Controlling Fluid-Induced Seismicity during a 6.1-km-Deep Geothermal Stimulation in Finland

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Introduction

- Seismic events possibly related to EGS have seriously affected/terminated some geothermal projects
- Implementation of safe stimulation strategies is critical for public acceptance of EGS projects

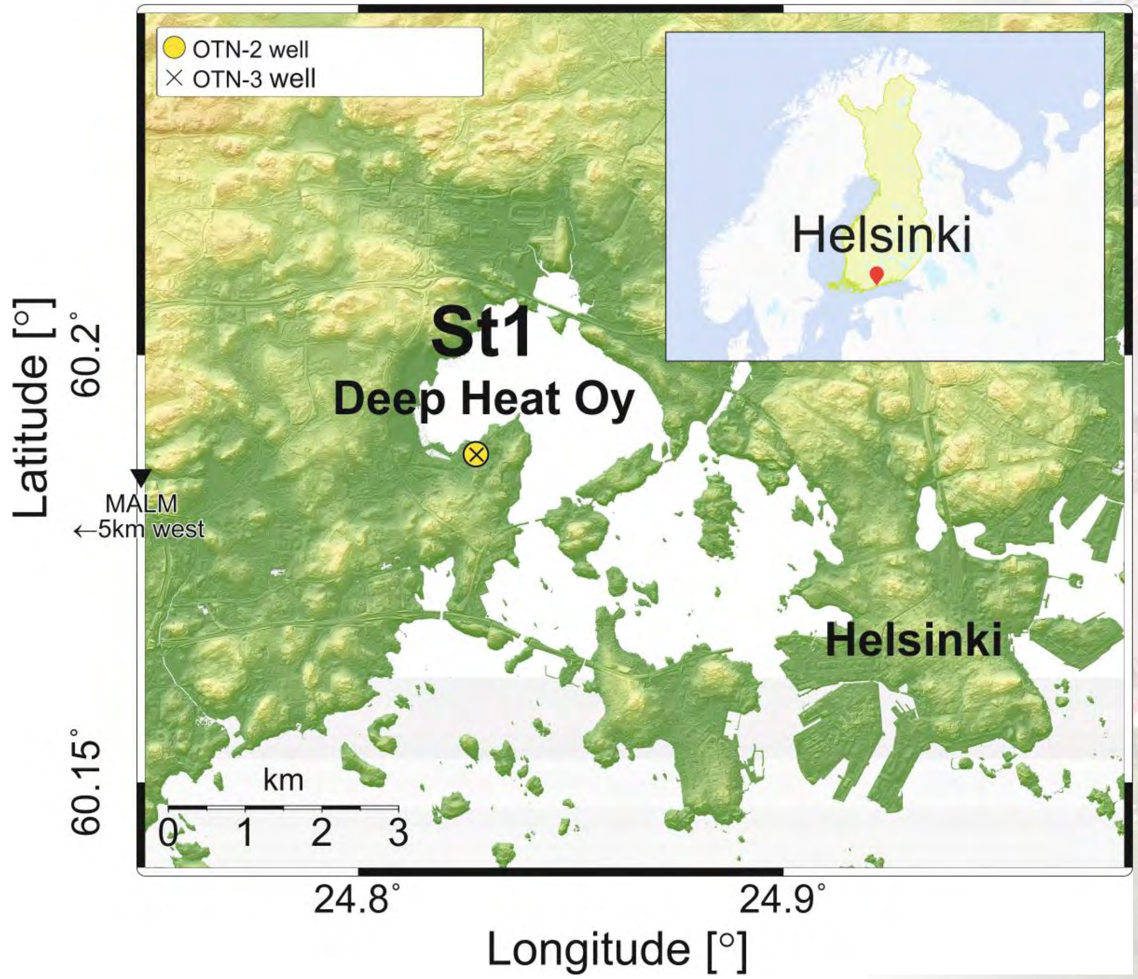
This study

- Near-realtime seismic monitoring allowed managing hydraulic energy input and avoid project-stopping M2.1 event during stimulation of a 6.1 km-deep geothermal well near Helsinki, Finland

St1 Deep Heat project

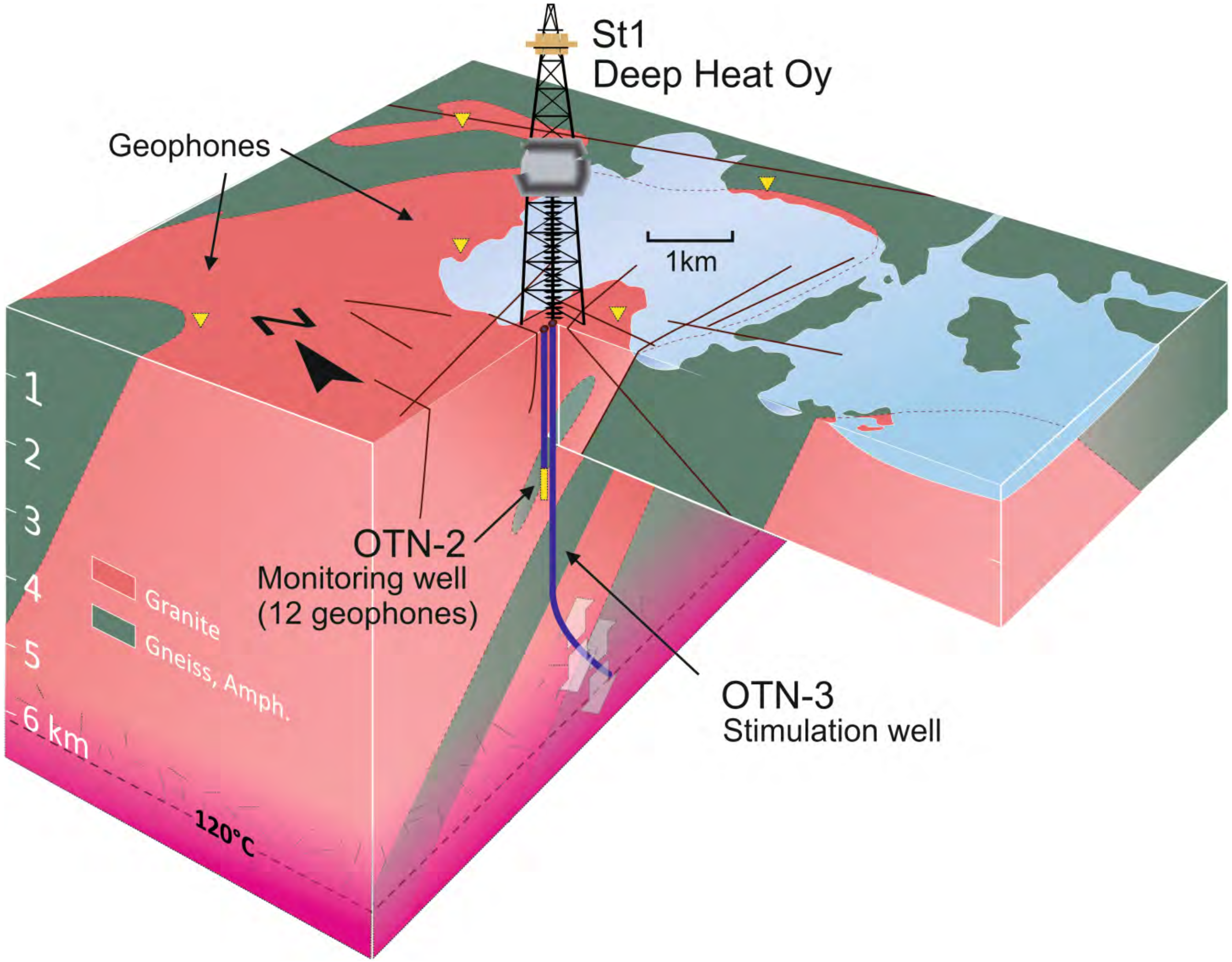
Located in Helsinki suburbian area (Aalto University, Espoo)

Provide sustainable baseload for the campus-area district heating network



Project site

- Well OTN-3: **6.4 km** MD
- Open bottom-hole **1000 m** inclined at **45°**
- Target formations at **5.1-6.1 km** depth with bottom hole temperature **120°C**
- Simple geology
  - 10 m sedimentary overlay
  - precambrian granites, gneisses, amphibolites
- Complex small-scale tectonic structures (folded, foliated, jointed, faulted...)
  - Broad steeply dipping damage zones trending SE-NW (drilling problems)
  - FZ 8km away (M2.6), Inactive TF 1.5km away



OTN-3 stimulation campaign in June-July 2018

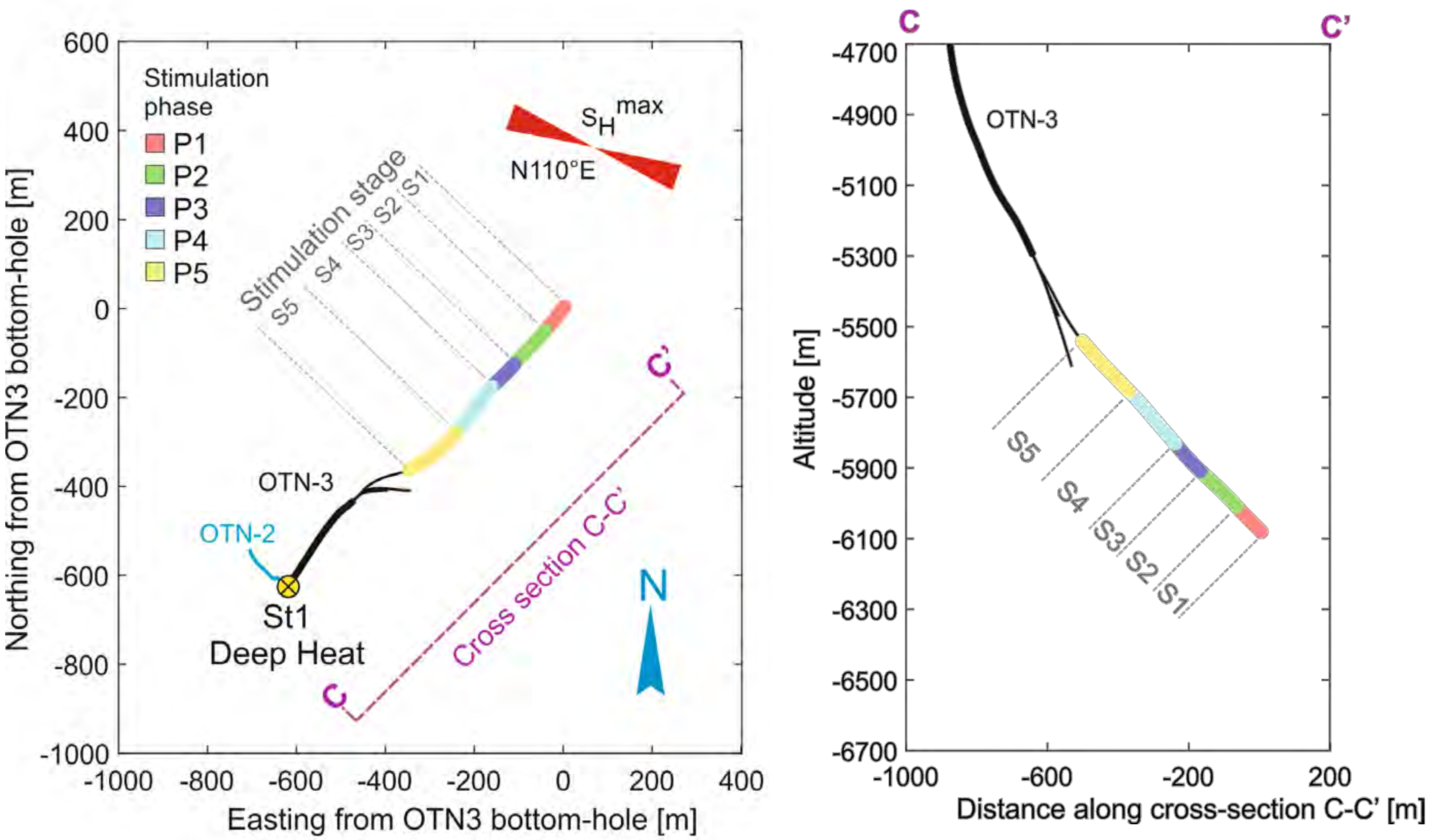
- **Five** stimulation stages selected using borehole logs
- Continuous stimulation of selected stages:
  49 days
  Water injected:
  18,500 m^3
  Well head pressures:
  60-90 MPa
  Injection rates:
  400-800 l/min

TLS RED **M 2.1**

Comparison:

Cooper Basin: ***20,000*** *m^3*

Basel: ***11,500*** *m^3*



Seismic activity during stimulation campaign

6,152 located in the vicinity of the project site with magnitude estimate within 5 minutes after occurrence ▸ TLS system

+10 minutes with manual refinement

St1: M^{max} **1.9** @ **18,500**m^3 injected

No project-stopping red alert (M_{LHEL} 2.1)

*Cooper Basin: M^{max} **3.7** @ **20,000** m^3*

*Basel: M^{max} **3.4** @ **11,500** m^3*

<u>Postprocessing:</u>

Pick/amplitude pattern matching:

+**40,000** events (**M_{LHEL}>-1.21**)

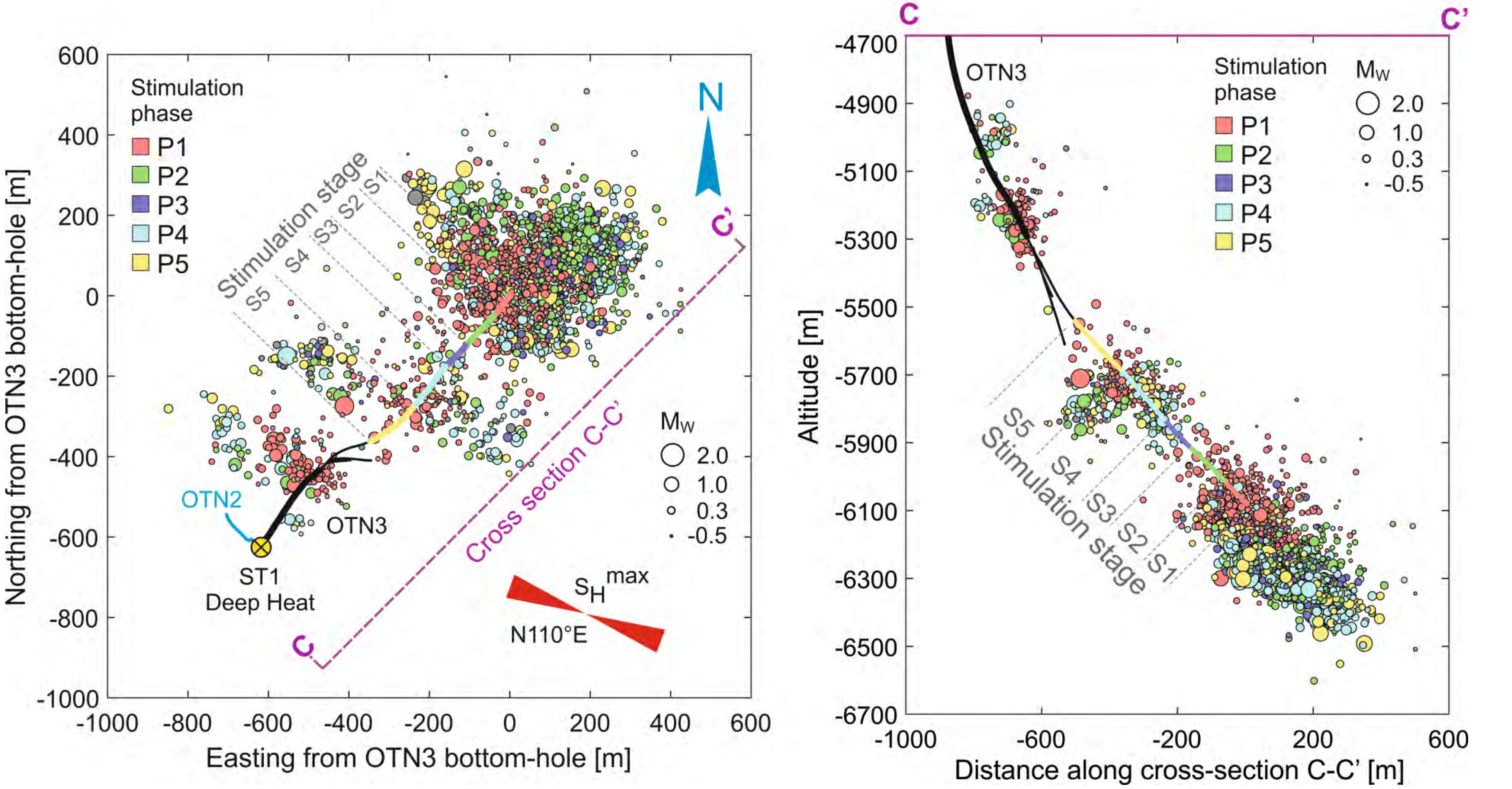
DD relocation: **~2000** events

(rel. precision 66-27m for 95%-68% of dataset)

Stimulation phase
- **Phase 1**
- **Phase 2**
- **Phase 3**
- **Phase 4**
- **Phase 5**

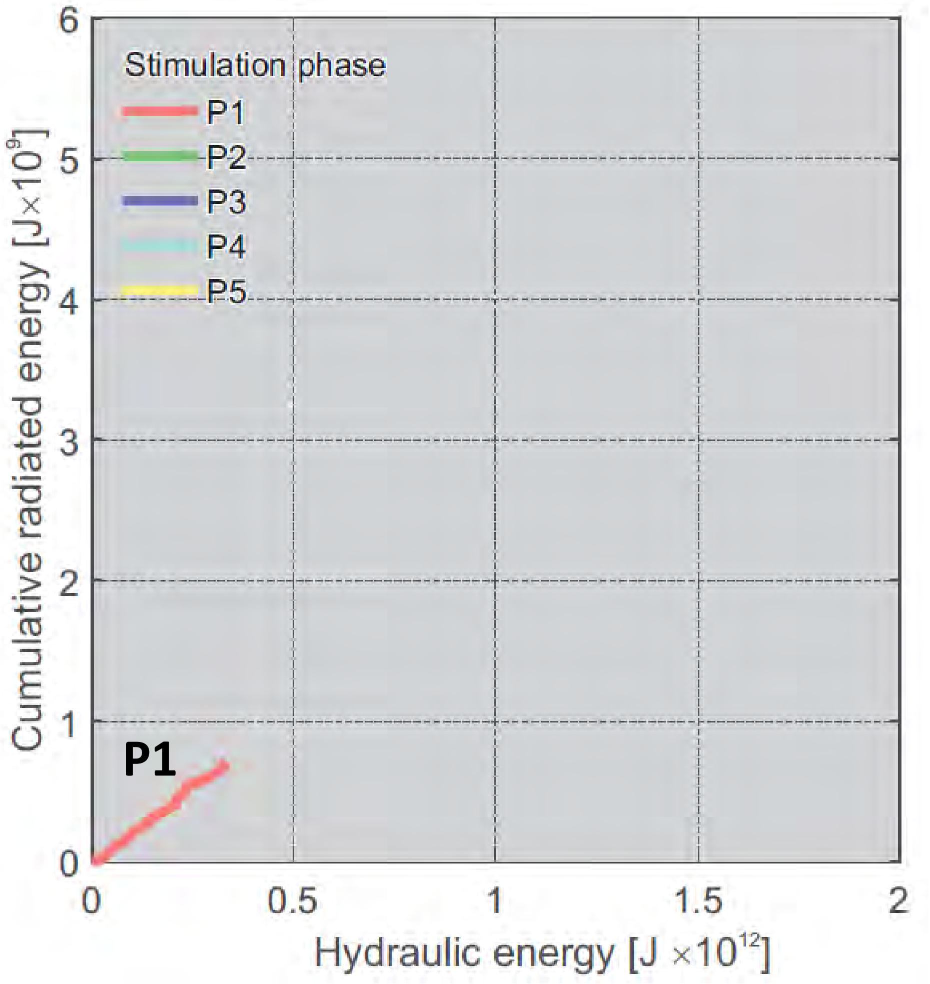
Seismicity during stimulation

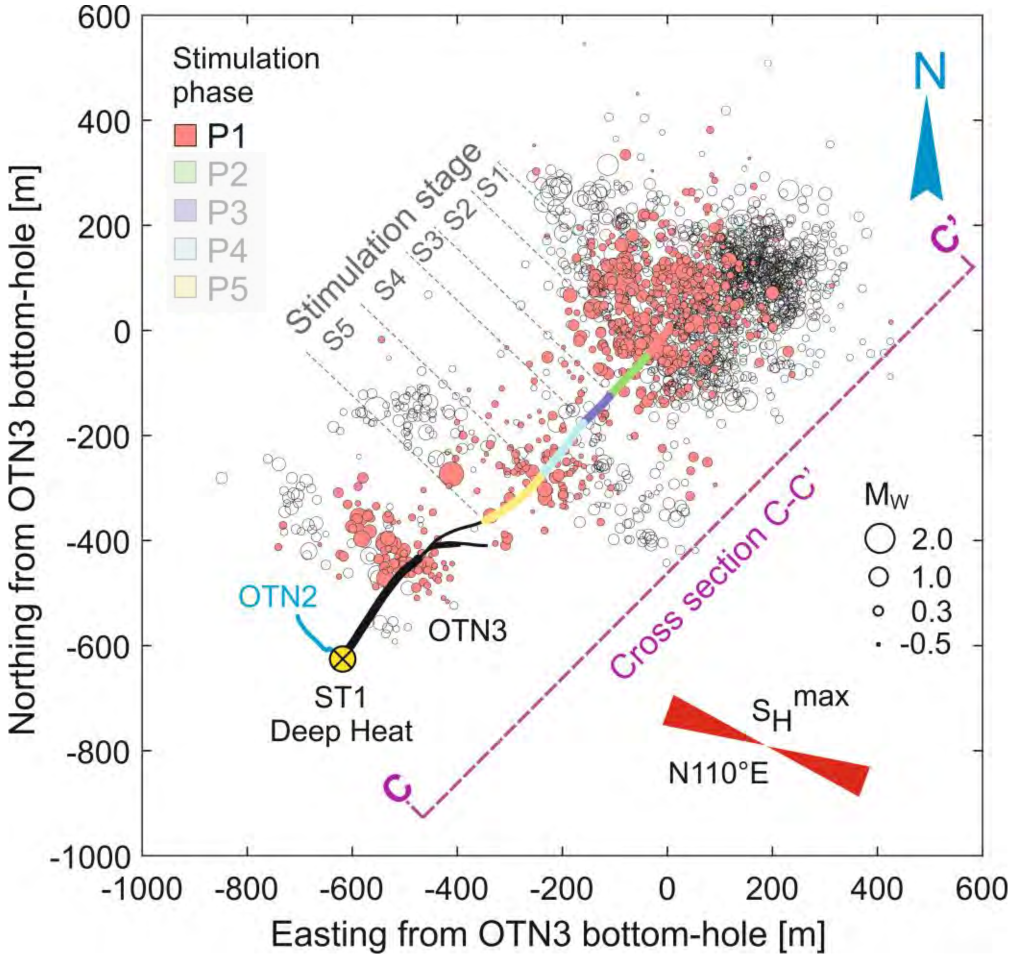
- Three major clusters activated simultaneously
- No spatiotemporal correlation injection ports-seismicity ▸ leak bypassing stage packers near borehole
- Downward migration, propagation of seismicity along SE-NW subparallel to the direction of S_H^{MAX}



Controlling induced seismicity (Phase **P1**)

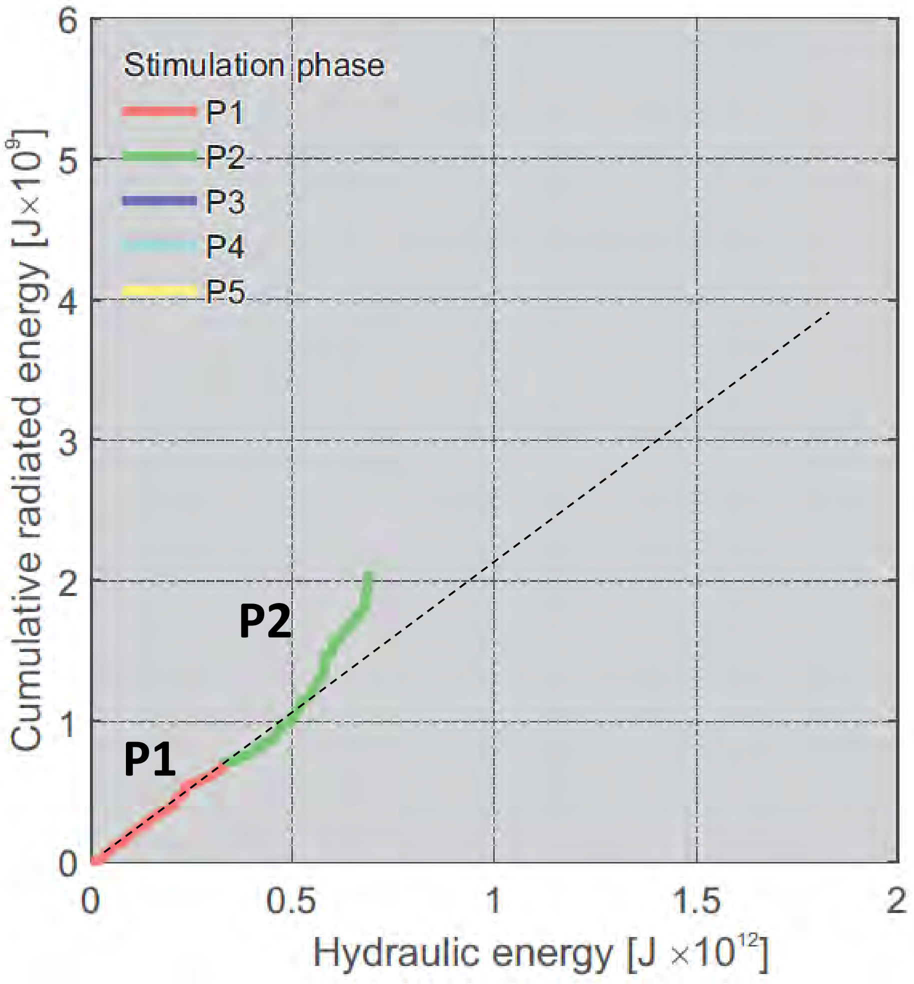
- Seismic activity occurs immediately after 75 MPa of WHP is exceeded ▶ no Kaiser effect
- Seismic energy release proportional to the hydraulic energy (P*V)
- Quick reduction of seismic activity after injection subphases

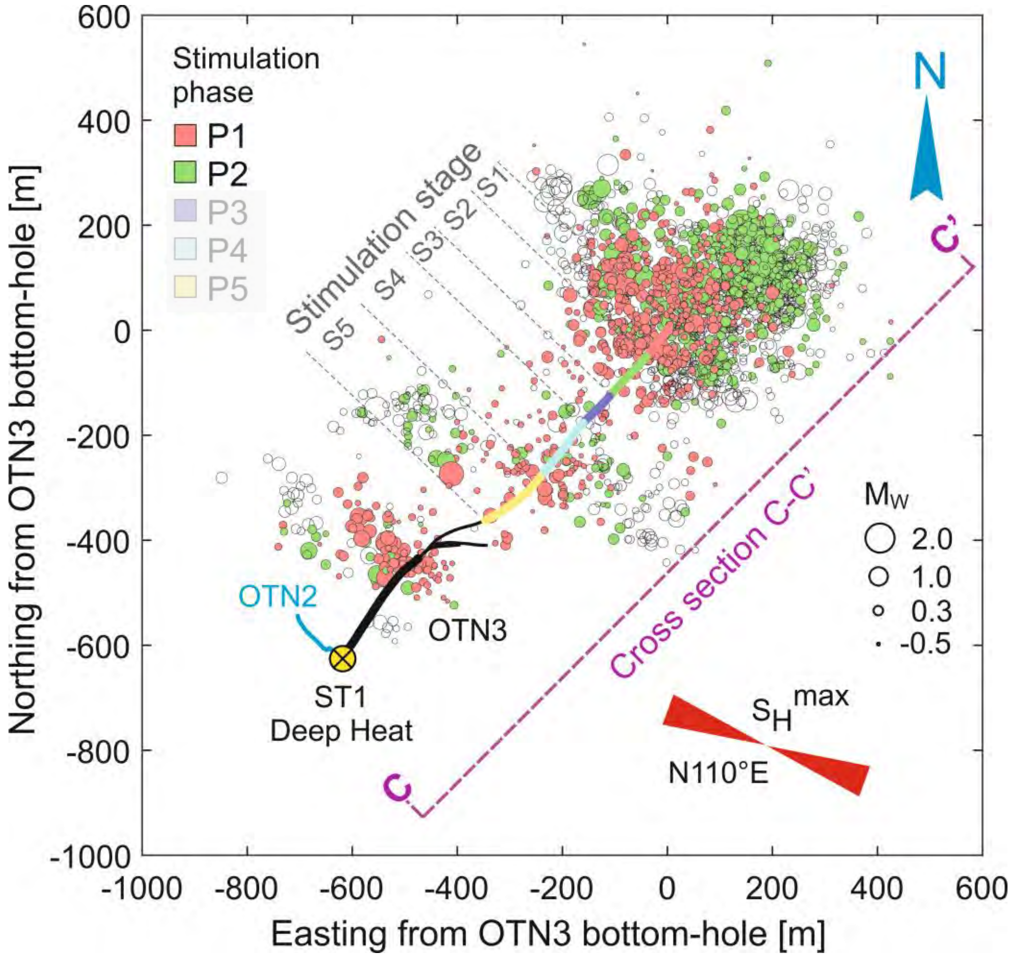




Controlling induced seismicity (Phase **P2**)

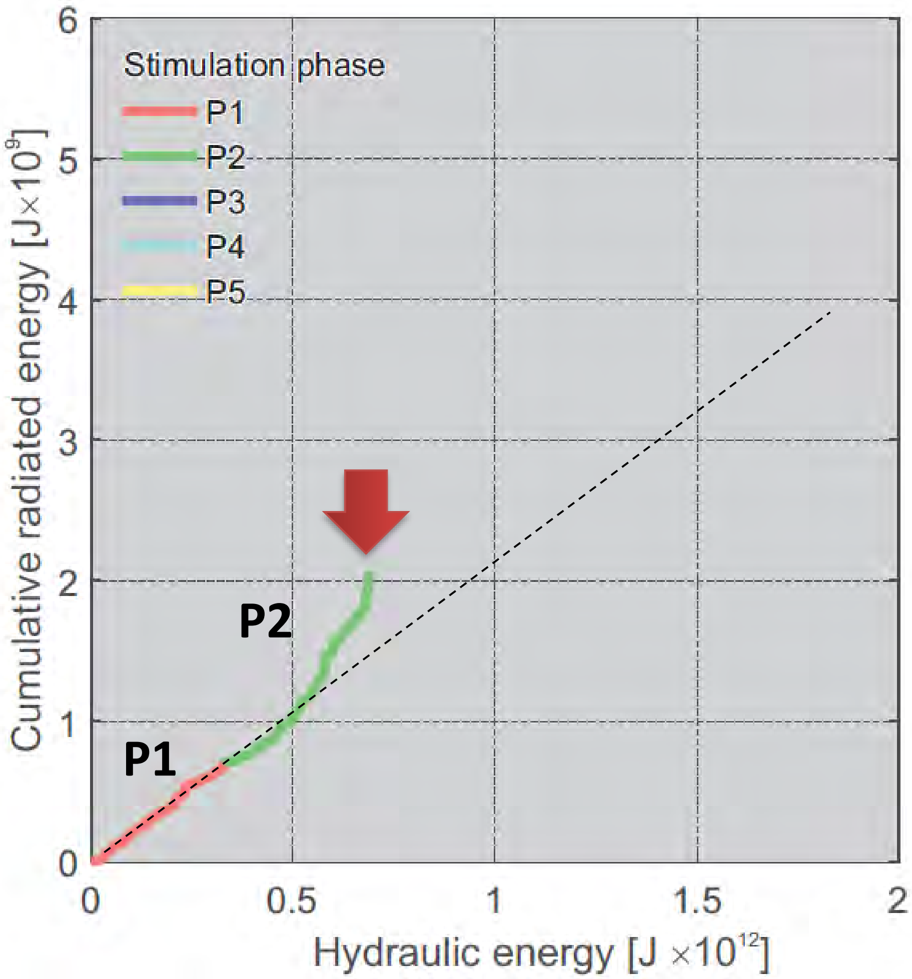
- Change in injection strategy led to accelerated seismic moment release
- Series of large events forced premature finish of P2
- Stimulation stopped for a few days.

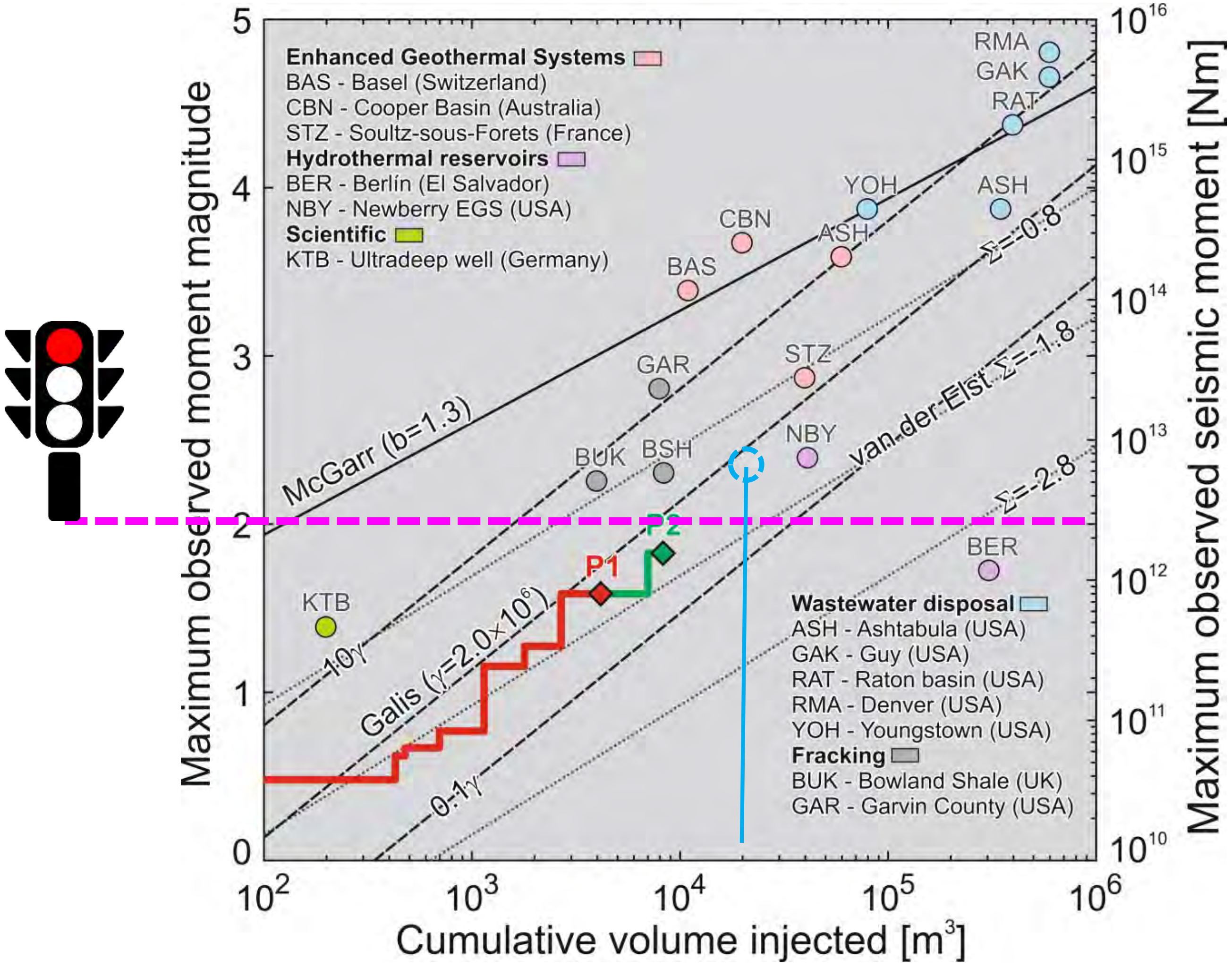




Controlling induced seismicity (Phase **P2**)

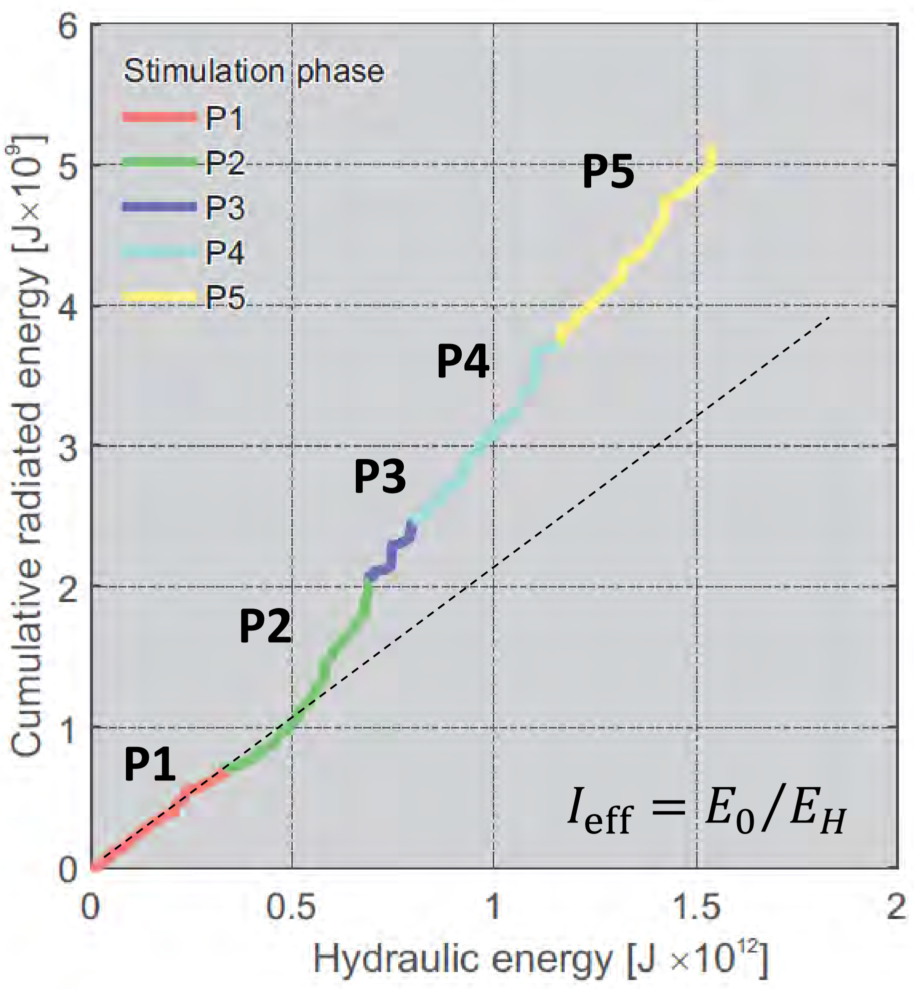
- Increase of M^{max} with cumulative injected fluid volume. Trend following *Galis et al. (2017)*.
  - $M^{max,arr}$ depends on amount of stored elastic (~hydraulic) energy available for rupture propagation
  - Modified injection strategy: Reduce the amount of stored energy!

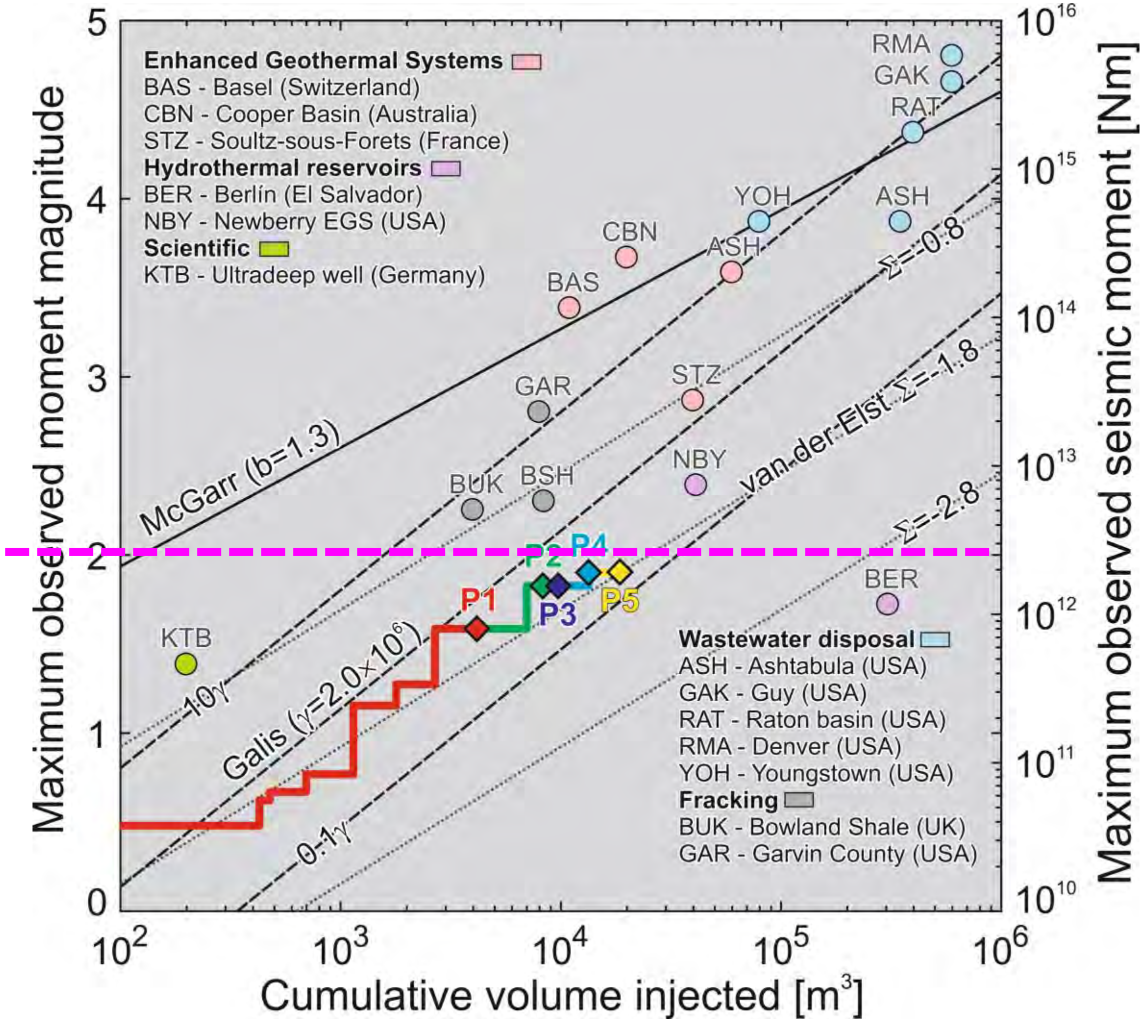




Controlling induced seismicity (Phase P3 P4 P5)

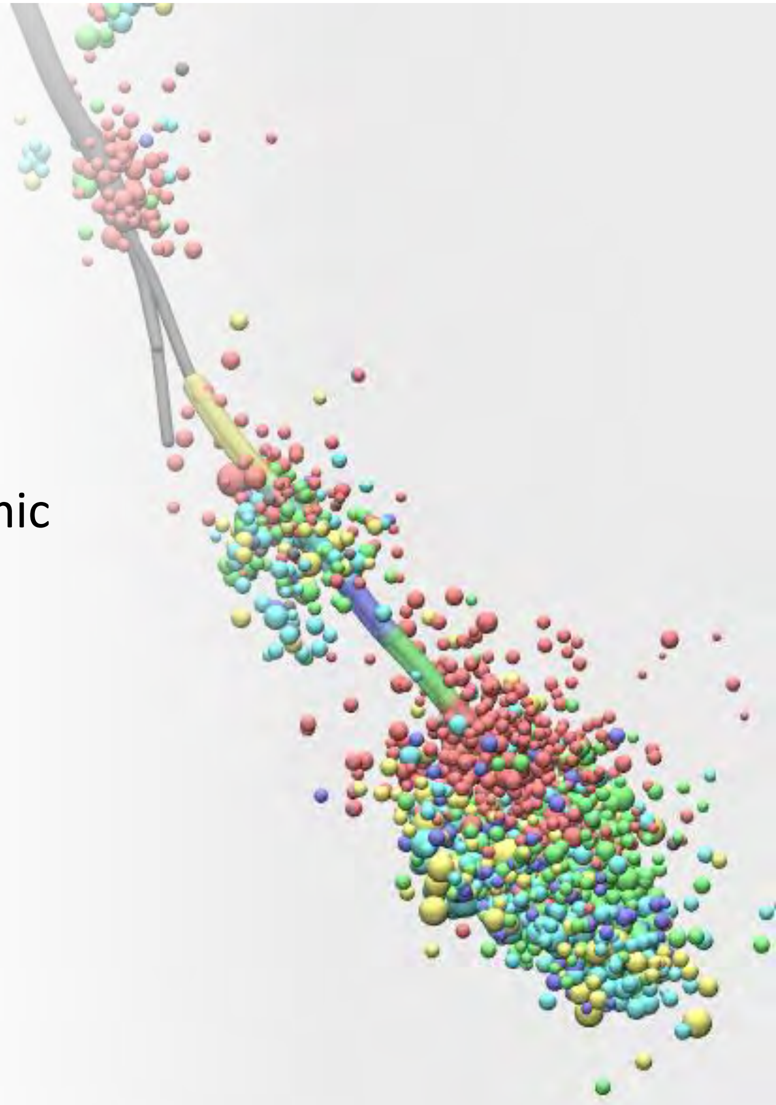
- P3: Reduction of WHP to < 90 MPa,
- P4-P5: Changing injection plan: up to 18 hrs injection / up to 12 hrs resting period, direct reaction on accelerating seismicity and occurrence of large events ▸ Stabilized injection efficiency





Successful control of M^{max} likely due to:

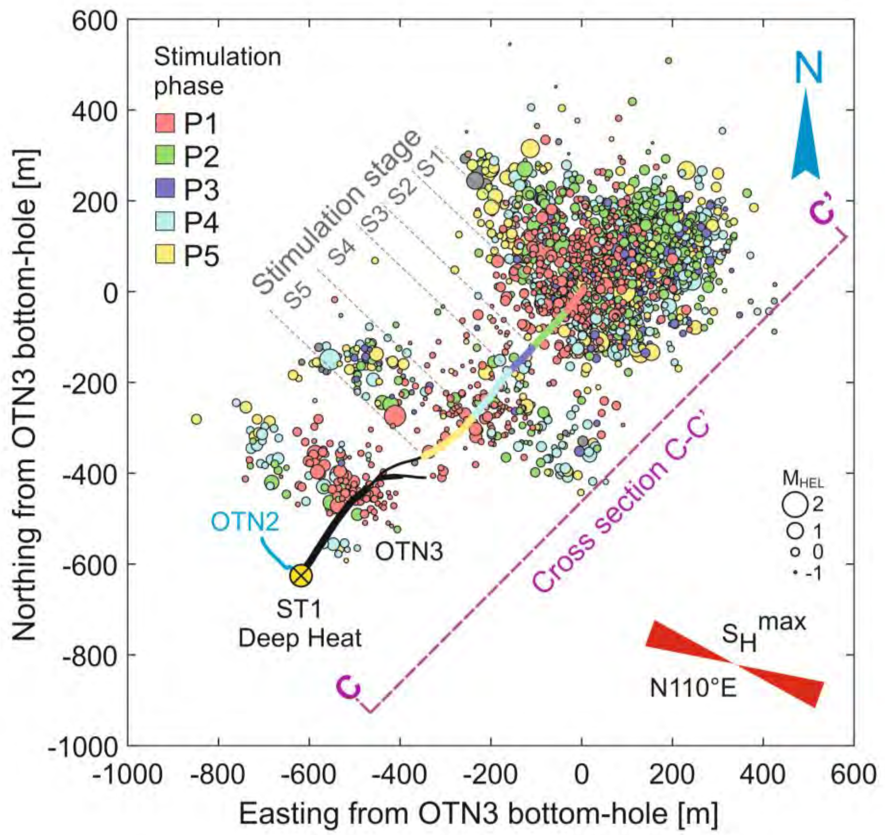
- **Adaptive injection strategy** guided by real-time seismic monitoring - limiting **hydraulic energy input rate**.
- Possible **favorable stress conditions**, and **geological basement structures** of the reservoir
- *...Fortune favours the brave*

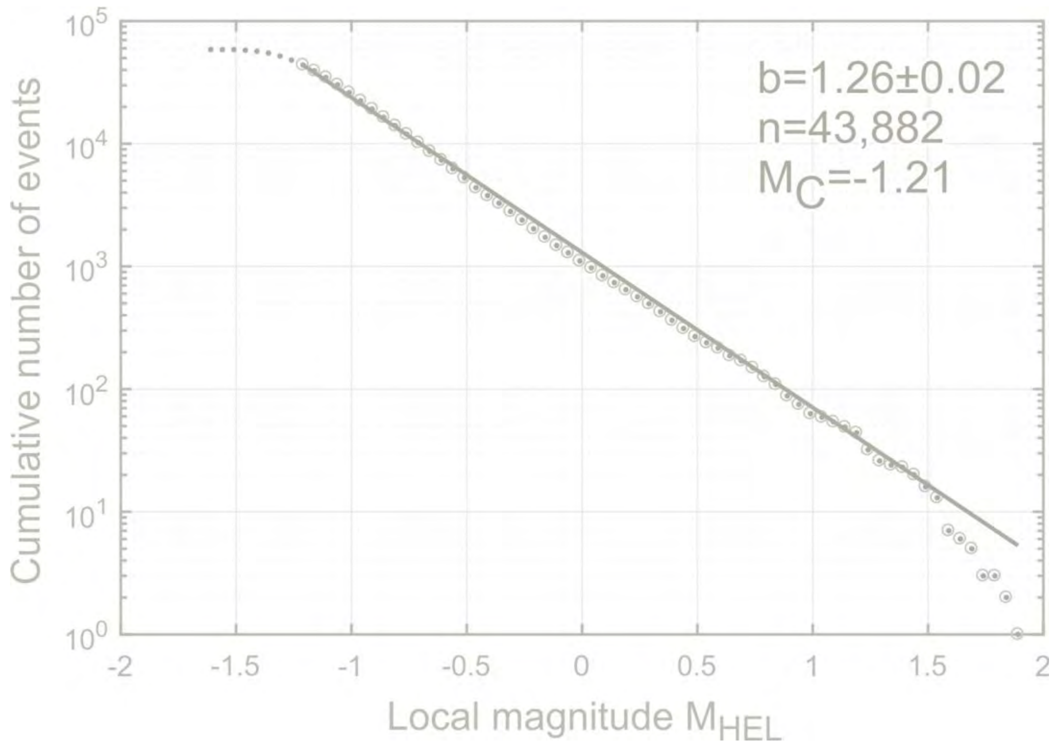


Re-activation of distributed fracture network (1)

- DD relocated data provides no evidence for alignment of seismicity along a large fault
- Damage zones visible in available engineering (log) and geological data
- Significant drop-off in the number of events above M>1.5

  No faults large enough to sustain larger events? Faults can't store enough elasting energy to support a runaway rupture?
- Seismic injection efficiency suggest reactivation of limited fracture network

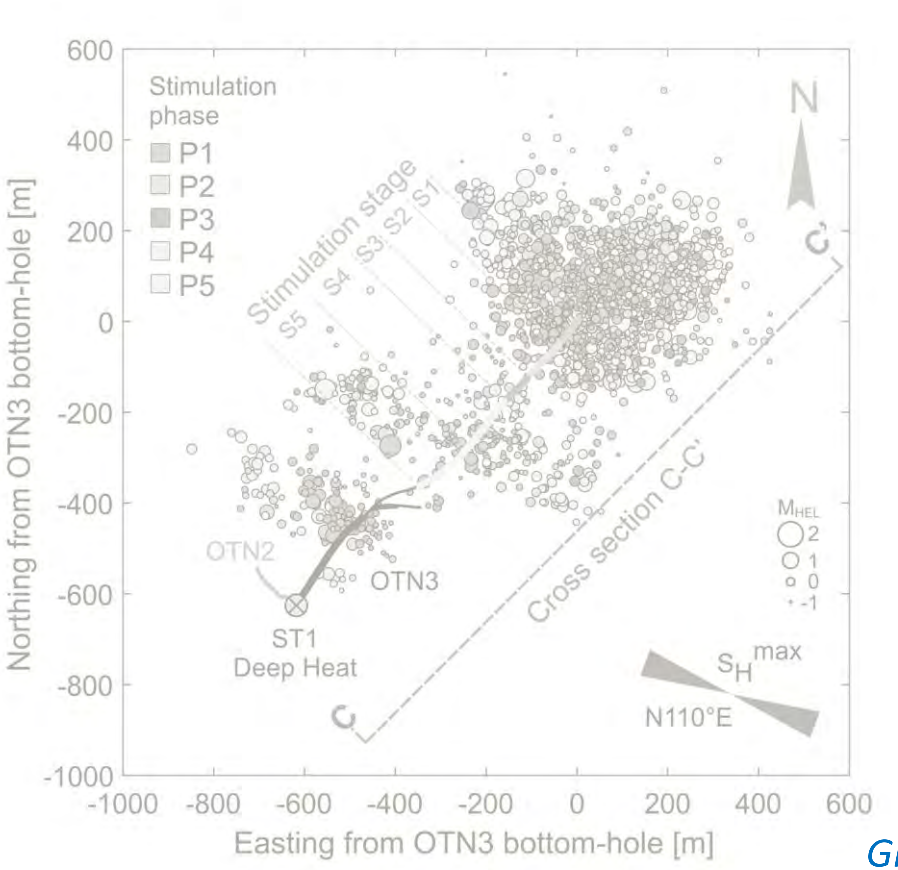


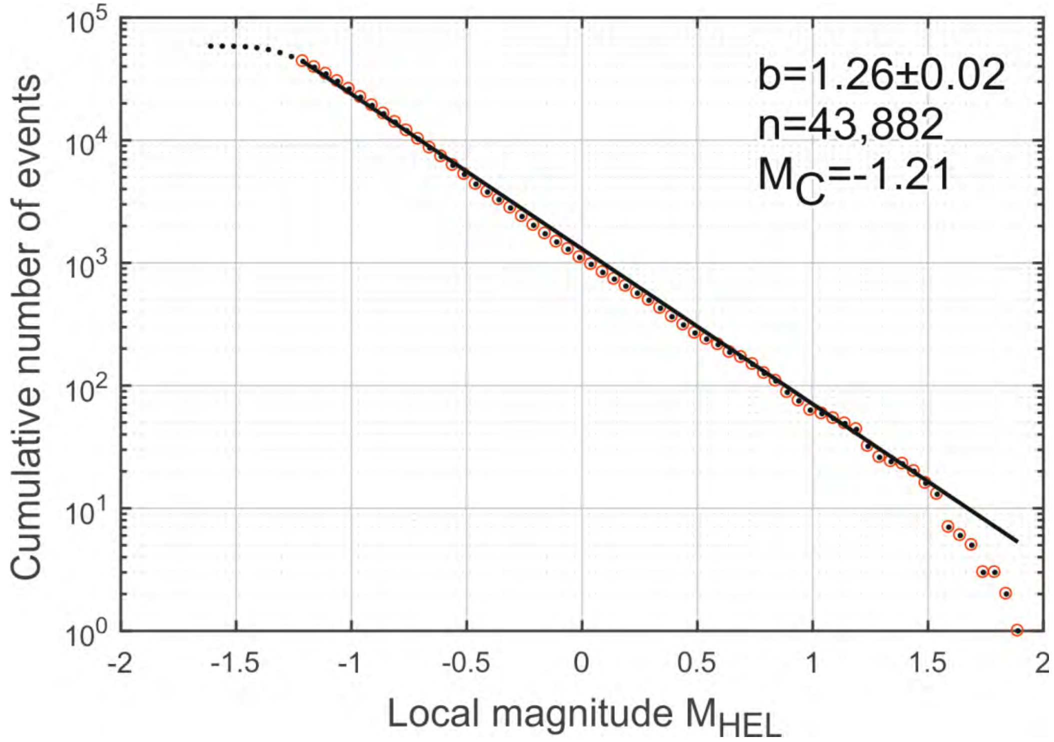


Re-activation of distributed fracture network (2)

- Seismicity shows no evidence for alignment along a large fault
- Damage zones visible in available engineering and geological data
- Significant drop-off in the number of events above M>1.5

  No faults large enough to sustain larger events? Faults can't store enough elastic energy to support a runaway rupture?
- Seismic injection efficiency suggest reactivation of limited fracture network

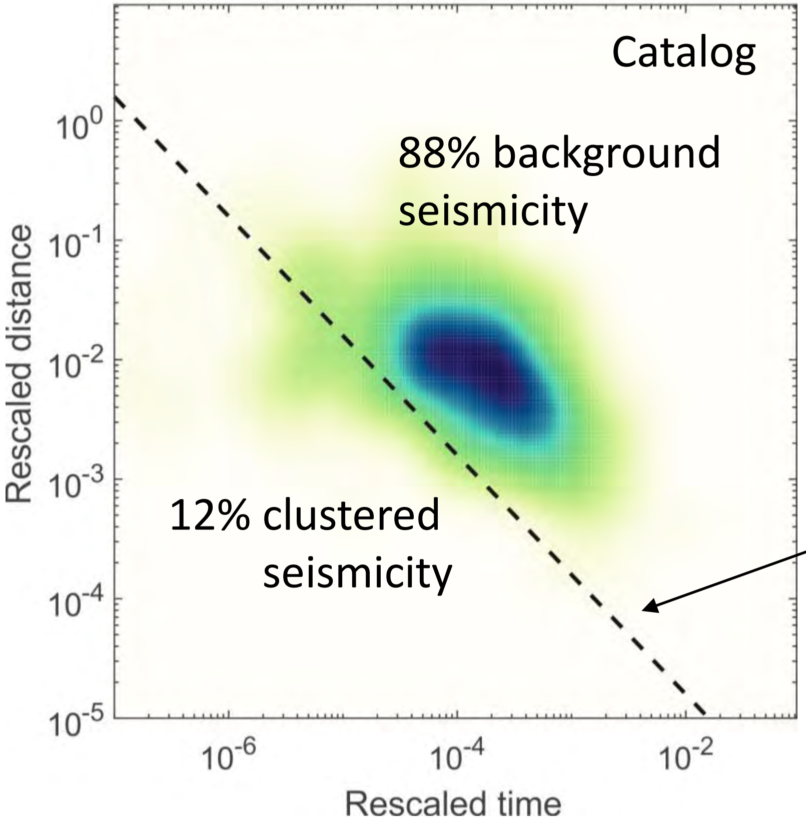


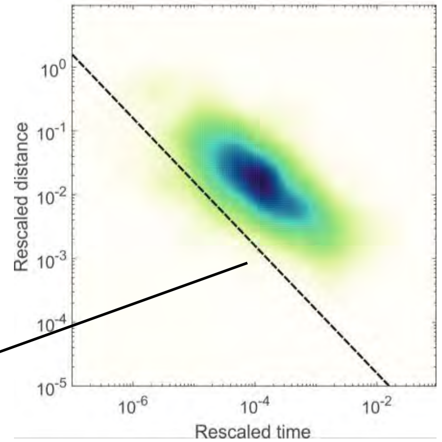


*GR distribution complexity testing following **Lasocki and Papadimitriou, JGR, 2006***

Low stress perturbation (1)

- Lower background tectonic stresses
- No pronounced clustering ‣ minor triggering? ‣ minor stress transfer?
- Relatively rapid dissipation of injected hydraulic energy
- Stationary b-value in later injection phases – no change in deviatoric stress ?
- Hazard seemingly controlled by GR a-value changes



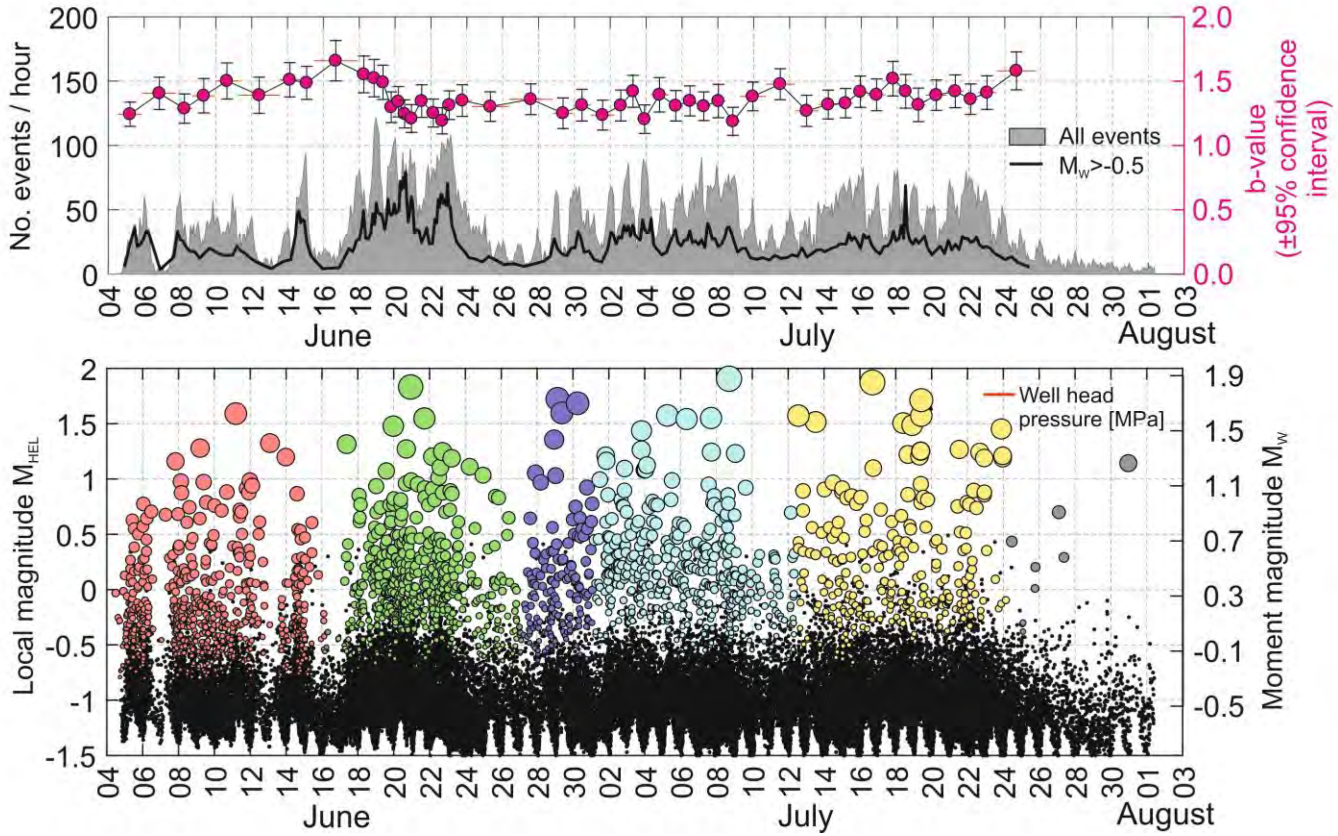


Reshuffled catalog used to select separation level between clustered and background seismicity

Clustering procedure: ***Baiesi and Paczuski, Phys. Rev. E, 2004;*** *Separation clustered-background:* ***Davidsen et al., PRL, 2017***

Low stress perturbation (2)

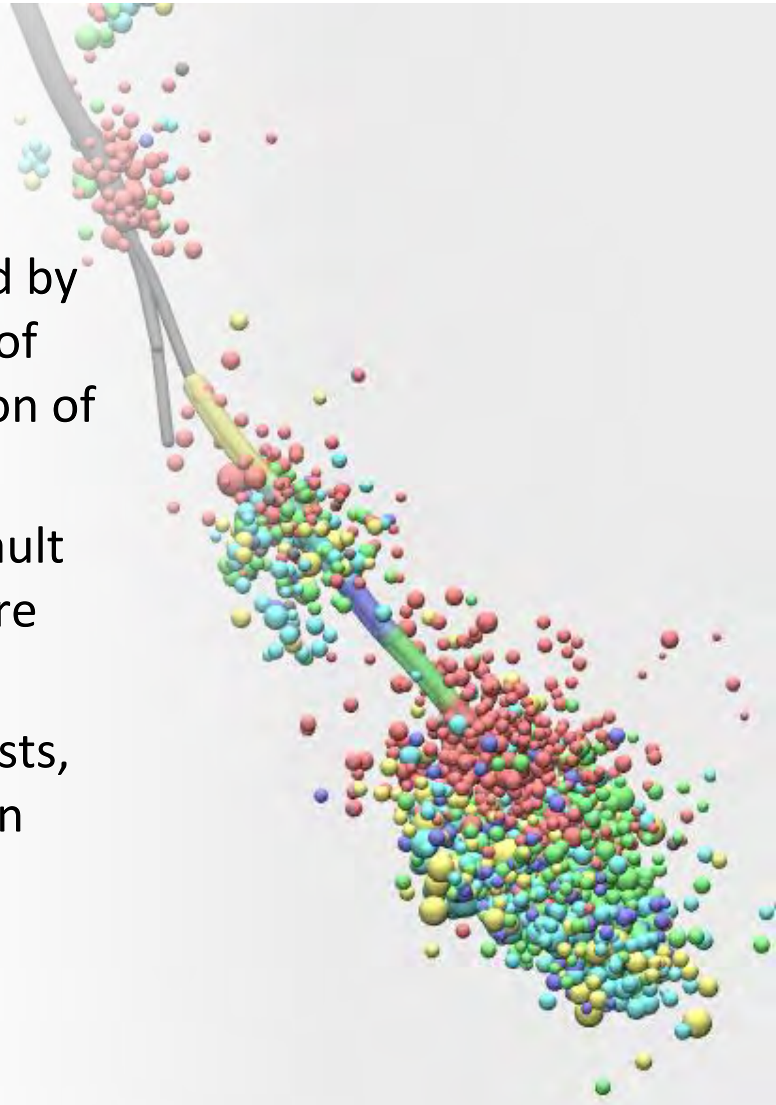
- Lower background tectonic stresses than at other sites (Basel, Pohang)
- No pronounced clustering ▸ minor triggering? ▸ limited stress transfer?
- Relatively rapid dissipation of injected hydraulic energy
- Stationary b-value in later injection phases ▸ no change in deviatoric stress? *(Scholz, 1968)*
- Hazard seemingly controlled by GR a-value changes



*b-value stationarity: ADF test (**Dickey and Fuller, J. Am. Stat. Assoc, 1979**)*

Summary and conclusions

- Project stopping M_{LHEL}2.1 earthquake was successfully avoided by adapting injection operations using near-realtime monitoring of induced earthquake rates, locations, magnitudes, and evolution of seismic and hydraulic energy
- Fluid injection was likely performed into a complex fracture/fault network leading to low stress perturbation. No major faults are known/were found in the reservoir
- Successful operation required close cooperation of seismologists, site operator, TLS team and local authorities during stimulation
- The outcome of the St1 DH project may indicate a possible approach allowing to manage induced seismicity in similar geothermal projects



Thank you very much for your attention!

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https://induced.pl/about

Stay tuned!

- ***Kwiatek et al. (2019), Science Advances, in press***

GFZ Helmholtz Centre Potsdam

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Spare slides

Re-activation of distributed fracture network (3)

- Seismicity shows no evidence for alignment along a large fault
- Damage zones visible in available engineering and geological data
- Significant drop-off in the number of events above M>1.5

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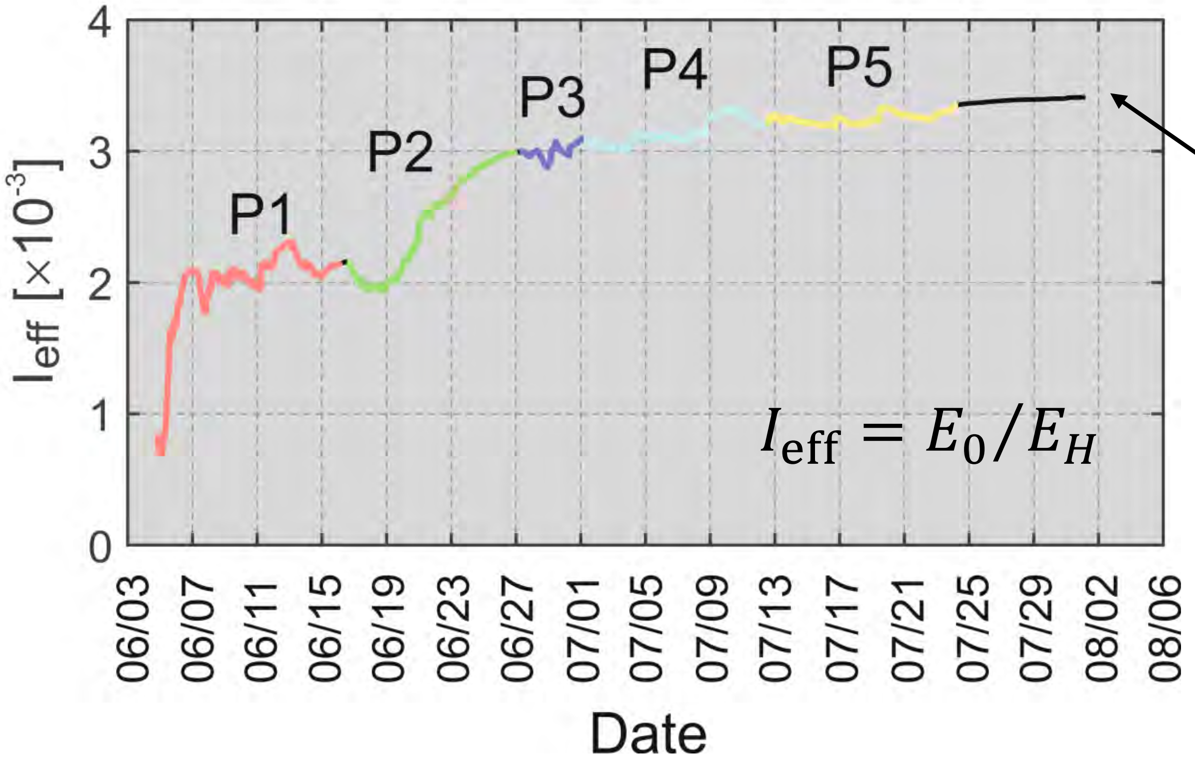


Bowland Shale: 10^{-1}
Horn River Basin 10^{-2}
Basel 7 x 10^{-3}
This study 3 x 10^{-3}
Aspo laboratory 10^{-5}
Horn River Basin 10^{-5}
Barnett: 10^{-9} - 10^{-7}
Laboratory: 10^{-10} - 10^{-7}

Reactivation

Creation

*Seismic injection efficiences **Goodfellow et al., GRL, 2015***

Seismic monitoring networks

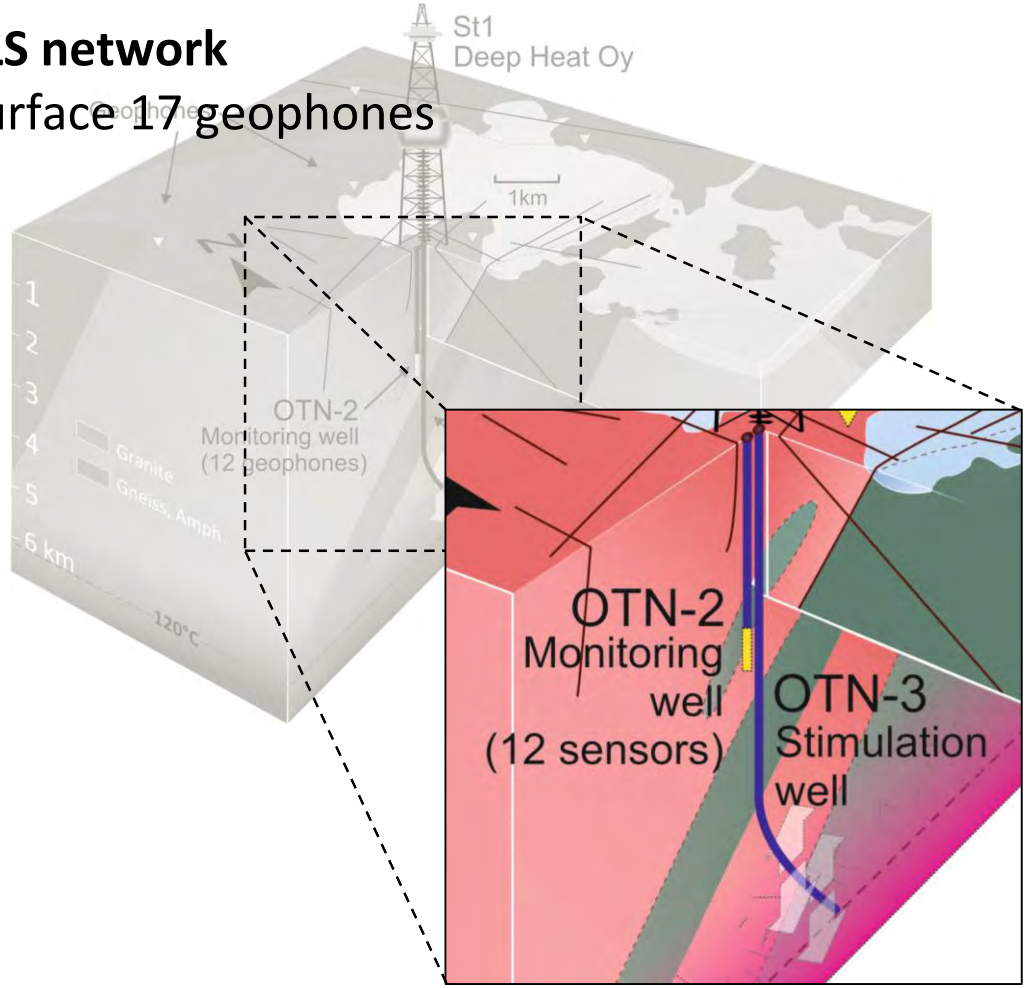
Stimulation

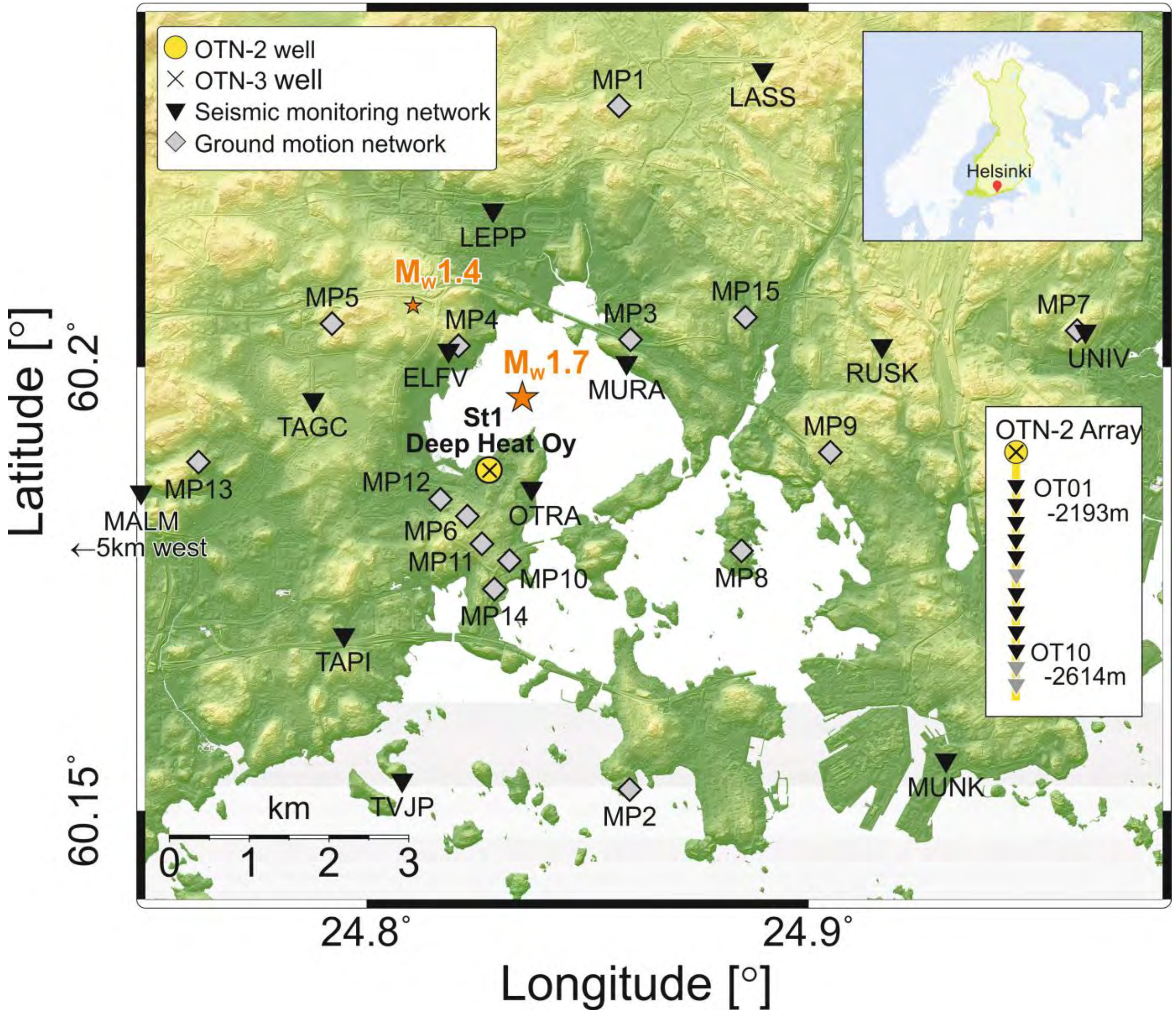
12 Shallow (0.3-1.3 km) borehole geophones

12 Deep (2.0-2.6 km) borehole sensors in OTN-2

TLS network

Surface 17 geophones



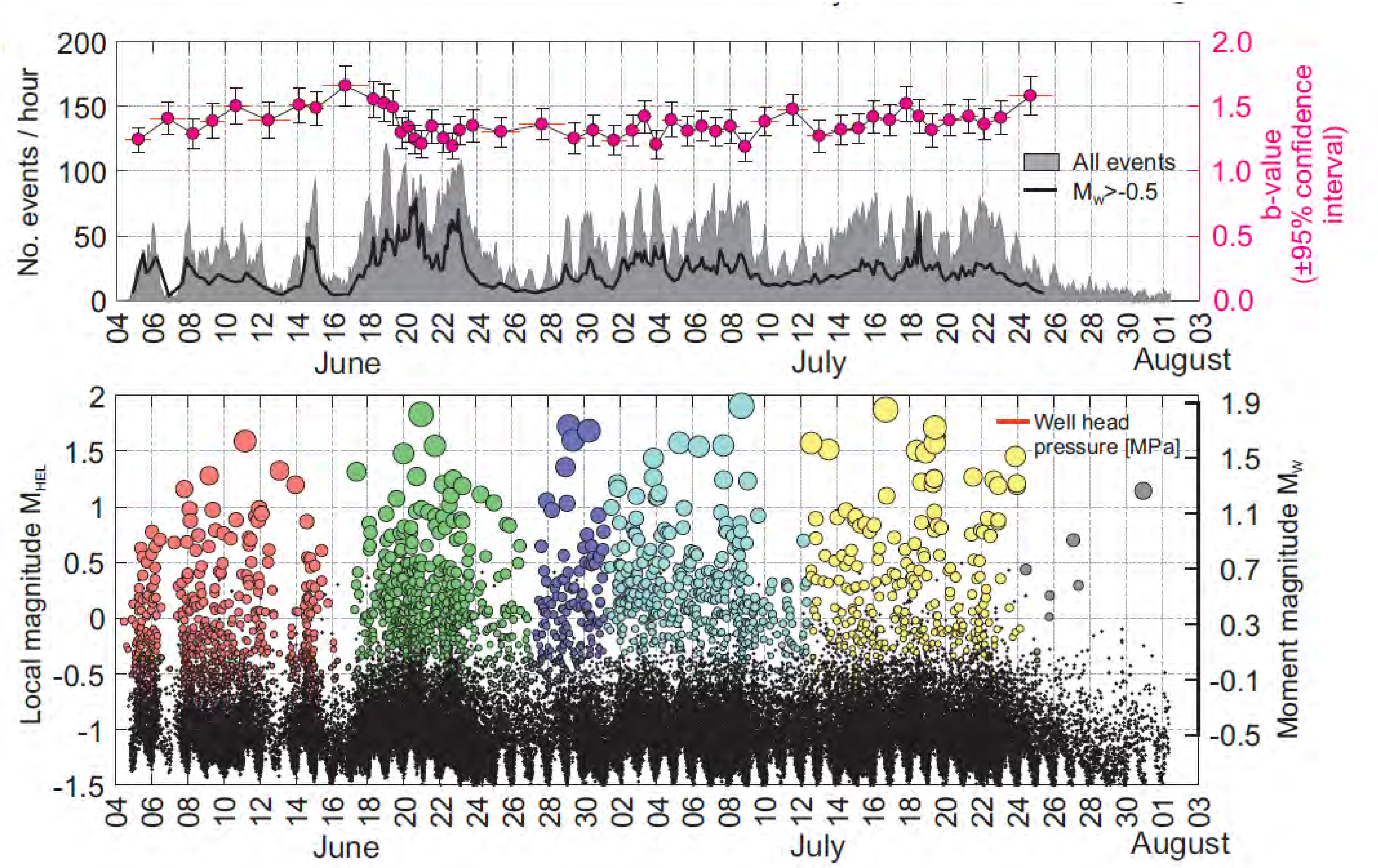


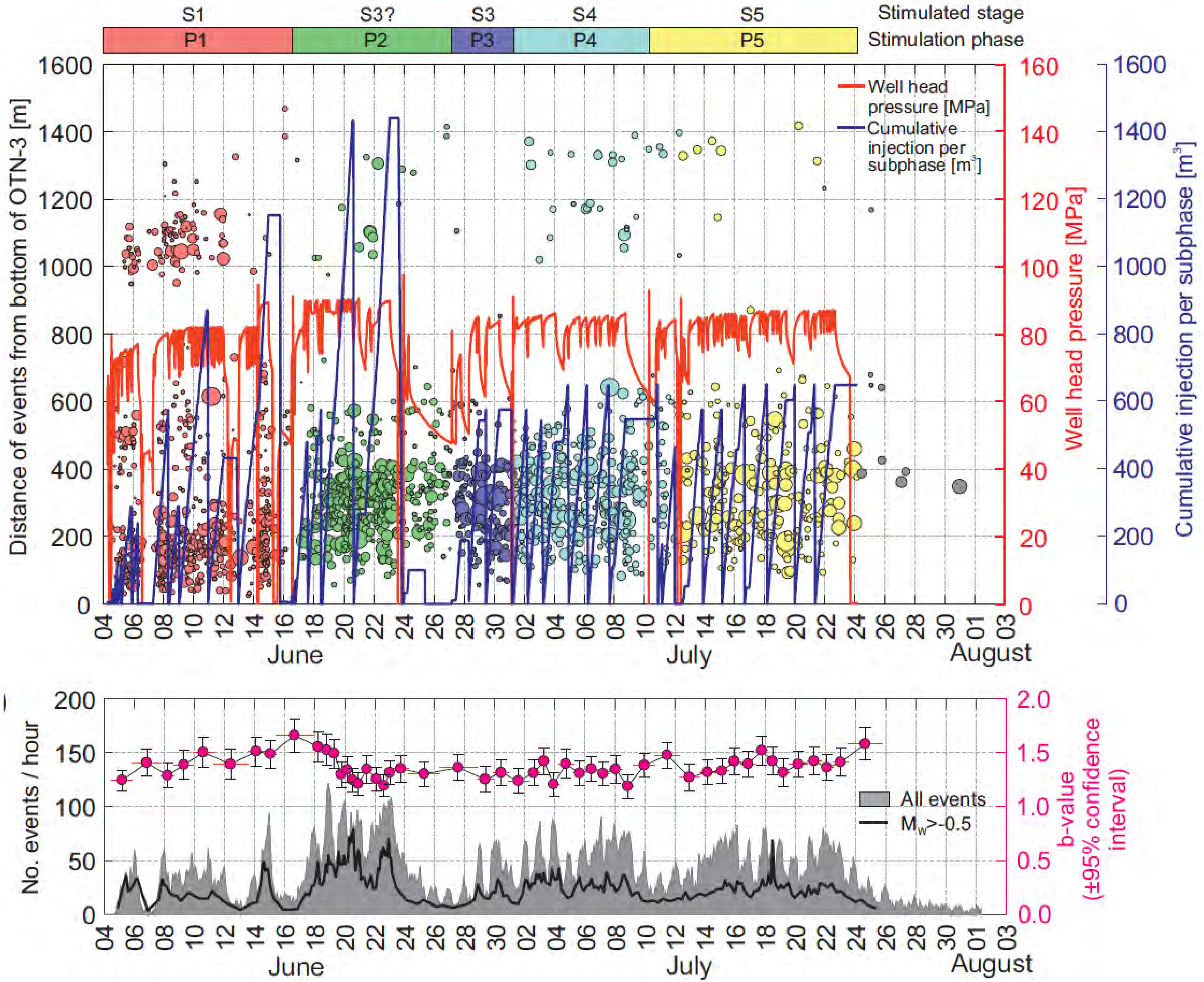
Stress magnitudes at the drill site were estimated from wellbore breakouts and minifrac shut-in pressures measured down to a depth of 1.8 km (*13*). Extrapolated to 6.1 km depth, these were estimated to be a S_H^{min}=110 MPa, a S_V=180 MPa, and a S_H^{max}=240 MPa. Pore pressures were assumed to be hydrostatic, equaling to approx. 60 MPa. Assuming a friction coefficient of 0.6, these results suggested that optimally oriented fractures and faults could be readily activated with moderate fluid pressure increases.

Data extension and refinement

Data reprocessing

- data refinement
- data reduction:
  - Full catalog including detections (~43,000 earthquakes above M-1.21), sometimes constrained to M-1.0 due to night-day cycle **> energy budget, b-value**
  - Relocated catalog using DD method (~1,950 earthquakes) with relative location precision ~60 m (95% confidence ellipse) **> spatio-temporal evolution, clustering**

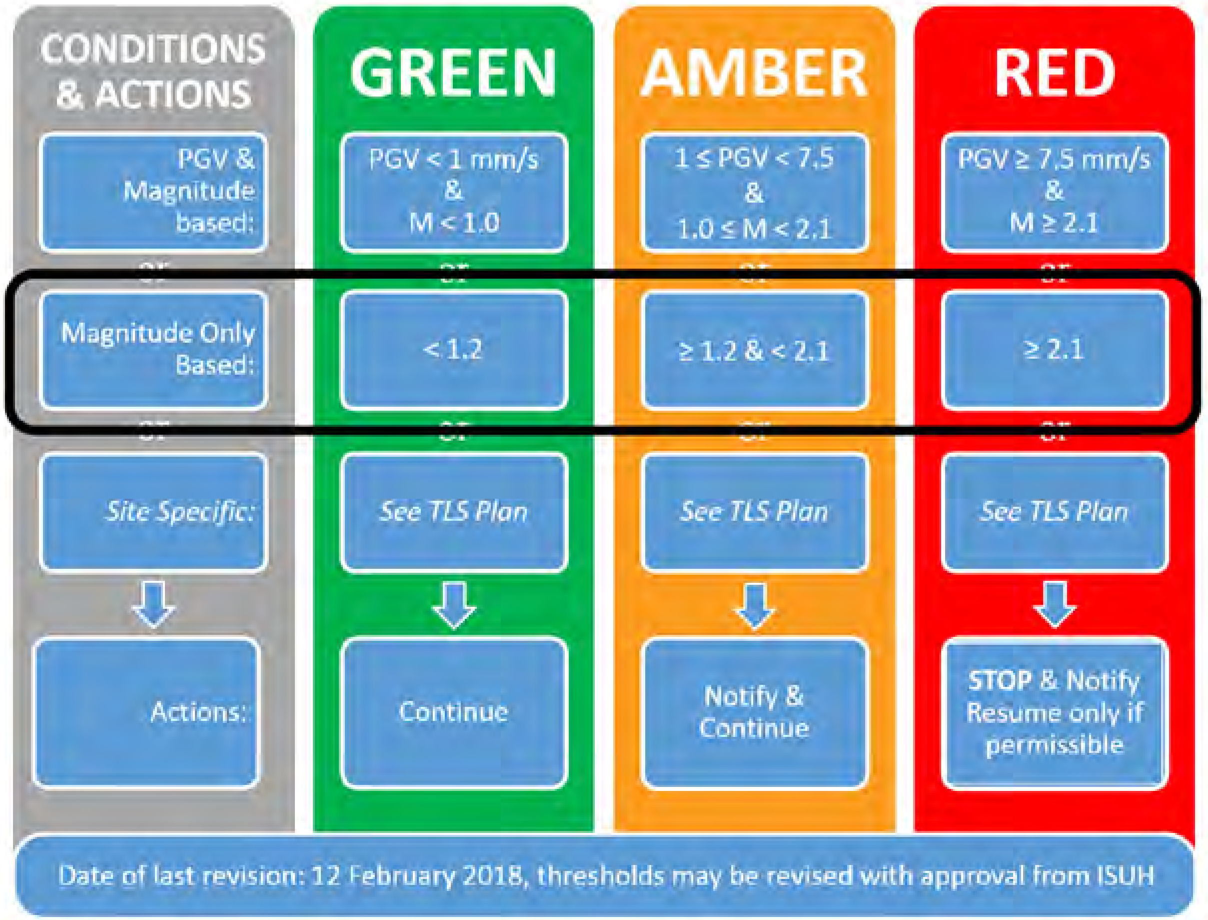




S1
S3?
S3
S4
S5
Stimulated stage
P1
P2
P3
P4
P5
Stimulation phase
Well head pressure [MPa]
Cumulative injection per subphase [m3]
Distance of events from bottom of OTN-3 [m]
Well head pressure [MPa]
Cumulative injection per subphase [m3]
June
July
August
All events
Mw>-0.5
No. events / hour
b-value (±95% confidence interval)

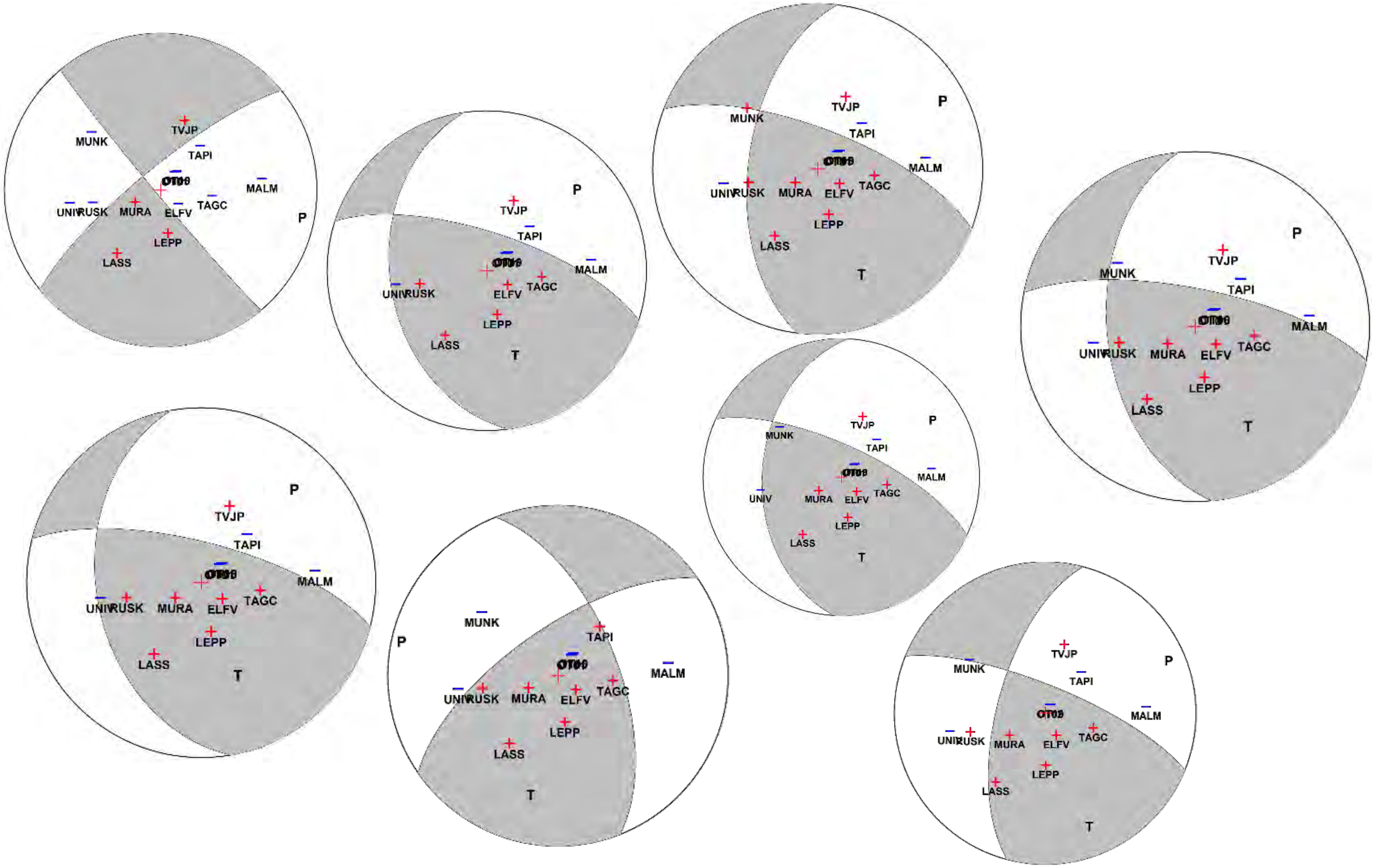
Traffic Light System

- Thresholds based on PGV (critical facilities located nearby)
- All M_{LHEL} > 1.2 reported within 20 minutes to local authorities.
- M_{LHEL} > 2.1 Stop of the stimulation (...and waiting for approval from Finnish Authorities)



ARUP

Mechanisms



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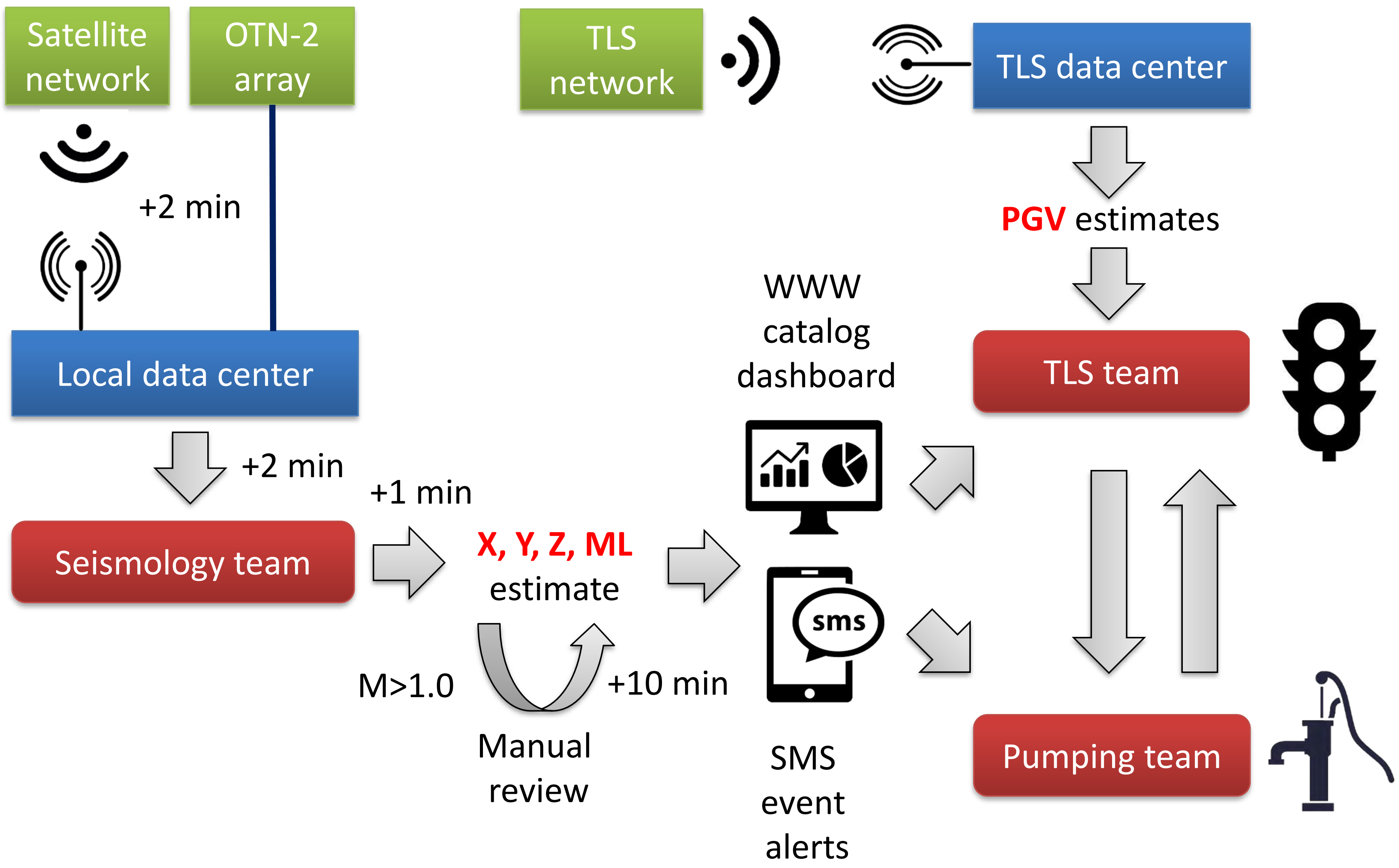
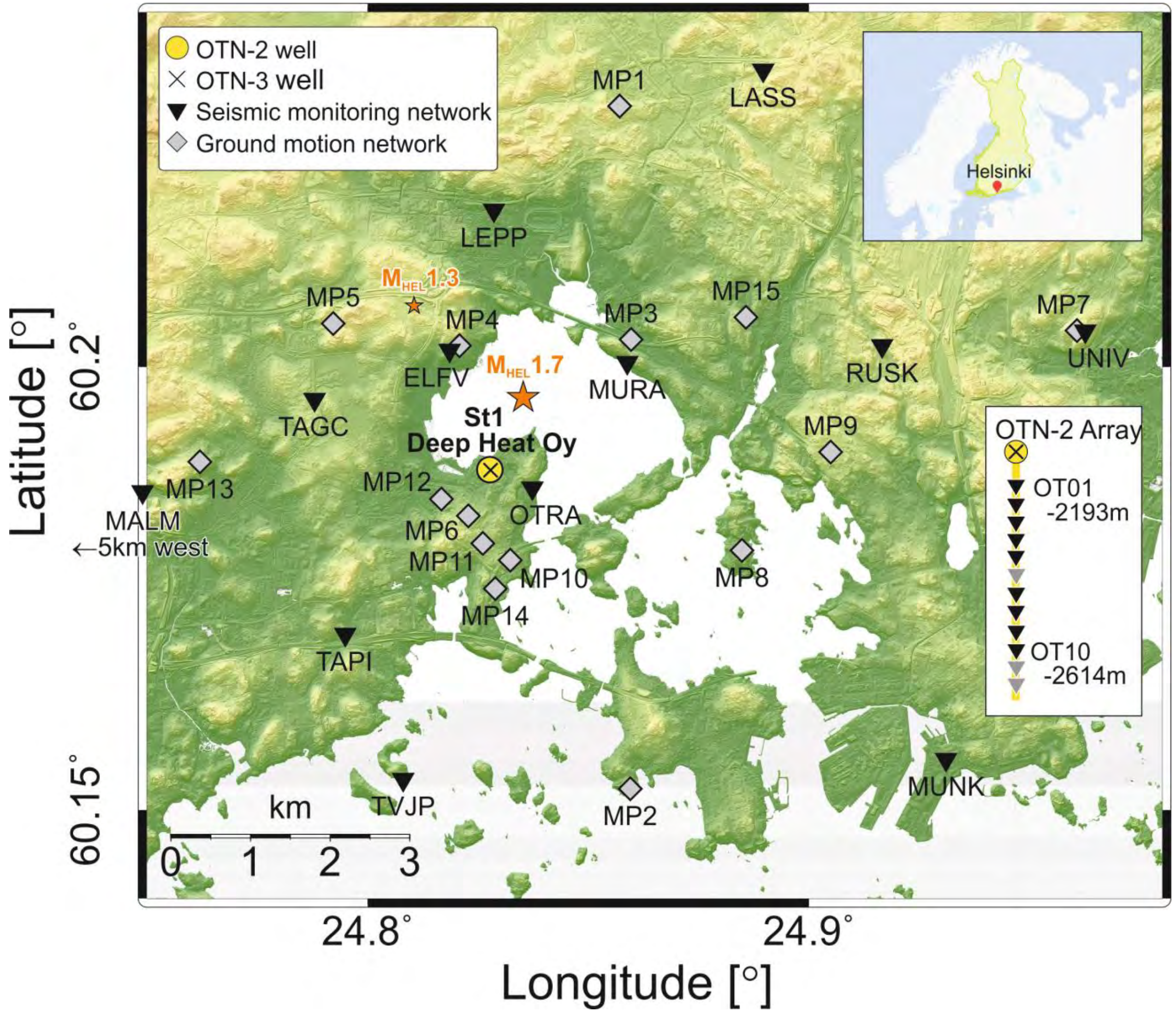
Seismic center operation

- Performance for M>1.1 without/with manual reprocessing: 5 / 15 minutes



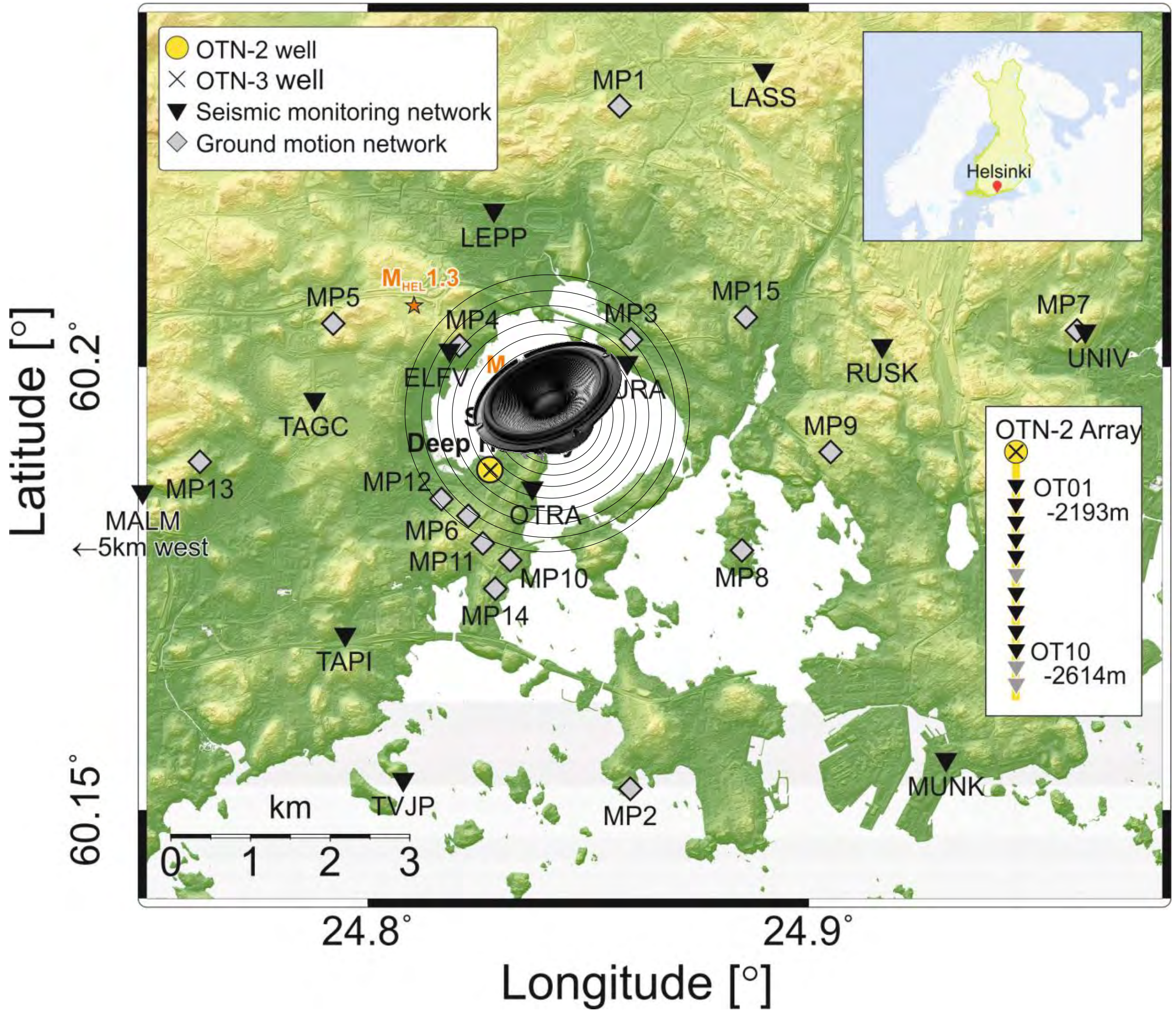
Public response

- No complaints on ground motions during whole stimulation
- ... but nature likes to surprise us



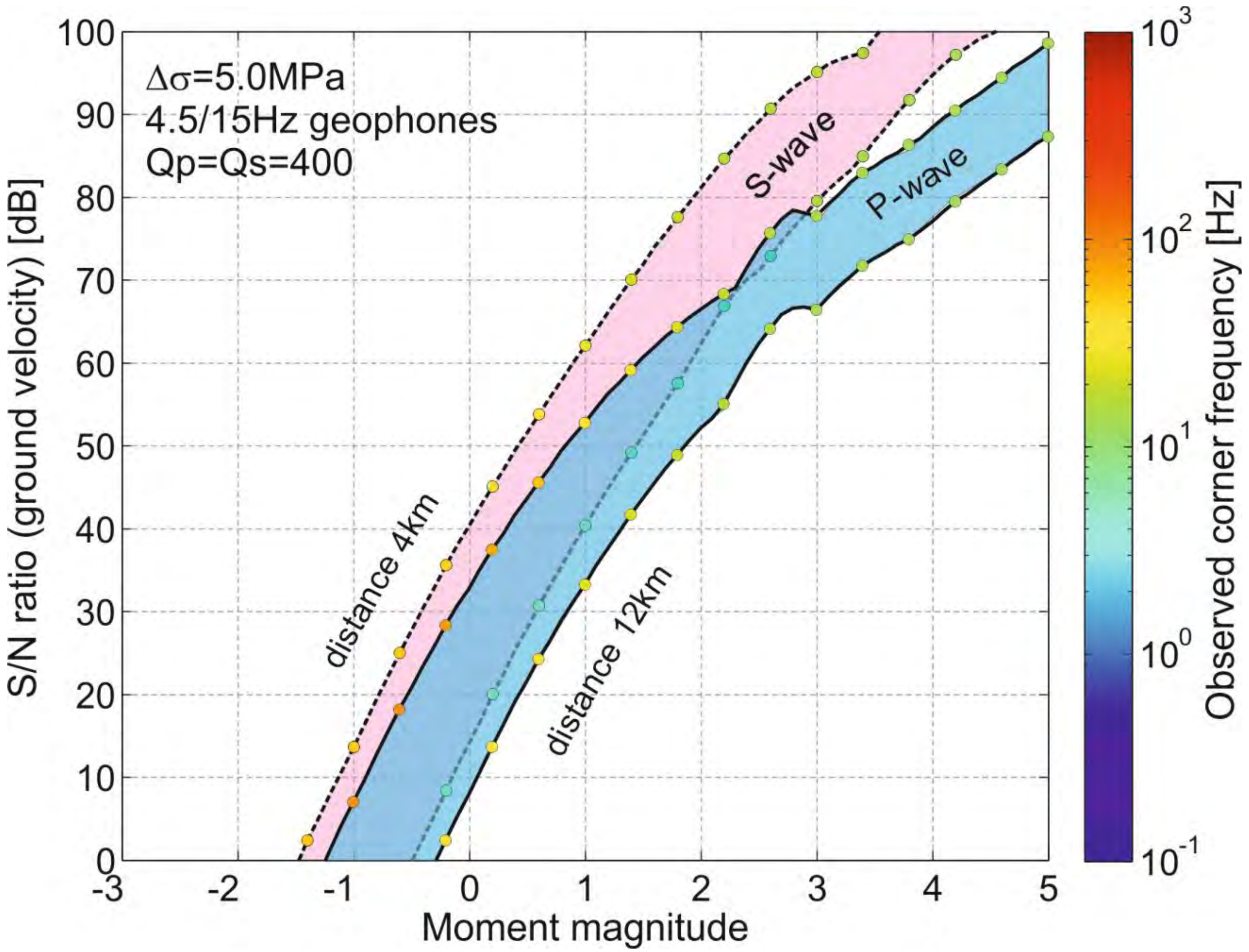
Public response

- Over 60 complaints related to audible earthquake signals
- Remedy: Don't inject in the night



Detection limits

- Target: TLS (location+magnitude), tracking fracture network (optional)
- Outcome: EQs with M > -0.3 possible to locate, detection limit M ≅ -1.4



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Courtesy of fastloc GmbH