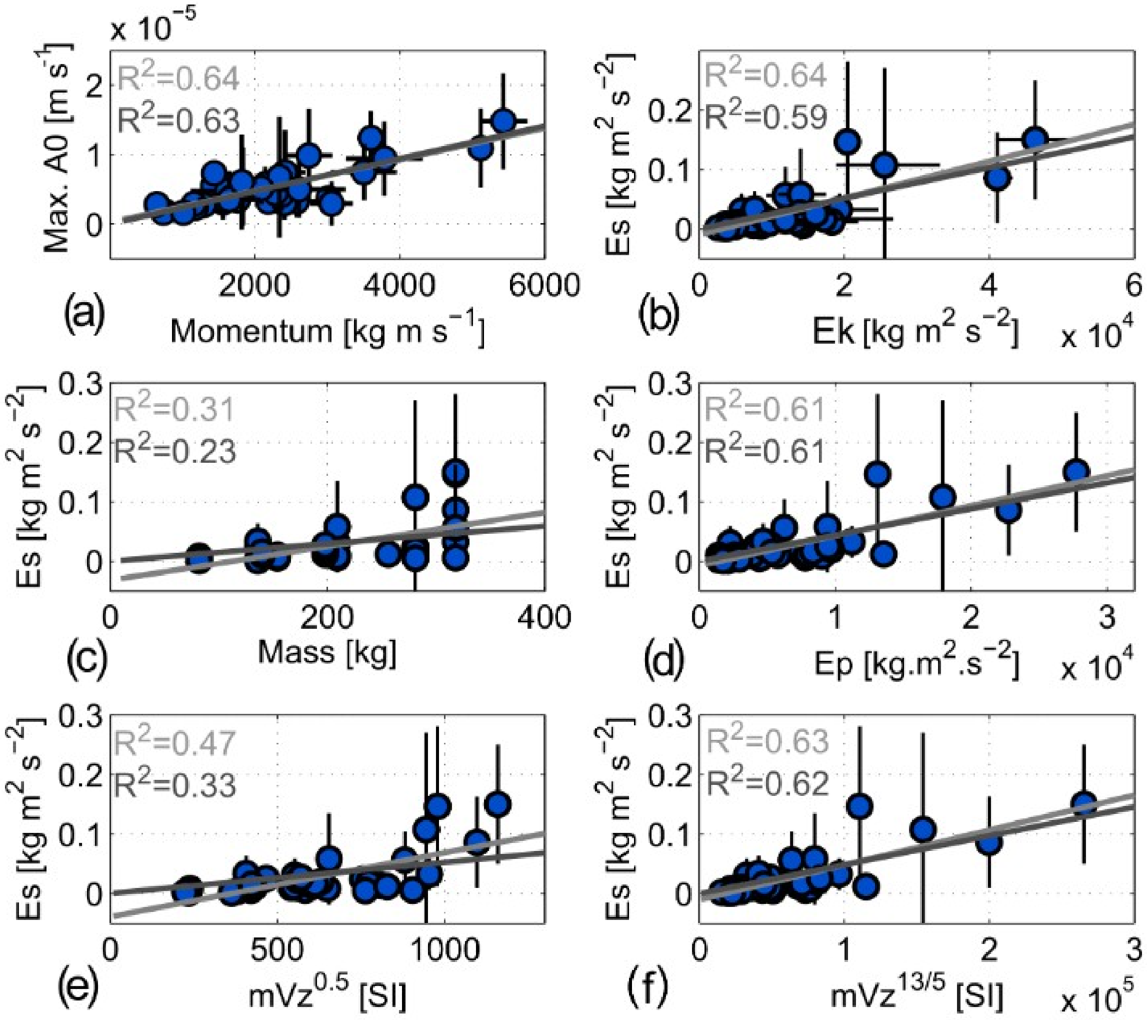
The action of gravity… Example B: debris flow-like granular systems



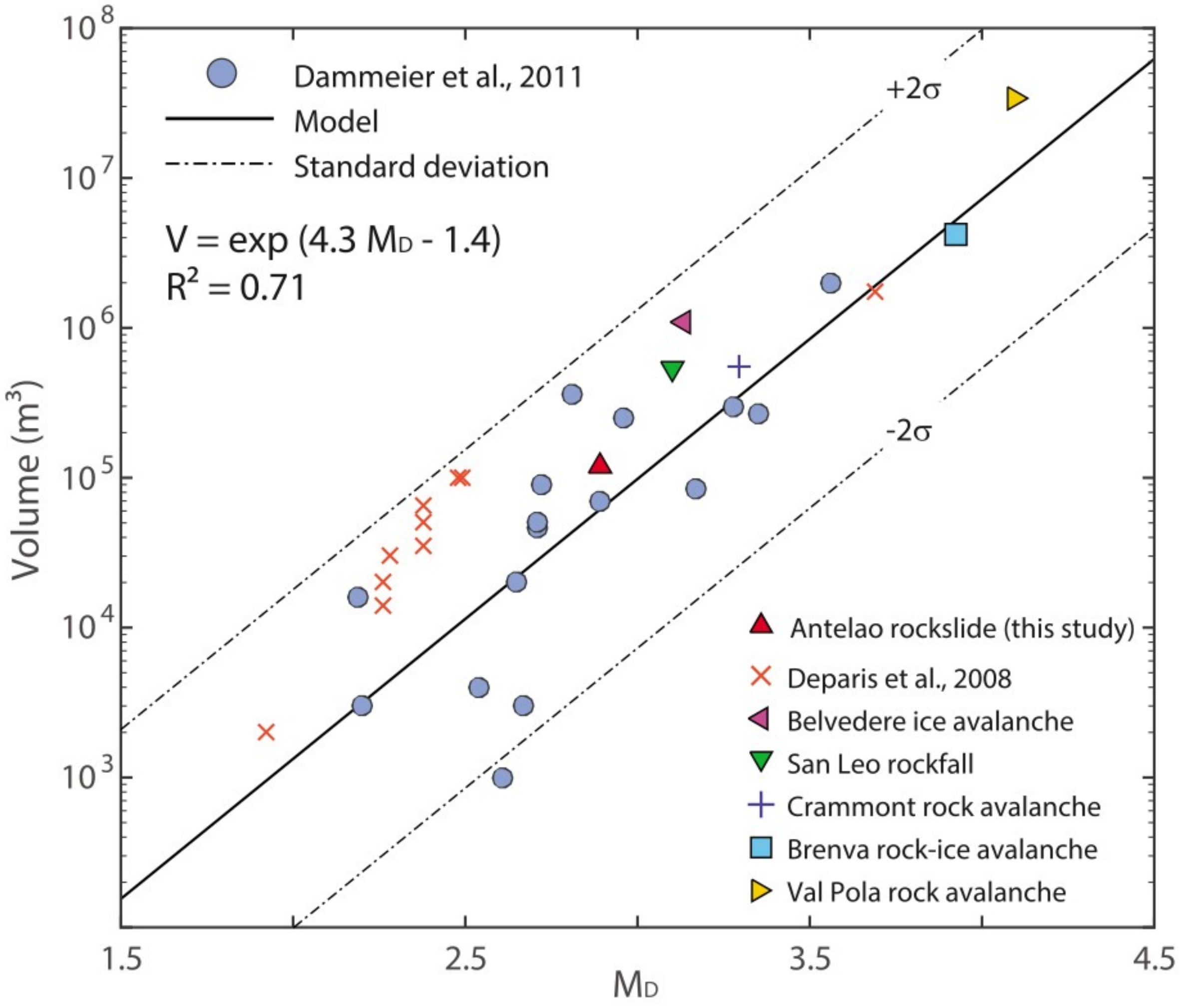


$$PSD(f, r_0, t, D) = R_{impact} W \frac{\pi^2 (1+e_b)^2 m^2 \bar{u}_x^2 f^3}{4 \rho_0^2 v_c^3 v_u^2} N_{jz}^2 f_j^2 \chi(r_0, f).$$

The action of gravity... Processes in between



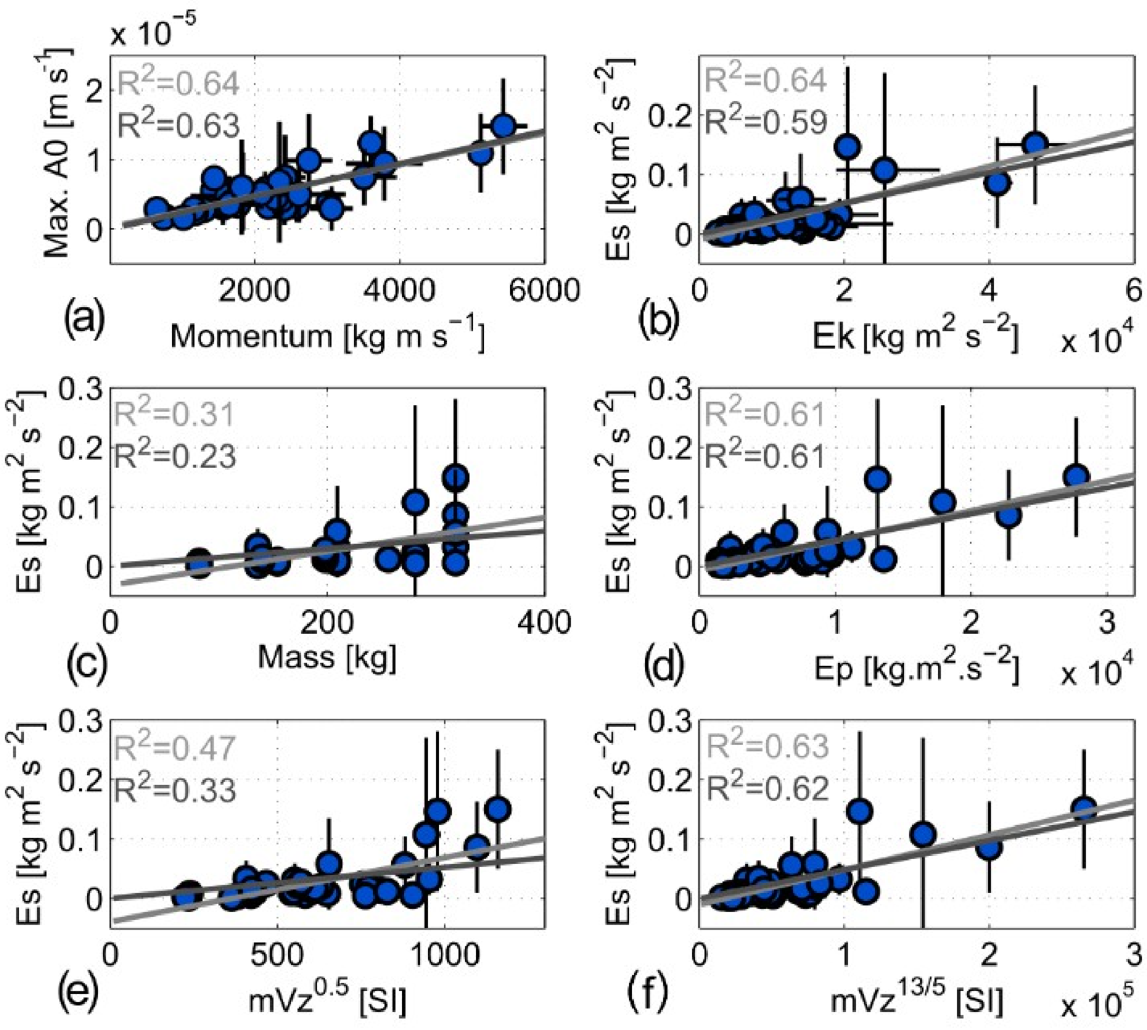
Hibert et al. (2017, ESurf)

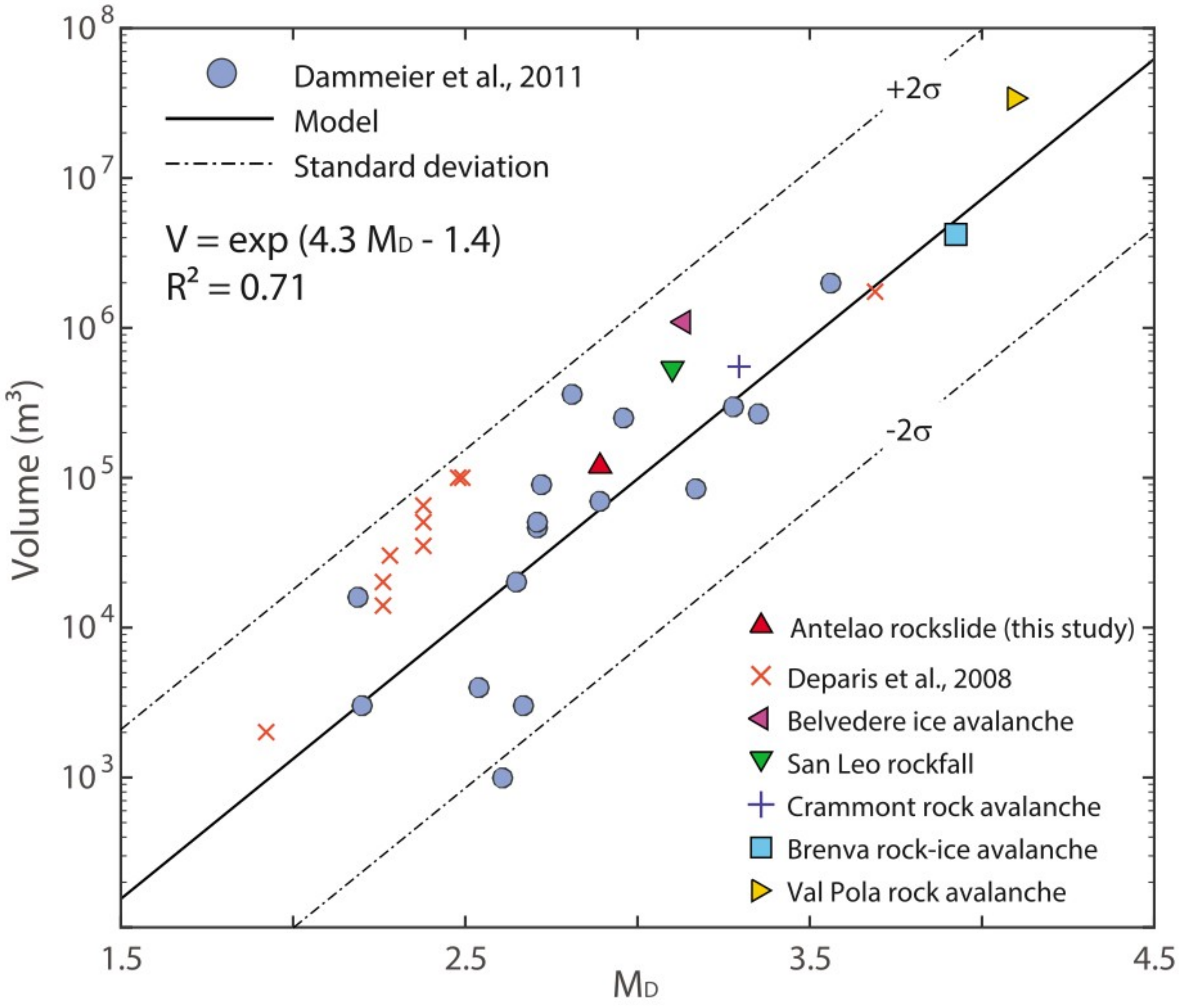


Manconi et al. (2016, GRL)

The action of gravity… Processes in between

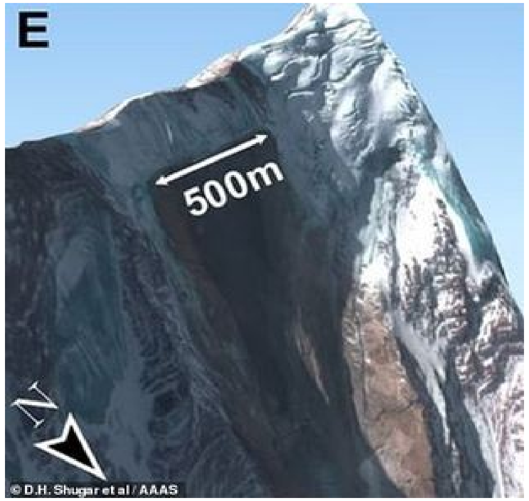
"Only" correlative understanding

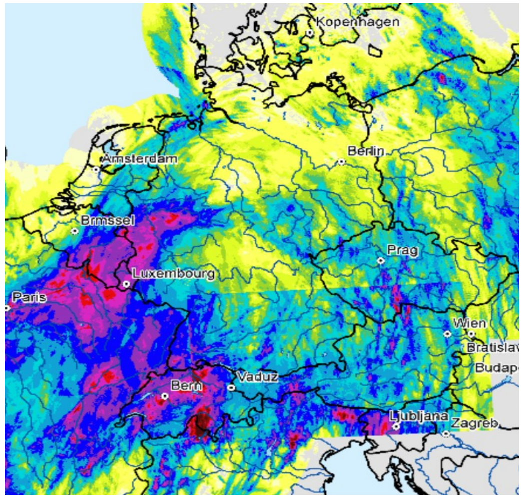




The consequences of flowing water (2021)

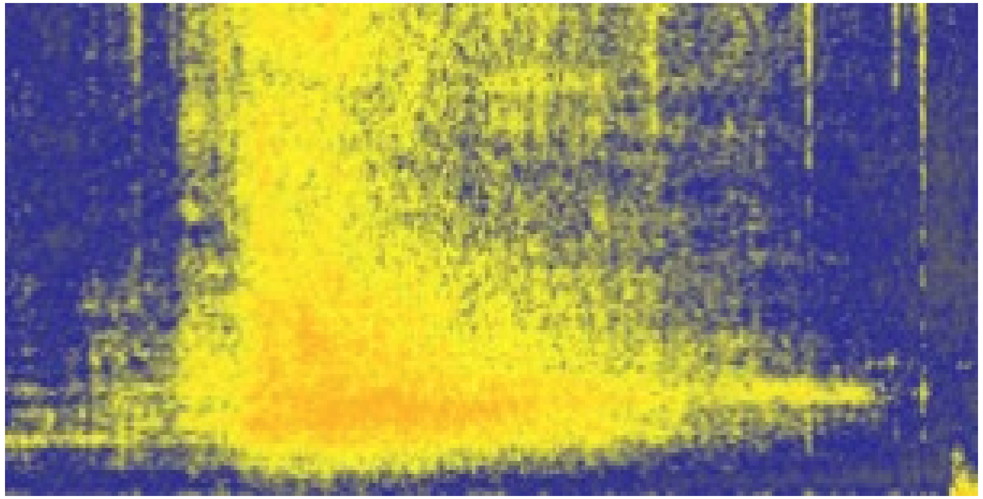
The causes

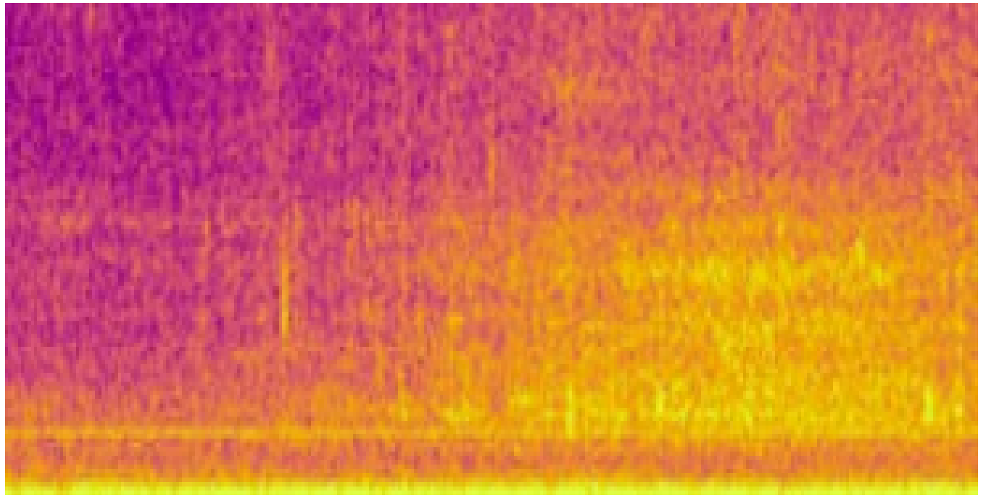




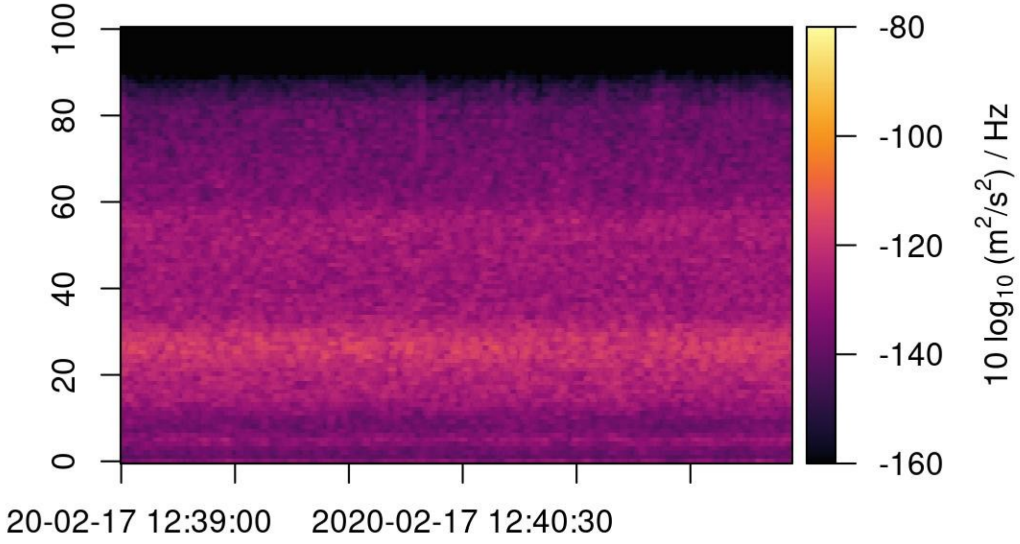
The consequences

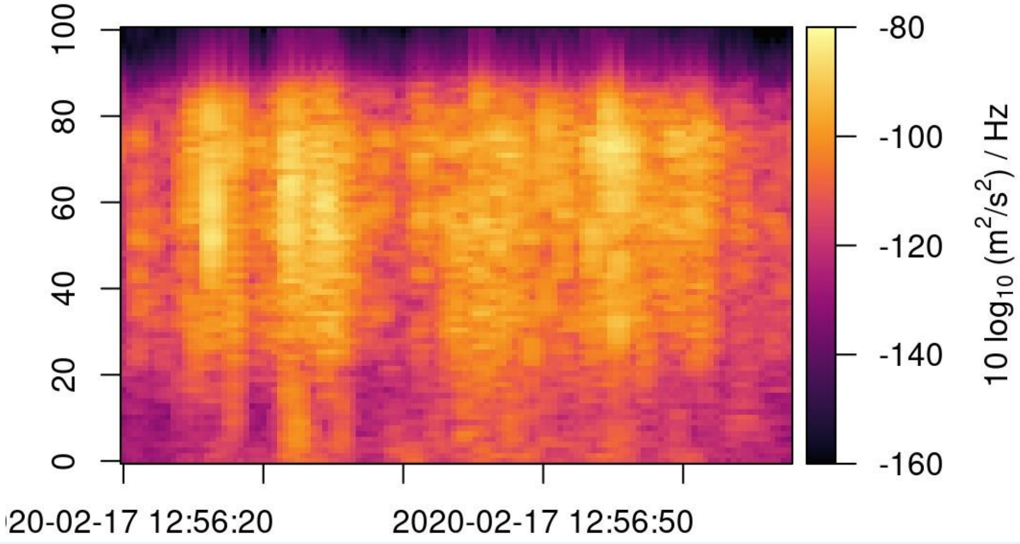
The seismic imprints (0.5–10 Hz, 2 vs. 1 h duration)





Water moving sediment, probing the hidden dynamics





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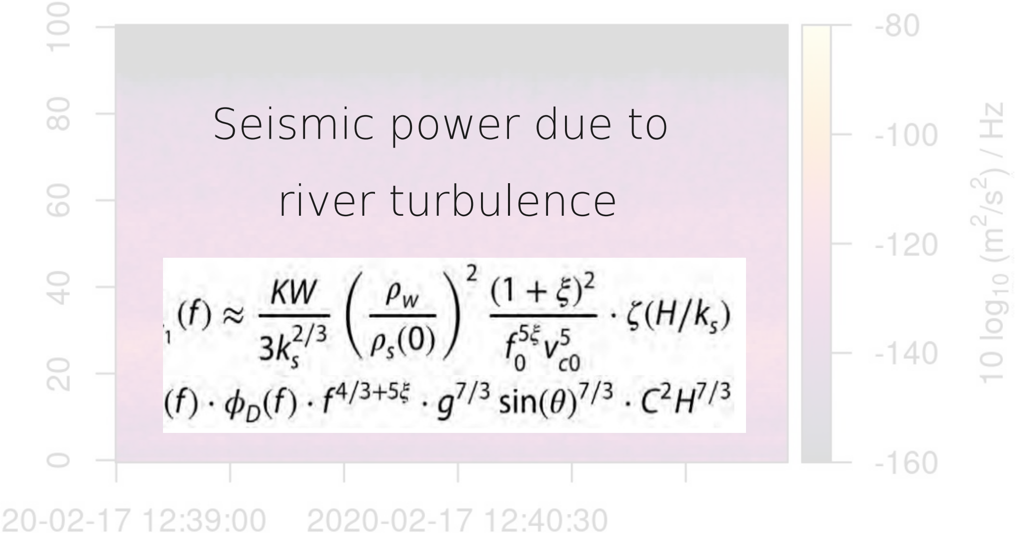
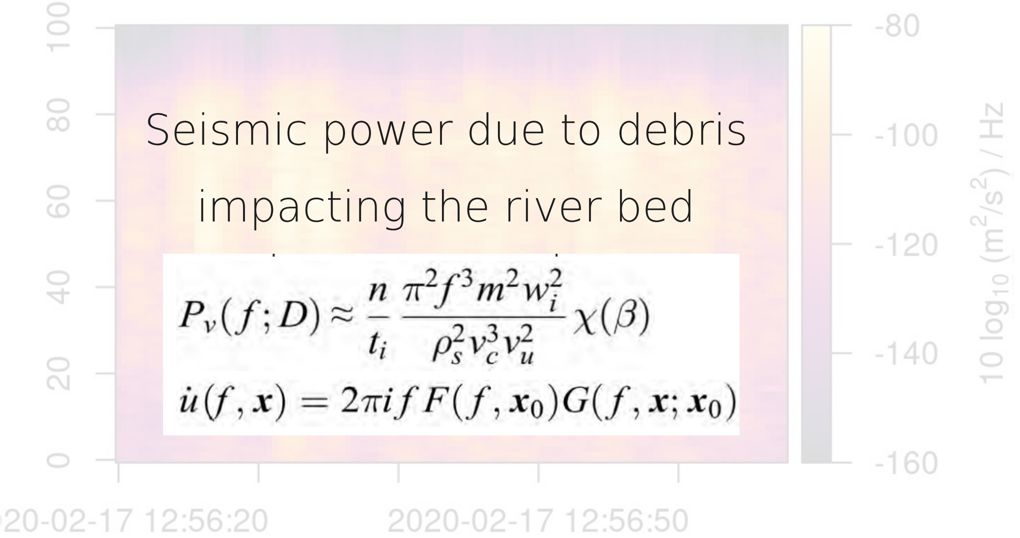


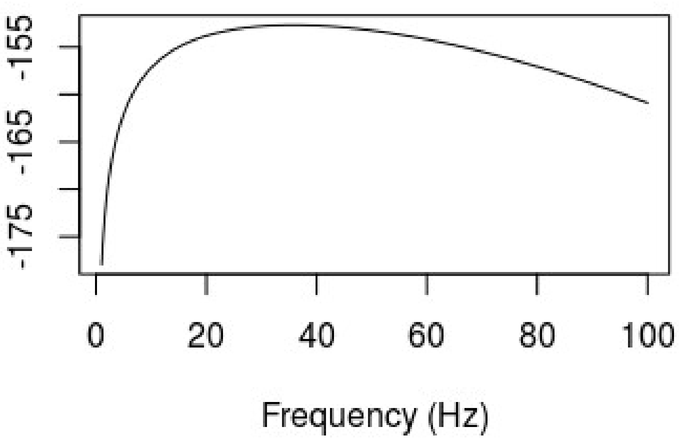


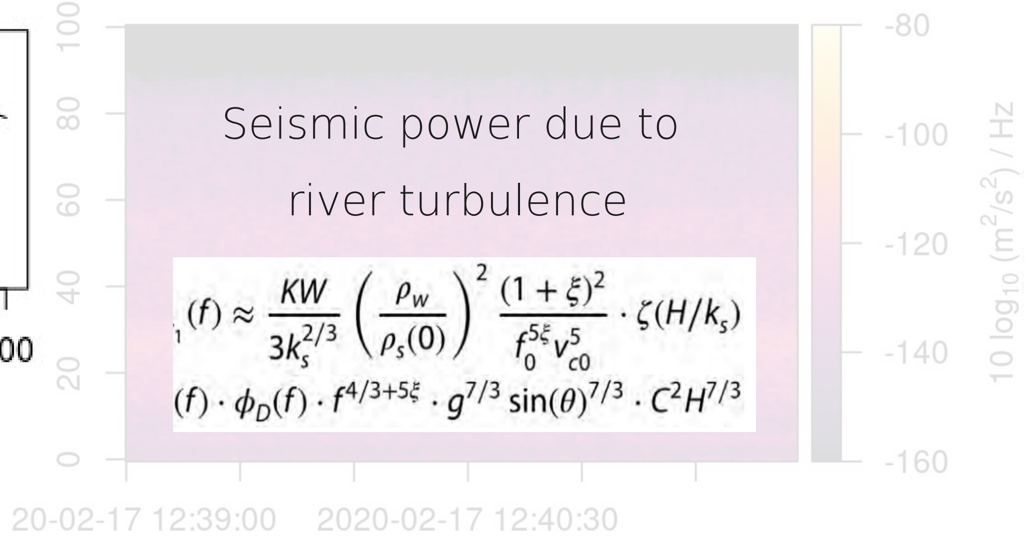
Matthews et al. (2022, EGU Sphere)

Gimbert et al. (2014) Tsai et al. (2012)

Water moving sediment, probing the hidden dynamics

```
model_turbulence(d_s = 0.03,
                 s_s = 1.35,
                 r_s = 2650,
                 h_w = 0.8,
                 w_w = 40,
                 a_w = 0.0075,
                 f = c(1, 100),
                 r_0 = 10,
                 f_0 = 1,
                 q_0 = 10,
                 v_0 = 2175,
                 p_0 = 0.48,
                 n_0 = c(0.6, 0.8))
```



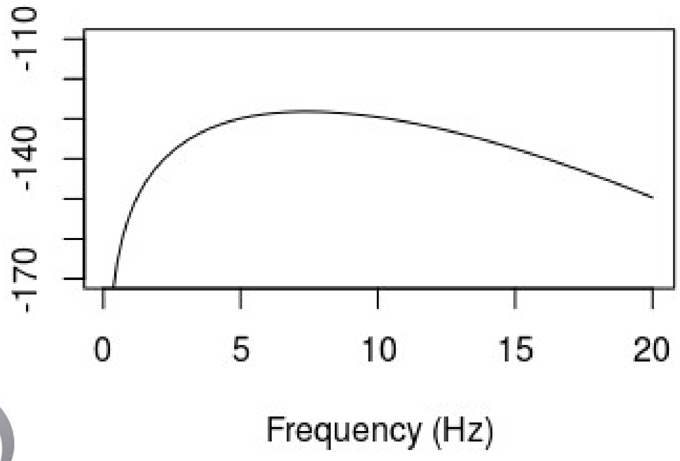


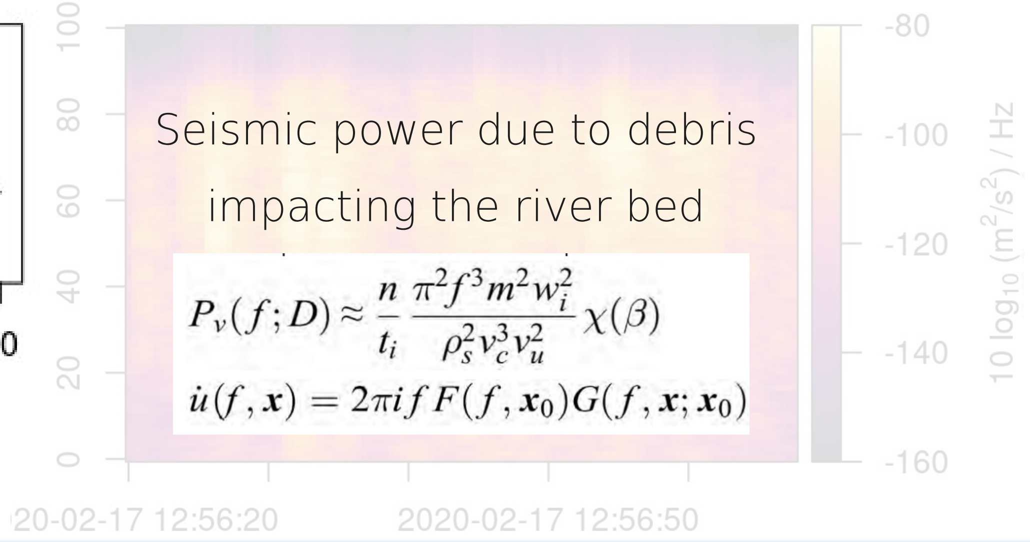
Seismic power due to river turbulence

$$_1(f) \approx \frac{KW}{3k_s^{2/3}} \left(\frac{\rho_w}{\rho_s(0)}\right)^2 \frac{(1+\xi)^2}{f_0^{5\xi} v_{c0}^5} \cdot \zeta(H/k_s)$$

$$(f) \cdot \phi_D(f) \cdot f^{4/3+5\xi} \cdot g^{7/3} \sin(\theta)^{7/3} \cdot C^2 H^{7/3}$$

```
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, 20),
              r_0 = 600,
              f_0 = 1,
              q_0 = 20,
              e_0 = 0,
              v_0 = 1295)
```



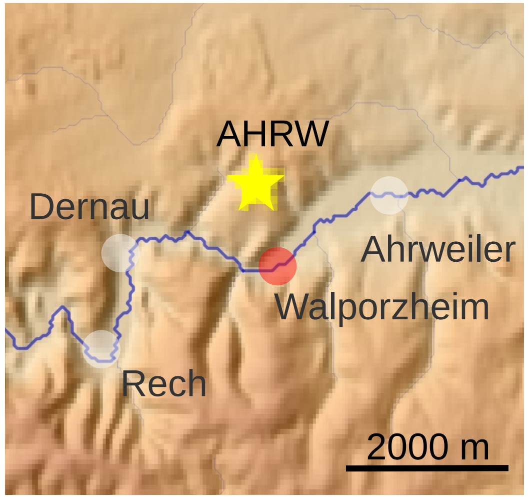


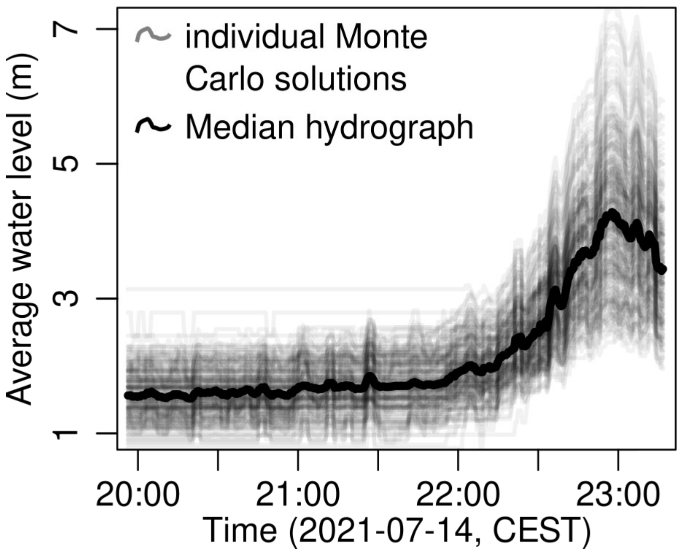
Seismic power due to debris impacting the river bed

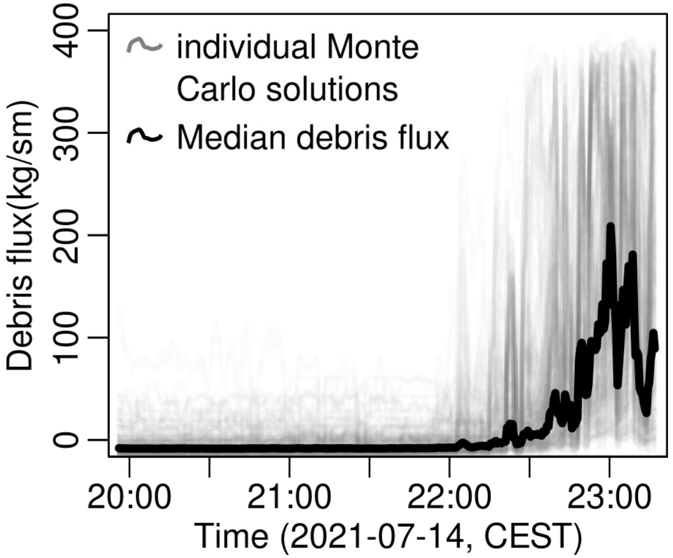
$$P_v(f; D) \approx \frac{n}{t_i} \frac{\pi^2 f^3 m^2 w_i^2}{\rho_s^2 v_c^3 v_u^2} \chi(\beta)$$

$$\dot{u}(f, \boldsymbol{x}) = 2\pi i f F(f, \boldsymbol{x}_0) G(f, \boldsymbol{x}; \boldsymbol{x}_0)$$

Water moving ~~sediment~~ debris, an example from the Ahr Valley (2021)







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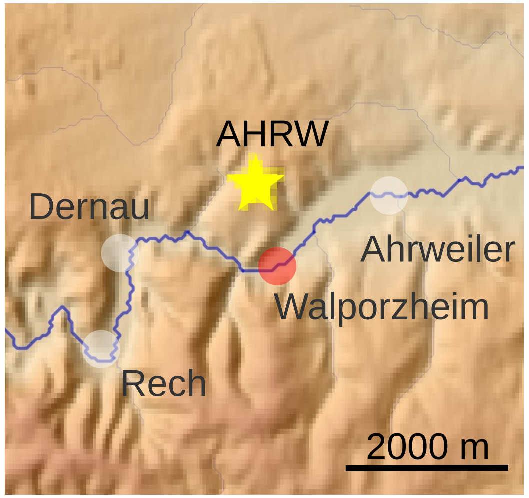
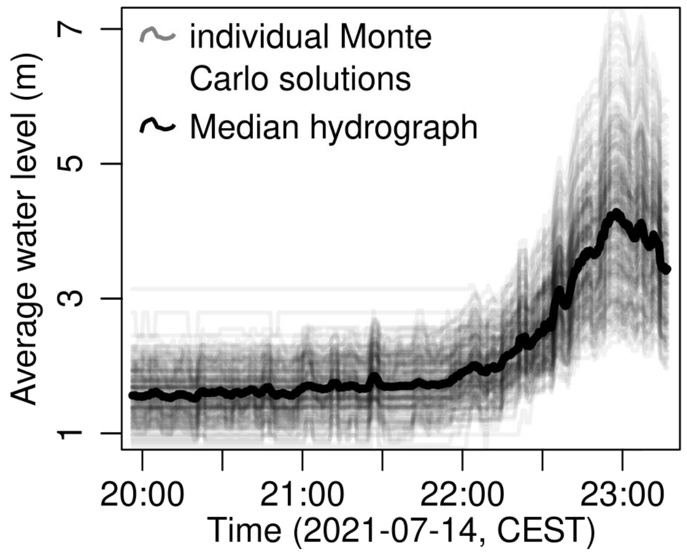
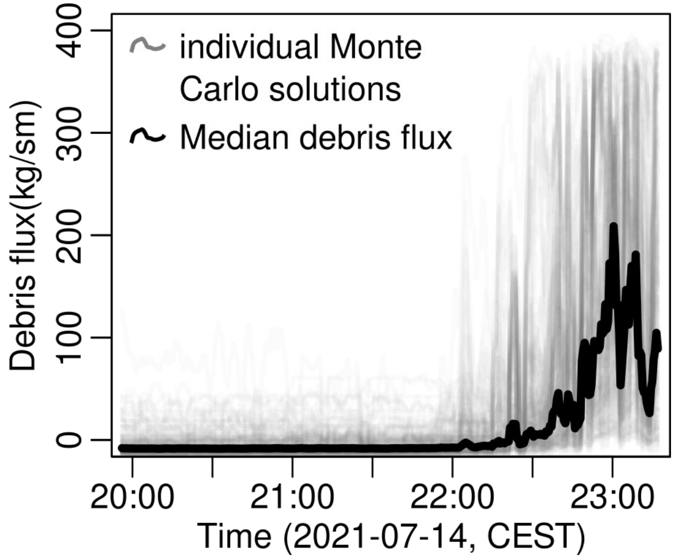
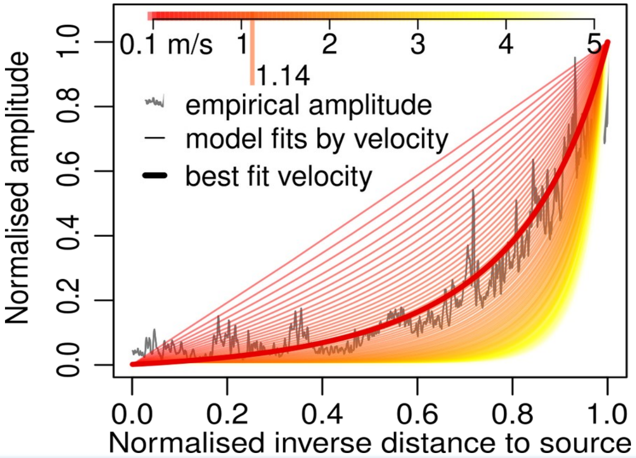








Seismic amplitude as function of distance

$$A_i(R) \approx \frac{S_{\text{flow}}}{\sqrt{R}} \times \exp\left(\frac{\pi f R}{Q_c V}\right)$$

All excellent and fine? Unsolved issues with the approach

Particles & obstacles

Process

Wave representation

Ground architecture

Shortcomings & Unknowns

1a) Models operate with *parametric* (unimodal) grain size distribution
1b) *Bed and mobile* fraction are treated Identical in models
1c) *Obstacles* change hydraulic geometry (Nativ et al., 2025)

2) *Modes of bedload transport* based on saltation, only (n.b. Gimbert et al. (2018) modify towards other processes to some extent)

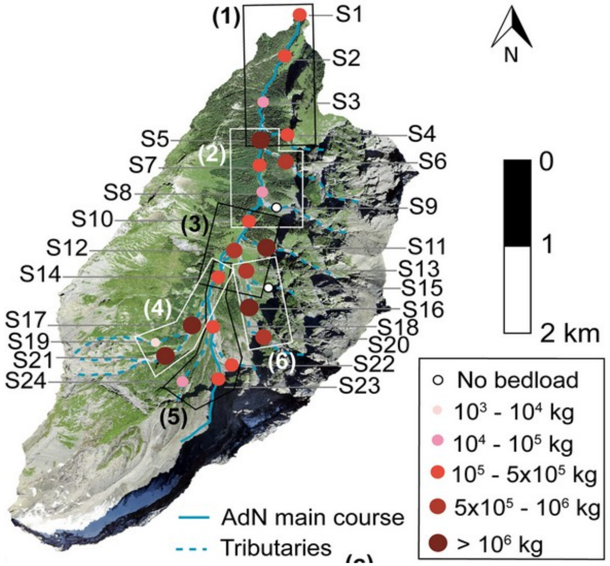
3) Depth-dependent attenuation of Rayleigh wave *particle motion* not not accounted for (see rain model)

4) Very simplistic, time-invariant ground property representation (*Greens function*)

Why carrying on?

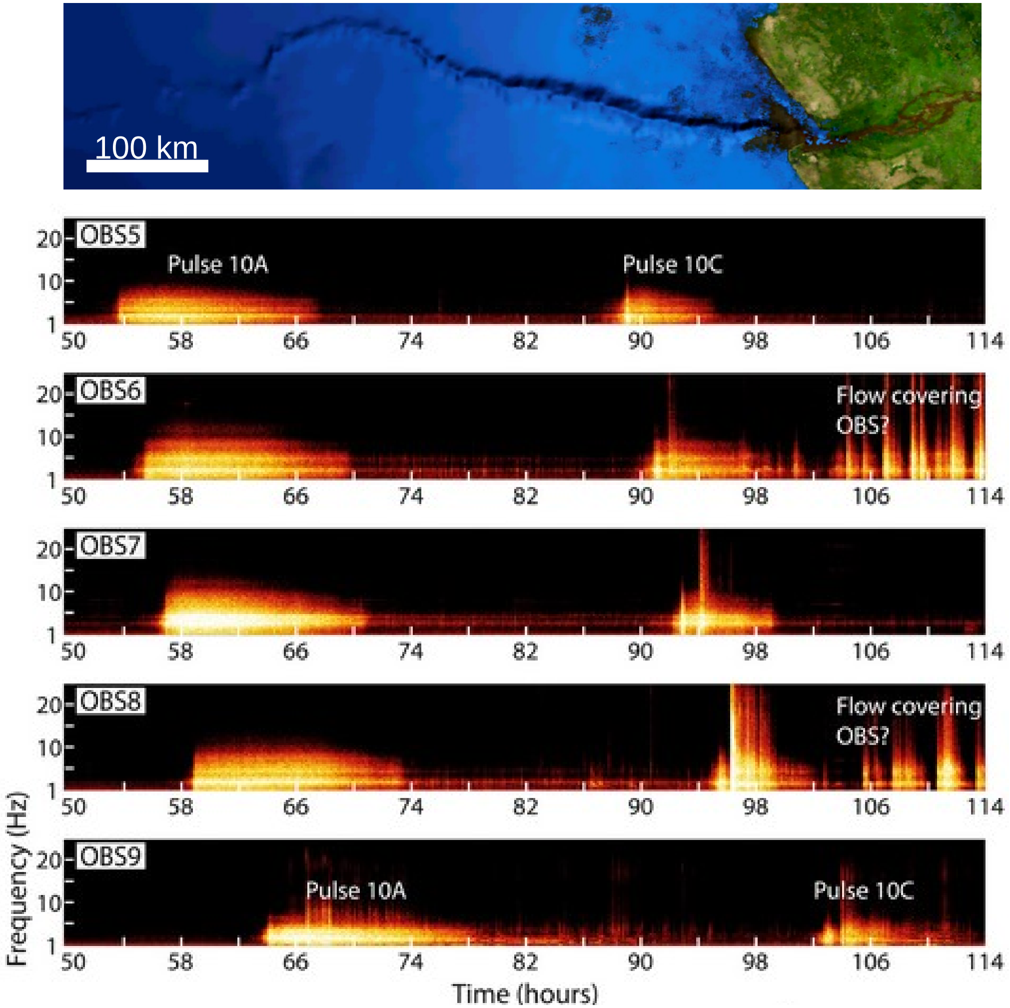
Look below ice & at episodic events

Catchment-wide process propagation

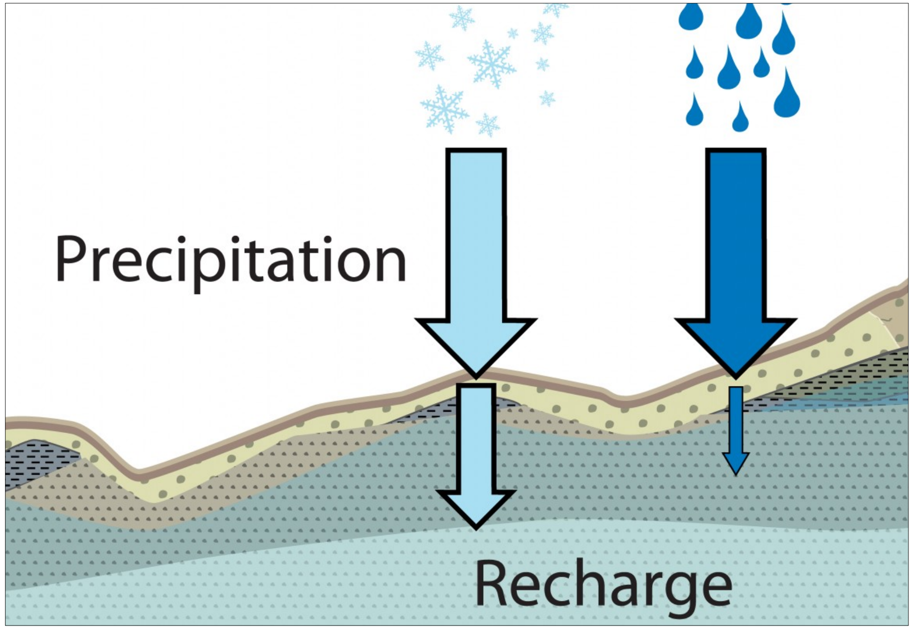


Quantify biogeomorphic effects

Beyond-continent fluxes of mass & carbon



Water below our feet



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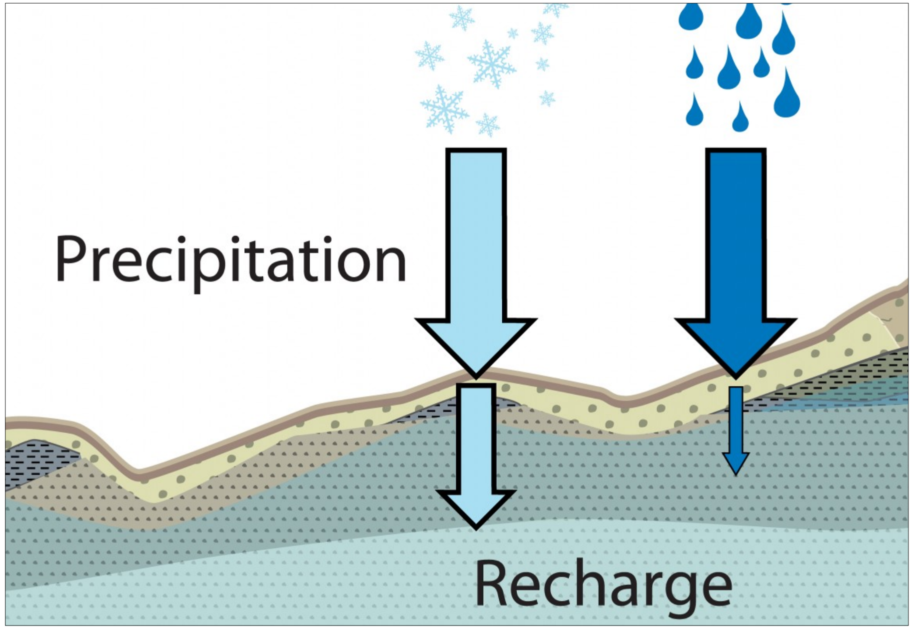
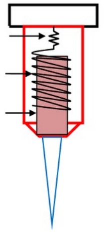
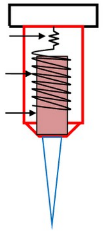
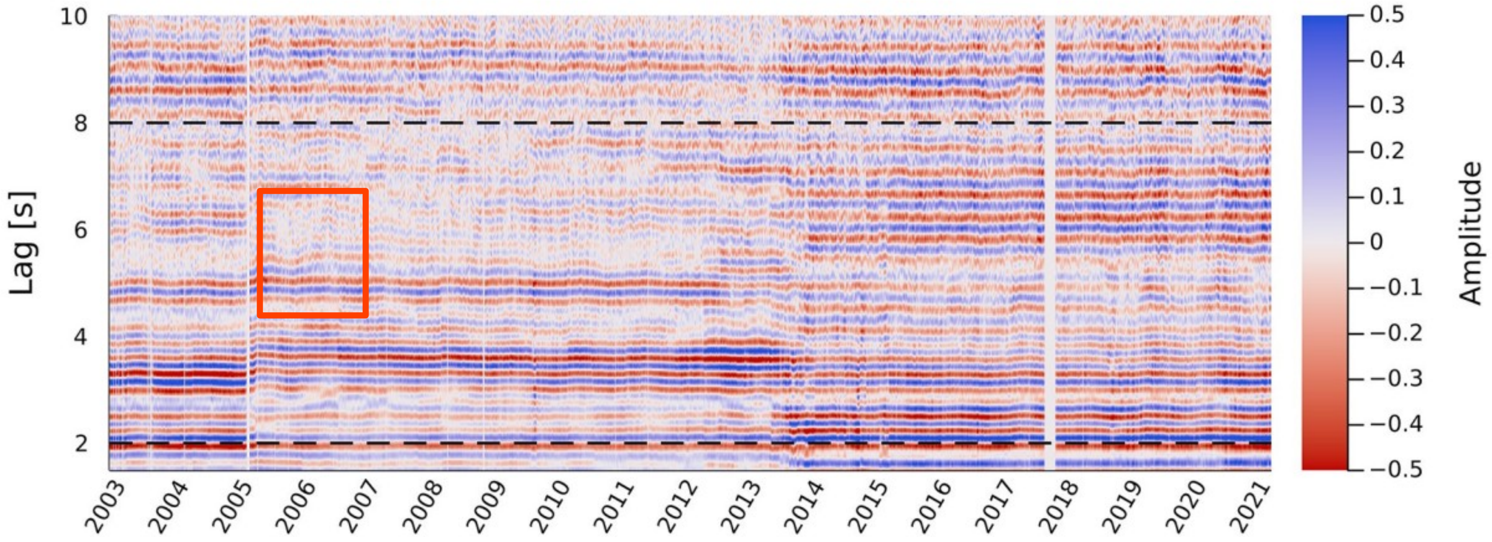
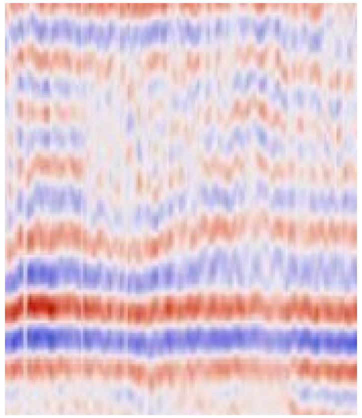
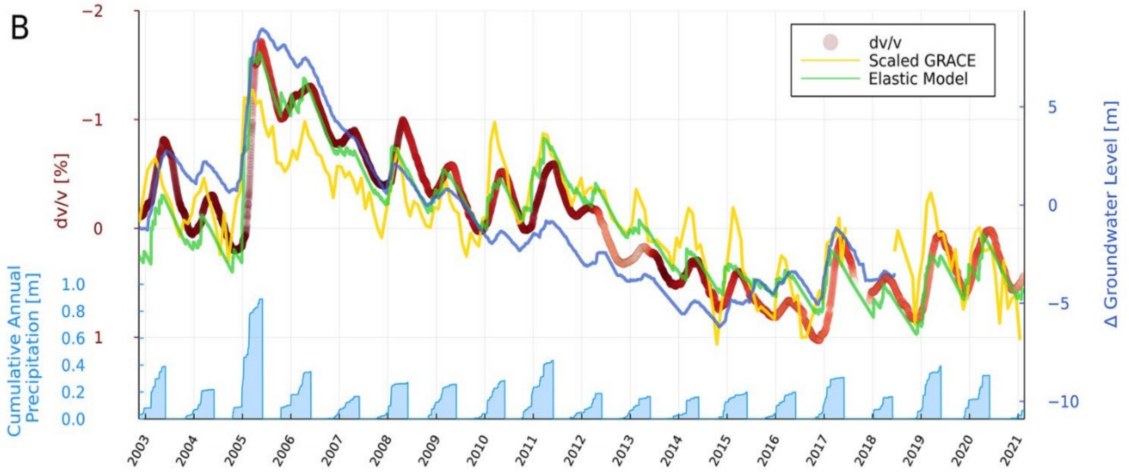




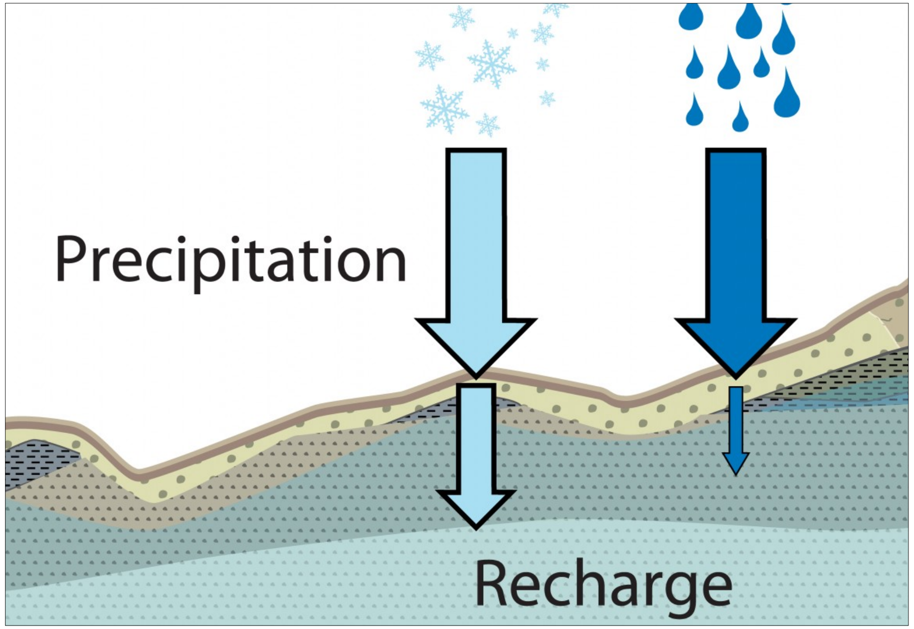








Water below our feet

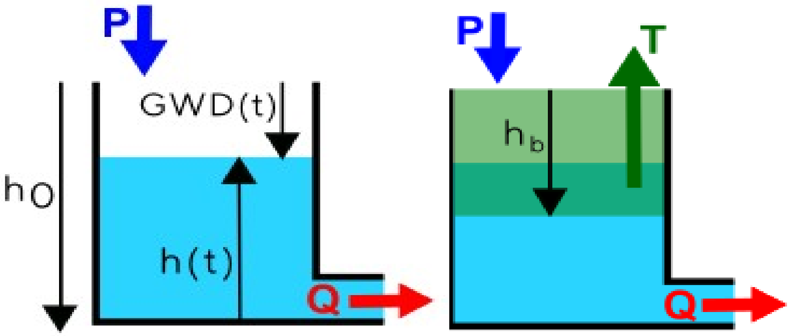


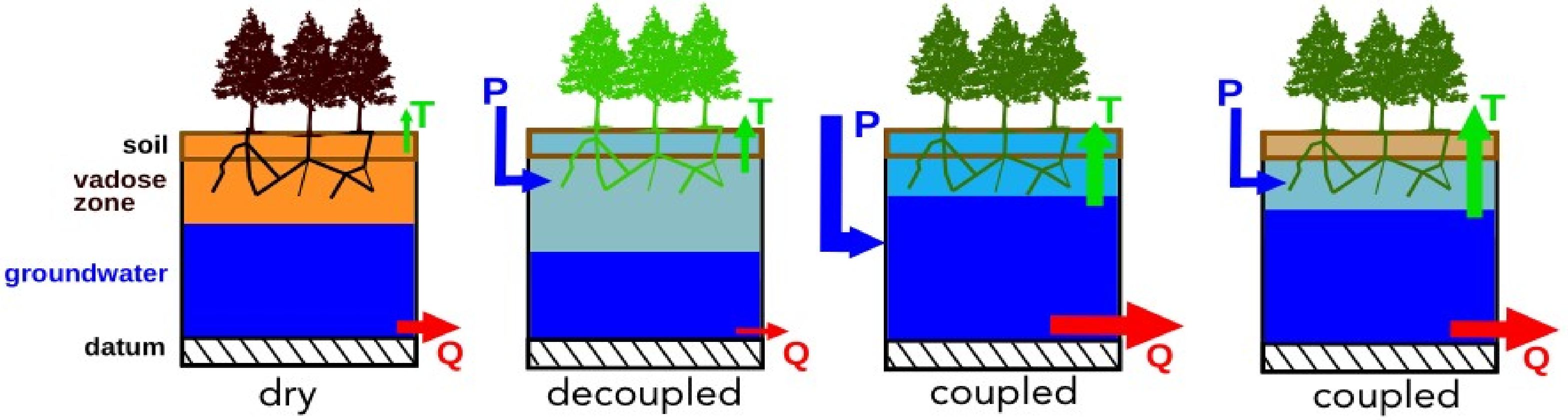
$$\Delta h(t) = \sum_{i=0}^{n} \frac{P_i}{\phi} e^{(-a(t-t_i))}$$ GW discharge

$$P(z,t) = \frac{B(1+\nu_u)}{3(1-\nu_u)}$$ Poroelastic load effect

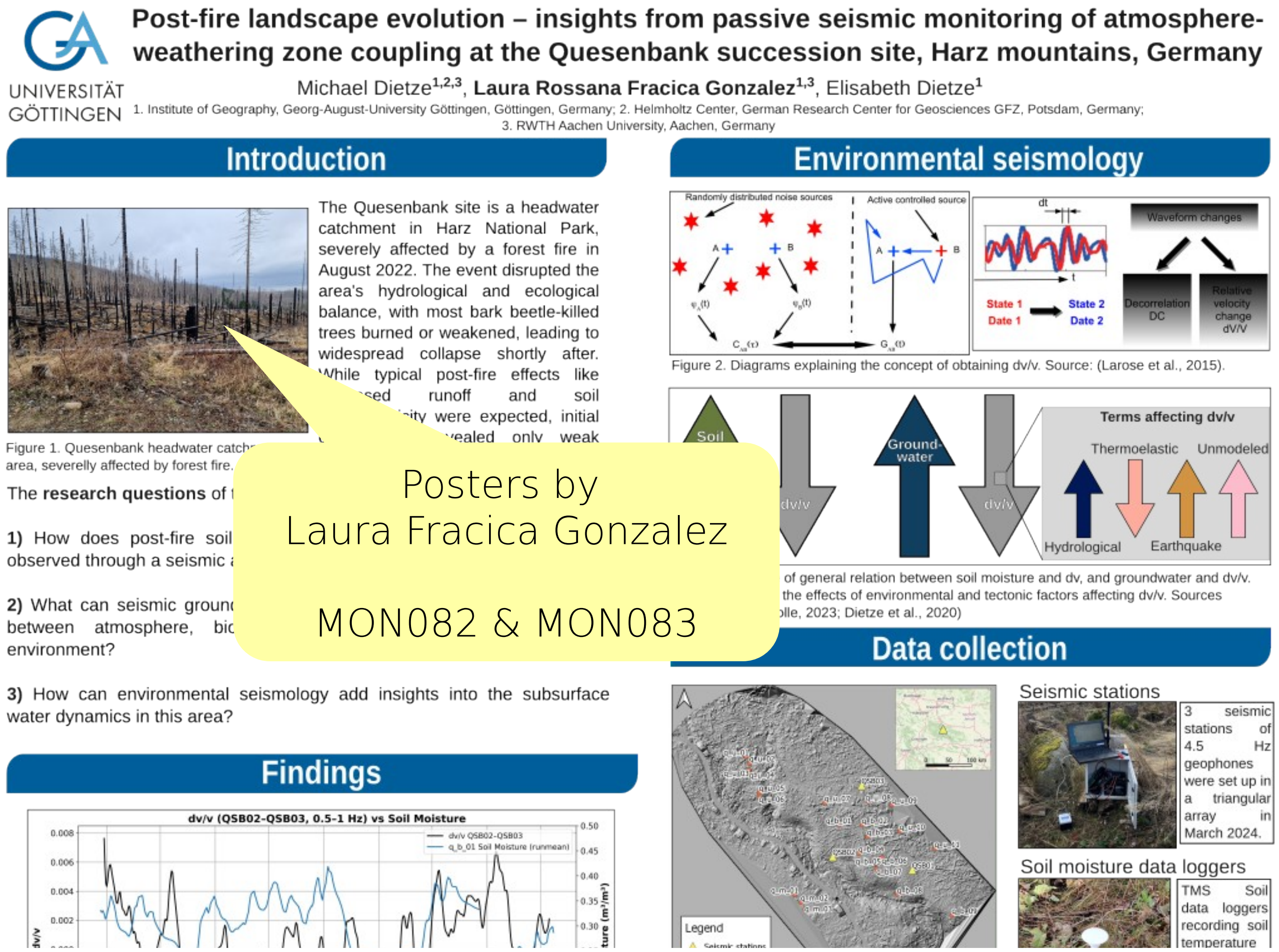
$$\sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} = 2G\epsilon_{ij}$$ Hydr. head & pore pressure

$$CDM_{ik} = \sum_{j=1}^{i} P_i - \bar{P}_{ik}$$ K days rain deficit reaction





Water below our feet … but not as deep as groundwater



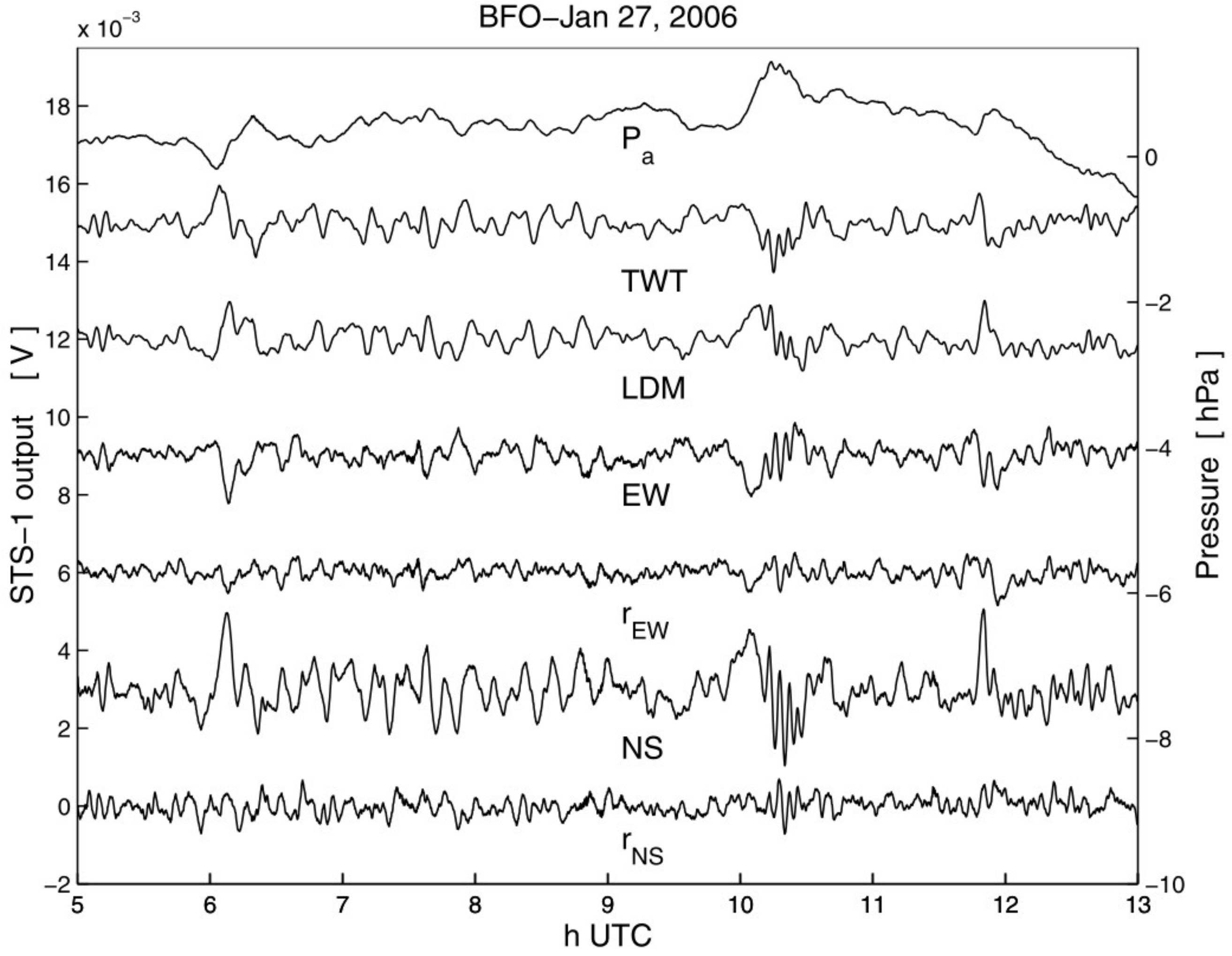
Posters by
Laura Fracica Gonzalez

MON082 & MON083

(What)
(Where)
When
(Why)

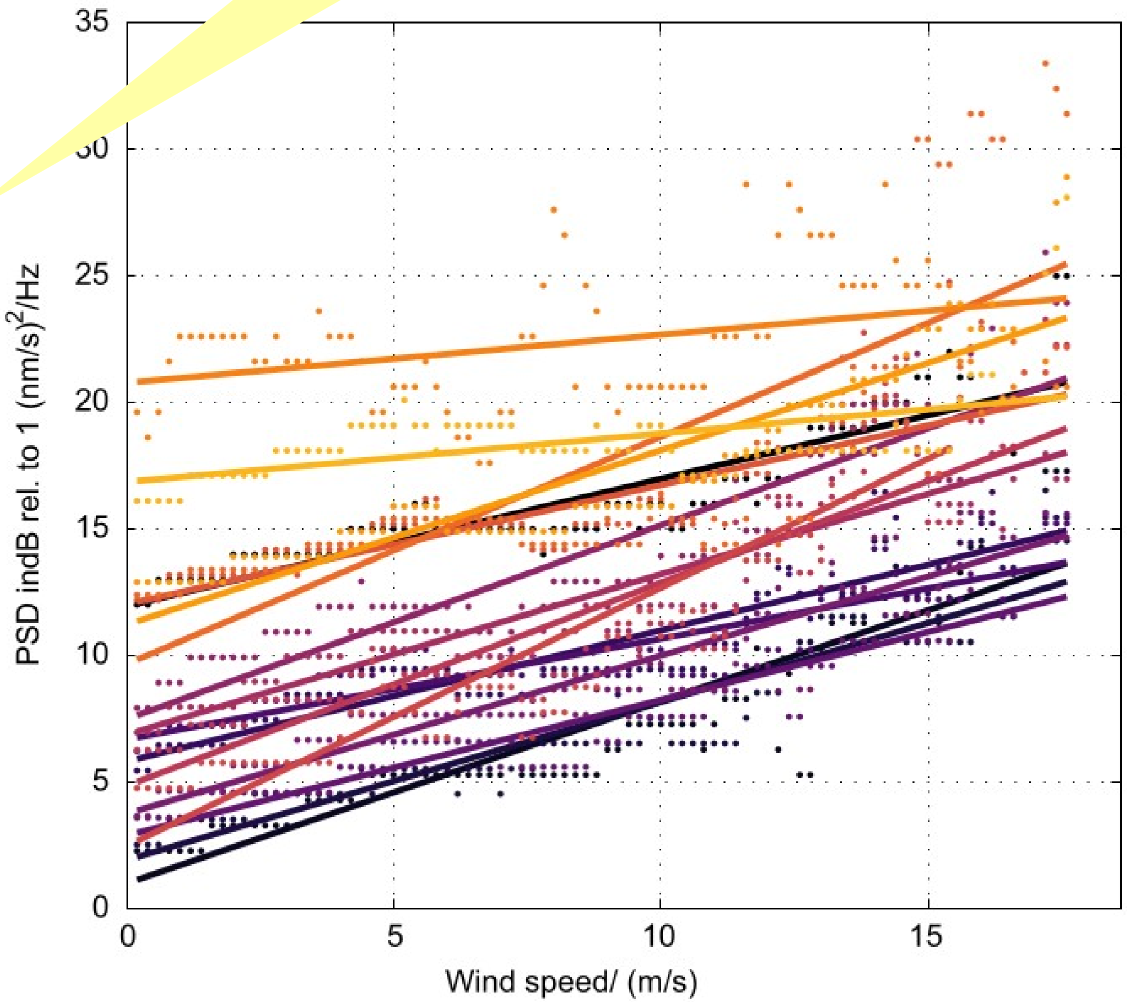
But: no model
And: simplified approaches

Air pressure systems … and wind effects



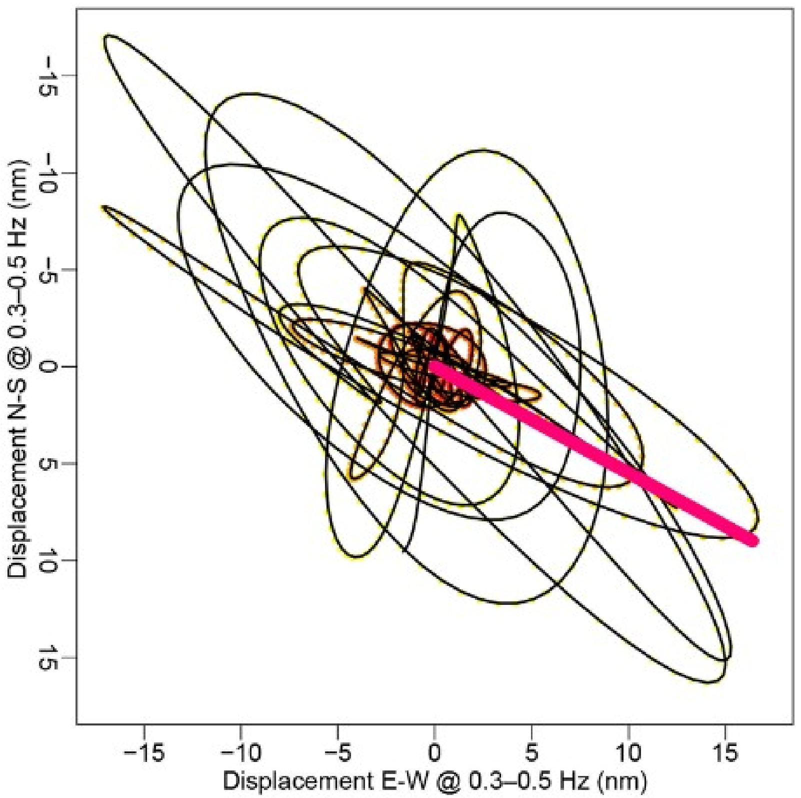
Zürn et al. (2007, GJI)

Get rid of the noise



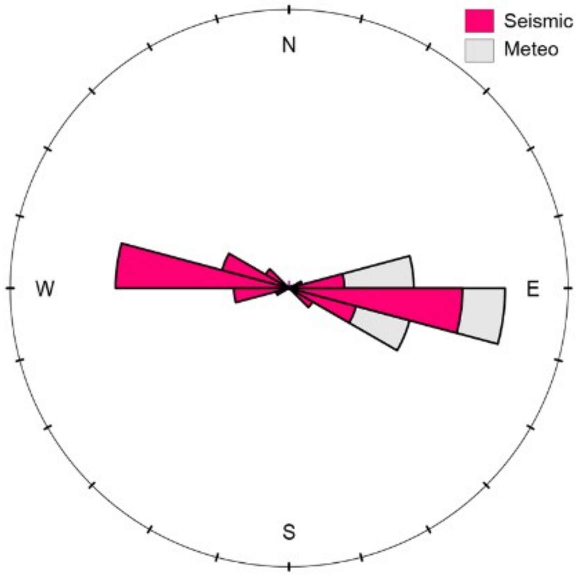
Lott et al. (2017, JApplPhys)

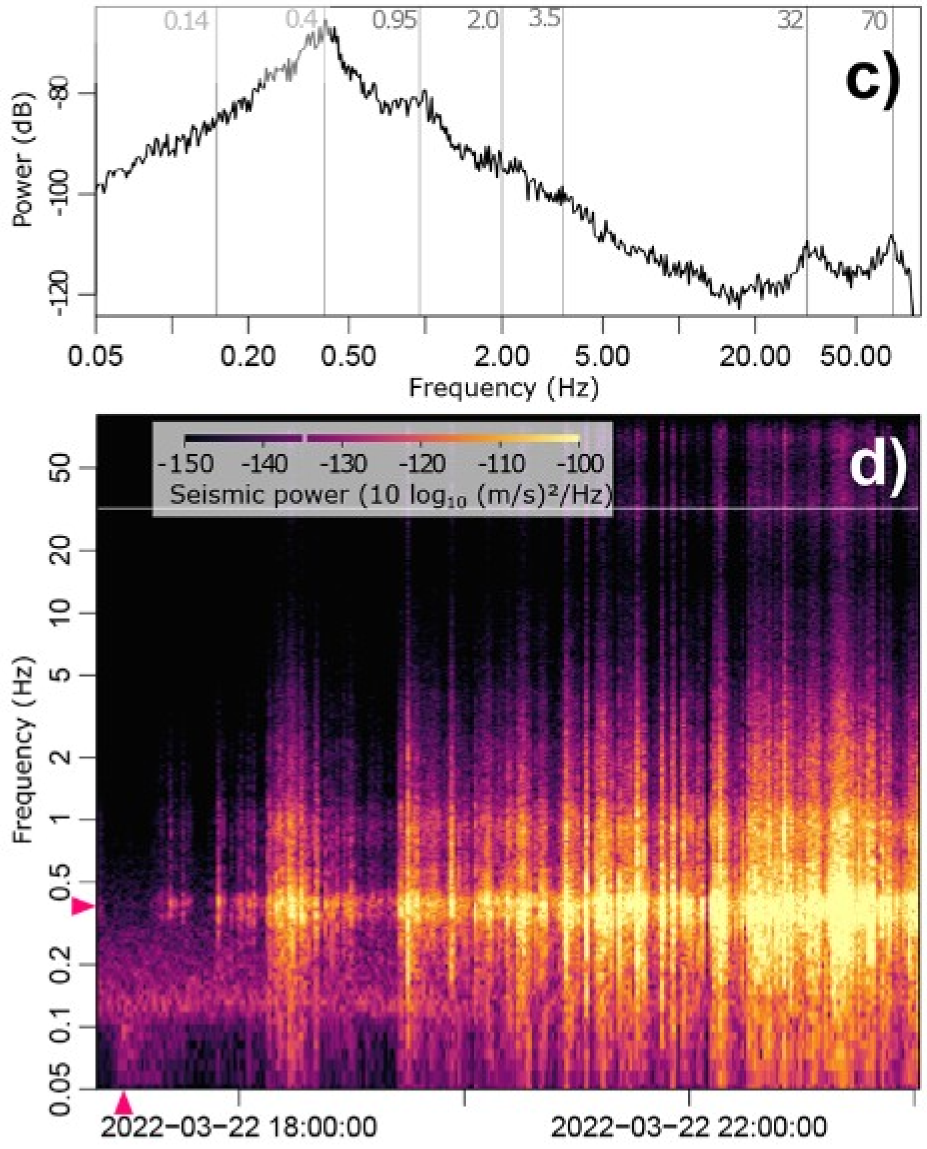
Wind interacting with the biosphere



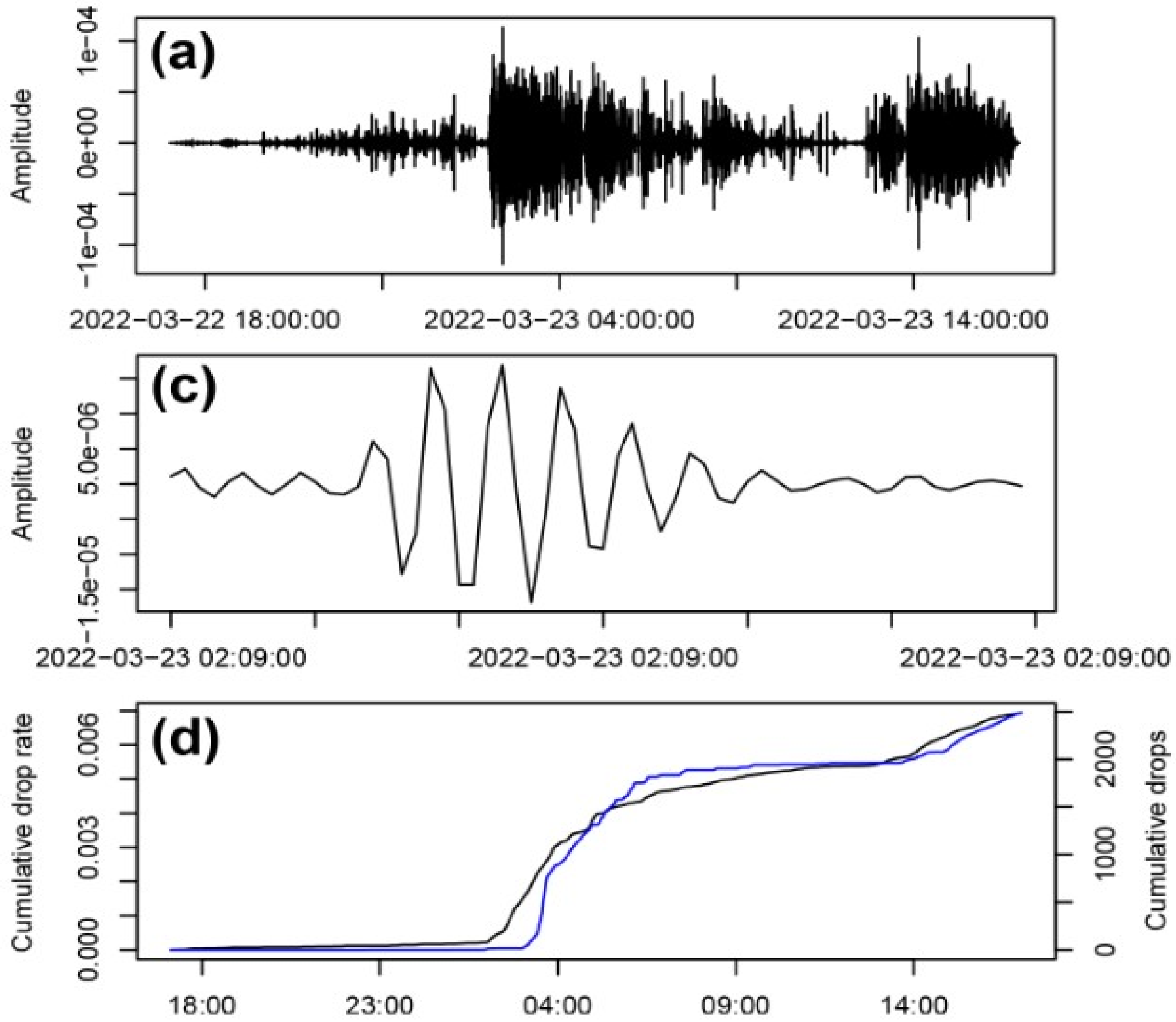
What
(Where)
When
(Why)

But: no model





Precipitation interacting with the surface



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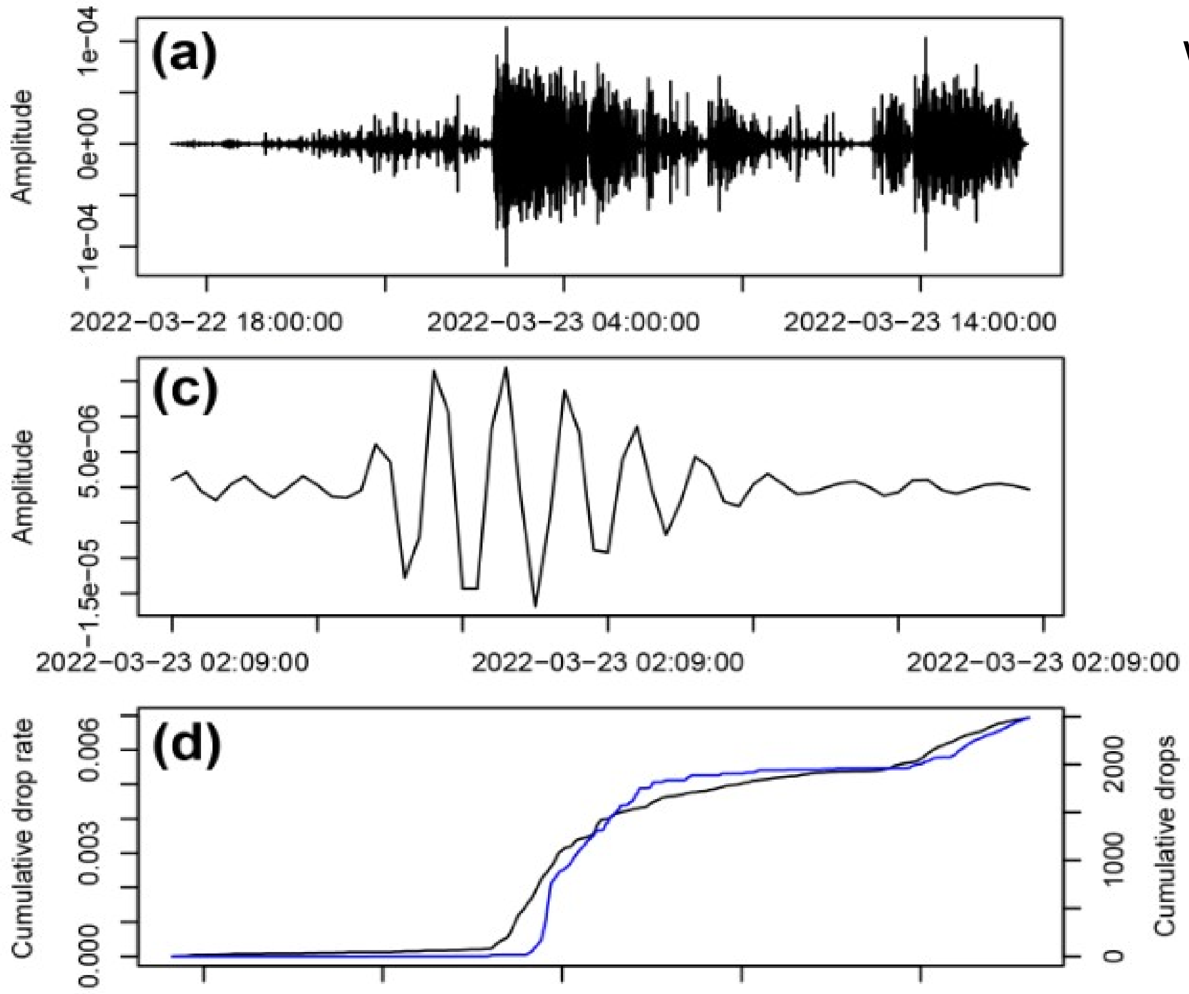
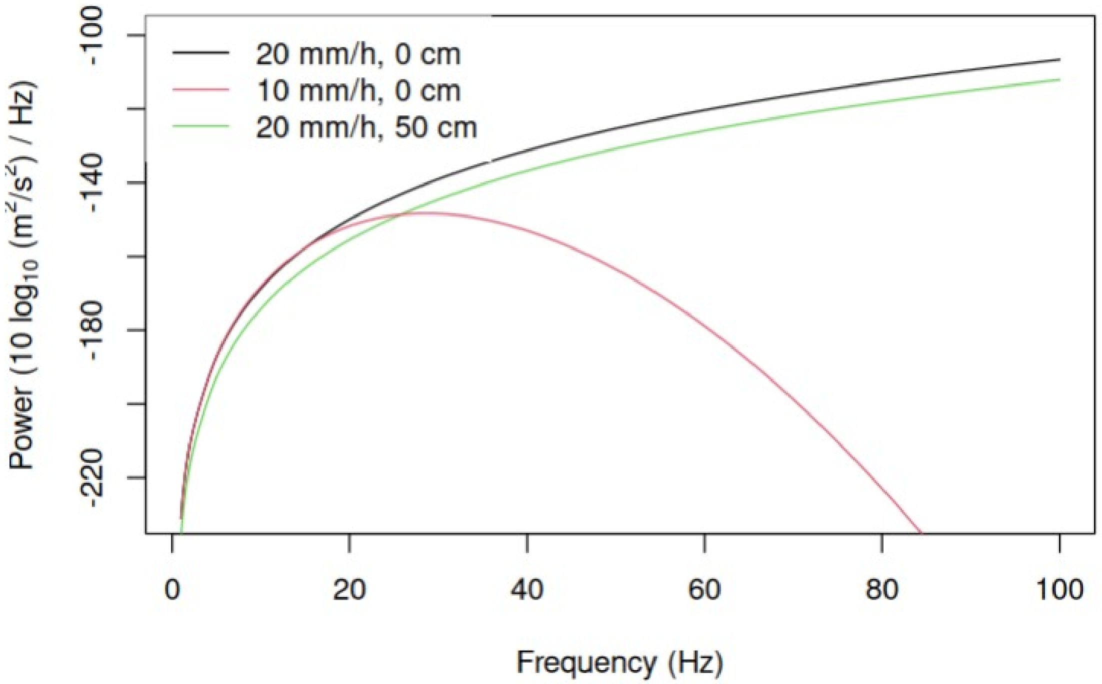


What
Where
When
Why

$$P(f) = 8\pi^3 f^2 \int_r J_P \widetilde{G}^2(f,r) r dr$$

$$J_P = \left(\frac{4}{3}\pi\rho_w\right)^2 \gamma \sum_{i,j} N_{i,j}(D)(0.5D_i)^6 v_j^2$$



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For some processes there are physical models ready for inversion

For may more processes there are simplistic models, at best

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Thanks!