Freie Universität Berlin

Triggering strong earthquakes by subsurface operations in the seismotectonic continuum

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Injection-induced seismicity in a seismotectonic continuum:

$$\log N_M(t) = a(t) - bM; \quad \text{GR-Statistic}$$

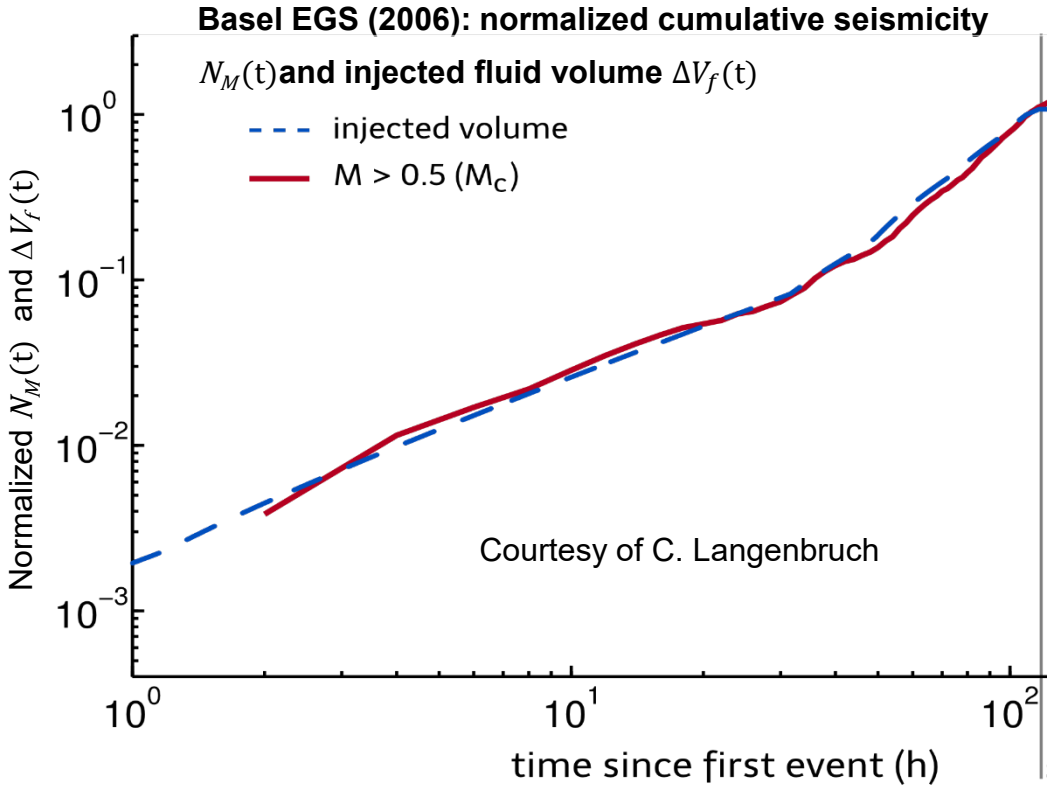
$$\log N_M(t) = \Sigma + \log \Delta V_f(t) - bM; \text{ Seismogenic-Index model}$$

Conditions for this simple formulation:

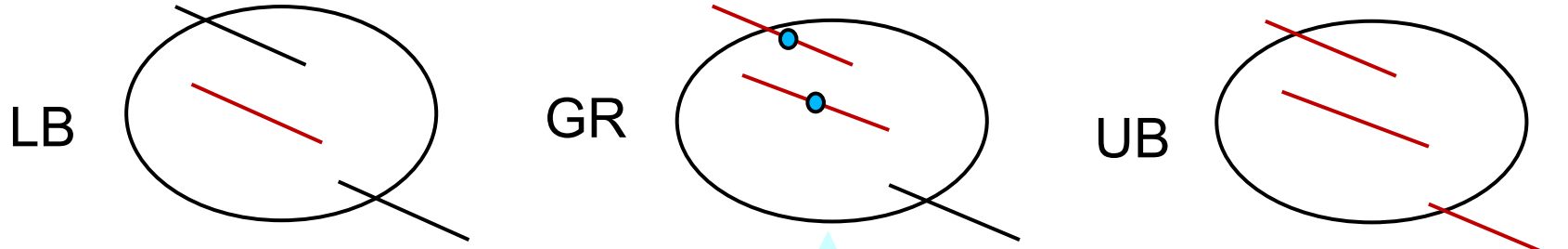
- Monotonic non-decreasing injection.
- Triggering by pore pressure.

Shapiro et al., 2010, The Leading Edge

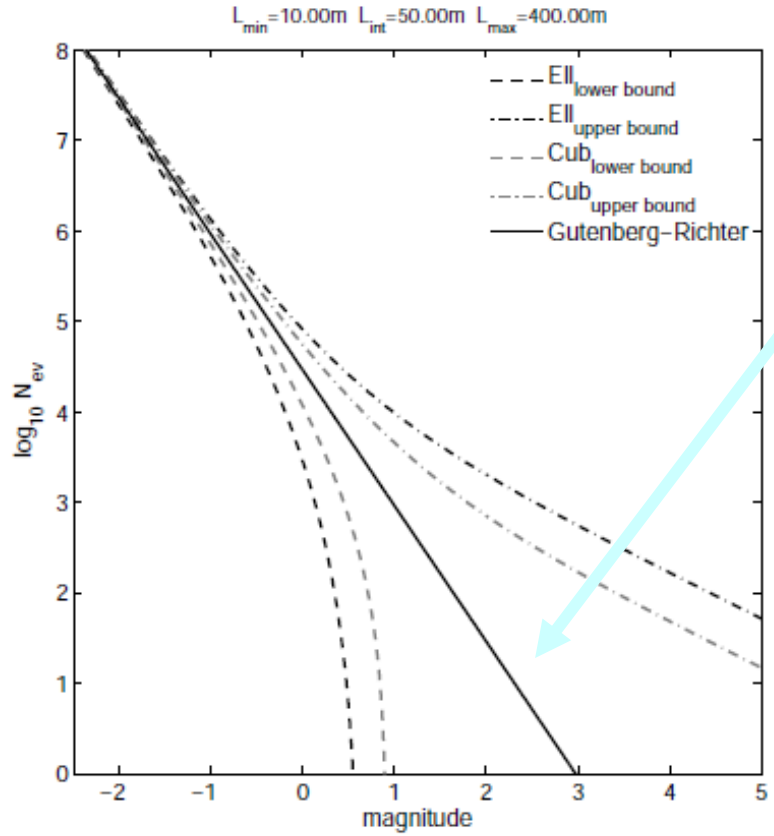
+ further developments in 2011 - 2024.

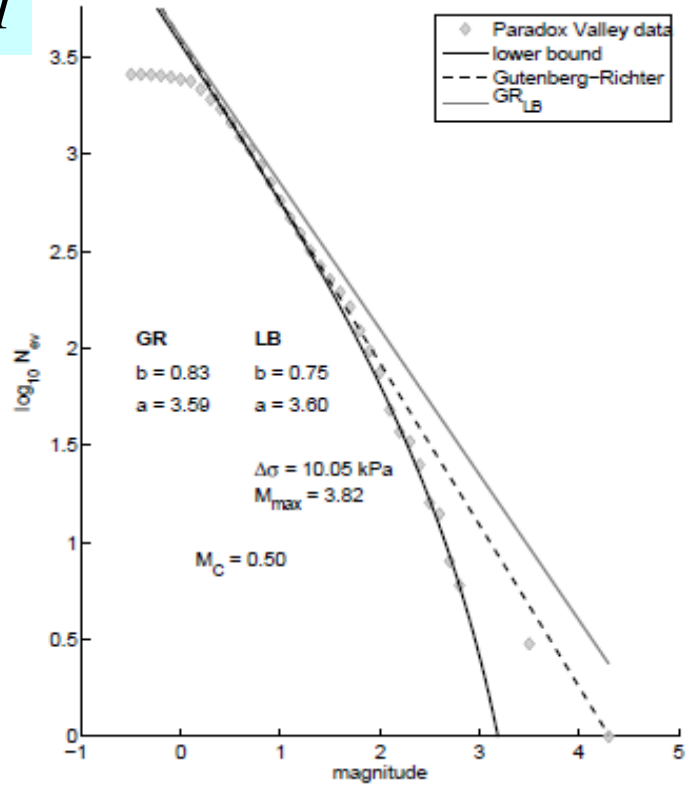


Geometry of the lower- and upper-bound frequency-magnitude statistics (Shapiro et al, *Geophysics, 2011 & JGR, 2013*)



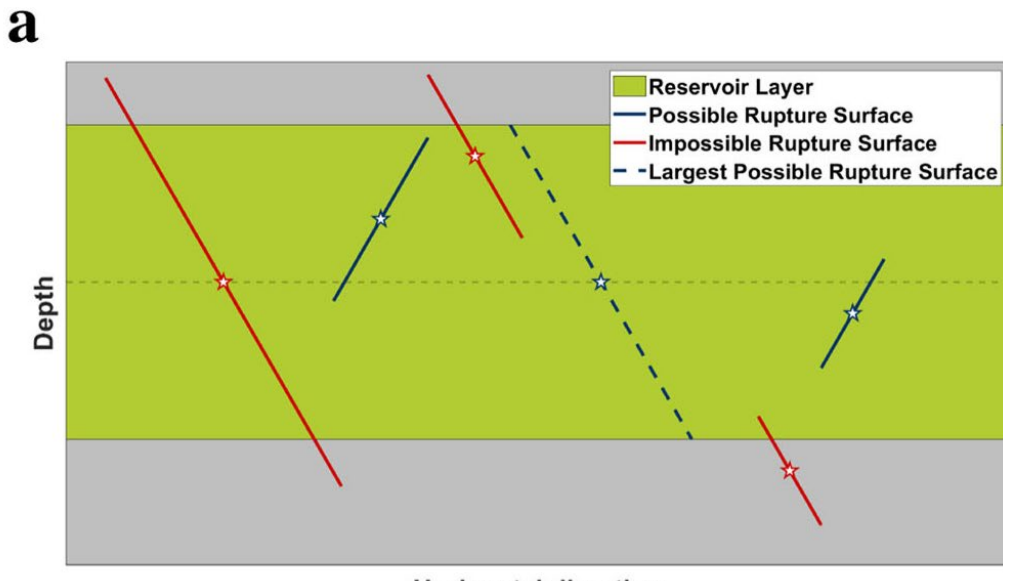
$$\log N_M = a - bM$$

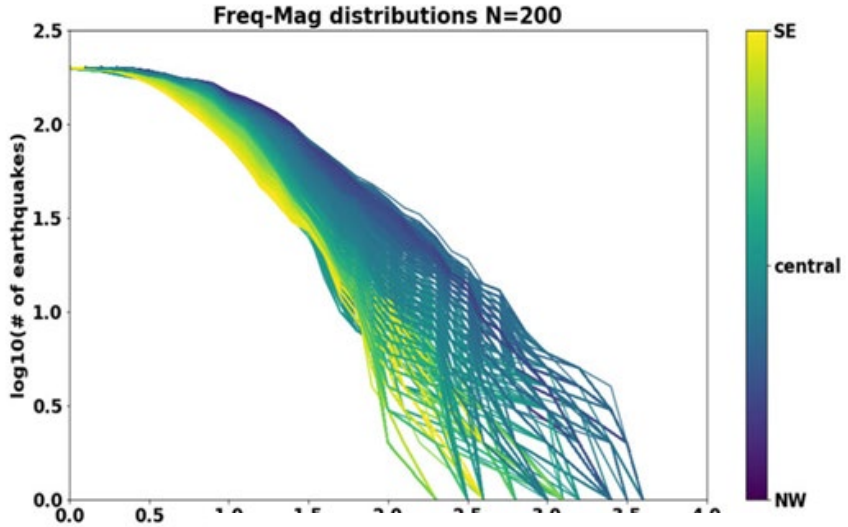




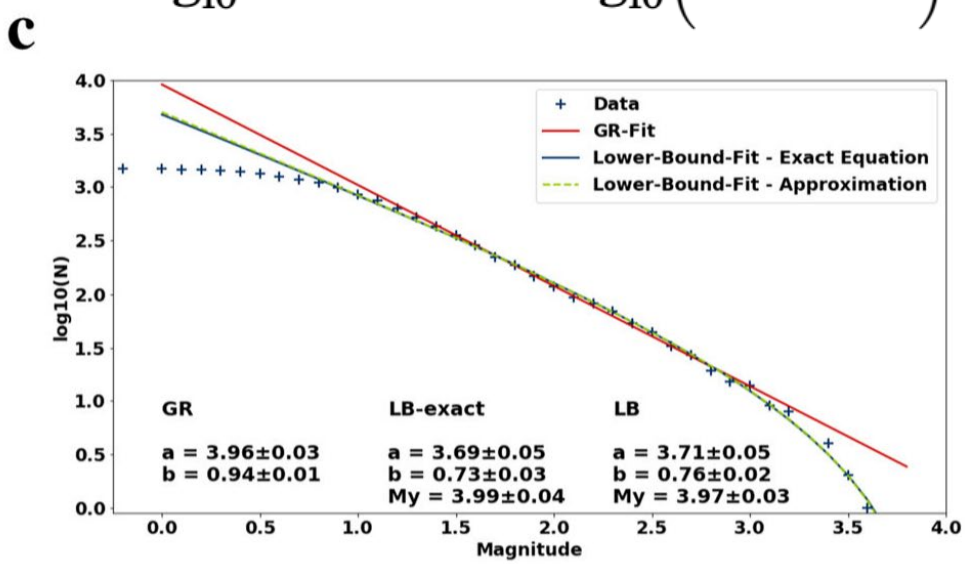
Lower-bound frequency-magnitude statistic in the Groningen gas field

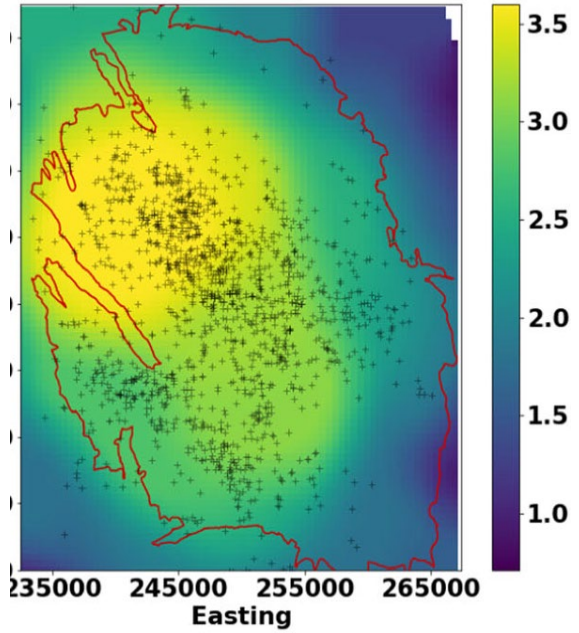
N. Boitz et al., *Nat. Com.*, 2024





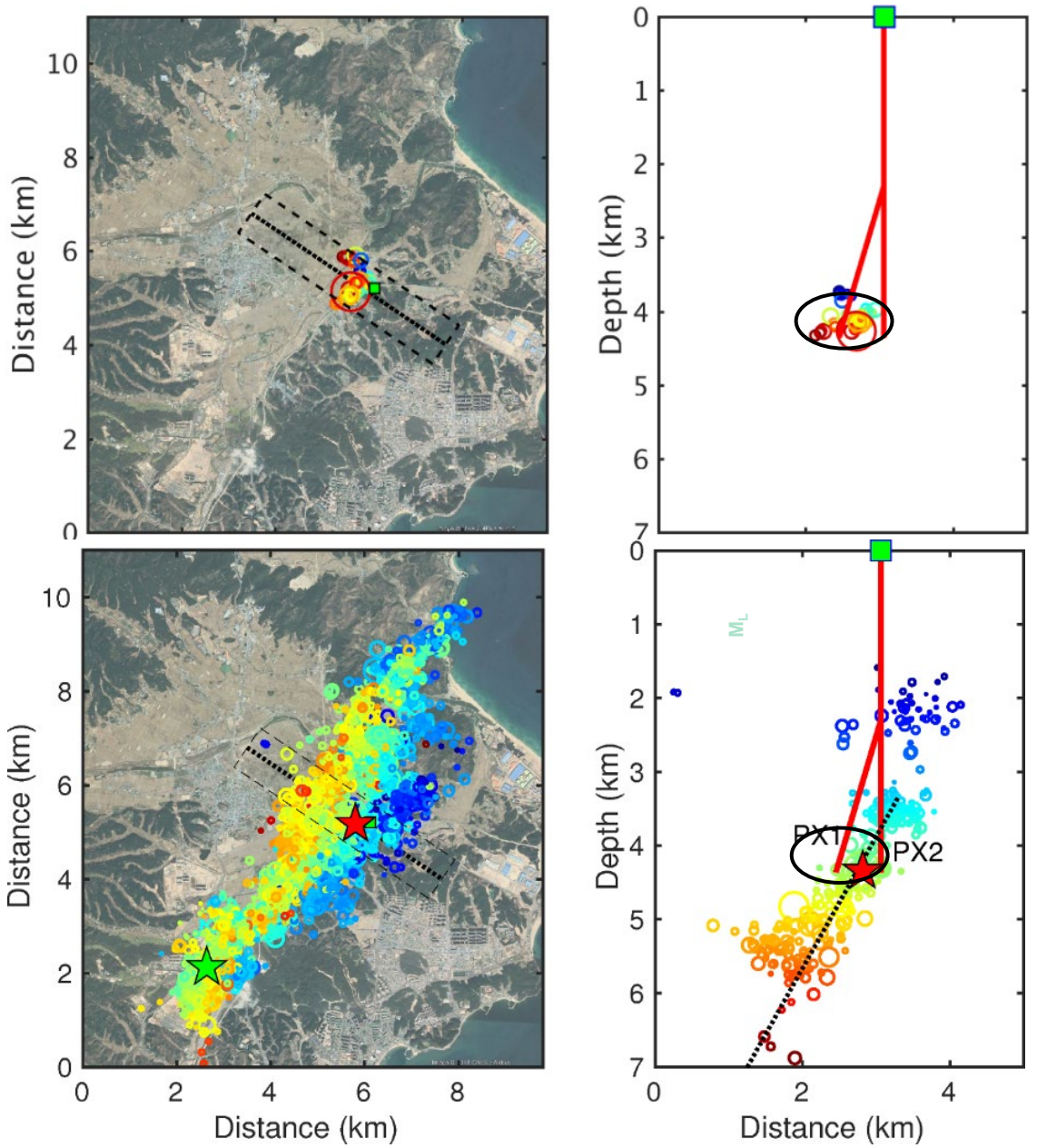
$$\log_{10} N = a - bM + 2\log_{10}\left(1 - 10^{\frac{M - M_Y}{2}}\right)$$

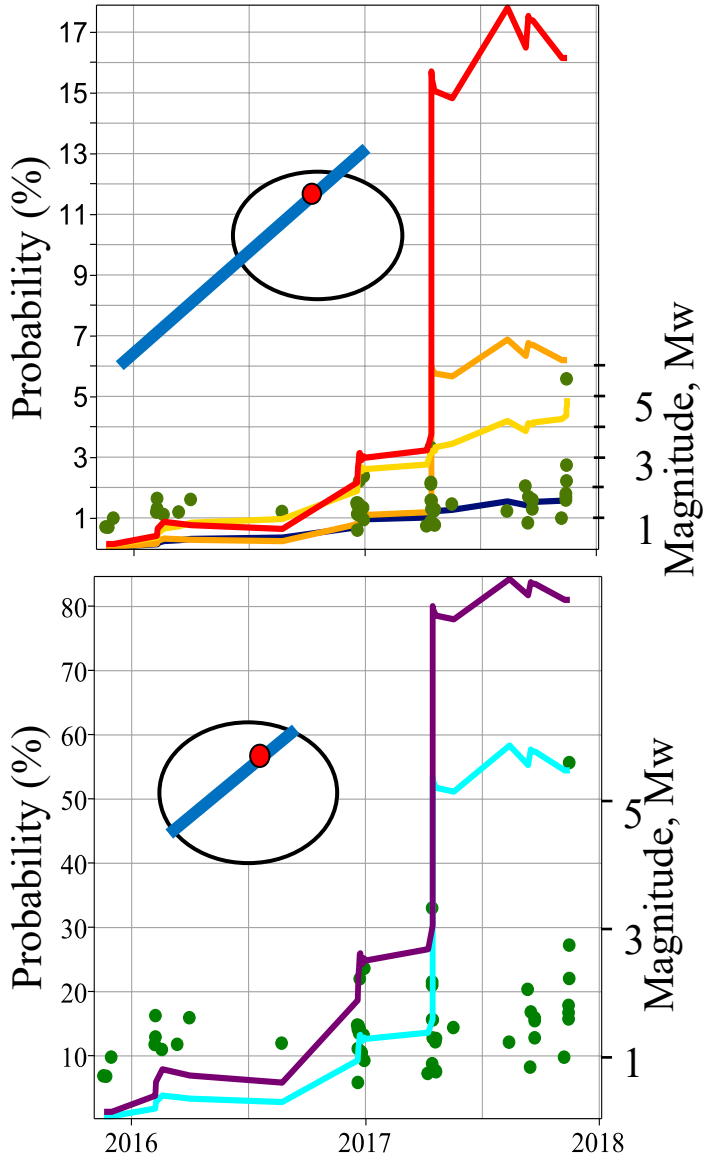




Pohang EGS

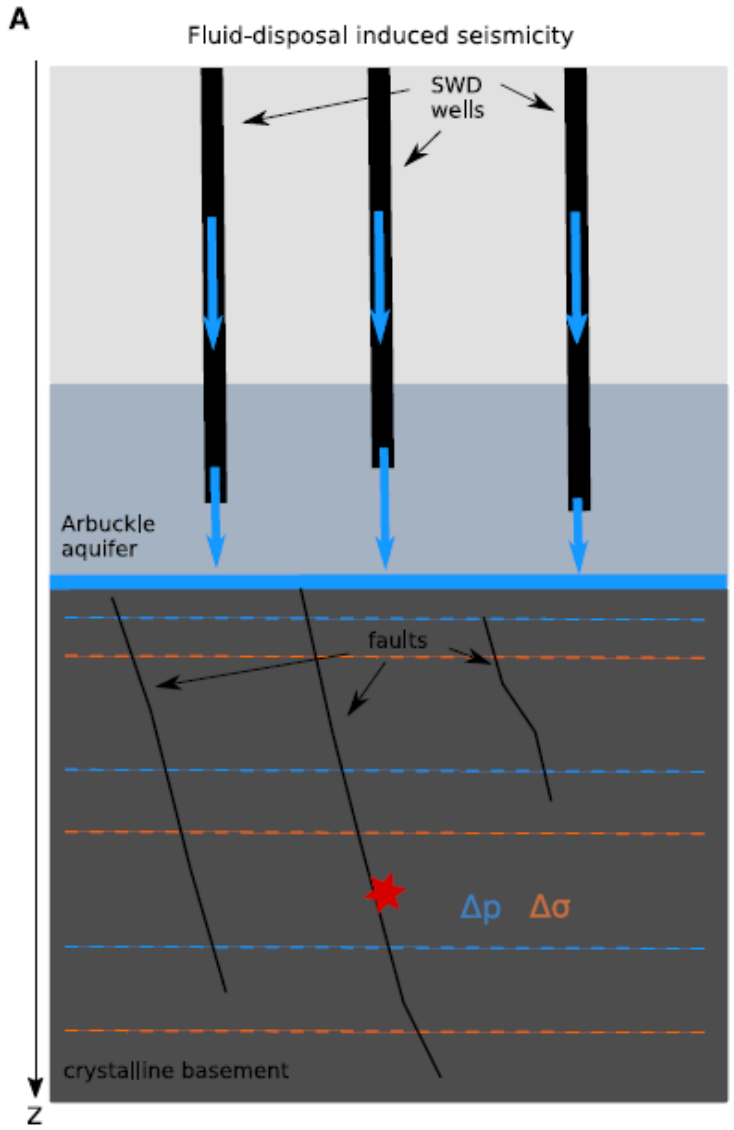
$$W_{ev \geq M} = 1 - exp\left[-\Delta V_f(t)\, 10^{\sup\{\Sigma(t)\} - \inf\{b(t)\} M}\right]$$

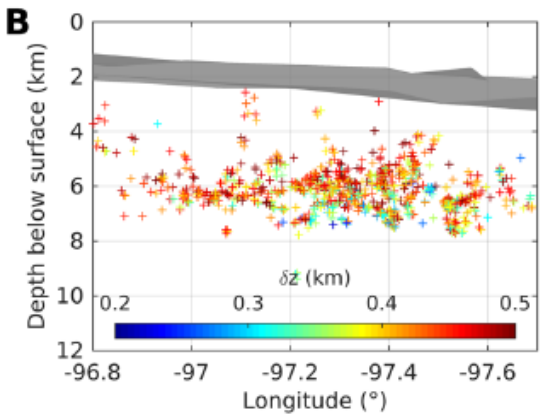


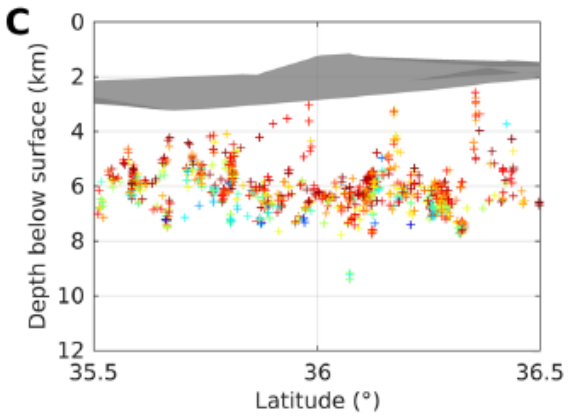


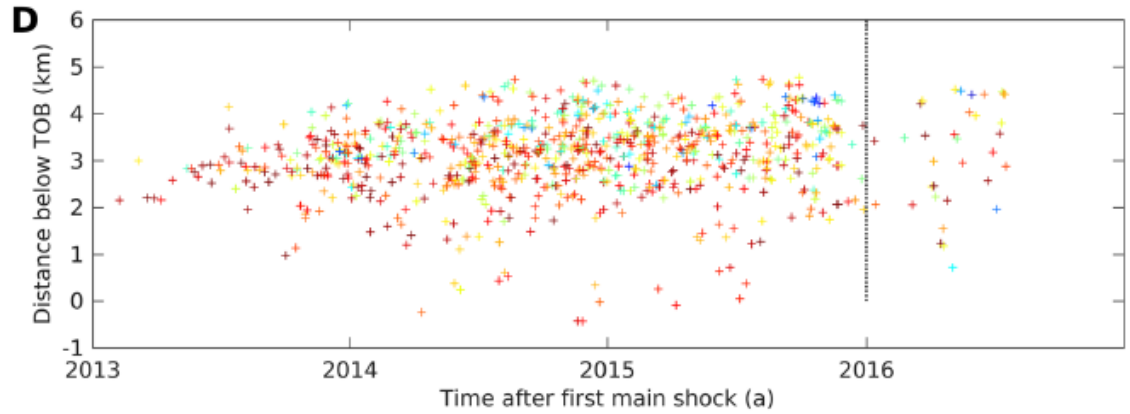
Shapiro et al., Nat. Comm. (2021).

The surge of earthquakes in Central Oklahoma has features of reservoir-induced seismicity, Lisa Johann, et al., *Sci. Rep.*, 2018









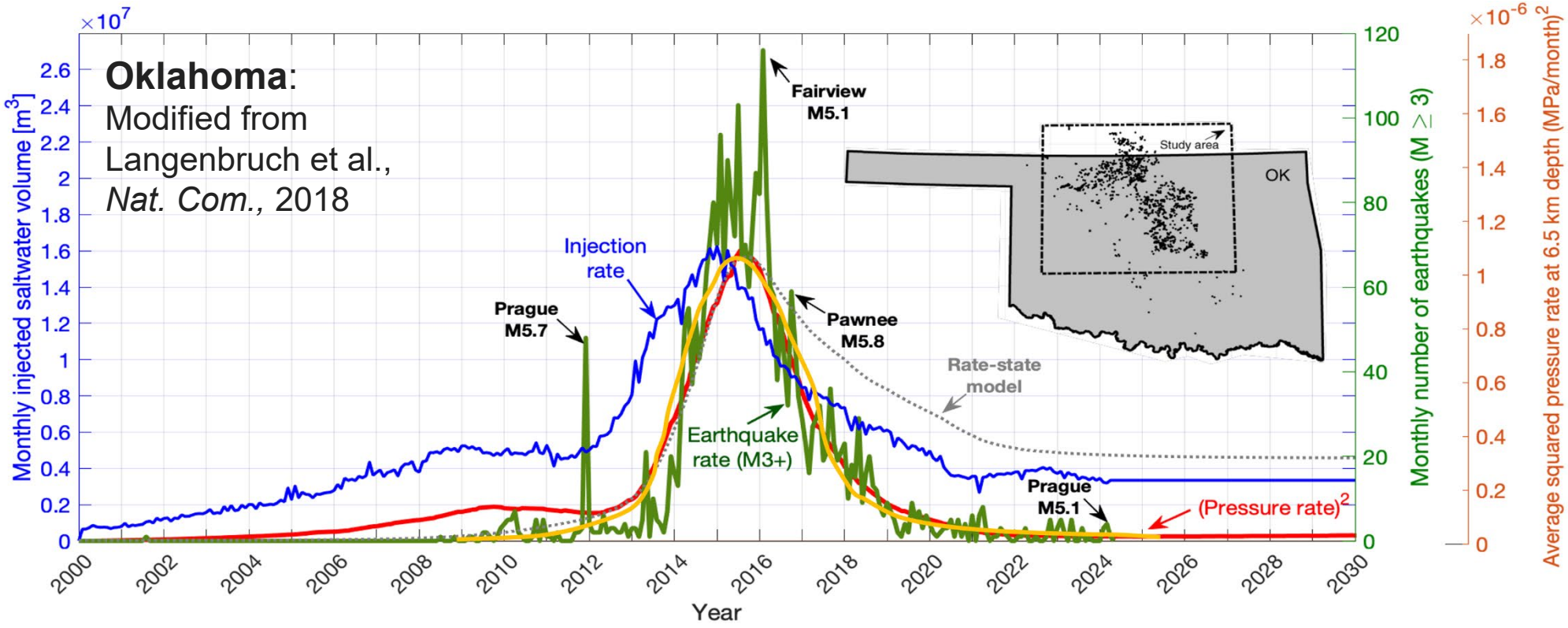
$$P_H(z,t) = P_0 \operatorname{erfc}\left[\frac{z}{\sqrt{4Dt}}\right]$$

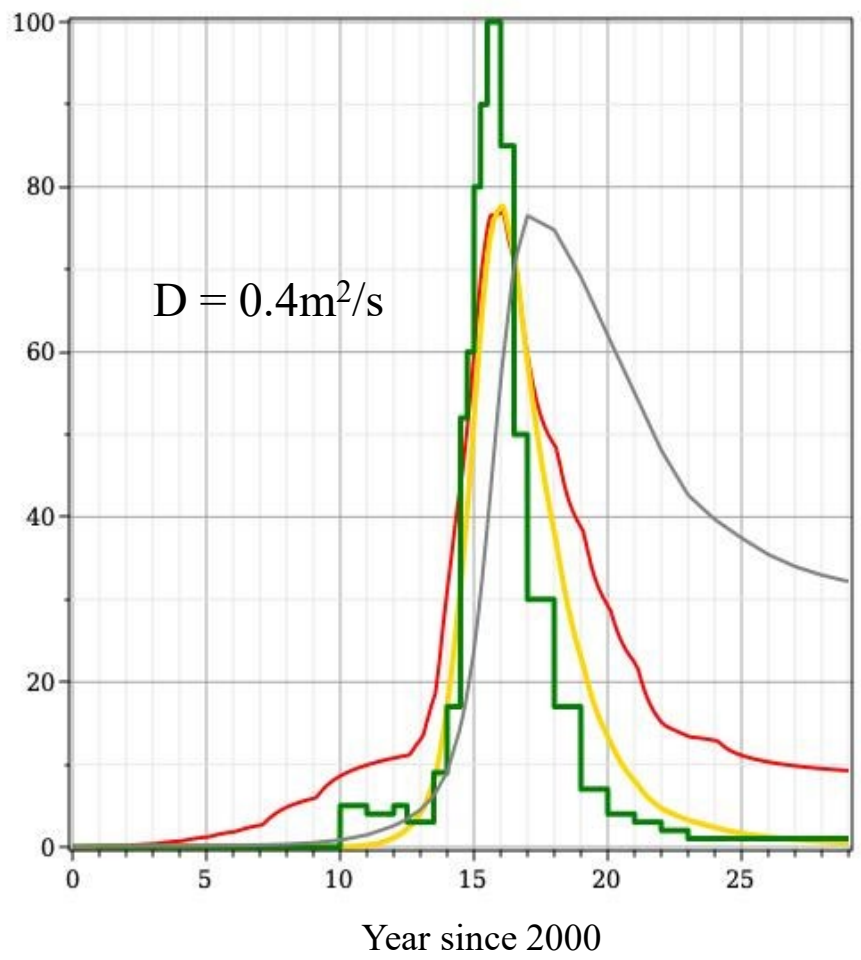
$$\frac{\partial}{\partial t}P(z,t) = \frac{\partial}{\partial t}[P_H(z,t) * \frac{\partial f_p(t)}{\partial t}]$$

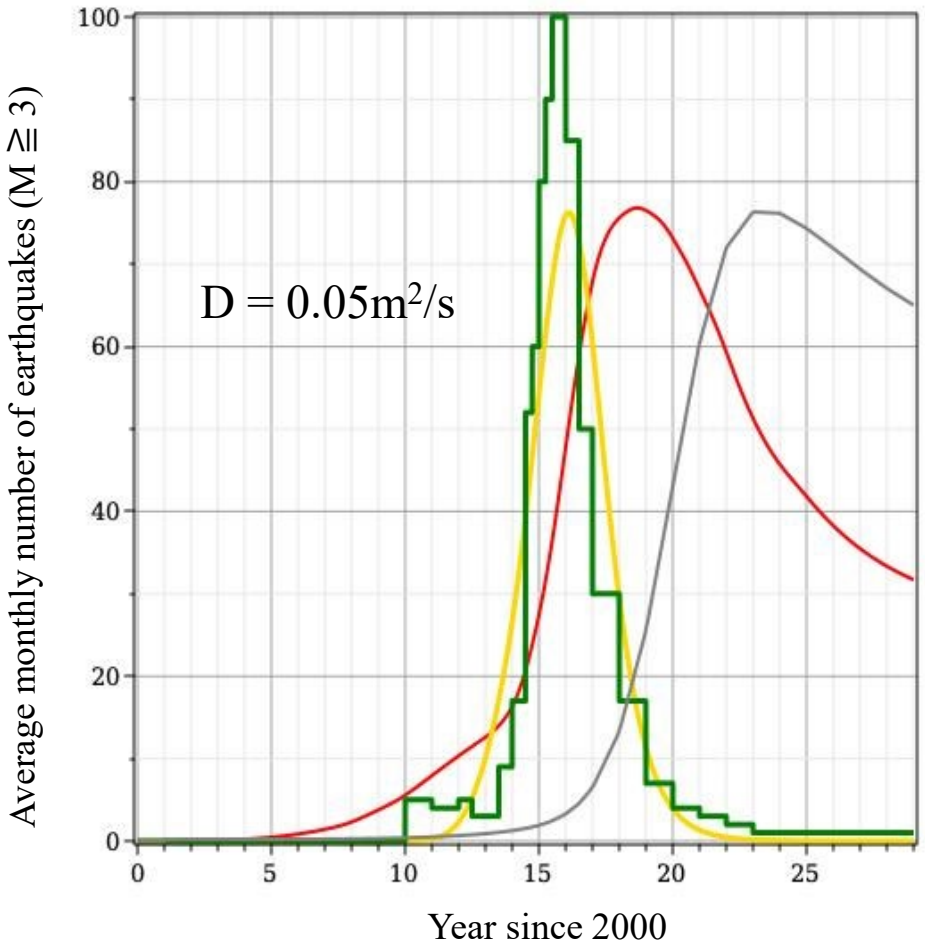
Seismogenic-index model of seismicity rate

$$R_{SI}(\boldsymbol{r},t) = S\, C_{max}\ \ 10^{\Sigma_0}\, F_C\big(\Omega(\boldsymbol{r},t)\big)\,\frac{\partial\Omega(\boldsymbol{r},t)}{\partial t}$$

$$R_{RSF}(\boldsymbol{r},t) = S\, C_{RSF} 10^{\Sigma_0}\, \Psi^{-1}(\boldsymbol{r},t)\,\frac{\partial\Psi(\boldsymbol{r},t)}{\partial t}$$




D = 0.4m²/s
100
80
60
40
20
0
0
5
10
15
20
25
Year since 2000


Average monthly number of earthquakes (M ≧ 3)
D = 0.05m²/s
100
80
60
40
20
0
0
5
10
15
20
25
Year since 2000

Conclusions

Parameters of the seismogenic continuum: Seismogenic Index and the Gutenberg-Richter b-value.

The seismogenic index is a monitoring quantity that provides information about the seismo-tectonic state of the activated rock volume.

Groningen: induced seismicity; lower-bound magnitude statistics; ruptures are constrained by the boundaries of the seismogenic layer.

Pohang, Oklahoma: runaway ruptures; unconstrained seismogenic continuum.

The statistics of critical stress perturbations seem to be very particular and specific at different depths in the crystalline basement. This may lead to the need for specialized, targeted underground laboratories at different depths and geologies.