A modified Coulomb failure seismicity model to study earthquake occurrence and frequency-magnitude distributions

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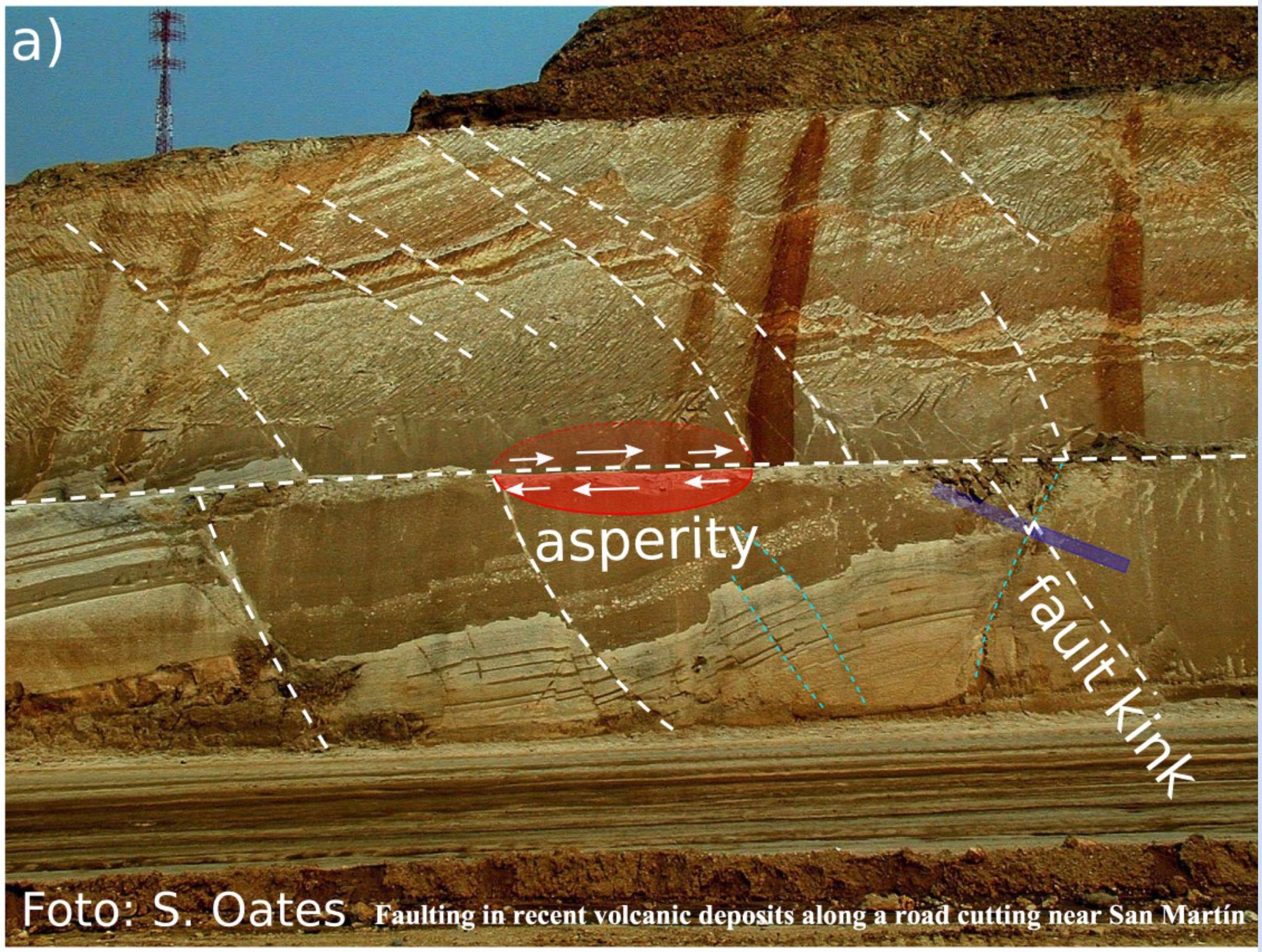


- Can we use a single model to explain all aspects of seismicity
- What is the relationship between background seismicity & stress?
- What controls aftershock activity?
- What does the short-term absence of seismicity mean?
- Is the Gutenberg Richter relation valid for time-dependent loads?

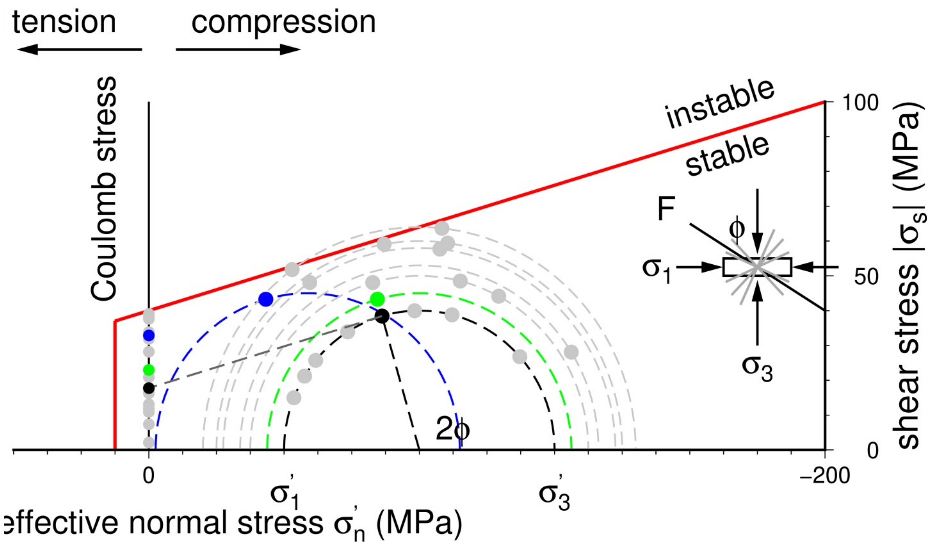
Seismicity models

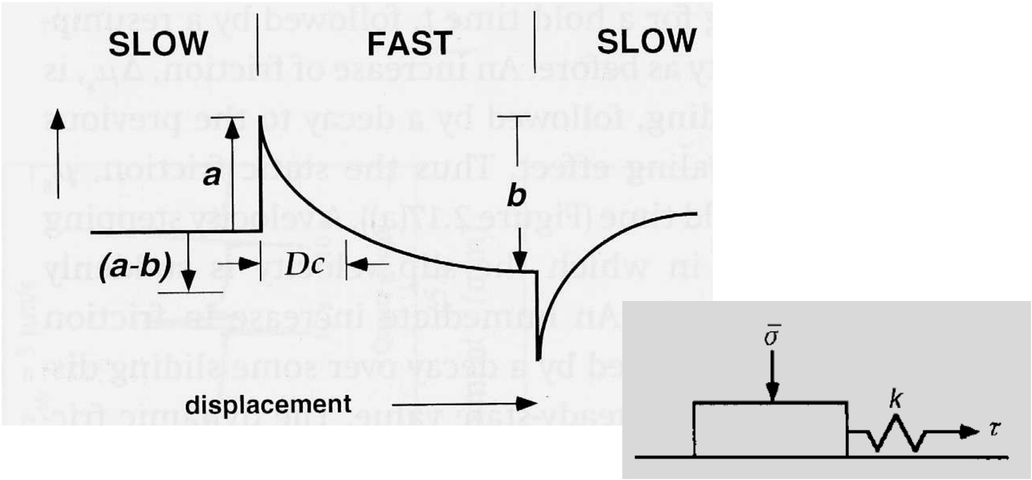
1) Forecast rate and magnitude of earthquakes in a region under specified stressing
2) In addition to the background rate the temporal response of stress steps must also be explained.

Existing models (not complete):

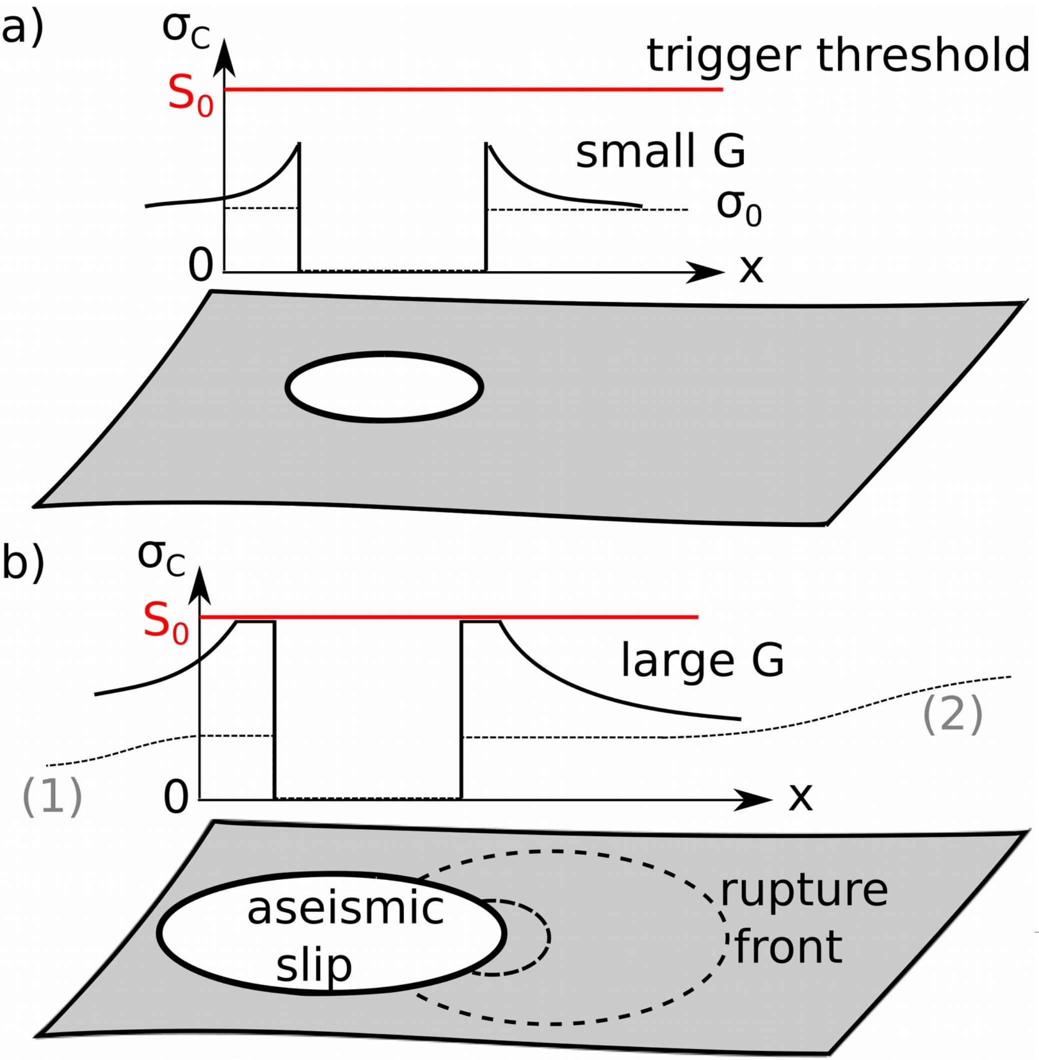
A) Linear Coulomb failure (1 parameter)

B) Rate & state frictional (Dieterich, 1981, 1994) (3 parameter)





Concept of earthquake nucleation at fault asperities



Snap shots of a growing, crack-type asperity

a) subcritical state:

asperity has a subcritical length and the stress intensity in the cohesion zone is below S_0

b) critical state, rupture begins:

asperity has grown to critical length and the stress intensity exceeds the strength S_0

from Dahm (submitted to GJI)

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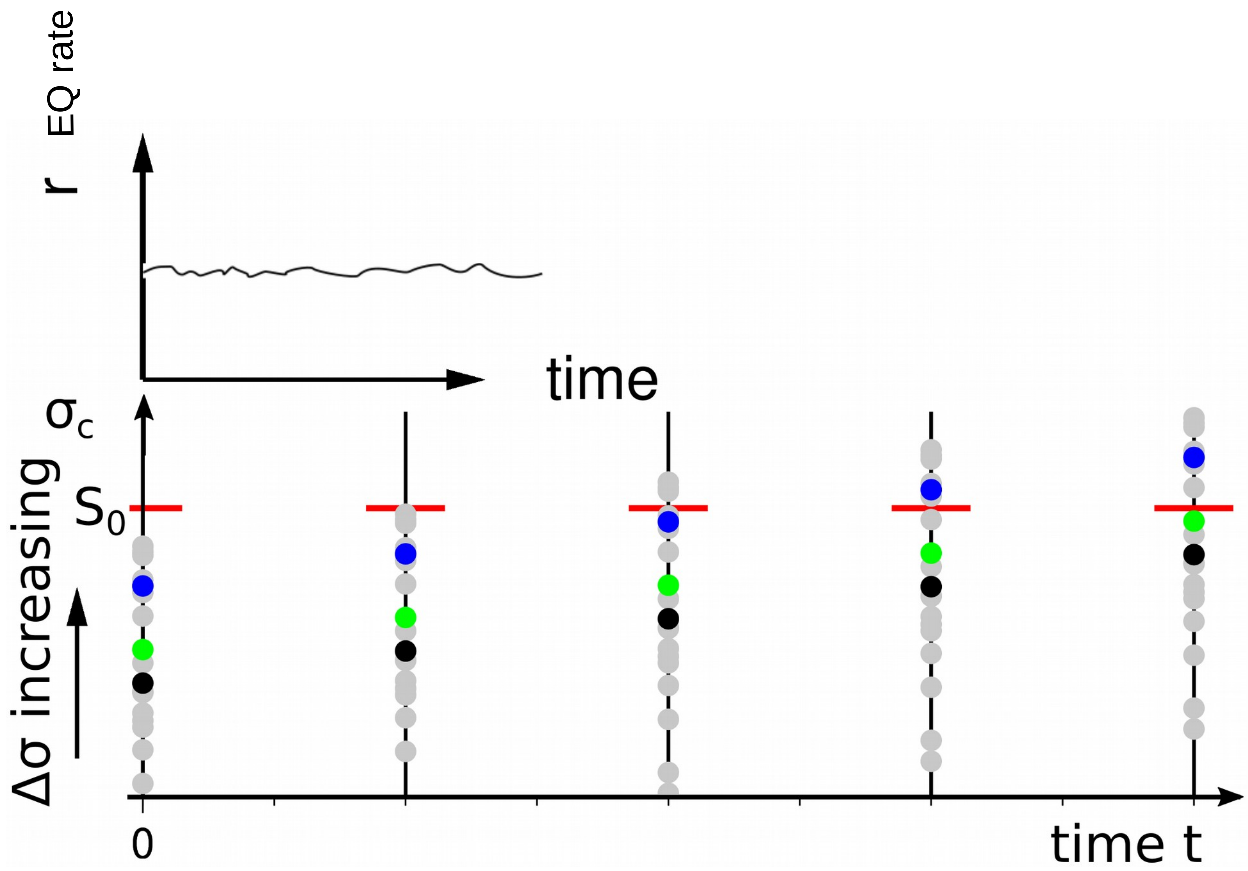
Implementation: concept



1. Random distribution of asperities at different stages of peak stress σ_c
2. Stress loading acting on volume V affects each asperity equally
3. Asperities with σ_c above strength S_0 are triggered and “removed” from distribution (points above red line)

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Implementation: numerical scheme

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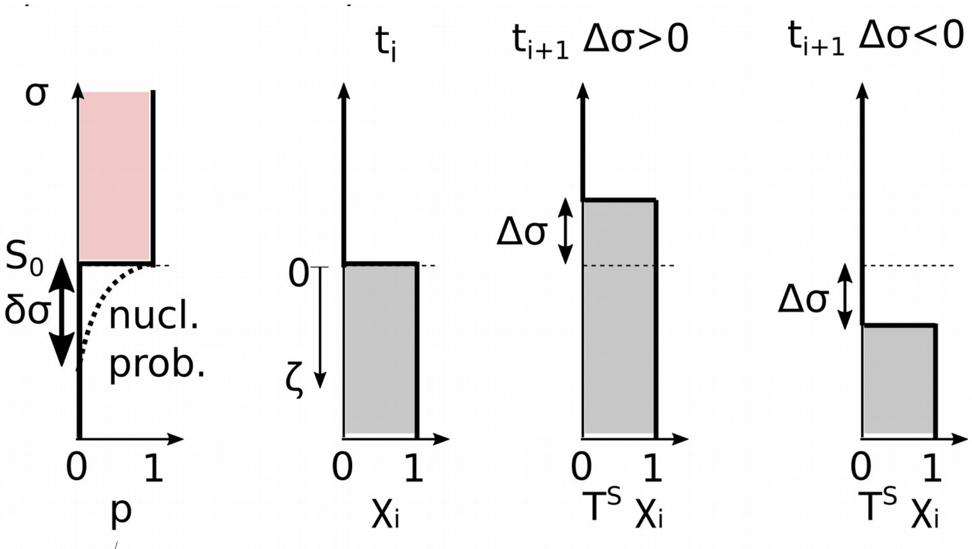


$$p(\sigma) \;=\; H(\sigma - S_0) + H(S_0 - \sigma)e^{-(S_0-\sigma)/\delta\sigma}$$

Numerical scheme:

p: probability to be triggered
(depends only on stress, not on t)

X: distribution of asperities
(function of stress and time t= iΔt)

n: number of EQ triggered in interval Δt

$$t = t_0: \quad p = H(\sigma - S_0), \quad \chi = \chi_0 V \cdot H(S_0 - \sigma)$$

$$n = 0$$

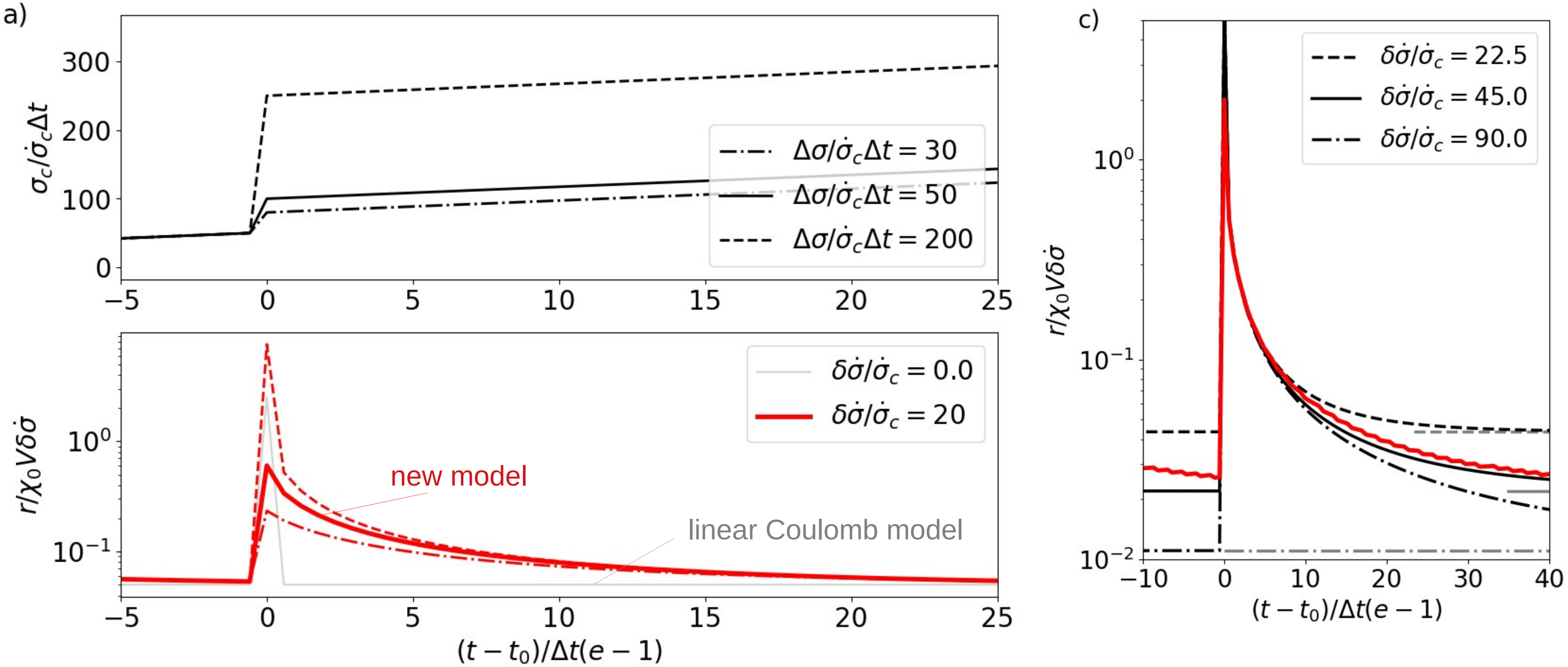
$$t_{i+1} = t_i + \Delta t: \quad \sigma_c(t_{i+1}) = \sigma + \dot{\sigma}_c(t_i)\Delta t = \sigma + \Delta\sigma_c$$

$$\chi^{(\mathrm{tmp})} = \chi_0 V \cdot H\left(S_0 - \sigma_c(t_{i+1})\right) = T^S(\Delta\sigma_c) \cdot \chi_i$$

$$\Delta n = \int_{-\infty}^{\infty} \chi^{(\mathrm{tmp})}(\sigma) \cdot p(\sigma)\, d\sigma$$

$$\chi_{i+1} = \chi^{(\mathrm{tmp})} \cdot (1 - p) \quad \text{(update distribution)},$$

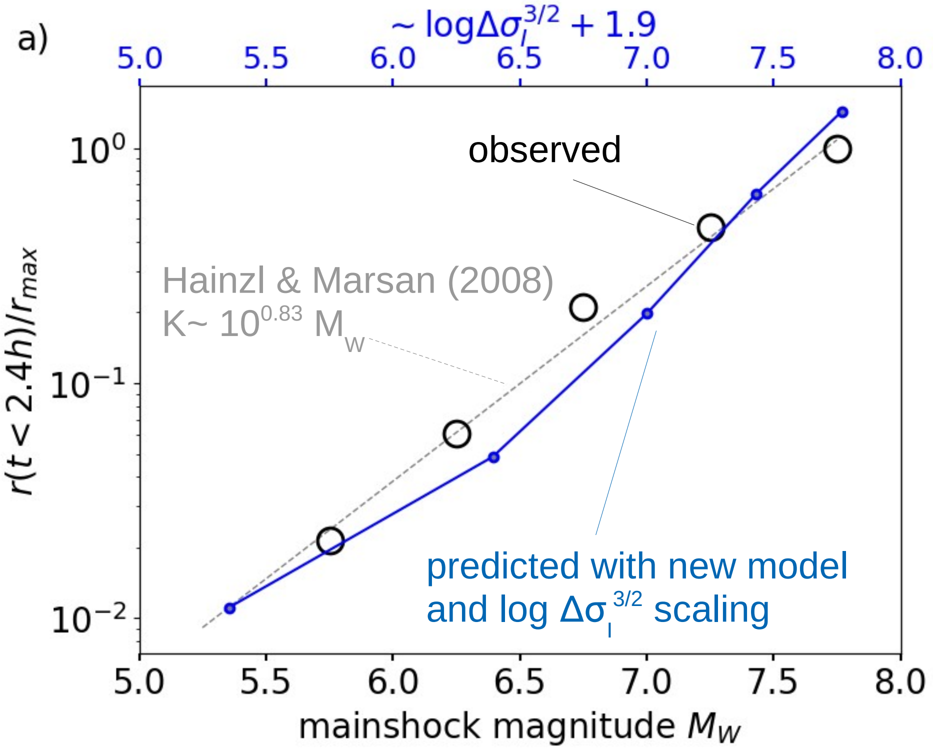
Positive stress step Δσ to simulate aftershock distributions



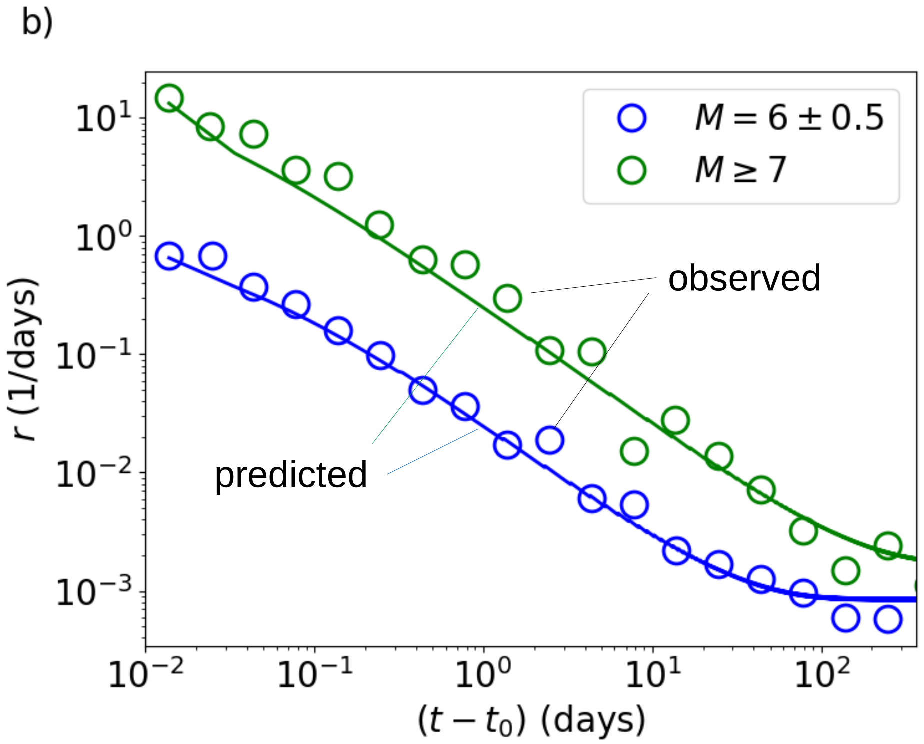
Aftershock rate: $$r(t) - r(\infty) \leq \chi_0 V \cdot \delta\dot{\sigma} \left[e^{-\frac{\dot{\sigma}_c}{\delta\dot{\sigma}\Delta t}\cdot t} + \frac{\Delta\sigma_c}{\delta\dot{\sigma}\Delta t}\delta(t) \right] \cdot \frac{\Delta t}{(\Delta t + t)} \qquad \text{with } t \geq 0$$

Application – global aftershock productivity and decay times

Earthquake productivity ($t-t_0 < 2.4h$) as a function of the main shock magnitude



Aftershock decay rates over lapse time for different main shock intervals



data from Hainzl & Marsan (2008)

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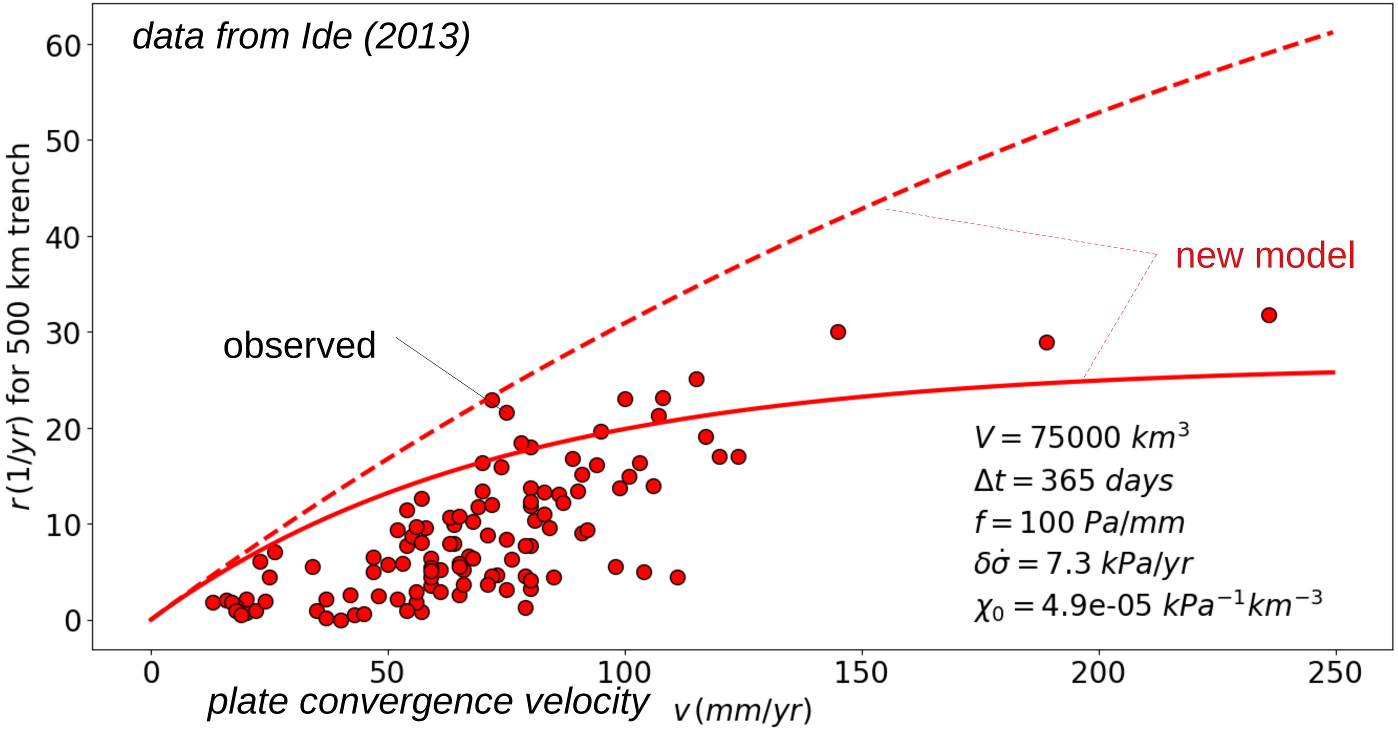
Background seismicity rate at subduction zones



- The background rate depends on 2 parameters
- Increase nonlinear with stressing
- Saturates if $e^{-[...]} = 0$

stress change per time increment

stress depletion depth

Background rate: $$r_\infty = \chi_0 V \cdot \delta\dot{\sigma}\left[1 - e^{-\frac{\dot{\sigma}_c}{\delta\dot{\sigma}}}\right]$$

susceptibility [#/Pa m³]

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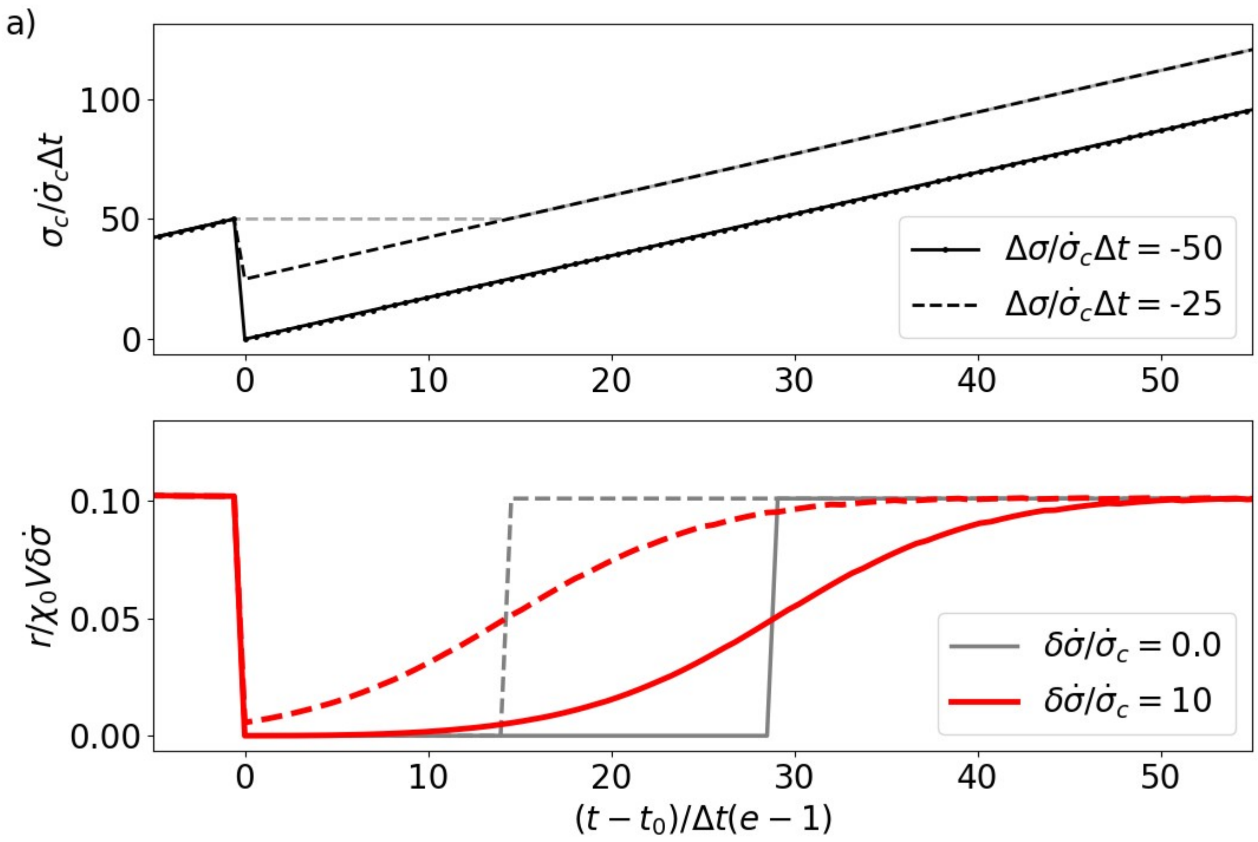
Negative stress step to simulate stress shadow effects



The effect of $\Delta\sigma<0$ is similar to RS:

- r is reduced but > 0
- recovery starts immediately
- the larger $|\Delta\sigma|$ the longer the time needed to recover to r_∞

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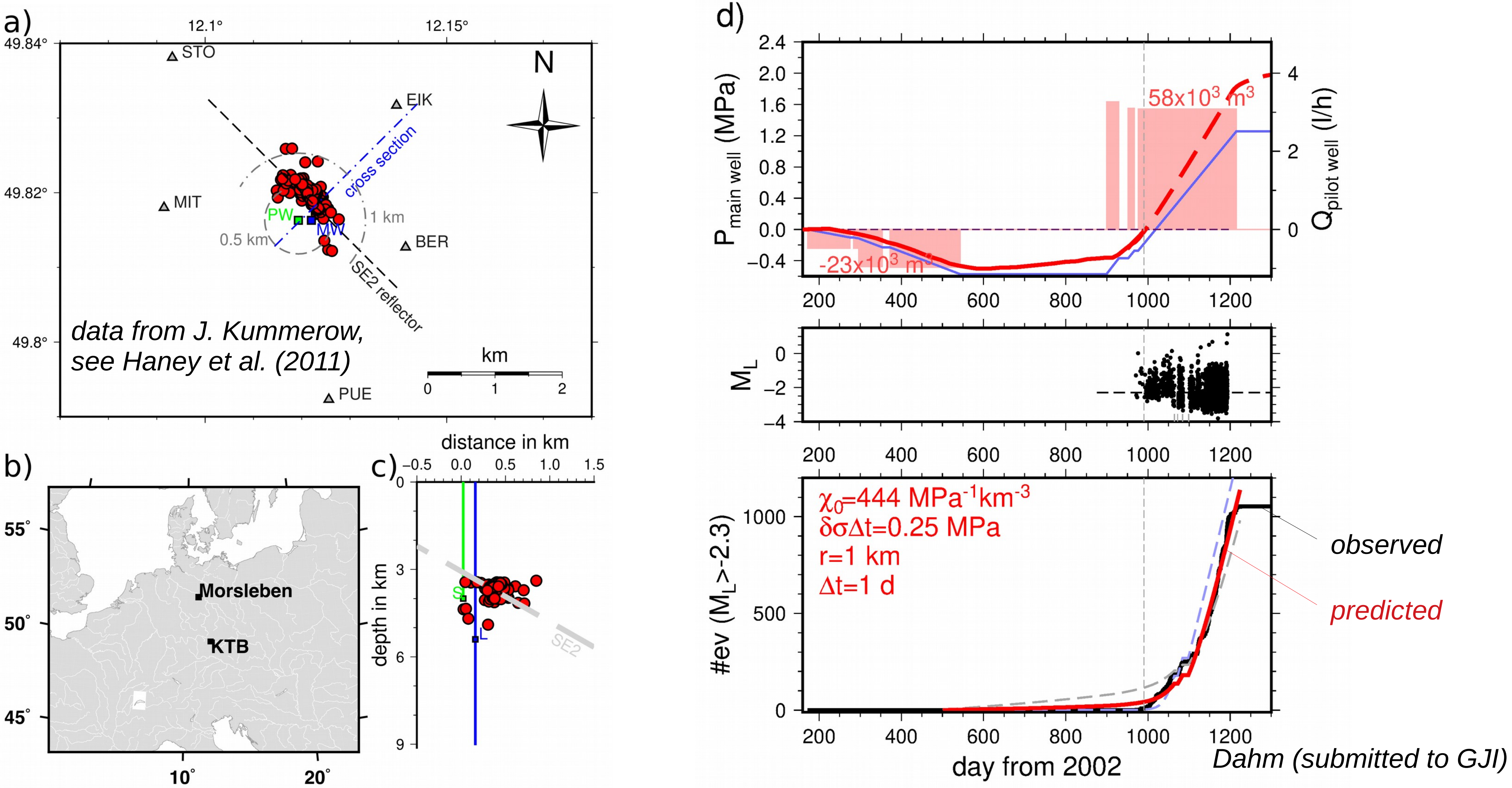
Application KTB: 2 yrs of pumping & injection in 4 km depth



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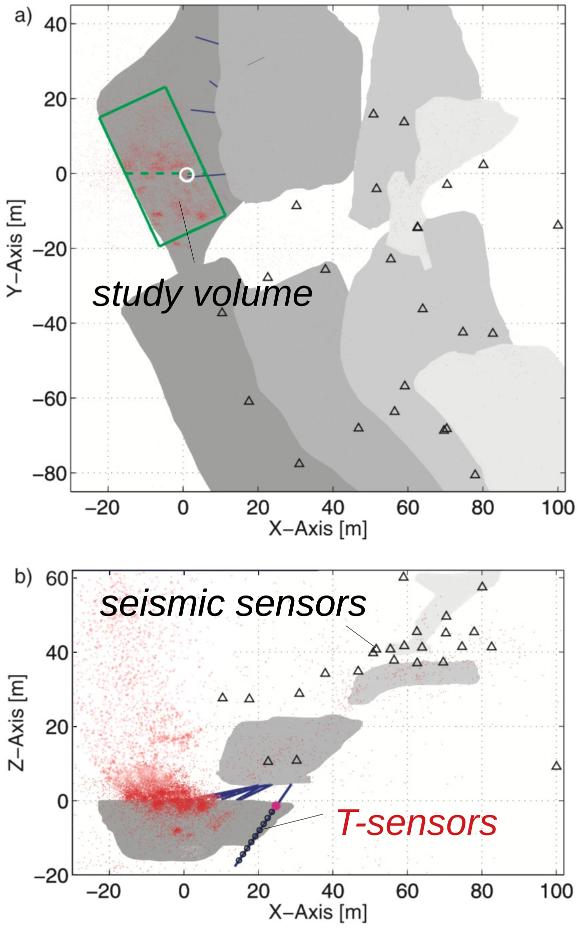
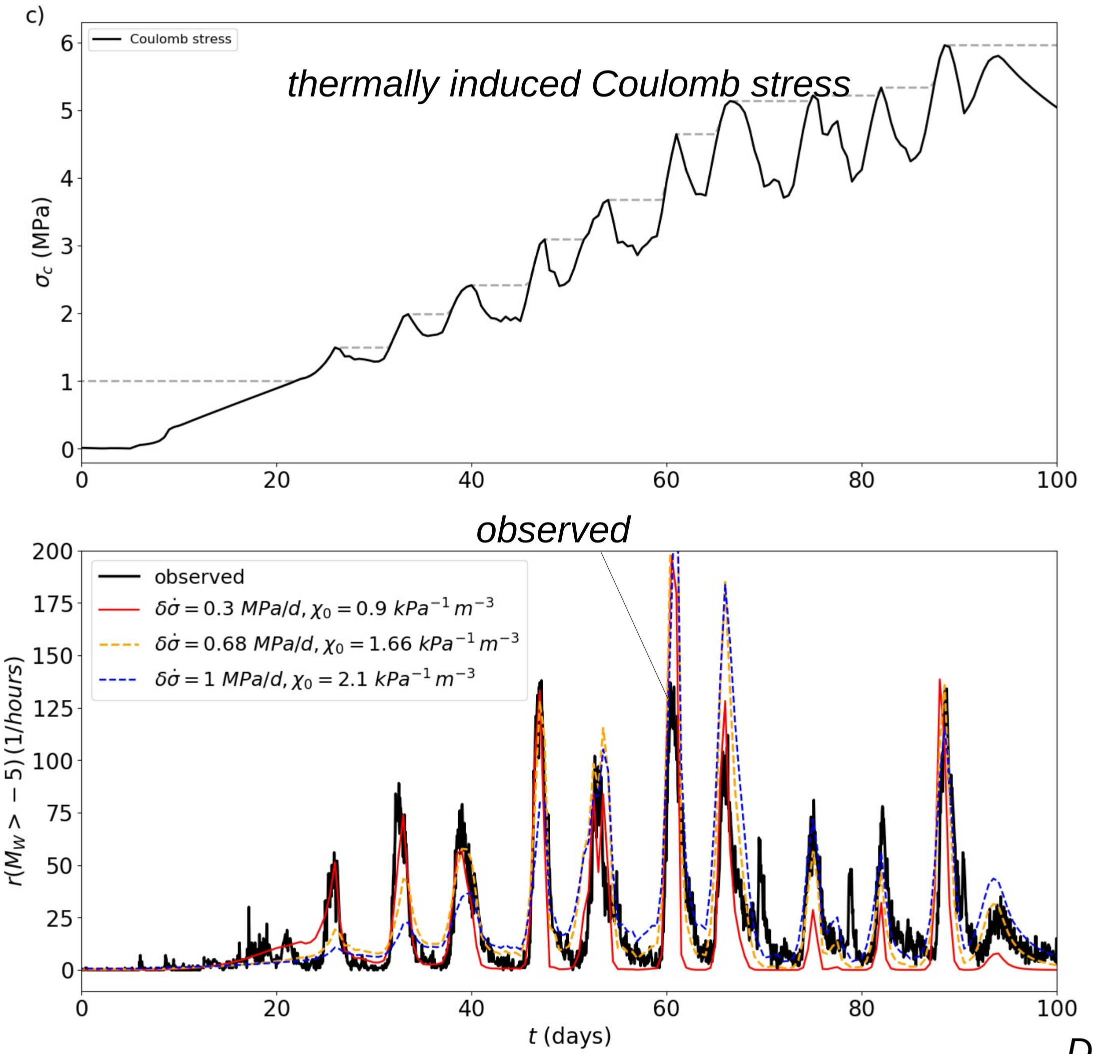
Weekly loading in a salt mine (Morsleben) from cement refilling



from Becker et al. (2010)



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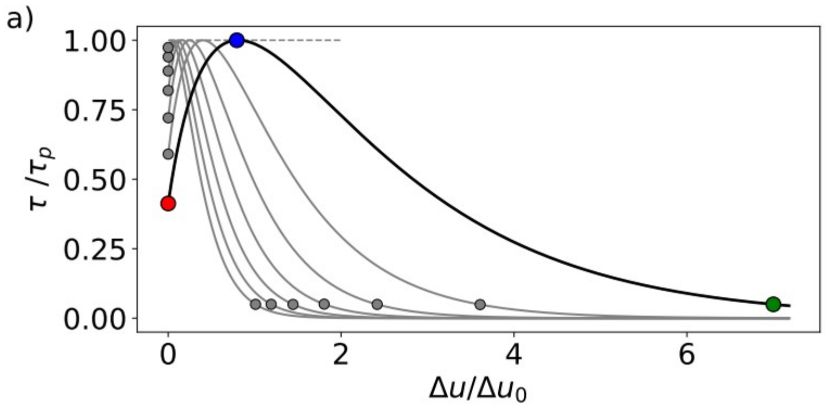
What about frequency magnitude distributions ?



The asperity nucleation model (e.g. Ohnaka, 2013) suggests that the seismic moment M_0 is controlled by the size a_c of the asperity (or breakdown slip Δu).

We assume a fractal distribution of asperities by

$$\rho(a_c) = \frac{1}{a_0}\left[\frac{a_c}{a_0}\right]^{-2}$$

This leads to Gutenberg Richter scaling for steady state background seismicity as:

$$r_\Sigma(M_0, t=\infty) \;=\; \chi_0 V \cdot \left[\frac{M_0}{M_r}\right]^{-2/3} \cdot f \,, \quad \textbf{with } f = \delta\dot\sigma\left[1 - e^{-\dot\sigma_c/\delta\dot\sigma}\right]$$

By analogy, we suggest a scaling of time dependent rates as:

$$\frac{M_0(t)}{M_r} = \left(\frac{\chi_0 V}{\Delta t}\right)^{3/2} \cdot \left[r_\zeta(M_0, t)\right]^{-3/2}\left[e^{-\dot\sigma_c^\star(t)/\delta\dot\sigma}\right]^{3/2}$$

*convolution with step response of duration t**

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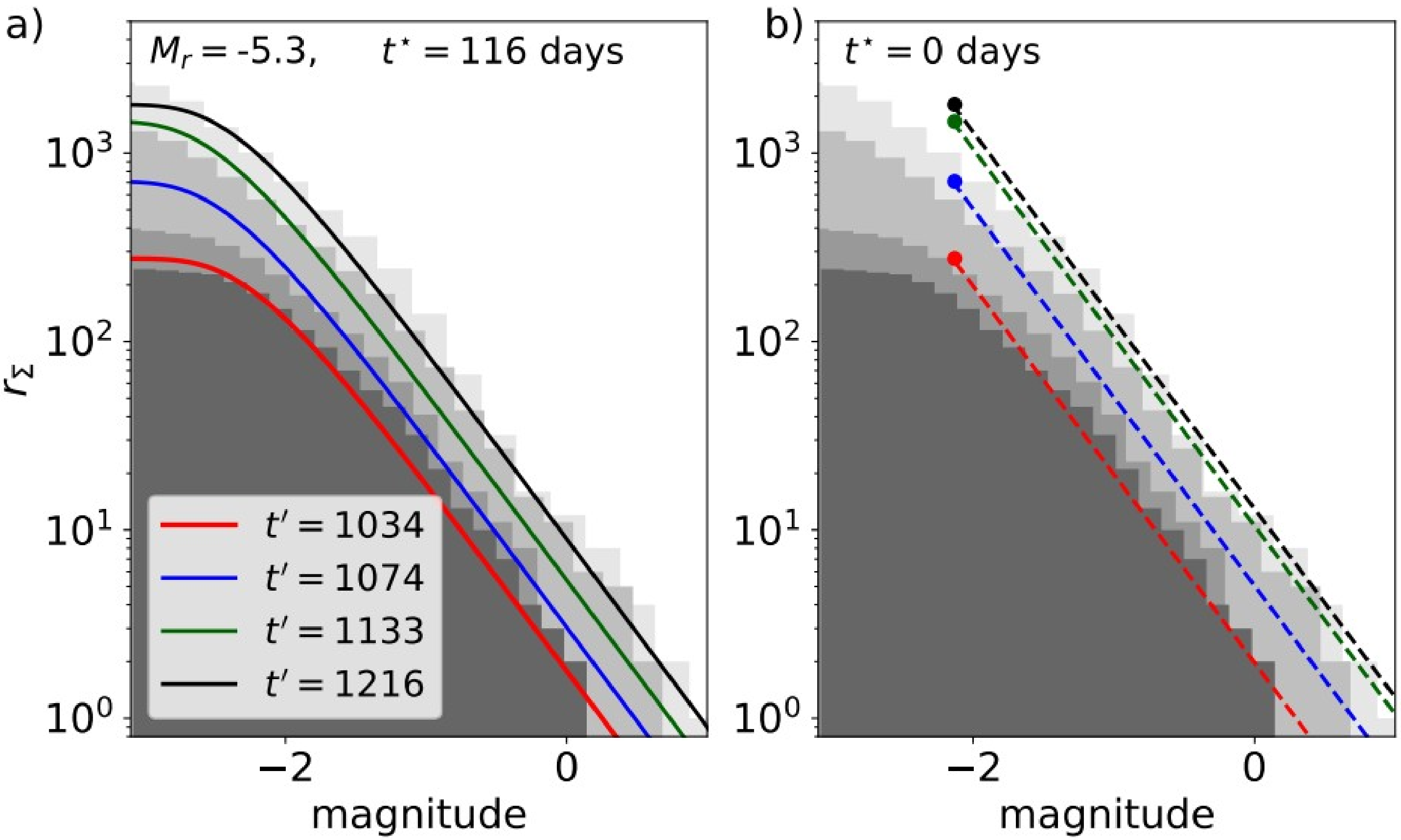
Application to KTB seismicity

Predictions if t* > 0 | Traditional approach if t* = 0



Measured f-M distributions at different times after the onset of seismicity (grayish)

Predicted f-M relations if a memory effect is considered (t*>0) or not considered (t*=0)

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data from J. Kummerow, see Haney et al. (2011)

Parameter comparison

Application	M_c	V $[10^9\, m^3]$	χ_0 $[\frac{1}{MPa\, km^3}]$	$\delta\dot{\sigma}$ $[MPa/a]$	References
Morsleben salt	-5	$2.25 \cdot 10^{-6}$	$0.9 \cdot 10^{12}$	110	Becker et al. (2010)
KTB pump-inject	-2.3	2.25	444	91	Haney et al. (2011) Shapiro et al. (2006)
M6 aftershocks	4.5	$1 \cdot 10^3$	2.2	2	Hainzl & Marsan (2008)
M7 aftershocks	4.5	$3 \cdot 10^4$	2.2	20	

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Summary

- The modified Coulomb failure model considers time-dependent nucleation
- It has only 2 independent parameter to explain seismicity *(but Δt !)*
- The Omori-Utsu relation is explained, but intensity is t-dependent and p=1
- A instantaneous peak of seismicity is predicted at the time of the mainshock
- Stress shadow effects can be modelled
- A small parameter range indicated for very different applications