Limits on detection and analysis of (induced) earthquakes

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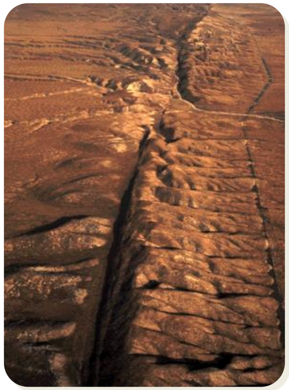
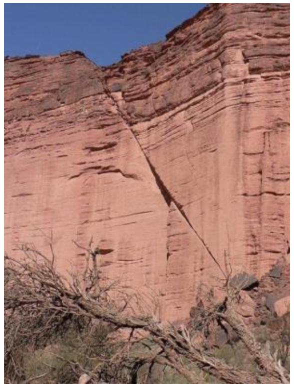
Detection and analysis of small seismic events

- HR monitoring allows for better understanding of seismo-mechanical processes occuring in geo-reservoirs.
- Linking field studies with laboratory experiments.
  Understanding physics of earthquakes across scales.
  Development of in-situ geo-labs to study induced seismicity.
- Detection limits in various conditions not well established for small earthquakes.

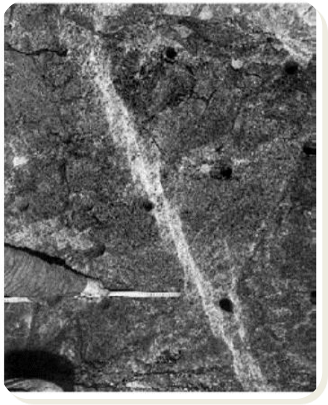
100km-scale



km-scale



m-scale



mm-scale

micro- nano- pico- seismicity

Source radius [m]	10^5	10^4	10^3	10^2	10^1	10^0	10^{-1}	10^{-2}	10^{-3}

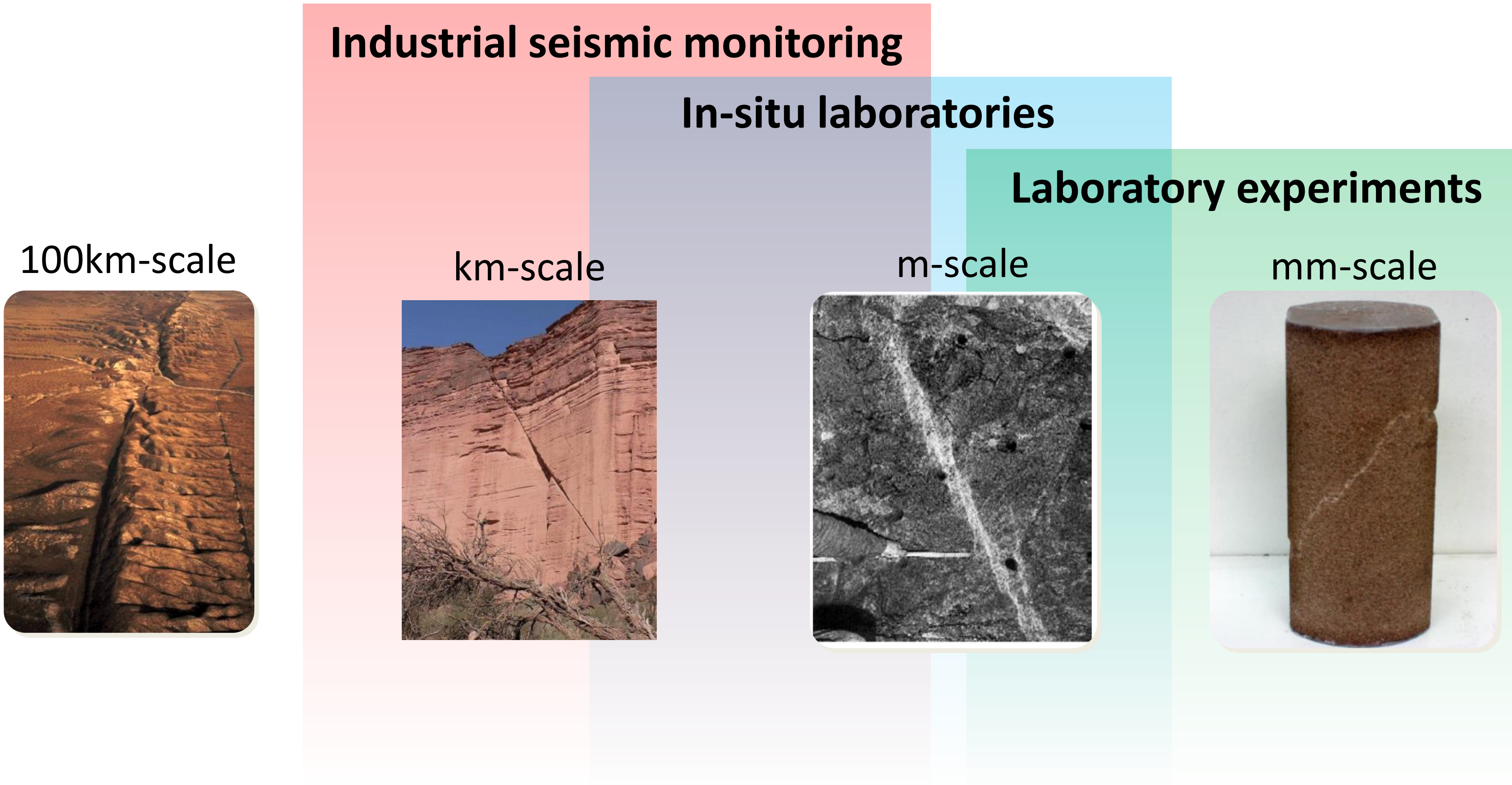
Moment magnitude	8	7	6	5	4	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8

Outline

- Seismic monitoring at very small (fault) scales.
- Modelling theoretical limits to detection and reliable assessment of source properties.
- Case study: Hydraulic fracturing monitoring.
- Summary and conclusions.

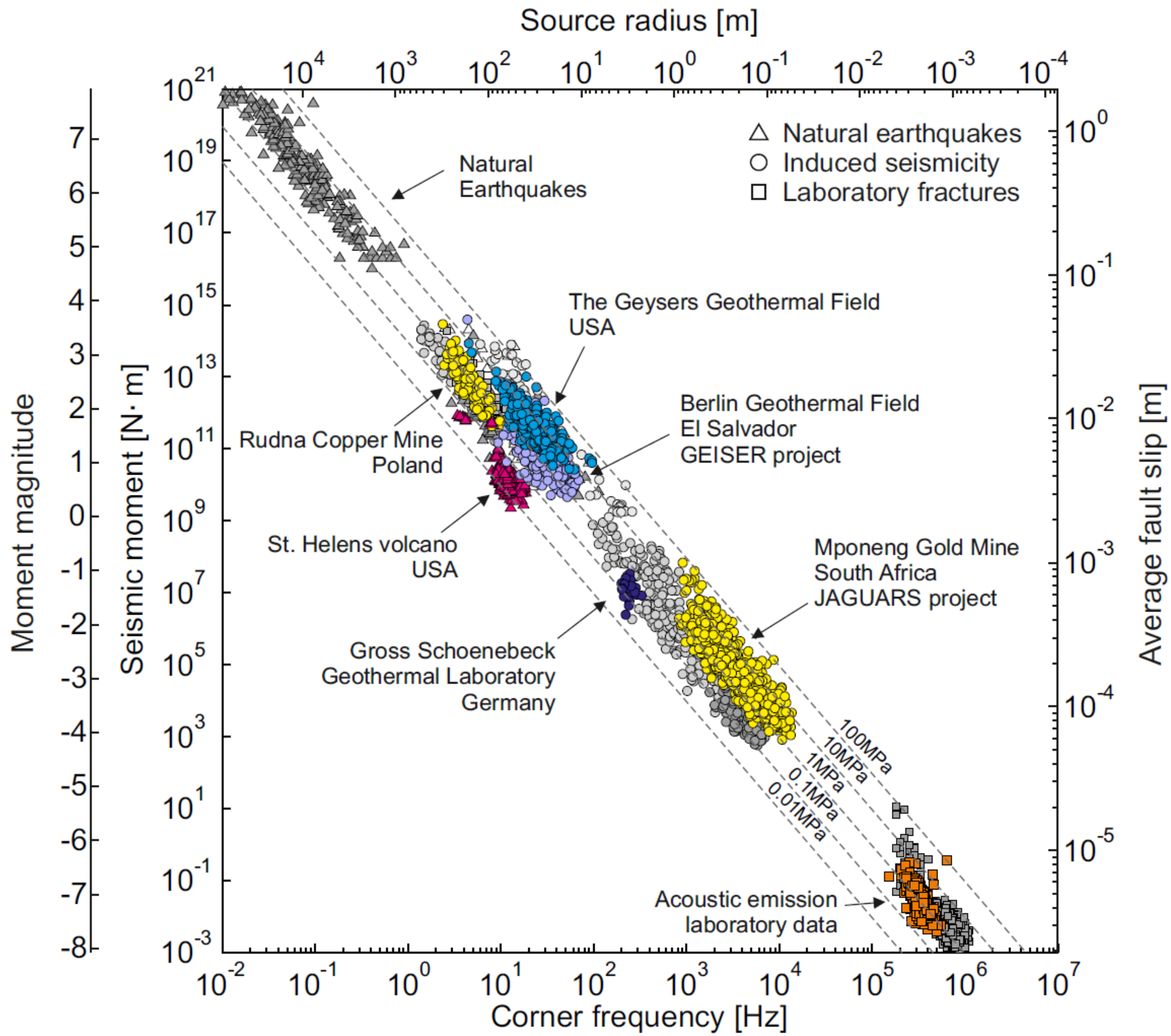
Starting point: Monitoring target

- Know source properties of earthquakes that are your monitoring target:
  - length scale (target fault sizes)
  - rupture dynamics (slow/fast earthquakes)



modified after: ***Kwiatek et al., BSSA, 2011****; see also:* ***Bohnhoff et al., System Erde, 2016***

Starting point: Monitoring target



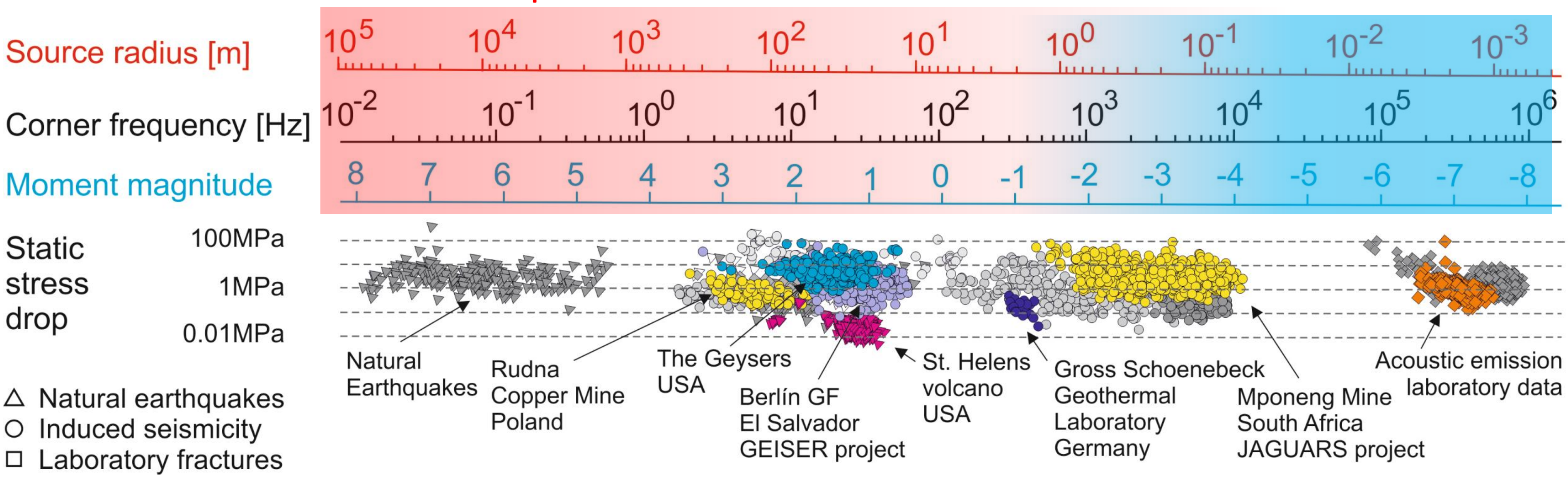
modified after: ***Kwiatek et al., BSSA, 2011****; see also:* ***Bohnhoff et al., System Erde, 2016***

Starting point: Hardware

- ~~*„15-Hz phone is enough"*~~ *– not really for in-situ labs*
- Hardware limitations: lack of sensitivity, low sampling rate, inappropriate sensors
- It's virtually impossible to monitor in full frequency range
  - Bad acquisition has potential serious implications for intepretation

Geophones+Accelerometers

Acoustic emission sensors



sensors' pictures: www, K. Plenkers

Monitoring in cm- to 100m- scale: JAGUARS project (2007-2009)

- Mponeng deep gold mine, South Africa.
- Source physics experiment

https://induced.pl/jaguars

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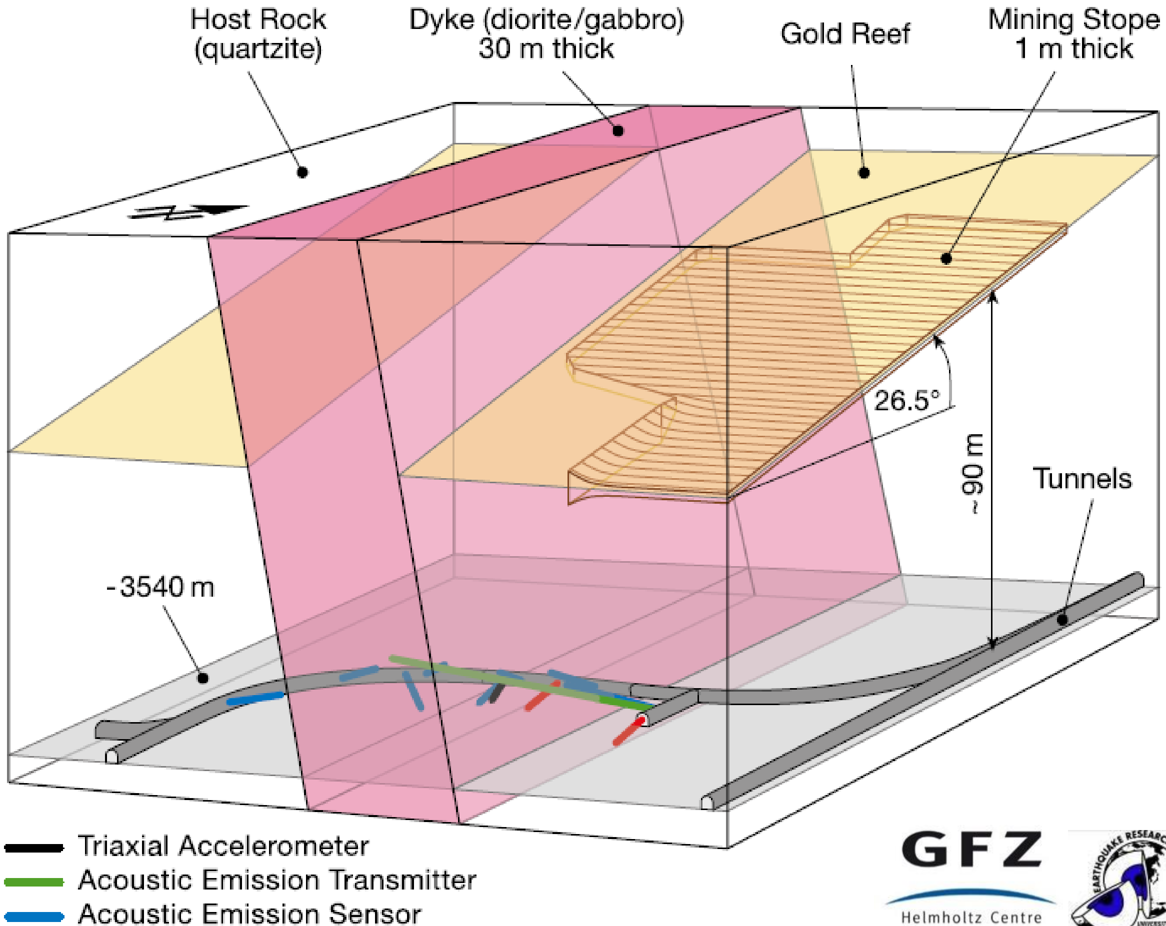
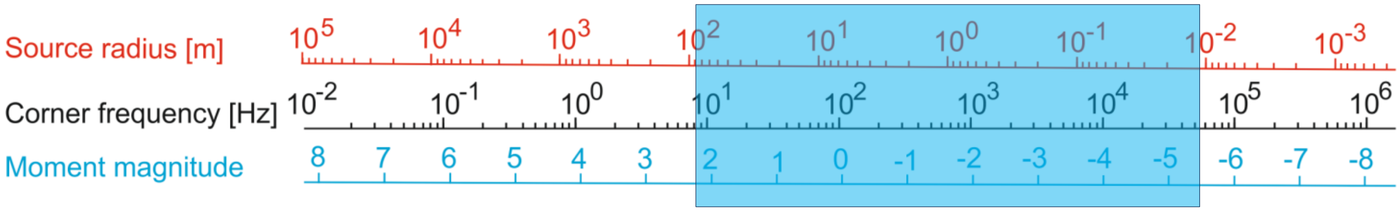
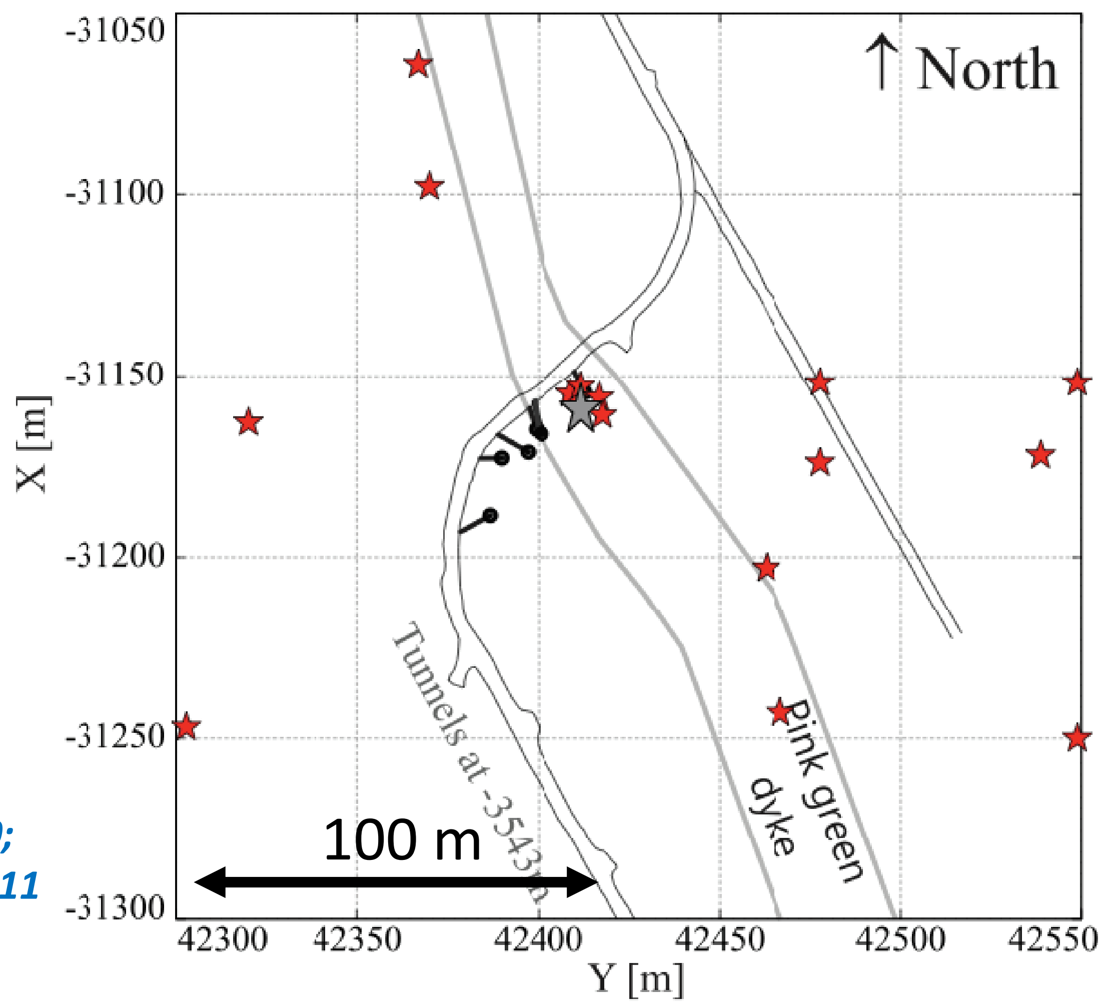


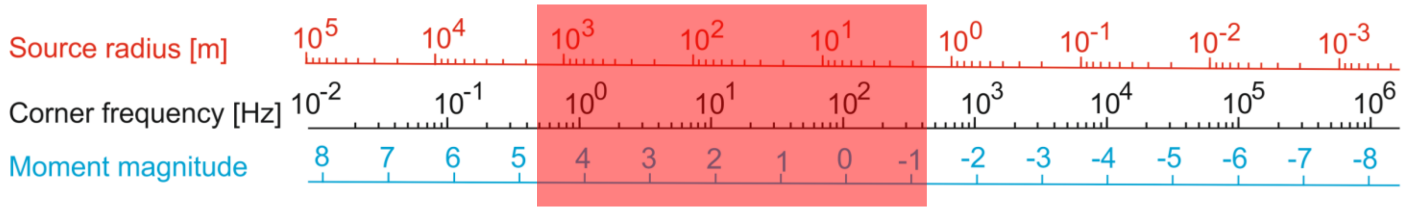


Merry Christmas earthquake 2007.12.27 M_W2.1 case

- Local mine network (geophones) located 6 aftershocks.
- Most of EQs outside of frequency band of geophone network ▸ no gain from close-by geophones!



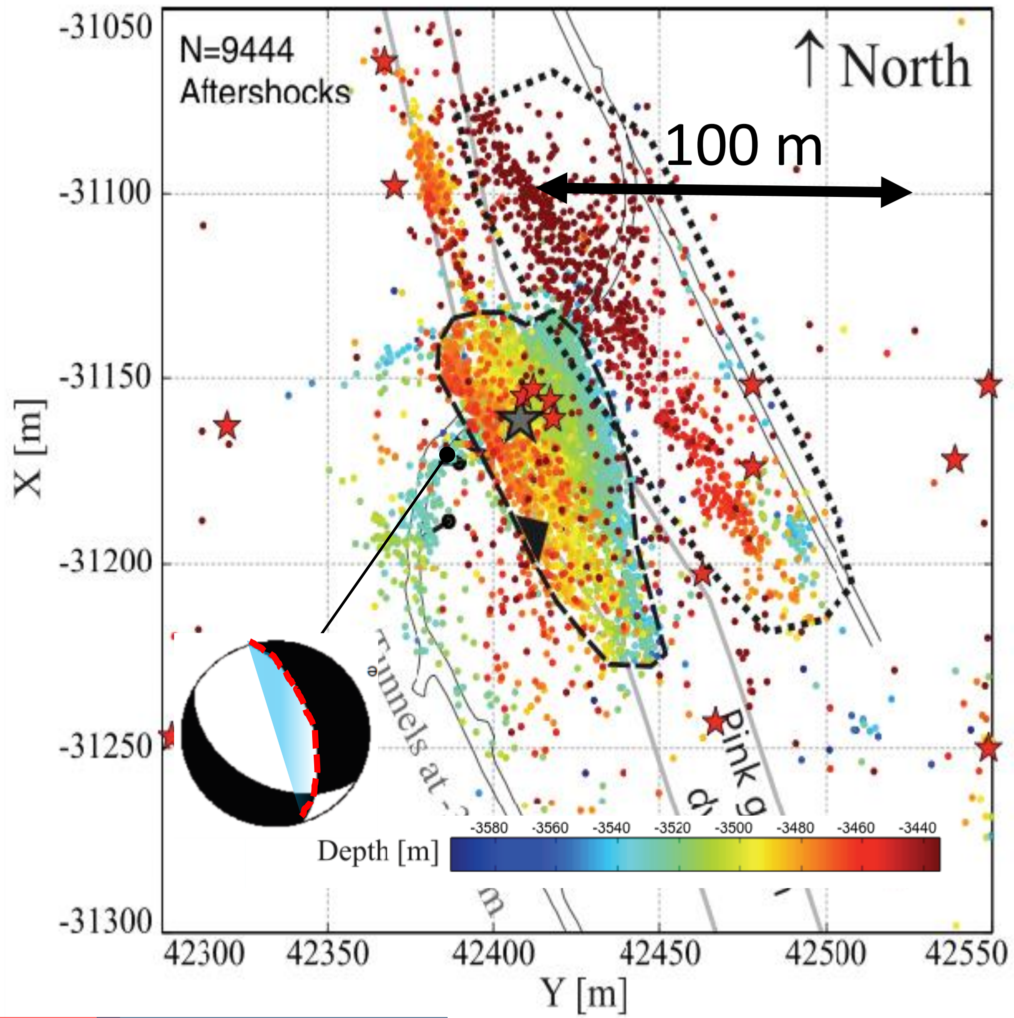
Plenkers et al. SRL, 2010; Plenkers et al., BSSA, 2011



K. Plenkers, PhD thesis

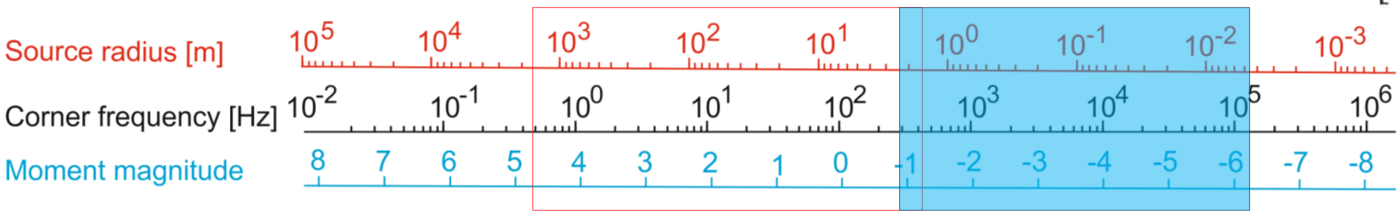
Merry Christmas earthquake 2007.12.27 M_W2.1 case

- Nearly 30,000 aftershocks recorded by JAGUARS network ($-5.5 < M_W < -0.8$)
- Allowed to link observations from lab experiments to seismicity in-situ
- Appropriate sensor installation key element of HF monitoring success.



https://induced.pl/jaguars

Plenkers, Kwiatek et al. SRL, 2010;
Plenkers et al., BSSA, 2011

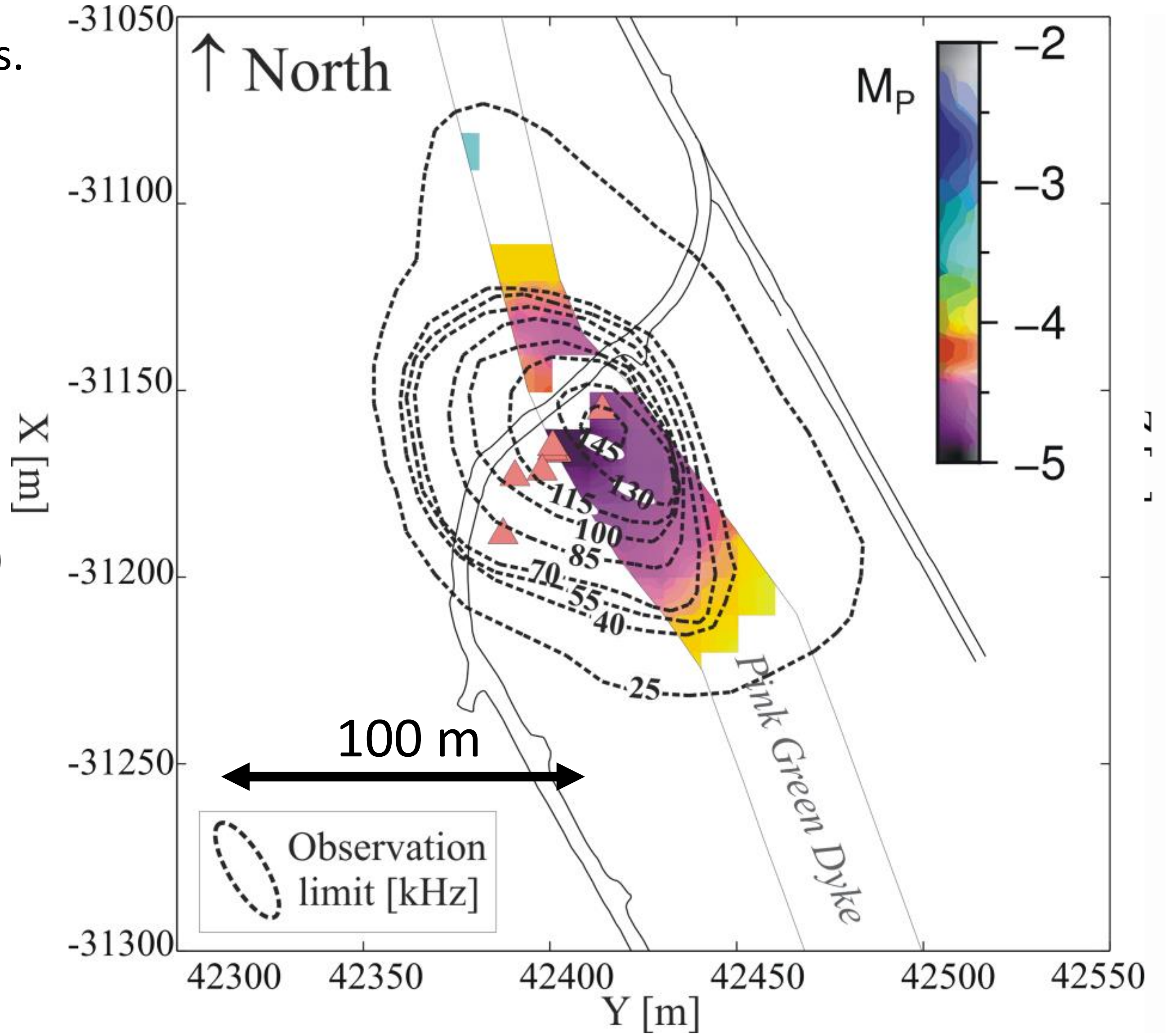


In-situ detection limits for ultra-small events

EQs mostly detected by acoustic emission sensors. Too high frequencies for PZ accelerometer.

- M_W < -6.0 meters away from the sensor
- M_W < -5.0 ca. 10 - 20 meters away
- M_W < -4.0 ca. 100 – 200 m, ca. 10 kHz fc

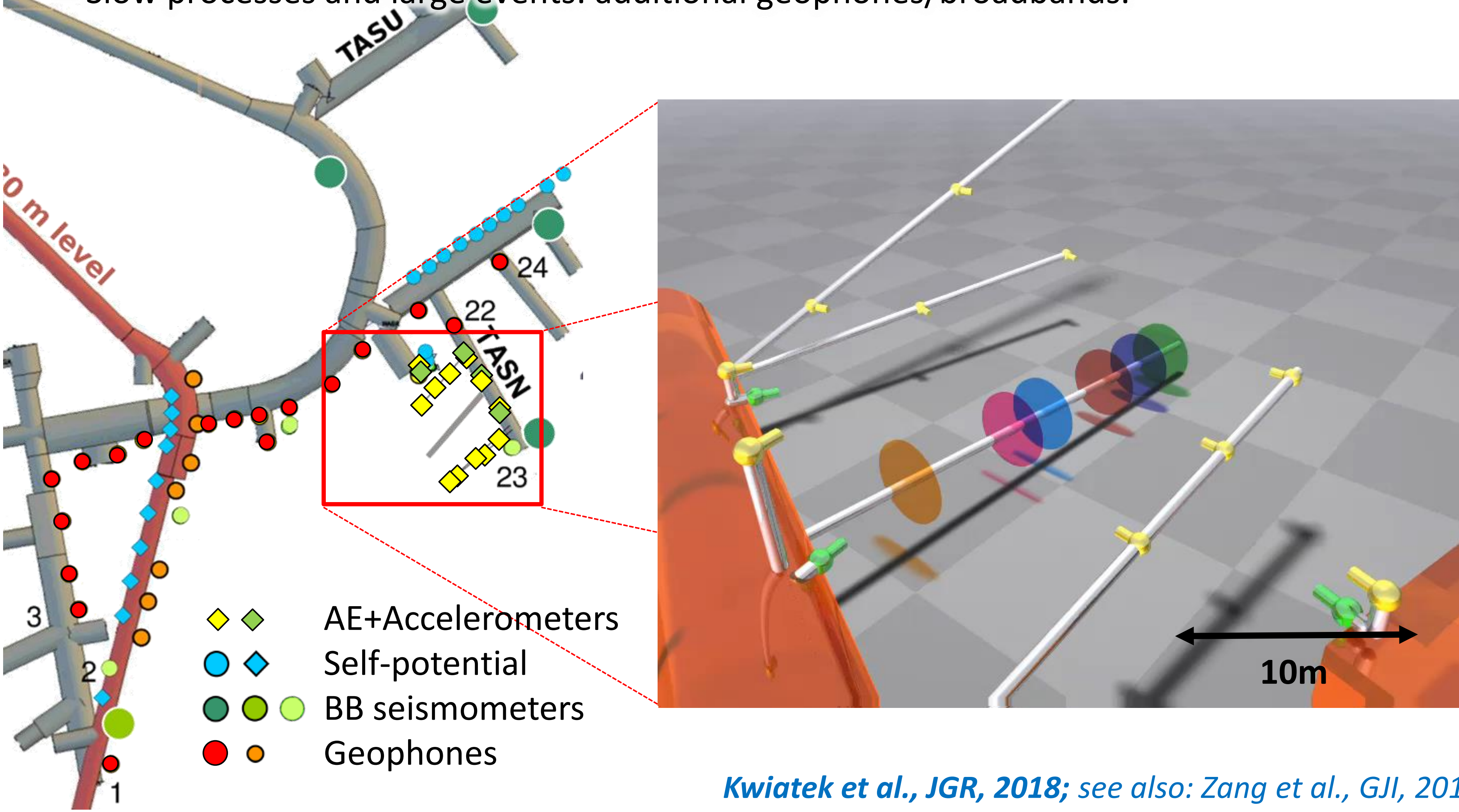
Note: this is favorable case (low attenuation!)



Plenkers, Kwiatek et al. SRL, 2010; Plenkers et al., BSSA, 2011

Monitoring hydraulic stimulation in dm-scale (NOVA)

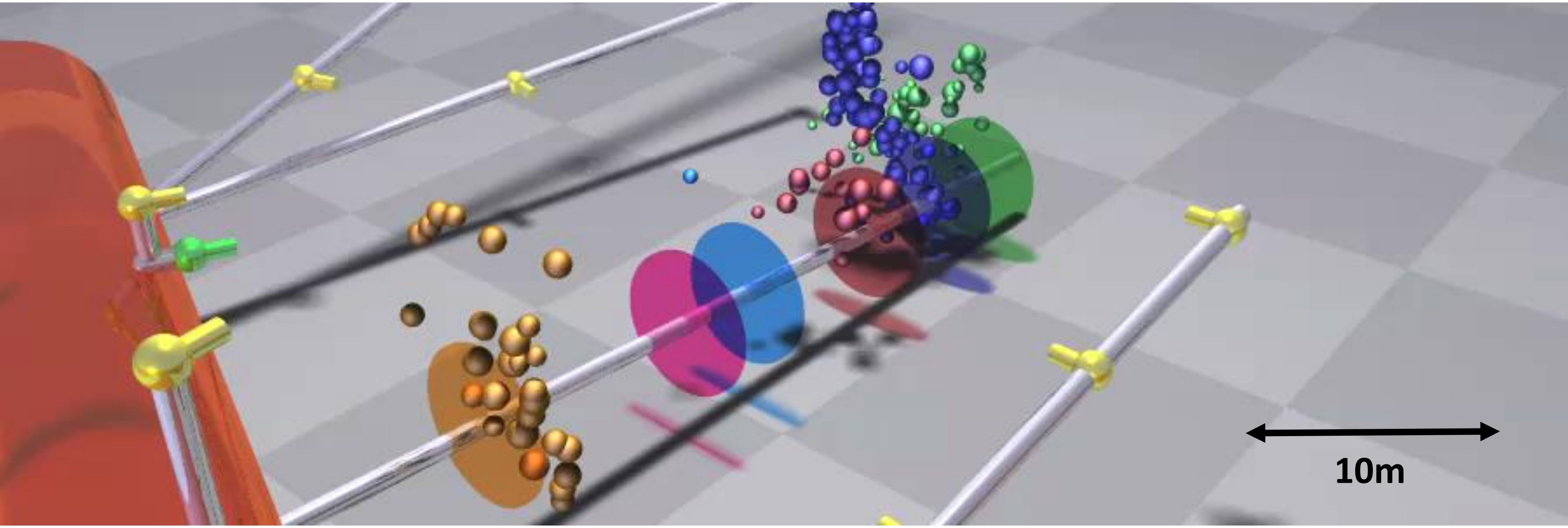
- „Soft stimulation” in Äspö underground laboratory, Sweden (depth 400 m)
- Monitoring with multiple networks:
  - Fracturing processes: 11 AE sensors and 4 accelerometers @ 1MHz sampling rate.
  - Slow processes and large events: additional geophones/broadbands.



Kwiatek et al., JGR, 2018; see also: Zang et al., GJI, 2017

Monitoring hydraulic stimulation in dm-scale (NOVA)

- Real time fracture propagation: M_W -4.2 to -3.5 eqs.
- Thousands eqs. - template matching post-processsing.
- Slow tensile opening detected by broadband sensors.



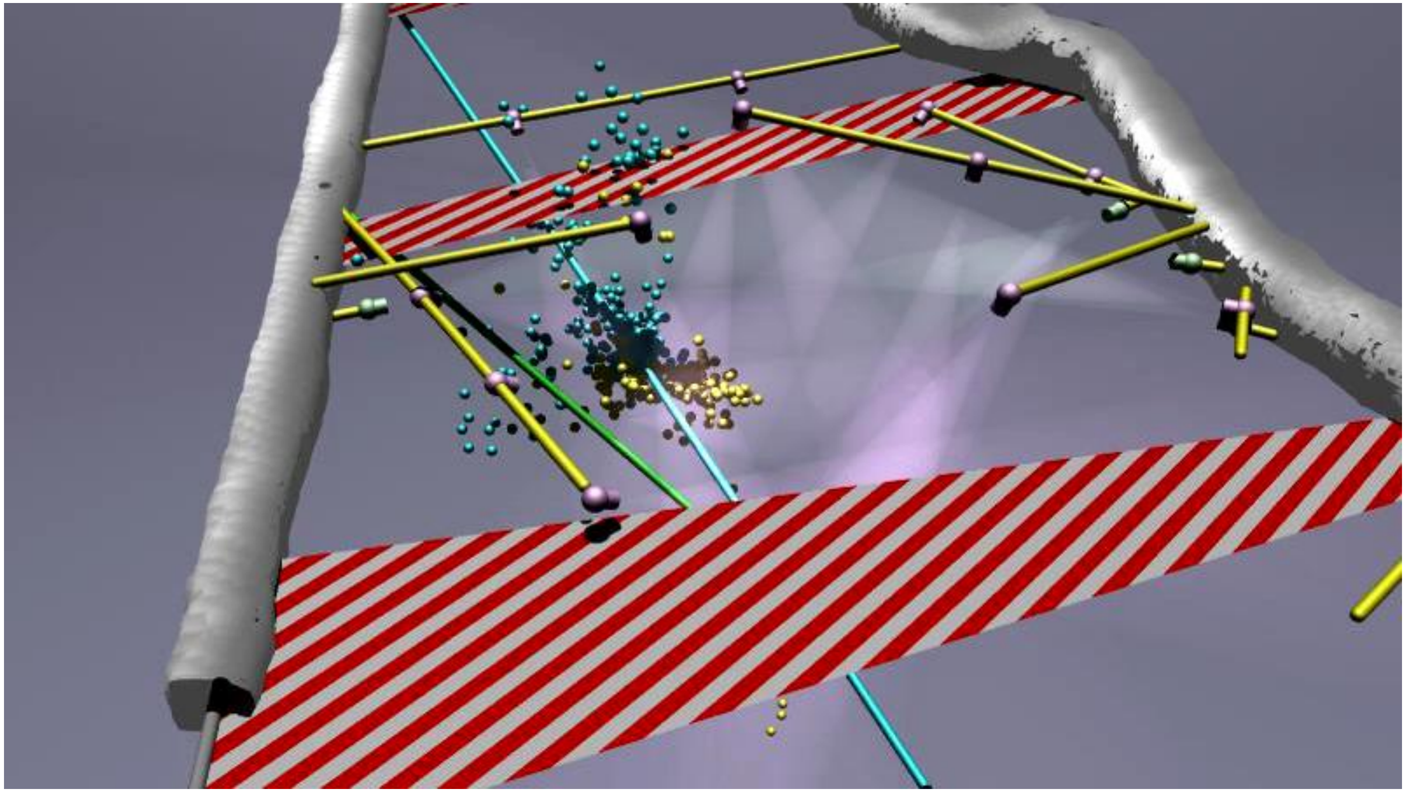
Learning curve...

- High attenuation at low confining stresses is really an issue for detecting small events, even at this extremely close distances.
- In this scale information on rock mass is essential (e.g. water-bearing layers).

Kwiatek et al., JGR, 2018; *see also: Zang et al., GJI, 2017, López-Comino et al., IJRMMS, 2017*

Monitoring hydraulic stimulation in dm-scale (STIMTEC)

- Testing different hydraulic stimulations concept (Freiberg, Germany, 200 m depth).
- Acoustic emission + acceleromenters + broadband sensor used.
- Careful network design and site scanning (damage zone identification, signal transmission testing at different frequencies).



Initial AE data: K. Plenkers, GMuG

Modelling limits for detection

- *Detection limits in various source/path/instrumental effects not well established, especially for very small events*
- Improve understanding of theoretical limits to detection of (small) seismic events.
- Clarify limitations for reliable derivation of source characteristics.

Forward modelling scheme

- **Seismic source**
  - *size, slip, rupture velocity*
  - *radiation pattern*
  - *STF directionality*
- **Path effects**
  - *geometrical spreading*
  - *attenuation*
- **Noise effects**
  - *HF noise*
- **Sensor effects**
  - *BB, short period*
  - *Fixed sampling rate and AA filter*

Source: $\dot{M}_0(t; \boldsymbol{V}_R, \boldsymbol{\Delta\sigma}, \boldsymbol{M_0}; \Theta)$

Radiation: $\dot{S}(t) = \boldsymbol{R}_C(\Phi, \theta) \cdot \dot{M}_0\,(\mathrm{t})$

↓

Path: $G(f) = \frac{1}{\boldsymbol{r}} \exp(-\pi f \boldsymbol{r} / \boldsymbol{Q}_C \boldsymbol{V}_C)$

↓

Noise: $N(f)$

↓

Sensor: $\boldsymbol{T}(f)$

↓

$$U(t) = \dot{S}(t) * G(t) * T(t) + N(t)$$

Kwiatek and Ben-Zion, JGR, 2016

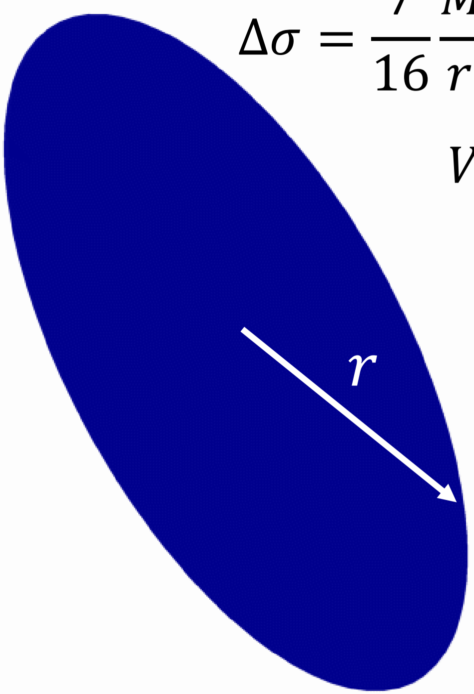
Source modelling

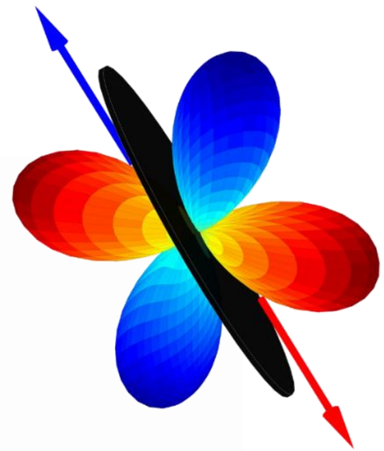
- Rupture process described by M_0, $\Delta\sigma$, and V_R.
- Rupture propagates radially with constant V_R and stops abruptly
- Radiation pattern: **pure shear** and pure tensile failure, **P-** and S- waves considered

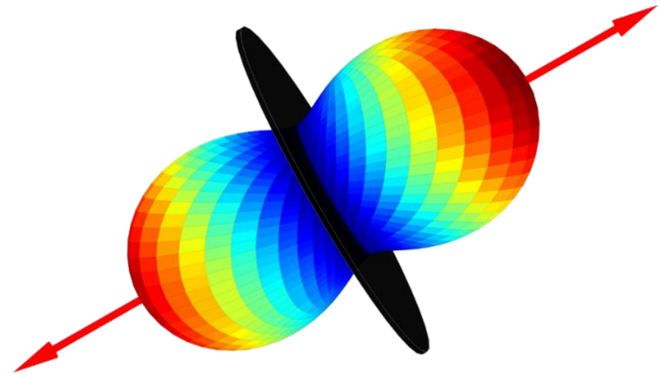
$$M_0 = \mu\, U\, \pi r^2$$

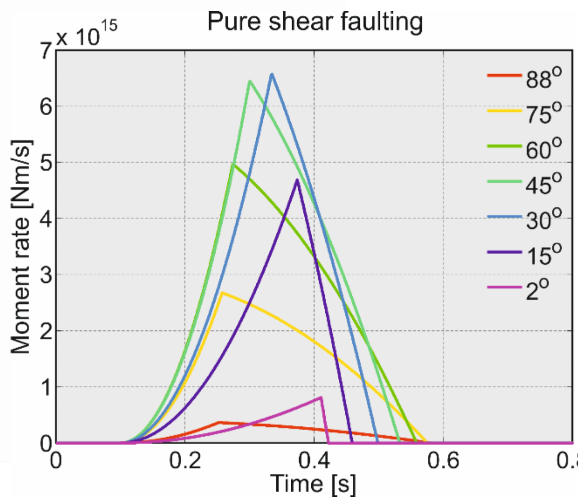
$$\Delta\sigma = \frac{7}{16}\frac{M_0}{r^3}$$

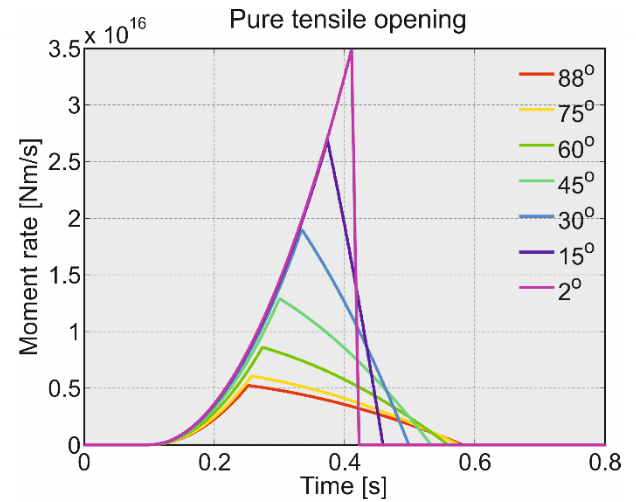
$$V_R$$







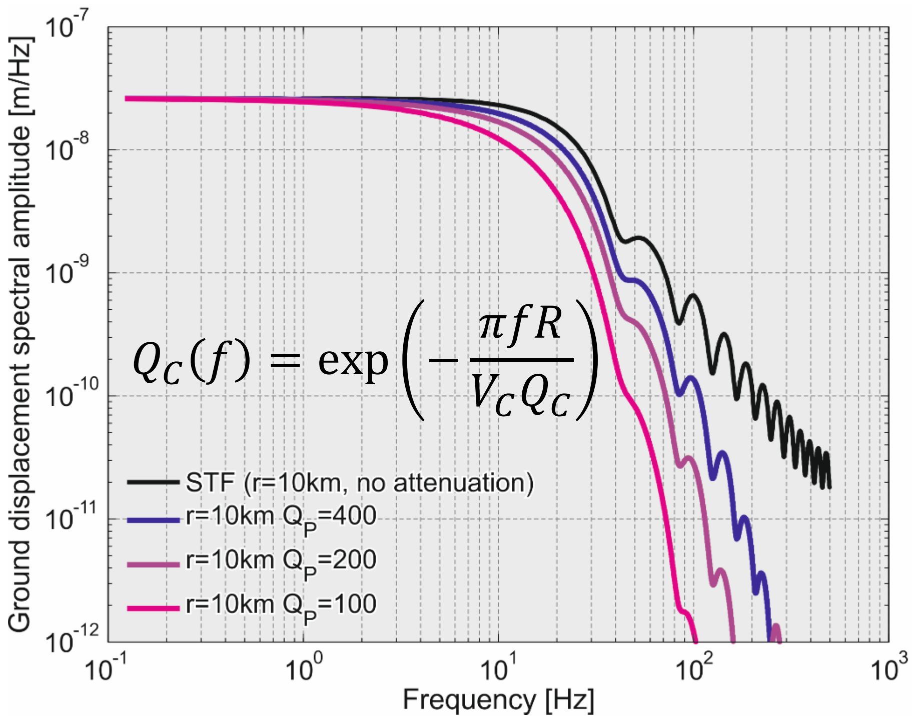


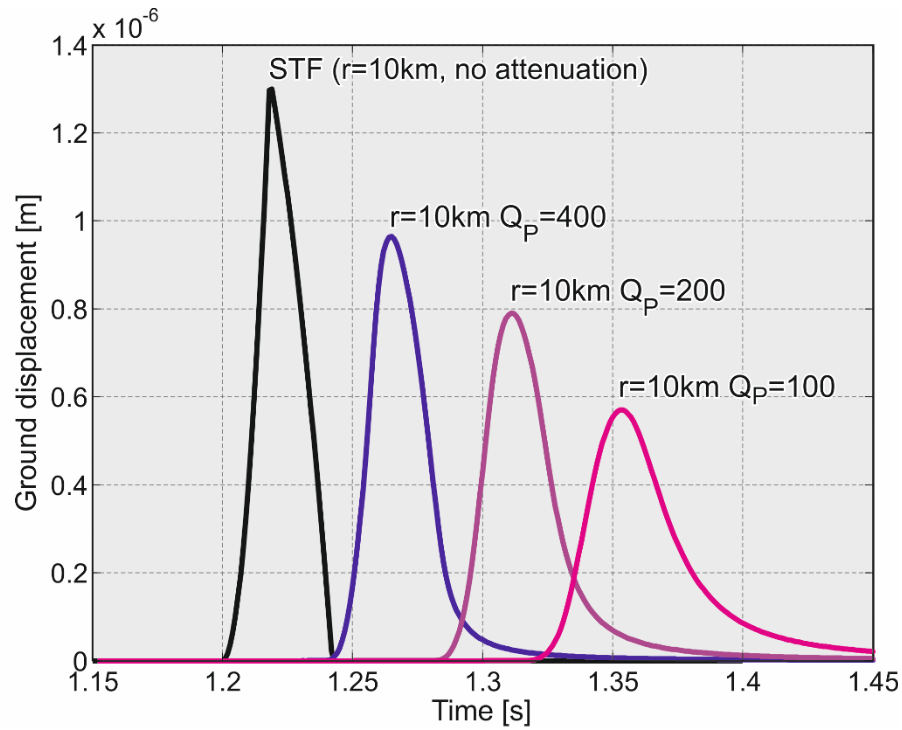


Kwiatek and Ben-Zion, JGR, 2016

Path effects modelling

- Attenuation: Frequency-independent attenuation operator.
- Geometrical spreading: $1/R$ factor

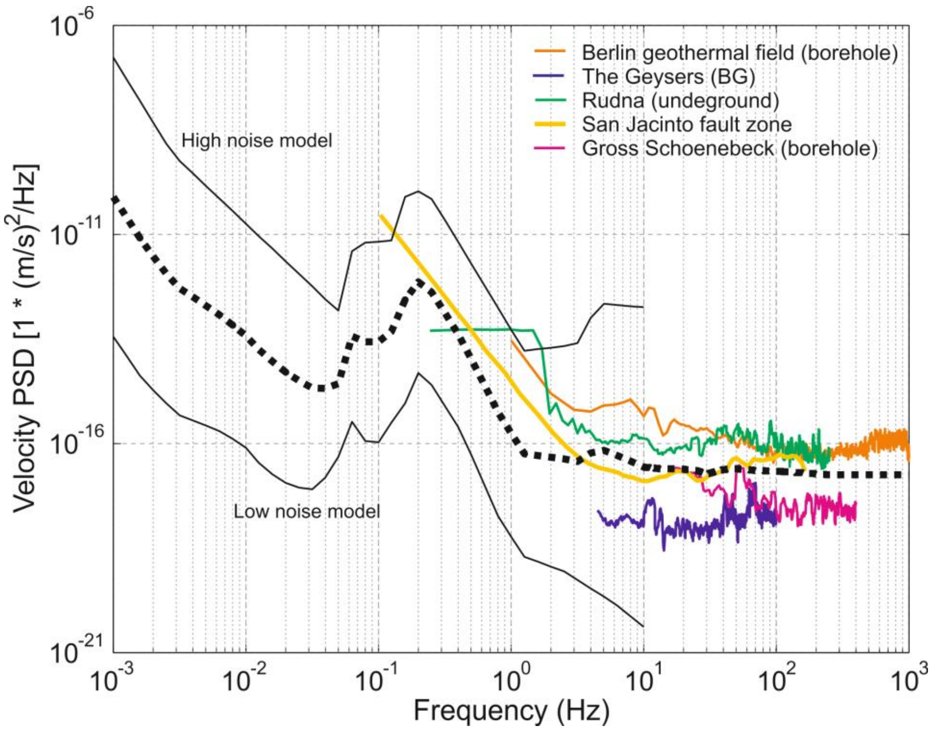


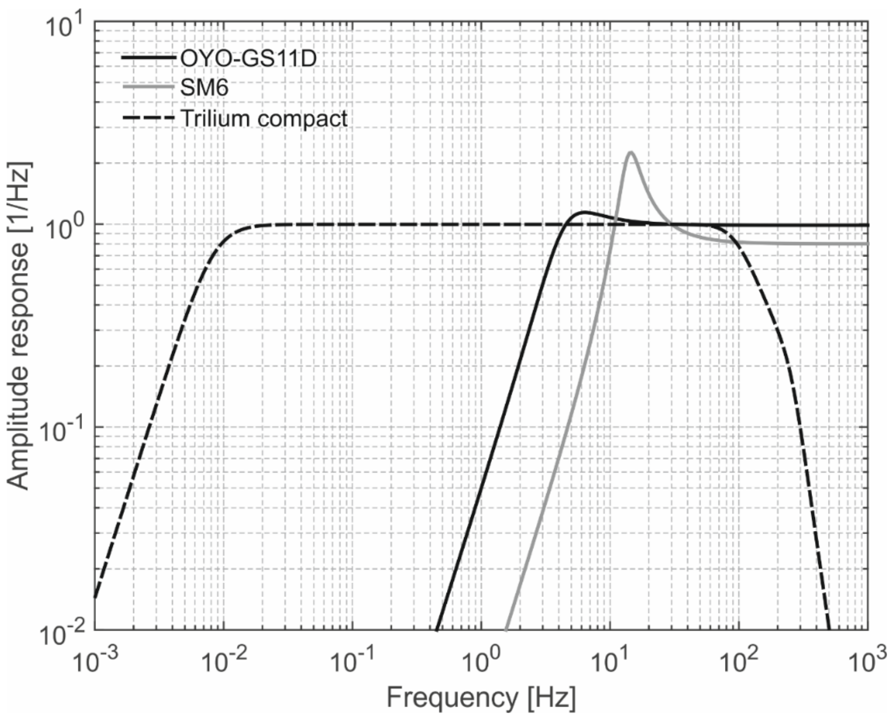


Kwiatek and Ben-Zion, JGR, 2016

Noise and sensor characteristics modelling

- Low-freq. noise from *Peterson* (1993)
- High-freq. noise from empirical data
- Popular broadband and short-period sensors used

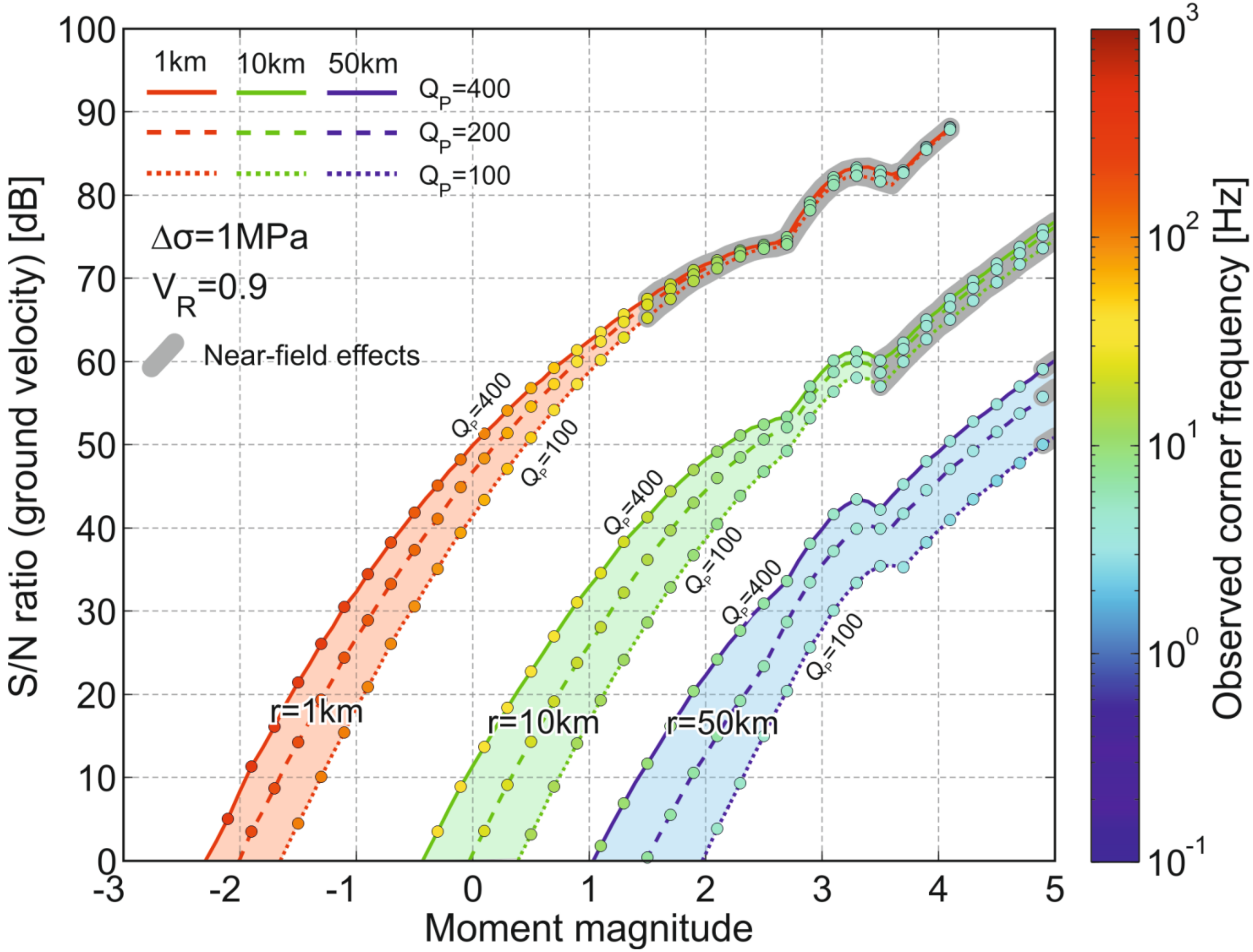




Kwiatek and Ben-Zion, JGR, 2016

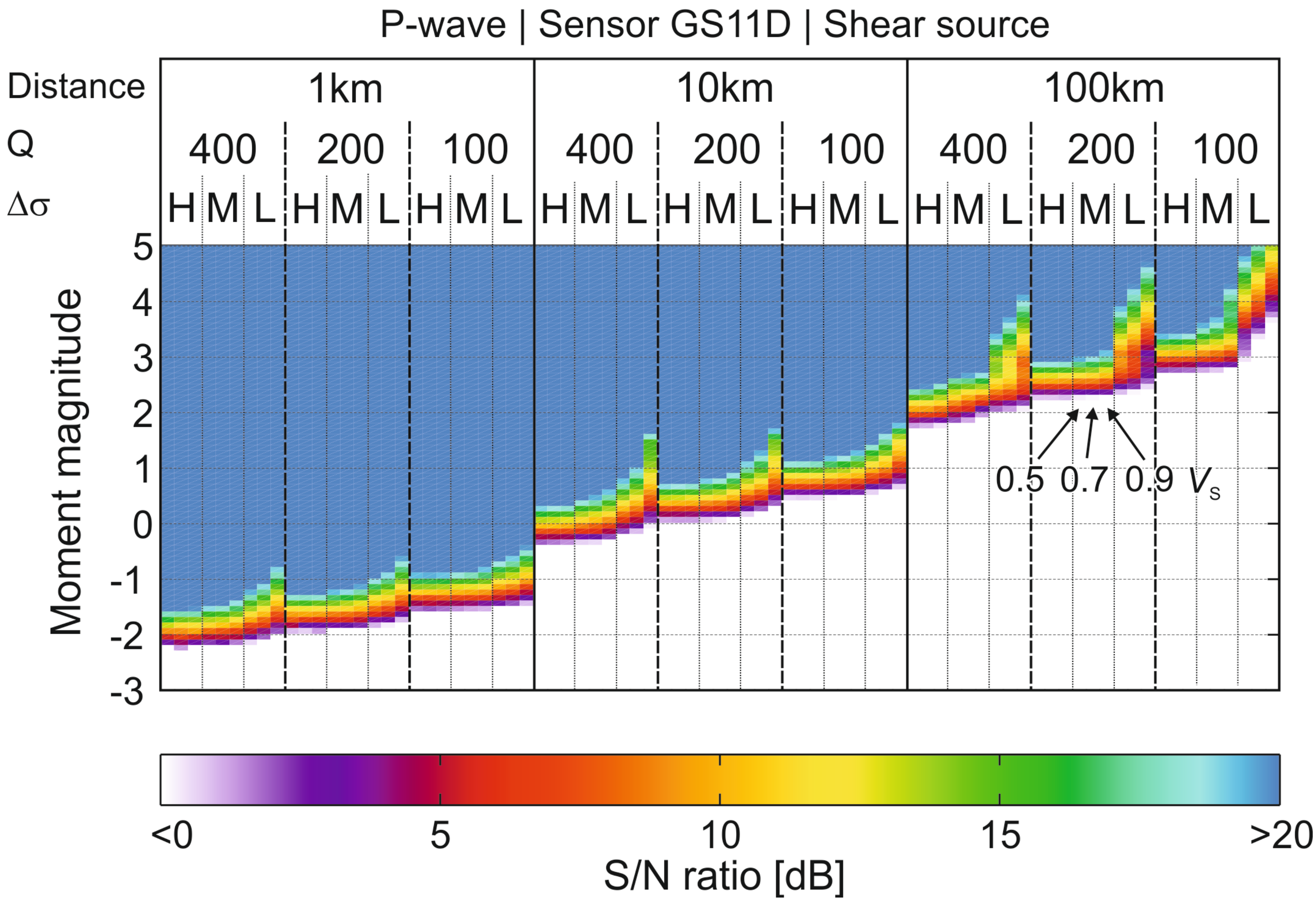
Synthetic detection limits

- Sample detection limits using *P*-waves, GS11D sensor, $\Delta\sigma = 1\mathrm{MPa}$ and $V_R = 0.9V_S$



Kwiatek and Ben-Zion, JGR, 2016

Synthetic detection limits (overview)

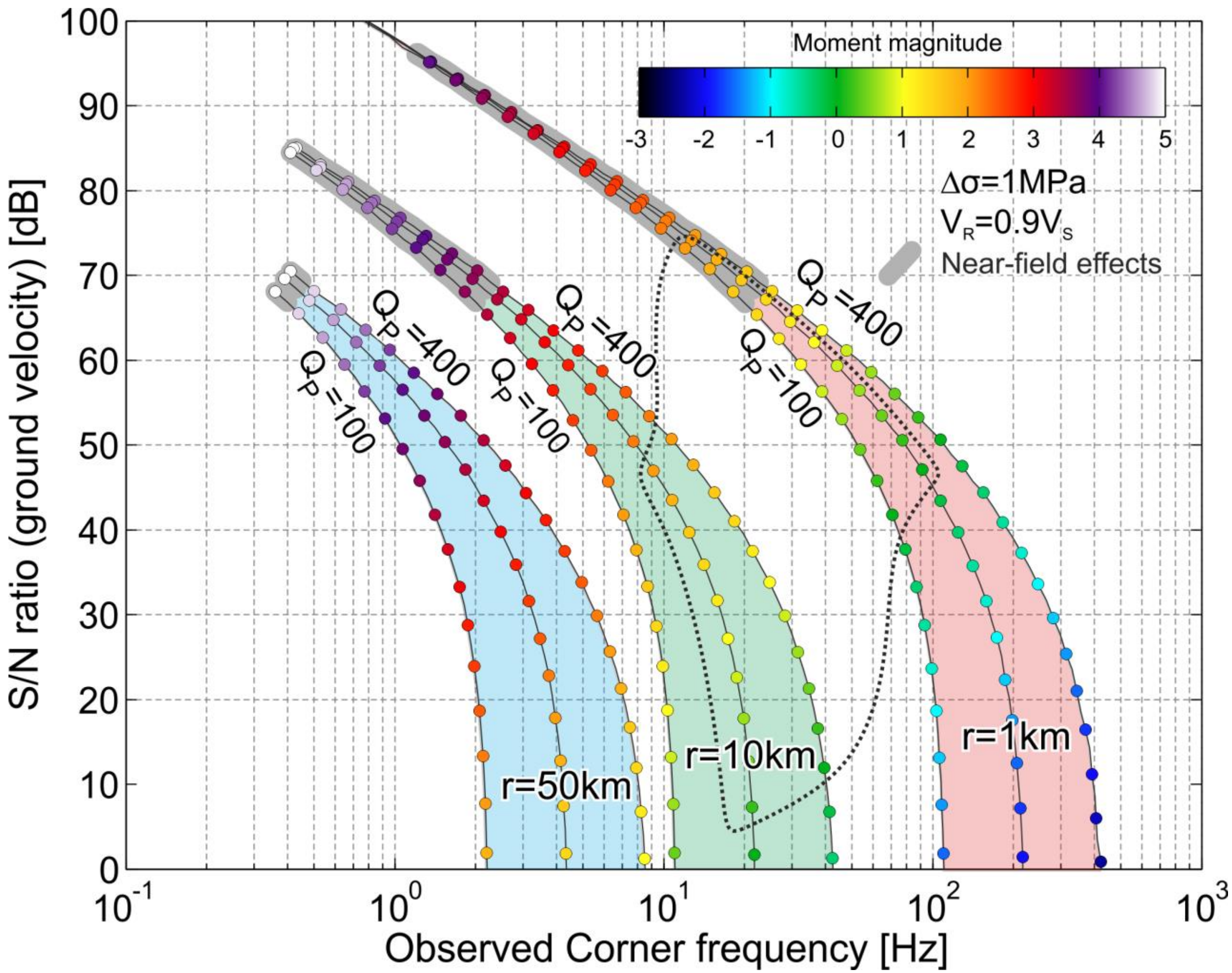


- Detection limits for different source, path and sensor characteristics are in supplementary materials of *Kwiatek and Ben-Zion, JGR, 2016*

Synthetic frequency content limits

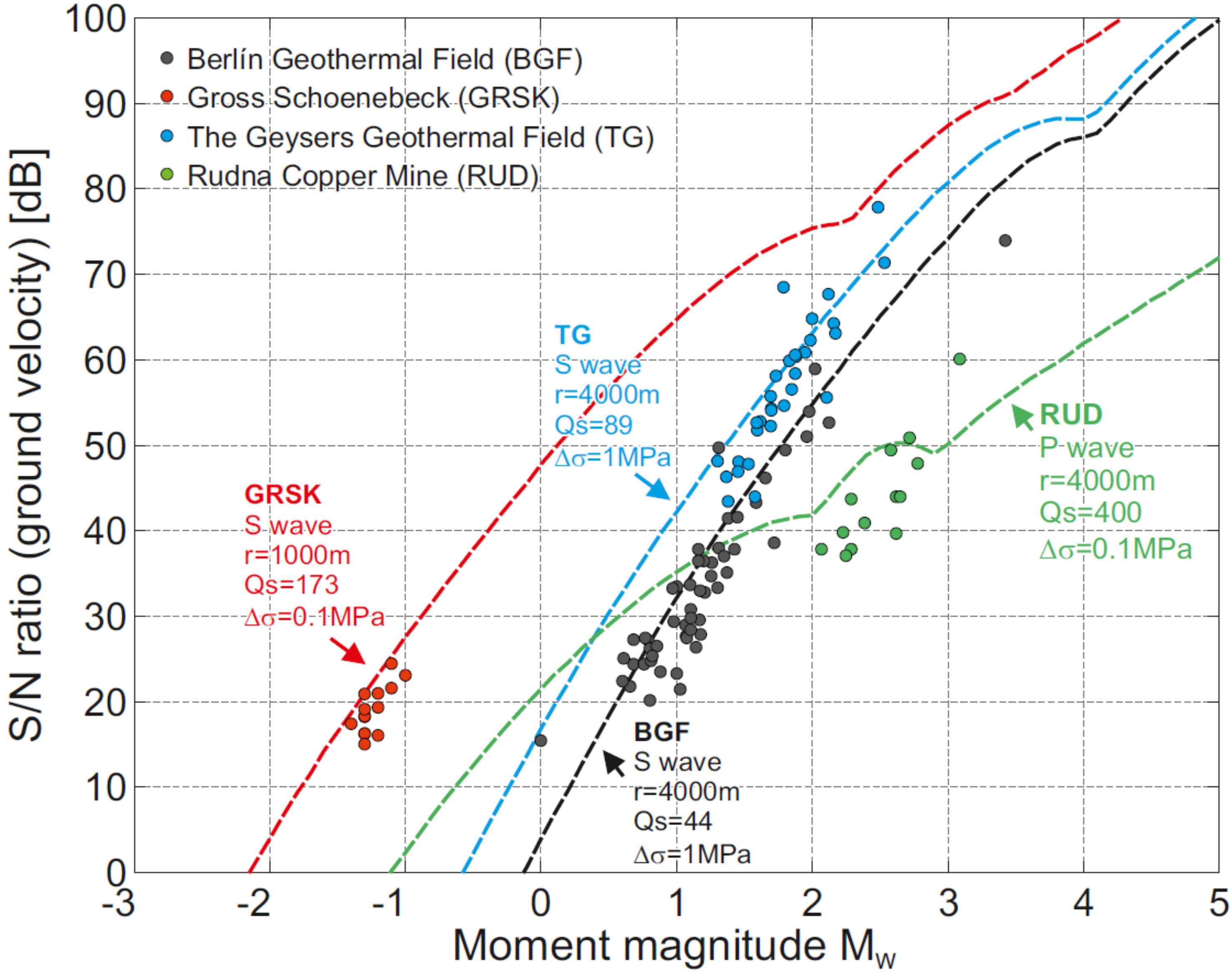
- High frequencies suppressed due to attenuation

  (P-waves, $\Delta\sigma = 1\text{MPa}, V_R = 0.9V_S$)



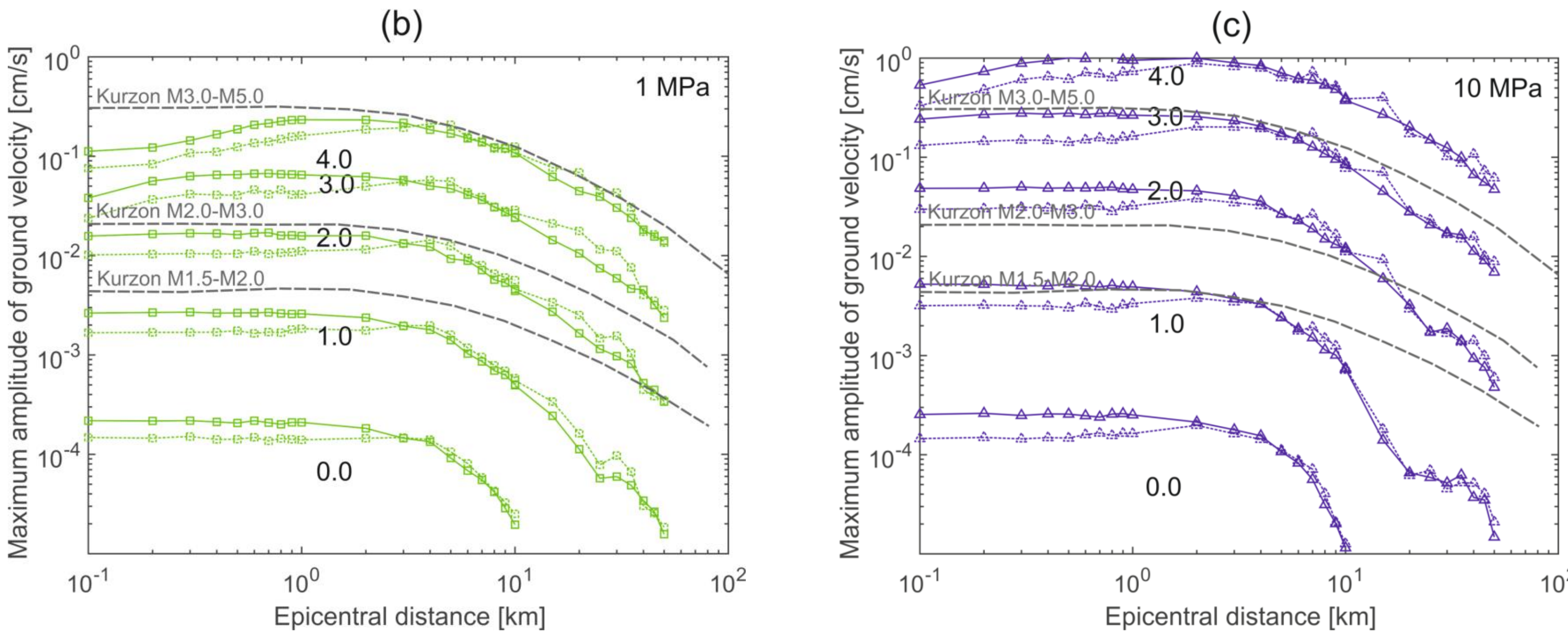
Kwiatek and Ben-Zion, JGR, 2016

Validation: Comparison with empirical data



Case study: Ground motions simulations

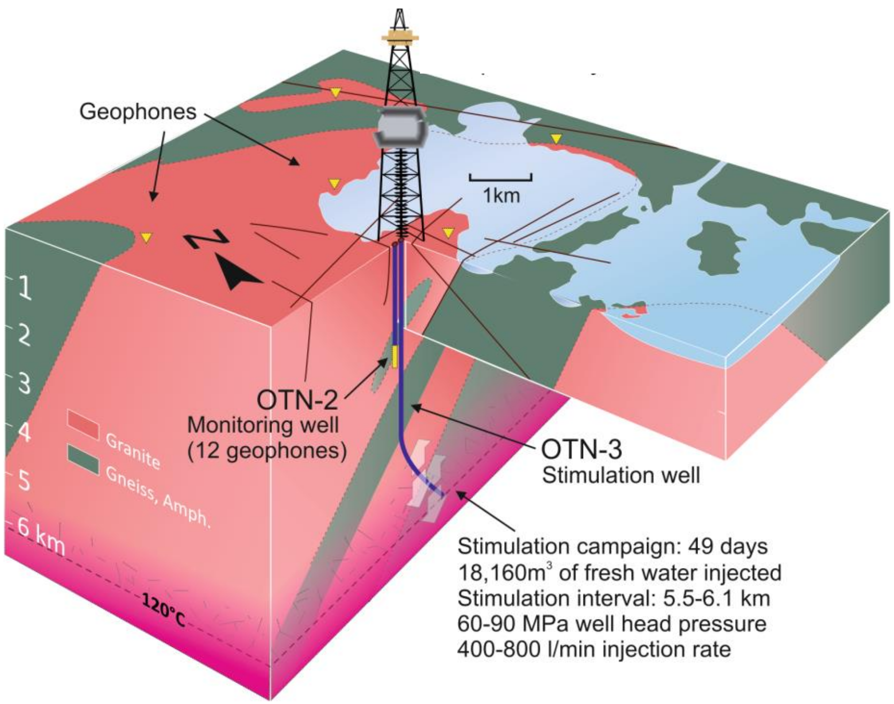
- Ground motion simulation for Southern California
- Source kinematics influence visibly ground motions at short source-receiver distances

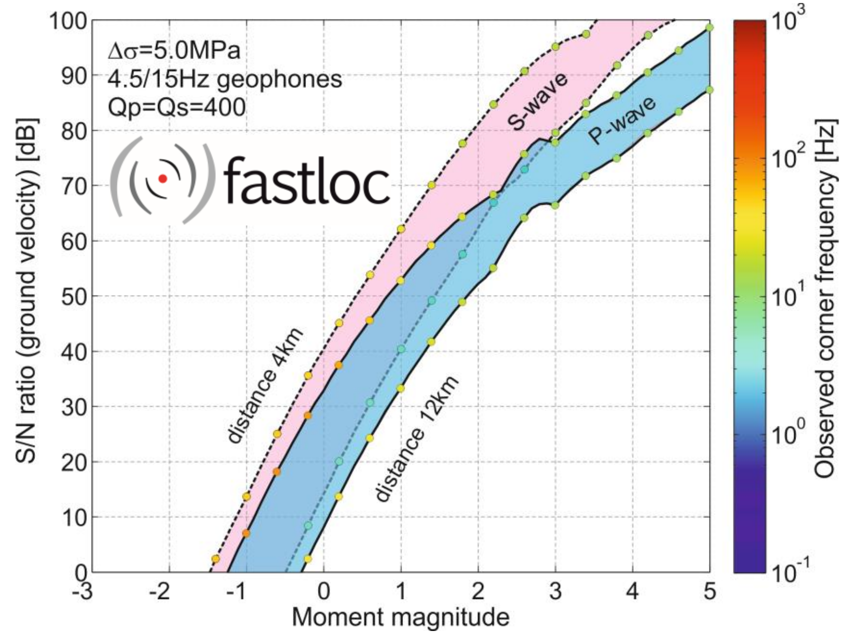


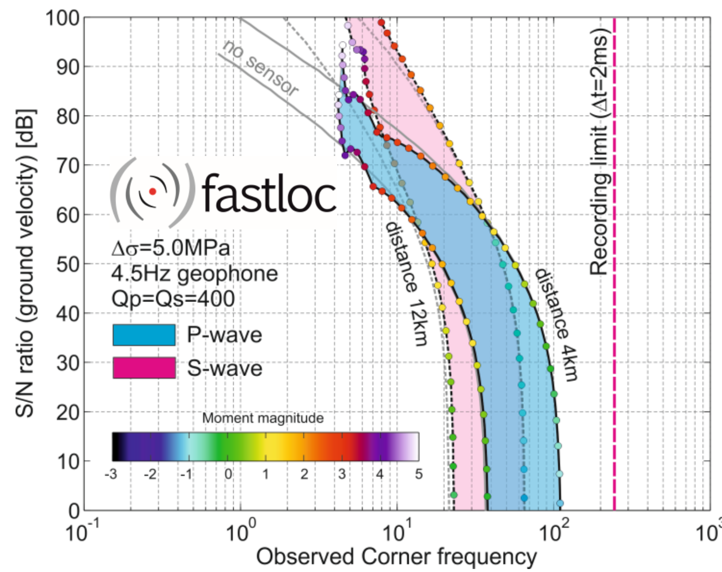
From Kwiatek and Ben-Zion, in preparation

Case study: Detection limits in hydraulic stimulation campaign

- Target reservoir at depth of 6km
- Relatively simple geological situation
- Seismic network: shallow borehole geophones (4.5Hz) and borehole sensors (15Hz) at a depth of ~2.0 km
- Target: TLS, Tracking fracture network development







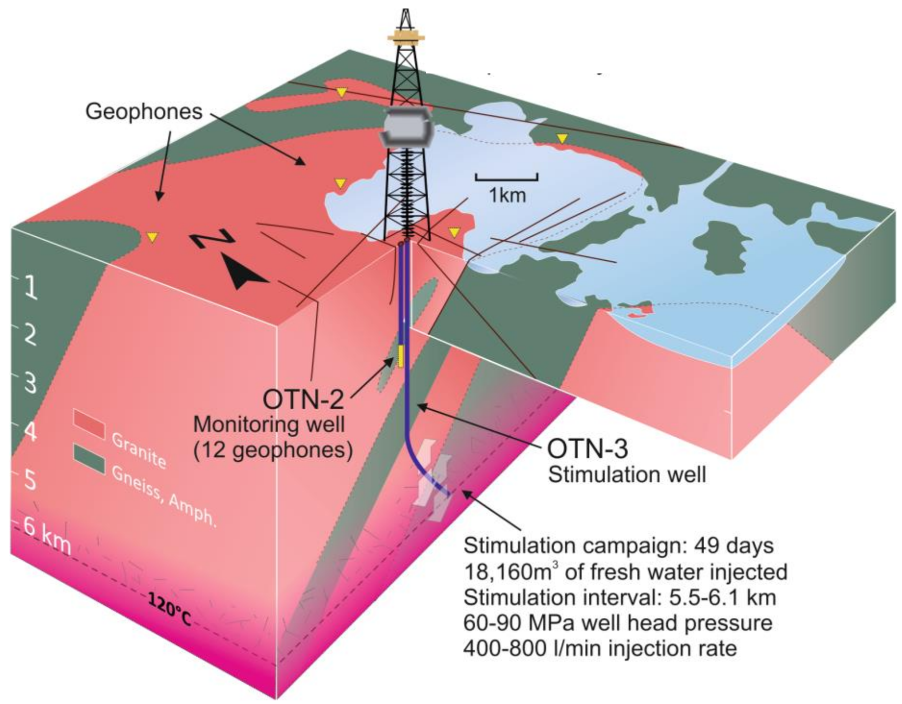
Kwiatek et al., in prep., 2018

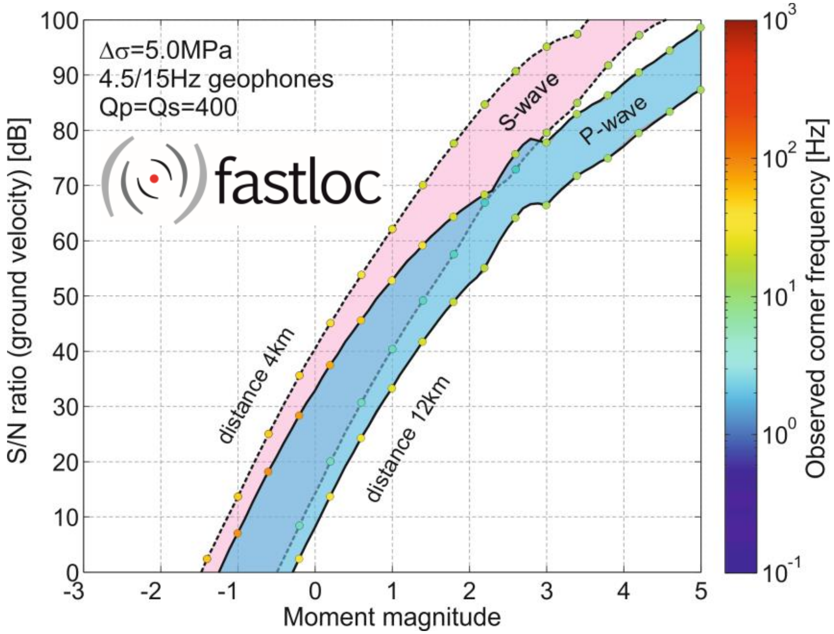
Courtesy of fastloc GmbH

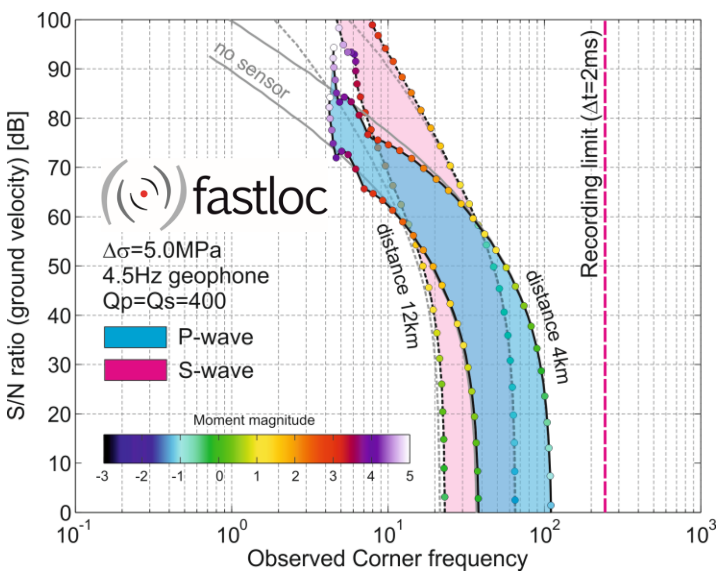
Case study: Detection limits in hydraulic stimulation campaign

Actions:

- Reduce lateral station distances to the injection well head
- Modify sampling rates to fit better the expected frequency band







Kwiatek et al., in prep., 2018

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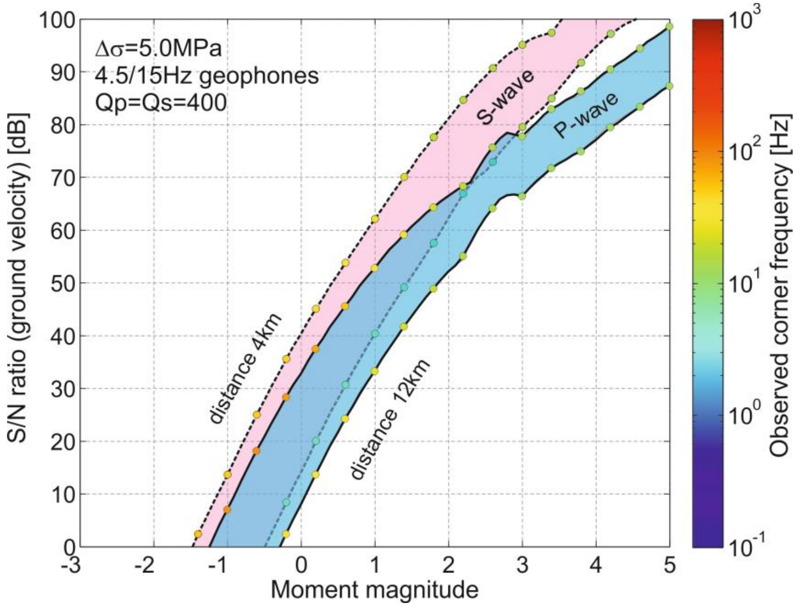
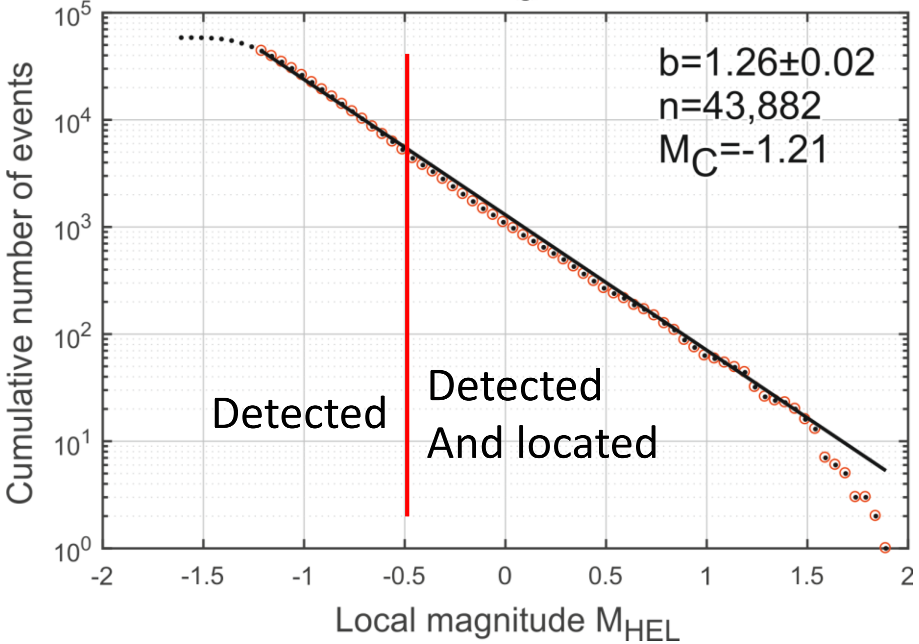
Case study: Detection limits in hydraulic stimulation campaign

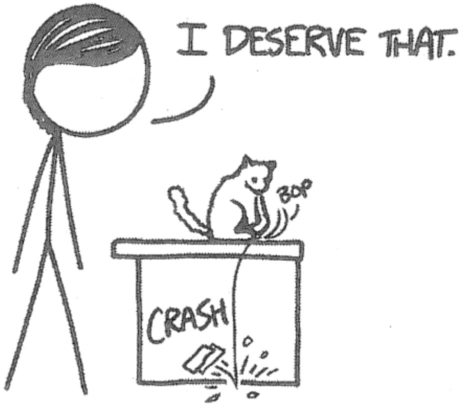




Kwiatek et al., in prep., 2018

Summary and Conclusions

- Analysis of small earthquakes important – bridging the gap between lab and field studies.
- Successul outcome of monitoring at high frequencies strongly related to expertise of people involved in the project.
- The expertise is scarce wrt demands. We do not communicate enough!
- Monitoring of induced seismicity on small fractures/faults sometimes requires different types of sensors.
- Acquisition system characteristics seriously affect the detection and ability to analyze source properties for very small earthquakes.
- Amplitude and frequency content of waves from small sources is predominantly controlled by M_W and $\Delta\sigma$ with minor influence of rupture velocity, earthquake kinematics, directivity.
- Distance and attenuation key not-acquisition-related limiting factors for EQ detectability and analysis of source properties of very small earthquakes.



Magnitude -3

A cat knocking your cell phone off your nightstand

Thank you! Questions?

contact: kwiatek@gfz-potsdam.de

https://induced.pl/about

See also:

Kwiatek, G., and Y. Ben-Zion (2016). Theoretical limits on detection and analysis of small earthquakes, *JGR-Solid Earth* **121**.

Kwiatek, G., P. Martínez-Garzón, et al. (2018). Insights Into Complex Subdecimeter Fracturing Processes Occurring During a Water Injection Experiment at Depth in Äspö Hard Rock Laboratory, Sweden. *JGR-Solid Earth* **123**

Magnitude -2

A cat falling off a dresser