Stress-based forecasting of induced seismicity

Application to Groningen

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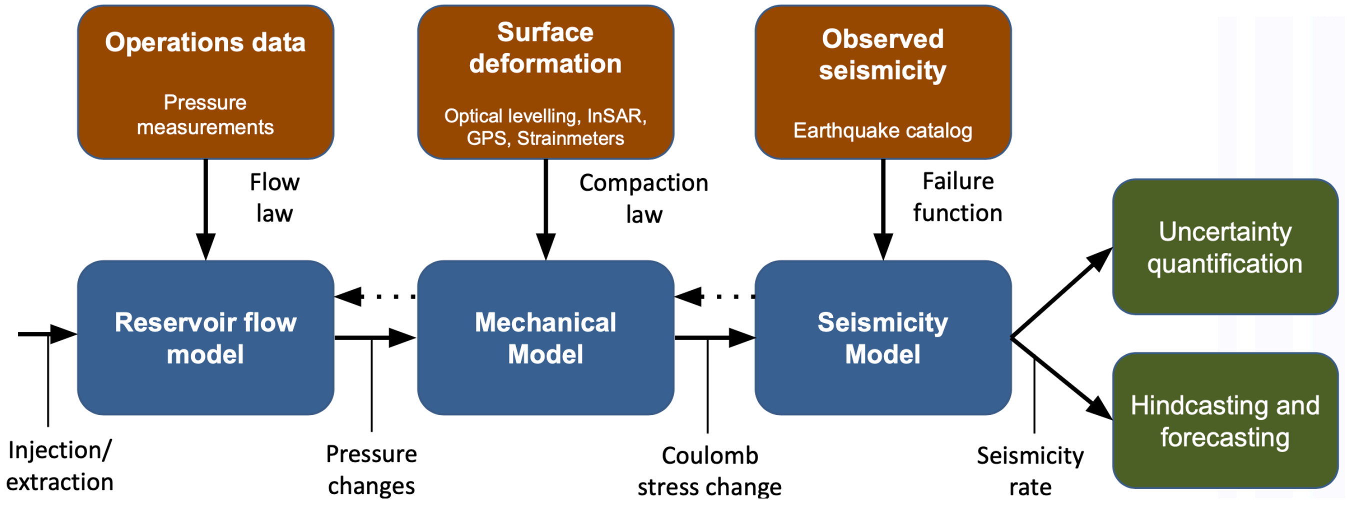
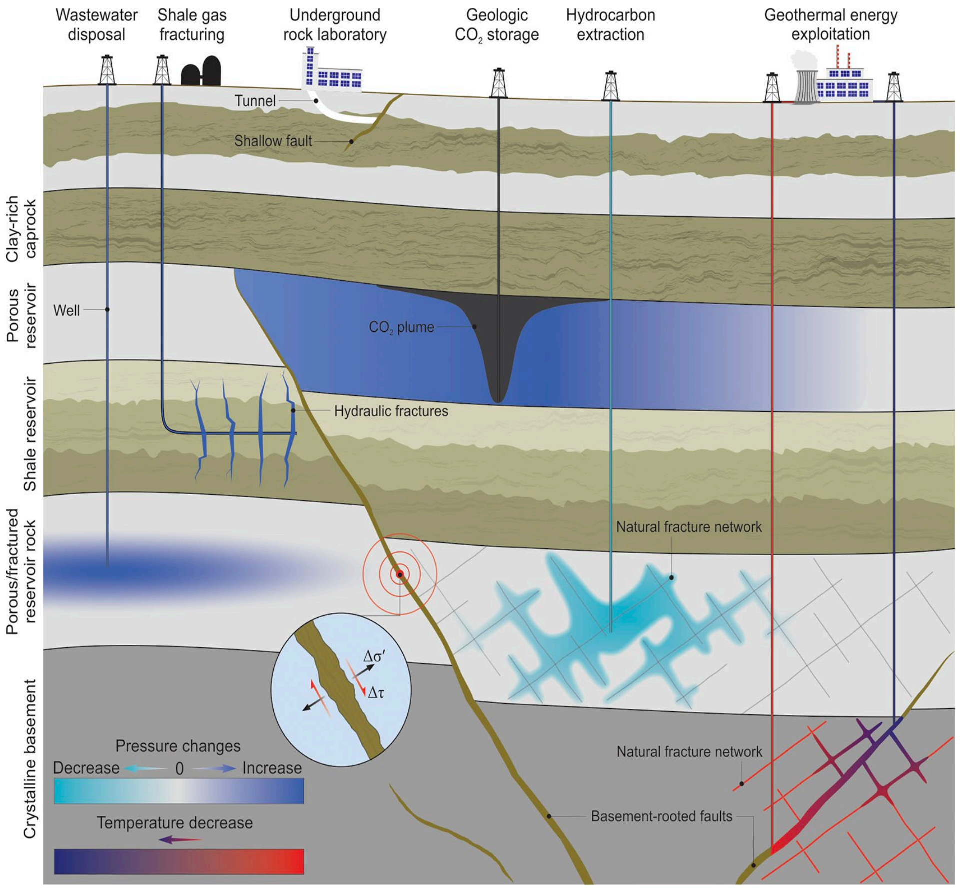
Shell : Stephen Bourne

FLOW2QUAKE

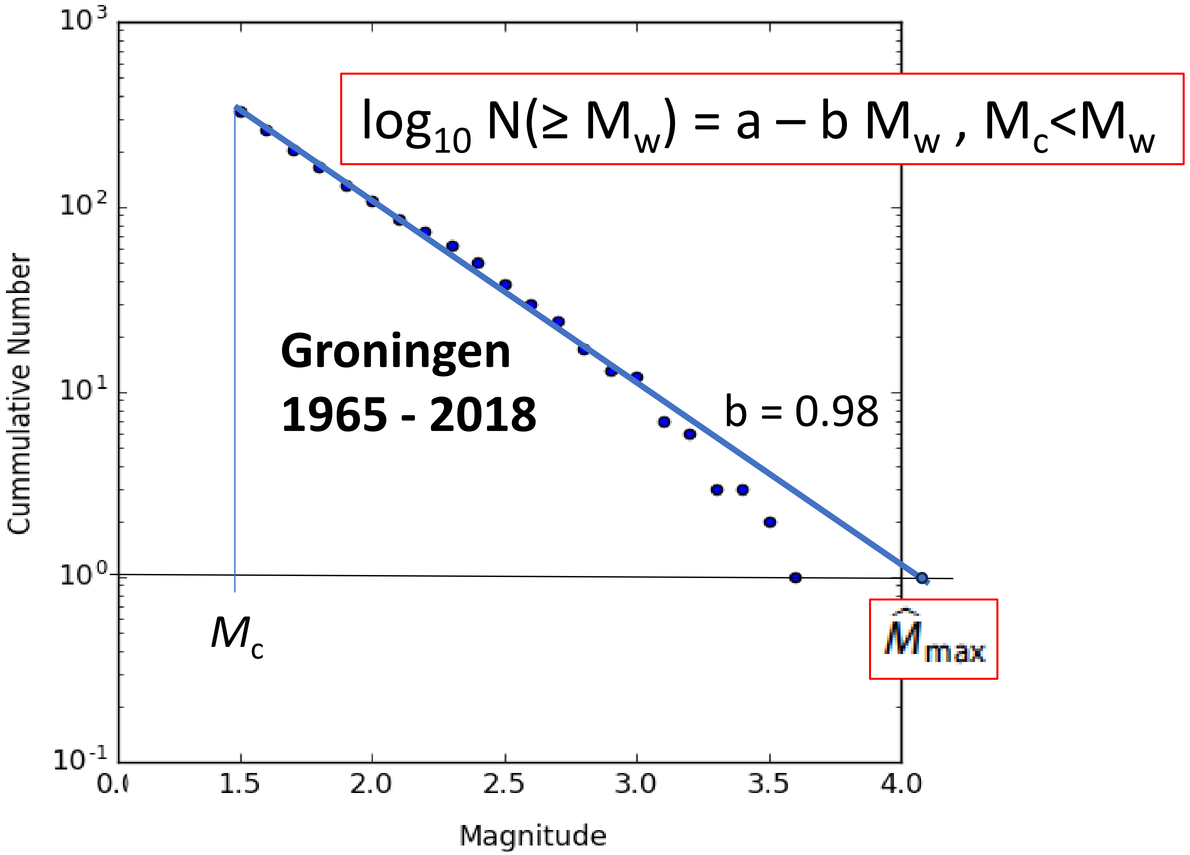


(Acosta et al., GRL, 2023)

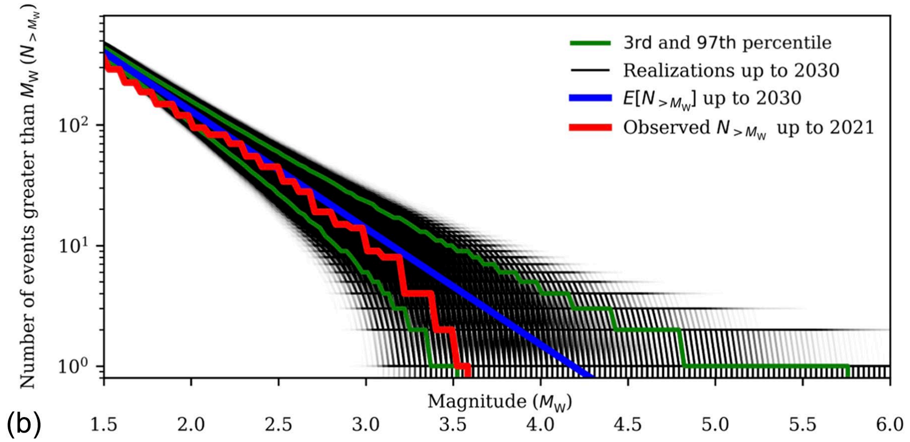


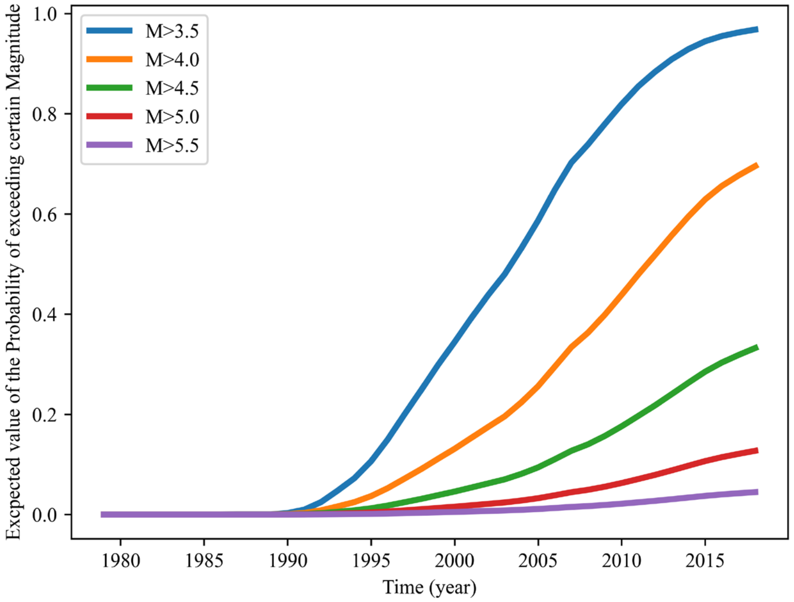
(Kivi et al, 2024)

From $N\ (>M_c)$ to $p(>M)$



assuming a Gutenberg-Richter model





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

$$\widehat{M}_q = \widehat{M}_{max} - \frac{1}{b}\log_{10}\left[N\left(1 - q^{1/N}\right)\right],$$ (van der Elst et al., 2016)

$$p(>M) = 1 - \left(1 - \frac{1}{N}10^{b(M-\widehat{M_{max}})}\right)^N$$

(Kaveh et al., SRL, 2023)

To estimate the hazard level we need :

1. Earthquake occurrence model (time and space)
2. Magnitude-frequency distribution model (*e.g.*, Gutenberg-Richter distribution, eventually truncated or a tapered)

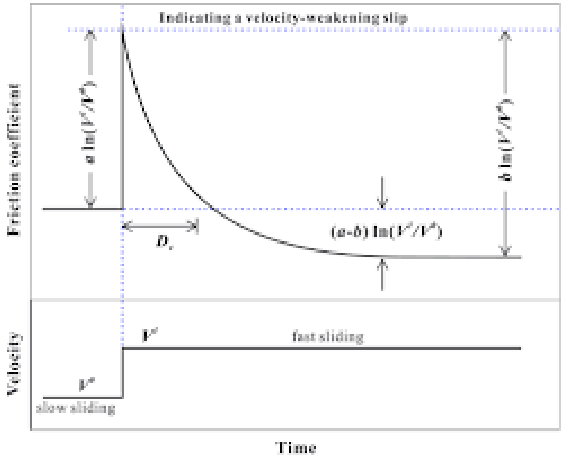
$$\boxed{\log_{10} N(\geq M_w) = a - b\, M_w\ ,\ M_c < M_w < M_{abs\_max}}$$

(truncated GR)

→ We need to estimate (with UQ):

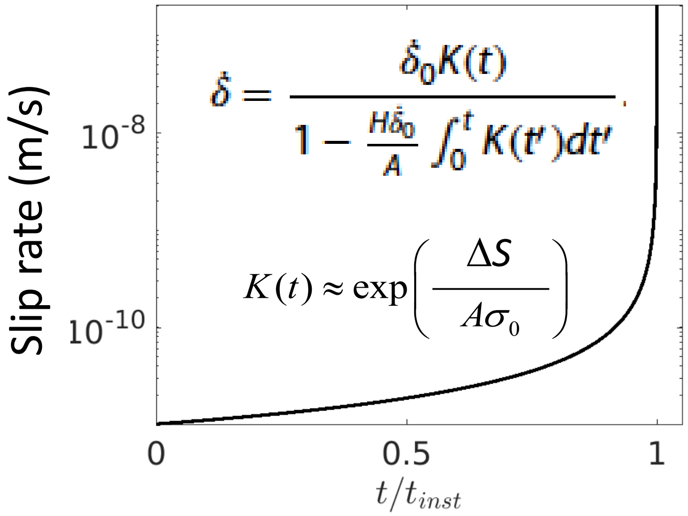
- **a(x,y,t)**
- b(x,y,t)
- *M_{corner} (if MFD is tapered)*
- *$M_{abs\_max}(x,y,t)$ (if MFD is truncated)*

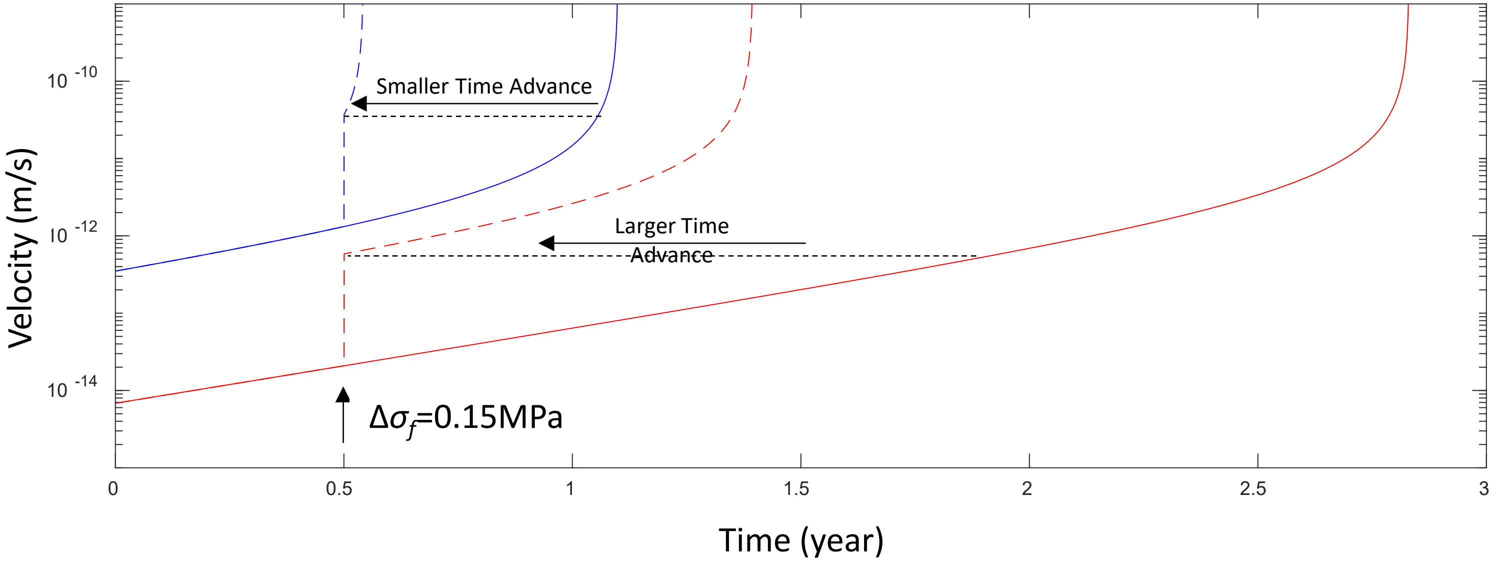
EQ nucleation based on Rate and State friction (Dieterich, 1992, 1994)



$$
\begin{cases}
\mu = \tau / \sigma = \mu^* + a \ln \dfrac{V}{V^*} + b \ln \dfrac{\theta V^*}{D_c} \\[2ex]
\dfrac{d\theta}{dt} = 1 - \dfrac{\theta V}{D_c} \qquad \text{'Aging Law'}
\end{cases}
$$

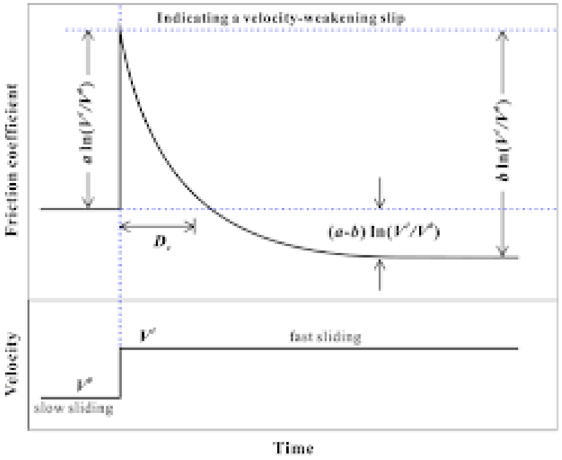
(Dieterich 1981; Ruina 1983)





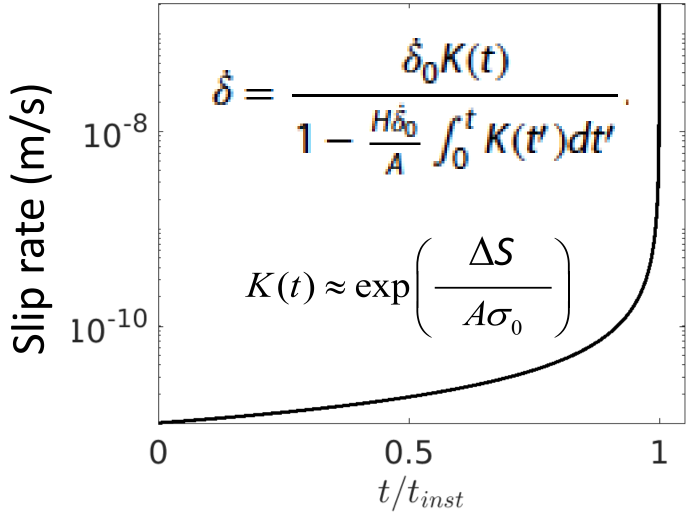
(Im and Avouac, GJI, 2023)

EQ nucleation based on Rate and State friction (Dieterich, 1992, 1994)

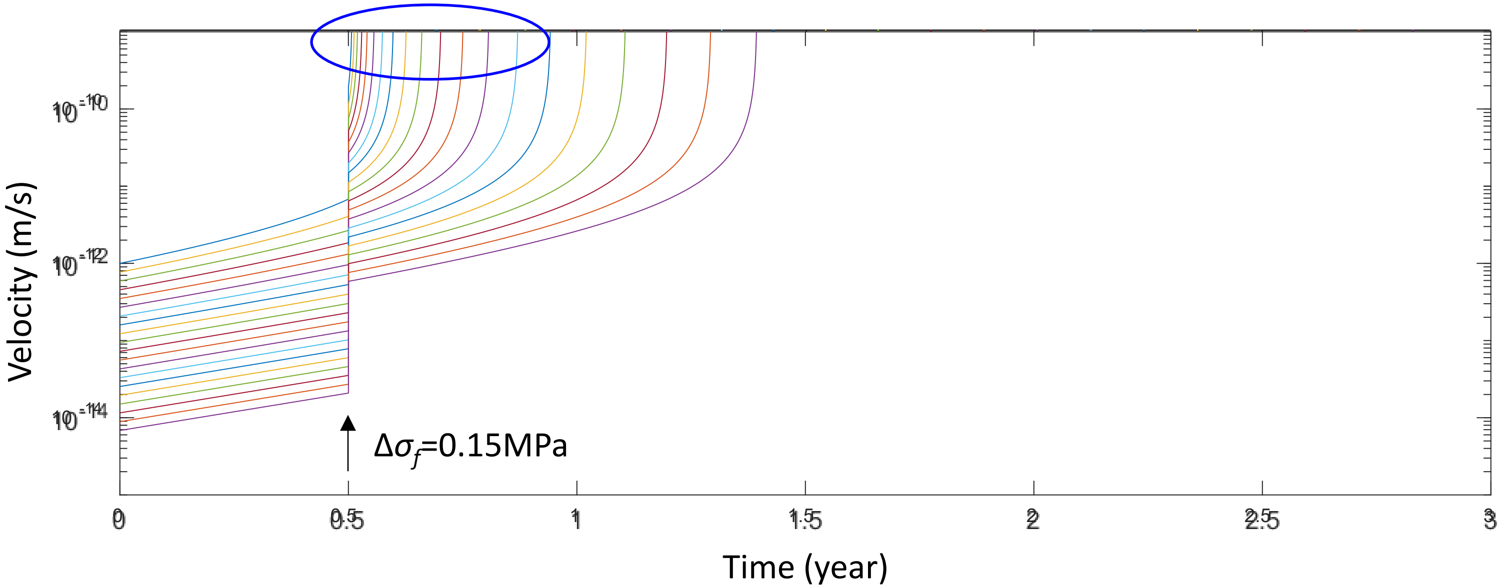


$$
\begin{cases}
\mu = \tau / \sigma = \mu^{*} + a \ln \dfrac{V}{V^{*}} + b \ln \dfrac{\theta V^{*}}{D_c} \\[2ex]
\dfrac{d\theta}{dt} = 1 - \dfrac{\theta V}{D_c} \qquad \text{‘Aging Law’}
\end{cases}
$$

(Dieterich 1981; Ruina 1983)

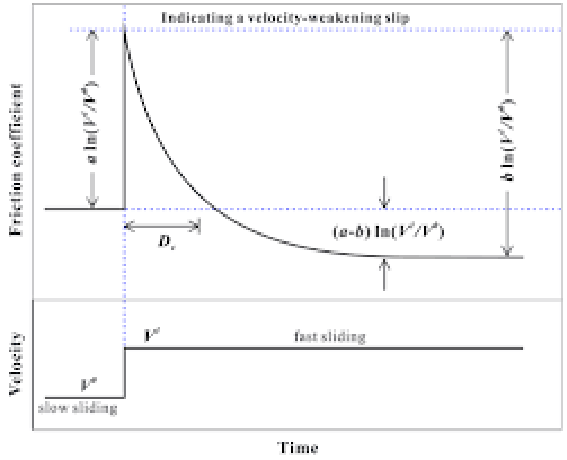


Omori Law



(Im and Avouac, GJI, 2023)

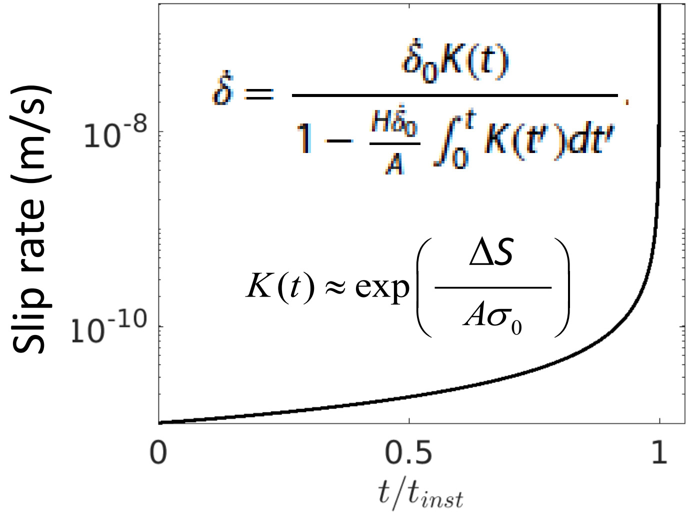
Seismicity Model: Coulomb threshold rate-and-state model (Heimisson et al., 2022)



$$\begin{cases} \mu = \tau / \sigma = \mu^* + a \ln \dfrac{V}{V^*} + b \ln \dfrac{\theta V^*}{D_c} \\ \dfrac{d\theta}{dt} = 1 - \dfrac{\theta V}{D_c} \end{cases}$$

'Aging Law'

(Dieterich 1981; Ruina 1983)

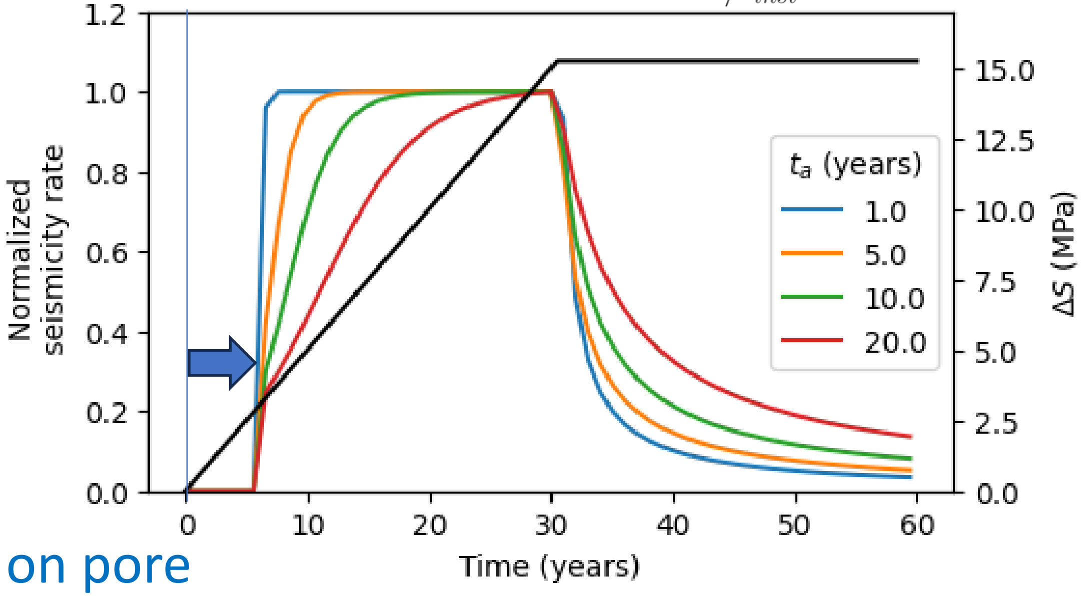


Predicted Seismicity rate for any stress evolution:

$$\frac{R}{r} = \frac{\exp\left(\frac{\Delta S(t) - \Delta S_c}{A\sigma_0}\right)}{\frac{1}{t_a}\int_{t_b}^{t} \exp\left(\frac{\Delta S(t') - \Delta S_c}{A\sigma_0}\right) dt' + 1}$$

with $\boldsymbol{t_a = \dfrac{A\sigma_0}{\dot{\tau}_0}}$

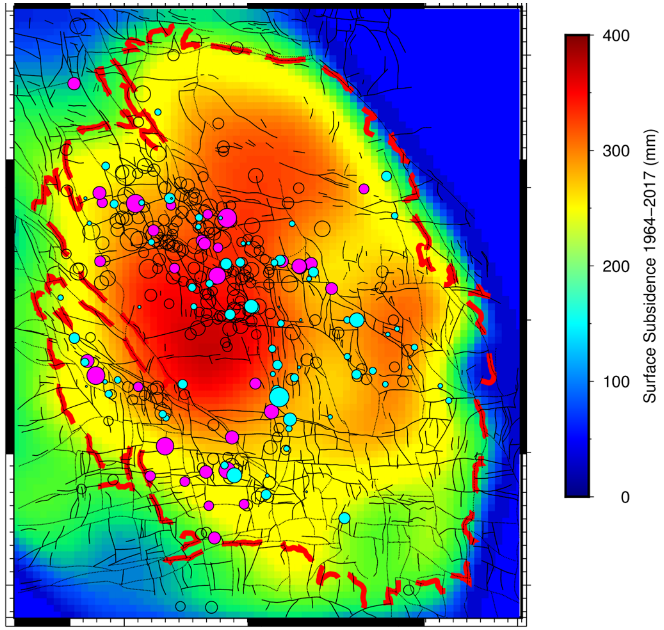
and $\Delta S(t_b) = \Delta S_c$

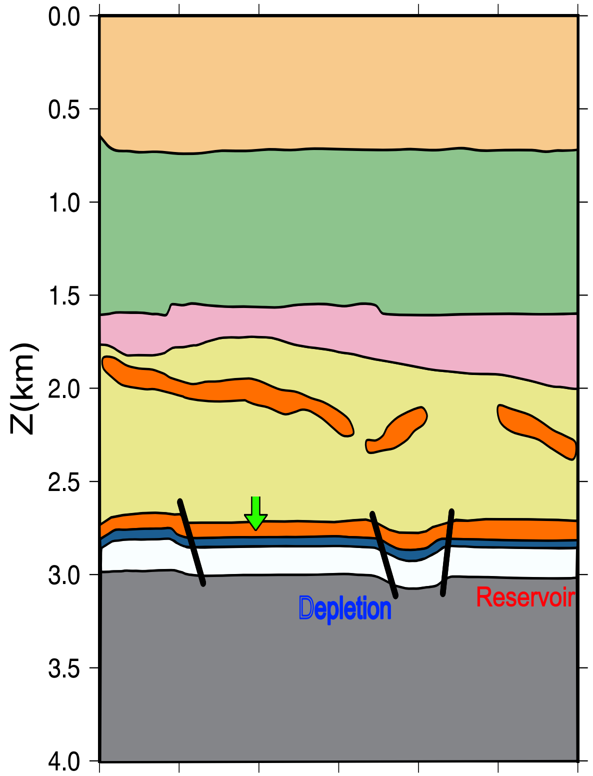


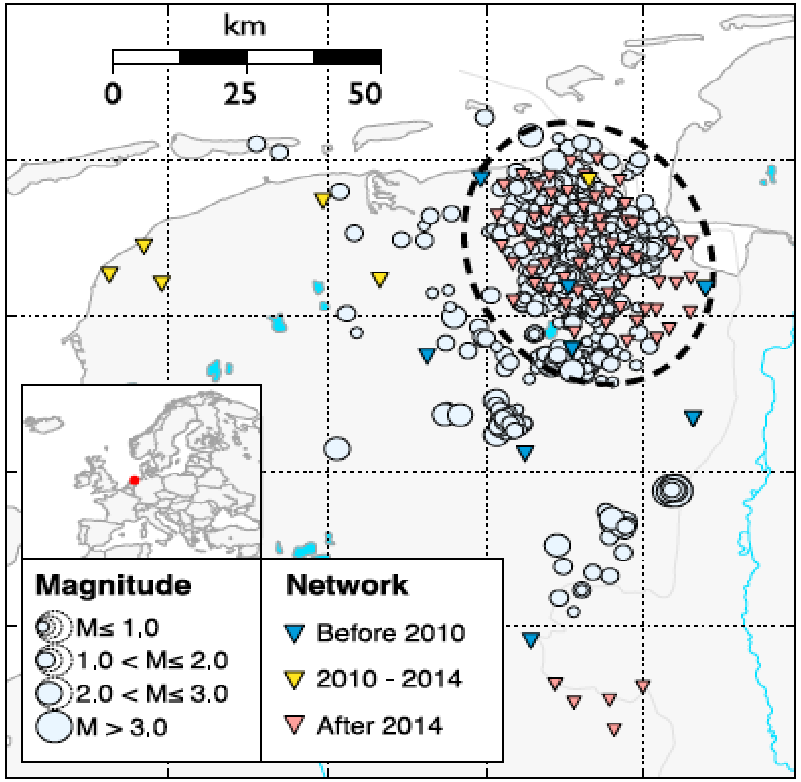
The seismicity response to reservoir operations depends on pore pressure diffusion, on $\boldsymbol{\Delta S_c}$ and on the nucleation process ($\boldsymbol{t_a}$, $\mathbf{A\sigma_0}$)

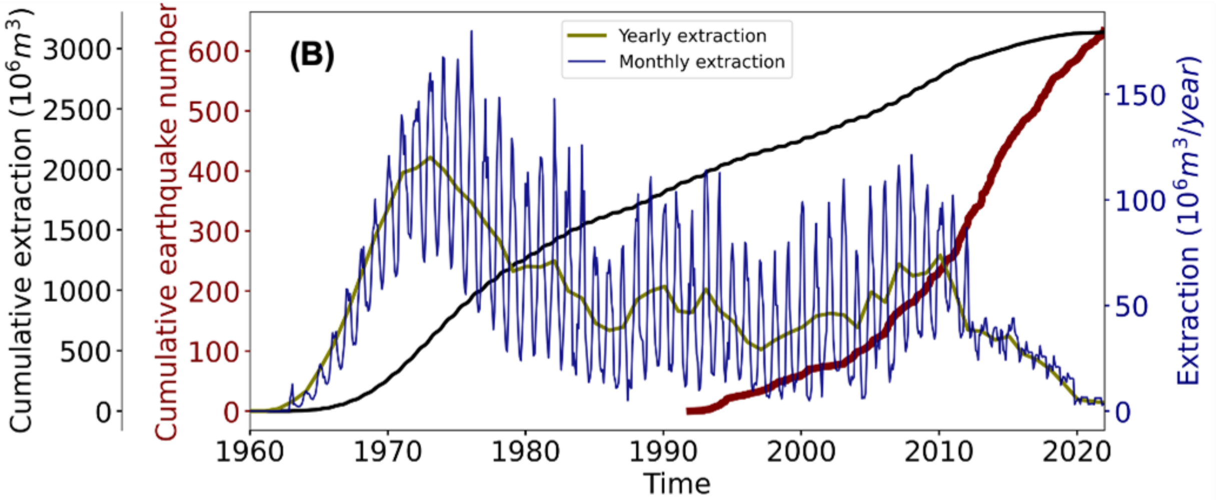
(Heimisson et al. 2022)

Application to Groningen (gas extraction)



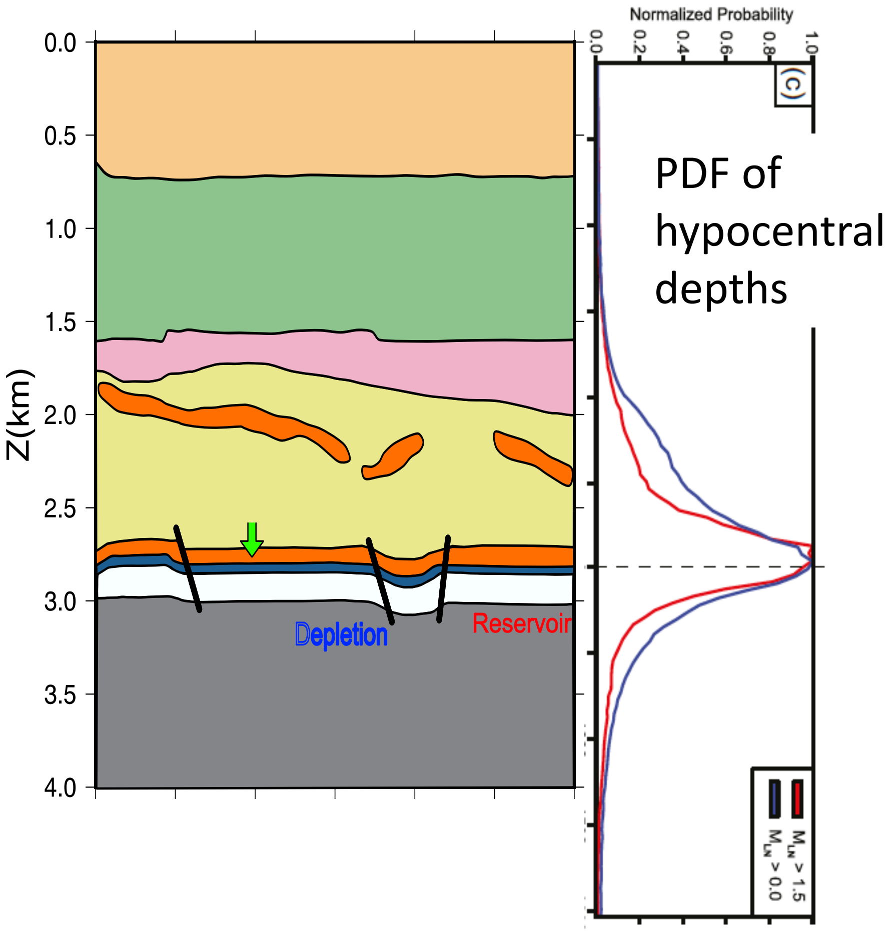


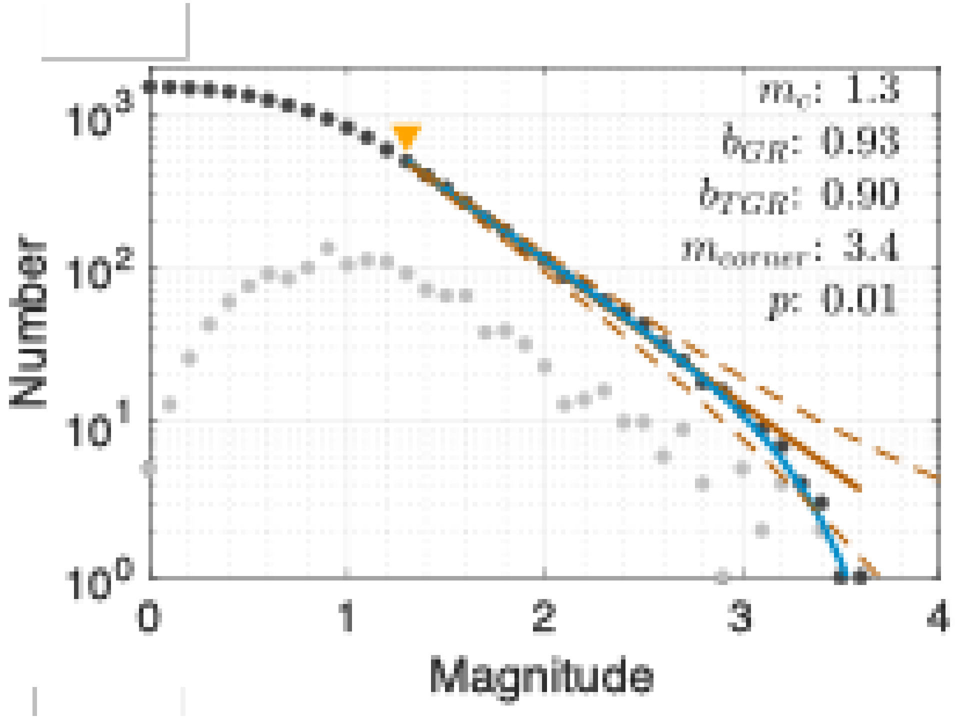




- Gas pressure dropped by ~30 MPa resulting in up to 50 cm of ground subsidence.
- Induced seismicity lagged production by 20 years.

(Smith et al, JGR, 2019; GJI, 2020; Acosta et al., GRL, 2023)





Linxuan Li

(Smith et al., GJI, 2020)

The overall catalog follows a TGR distribution with a b-value of 0.90 (90% confidence interval: 0.80–1.00) and an m_{corner} of 3.4 (90% confidence interval: 3.2–3.6).

-> Tapering is significant with less that 1% probability that it would be due to chance

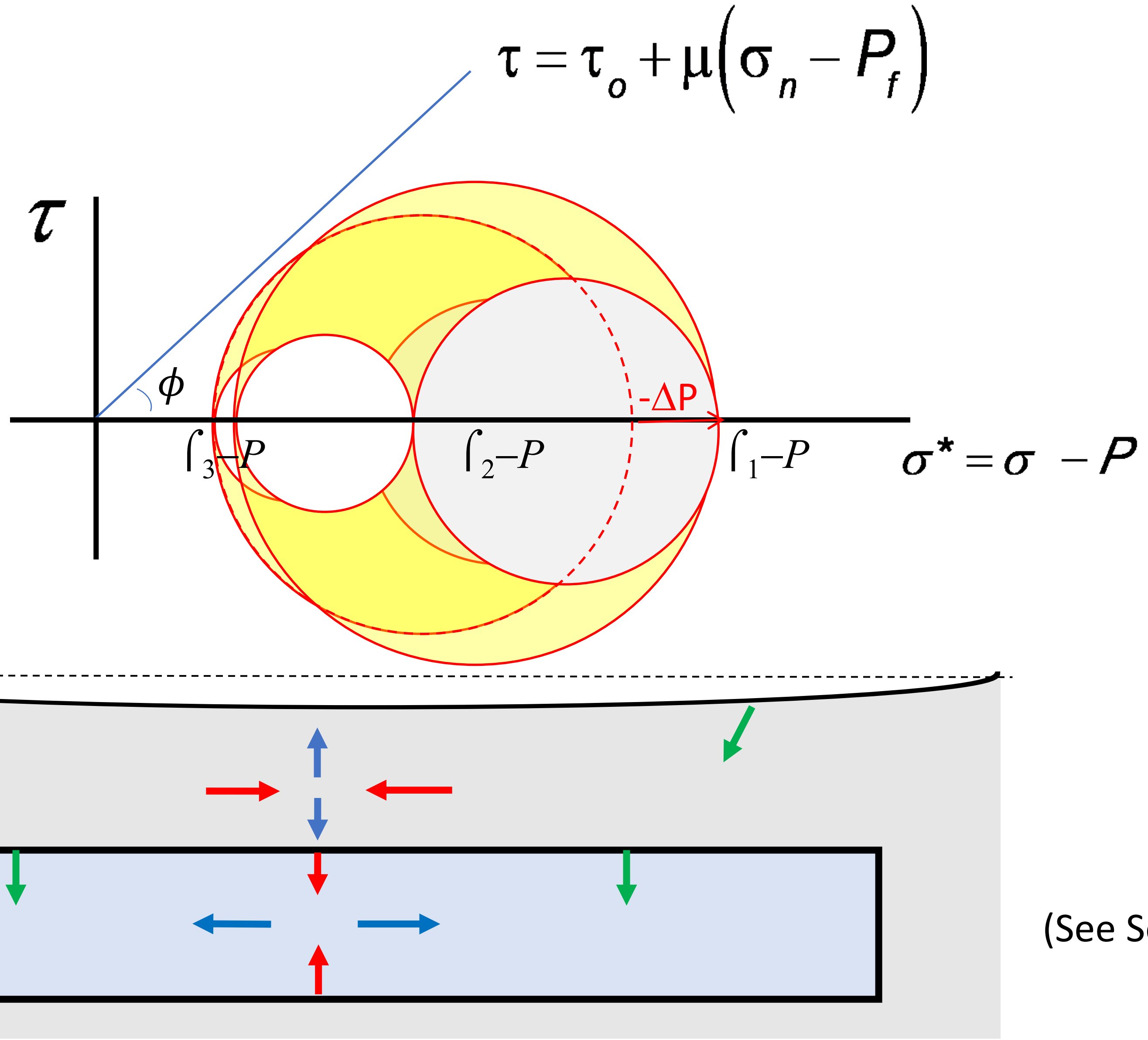
Linxuan Li

Effect of pressure drop– with poroelastic response

A pressure drop can destabilize faults in the reservoir only if the Biot coefficient, α, exceeds a critical value

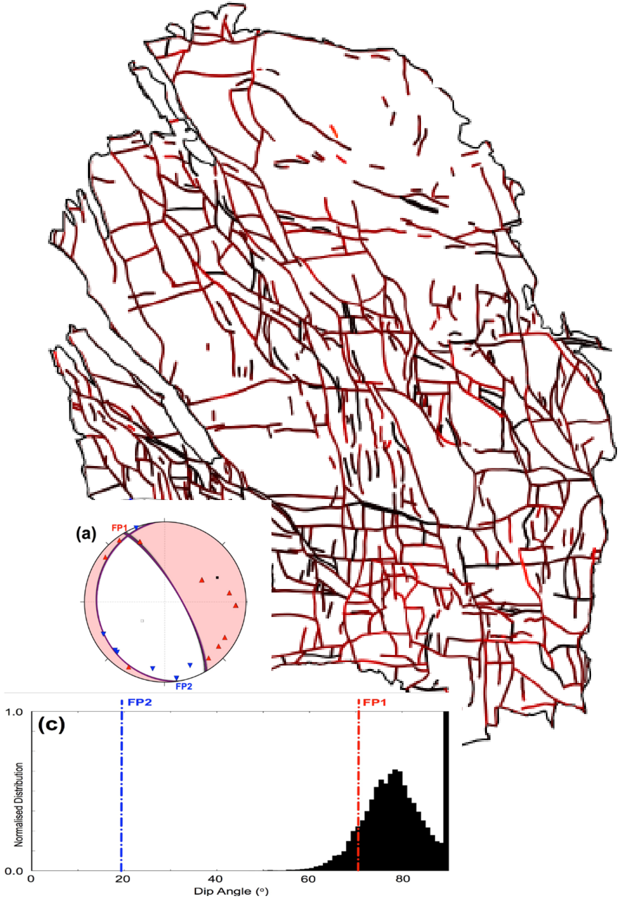
$$\alpha < \alpha_c = \frac{1-\nu}{1-2\nu}\frac{2sin\phi}{1+sin\varphi}$$

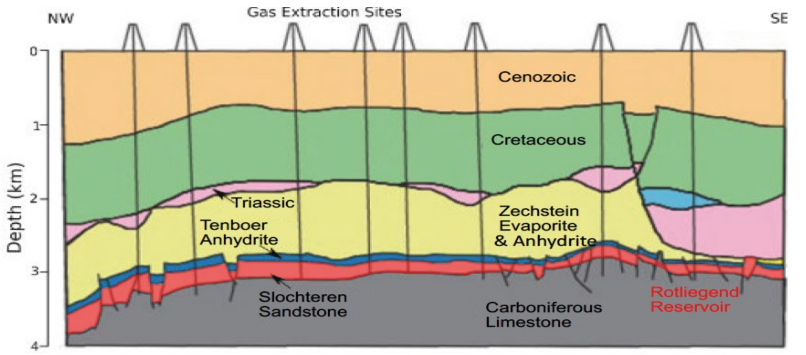
For v=0.25, ϕ = 30,
α_c=1.07 >1 so failure inside the reservoir is not possible

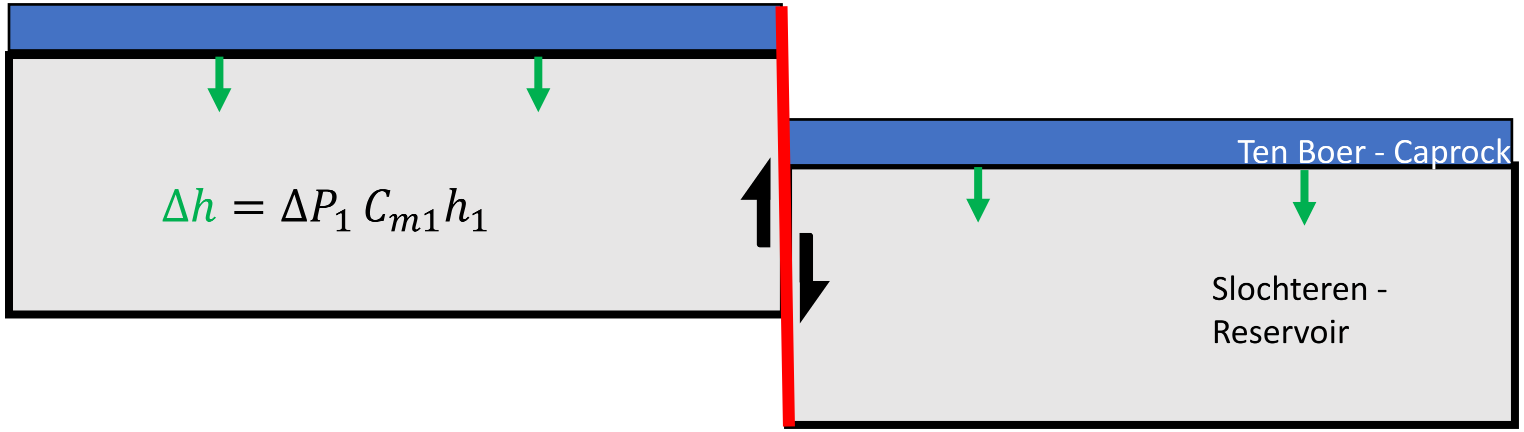


(See Segall et al, 1998)

Shear strain at faults offsetting the reservoir

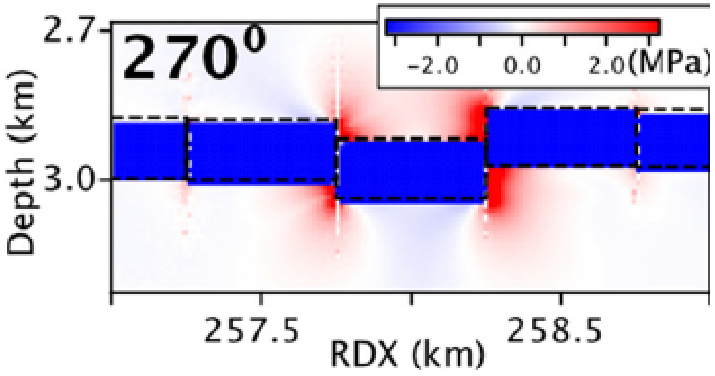




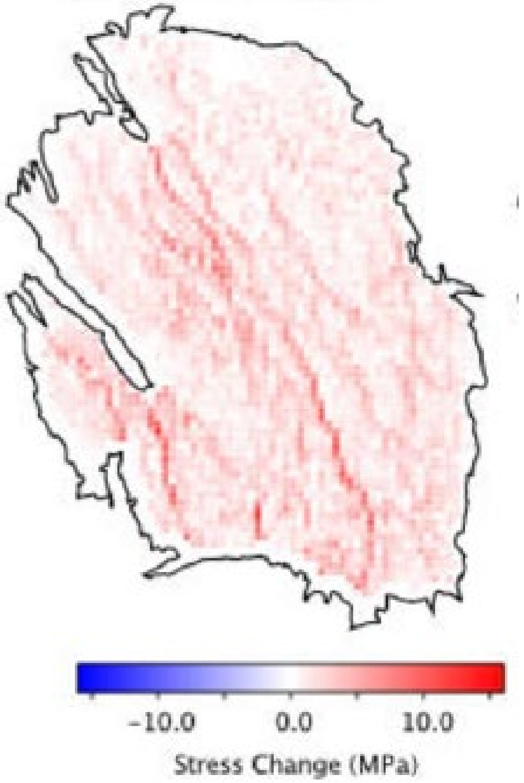


➢ Reservoir compaction drives shear strain on the faults offsetting the reservoir

Coulomb stress change: ΔS

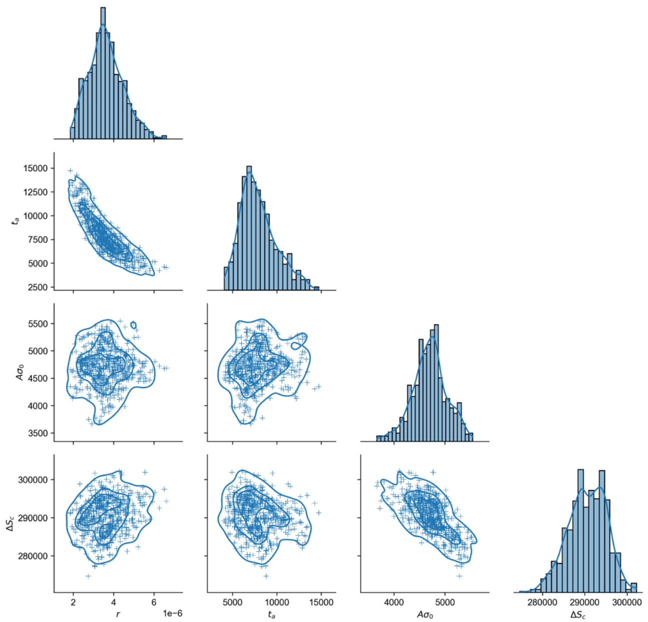


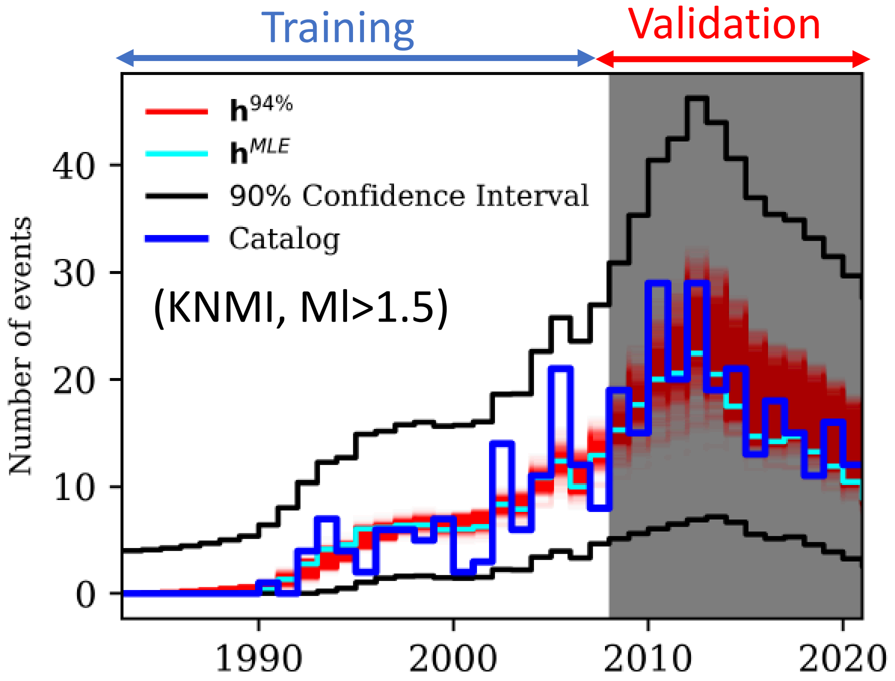
(Smith et al, EPSL, 2022)



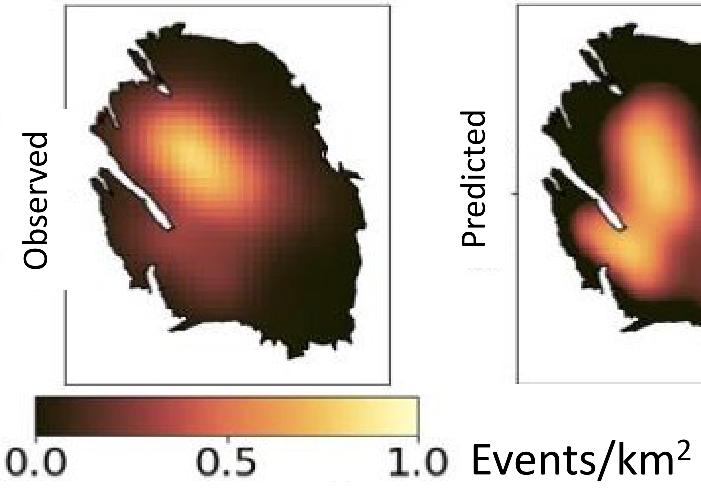
Inversion of model parameters and validation

$$\frac{R}{r} = \frac{\exp\left(\frac{\Delta S(t) - \Delta S_c}{A\sigma_0}\right)}{\frac{1}{t_a}\int_{t_b}^{t} \exp\left(\frac{\Delta S(t') - \Delta S_c}{A\sigma_0}\right) dt' + 1}$$





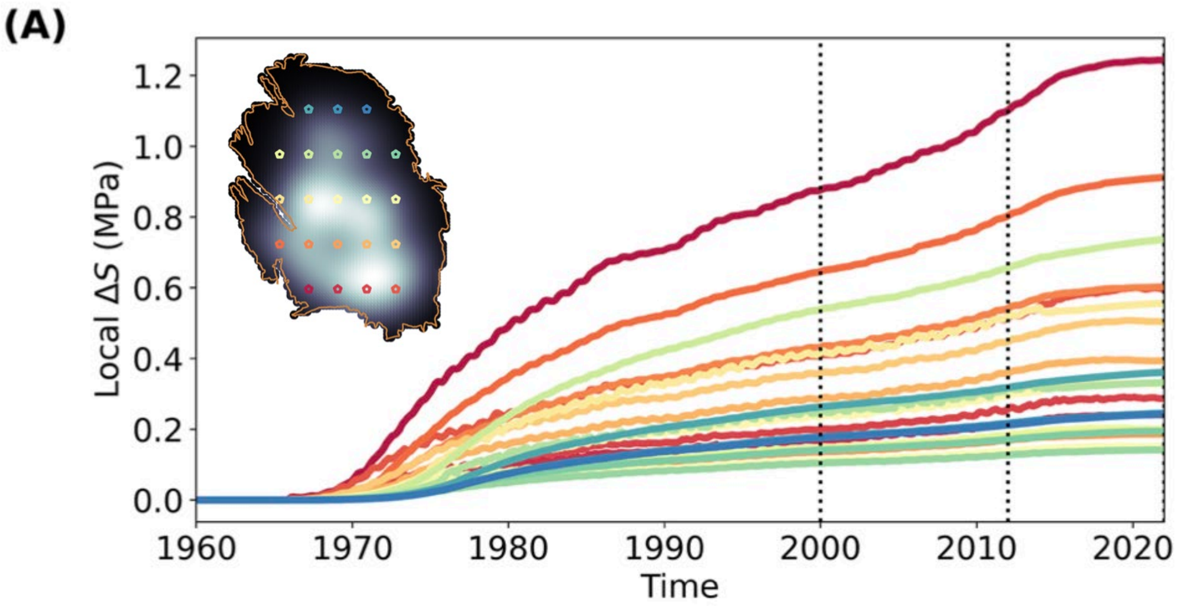
ΔS_c ~ 0.3 MPa
$A\sigma$ ~ 5 kPa
t_a~ 7000 yr
r ~4 10^{-6} /km^2·yr

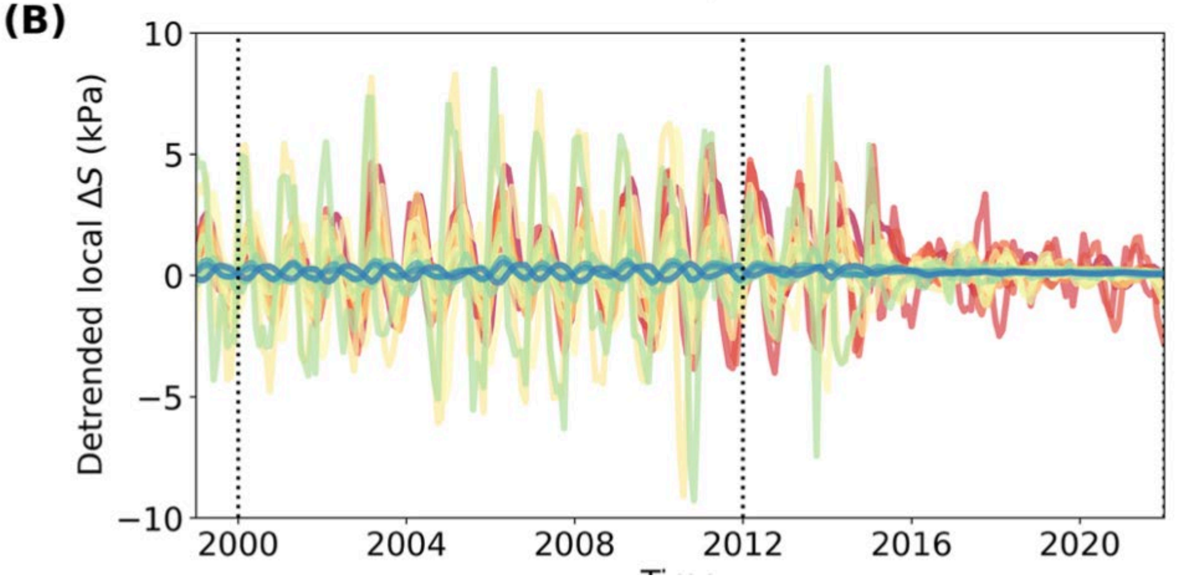


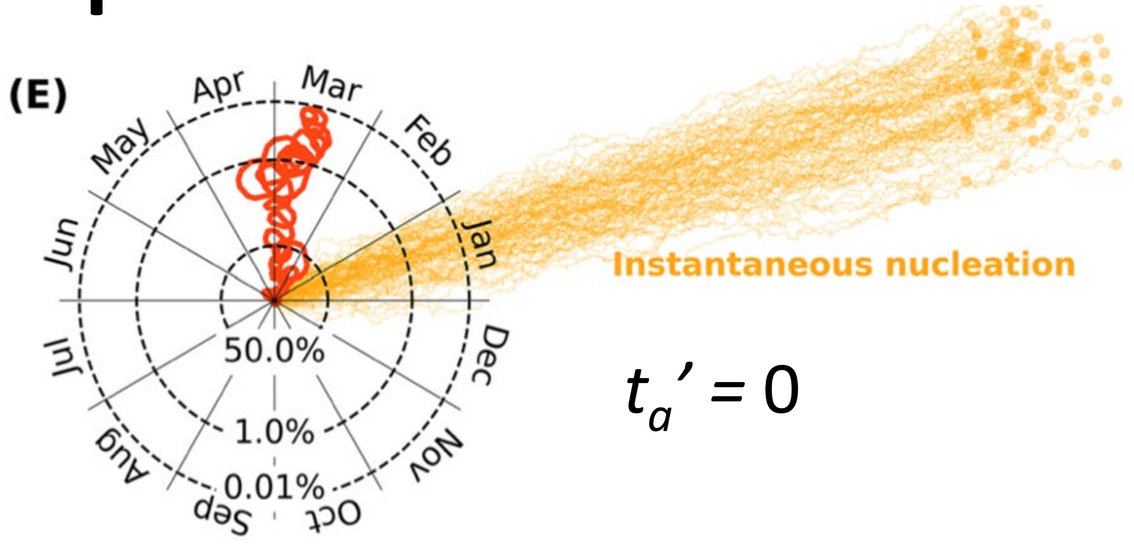
- The model explains well the seismicity in time and space.
- The initial strength excess explains the lagged response of seismicity to production.
- Nucleation is not instantaneous

(Kaveh et al., SRL, 2023; Acosta et al., GRL, 2023)

Seismicity response to seasonal production constraints the nucleation process

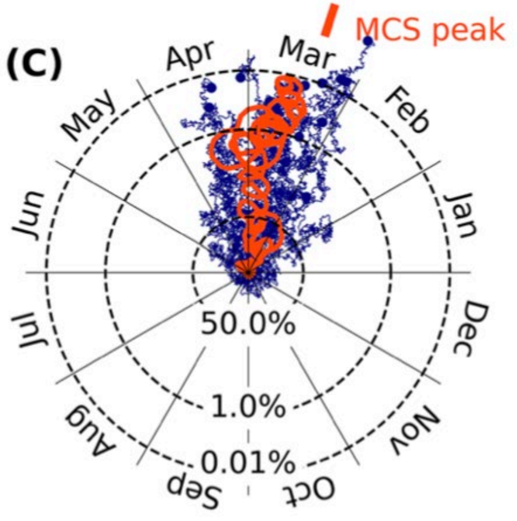






$t_a' = 0$

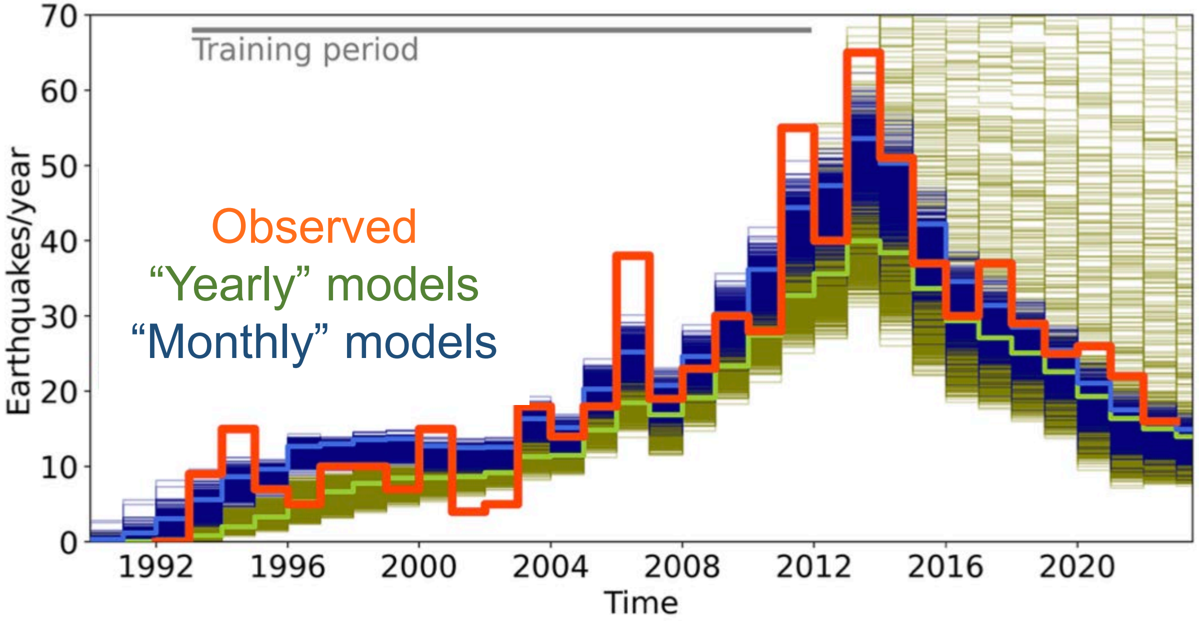
- Seasonal production drives significant seasonal seismicity (p-value ~ 10^{-4})
- Nucleation is not instantaneous

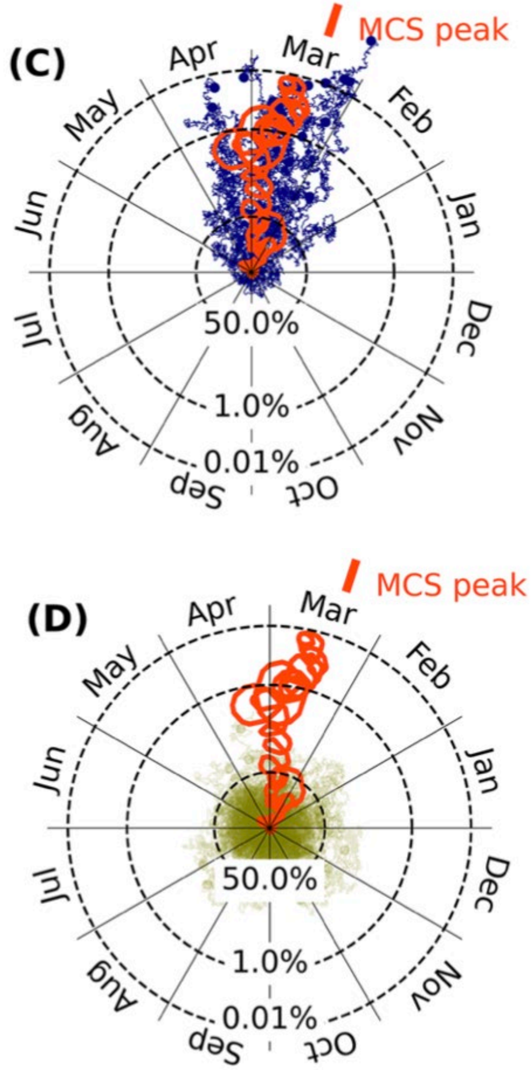


t_a' ~ **0.1 - 1 year**

(Acosta et al., GRL, 2023)

Seismicity response to seasonal production tightens forecast





Effective
'nucleation time':

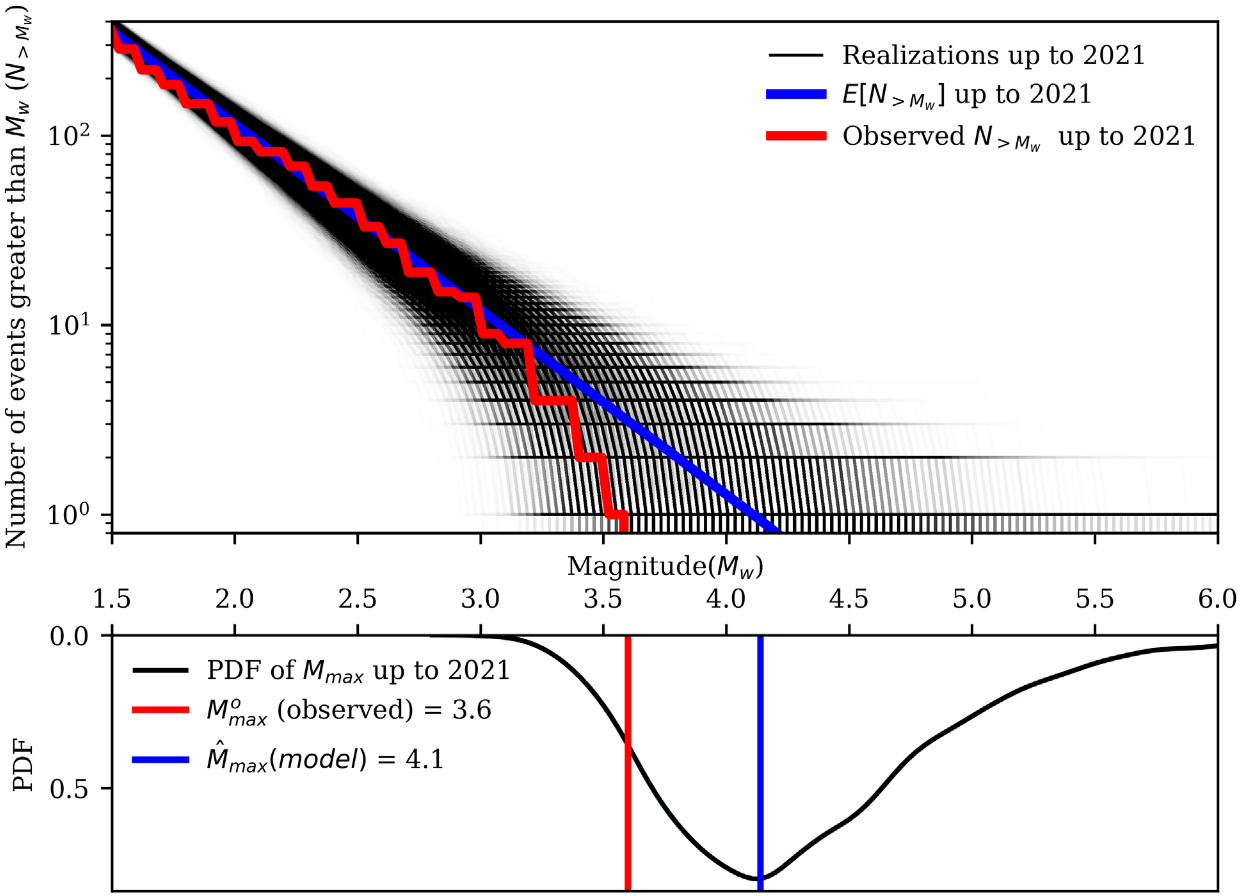
0.1 - 1 year

5 - 100 years

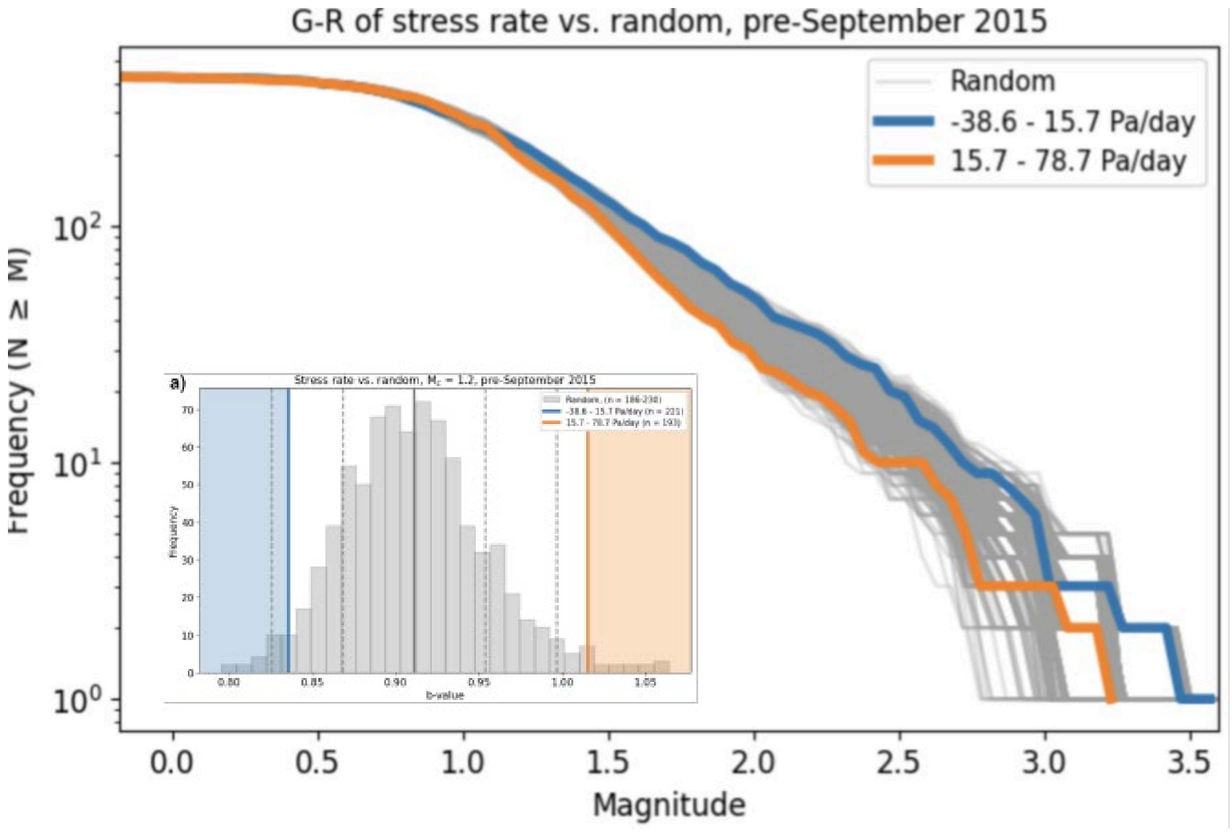
- ➢ Fitting the seasonal variations places constraints on the nucleation process.
- ➢ …and helps tighten the forecast

(Acosta et al., GRL, 2023)

Frequency-Magnitude Distribution



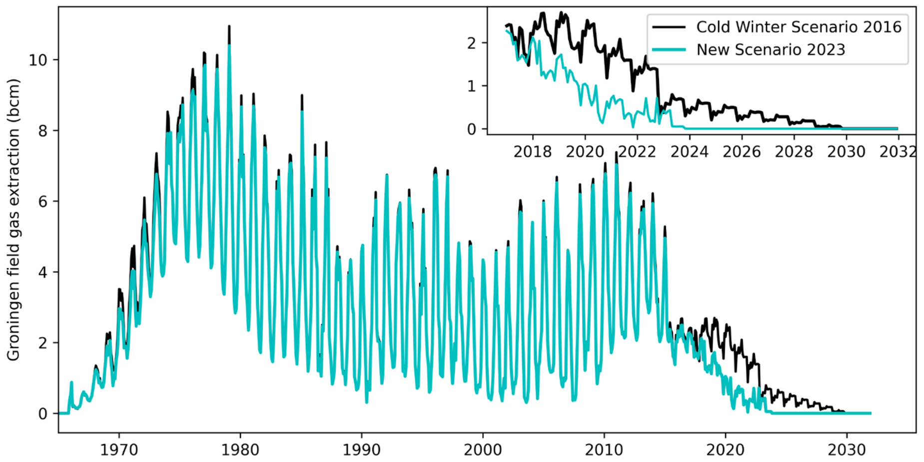
(Kaveh et al, SRL, 2023)

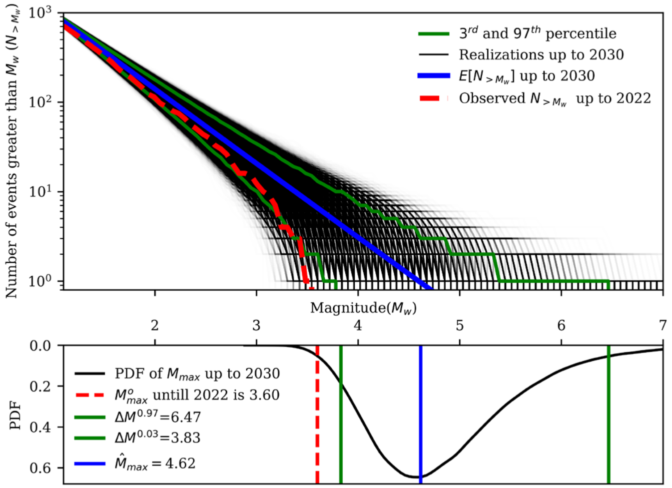


(Tamama et al, GRL, 2024)

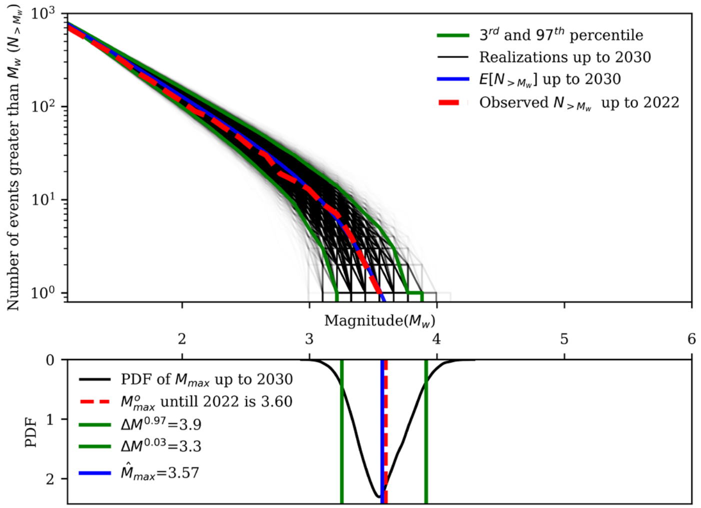
- **The MFD is significantly tapered and is not stationary: earthquakes grow more easily to larger magnitudes under lower stressing rate.**

EQ rate and Magnitude Forecasting

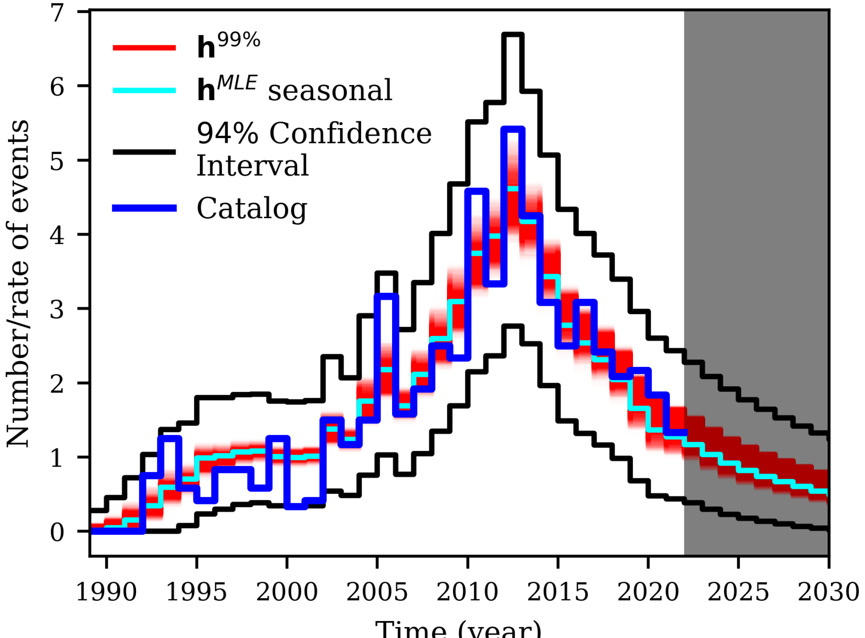


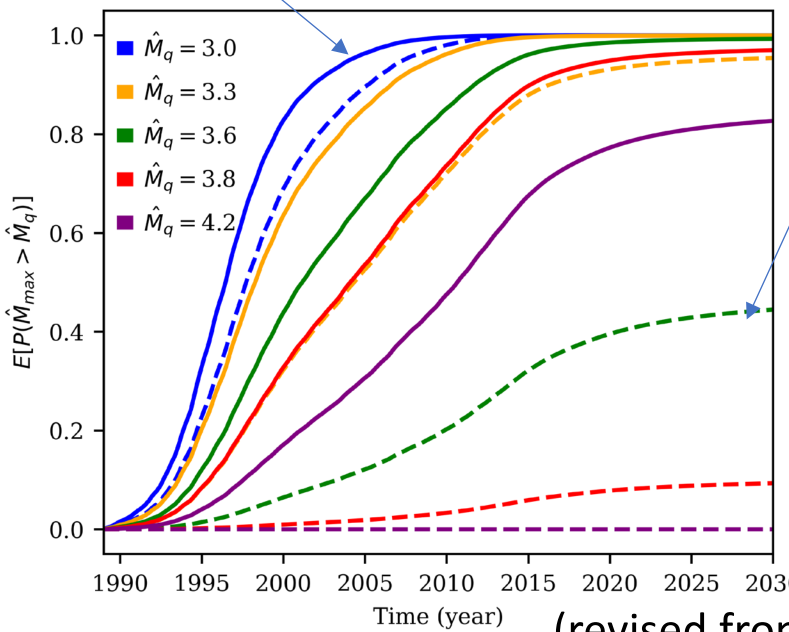


Non Tapered MFD



Tapered MFD



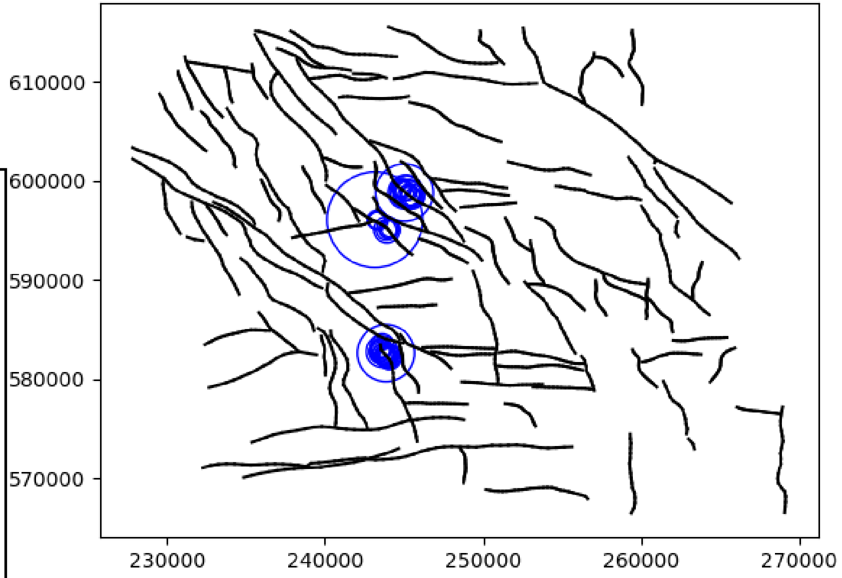


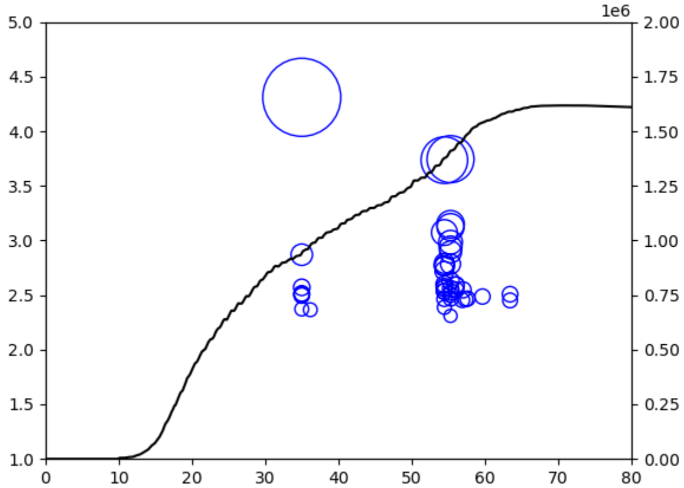
(revised from Kaveh et al. 2024)

Magnitude Forecasting- Perspective

Magnitude forecast based on physics-based simulation using a Discrete Fault Network model, with faults goverened by rate and state friction (**Quake-DFN**, Im and Avouac, BSSA,2025)

Benchmark: 2-D simulations of Buijize et al (2019)





$a = 0.003$
$b = 0.006$
$D_c = 1e4$

$\theta_I = 1e3$
$V_i = 1e\text{-}10$ m/s
$\nu = 0.15$

Conclusions

- The rate of induced earthquakes at Groningen is well predicted based on **Coulomb stress changes**, assuming **nucleation governed by rate and state friction** and taking into account initial strength excess (**stress threshold** to be exceeded to initiate seismicity).
- The magnitude frequency distribution is significantly **tapered** suggesting that earthquake can’t rupture outside the reservoir interval.
- **b-value depends on stress rate**.
- Understanding and predicting magnitudes using physics-based models remains a challenge.

Caltech Geomechanics and Mitigation of Geohazards

Thank you!

GMG

NSF

Chevron

CALIFORNIA RESOURCES CORPORATION

ExxonMobil

LA DWP Los Angeles Department of Water & Power

MAZAMA ENERGY

OptaSense®
A LUNA company

REPSOL

Shell

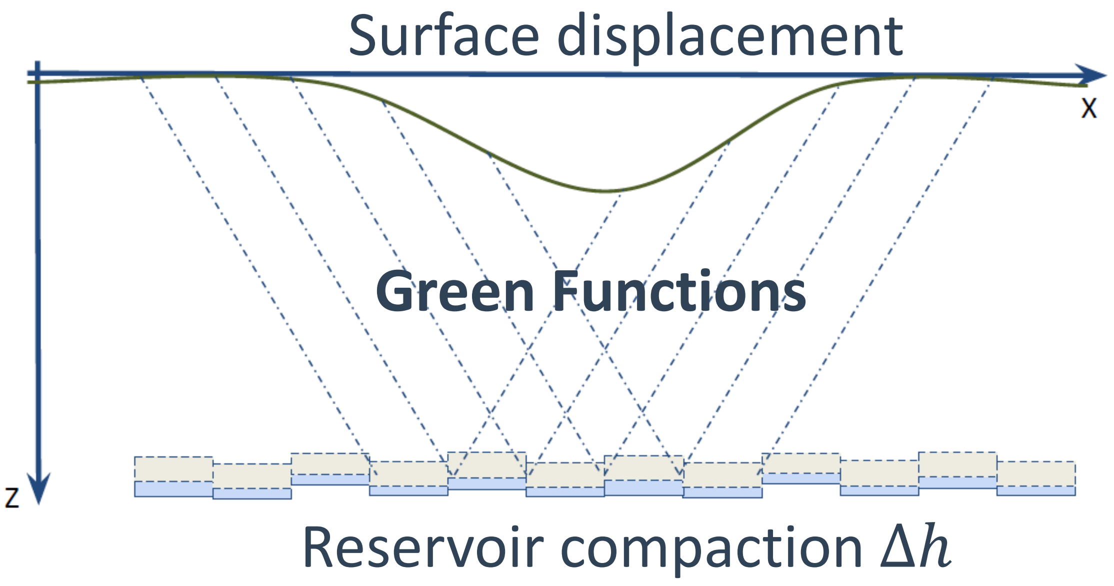
TotalEnergies

RESNICKINSTITUTE
science + energy + sustainability

CE2S2
Center of Excellence for Earth and Space Science
CE2S2 establishes a partnership between King Abdulaziz City for Science and Technology (KACST) and the California Institute of Technology (Caltech).

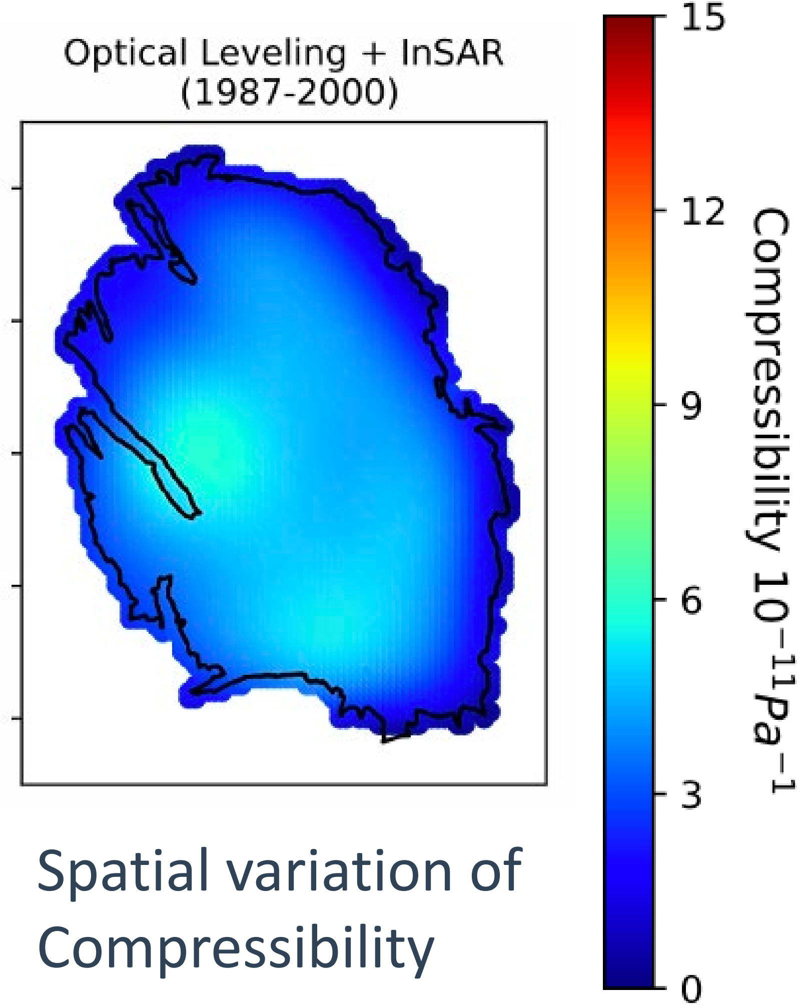
Geomechanical Model

Inversion for reservoir compressibility



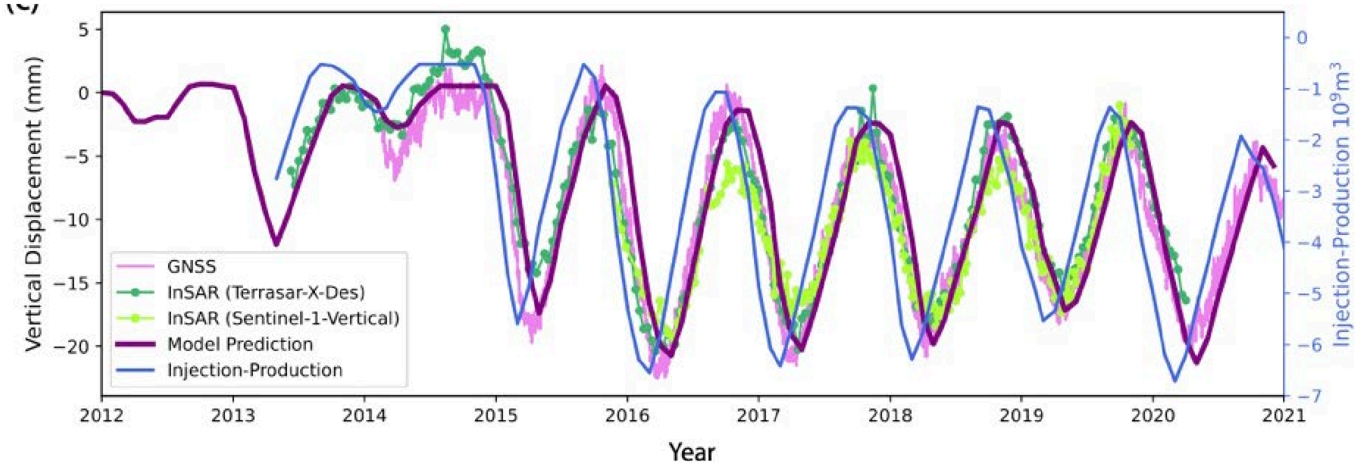
$$\boxed{C_m = \frac{\Delta h}{h\Delta P}}$$

Groningen



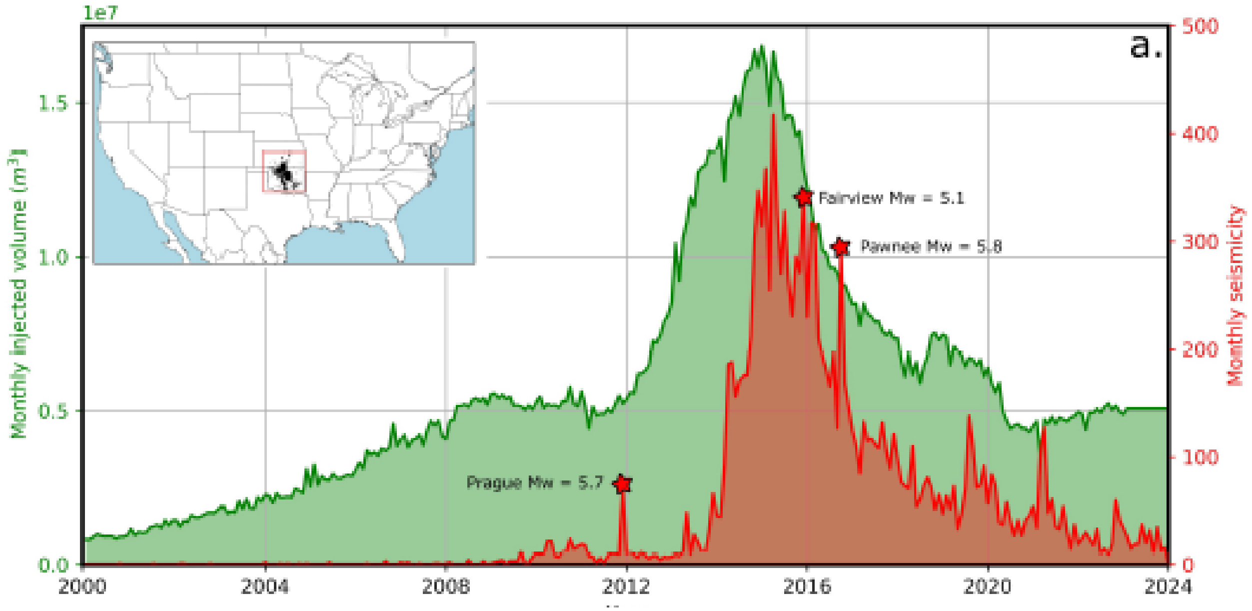
Spatial variation of Compressibility

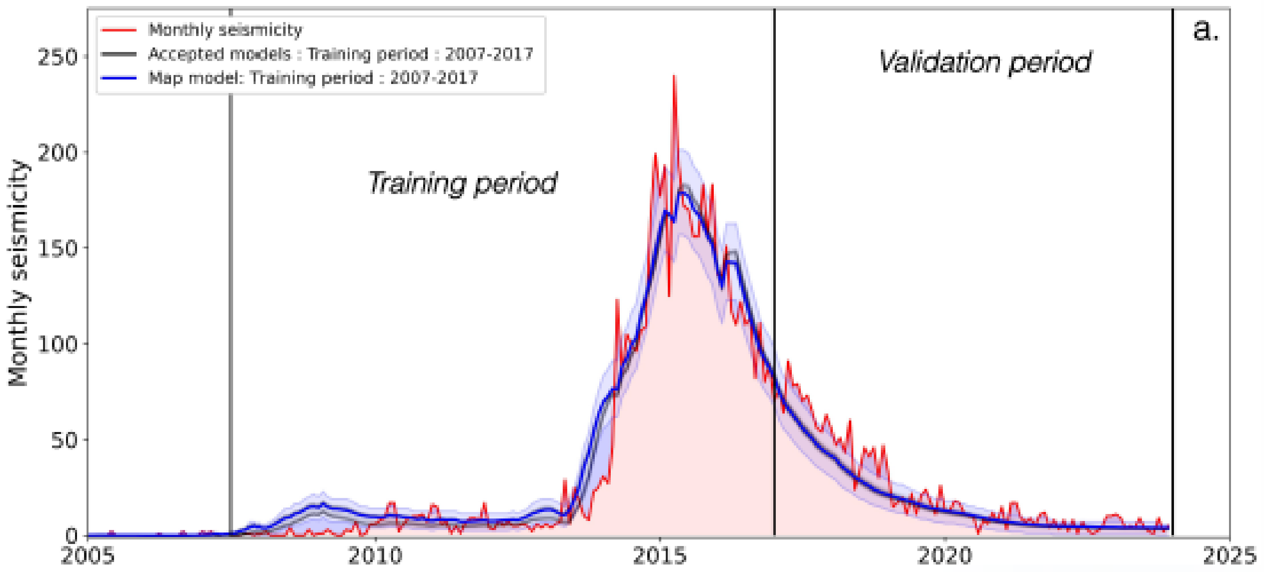
Norg $C_m = 5\ 10^{-11}\ Pa^{-1}$

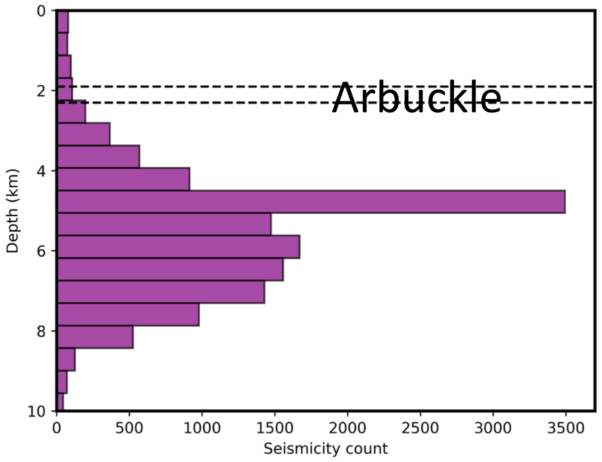


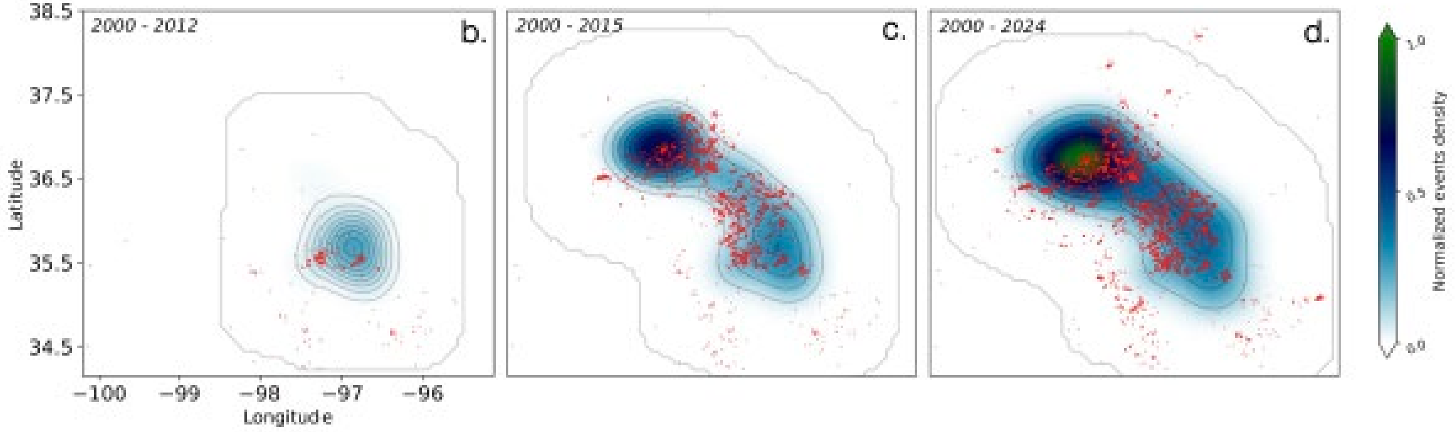
(Yuexin Li, et al.,JGR, in press)

Wastewater Disposal Oklahoma



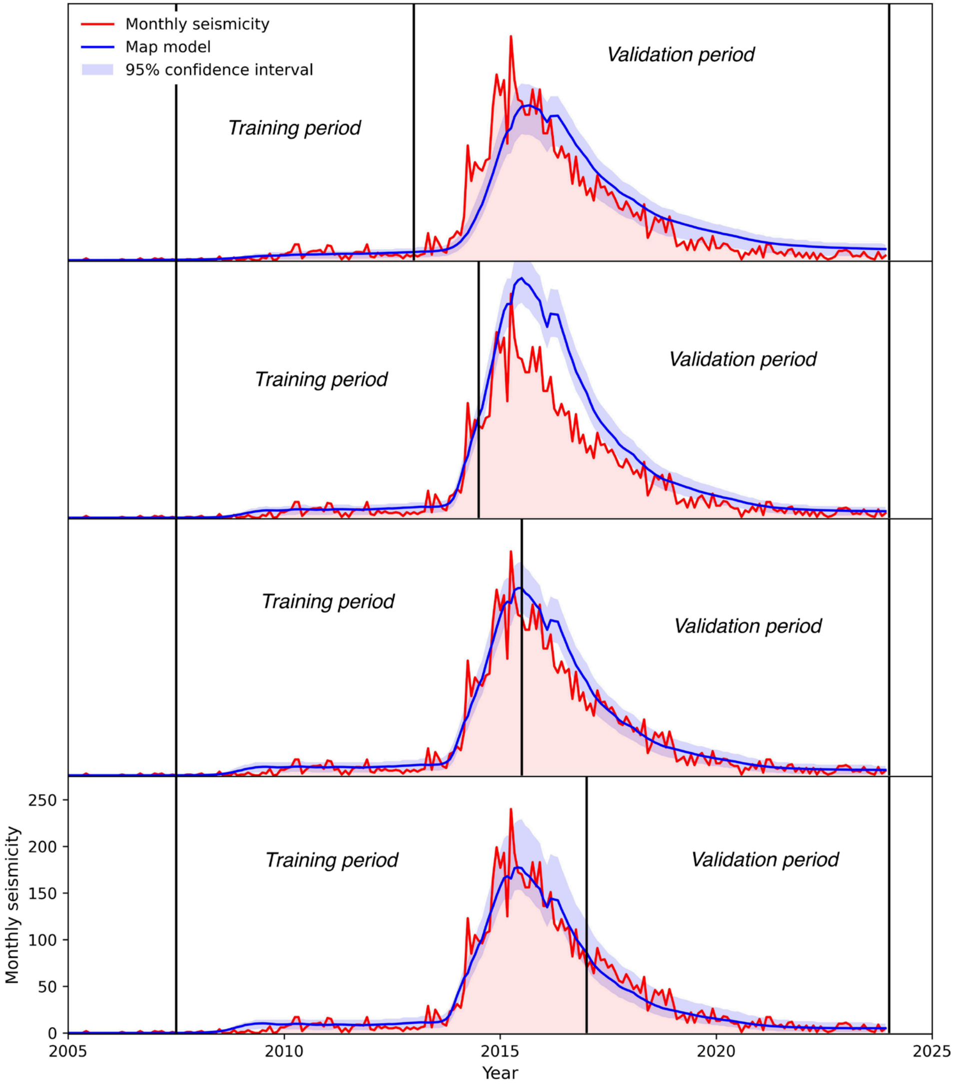




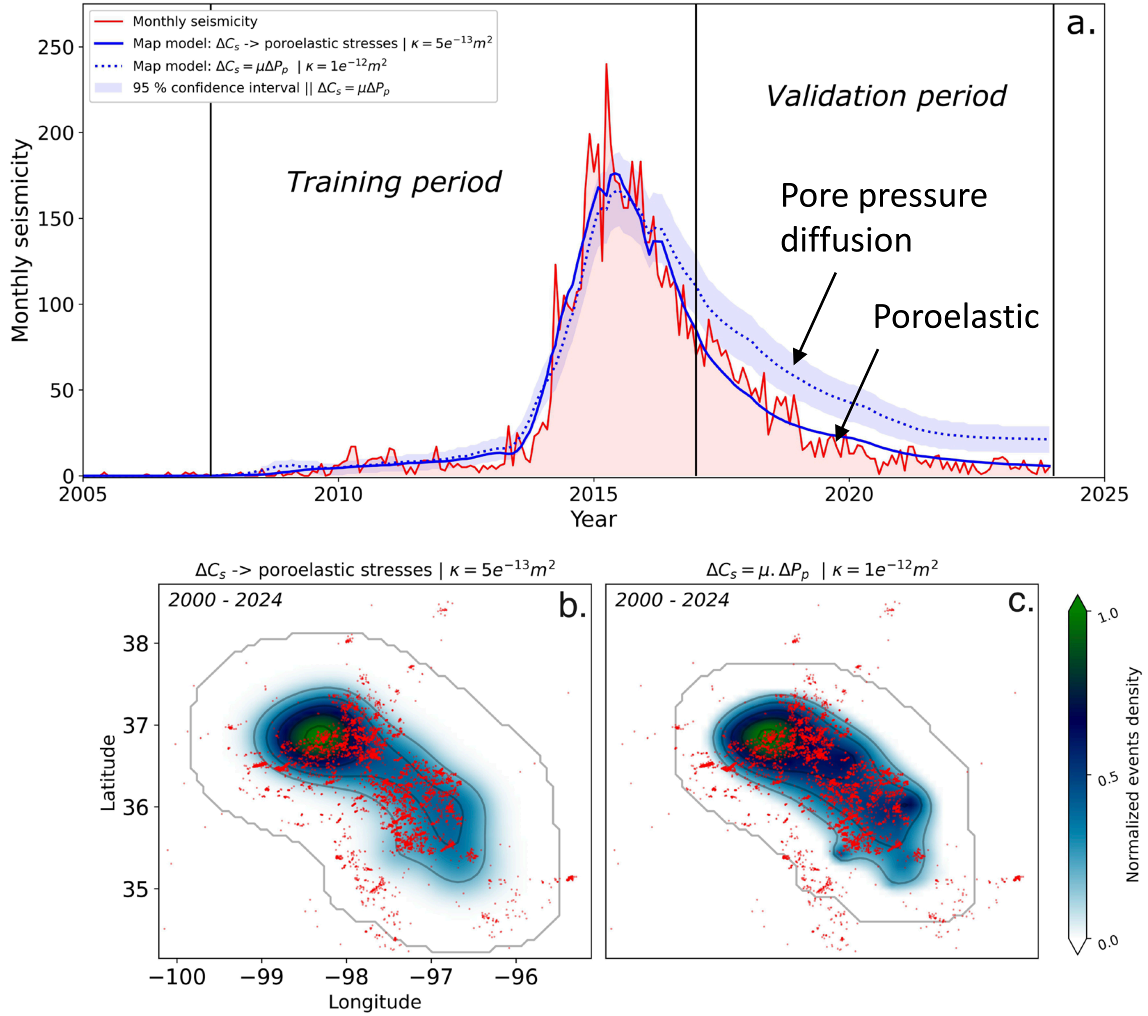


(Samson Marty, et al.,)

Wastewater Disposal Oklahoma



Effect of training period.

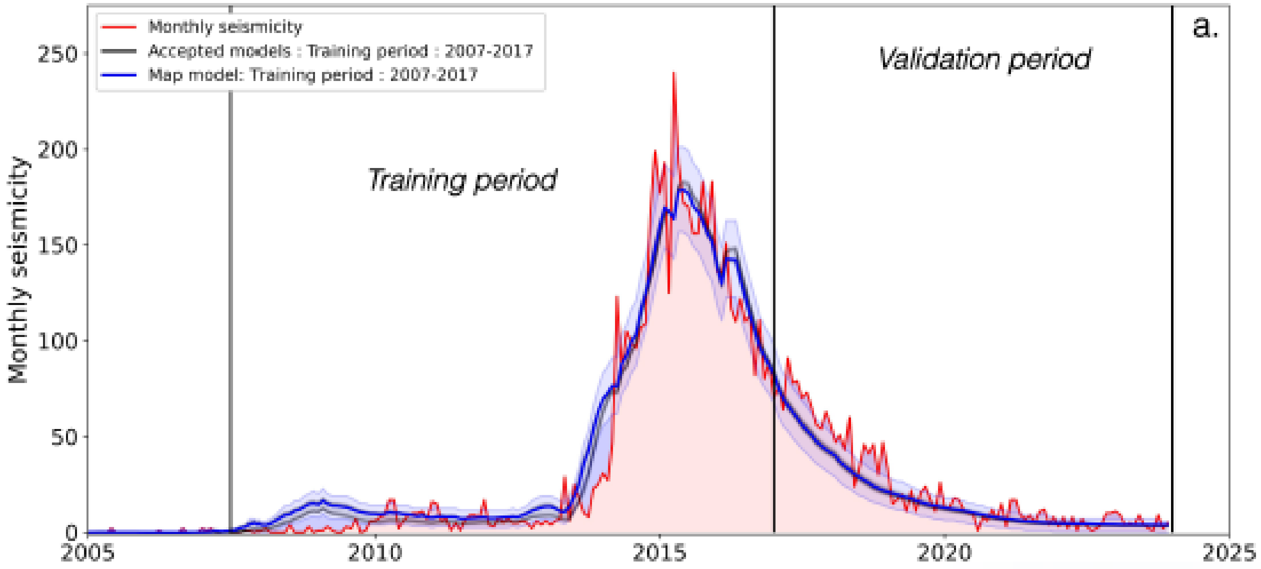


Triggering due to poro-elastic stress changes or pore pressure diffusion along basement faults.

(Samson Marty, et al.,)

Wastewater Disposal Oklahoma

- The model applies well to earthquakes induced by wastewater disposal.
- It is important to to account for ΔS_c



MAP model parameters:

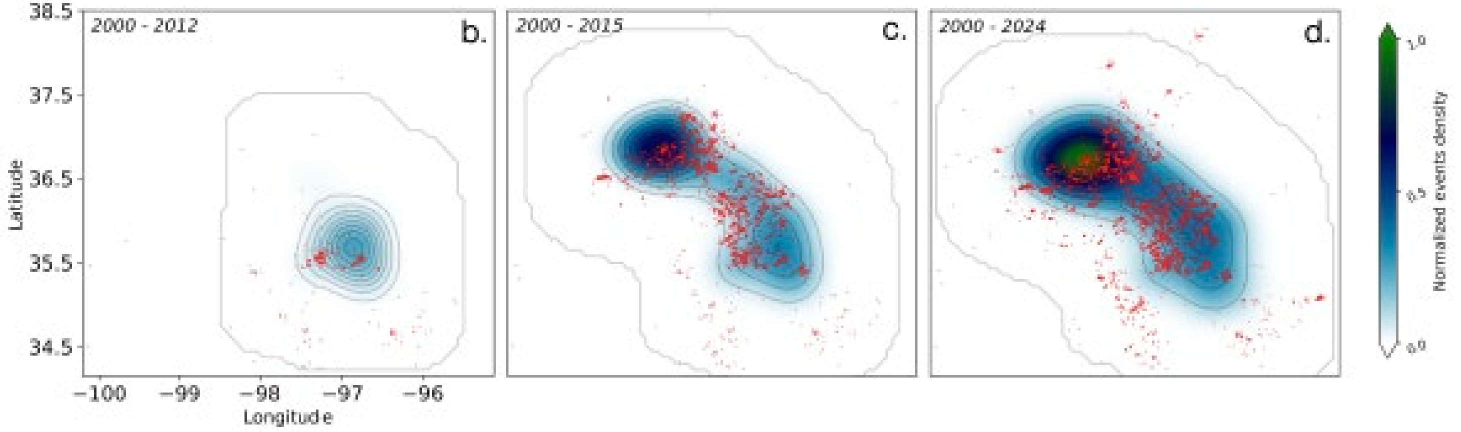
$A\sigma$ = 8.0 kPa

ΔS_c = 0.5 MPa

t_a = 158 years

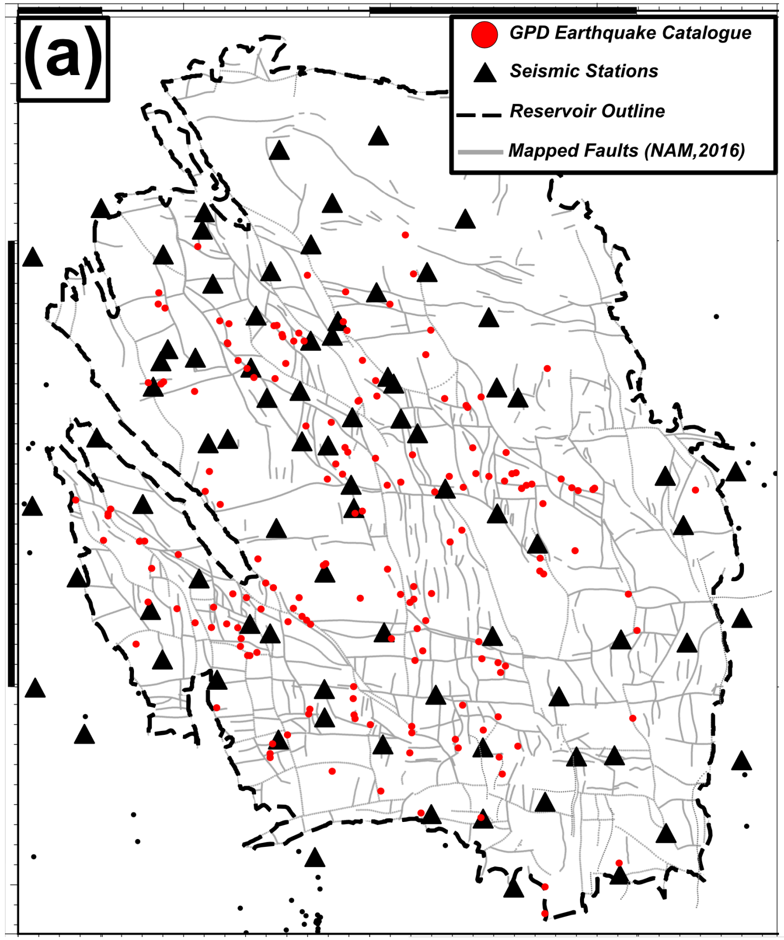
r = 5.53 * 10^{-3} EQ/km^2/year

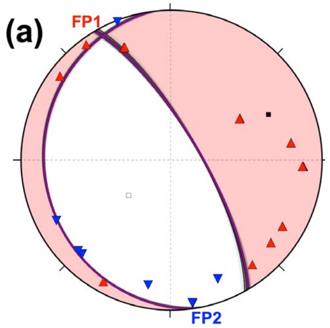
k= 10^{-12} m^{-2}

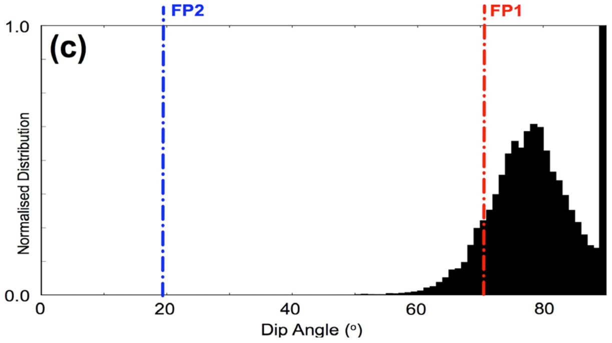


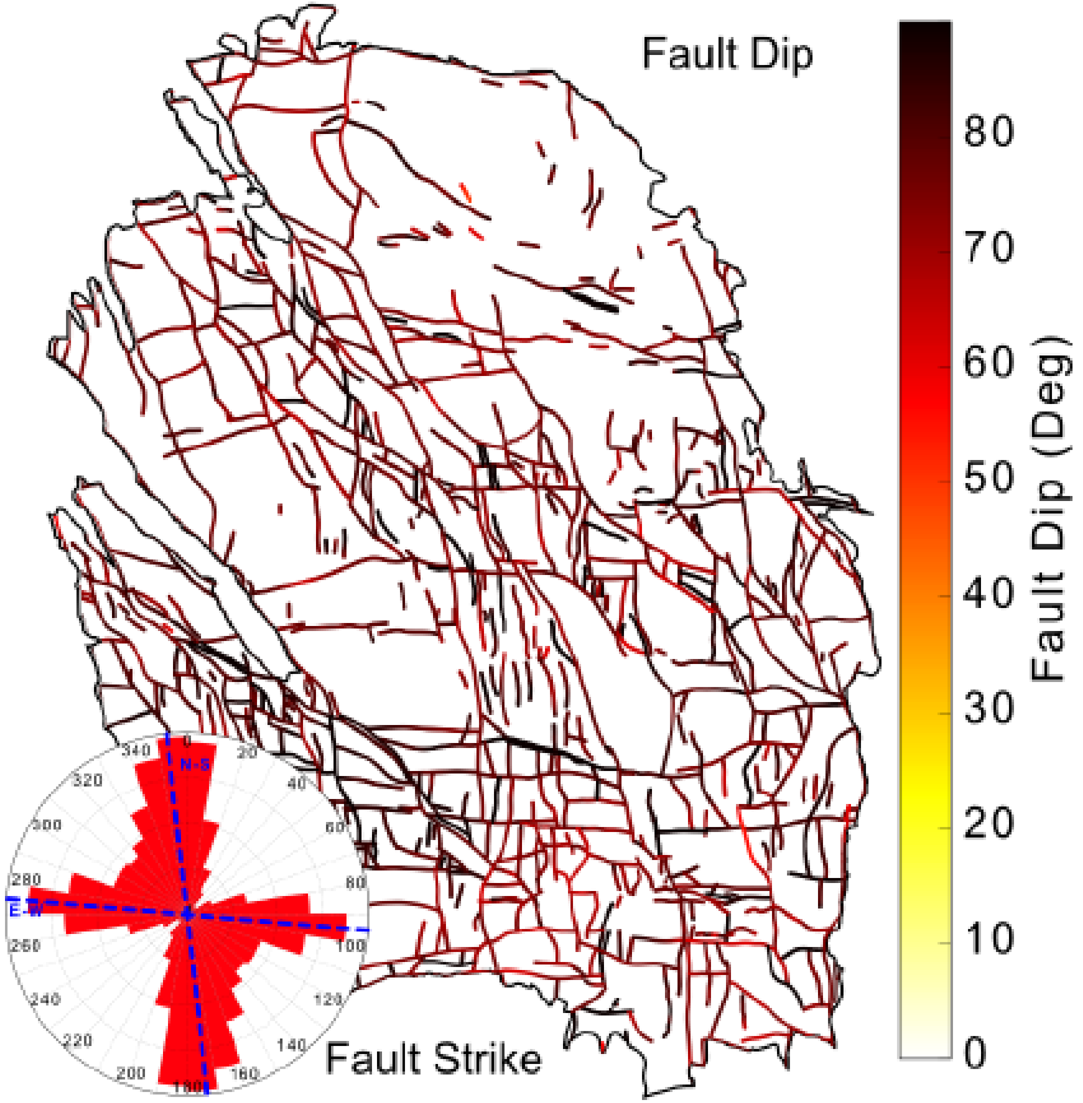
(Samson Marty, et al.,)

Seismicity - Key features









"Earthquake forecasting and prediction involve statements about the location, time, and magnitude of future fault ruptures."

"An **earthquake forecasting model** is a systematic method for calculating the probabilities of target events within future space-time domains."

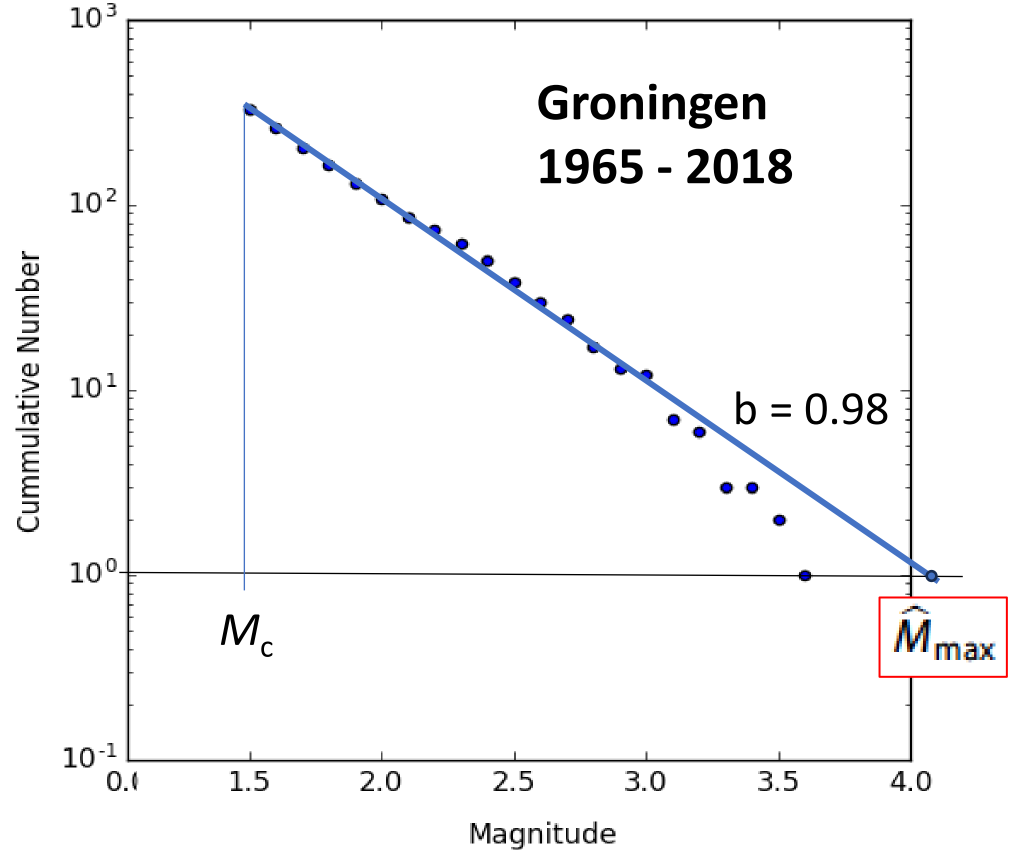
International Commission on Earthquake Forecasting for Civil Protection (2011)

Earthquake Forecasting = assessing the probability of an earthquake with magnitude exceeding some value, M, in a particular area, A, and a particular time window$[t, t + \Delta t]$.

$$\boxed{P(>M, [t, t + \Delta t], A)}$$

Principles of forecasting method

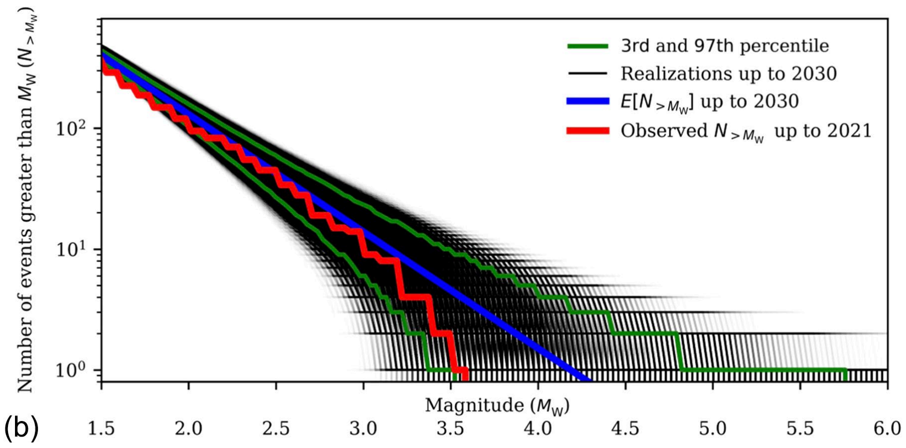
From $N(>M_c)$ to $p(>M)$

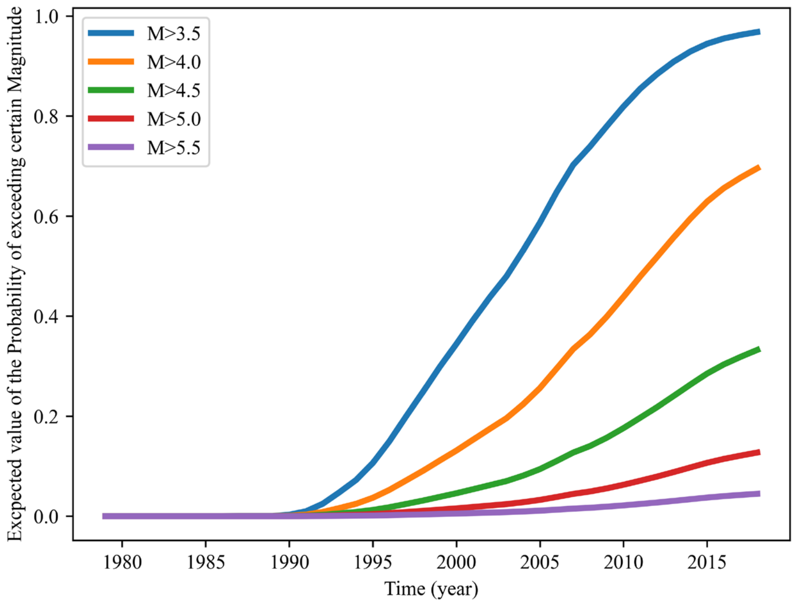


$$\widehat{M}_{max} = M_c + \frac{1}{b}\log_{10}N,$$

$$\widehat{M}_q = \widehat{M}_{max} - \frac{1}{b}\log_{10}\left[N\left(1-q^{1/N}\right)\right],$$ (van der Elst et al., 2016)

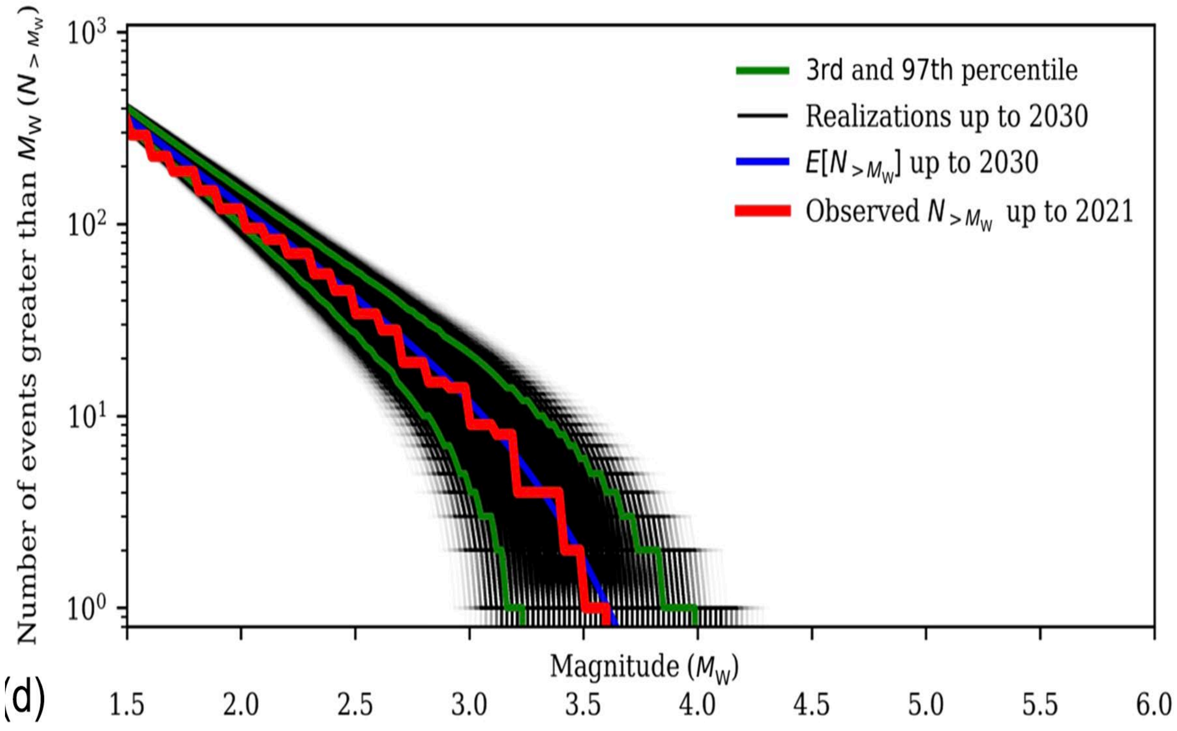
$$p(>M) = 1 - \left(1 - \frac{1}{N}10^{b(M-\widehat{M_{max}})}\right)^N$$

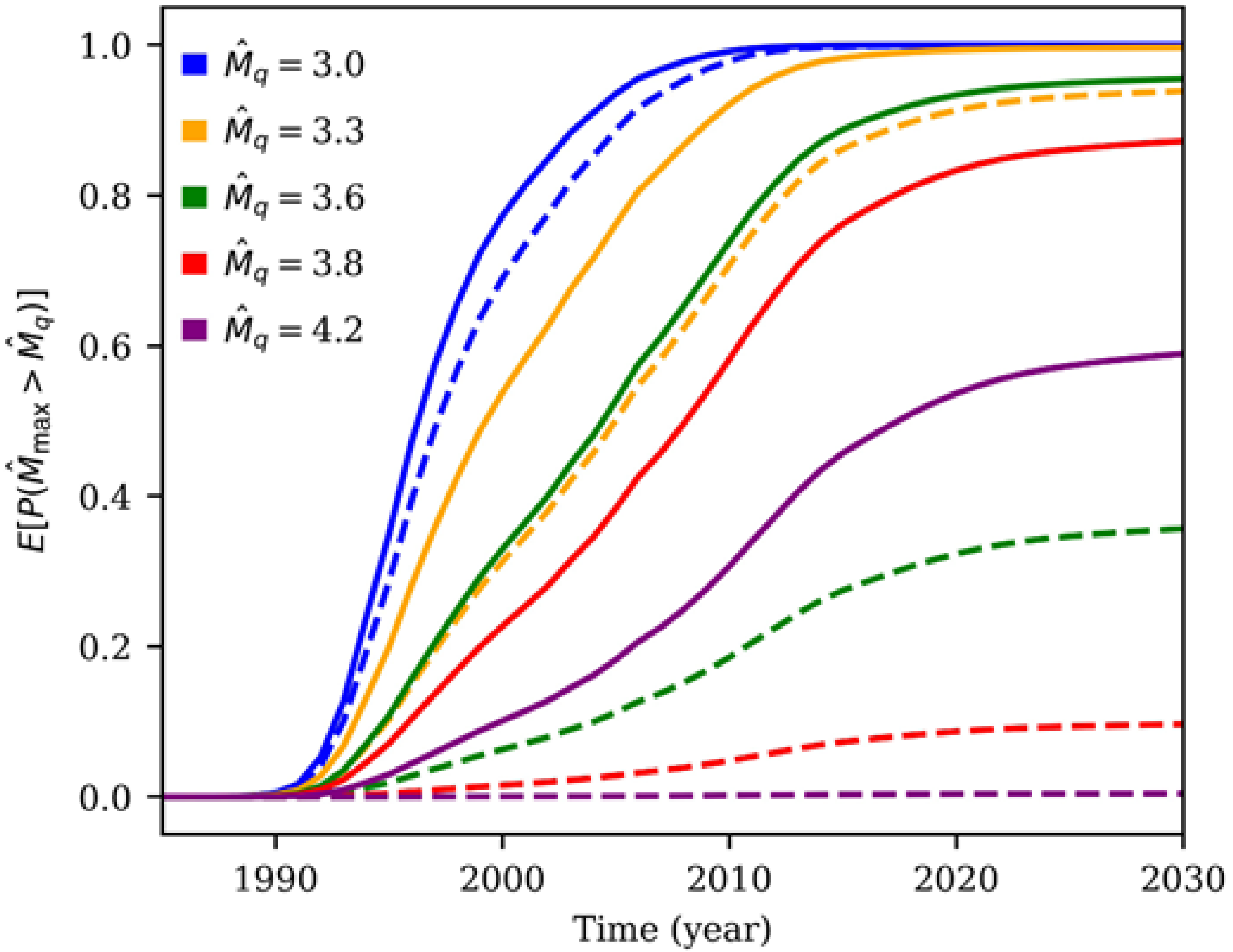




(Kaveh et al., SRL, 2023)

The shape of the MDF matters (b-value, M_{max} and tapering)





(Kaveh et al., SRL, 2023)

To forecast EQs we need :

- Earthquake occurrence model (time and space)
- Magnitude-frequency distribution, assuming a truncated Gutenberg-Richter distribution

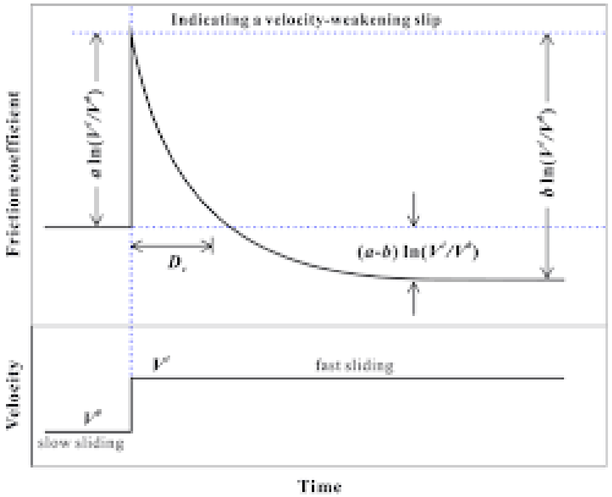
$$\boxed{\log_{10} N(\geq M_w) = a - b\, M_w \,,\; M_w < M_{max}}$$

→ We need to estimate (with UQ):

- **a(x,y,t)**
- **b(x,y,t)**
- **(M_{corner})**
- **M_{max}(x,y,t)**

→ How do these quantities vary in space and time?

EQ nucleation based on Rate and State friction (Dieterich, 1994)



$$\begin{cases} \mu = \tau/\sigma = \mu^* + a\ln\dfrac{V}{V^*} + b\ln\dfrac{\theta V^*}{D_c} \\ \dfrac{d\theta}{dt} = 1 - \dfrac{\theta V}{D_c} \end{cases}$$

'Aging Law' (Dieterich 1981; Ruina 1983)

- At steady state we get: $\boxed{\mu_{ss} = \mu^* + (a-b)\ln\dfrac{V}{V^*}}$

a-b>0 : stable sliding

a-b<0 : unstable slip possible

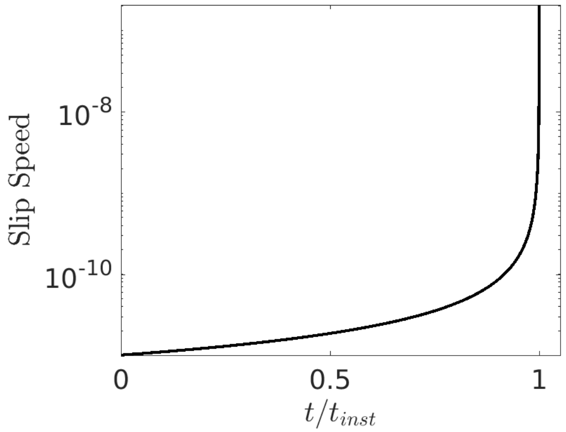
Condition for unstable slip:

$$\boxed{l > l\min \approx \frac{G(1-\nu)D_c}{(b-a)(\sigma_n - P)}}$$

$$\delta = \frac{\dot{\delta}_0 K(t)}{1 - \frac{H\dot{\delta}_0}{A}\int_0^t K(t')dt'}.$$

$$K(t) = \exp\left(\frac{\tau(t)}{A\sigma(t)} - \frac{\tau_0}{A\sigma_0}\right)$$

$$\int_0^{t_{inst}} K(t')dt' = \frac{A}{H\dot{\delta}_0}$$

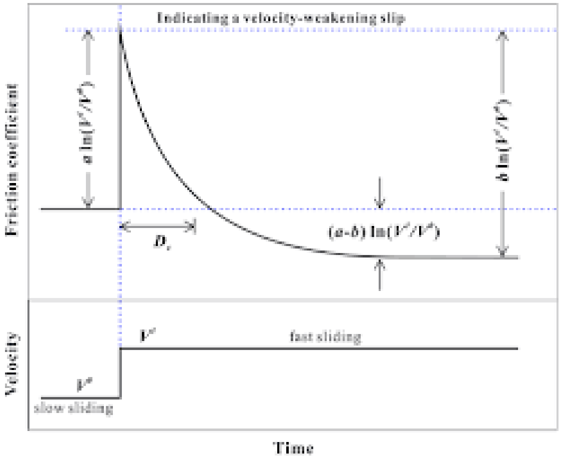


Predicted Seismicity rate for any stress evolution:

$$\boxed{\frac{R}{r} = \frac{\exp\left(\frac{\Delta S(t)}{A\sigma_0}\right)}{\frac{1}{t_a}\int_0^t \exp\left(\frac{\Delta S(t')}{A\sigma_0}\right)dt' + 1}.}$$

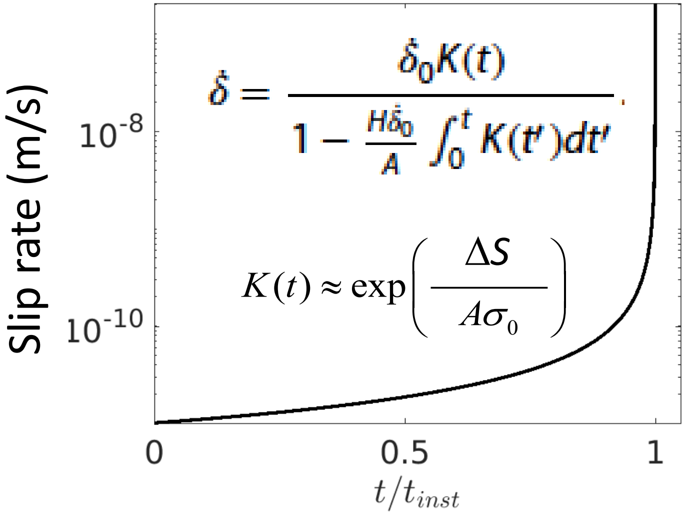
(See Heimisson and Segall, 2020)

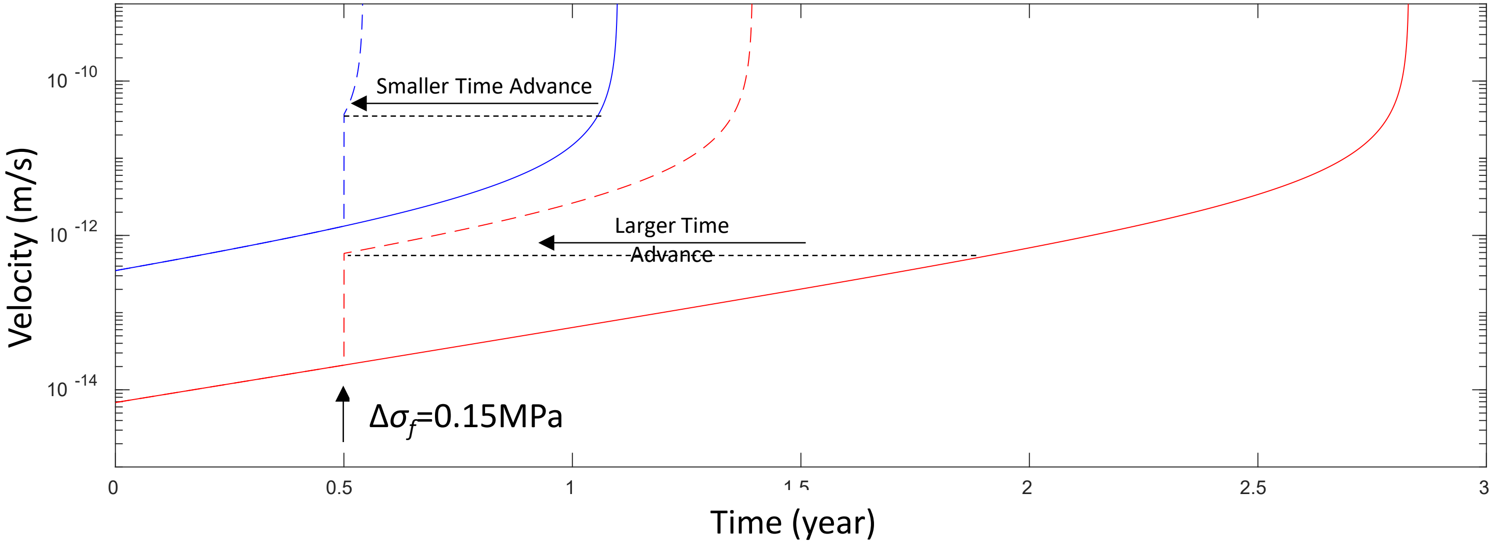
EQ nucleation based on Rate and State friction (Dieterich, 1992, 1994)



$$
\begin{cases}
\mu = \tau / \sigma = \mu^* + a \ln \dfrac{V}{V^*} + b \ln \dfrac{\theta V^*}{D_c} \\[2ex]
\dfrac{d\theta}{dt} = 1 - \dfrac{\theta V}{D_c} \qquad \text{'Aging Law'}
\end{cases}
$$

(Dieterich 1981; Ruina 1983)





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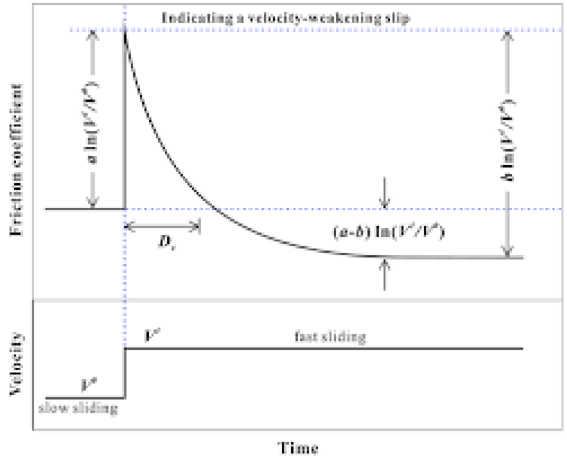

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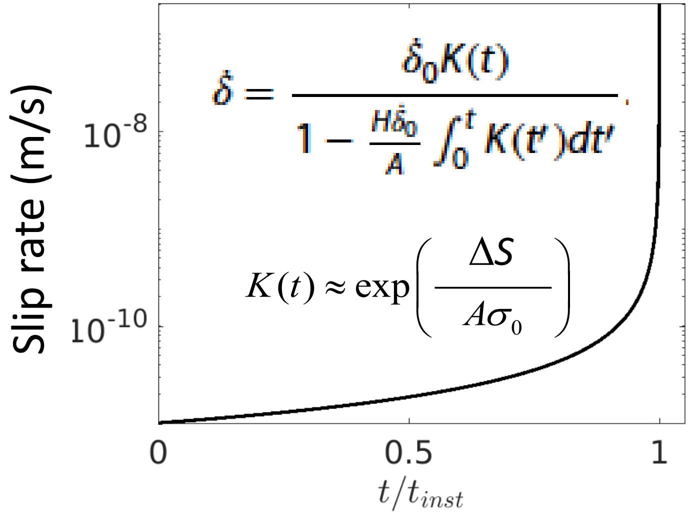
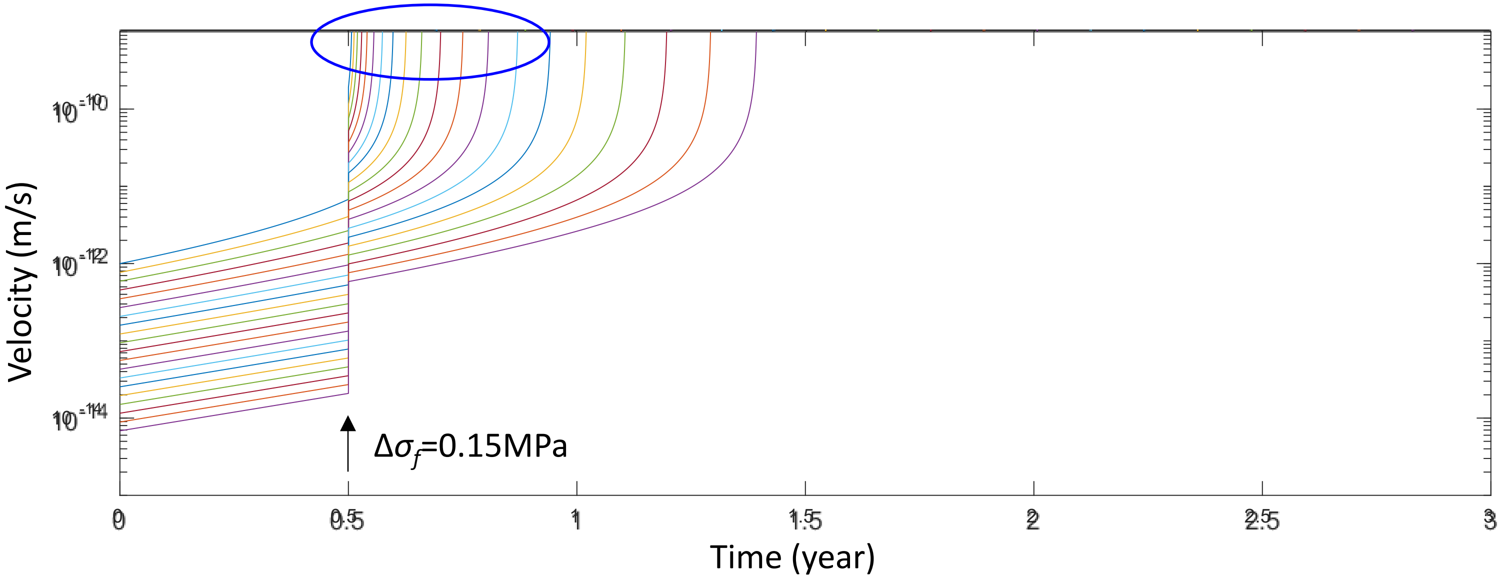
(Dieterich 1981; Ruina 1983)



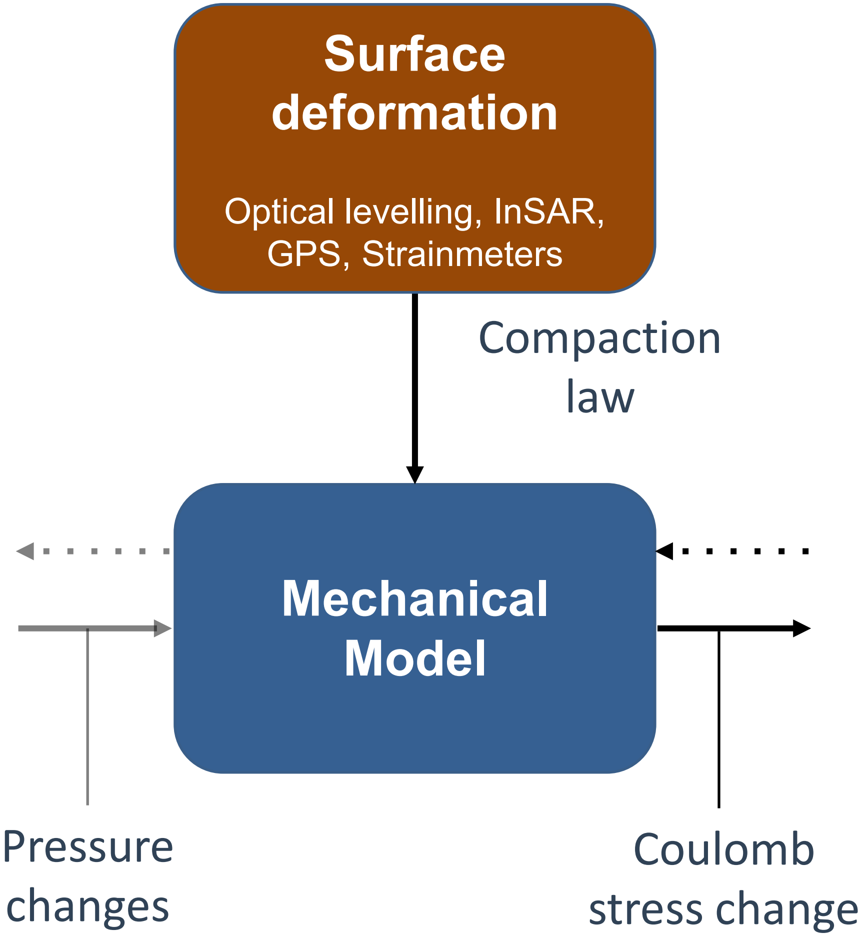
Omori Law

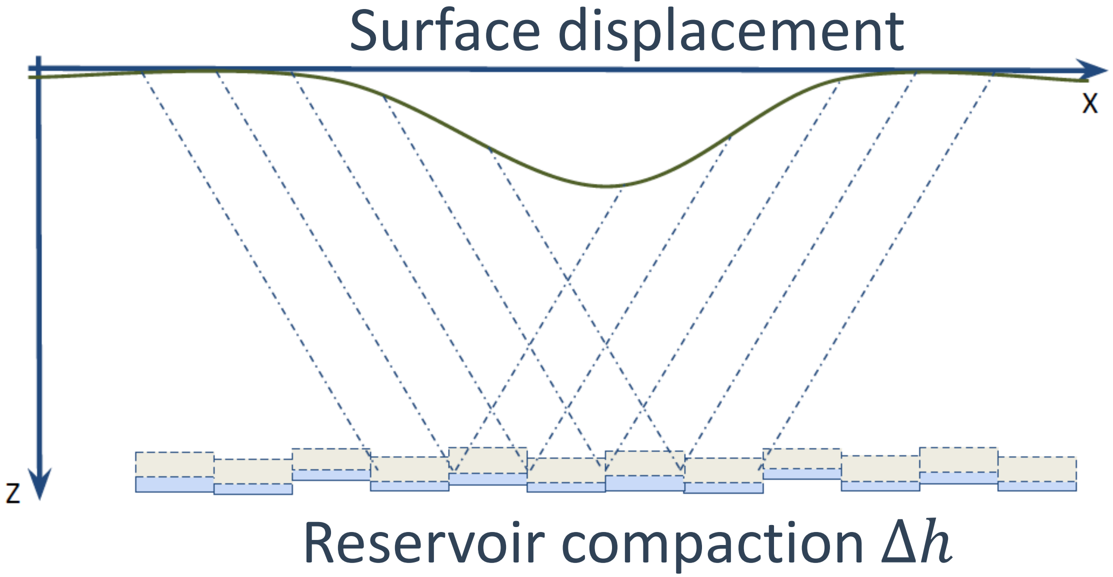


Time dependent forecasting of Induced Earthquake

- Gas extraction, Groningen (The Netherlands)
- Wastewater disposal (Oklahoma)
- Geothermal EGS, Otaniemi (Finland)

Geomechanical Model

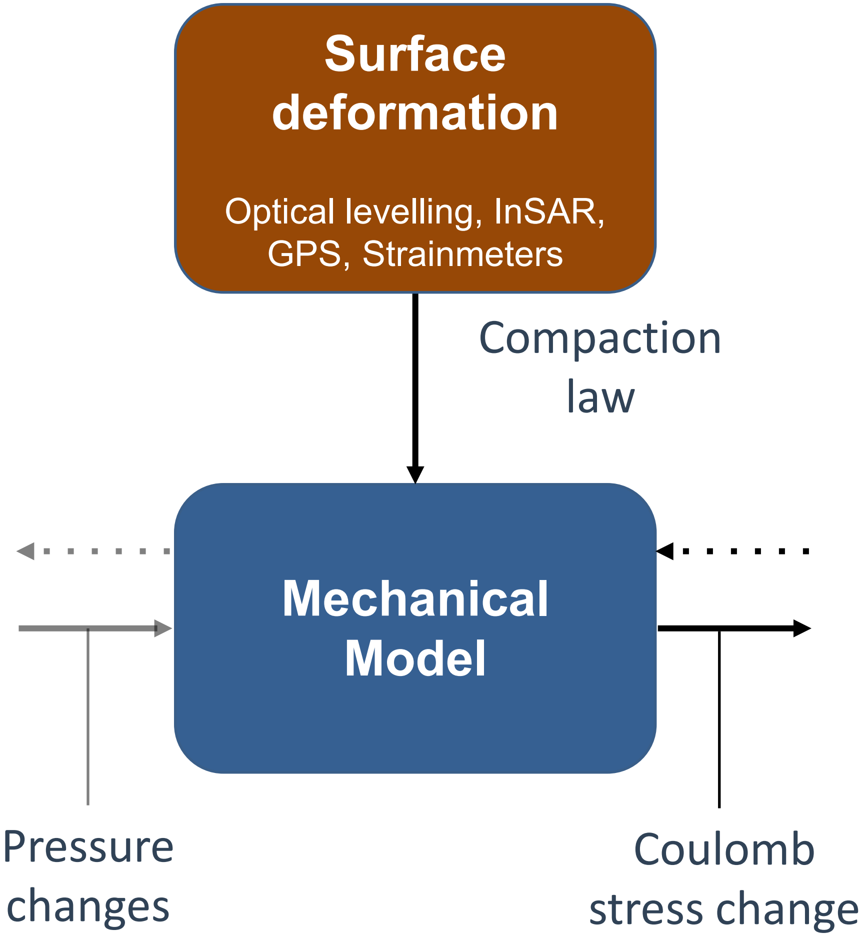


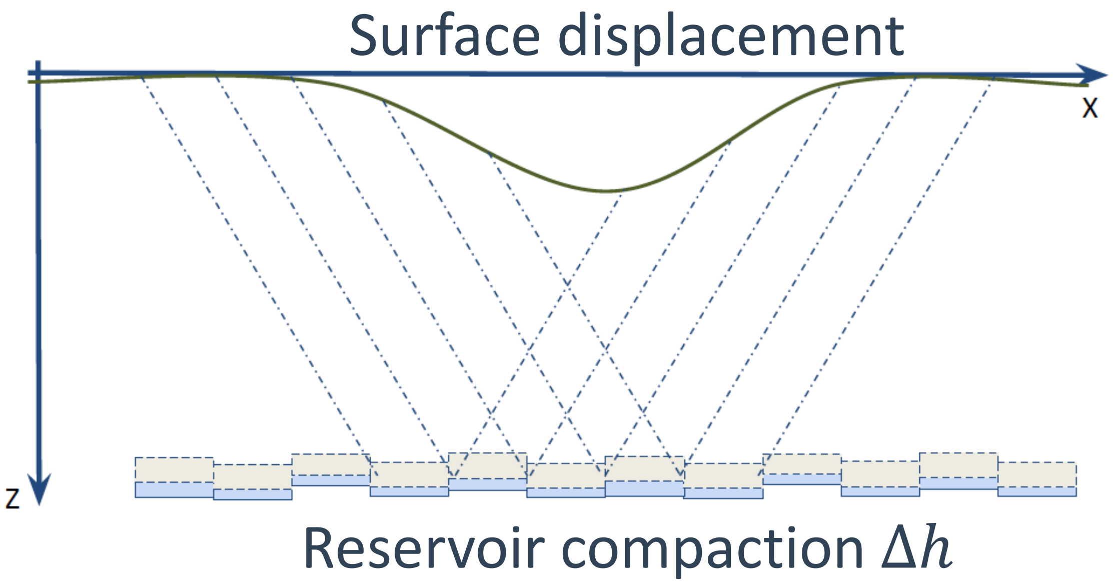


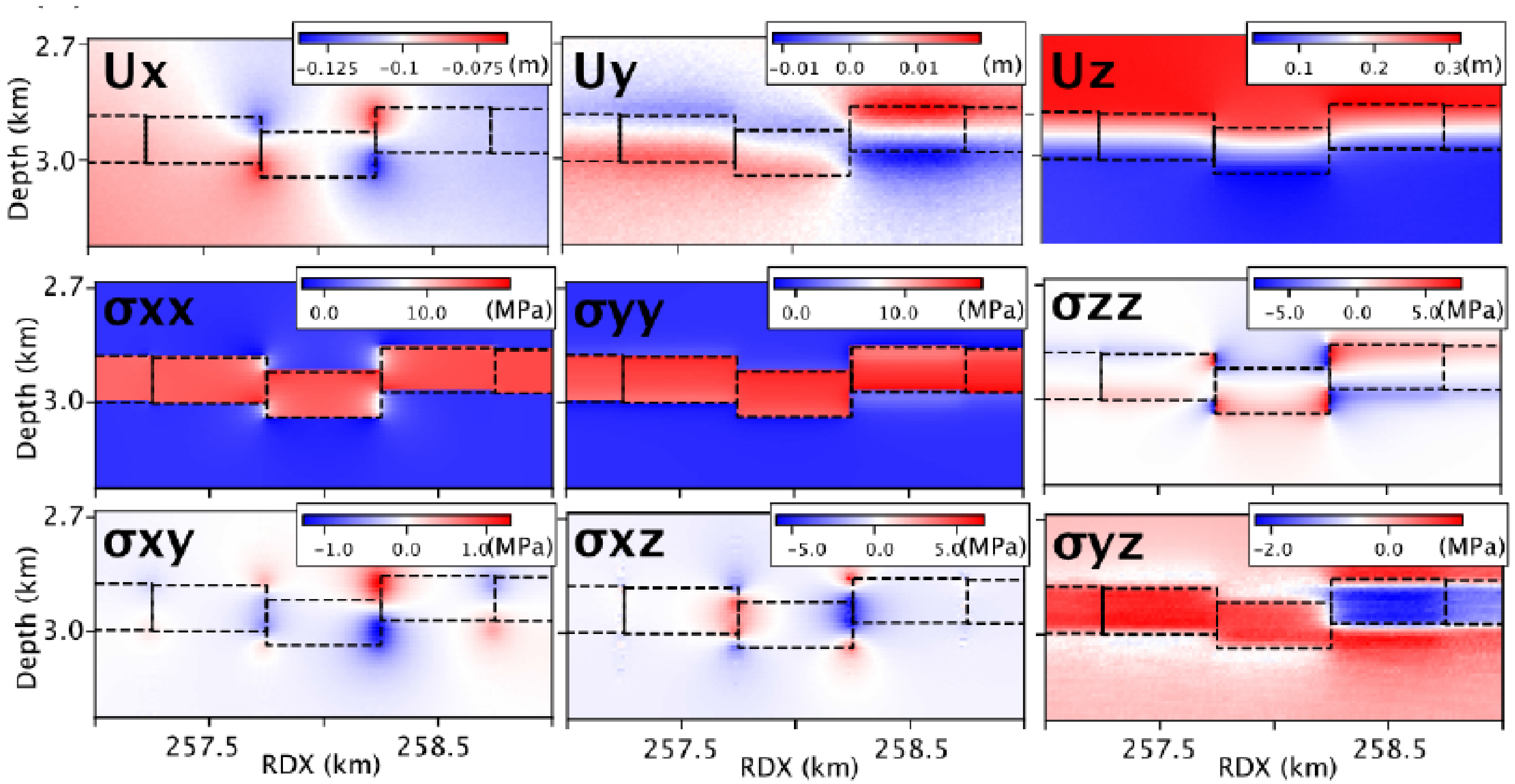
- Deformation due to poroelastic strain is calculated using **semi-analytical Green functions** for polyhedral volume (Kuvshinov, 2008),
- Reservoir is meshed in 3-D with cuboids with account for faults offsetting the reservoir.
- Compressibility, $C_m = \frac{\Delta h}{h \Delta P}$, is derived from surface deformation (inSAR, GNSS, levelling)

(Smith et al., 2019, 2022)

Geomechanical Model
Coulomb stress calculation



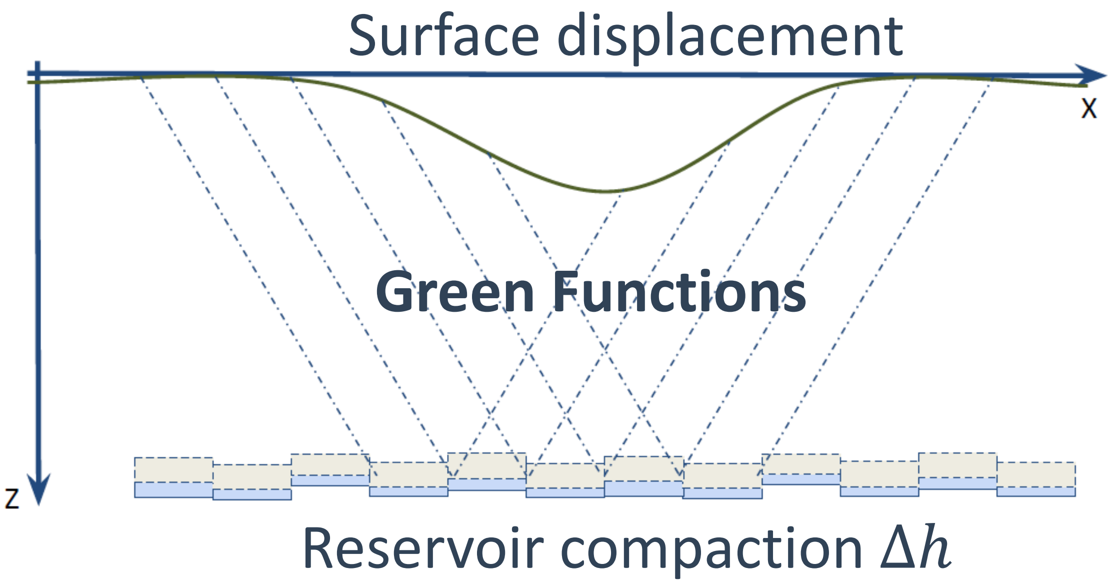




(Smith et al., 2019, 2022)

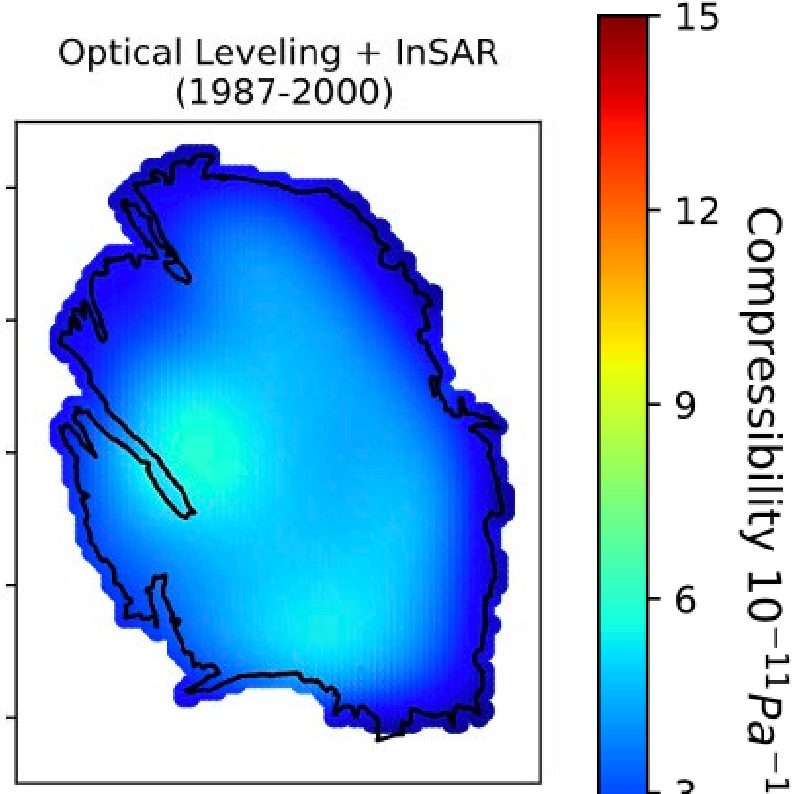
Geomechanical Model

Inversion for reservoir compressibility



$$\boxed{C_m = \frac{\Delta h}{h \Delta P}}$$

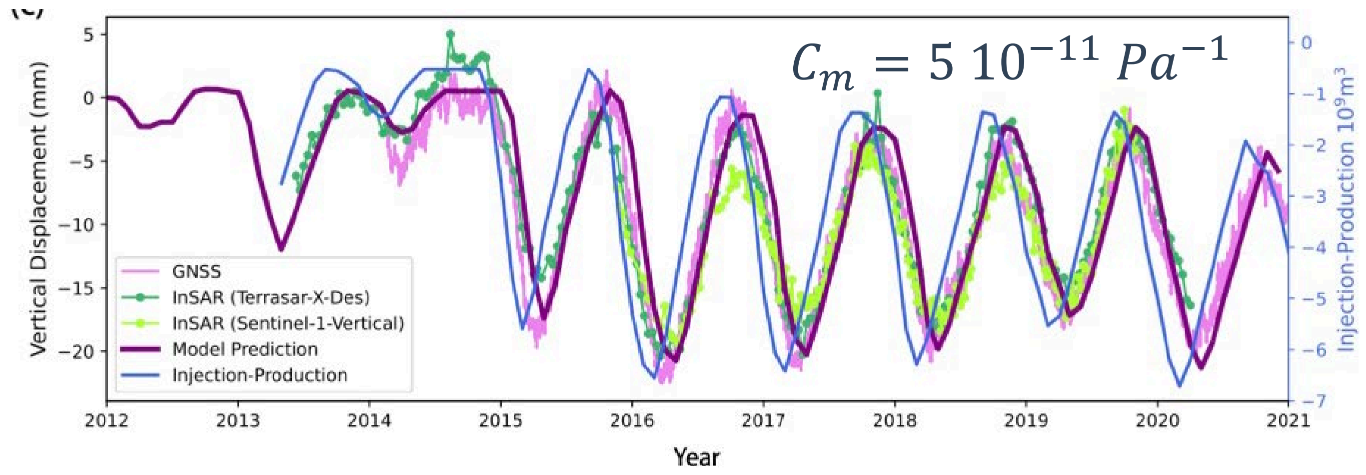
Groningen



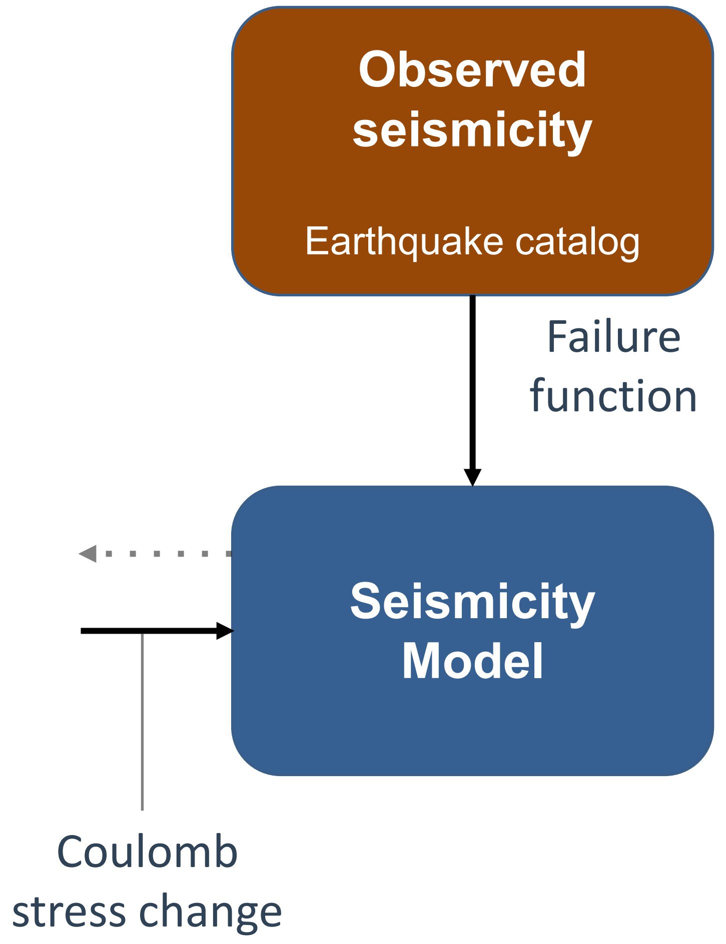
Spatial variation of Compressibility

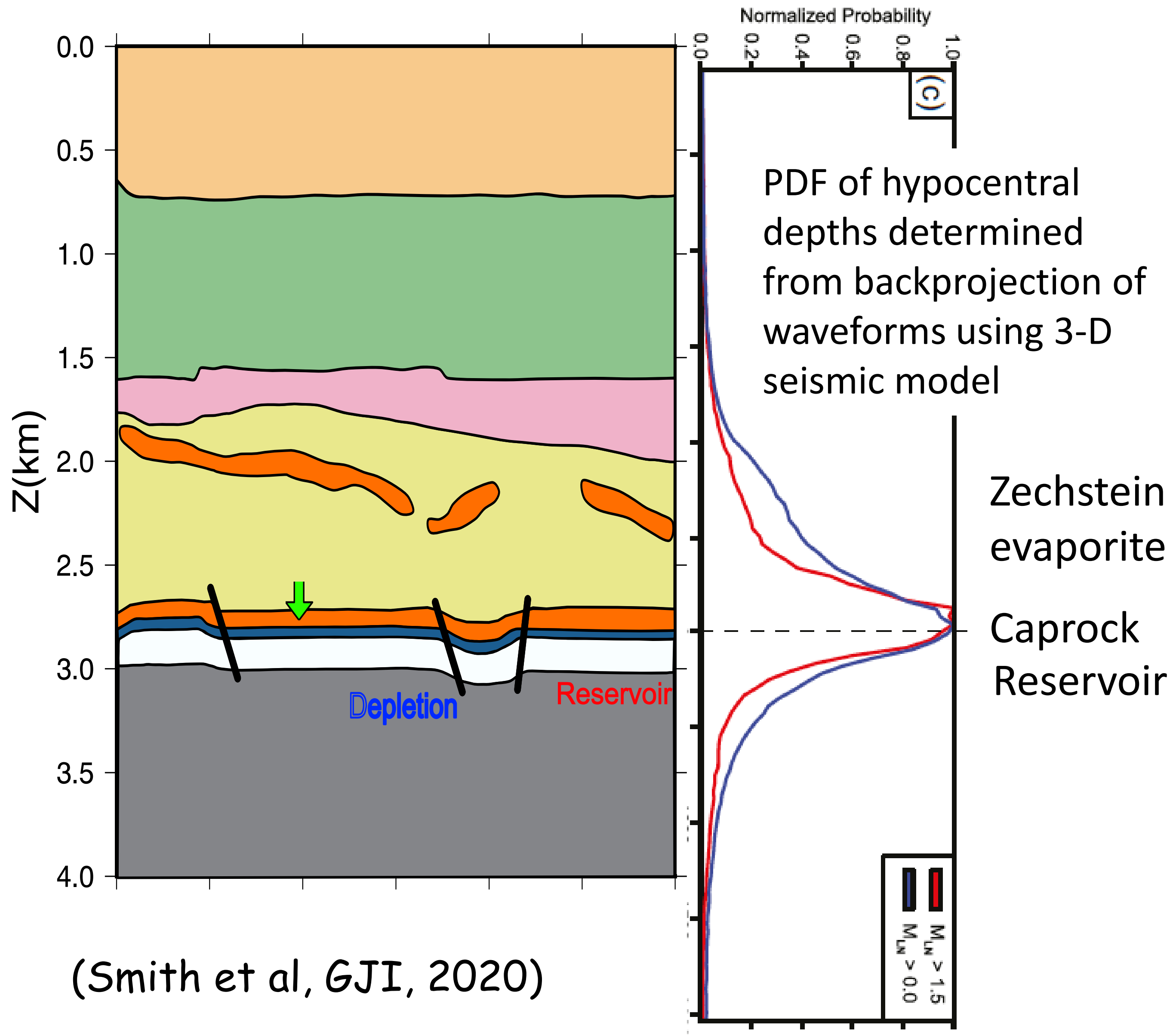
(Yuexin Li et al., submitted)

Norg



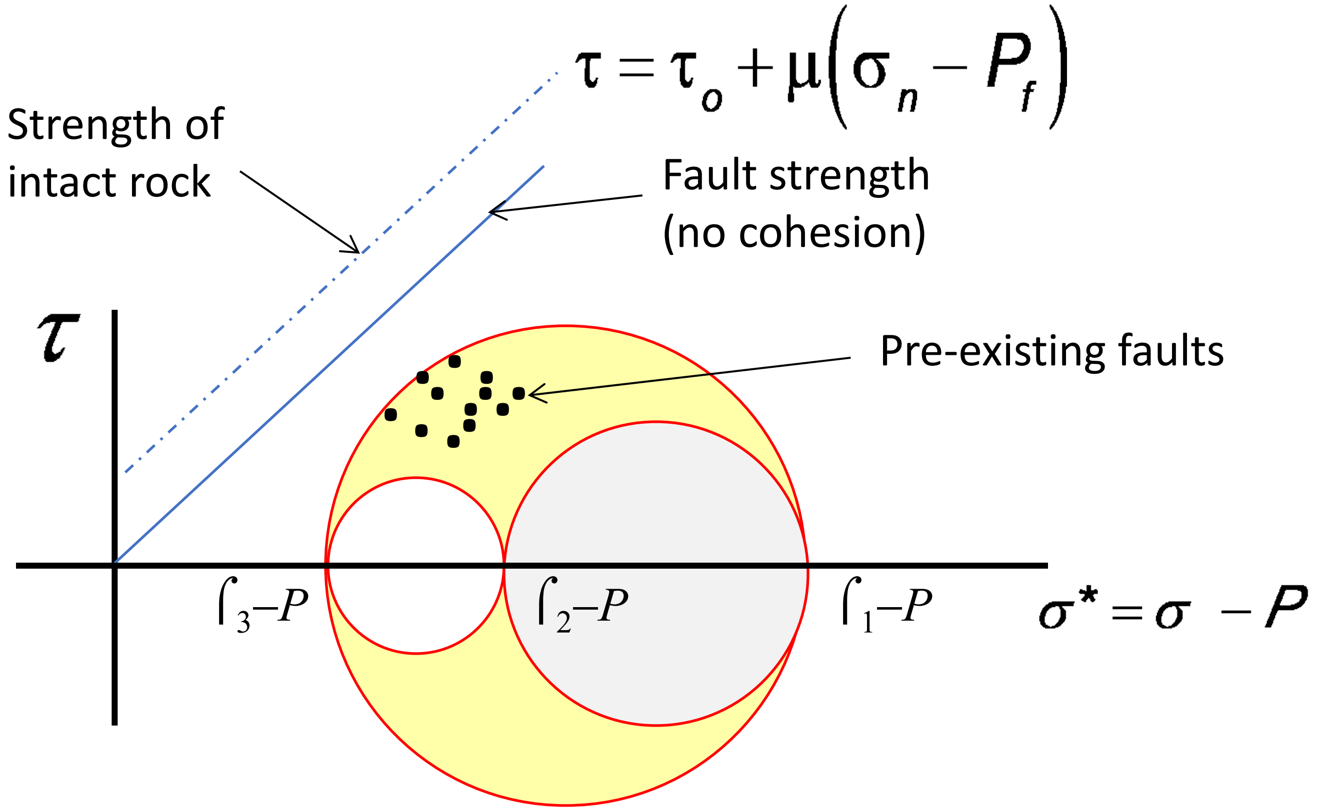
Seismicity Model





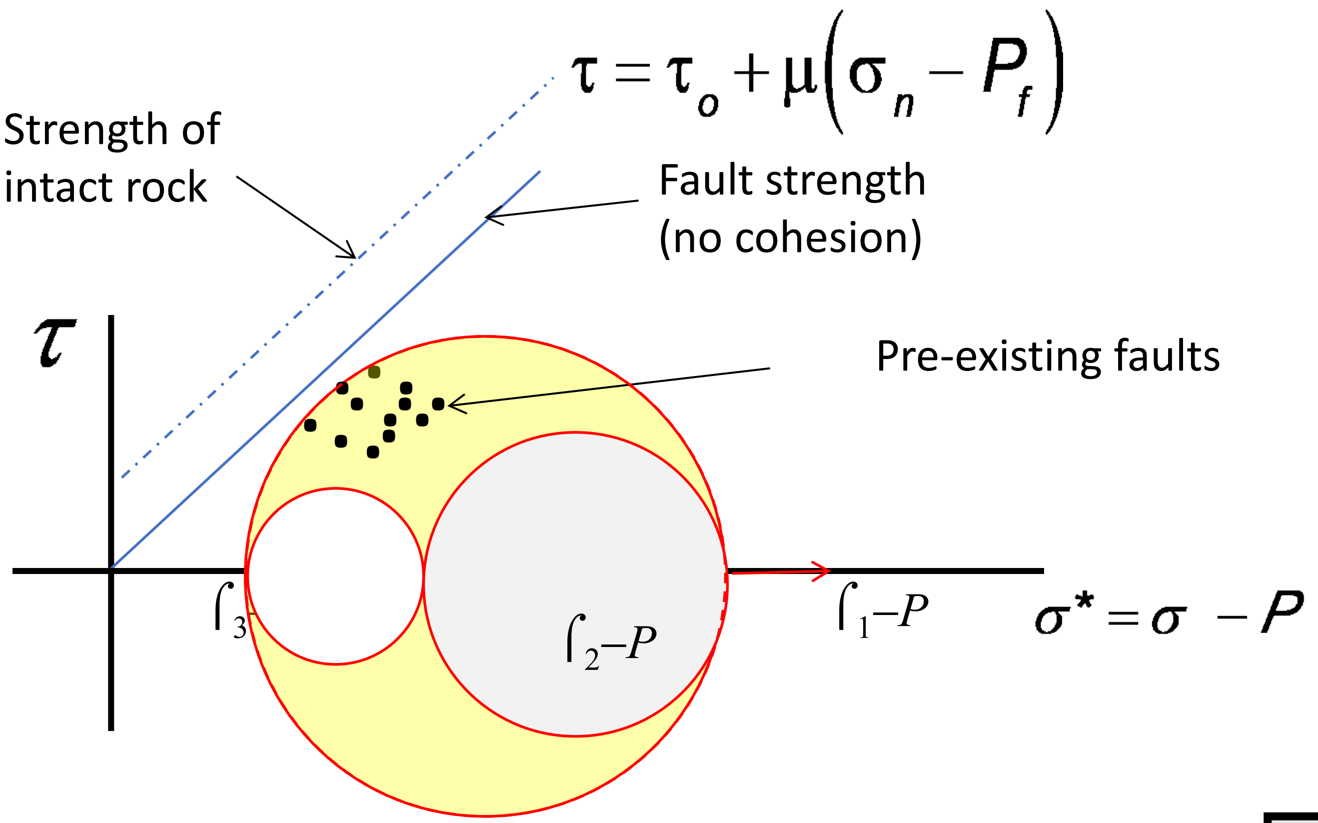
(Smith et al, GJI, 2020)

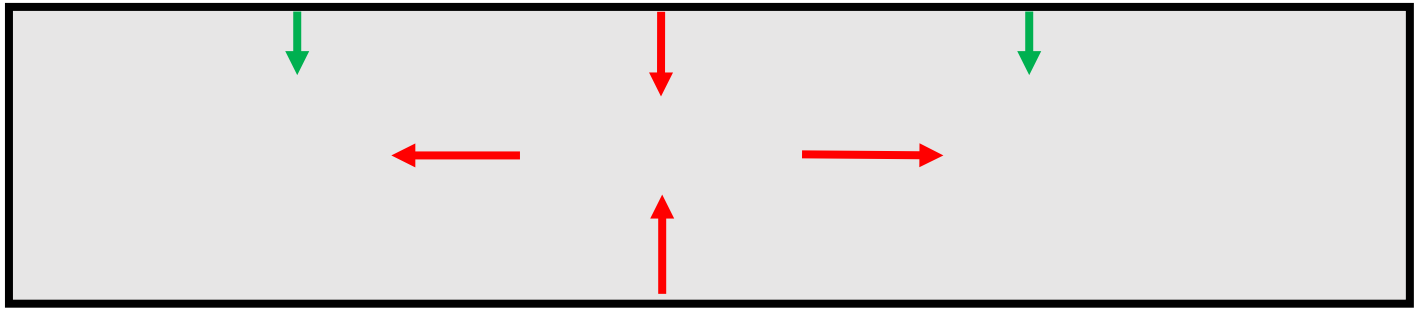
Effect of pressure drop– no poroelastic response

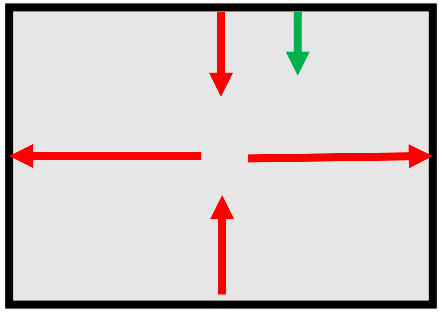


Let's assume a population of faults with same friction coefficient embedded in medium with larger strength

Effect of pressure drop– no poroelastic response



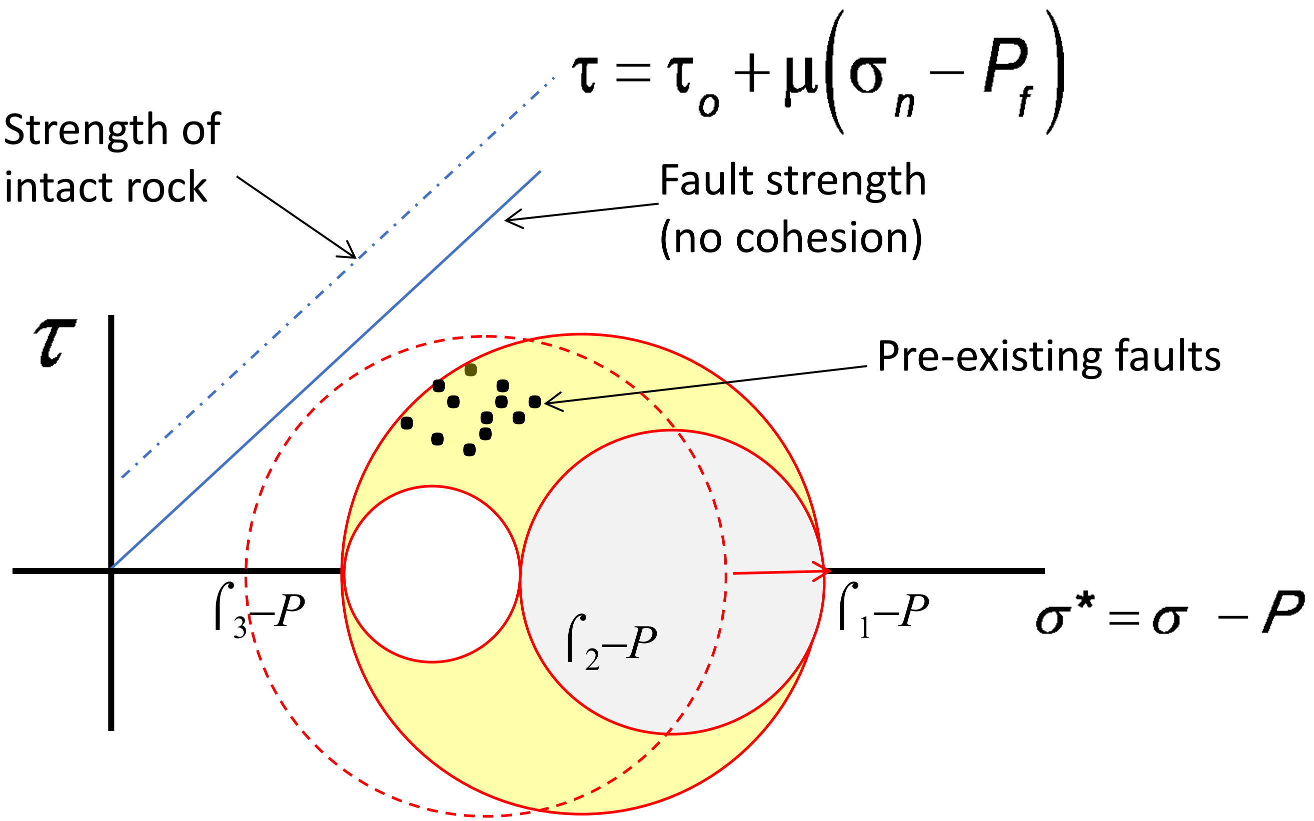




Effect of pressure drop– no poroelastic response

A pressure drop can only stabilize faults in the reservoir if the reservoir is uniform and

$\alpha < \alpha_c =$



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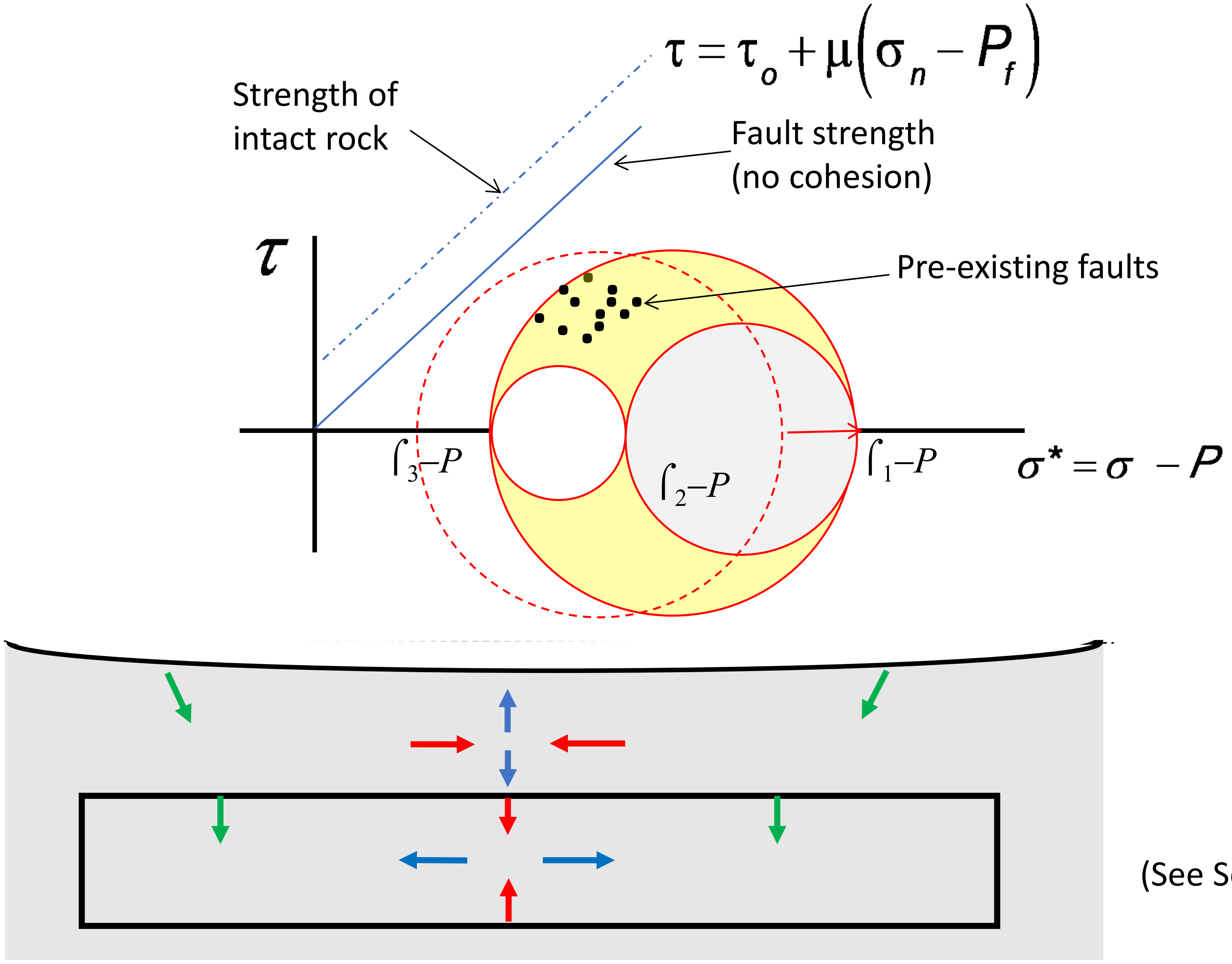
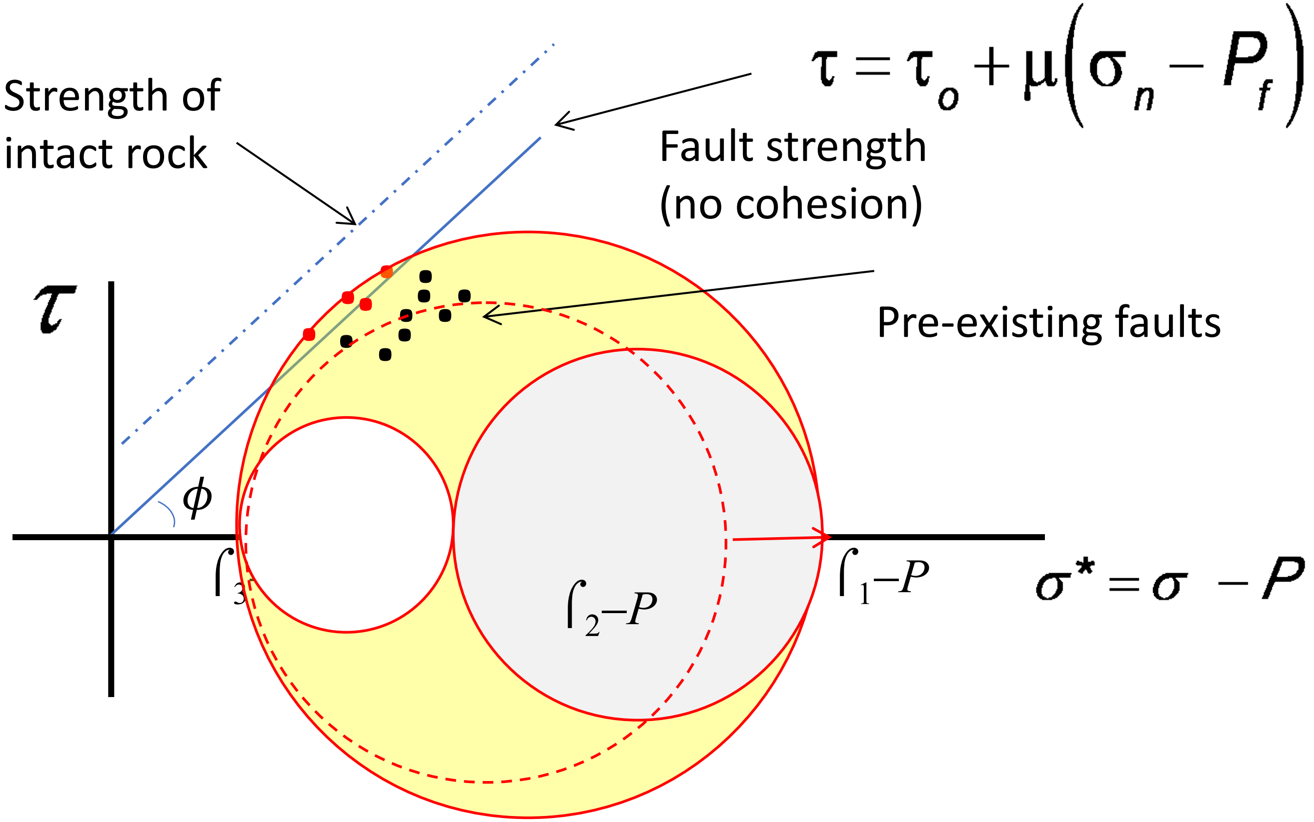


(See Segall et al, 1998)

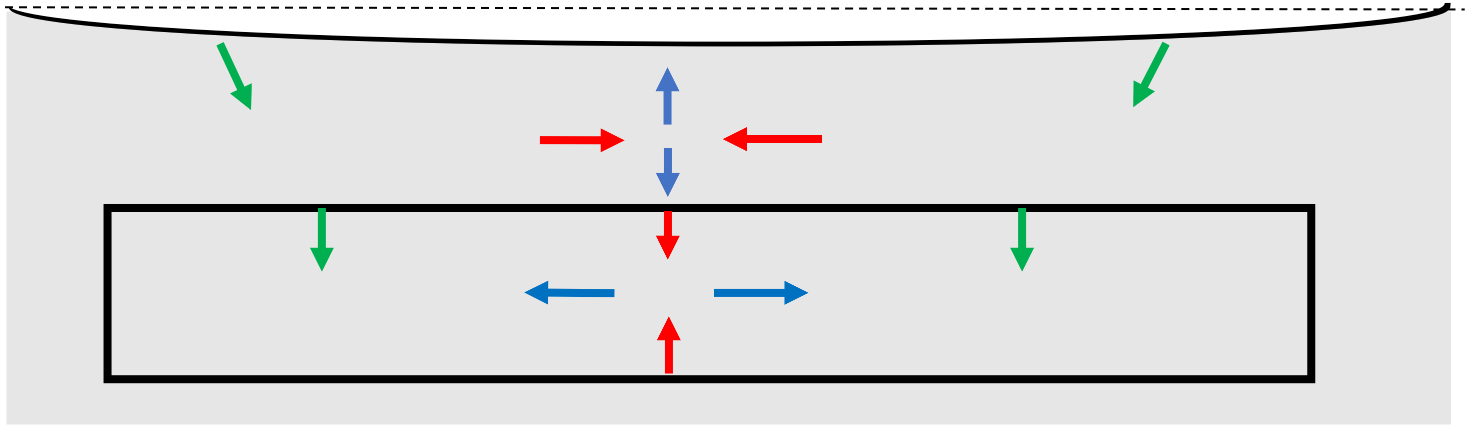
Effect of pressure drop– with poroelastic response

A pressure drop can destabilize faults in the reservoir if

$$\alpha > \alpha_c = \frac{1-\nu}{1-2\upsilon}\,\frac{2sin\phi}{1+sin\varphi}$$

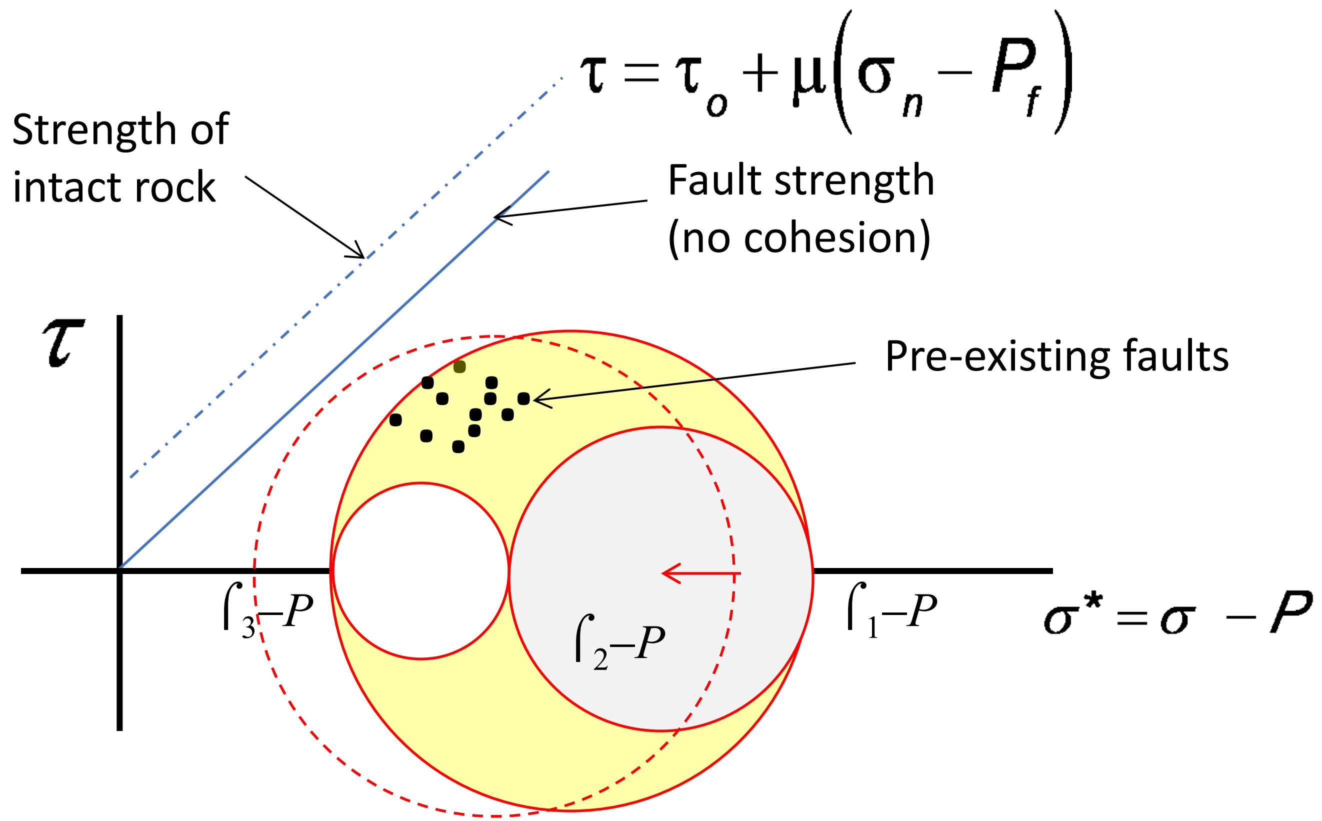


For v=0.25 and



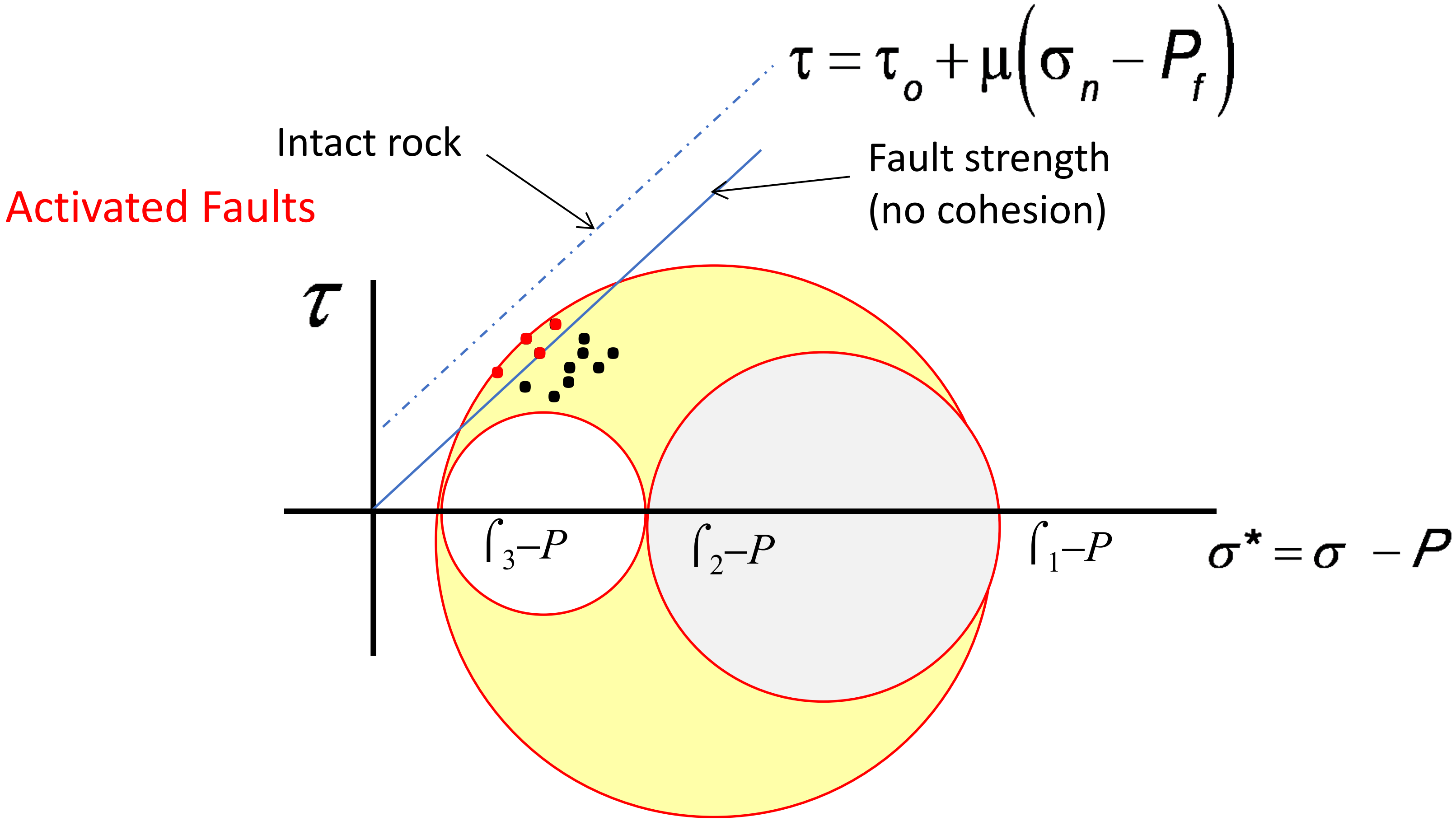
(See Segall et al, 1998)

The Coulomb failure criterion



Let's assume a population of faults with same friction coefficient embedded in medium with larger strength

The Coulomb failure criterion



Let's assume a population of faults with same friction coefficient embedded in medium with larger

Seismicity Model

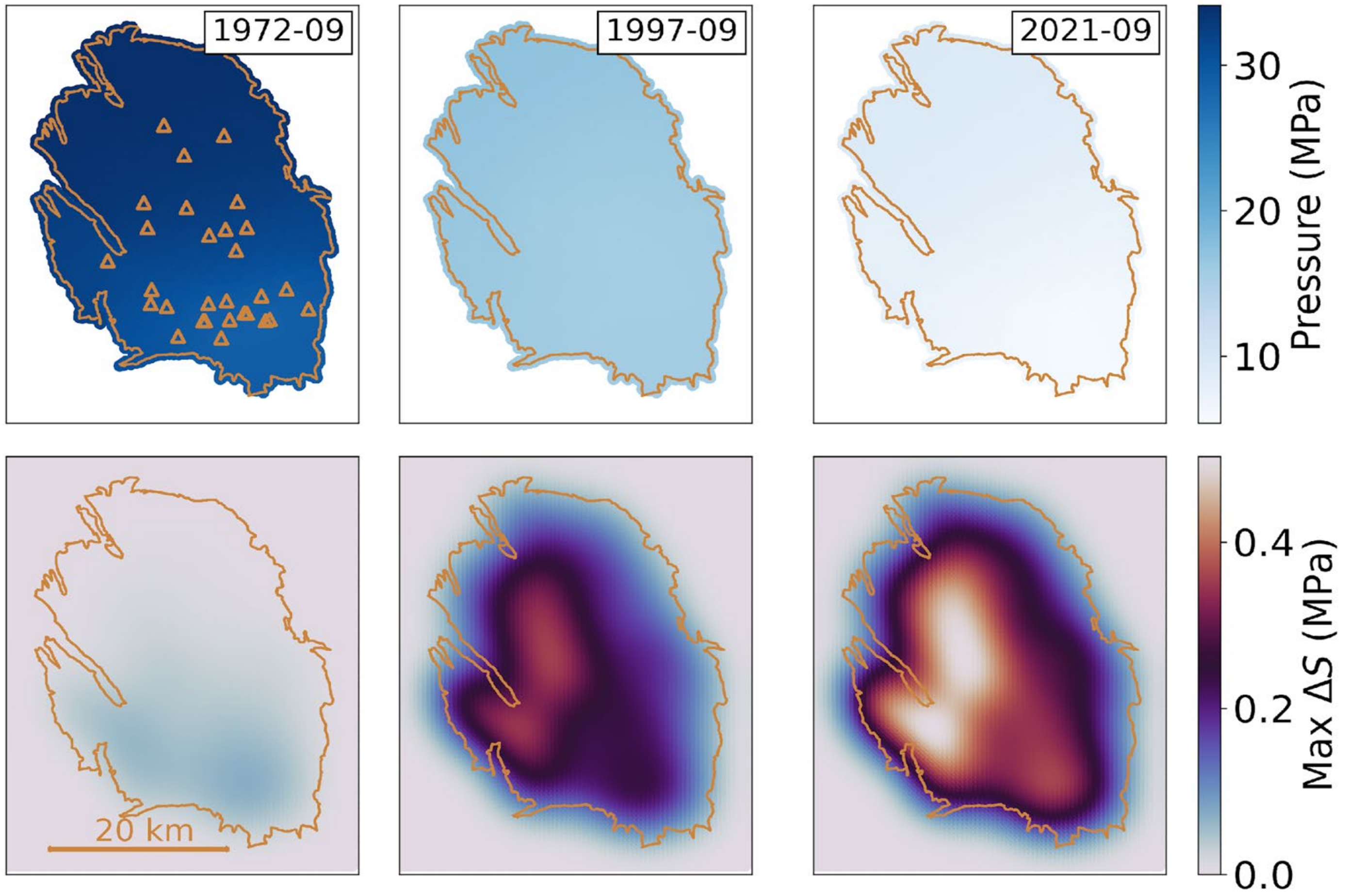
Observed seismicity

Earthquake catalog

Failure function

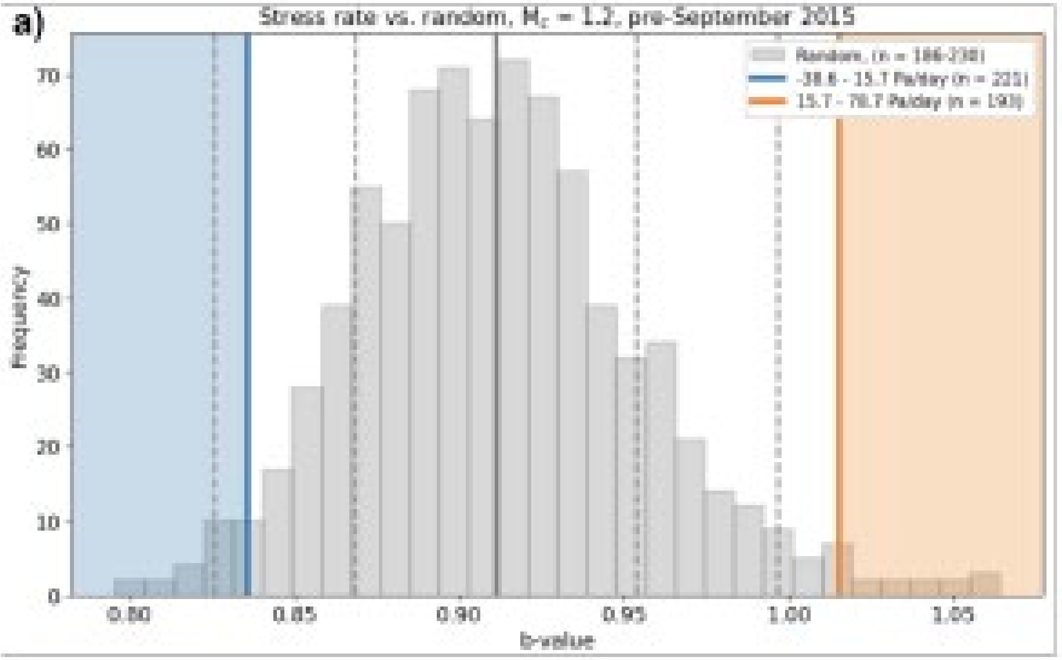
Seismicity Model

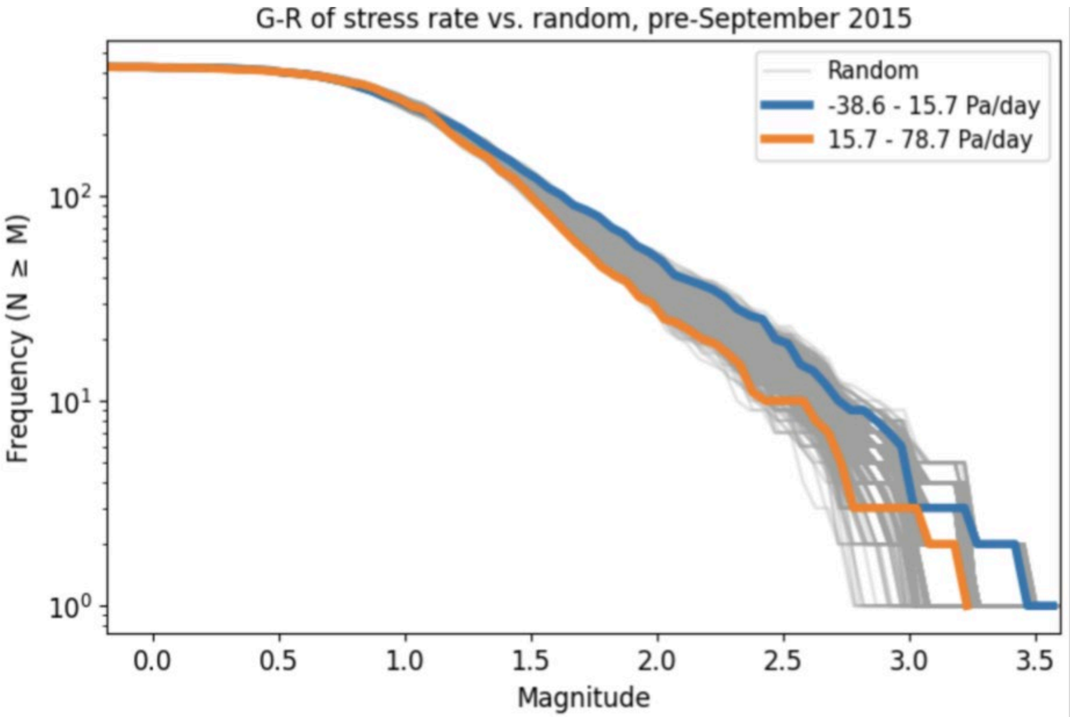
Coulomb stress change

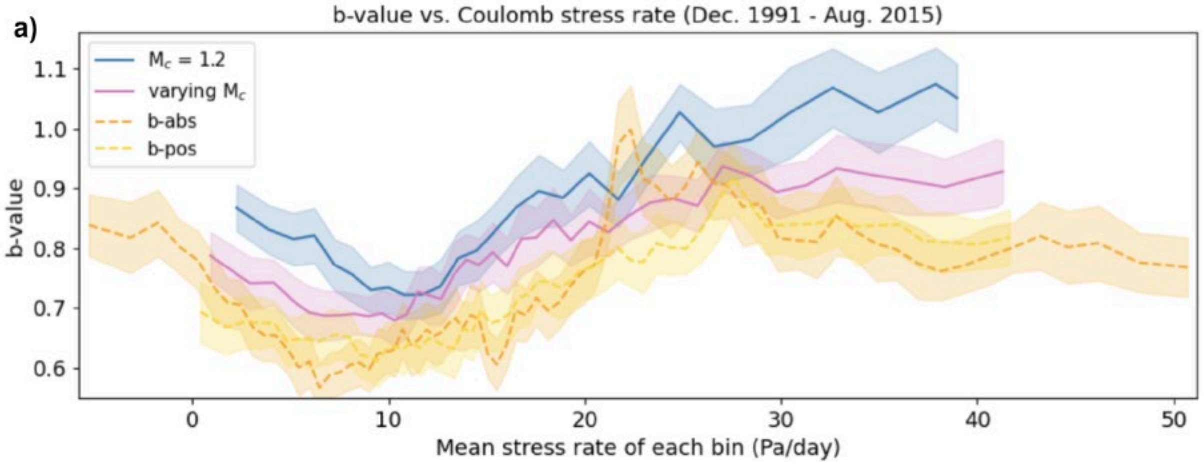


(Smith et al., 2020, 2022)

Application to Groningen (extraction)







Earthquakes grow more easily to larger magnitudes under lower stressing rate.

(Tamama et al, GRL, 2024)

Conclusions

- **CRS models explain quantitatively the seismicity induced by reservoir operations involving extraction and injection of fluids and at widely different stress rates (from MPa per year to MPa per minutes).**
- **The method can be used for probabilistic EQ forecasting (to design or manage operations).**
- **Non instantaneous earthquake nucleation is required at short time scales (sub-annual)**
- **Magnitudes are estimated based on a parametrized MFD distribution which is probably not stationary.**
- **Regarding the forecasting of individual events, we are not quite there….**

Tapering of magnitudes seems significant (3%):

- Is it due to subsurface geometry?
- Is due to spatial distribution of stress changes?
- Does it apply to future EQs?