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RESEARCH FOR GRAND CHALLENGES

M6.7 Turkey, Foto by H. Grosser S2.1 GFZ

Earthquakes close to anthropogenic activities: statistical discrimination without statistics ?

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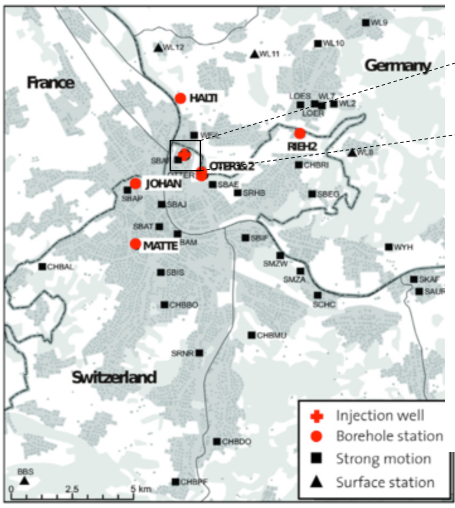
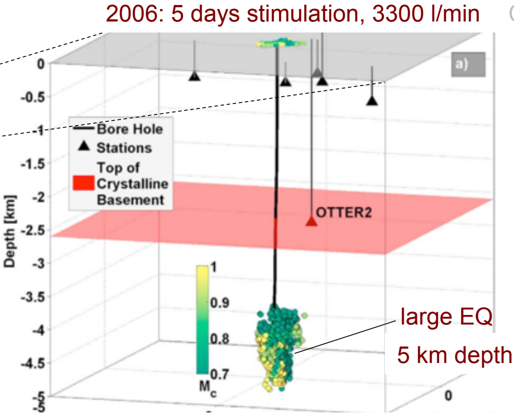
3rd Induced Seismicity Workshop, 5-9 March 2019 Schatzalp, Davos, Switzerland

The 2006 M_L 3.4 Basel induced by deep hot rock stimulation



2006: 5 days stimulation, 3300 l/min



large EQ
5 km depth

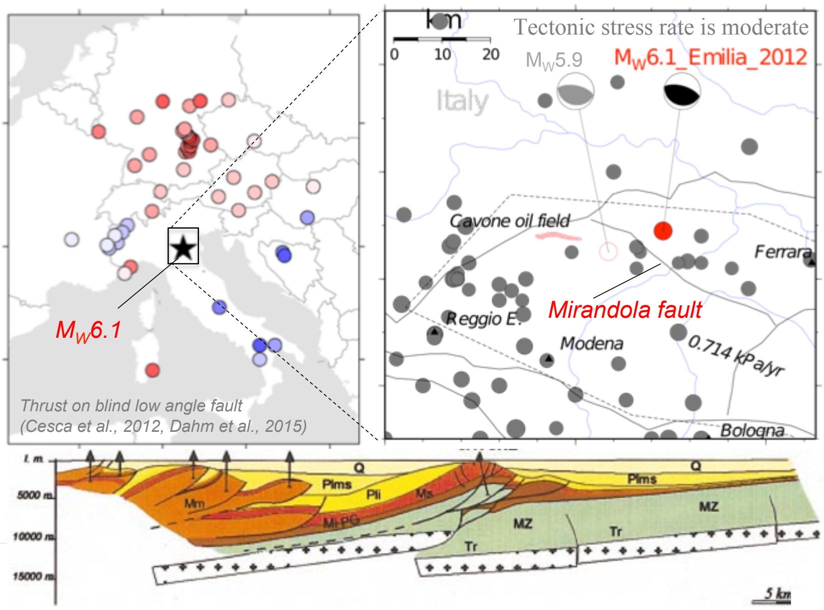
Consequences:

- ✓ project stopped in 2009
- ✓ loss of investment ≈56 Mio CHF

- ✓ seismic cloud growing in planar structure
- ✓ $M_L \leq 3.5$ mostly during shut-in
- ✓ EQ are fluid-triggered by P_{trig}>95%

e.g. Bachmann et al. (2012)

The 2012 M_W 6.1 Emilia EQ close to the Cavone oil field



- ✓ Blind thrust (7km) depth within Po basin under moderate stress rate
- ✓ ≈20km from Cavone oil field (3km, ΔP≈1MPa, 30-200E3m^3 over 32yr)
- ✓ Several commissions studied possibility that EQ can be triggered
- ✓ Not triggered: P_{trig}<1%

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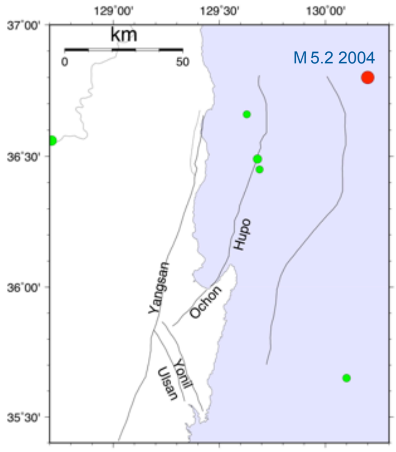
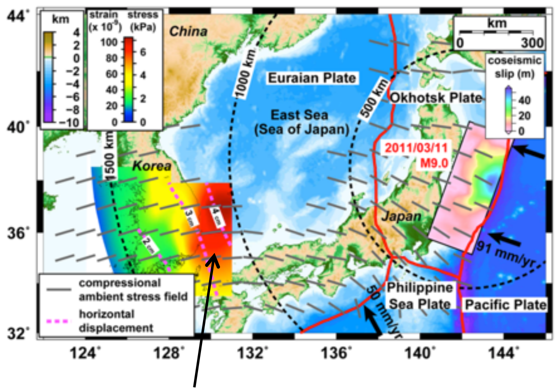
S-Korea – far-distance stress shadow from 2011 Tohoku M_W 9 ?

Seismicity Mar 2003 - Mar 2011



Is there a clock advance effect after 2011?

Hong et al. (2018)



region of increased stress

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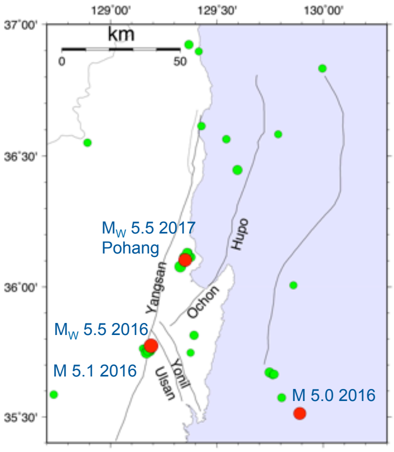
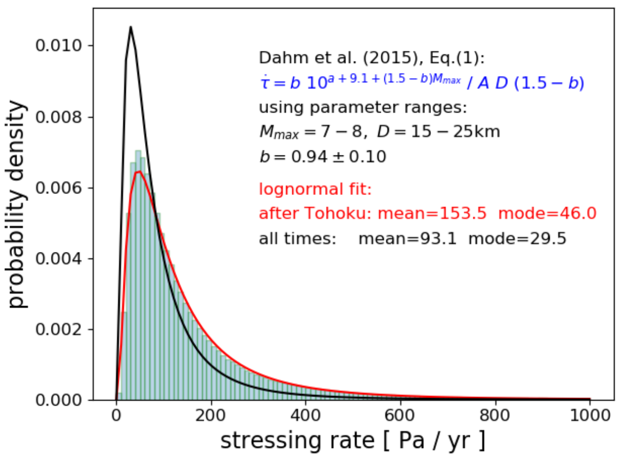
S-Korea – far-distance stress shadow from 2011 Tohoku M_W 9?

Seismicity Mar 2011 - Mar 2018



... four M>5 EQ in 2016 - 2017

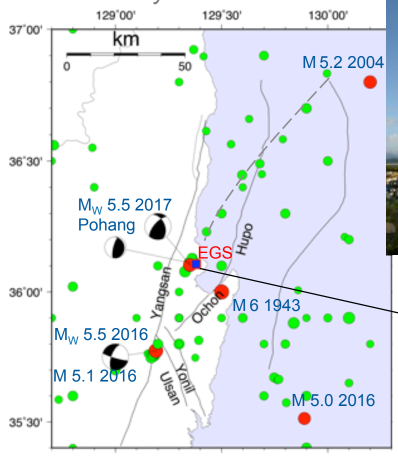
Stress rate estimated from seismic catalog before and after Tohoku



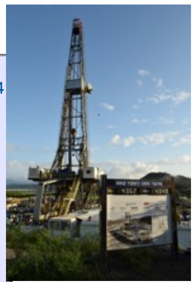
Kostrov (1975) $\dot{\tau} = \frac{\langle M_0 \rangle \cdot n/yr}{V}$

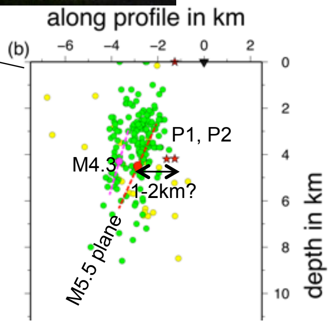
Pohang 2017 M_W 5.5 – induced, triggered or natural ?

Seismicity M>3 1903-2018

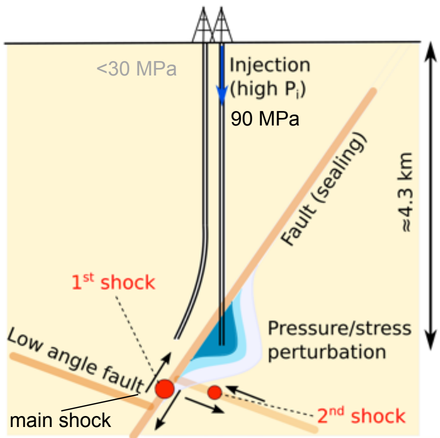


Grigoli et al., 2018





- Hypocenter close to EGS injections
- Injection volume small compared to M
- Injection stopped 58 days before EQ



Pohang 2017 – a key test for attribution models

① Tectonic stress rate increased after the Tohoku 2011

② Pohang EQ is shallow and close to injection operation (but “too large” and 58 days after shut-in)

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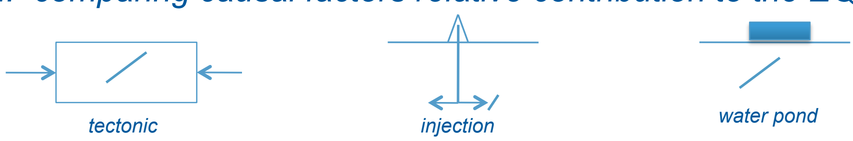
Discrimination: approaches

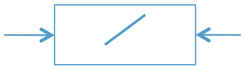
Attribution: comparing causal factors relative contribution to the EQ triggering



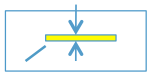
- **Seismic clouds**: is seismicity correlating with (human) forcing ?
- **Single (extreme) event**:
  - is it very close to anthropogenic activity ?
  - are there non-tectonic earthquake characteristics ?
    (origin time at noon, collapse-type, very shallow, ...
  - *probabilistic attribution* of relative causal factors to extreme EQ

Extreme event probabilistic attribution

Causal factors:(1) tectonic Coulomb stress rate $d\sigma_c/dt$



(2) anthropogenic stressing



Probabilistic attribution (adapted from climate research)**:**

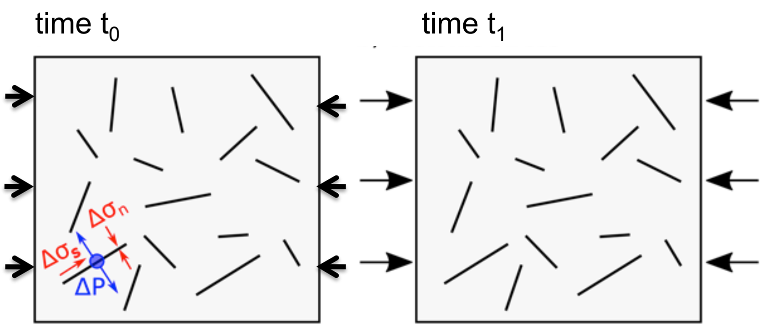
a) physics-based seismicity model to assess **relative contribution**

(1) theoretical EQ rate r^T from tectonic stressing

(2) theoretical EQ rate r^I from human action

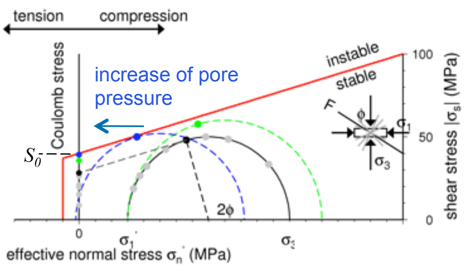
b) assigning **statistical confidence** that the EQ was human-triggered

Physics-based seismicity model



(1) static threshold
(Coulomb failure)

(2) frictional instability,
t-dependent nucleation
(Rate & state model)



Coulomb stress
(fault orientation, slip)

$$\sigma_c = |\sigma_s| + \mu(\sigma_n + P_p) \leq S_0$$

rock matrix contribution   pressure contribution

Discrimination method – theory

Dahm et al., 2015, JGR

We use rate & state and input Aσ and $\Delta\sigma_C$ to calculate:

- tectonic background rate r^T : e.g. from historical seismicity
- human related rate $r^I = r^I(x,t,\Theta)$: from "human forcing" model

The triggered is:

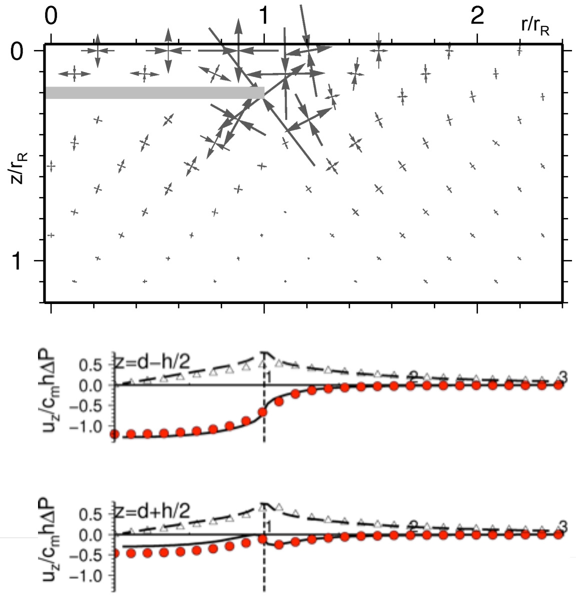
$$p(\text{triggered} \mid \vec{x},\Theta) = \frac{r^I}{r^I + r^T} = \frac{1}{1+\frac{r^T}{r^I}(\vec{x},\Theta)}$$

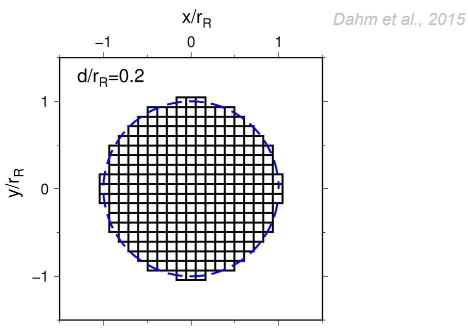
injection-related EQ rate $r^I = r - r^T$

tectonic EQ rate

location & model parameter

Example: reservoir depletion - BEM calculation, nuclei of strain





model parameter:

- pore pressure drop ΔP
- elastic parameter c_m
- field thickness h

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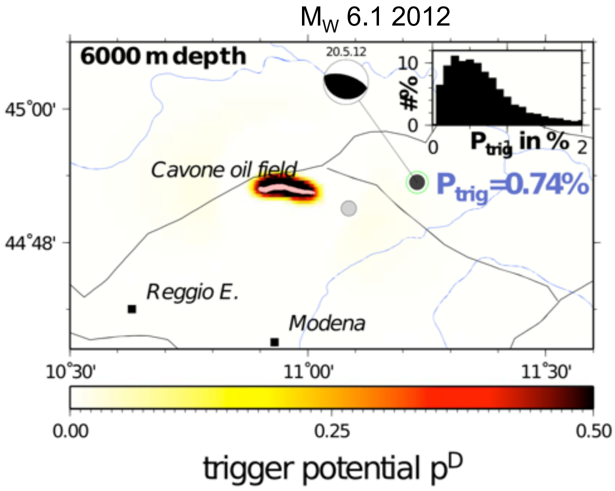
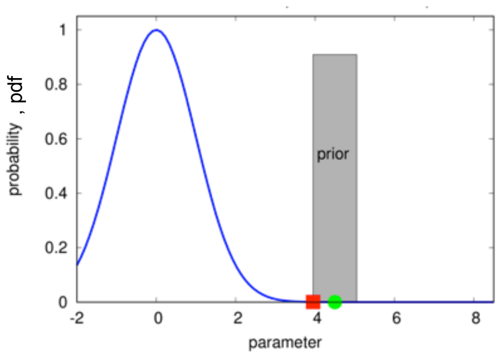
Case study: Emilia oil field

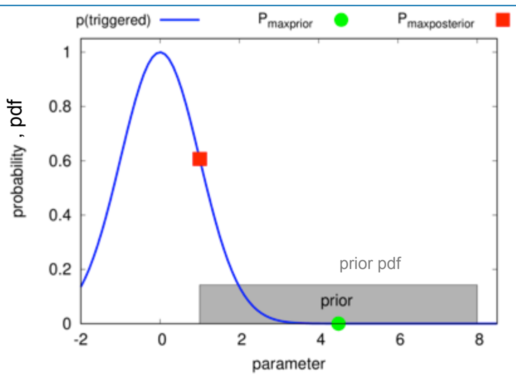


Dahm et al., 2015

P_{trig} = < 1%

How to handle uncertainties – two questions ?

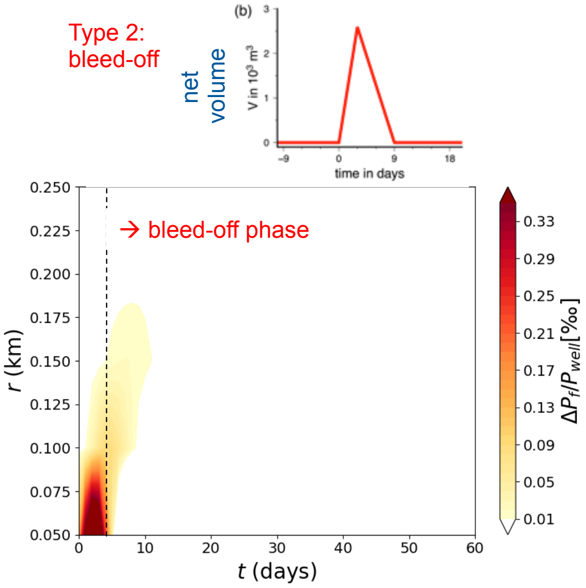


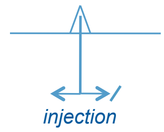


(1) What is the most likely p_{trig} (weighted integral – or p at mode of prior) ?
→ $P_{maxprior}$

(2) Can we exclude the EQ was triggered (maximum of posterior) ?
→ $P_{maxposterior}$ *(expert commissions evaluation ?)*

Example: short-term water injection – ΔP_f diffusion





- ✓ ΔP_f perturbation is finite but shows after-growth
- ✓ diffusion time is controlled by hydraulic diffusivity

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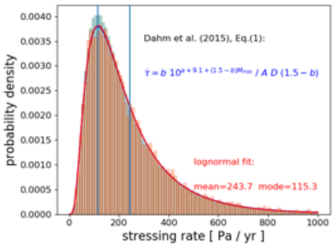
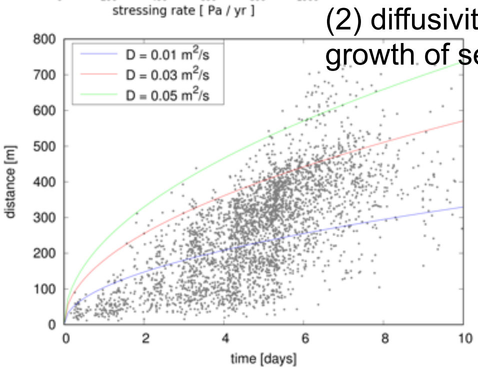
Case study: 5 days stimulation beneath Basel



(1) tectonic stressing rate

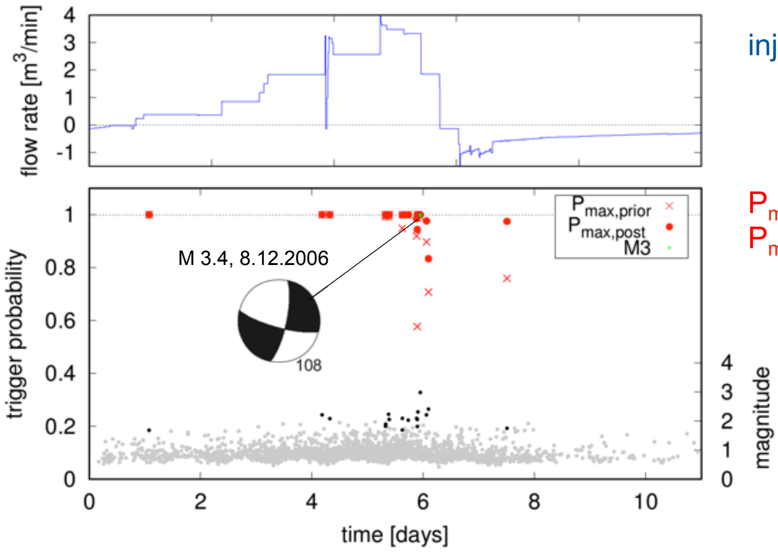
(2) diffusivity from growth of seismic cloud



(3) assumed parameter uncertainties

Parameter	Mode	$[min, max]$, $\pm std$	D
EQ relative location SED catalogue			
x, z, z in $[km]$	SED catalog	± 0.1	n
EQ mechanism			
see Deichmann & Giardini (2009)		$\pm 10°$	n
Rock and fluid parameter			
Frict. coeff. f	0.68	[0.5, 0.85]	u
Biot-Willies α	0.5	[0.1, 0.9]	u
Skempton α	0.5	[0.1, 0.9]	u
Poisson ν (drained)	0.245	[0.20, 0.29]	u
Poisson ν_u (undr)	0.3	[0.29, 0.31]	u
Rigidity $\mathcal{N}$ $[GPa]$	17.5	[5,30]	u
Fluid viscosity η $[Pa\ s]$	$3.5 \cdot 10^{-4}$	$[3,4]{\cdot}10^{-4}$	u
Permeability κ $[mD]$	0.1	[0.05, 0.5] 90% conf.	lg
Diffusivity c $[m^2/s]$	0.03	s$\pm$0.01	
Seismicity model parameter			
frict. value $A\sigma$ $[MPa]$	0.03	[0.01, 0.05]	u
tect. stress $\dot{\tau}$ $[Pa/yr]$	186.7	see figure	lg

Trigger probabilities for M>2 earthquakes



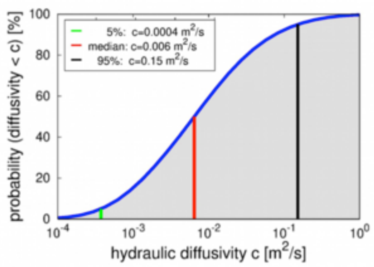
injection flow rate

$P_{max,prior}$ > 0.8 for all M>2

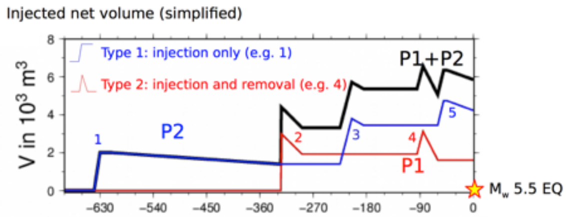
$P_{max,posterior}$ ≈ $P_{maxprior}$ if t<5.6d

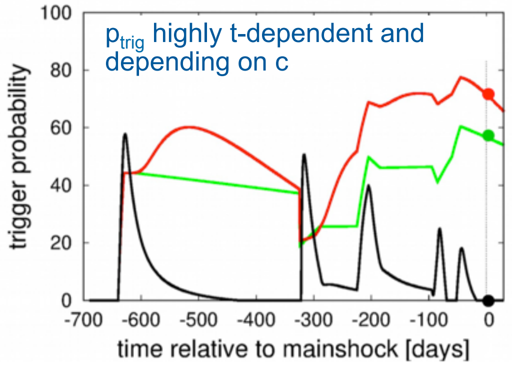
seismicity

Example: the late M_W 5.5 Pohang earthquake



f = 0.65 # friction coefficient
Strike=223 # [degree]
Dip = 70
Rake = 127
α = 0.4 # Biot-Willies coefficient
ν = 0.25 # drained Poisson ratio
ν_u= 0.30 # undrained Poisson ratio
N = 20 # Shear modulus [GPa]





Summary of case studies

Event	$P_{maxprior}$	$P_{maxposterior}$	Reference
	- quasi-static reservoir depletion -		
M_W 4.3 2001 Ekofisk	>99%	-	*Dahm et al. (2015)*
M_W 4.4 2004 Rotenburg	≈70%	-	*Dahm et al. (2015)*
M_W 6.1 2012 Emilia	<1%	-	*Dahm et al. (2015)*
	- time-dependent "injection" -		
M_W 6.1 1976 Tjörnes fracture zone	>90%	-	*Passarelli et al. (2011)*
M_W 3.4 2006 Basel	99%	>95%	
M_W 5.5 2017 Pohang			*in prep.*

Probabilistic attribution approach is flexible to be applied to different problems

Conclusion

✓ Expert panel reports usually assess the $P_{maxposterior}$
(assess whether triggering can be excluded assuming it was triggered)

✓ The likelihood to be triggered (mode, $P_{maxprior}$) is smaller than $P_{maxposterior}$

✓ We suggest to report both measures, as purely statistical bounds are more difficult to communicate