# The weal and woe of induced seismicity

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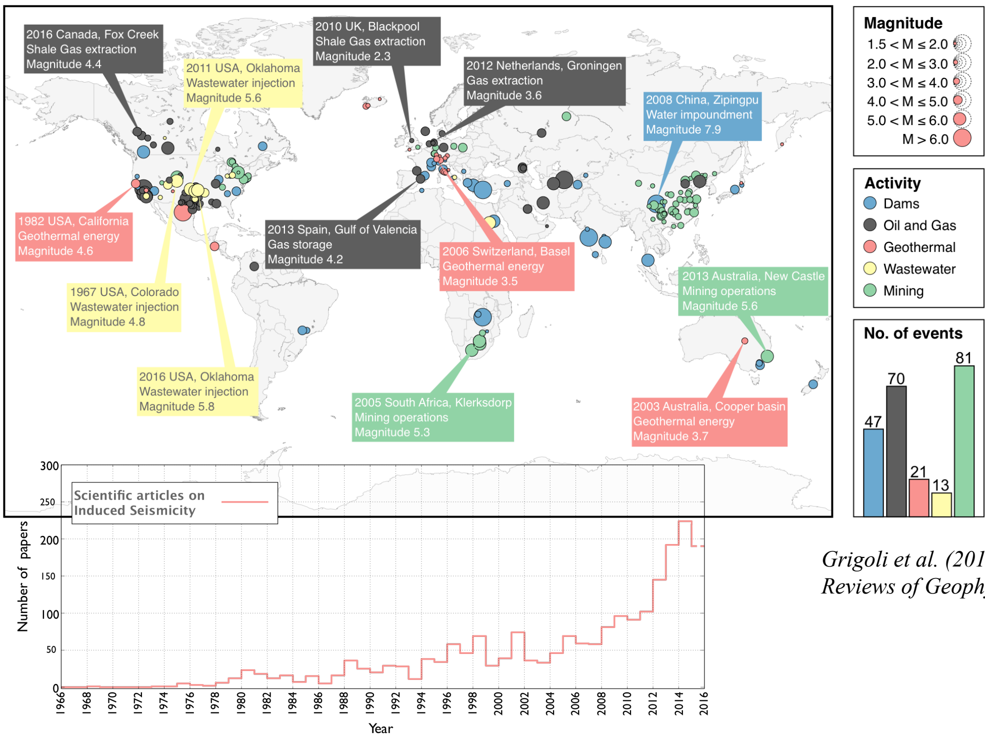
## Global aspects of induced and triggered earthquakes




*Grigoli et al. (2017)*
*Reviews of Geophysics*

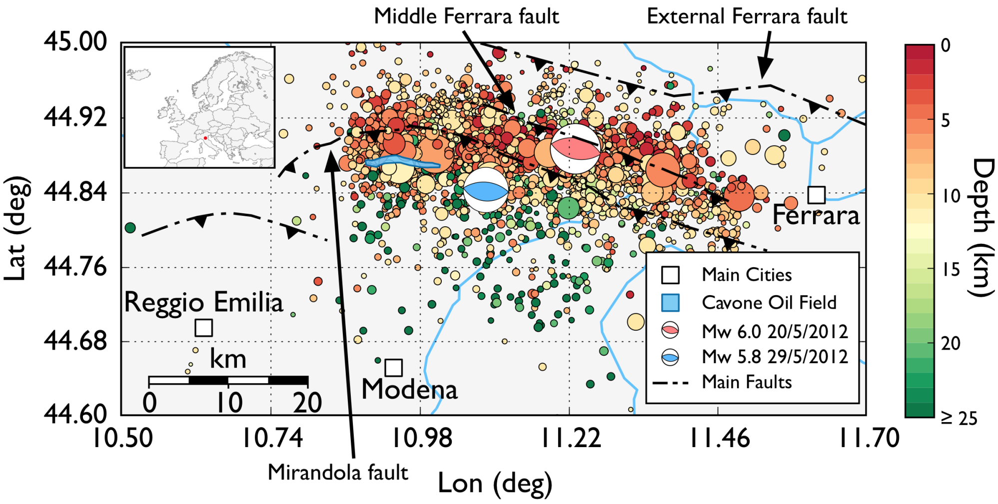
## The woe – large induced earthquakes lead to damage

20.05.2012 $M_W$=6.1 Emilia Romana / Italy



22.02.53 $M_L$=5, $I_0$=VII-VIII, Widdershausen / DE

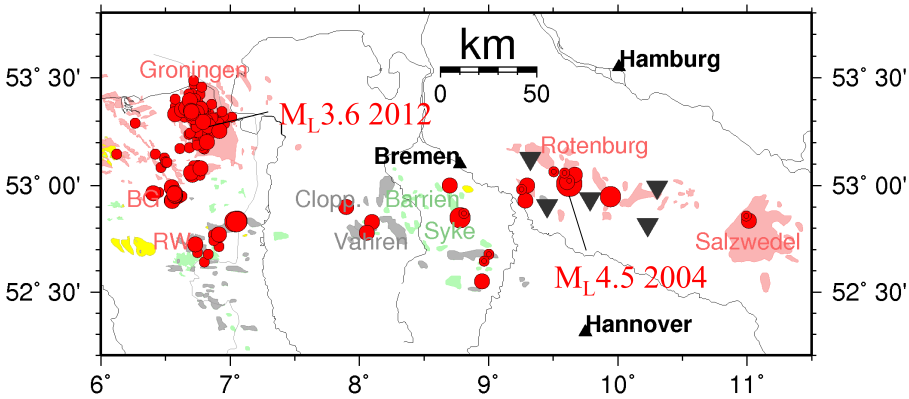
## Mw 6.0 Emilia earthquakes: were they triggered by oil field depletion?




27 dead (7 on 20 May and 20 on 29 May), ≈400 injured
up to 45,000 homeless

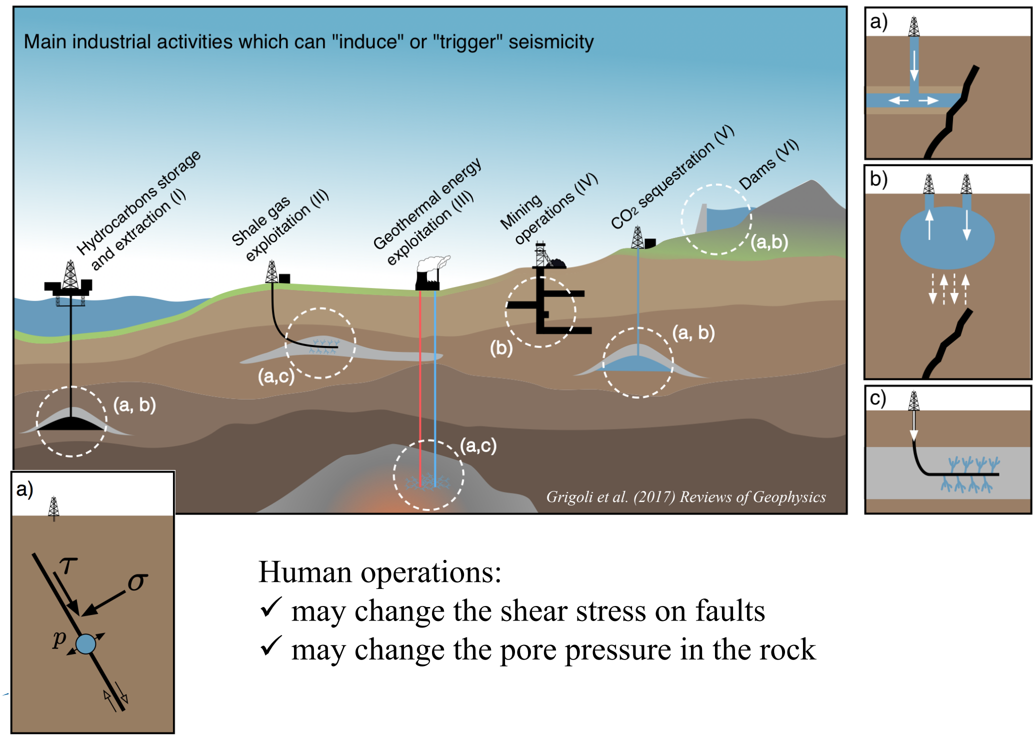
*Grigoli et al. (2017)*

## Earthquakes in North European gas fields during production




Consequences:
- first EQ occur only after ≈10-15 yr of production
- Ml 4.5 2004 Rotenburg - EQ initiated new "seismic survey" in Niedersachsen
- Ml 3.6 2012 Groningen - EQ led to reduction of gas production (16.6 Mrd $m^3$, ≈20%)
  - Huge investment for monitoring (60 borehole stations) and regulations (≈1.18 Mrd €)

## Mechanism of induced seismicity




Human operations:
- ✓ may change the shear stress on faults
- ✓ may change the pore pressure in the rock

## Challenges and approaches/schools

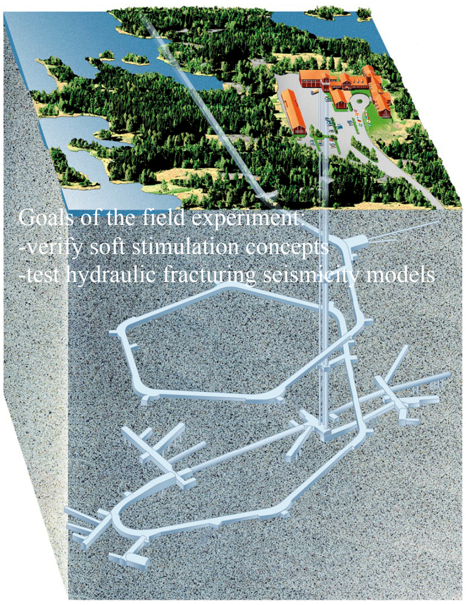
1. Forecast the rate of seismicity for planned human action
2. Forecast the expected magnitudes for planned action
3. How to reduce/limit the seismic hazard and risk

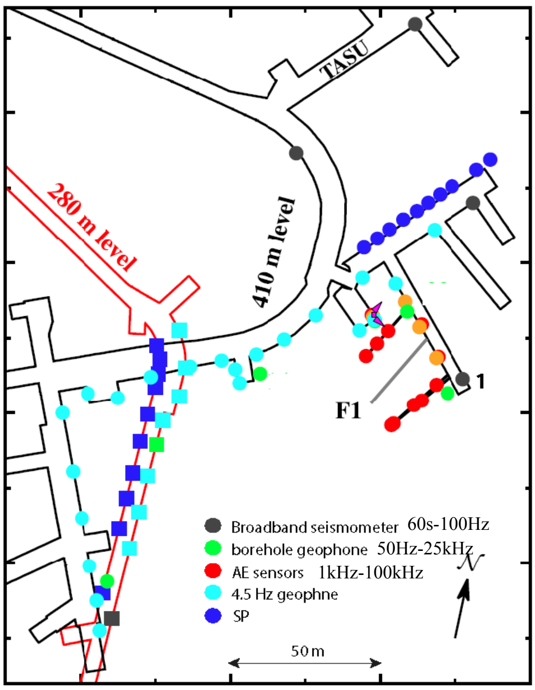
| Based on seismicity observations | Based on physical relations and lab studies |
| --- | --- |
| (1) ETAS statistical model,<br>(2) Seismogenic index,<br>(3) f-M distributions | (1) Coulomb failure threshold model<br>(2) Rate and state frictional instability<br>(3) Brownian passage time model |
| Need previous seismicity to predict future behaviour | Need model parameter to predict future behaviour |
| Only predict activity increase | Predict activity increase and decrease (stress shadow effects) |
| Expected maximal magnitude not handled | Expected maximal magnitude not handled |



## Example: hydrofracturing experiments in massive granite

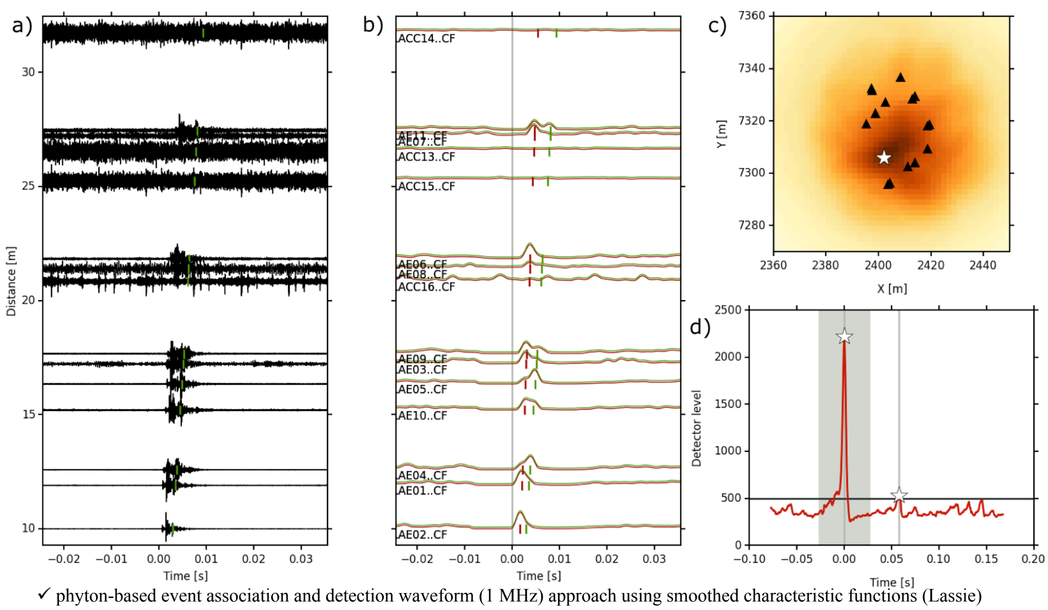
*Zang et al. (2017)*



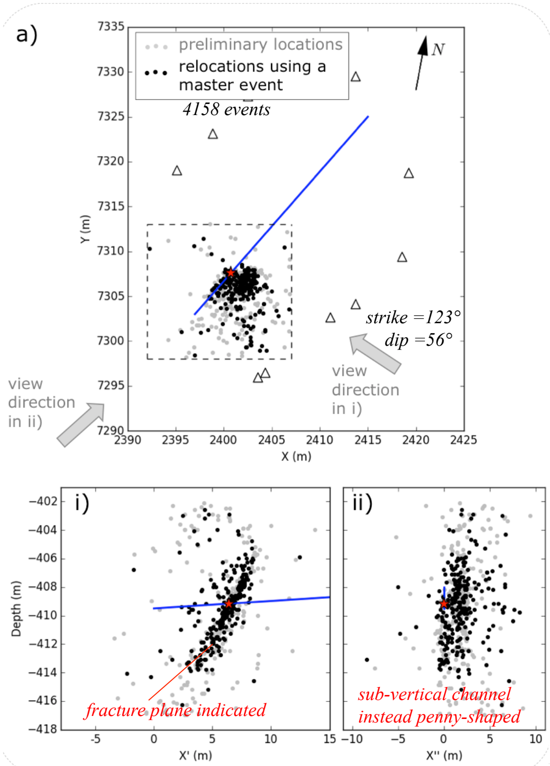



# Earthquake location procedure

*Lopez-Comino et al., submitted*

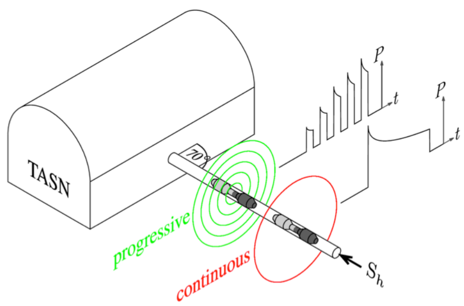


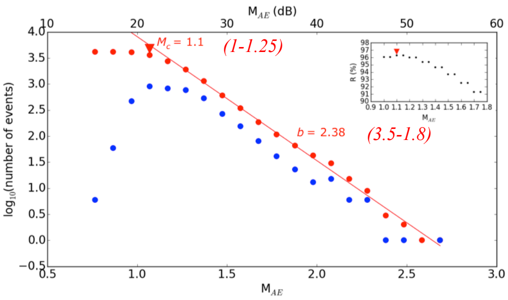

- ✓ phyton-based event association and detection waveform (1 MHz) approach using smoothed characteristic functions (Lassie)
- ✓ stacking of delayed P and S waves provides rough location and 'strength'
- ✓ beam pattern matching to discriminate noise events
- ✓ automatic master event location based on waveform coherences (Grigoli et al., 2014, 2016)



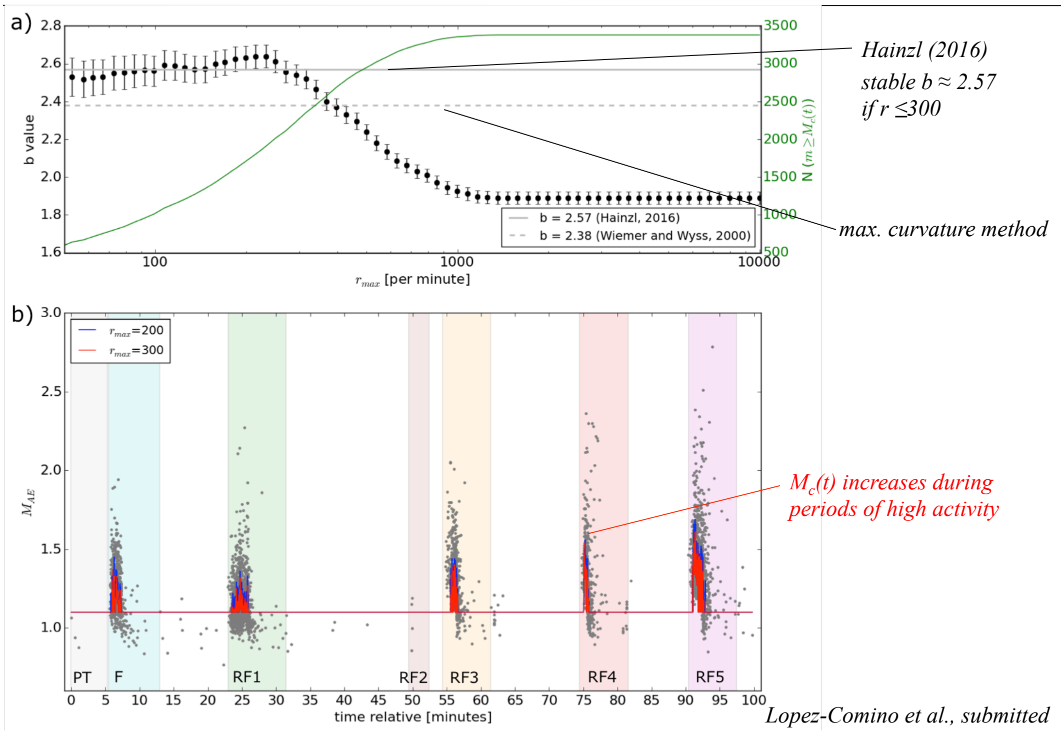

# Location and f-M distribution

*Lopez-Comino et al., submitted*

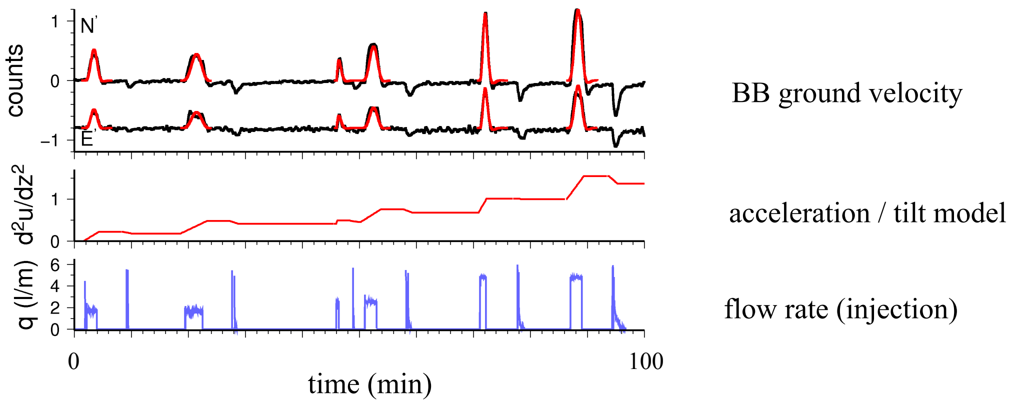


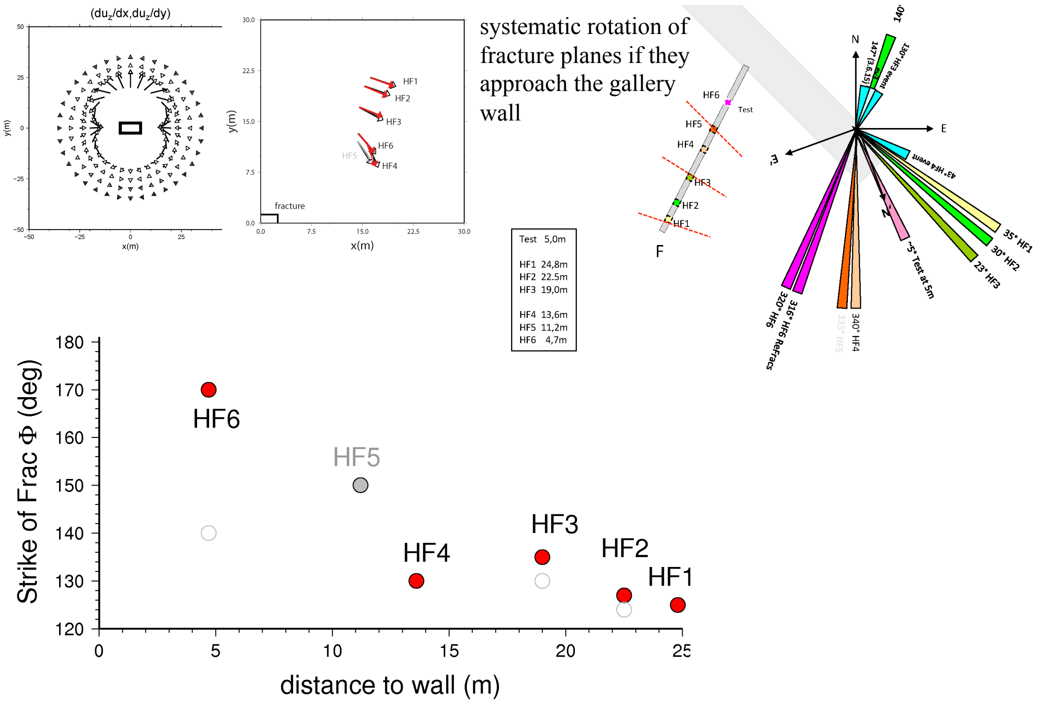
## Rate dependent magnitude of completeness and b-values



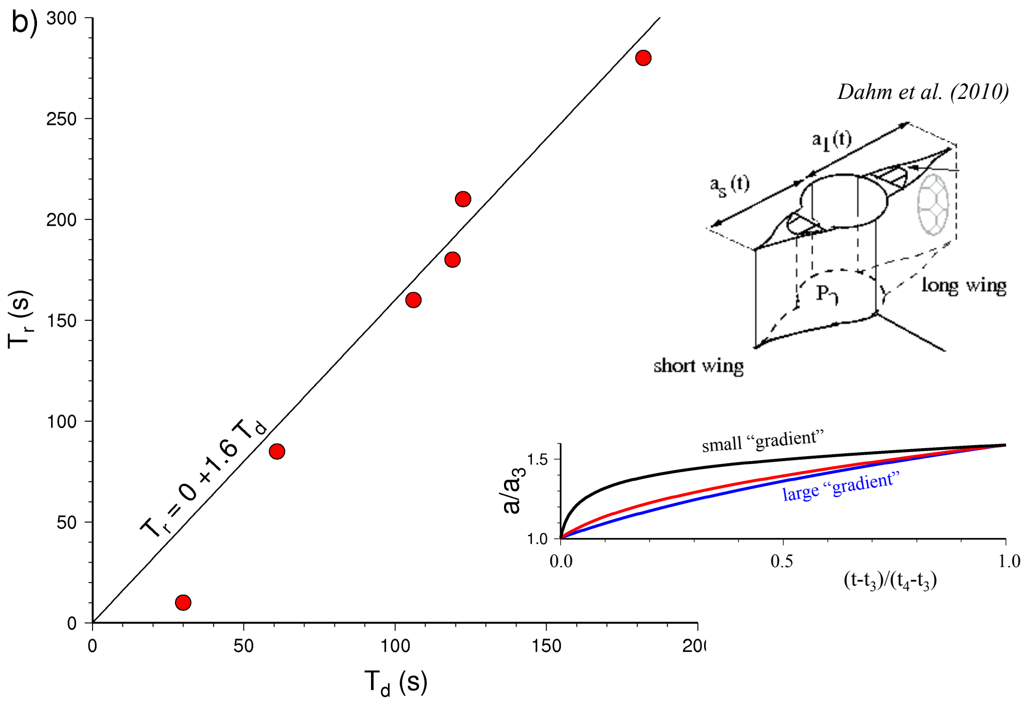

## Fluid injection is observed by tilt-induced signals on BB sensor



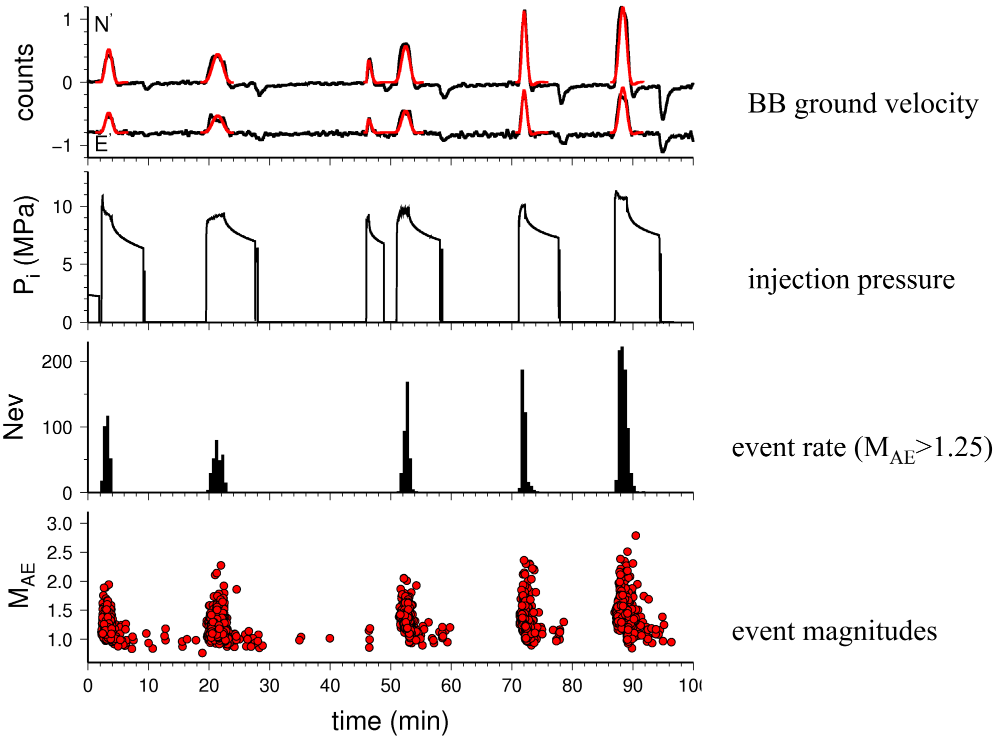
## Tilt-induced BB signals are used to infer orientation of fractures




## Duration of fracture opening ($T_r$) scales with duration of injection ($T_d$)

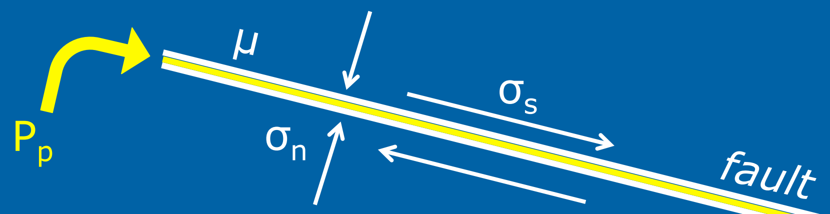


## Is seismicity controlled by pressure or by deformation ?




## How are earthquakes triggered: Coulomb failure criterion

Rupture is
- driven by acting shear stress
- resisted by cohesive strength and effective frictional force

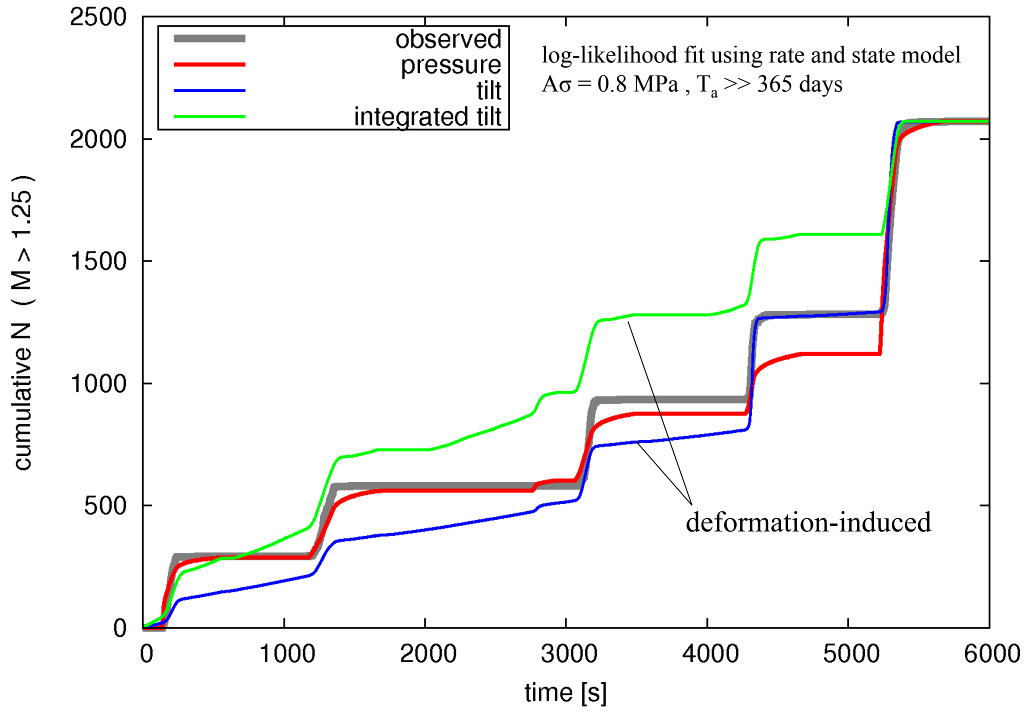



Stable if:

$$|\sigma_s| \leq S_0 - \mu_i(\sigma_n + P_p)$$

shear stress — cohesive strength — internal friction — normal stress — pore pressure — effective stress

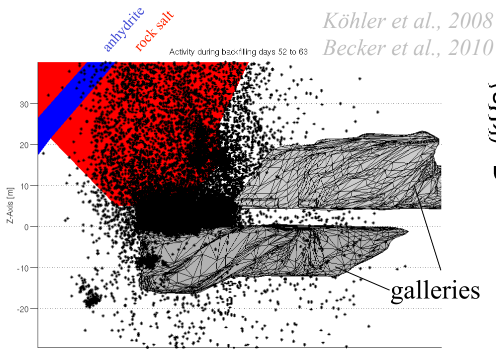
## AE event rate is controlled by pore pressure increase



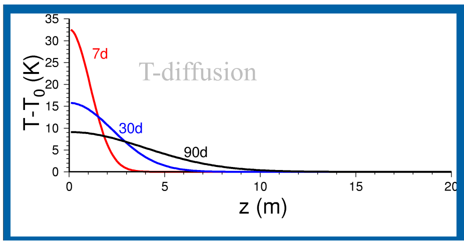

## Case study: seismicity from cyclic stress loading in a salt mine

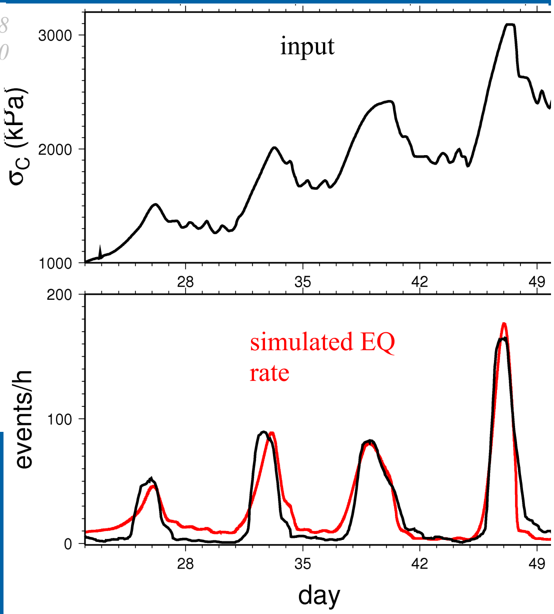
### microearthquakes above gallery

### cyclic Coulomb stress change



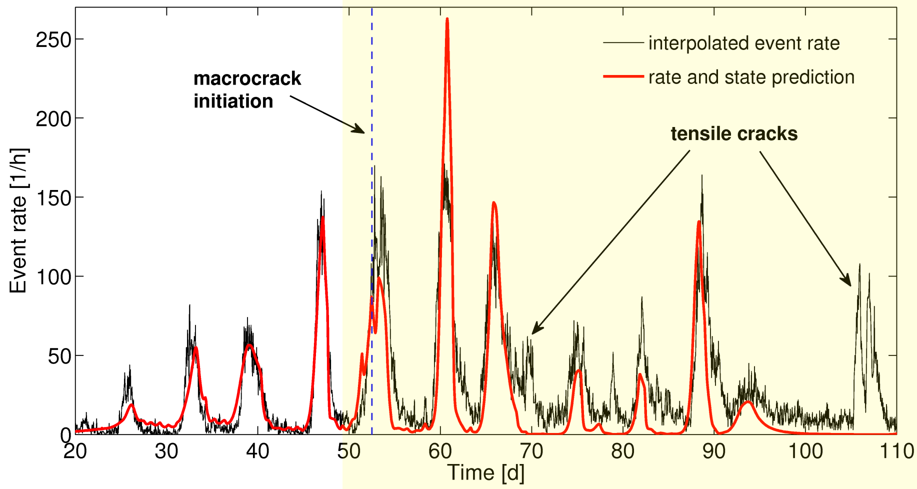

millions of events have been located during 1 year!



## Salt mine: event rate is controlled by thermally induced stress

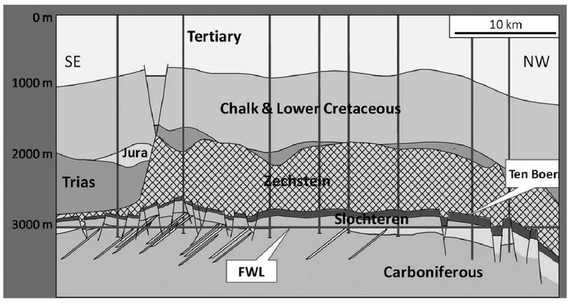
LogLikelihood fit: $A\sigma$=0.2MPa, $T_a$=2241 days, r =0.74 1/d




modeled

predicted without parameter change

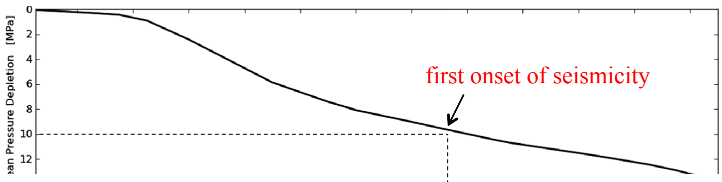
## Case study: gas-field depletion induced seismicity



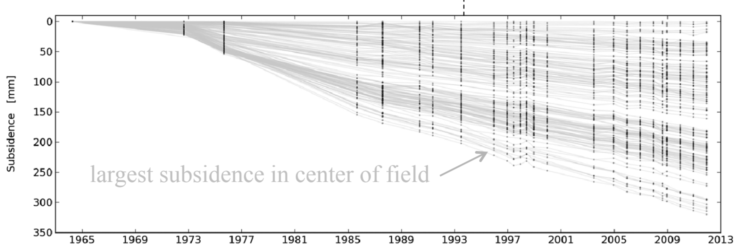

Groningen gas field, The Netherland

*Bourne et al., 2014.*
*J. Geophys. Res. 119,*
*10.1002/2014JB011663*

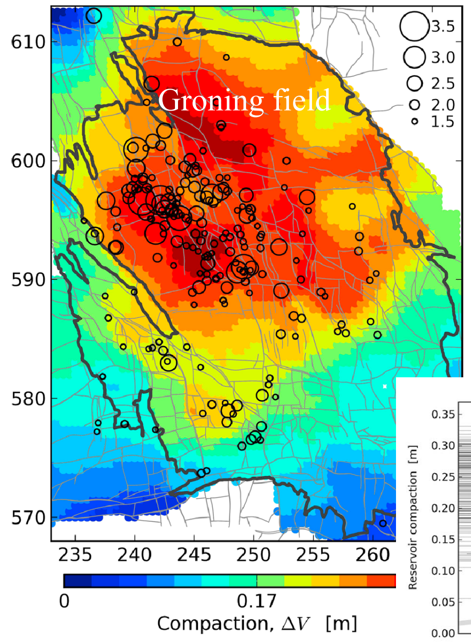
*Pore pressure depletion (MPa)*

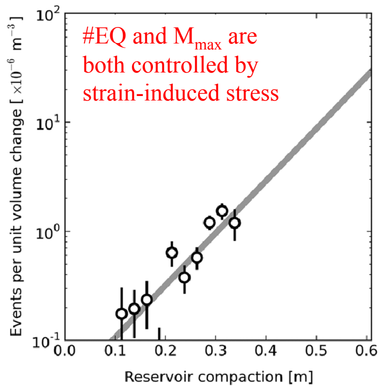


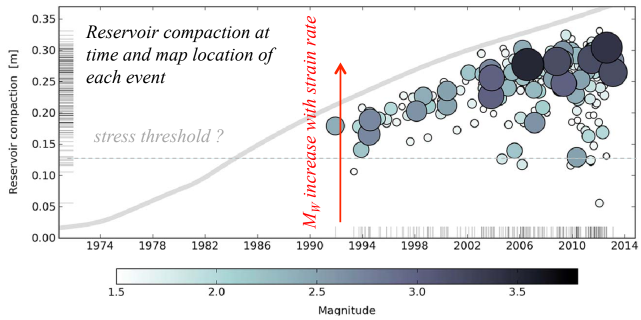

*subsidence (mm)*



## EQ ($M_L$>1.5, 1995-2012) and reservoir compaction (1960-2012)



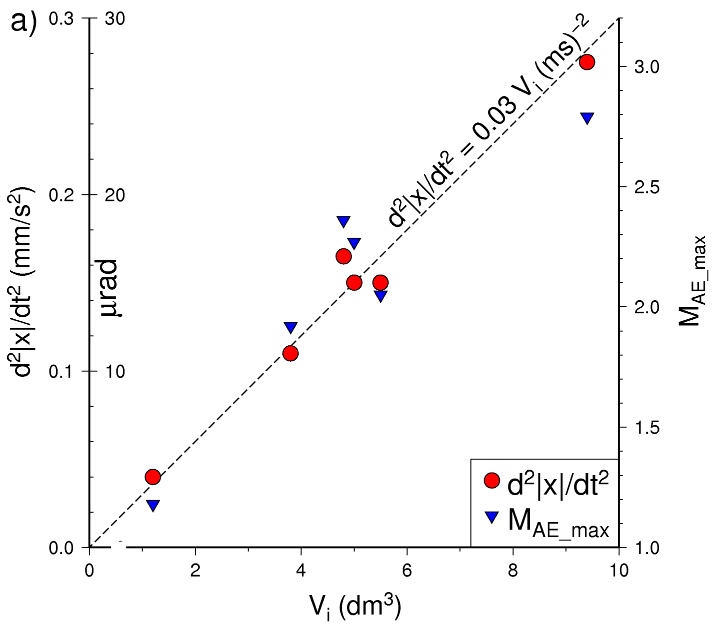




*Bourne et al., 2014. J. Geophys. Res.*

## $M_{AE\_max}$ is controlled by fracture size (stress anomaly)

Äspö experiment




*Note: - Mmax does not correlate to injection pressure*

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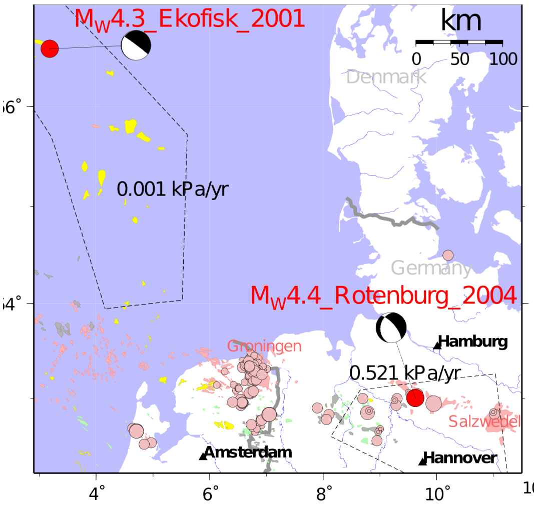
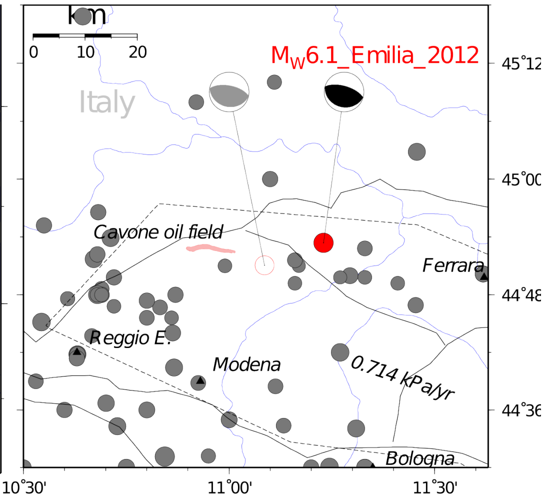
## Application: RS model to discriminate single significant earthquakes ?



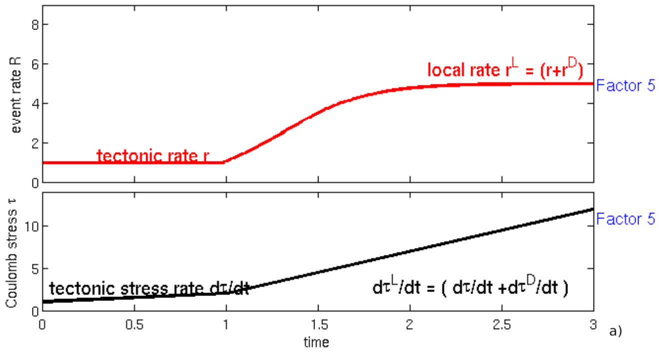




We estimate the relative EQ occurrence rate from the relative stress rate (tectonic versus depletion-induced) from rate-state seismicity model

*Dahm et al. (2015)*

- ✓ EQ on blind thrust fault at 7km depth within Po basin of moderate seismicity. Tectonic stress rate is moderate
- ✓ ≈20km from EQ Cavone oil field (3km, ΔP≈1MPa, 30-200E3m³ over 32yr)
- ✓ Several committees studied possibility that EQ were induced

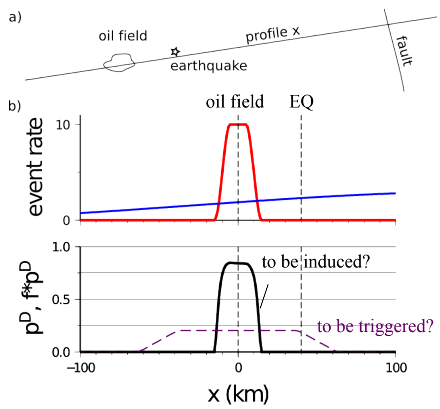
## Rate and state seismicity and how to estimate probabilities




depletion-induced

$$\frac{r}{r^T} = \frac{\dot{\tau}}{\dot{\tau}^T} \quad \text{or} \quad \frac{r^D}{r^T} = \frac{\dot{\tau}^D}{\dot{\tau}^T}$$

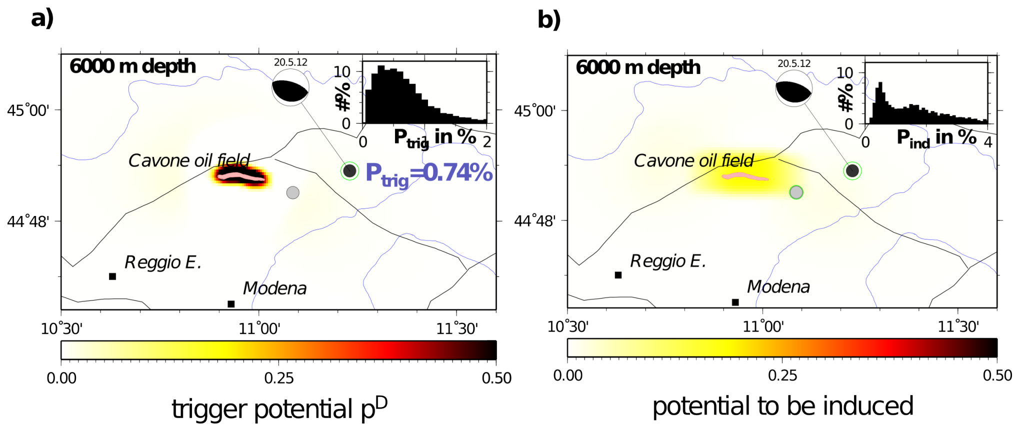
tectonic stress rate




potential to be induced / triggered

*Dahm et al. (2015)*

## Was the Emilia 2012 main shock triggered by oil field depletion ?




Cavone field in 3km depth, stress scales with $\Delta P$ h $c_m$
with $\Delta P \approx 1$ MPa over period of 32 years, $c_m = 0.001$ $GPa^{-1}$,
h =600m ($\lambda=\mu \approx 12$ GPa)

3D Boundary element model adapted to nuclei of strain theory

✓$\Delta P \approx 1$ MPa / 32 yr
✓ $d\tau^T / dt \approx 0.13$ kPa/yr
✓ location errors considered
✓max likelihood depth ≈ 5.5 km

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*Dahm et al. (2015)*

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## Summary of weal and woe's

✓ Largest EQ (M>6) were observed for large-scale and long-term operations (e.g. as dams, hydrocarbon production and mining)
✓ Shallowness of events can enhance the local damage and risk

✓ Induced seismicity challenges technical and methodical innovations
- new detection and automatic location methods
- reliable moments and moment tensors for weak EQ (still open)
- f-M is time dependent and highly variable
- probabilistic discrimination by rate-state and physics-based models

✓ New insights in to physics of earthquake triggering and rupture
- stress shadow effects are important for induced seismicity - rate and state modeling is suited to simulate stress shadows
- induced seismicity be used to "measure" the criticality of rock stress
- Aspo: event rate controlled by $\Delta P$, $M_{max}$ controlled size of fracture

✓ Challenge of maximum magnitude problem (still open)

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