The Physical Processes of Maximum Magnitudes of Induced Earthquakes

Cornelius Langenbruch, Mohammad J. A. Moein, Serge A. Shapiro

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Industrial activities that can cause induced seismicity

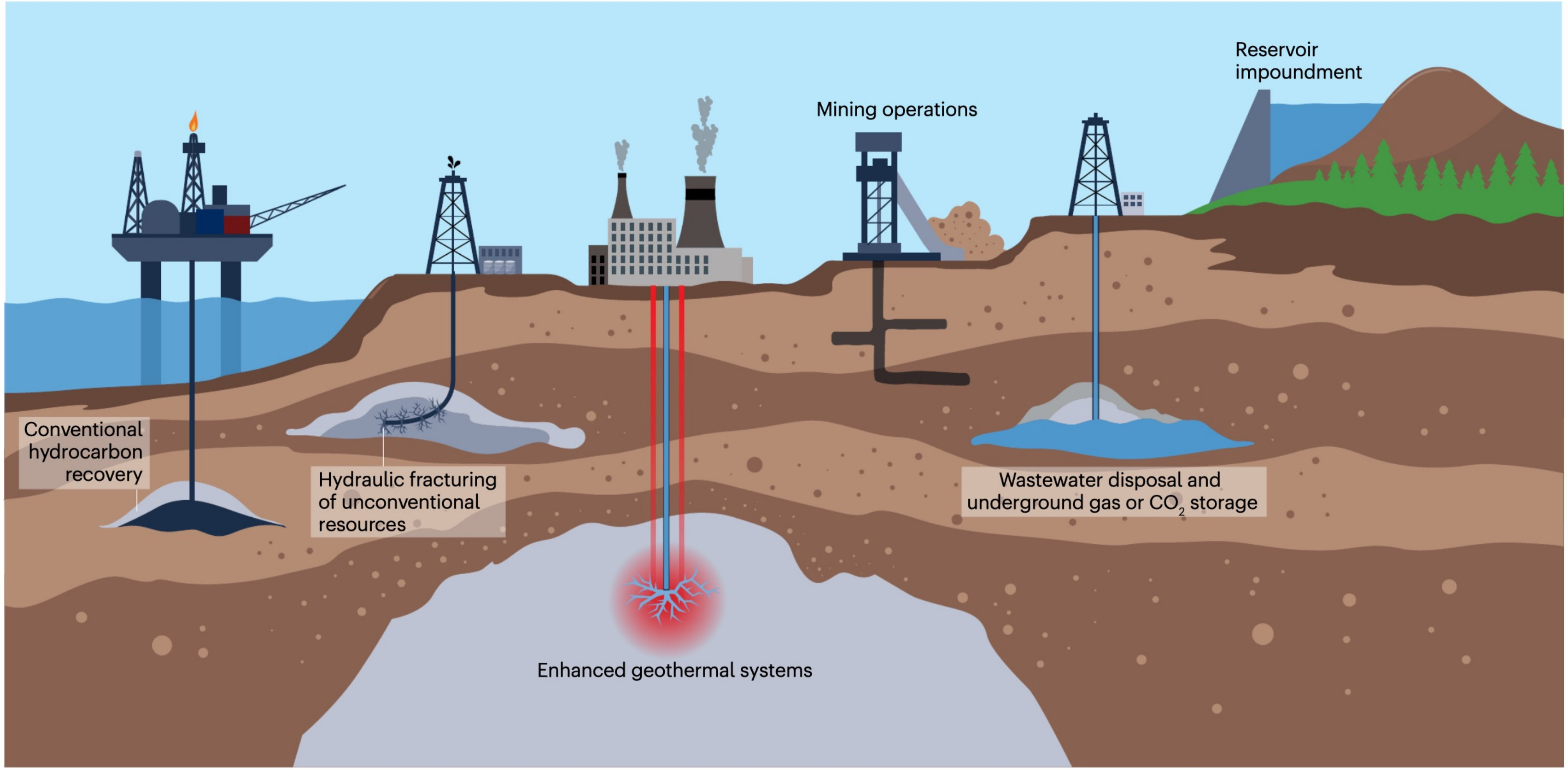
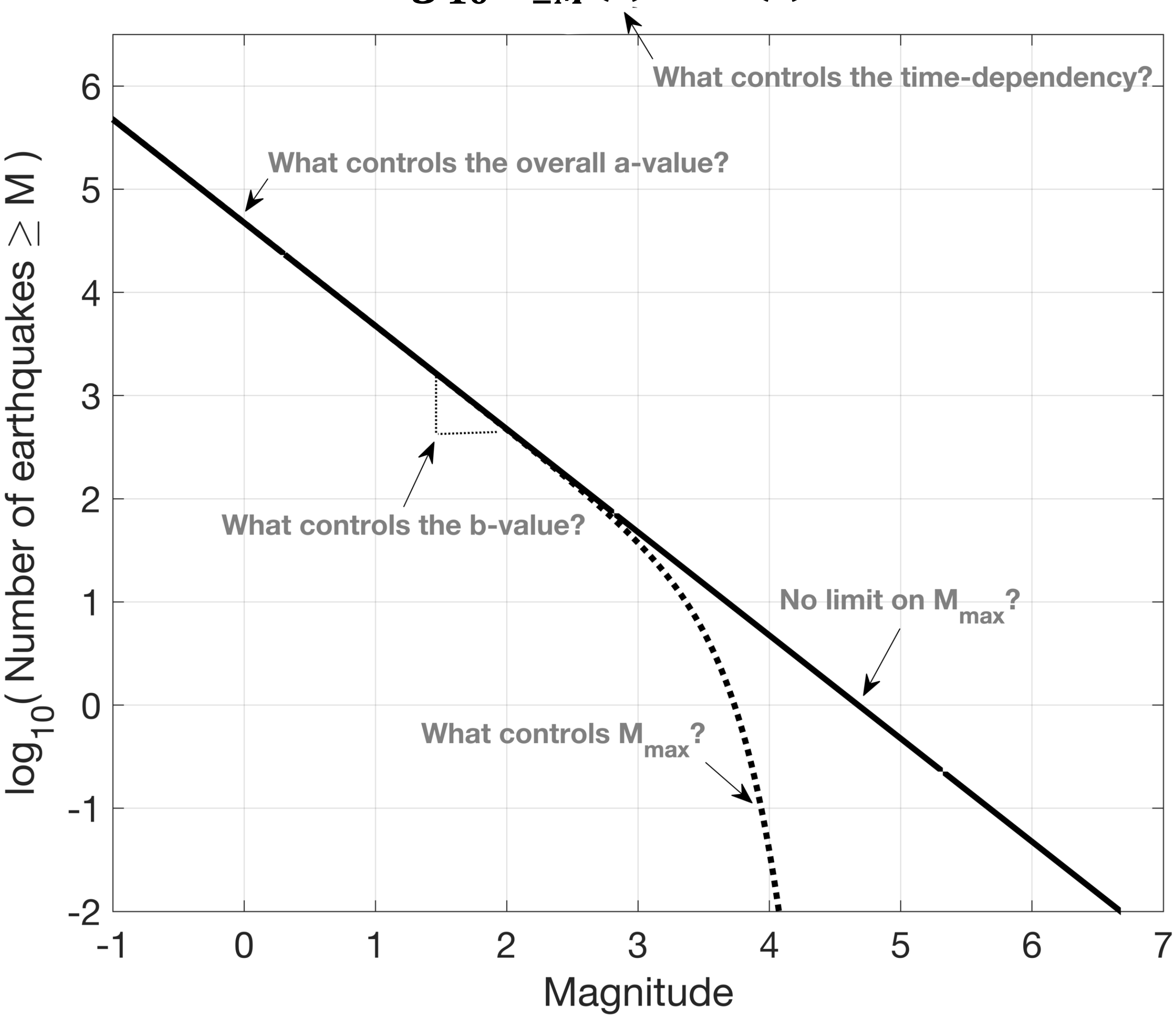


Fig. 1 | Industrial activities that can cause induced seismicity. Induced earthquakes can occur during conventional hydrocarbon recovery, hydraulic fracturing of unconventional resources, enhanced geothermal systems, mining operations, wastewater disposal, underground gas or CO_2 storage operations and reservoir impoundment.

Moein, Langenbruch, et al., 2023, Nature Reviews Earth & Environment

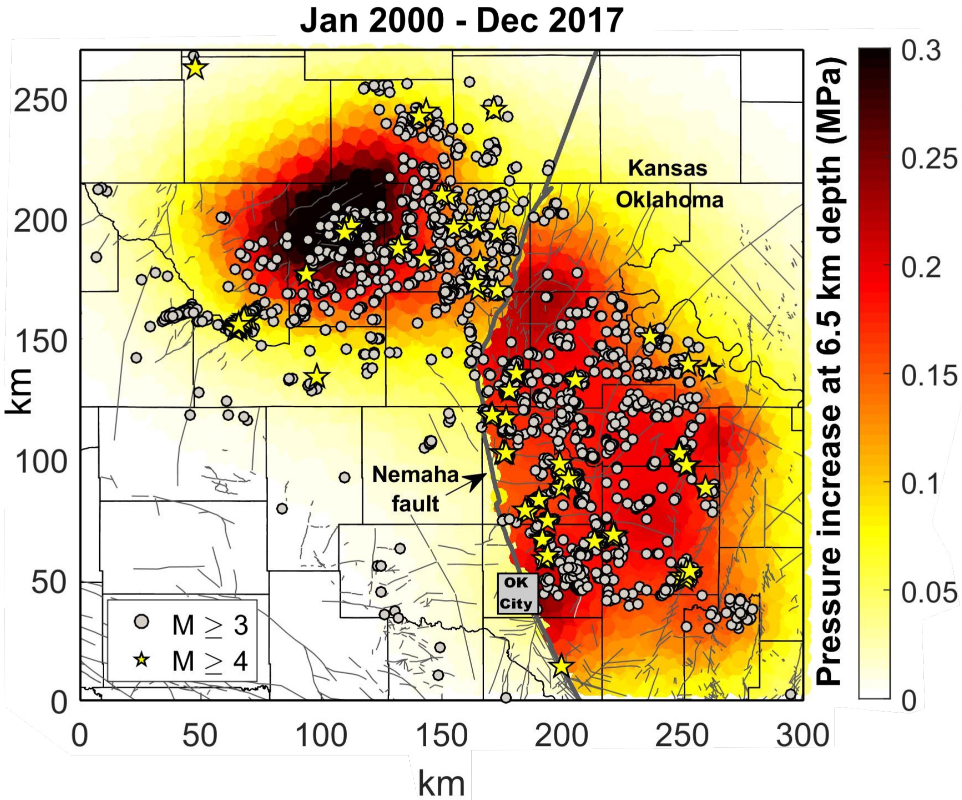
$$\log_{10} N_{\geq M}(t) = a(t) - b\,M$$



Challenges in forecasting the recurrence rates of induced earthquakes?

Water disposal

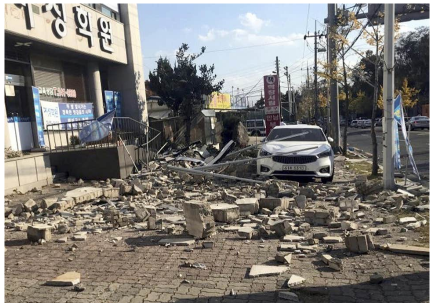
M=5.8, Pawnee, Oklahoma, USA, 2016



Langenbruch et. al, 2018, Nature Comm.

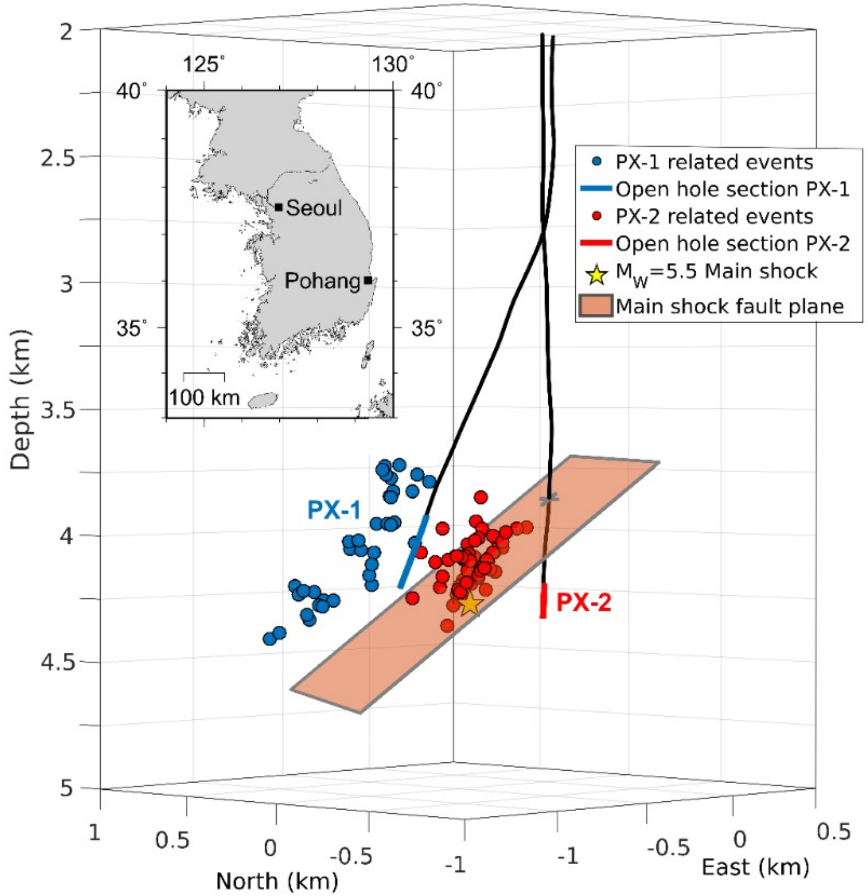
https://www.nbcnews.com/news/us-news/state-emergency-declared-oklahoma-after-magnitude-5-6-earthquake-n642676
https://arstechnica.com/science/2016/11/town-files-lawsuit-after-largest-earthquake-in-oklahoma-history/

M=5.5, Pohang, South Korea, 2017



https://www.independent.co.uk/news/world/asia/south-korea-earthquake-latest-pohang-quake-second-strongest-record-5-4-magnitude-a8057946.html
http://koreabizwire.com/life-on-hold-for-students-after-pohang-earthquake/101585

Enhanced Geothermal System (EGS)



Langenbruch et. al, 2020, GRL

M=6.3, Koyna, India, 1967

Reservoir impoundment

A view of a Koyna Dam in Satara, Maharashtra on Tuesday. Water level of the dam is decreasing due to hot summer. PTI Photo (PTI5_2_2017_000151A)

PHILOSOPHICAL
TRANSACTIONS A

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Research

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https://doi.org/10.1098/rsta.2023.0184

Are maximum magnitudes of induced earthquakes controlled by pressure diffusion?

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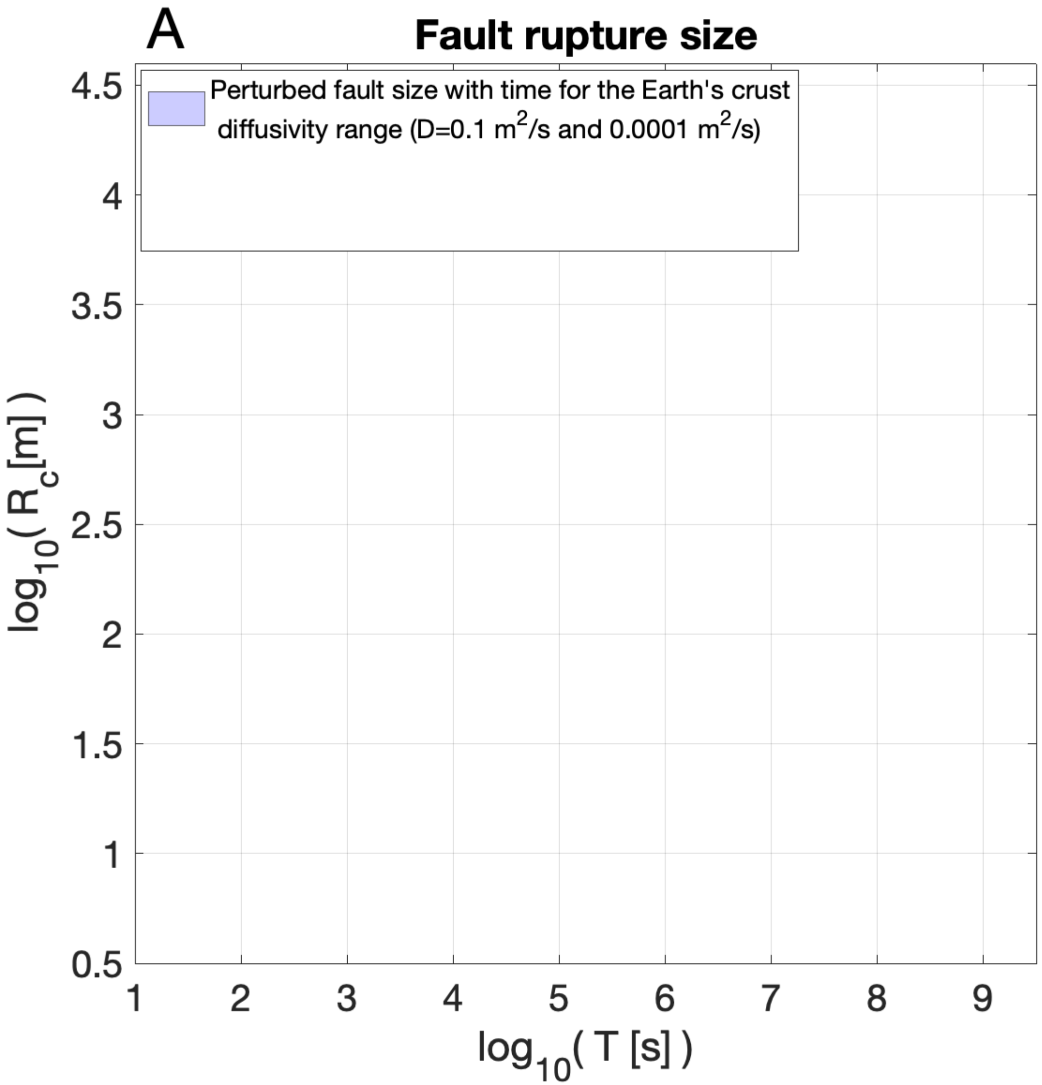


Pressure diffusion controlled growth of perturbed fault size (rock volume) with time?

Triggering front, *Shapiro et al., 1997, 2002*

$$R_c = \sqrt{4\,\pi\,D\,T}$$

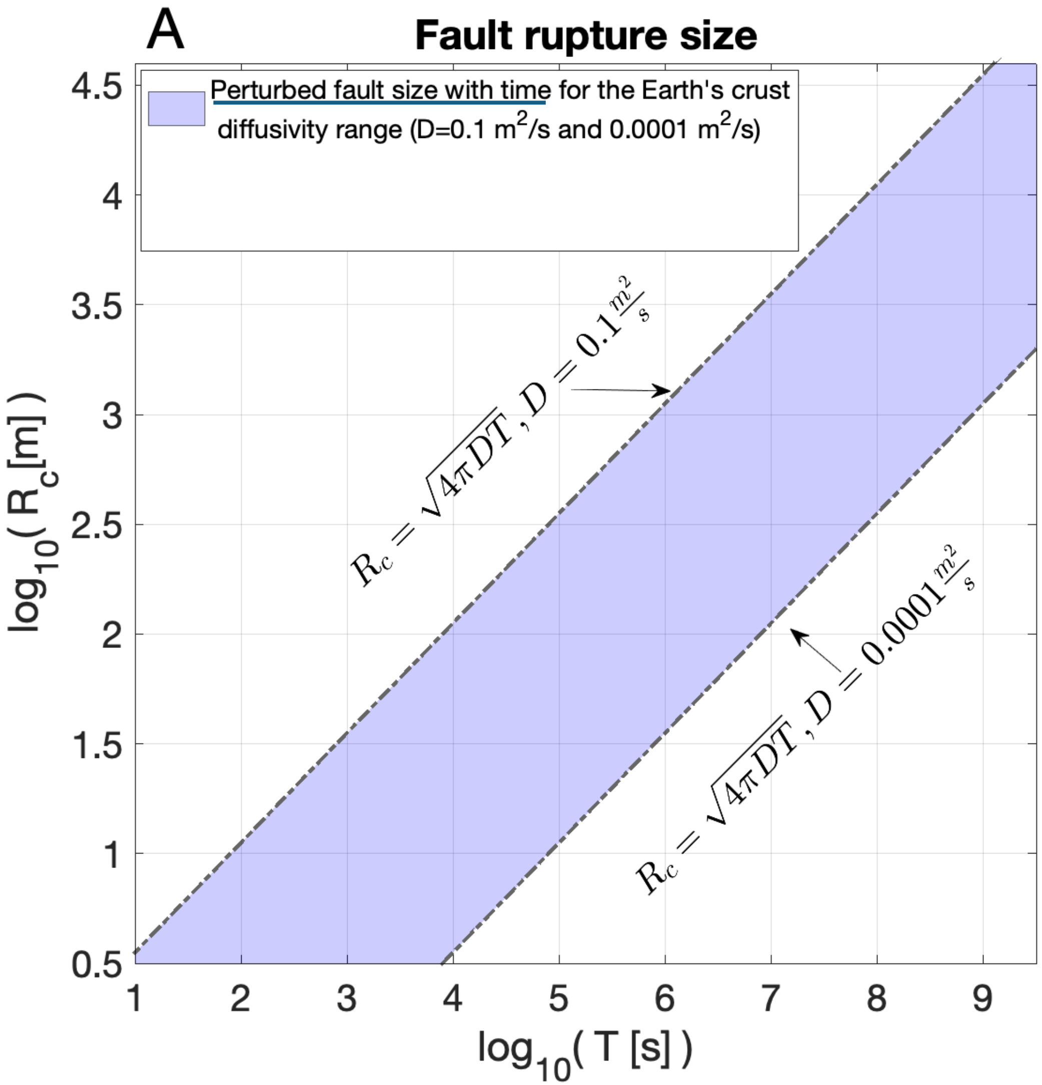
$$2\,log_{10}R_c = \;log_{10}T + log_{10}D + log_{10}4\pi.$$

Two conditions:

- Pressure diffusion occurs predominantly along pre-existing critically stressed faults

  (e.g. Townend and Zoback, 2000)
- The rupture size of induced earthquakes is in the order of the pressure perturbed part of a fault at occurrence time of an earthquake.

  (runaway ruptures and multi-physical processes are not excluded)



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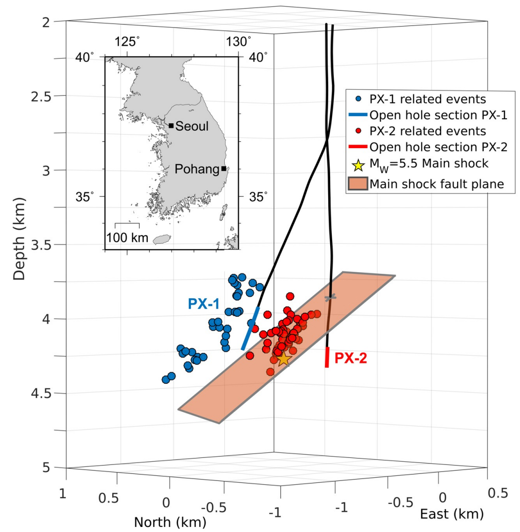
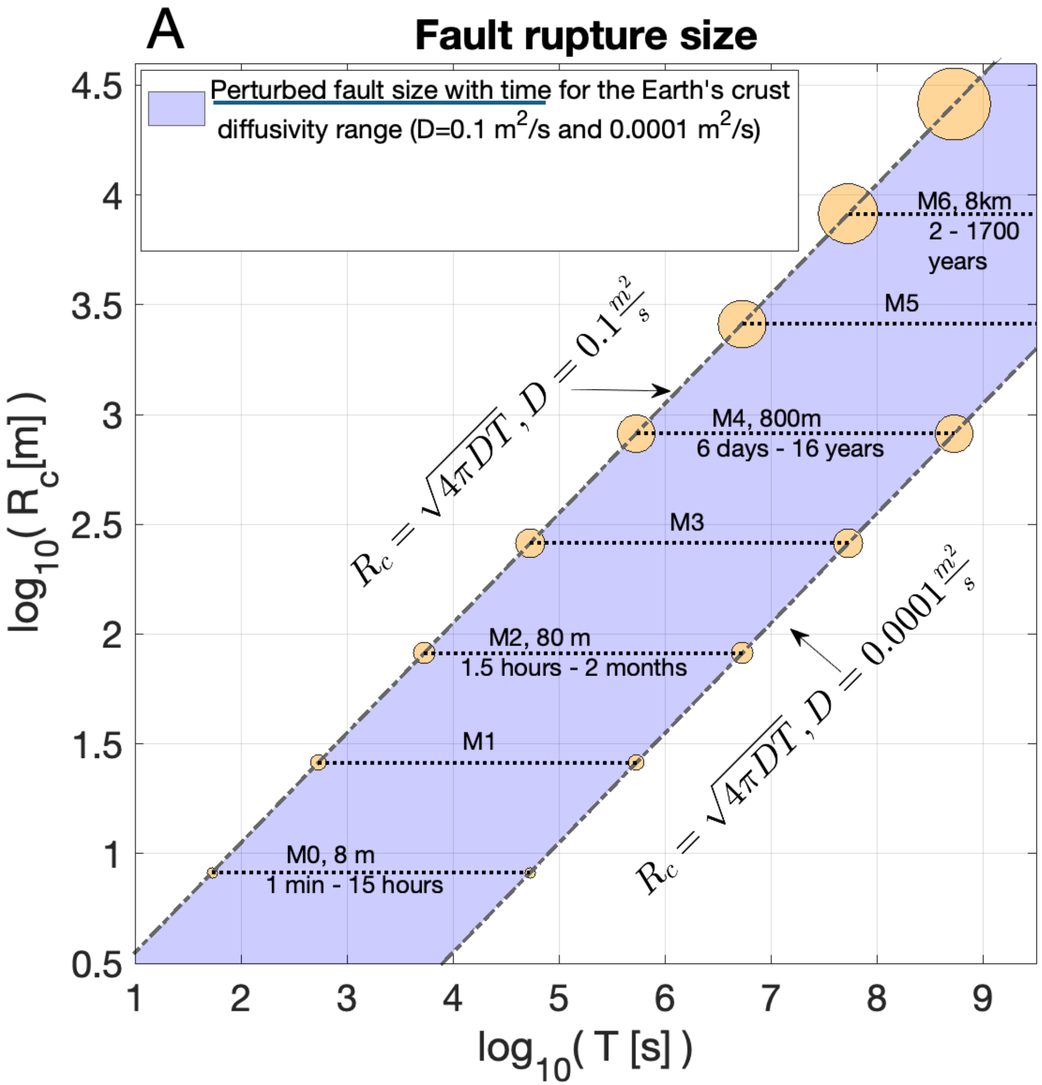
Brittle Earth's crust diffusivity range:
Townend and Zoback, 2000

$$D = 10^{-4}\;to\;10^{-1}\,\frac{m^2}{s}$$

Pressure diffusion occurs predominantly along pre-existing critically stressed faults.





Pressure diffusion controlled growth of perturbed fault size (rock volume) with time?

R_c can be considered as the pressure perturbed fault size!

What is the growth of the maximum magnitude over time if ruptures are in the order of the pressure perturbed part of a fault R_c at time T?

Kanamori, 1977, Hanks and Kanamori, 1979, Madariaga, 1979, Lay Wallace, 1995:

$$M_W = \frac{2}{3}(log_{10}M_0 - 9.1),\ M_0 = \frac{16}{7}\ {R_c}^3\Delta\sigma$$

Radius (R_c) of a circular rupture, seismic moment (M_0), moment magnitude (M_W) and stress drop ($\Delta\sigma$)

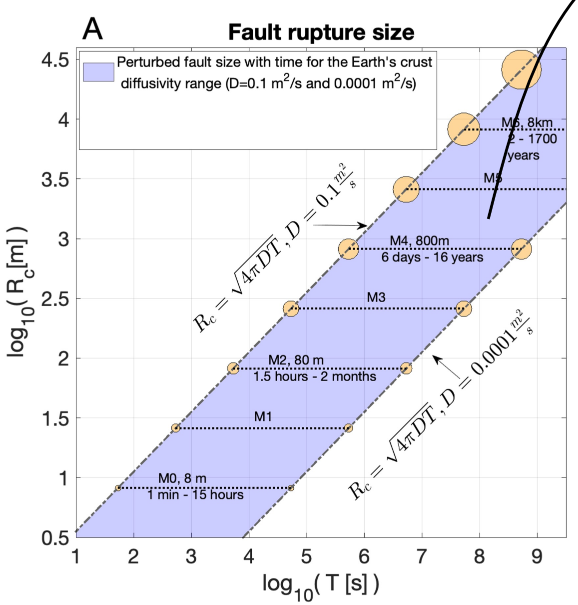
$$M_W = \frac{2}{3}(log_{10}M_0 - 9.1),\ M_0 = \frac{16}{7}\ {R_c}^3\Delta\sigma$$

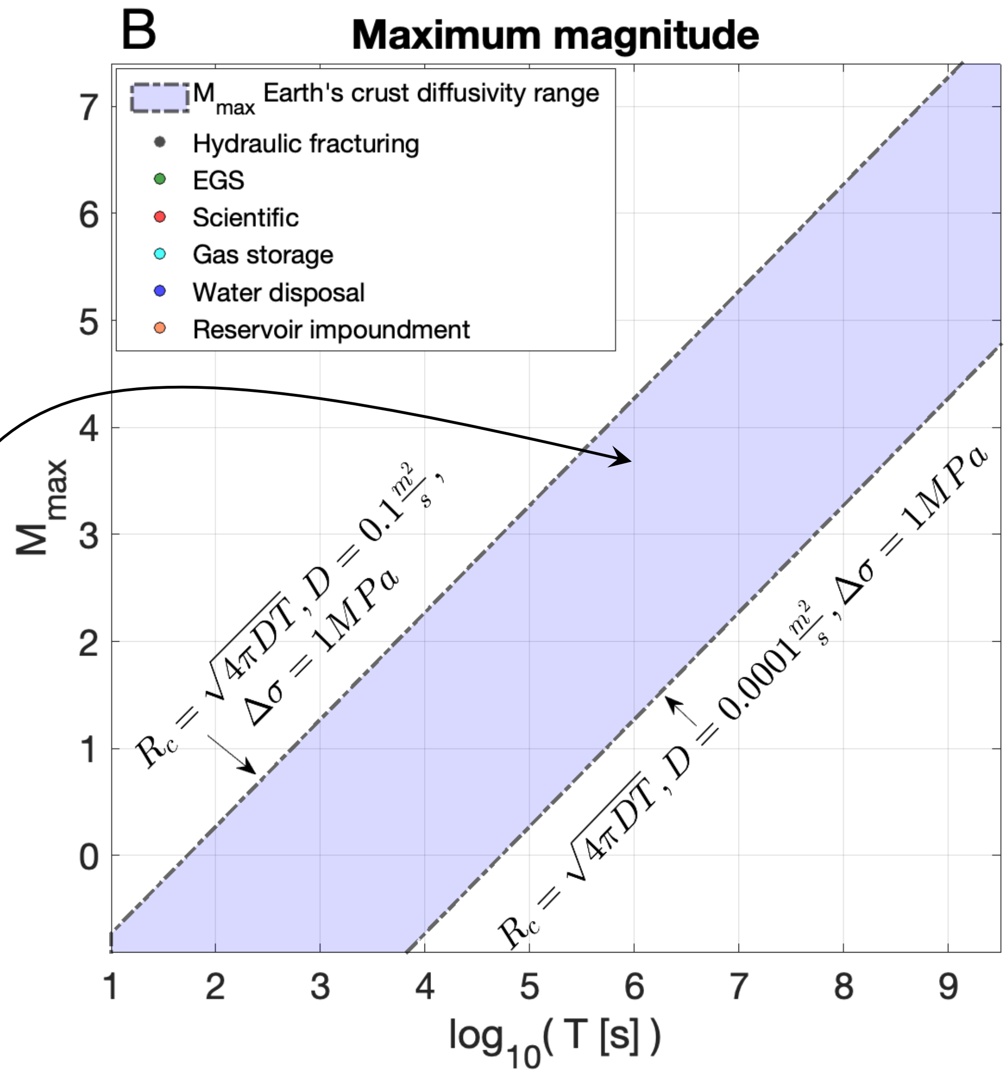
$$R_c = \sqrt{4\,\pi\,D\,T}$$

$$M_W^{max} = \ log_{10}T + \Theta_{D\sigma}$$

$$\Theta_{D\sigma} = log_{10}D + \frac{2}{3}log_{10}\Delta\sigma - 4.7281$$

The **seismic nucleation constant $\boldsymbol{\Theta_{D\sigma}}$** controls the characteristic time to reach a subsurface state allowing a given magnitude earthquake to occur





$$M_W = \frac{2}{3}(log_{10}M_0 - 9.1),\ M_0 = \frac{16}{7}\ {R_c}^3\Delta\sigma$$

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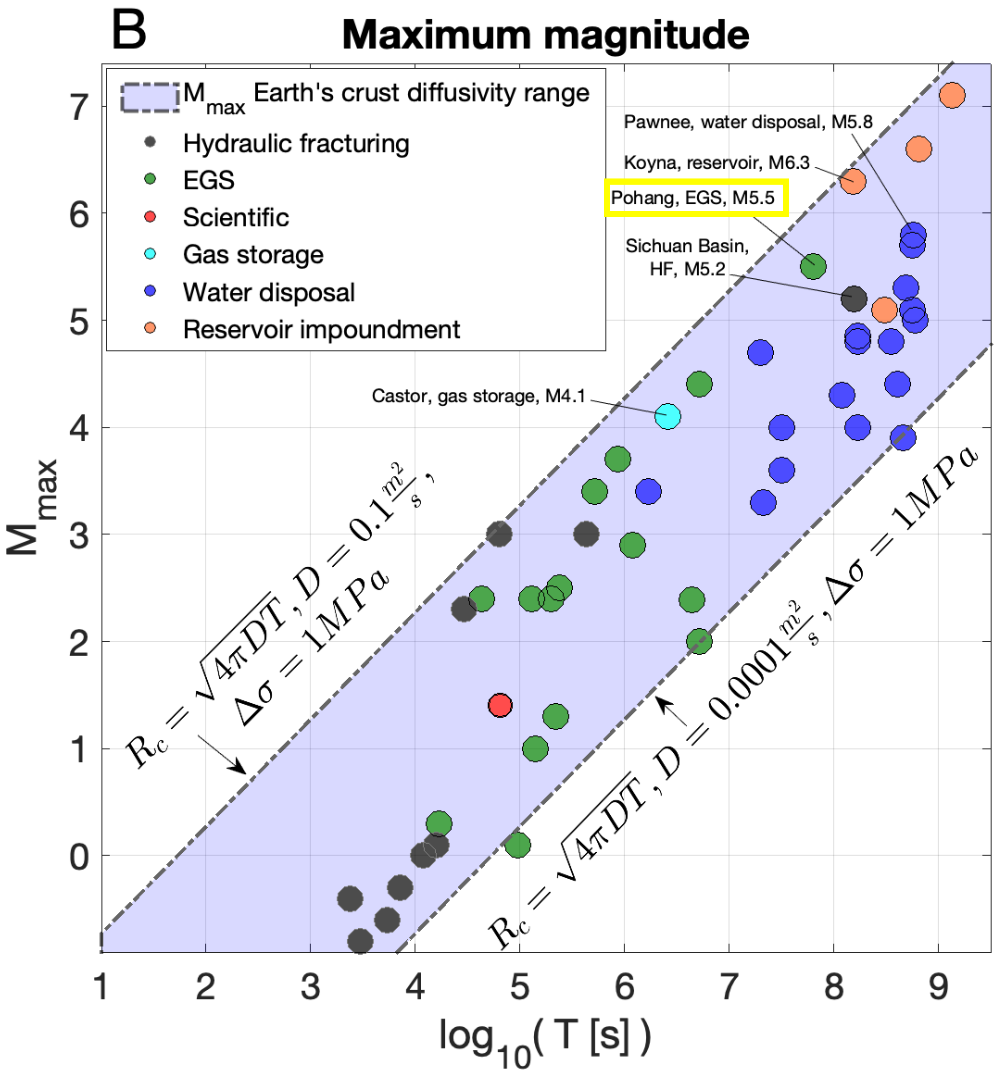
$\Theta_{D\sigma}$: Magnitude of nucleation time 1 second

Global compilation of maximum induced earthquake magnitudes

hydraulic fracturing, geothermal reservoir stimulation, water disposal, gas storage and reservoir impoundment

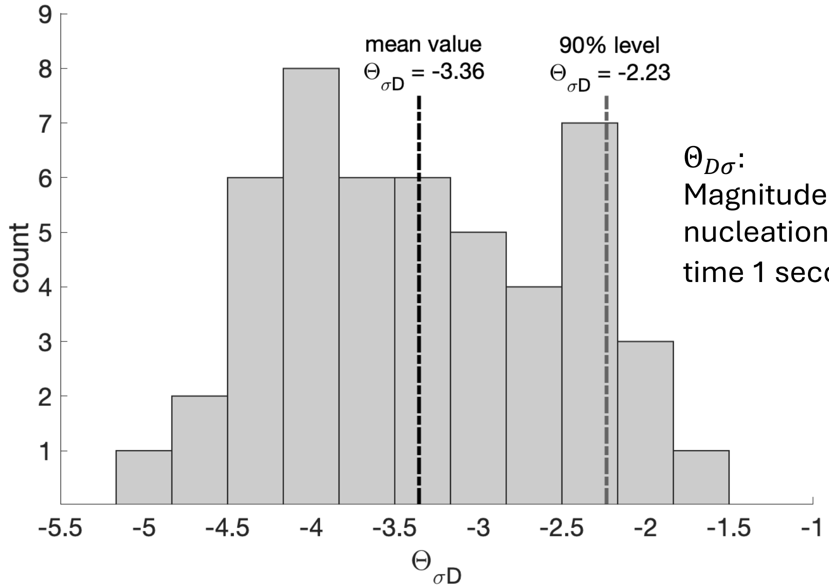


How to calibrate a first order seismic hazard model?

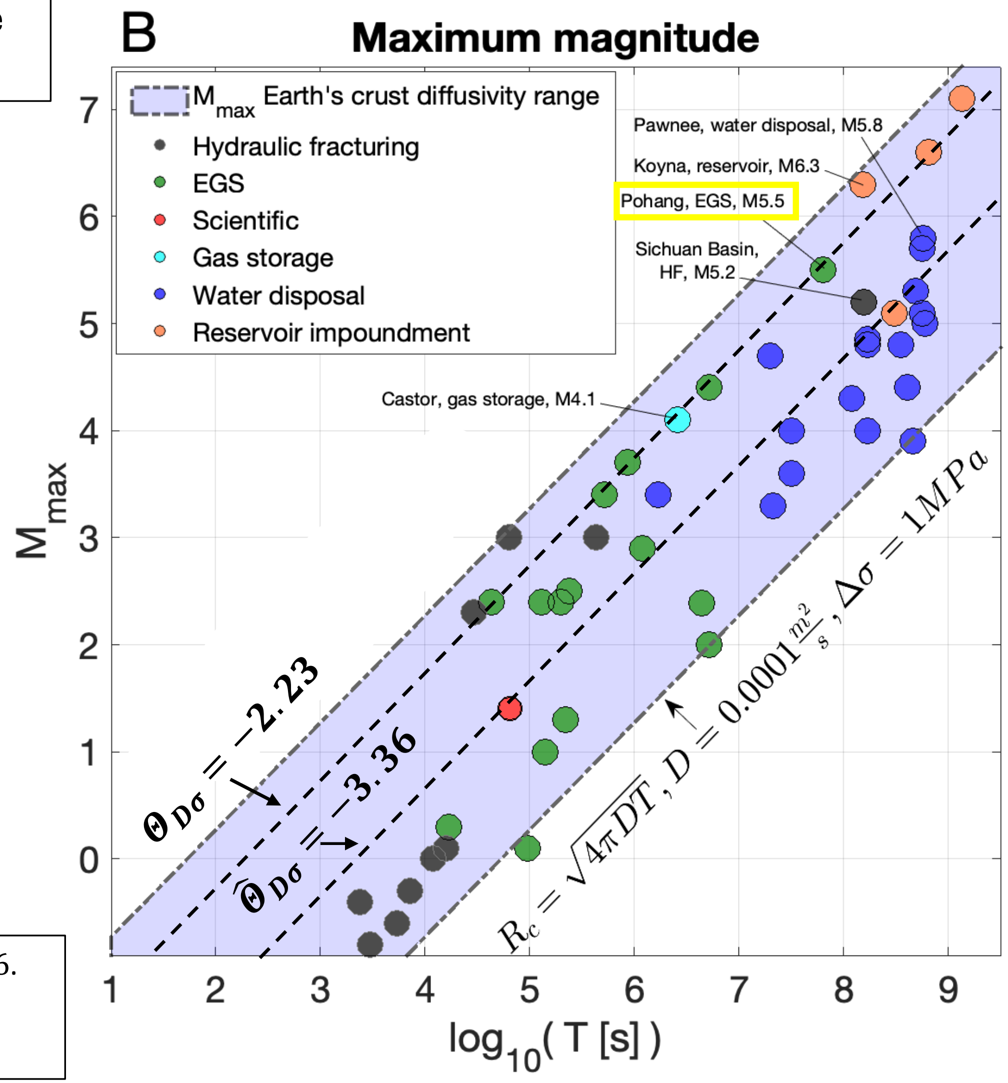
Can we estimate the expected maximum magnitude prior to the start of a geo energy project?

$$M_W^{max} = log_{10}T + \Theta_{D\sigma}$$

$$\Theta_{D\sigma} = log_{10}D + \frac{2}{3}log_{10}\Delta\sigma - 4.7281$$



$\Theta_{D\sigma}$: Magnitude of nucleation time 1 second



The maximum expected induced magnitude scales according to $\widehat{\Theta}_{D\sigma} = -3.36$.
The upper bound (90% level) of Mmax scales according to $\Theta_{D\sigma} = -2.23$.
These quantites can be used in seismic hazard studies pre-operation!

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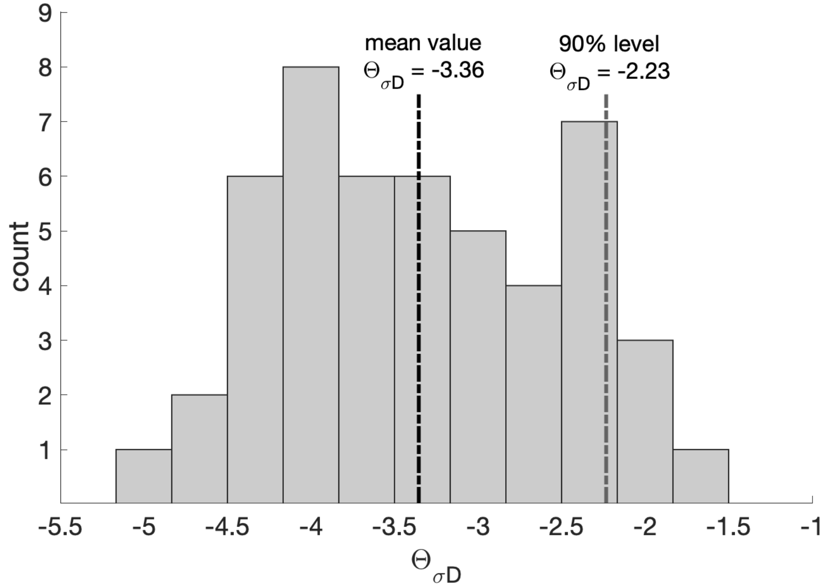

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Our calibrated maximum magnitude model can be used pre-operation!

Nucleation time	M_{max} upper bound (90%)	M_{max} expected
1 hour	1.3	0.2
1 day	2.7	1.6
1 week	3.6	2.4
1 month	4.2	3.1
1 year	5.3	4.1
10 years	6.3	5.1
100 years	7.3	6.1

Value at Induced Seismic Risk (VaIR)

A risk management approach based on low-probability high-impact events!

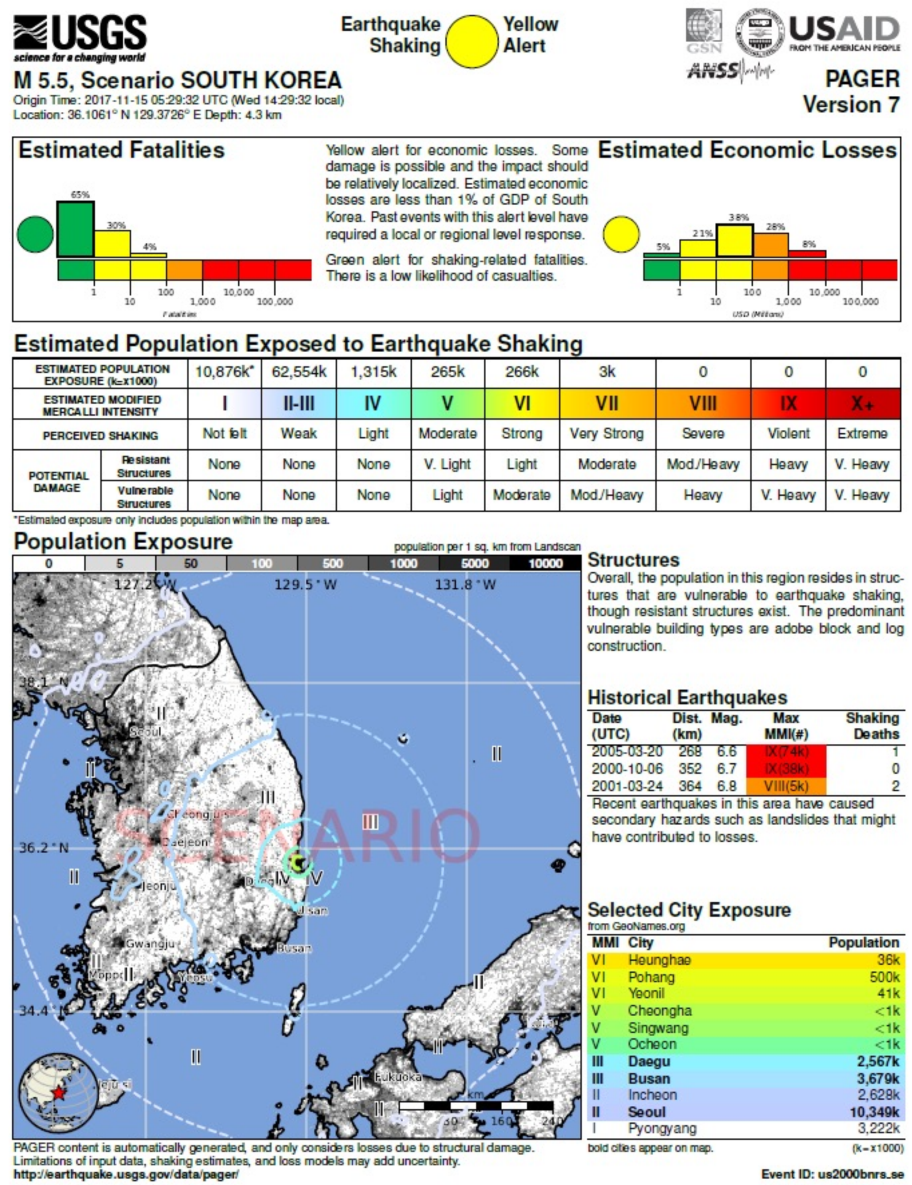
Langenbruch, Ellsworth, Woo and Wald, 2020, GRL

Pre-Operation

- **Perform scenario risk modelling to identify unacceptable magnitude levels**
- Determine quantitative thresholds of exceeding unacceptable losses in consultation with local authorities (e.g. 1% of exceeding US$10M)

Operation

- Monitor seismicity (time and magnitude)
- Compute magnitude exceedance probabilities
- Combine magnitude probabilities and pre-operation scenario risk modelling to monitor the Value at Induced Risk (VaIR) in real-time



USGS science for a changing world

Earthquake Shaking Yellow Alert

USAID FROM THE AMERICAN PEOPLE

PAGER Version 7

M 5.5, Scenario SOUTH KOREA

Origin Time: 2017-11-15 05:29:32 UTC (Wed 14:29:32 local)
Location: 36.1061° N 129.3726° E Depth: 4.3 km

Estimated Fatalities

Yellow alert for economic losses. Some damage is possible and the impact should be relatively localized. Estimated economic losses are less than 1% of GDP of South Korea. Past events with this alert level have required a local or regional level response.

Green alert for shaking-related fatalities. There is a low likelihood of casualties.

Estimated Economic Losses

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k=x1000)		10,876k*	62,554k	1,315k	265k	266k	3k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	None	None	None	V. Light	Light	Moderate	Mod./Heavy	Heavy	V. Heavy
	Vulnerable Structures	None	None	None	Light	Moderate	Mod./Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per 1 sq. km from Landscan

Structures

Overall, the population in this region resides in structures that are vulnerable to earthquake shaking, though resistant structures exist. The predominant vulnerable building types are adobe block and log construction.

Historical Earthquakes

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
2005-03-20	268	6.6	IX(74k)	1
2000-10-06	352	6.7	IX(38k)	0
2001-03-24	364	6.8	VIII(5k)	2

Recent earthquakes in this area have caused secondary hazards such as landslides that might have contributed to losses.

Selected City Exposure

from GeoNames.org

MMI	City	Population
VI	Heunghae	36k
VI	Pohang	500k
VI	Yeonil	41k
V	Cheongha	<1k
V	Singwang	<1k
V	Ocheon	<1k
III	**Daegu**	**2,567k**
III	**Busan**	**3,679k**
II	Incheon	2,628k
II	**Seoul**	**10,349k**
I	Pyongyang	3,222k

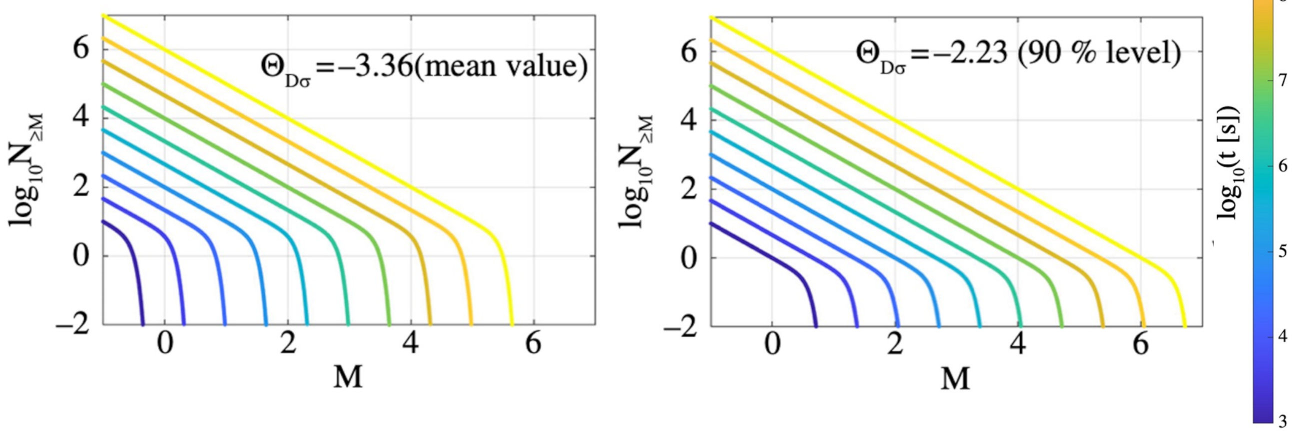
bold cities appear on map. (k=x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/data/pager/

Event ID: us2000bnrs_se

(PAGER) Prompt Assessment of Global Earthquakes for Response

Physics-based truncation of the Gutenberg-Richter law and the Seismogenic Index



Gutenberg-Richter law:

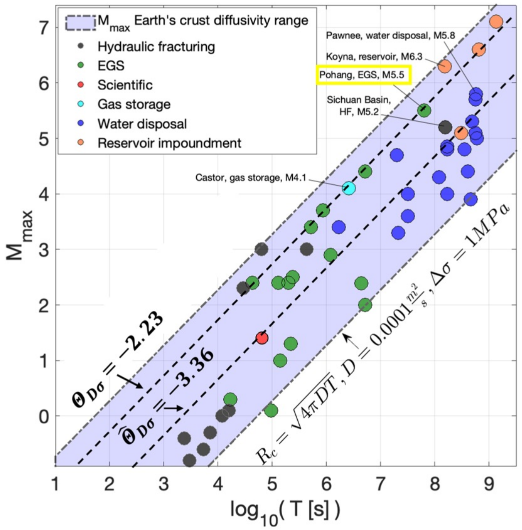
$$\log_{10}(N_{\geq M}) = a - bM$$

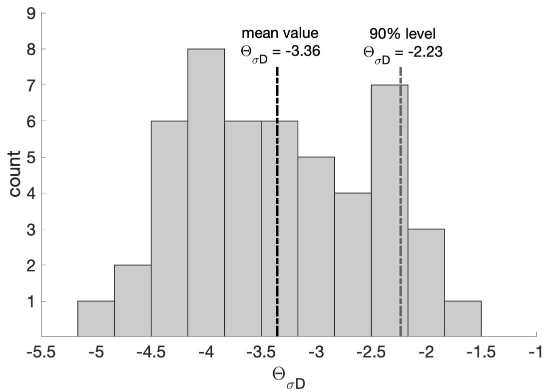
Exponential taper:

$$P(M) = \beta\left(e^{-\beta(M-M_c)-\gamma e^{\delta(M-M_m)}}\right), \mathrm{M} > \mathrm{M}_c\ ,$$

e.g. Kagan, 2010, Eaton et al., 2021

$$\beta = \log(10)b,$$

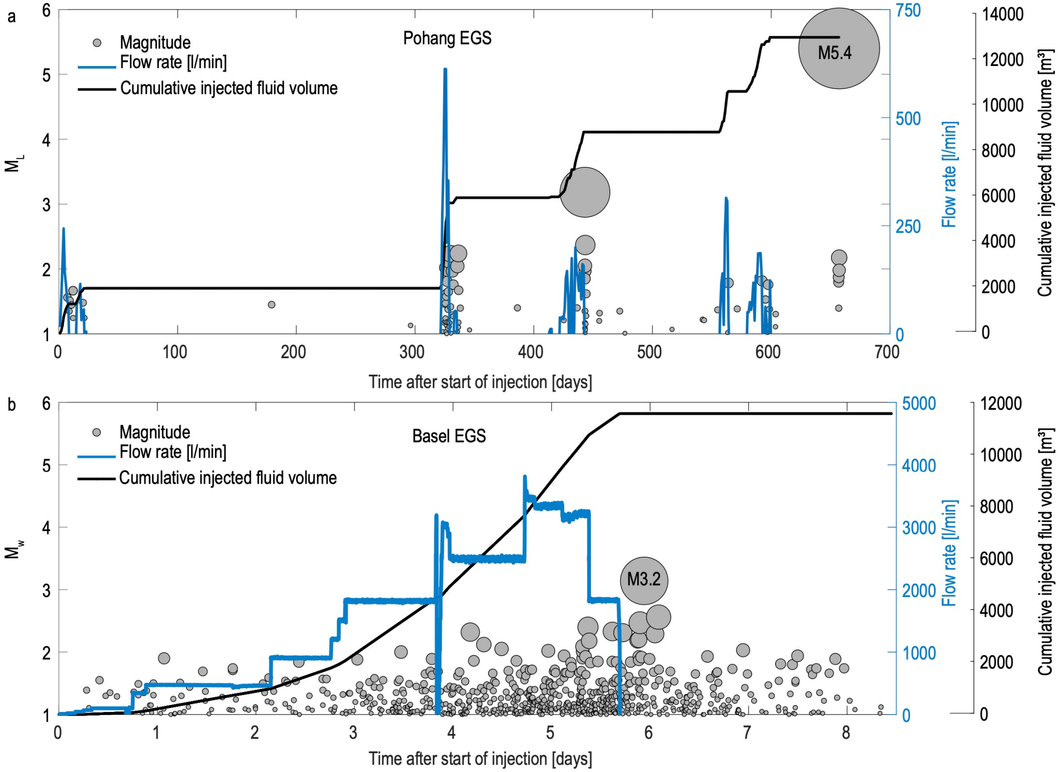


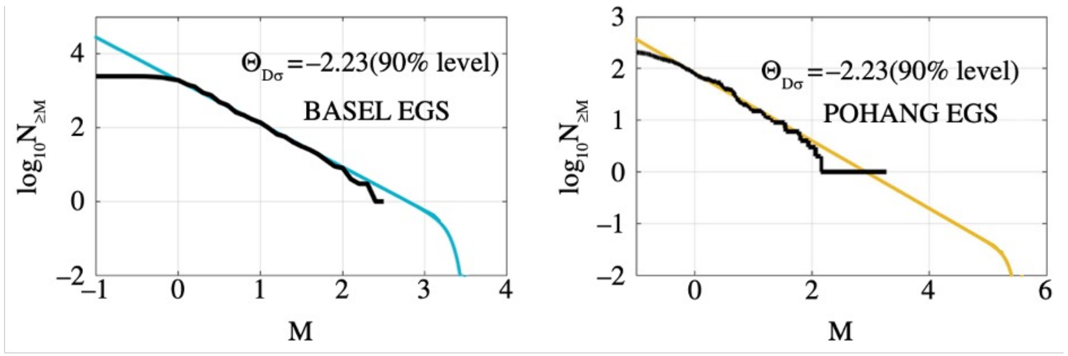


Corner magnitude M_m can be replaced by:

$$M_W^{max} = \ log_{10}T + \Theta_{D\sigma}$$

Physics-based truncation of the Gutenberg-Richter law and the Seismogenic Index





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e.g. Kagan, 2010, Eaton et al., 2021 $\beta = \log(10)b,$

Corner magnitude M_m can be replaced by:

$$M_W^{max} = log_{10}T + \Theta_{D\sigma}$$

To forecast the complete magnitude frequency distribution we must combine the M_{max} model with a model describing the earthquake productivity (a-value)!

The Seismogenic Index

Shapiro, Dinske, Langenbruch and Wenzel, 2010

Injection Volume-based:

Gutenberg-Richter law for fluid injection-induced seismicity

$$log_{10}\left[N_{\geq M}(t)\right] = \underbrace{log_{10}\left[V_I(t)\right] + \Sigma}_{\text{a-value of the classical GR relation}} - bM$$

$$\Sigma = log_{10}\left[\frac{\zeta}{C_{max}S}\right] + a_p$$

EGS, disposal and scientific

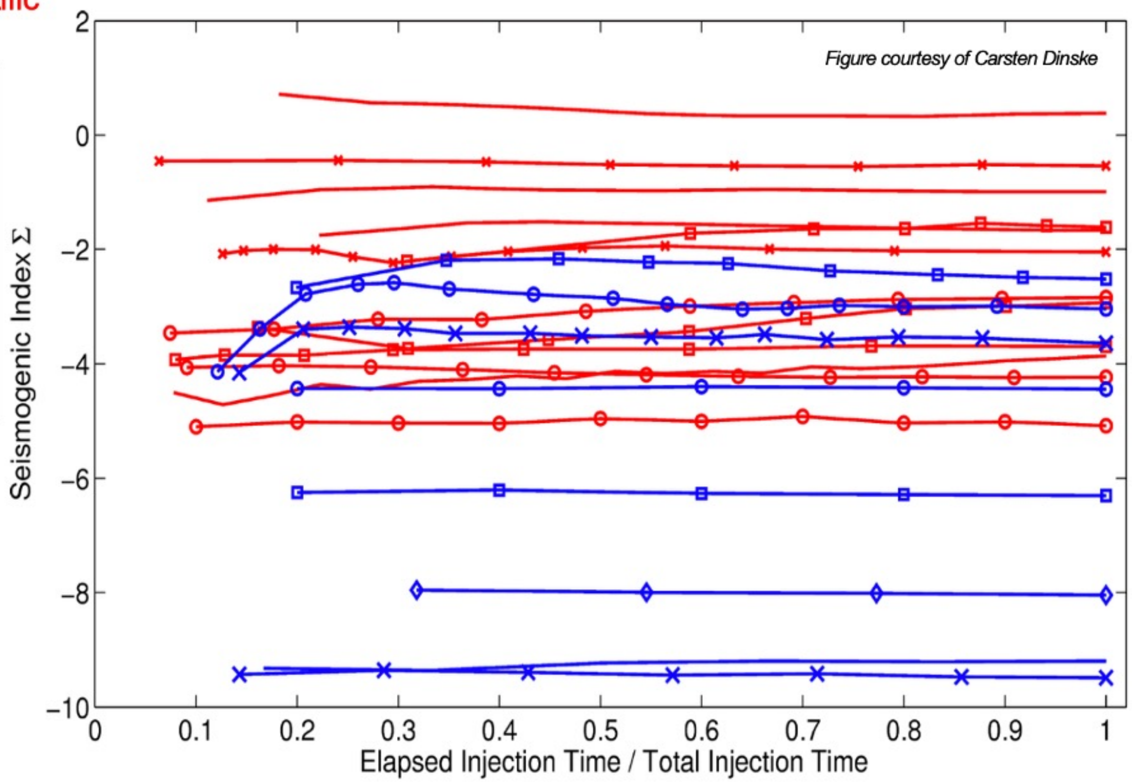
(crystalline basement)

location (type)	Σ
Basel (2006/EGS)	0.4
Cooper (2003/EGS)	-0.9
Ogachi (1991/EGS)	-2.6
Ogachi (1993/EGS)	-3.2
Soultz (1993/EGS)	-2.0
Soultz (1995/EGS)	-3.8
Soultz (1996/EGS)	-3.1
Soultz (2000/EGS)	-0.5
KTB (1994/SCI)	-1.65
KTB (2004-05/SCI)	-4.2
Paradox (1997-2000/WD)	-2.6
Unterhaching (HYD)	-4.8

Hydraulic Fracturing

(sediments)

Barnett Shale (FRAC)	-9.2
Cotton V. A (FRAC)	-6.2
Cotton V. B (FRAC)	-4.4
Cotton V. C (FRAC)	-9.4
Canada, BC, A (FRAC)	-2.9
Canada, BC, B (FRAC)	-2.3
Canada, BC, C (FRAC)	-3.5
Australia (FRAC)	-8.0



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Gutenberg-Richter law for fluid injection-induced seismicity

Injection Volume-based:

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$$\Sigma = log_{10}\left[\frac{\zeta}{C_{max}S}\right] + a_p$$

... reformulated for **incorporating multi-physics modelling** of pore pressure and stress changes:

$$\log \mathrm{N}_{\geq \mathrm{M}}(\mathrm{t}) = \Sigma + \log_{10}\left[\int \frac{S\, M(\Delta CFS(t))}{\sin(\varphi)}\, dV\right] - \mathrm{bM} = \Sigma + \mathrm{F}_{CFS}(\mathrm{t}) - \mathrm{bM} = \mathrm{a}_{IS}(\mathrm{t}) - \mathrm{bM}\,. \qquad (4)$$

Cacace et al., 2021, Shapiro et al., 2010, Langenbruch et al., 2024

Here, the fluid volume has been replaced by the integral of the change of the Coulomb Failure Stress ($\Delta CFS(t)$) over the entire reservoir domain (Cacace et al., 2021). In Eq. (4), S is the uniaxial storage coefficient, φ is the friction angle, and $M(\Delta CFS(t))$ is the minimum positive monotonic majorant of $\Delta CFS(t)$. Eq. 4 can be used in combination of a multi-physics-based model computing the change of ΔCFS in space and time.

Physics-based truncation of the Gutenberg-Richter law and the Seismogenic Index

Seismogenic Index model:

$$log_{10}\left[N_{\geq M}(t)\right] = log_{10}\left[V_I(t)\right] + \Sigma - bM$$

Exponential taper:

$$M_W^{max} = log_{10}T + \Theta_{D\sigma}$$

$$P(M) = \beta\left(e^{-\beta(M-M_c)-\gamma e^{\delta(M-M_m)}}\right), M > M_c ,$$

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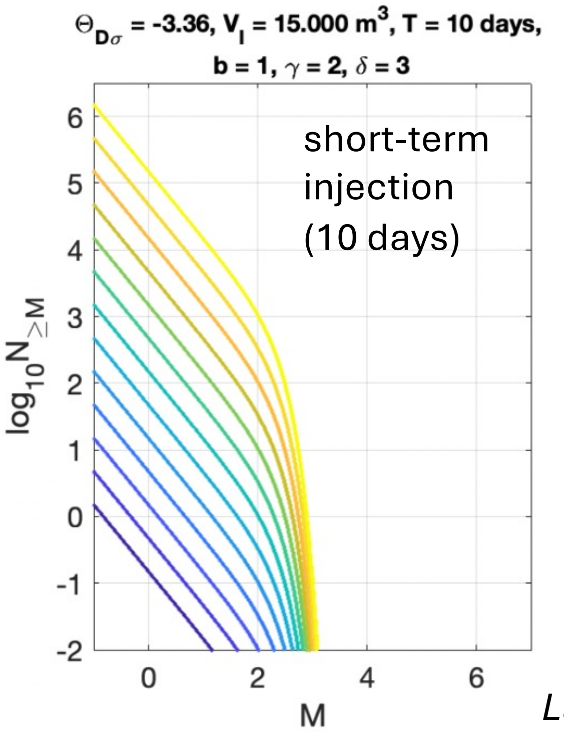
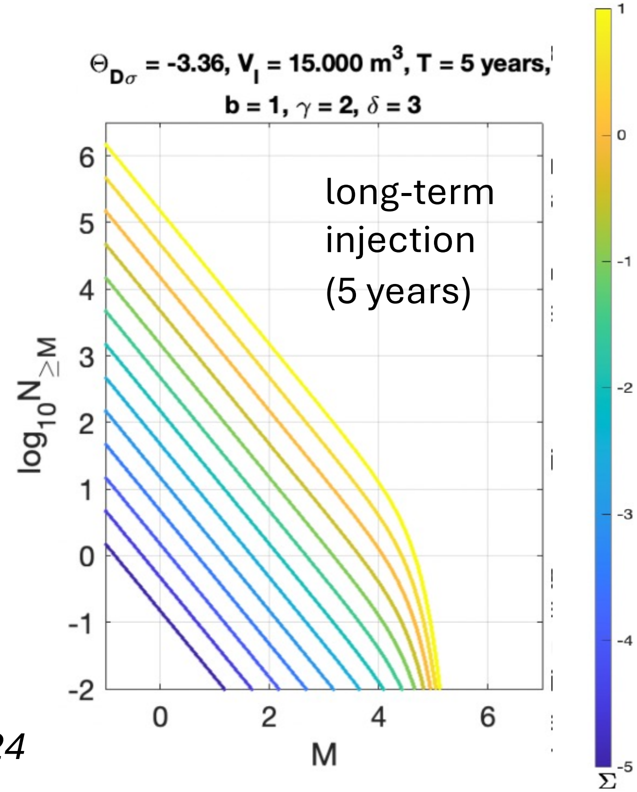


The same fluid volume is injected in both cases!

Langenbruch et al., 2024



The maximum magnitude is controlled by the injected volume (ΔCFS), the time and the seismo-tectonic conditions!

We combine the Seismogenic Index model and the Seismic Nucleation Constant.

Our GR-law includes a volume (CFS) based rate model (a-value) and time-based maximum magnitude (M_m)!

Conclusions

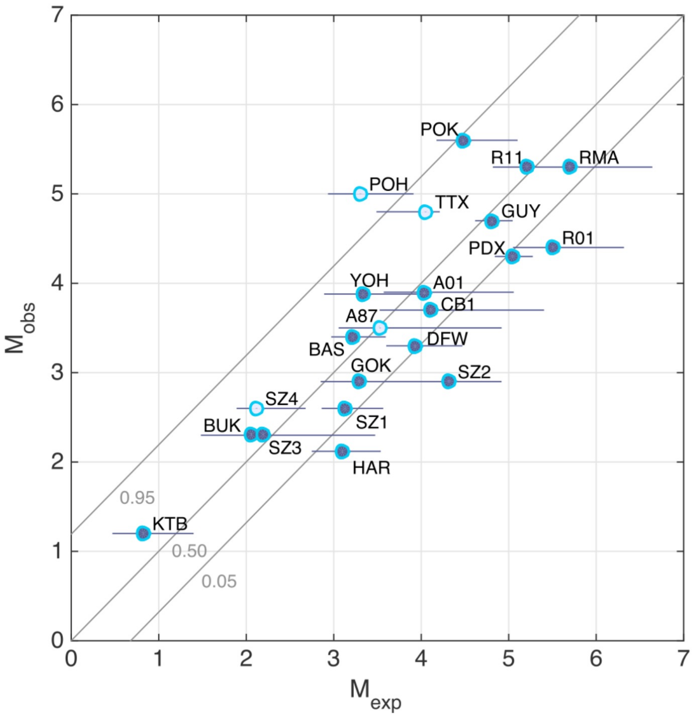
A simple model of pressure diffusion controlled rupture sizes explains the observed increase of maximum magnitudes of induced earthquakes with time.

Our model can be used for truncation of the Gutenberg-Richter law and to understand magnitudes to be included in pre-operational risk and hazard scenario models.

We combined the Seismogenic Index model and the Seismic Nucleation model and reformulated the GR-law. It includes a volume (ΔCFS) controlled earthquake productivity and a time controlled maximum magnitude.

What controls the maximum magnitude of induced earthquakes?

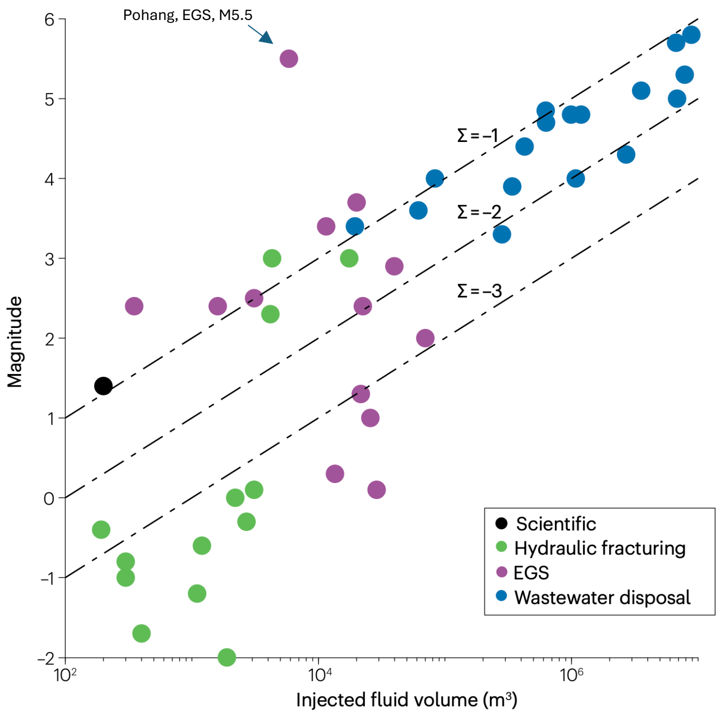
M_{max} as large as (statistically) expected



van der Elst et al., 2016, JGR

$$\widehat{M}_{max} = M_c + \frac{1}{b}\log_{10}N$$

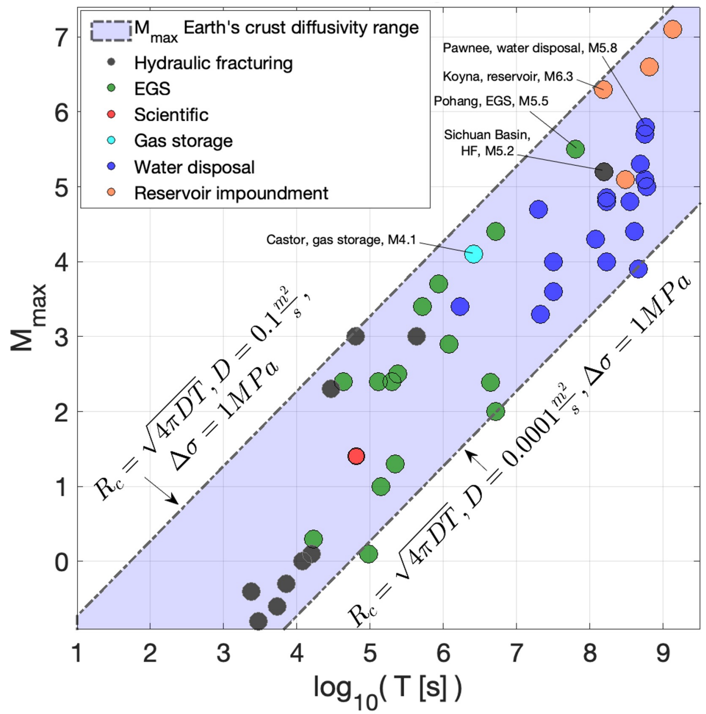
Volume-controlled M_{max}



Moein, Langenbruch et al., 2023, Nature Reviews Earth & Environment
Shapiro, Dinske, Langenbruch, Wenzel, 2010, TLE

$$M_{max}(t) = \frac{1}{b}[\Sigma + \log_{10} V(t)]$$

Time-controlled M_{max}



Langenbruch et al., 2024, Philosophical Transactions A
Shapiro et al., 2021, Nature Comm.

$$M_W^{max} = log_{10}T + \Theta_{D\sigma}$$

$$\Theta_{D\sigma} = log_{10}D + \frac{2}{3}log_{10}\Delta\sigma - 4.7281$$

Acknowledgements

Freie Universität Berlin

Thank you!