Helmholtz Centre Potsdam

Induced seismicity at St1 Helsinki shows limited earthquake interaction

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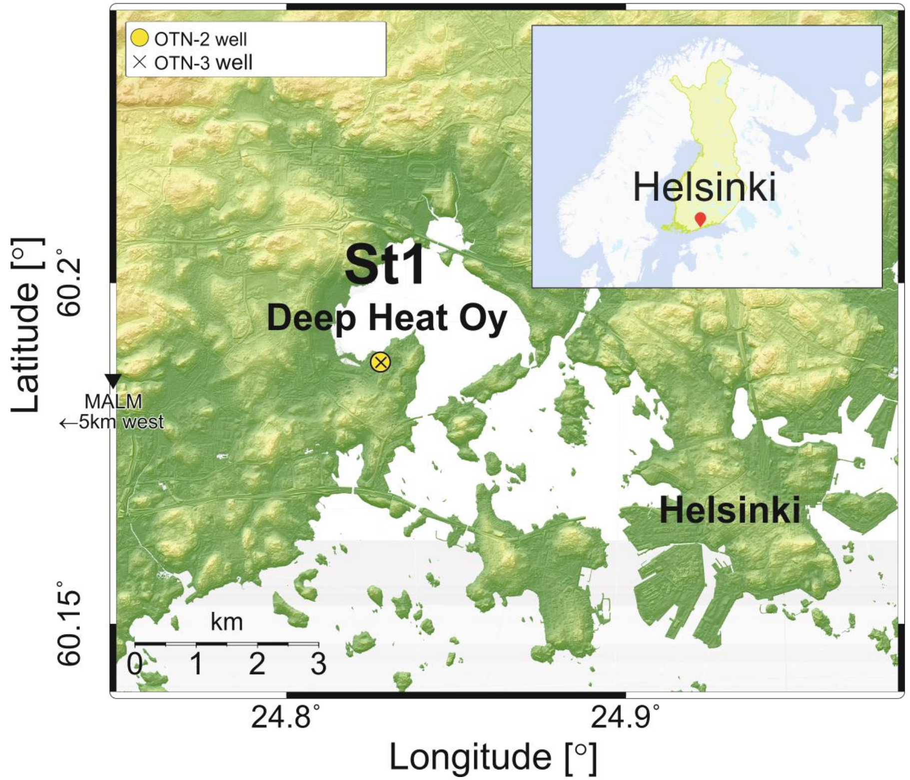
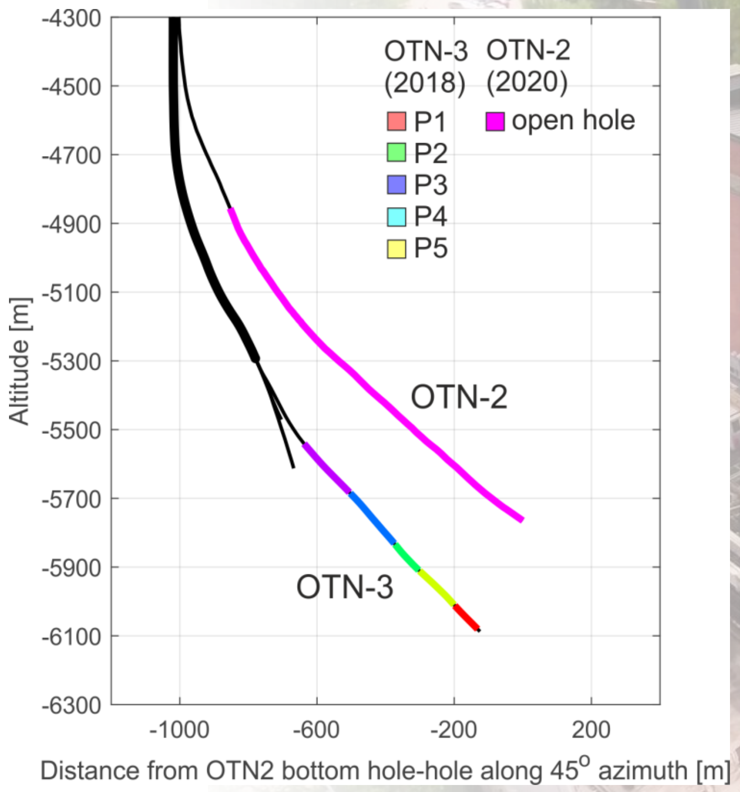
St1 Helsinki project

Deepest EGS (6100 m bsl) with OTN-2 / OTN-3 well doublet

Aims to provide a sustainable baseload for local heating network



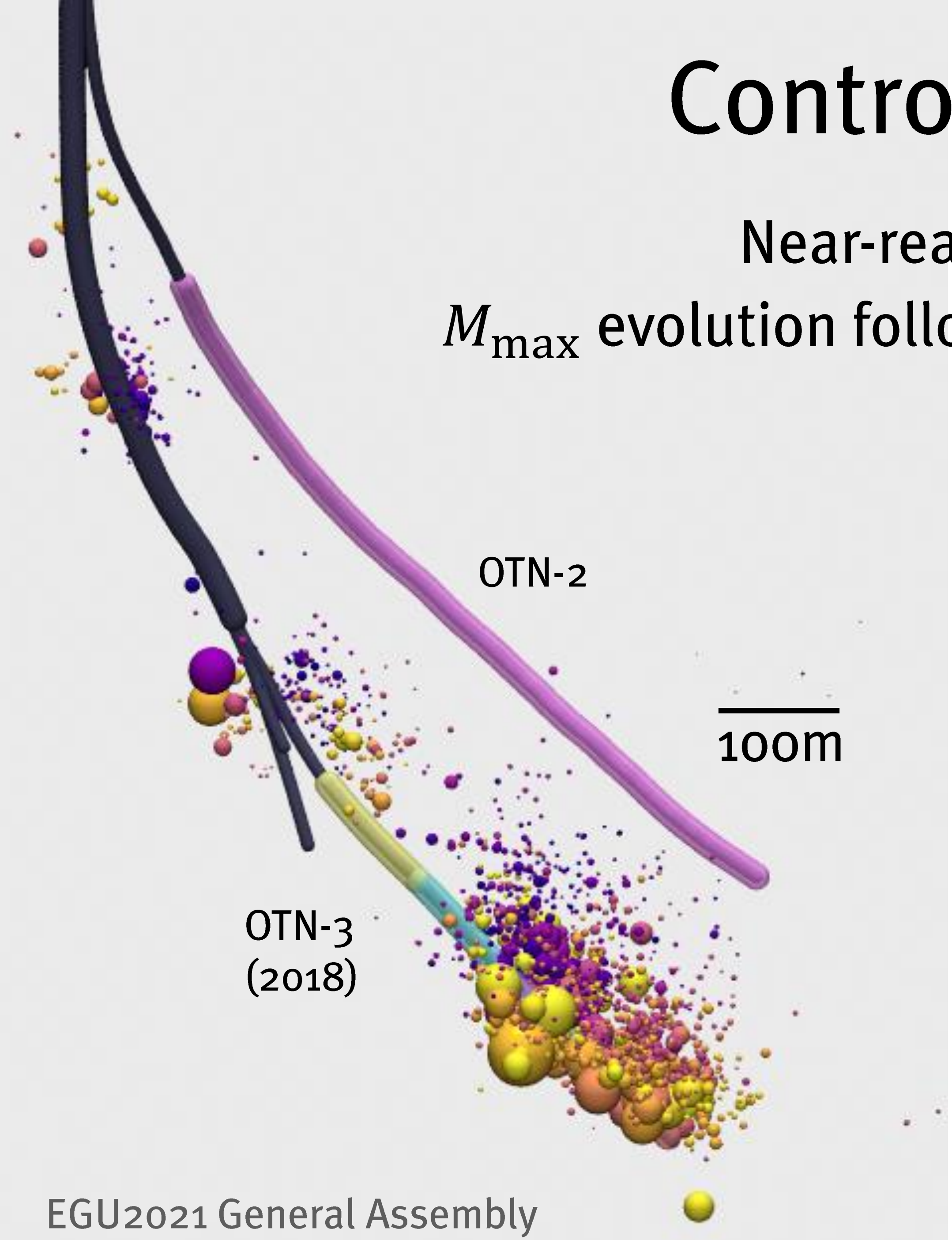


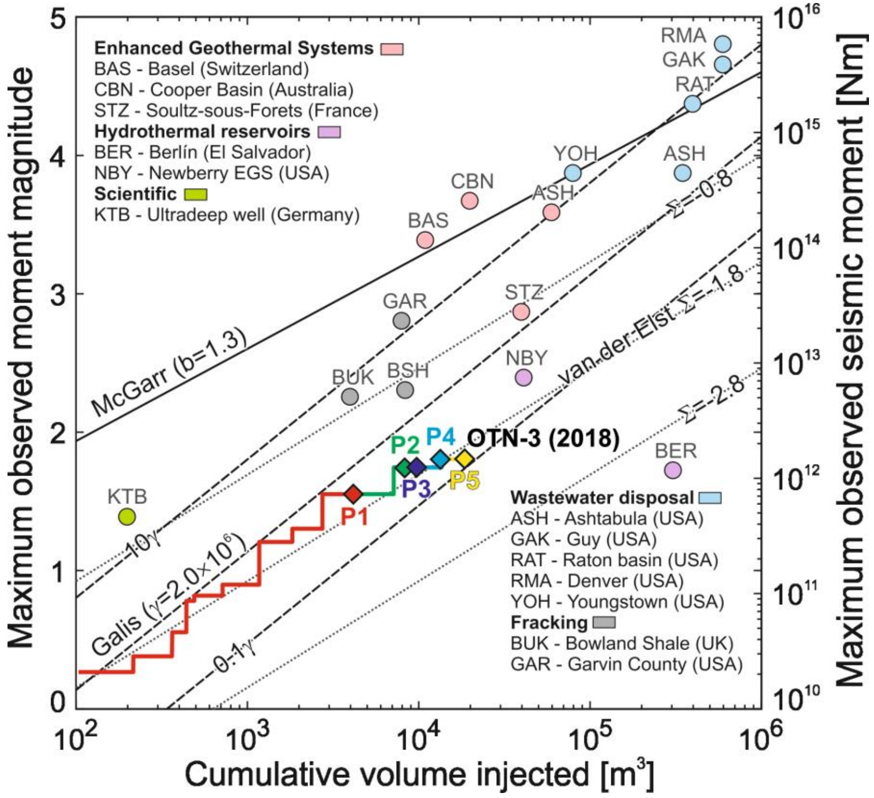
Controlling induced seismicity a St1

Near-realtime monitoring of seismic and hydraulic energy

$M_{\max}$ evolution follows pressure-controlled models of $M_{\max} \propto \Delta V^{3/2}$

(Galis et al., 2015; Shapiro et al., 2010; van der Elst et al., 2015)





(Kwiatek et al., 2019, SciAdv)

Motivation

Successful control of maximum magnitude M_{max} at St1 Helsinki (Kwiatek et al., 2019, SciAdv) :

- Adaptive injection strategy limiting hydraulic energy input rate
  (see follow up works for other EGS systems and Lab: Bentz et al., 2021 GRL; Wang et al., 2020,a,b GRL)
- Favorable reservoir structure and tectonic stress conditions
  (Leonhardt et al., 2021 Solid Earth)
- Limited stress transfer between earthquakes ?

This study

- Does seismicity only responds to hydraulic energy input?
- Does seismicity display evidences for stress transfer?
- What are implications for seismic hazard assessment at St1 Helsinki?

Hydraulic stimulation campaings

2018 OTN-3 stimulation

Fluid volume: 18,500 m³

WHP^{max}: 90 MPa

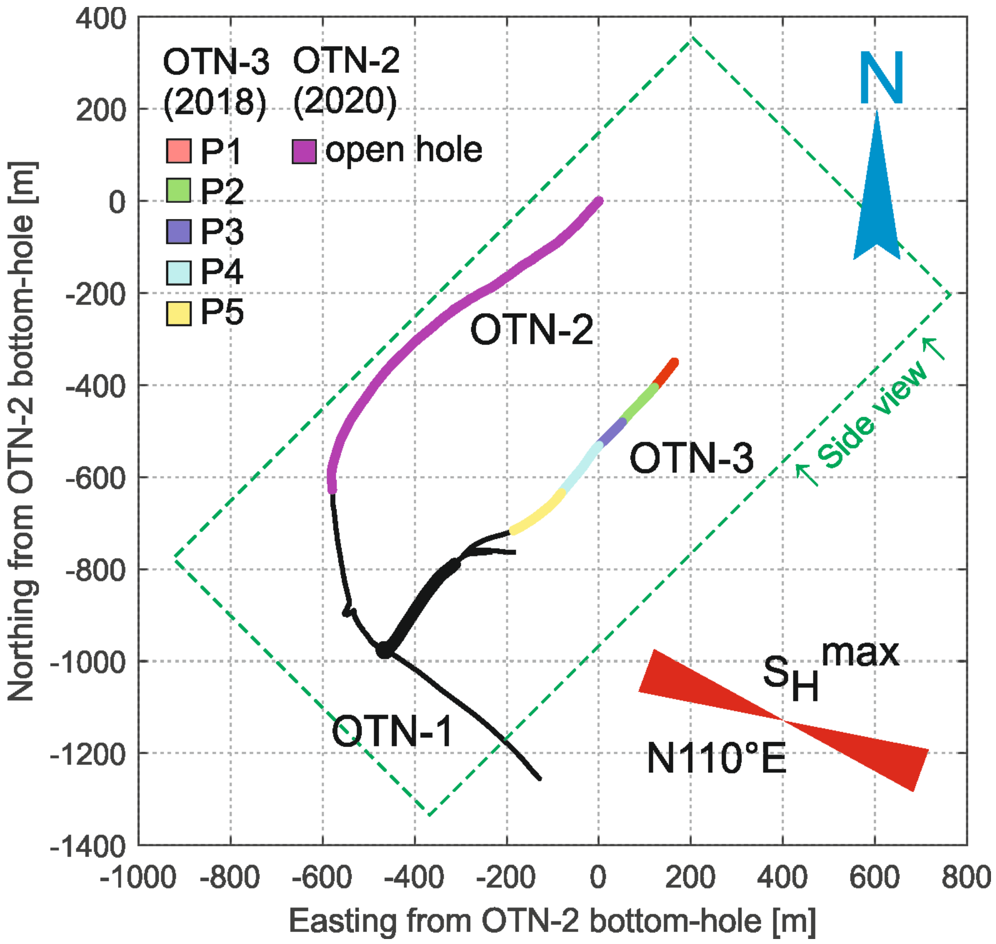
N=38,400 with $M_L > -1.2$

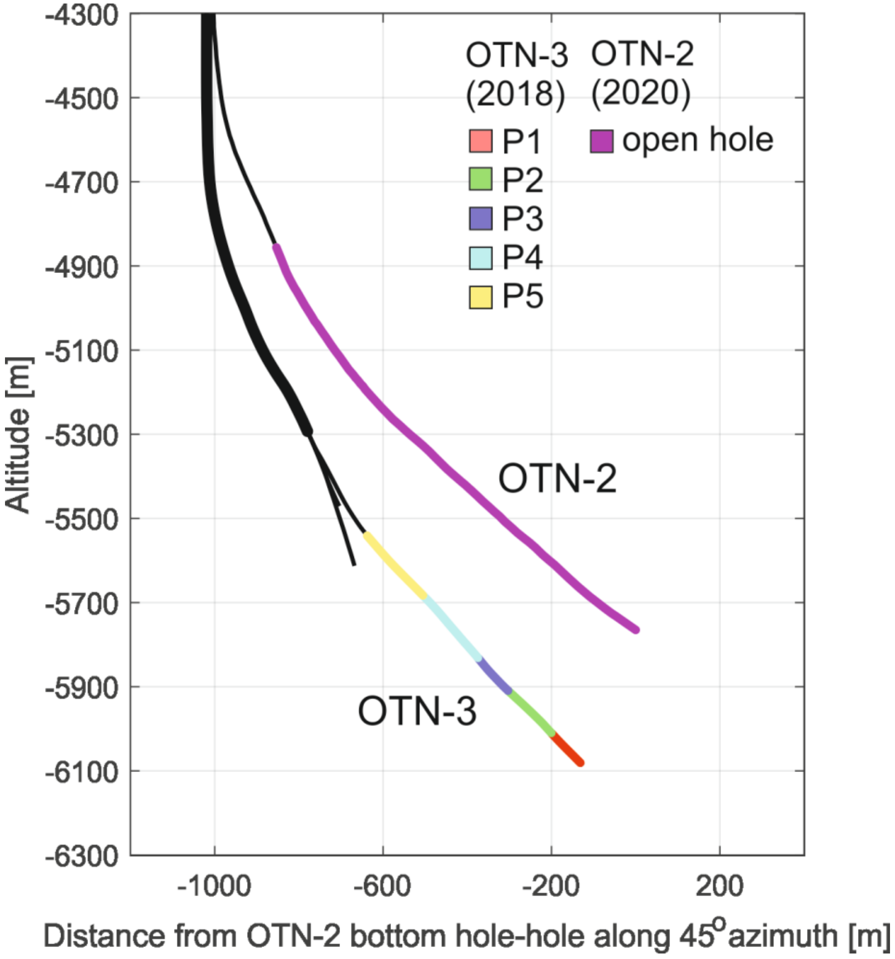
2020 OTN-2 stimulation

Fluid volume: 3,000 m³

WHP^{max}: 70 MPa

N=1,100 with $M_L > -1.2$

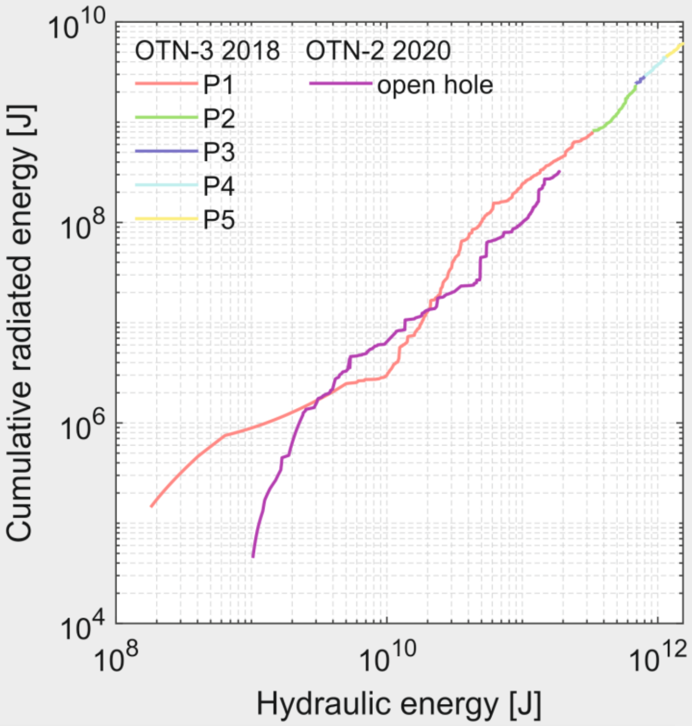


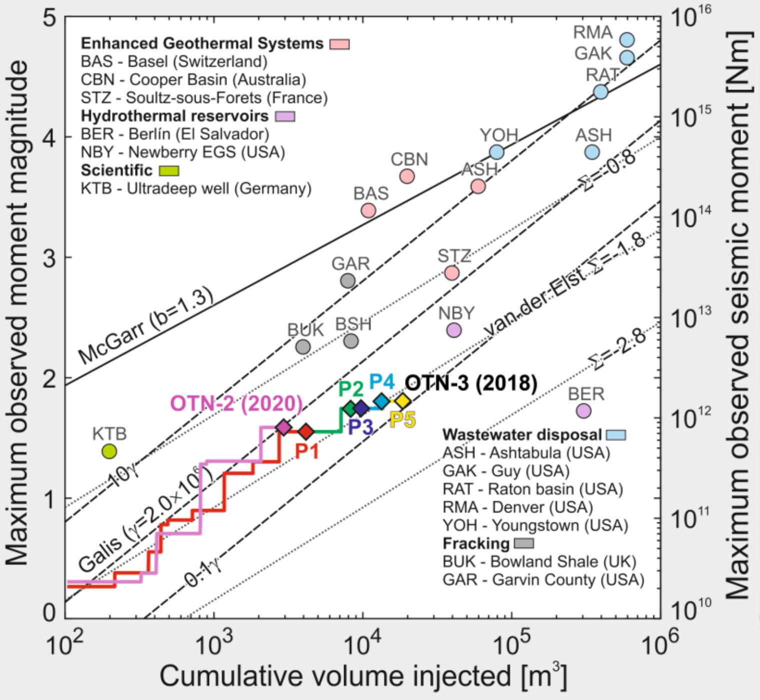


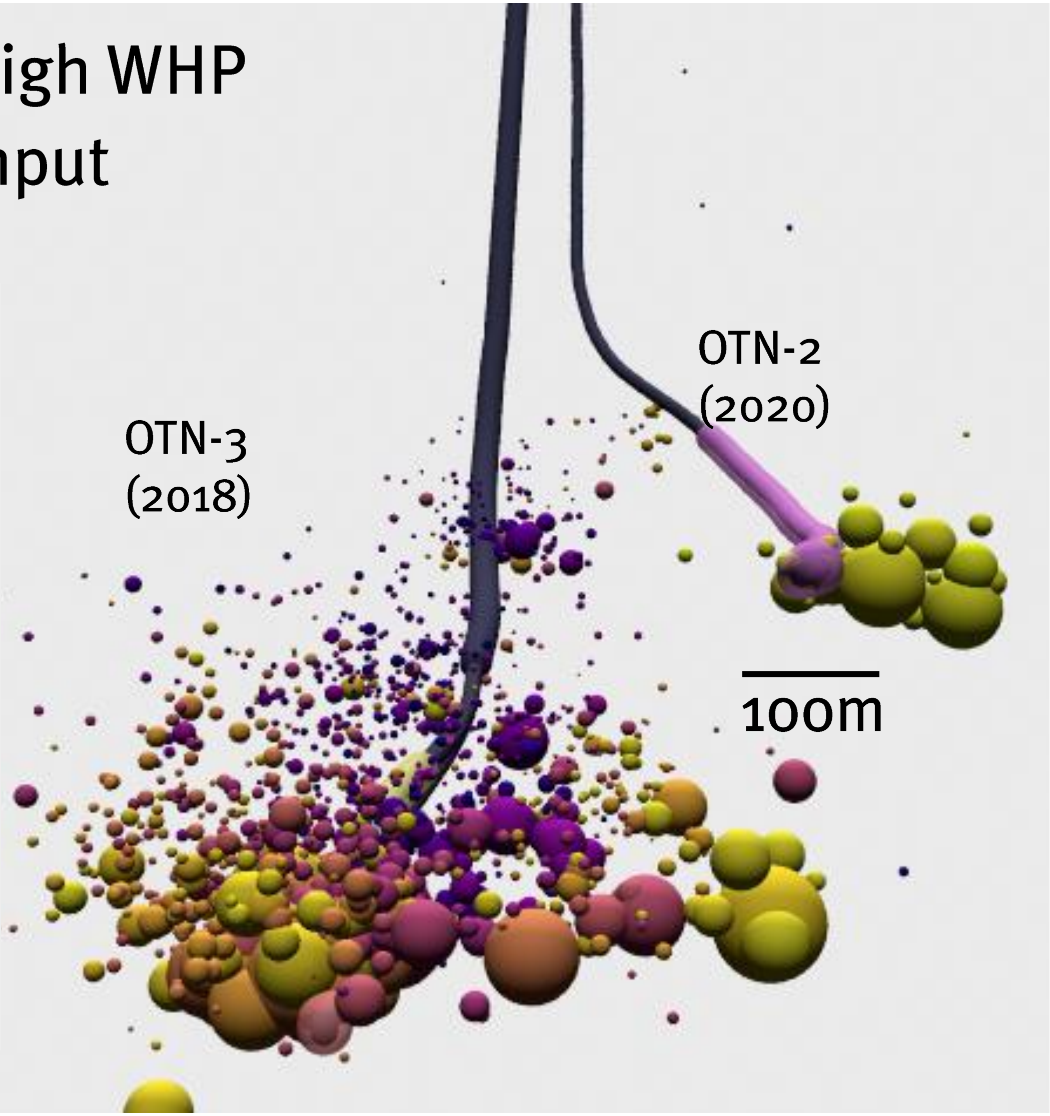
Seismicity evolution

Spatial expansion of seismicity observed only at high WHP

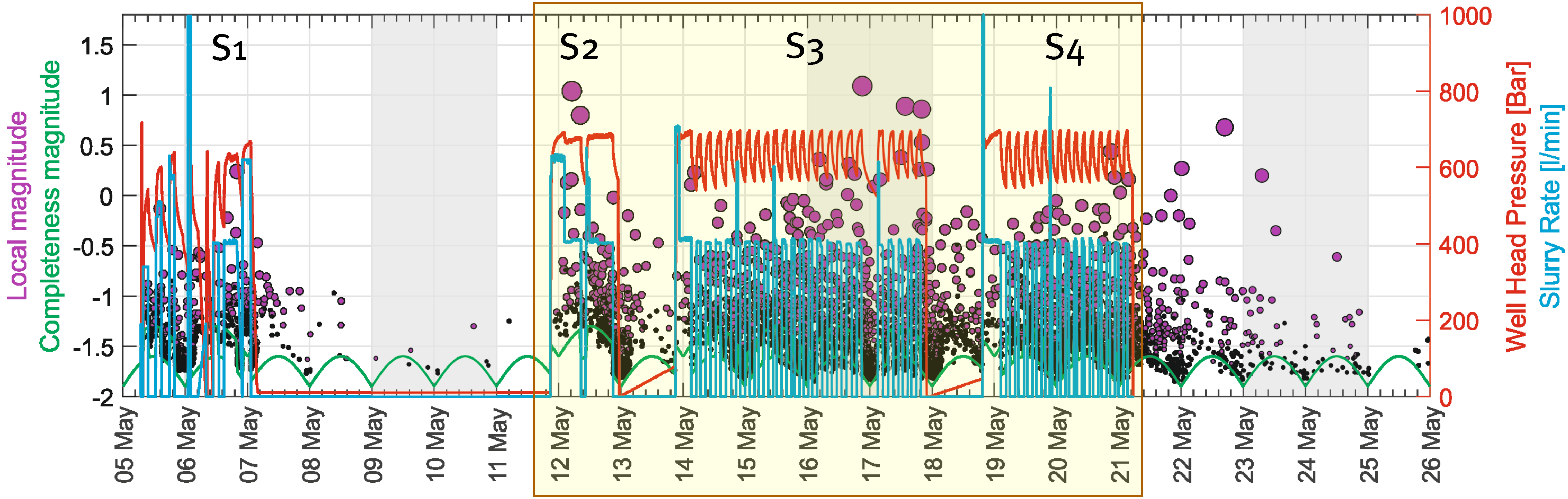
Seismic energy proportional to hydraulic energy input







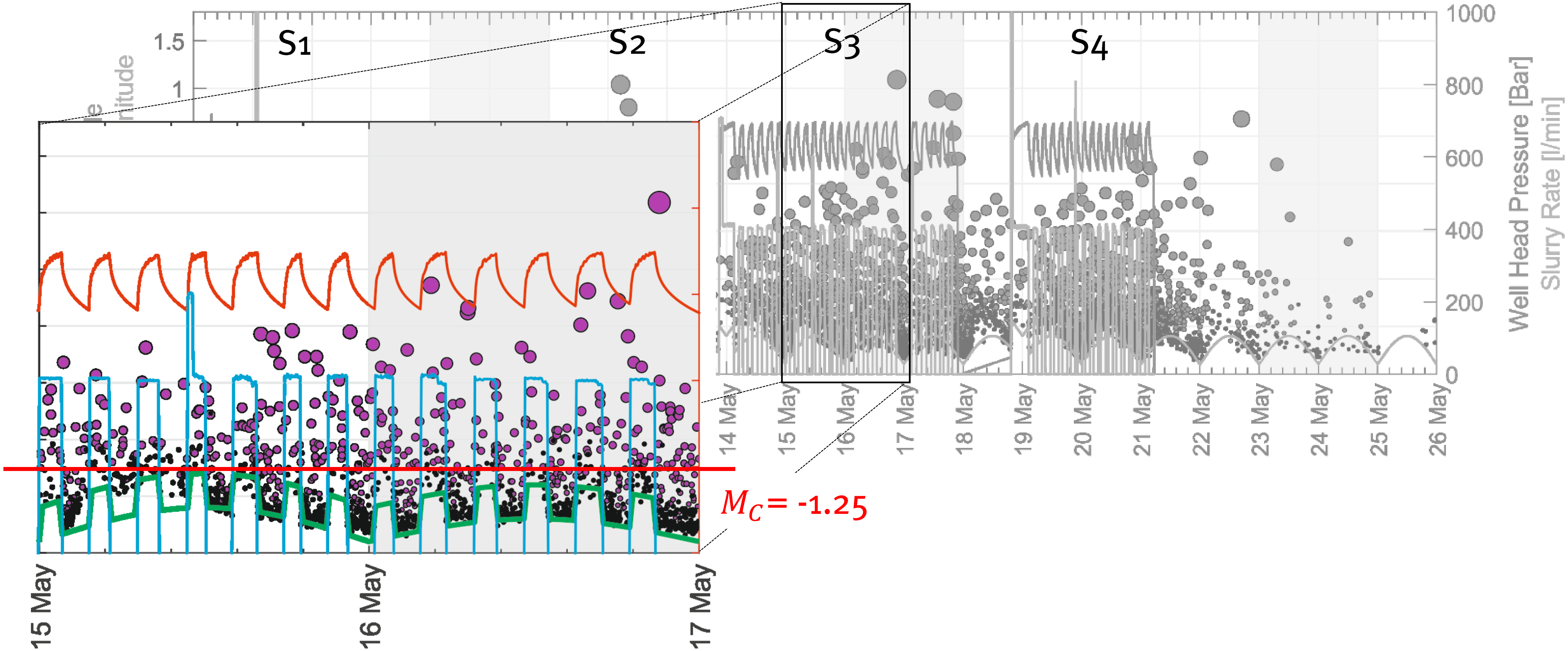
2020 Catalog selection (1)



~Quasi - stationary catalog used in the analysis

2020 Catalog selection (2)

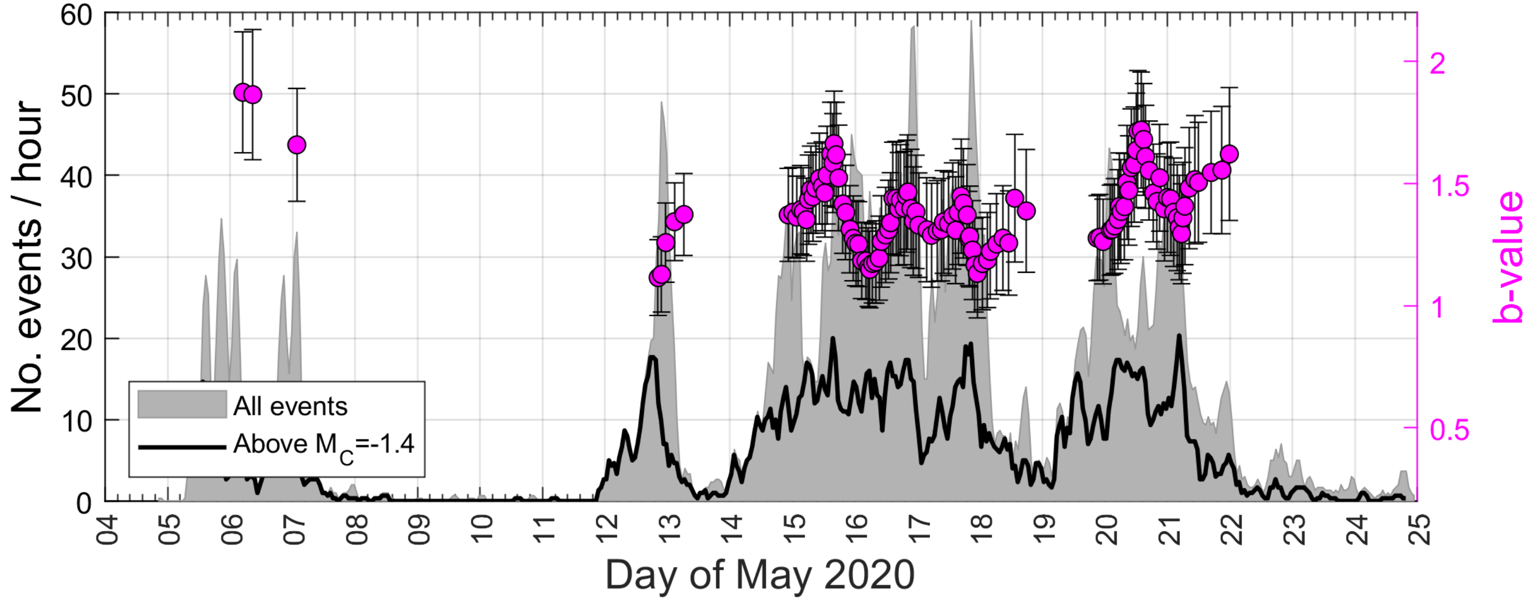
Time-varying magnitude of completeness important for the analysis!



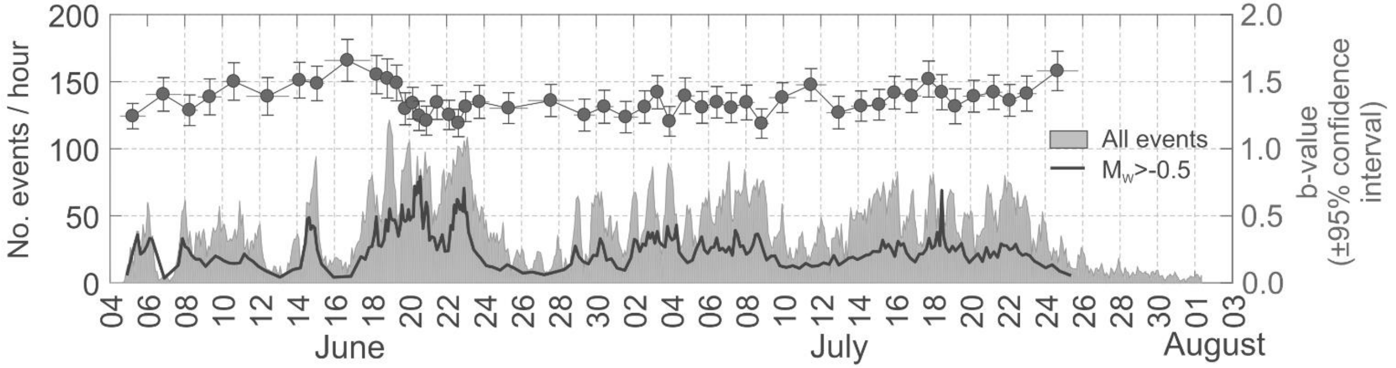
Stationary *b* - value

- No indications for deviatoric stress change or fractures coalescence (cf. Scholz, 1968; Main et al., 1991)
- Seismic hazard controlled by *a*-value changes

2020 OTN-2 stimulation



Comparison: 2018 OTN-3 stimulation (Kwiatek et al., 2019; SciAdv)



No magnitude correlations

- No cascading deceleration/acceleration of seismic energy release
- Correlation of magnitudes (deceleration) visible only after shut-in

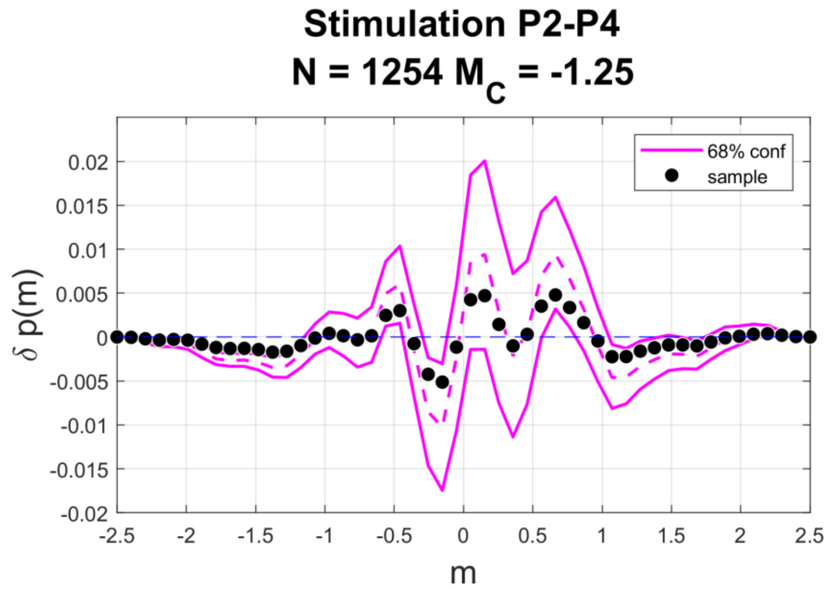
$$\boldsymbol{\Delta M} = [\Delta M_i] = M_{i+1} - M_i$$

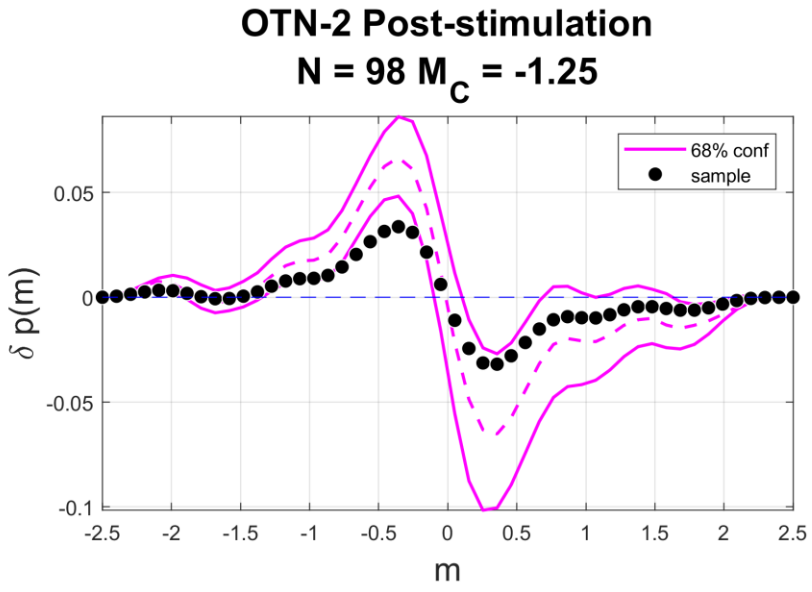
$$\boldsymbol{\Delta M}^* = [\Delta M_i] = M_{i+1} - M_i^*$$

M_i^* randomly drawn from $\{M_i\}$

(e.g. Davidsen et al., 2012, PRL)

$$\delta p(m) = p(\mathbf{\Delta M} < \mathrm{m}) - p(\mathbf{\Delta M}^* < \mathrm{m})$$



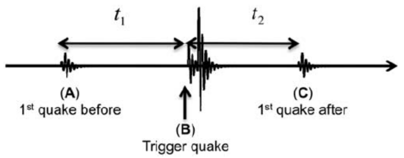


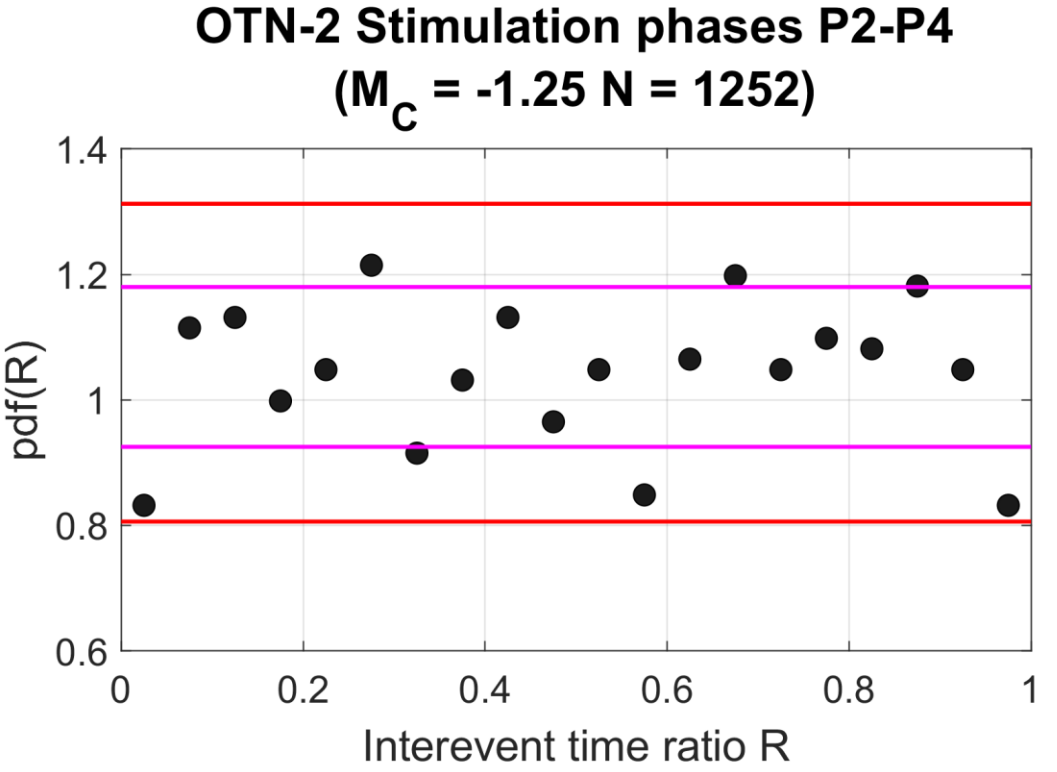
No significant temporal clustering

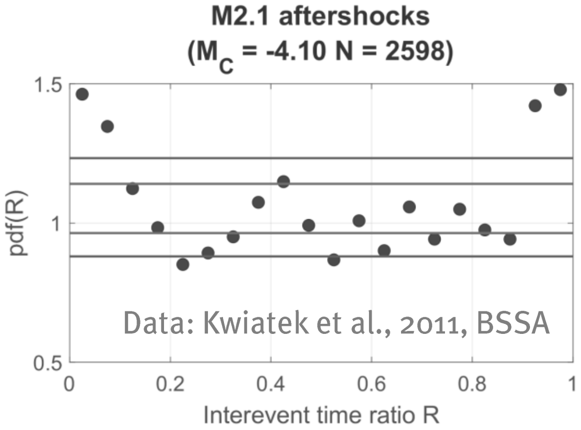
Using interevent-time ratio R statistics (van der Elst and Brodsky, 2010)

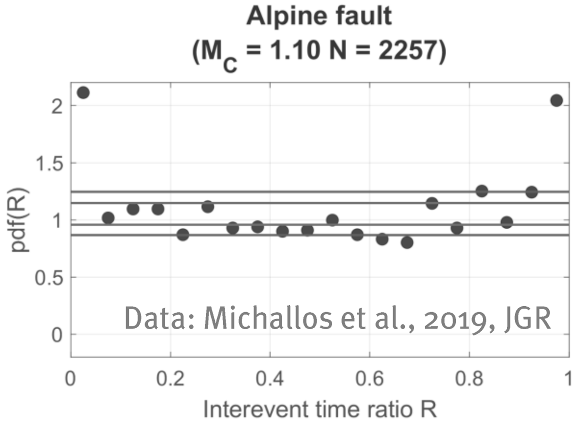
- No significant temporal (anti-)clustering observed

$$\boldsymbol{R} = [R_i] = \frac{t_{i+1} - t_i}{t_{i+1} - t_{i-1}}$$









Summary and conclusions

- Statistical and source properties of IS covering 2018 and 2020 stimulation campaings are comparable
- No indications for static or dynamic stress transfer between induced earthquakes
- Seismicity as a passive response to injection operations following quasi-stationary Poisson process
- Seismic hazard and maximum magnitude is controlled by seismicity rate changes (a-value), and likely linked to the hydraulic energy rate
- Limited possibility for runaway ruptures
- Hazard assessment through probabilistic methods - tapered G-R works just fine
- Importance of accounting for rapid changes in magnitude of completeness

Thank you very much for your attention!

Presentation:

https://youtu.be/In2xPrAg-2k

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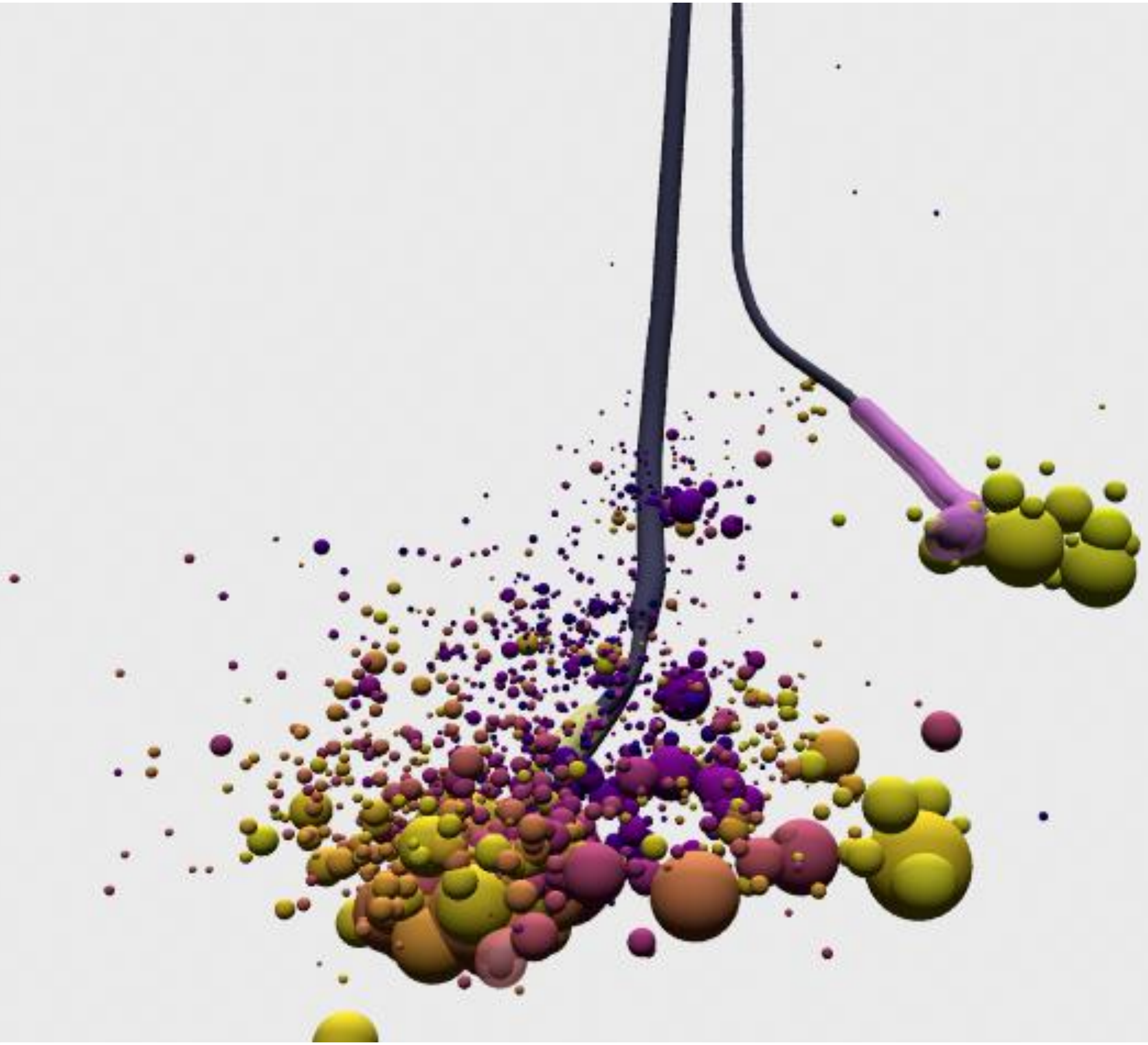
see also:

https://induced.pl/st1



Supplementary information

More about St1 Deep Heat project research:

https://induced.pl/st1

St1-related papers cited in this presentation:

Bentz, S. et al. (2020). Seismic moment evolution during hydraulic stimulations, Geophys. Res. Lett. DOI: 10.1029/2019GL086185.

Leonhardt, M. Et al. (2021). Seismicity during and after stimulation of a 6.1 km deep enhanced geothermal system in Helsinki, Finland. Solid Earth, DOI: 10.5194/se-12-581-2021.

Kwiatek, G. Et al. (2019). Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland, Sci. Adv. DOI: 10.1126/sciadv.aav7224.

Wang, L. et al. (2020). Injection-Induced Seismic Moment Release and Laboratory Fault Slip: Implications for Fluid-Induced Seismicity. GRL, DOI: 10.1029/2020GL089576.

Wang, L. et al. (2020). Laboratory study on fluid-induced fault slip behavior: The role of fluid pressurization rate, GRL, DOI: 10.1029/2019GL086627.