

# The Static Behaviour of Induced Seismicity

A. Mignan (ETH Zurich)

*Schatzalp Workshop*

*Understanding and Modeling of Induced Seismicity (II)*

*Thursday, 16 March 2017, 08:35-08:50*

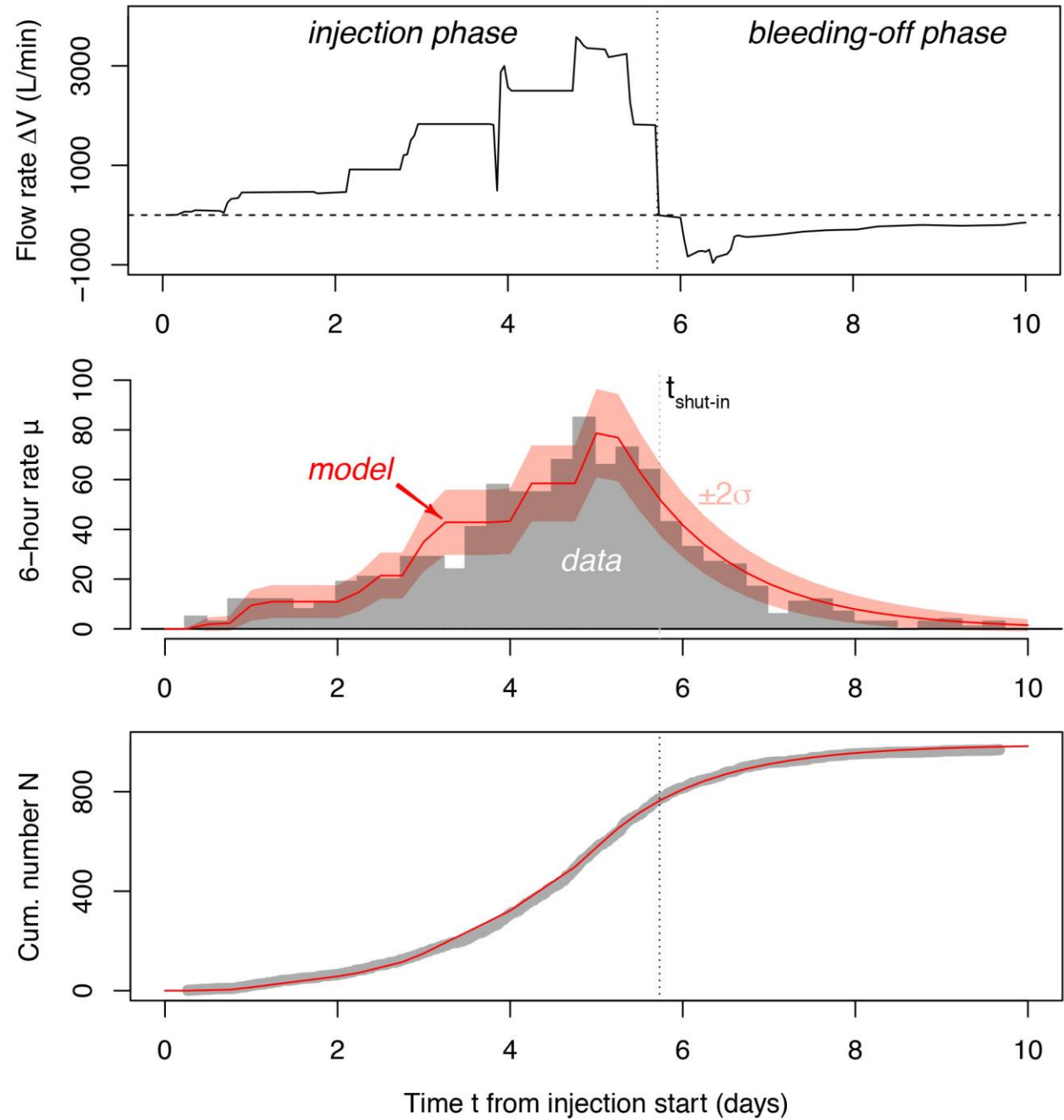
**ETH**

Eidgenössische Technische Hochschule Zürich  
Swiss Federal Institute of Technology Zurich



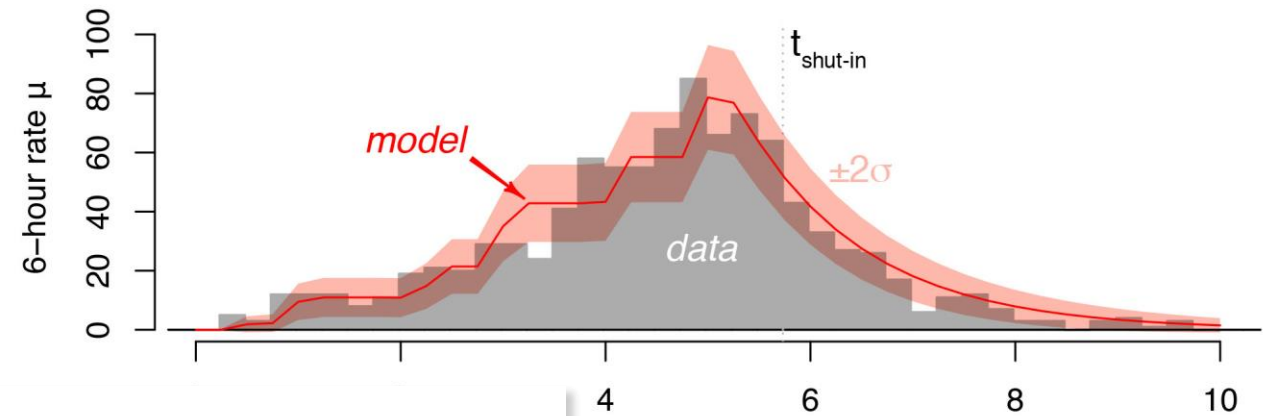
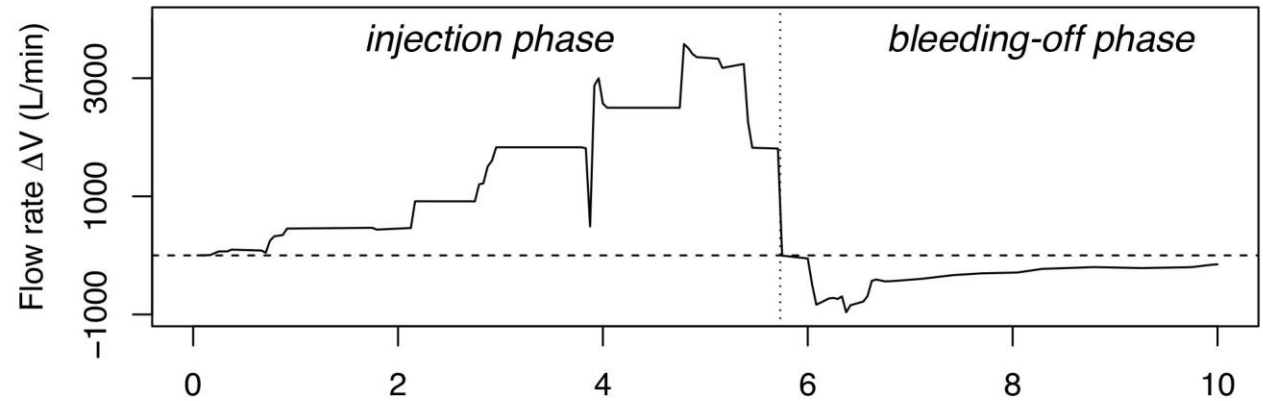
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# The 2006 Basel EGS textbook example

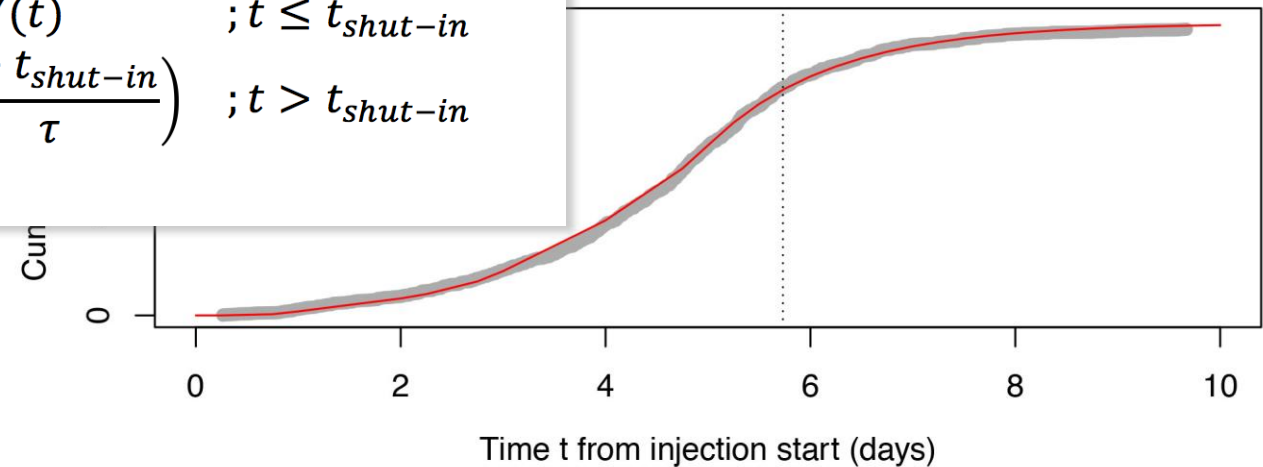


2006 Basel EGS data sources:  
Håring et al. (2008);  
Kraft & Deichmann (2014)

# The 2006 Basel EGS textbook example



$$\begin{cases} \mu(t) = 10^{afb} 10^{-bM_c} \Delta V(t) & ; t \leq t_{shut-in} \\ \mu(t) = \mu(t_{shut-in}) \exp\left(-\frac{t - t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases}$$



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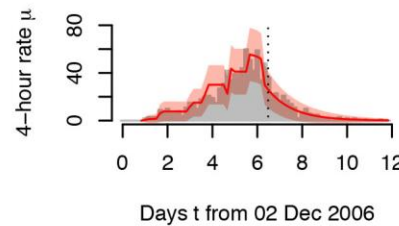
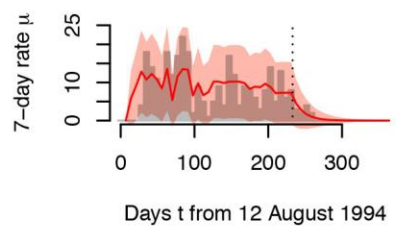
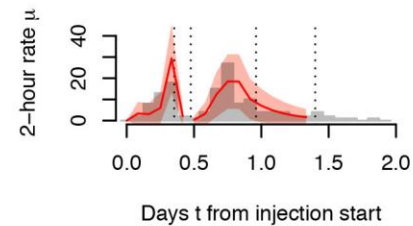
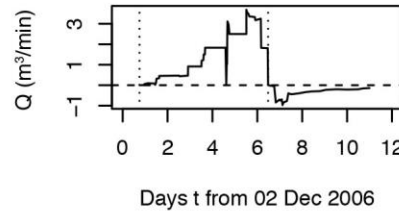
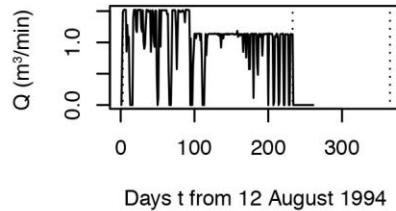
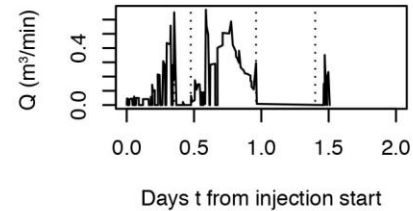
Very reasonable results  
obtained quite systematically  
with very SIMPLE MODEL

$$\begin{cases} \mu(t) = 10^{a_{fb}} 10^{-bM_c} \Delta V(t) & ; t \leq t_{shut-in} \\ \mu(t) = \mu(t_{shut-in}) \exp\left(-\frac{t - t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases}$$

KTB 1994 (DE)

Paradox Valley 1994 (US)

Basel 2006 (CH)



**Linear relationship  $\mu \approx \Delta V$**

✓ Empirical

✓  $a_{fb}$  equivalent to  
seismogenic index  $\Sigma$   
(*Shapiro et al.*)

**Normal diffusion**

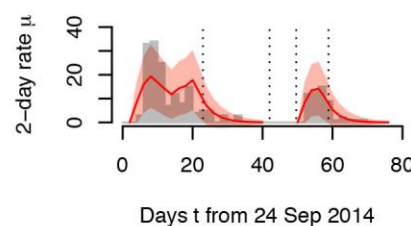
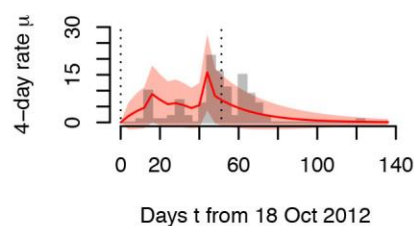
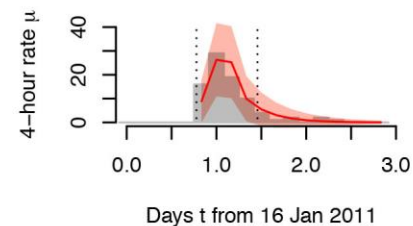
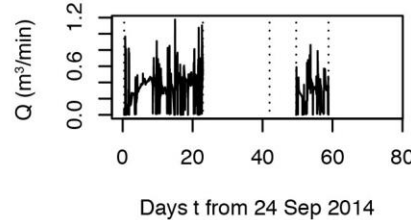
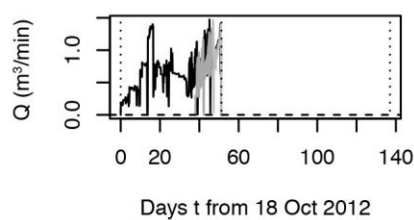
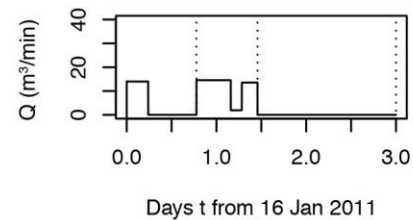
✓ 5 out of 7 time series best  
described by **exponential  
function** (stretched exp.  
better in 2 cases)

✓ Same principle as for  
tectonic aftershocks  
(*Mignan, GRL 2015*)

Garvin 2011 (US)

Newberry 2012 (US)

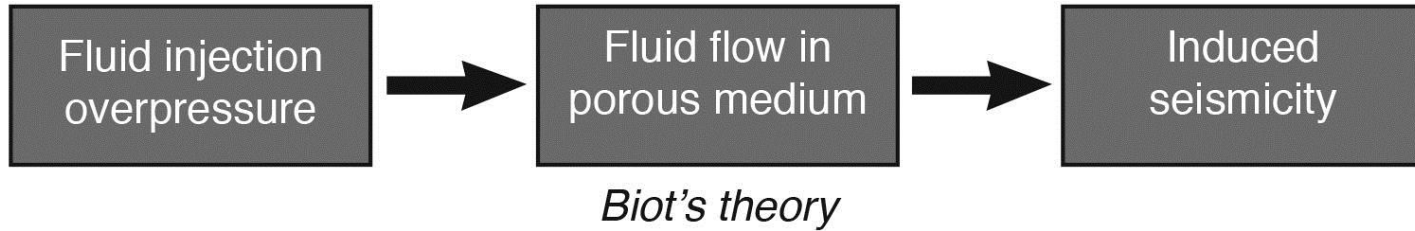
Newberry 2014 (US)



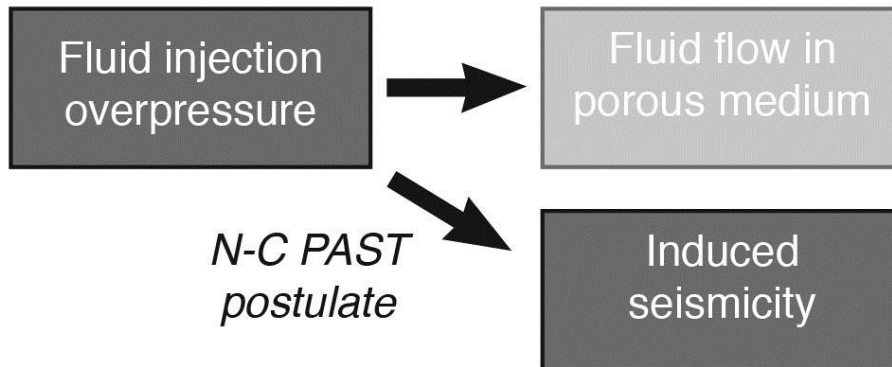
Source: *Mignan et al. (sub.)*

This model can be based on simple physics, using **GEOMETRY** instead of poroelasticity

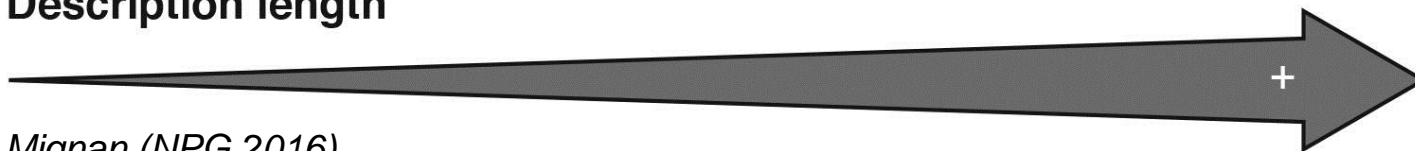
**Poroelastic approach**



**Geometrical approach**

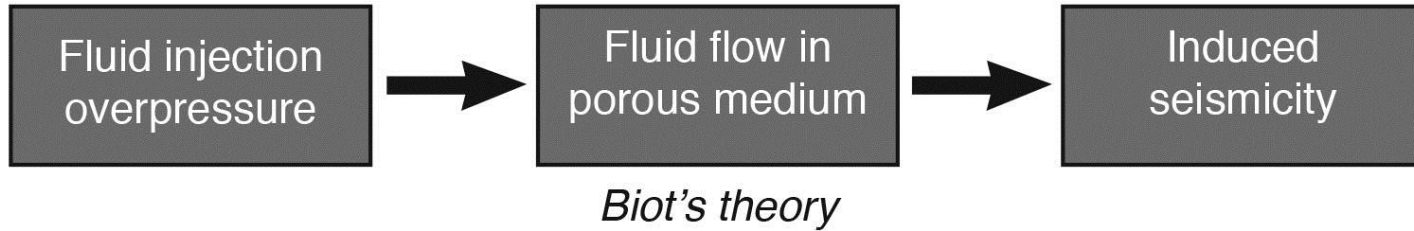


**Description length**

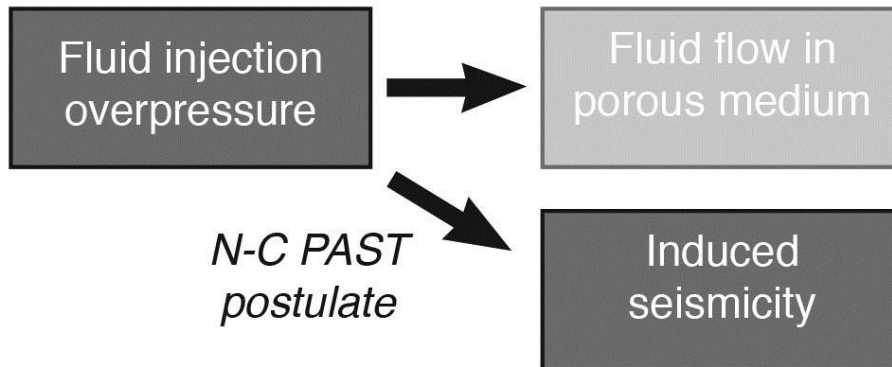


# This model can be based on simple physics, using **GEOMETRY** instead of poroelasticity

## Poroelastic approach

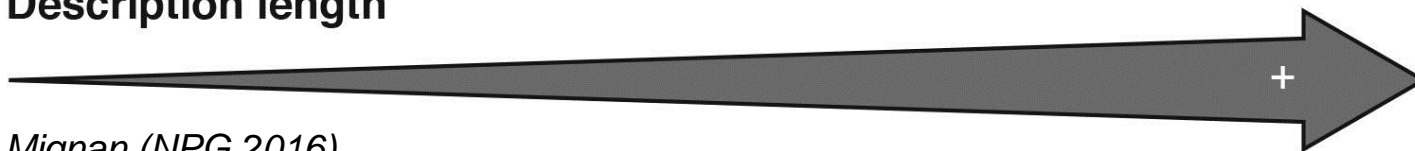


## Geometrical approach



- ✓ Algebraic model (**INTEGRABLE** in analytical risk management, e.g., closed-form TLS)
- ✓ Few physical parameters (**PARSIMONIOUS**)
- ✓ Same physics as tectonic earthquakes (**UNIFYING**)

## Description length



## REDUCTIONIST GEOMETRIC approach with STATIC stress top-down loading as driver

- ✓ **Opposite to complexity theory**, which is holistic (stem of “complex” means “intertwined”), dynamic, controlled by bottom-up triggering (& critical points)
- ✓ **Postulate.** *Seismicity is strictly categorized into three regimes of constant spatiotemporal densities – background  $\delta_0$ , quiescence  $\delta_-$  and activation  $\delta_+$  (with  $\delta_- < \delta_0 < \delta_+$ ) – and depends on the static stress step function  $\delta(\sigma)$  with  $\Delta\sigma_*$  the background static stress amplitude range*

$$\delta(\sigma) = \begin{cases} \delta_- & \text{if } \sigma < -\Delta\sigma_* \\ \delta_0 & \text{if } \sigma \leq |\Delta\sigma_*| \\ \delta_+ & \text{if } \sigma > \Delta\sigma_* \end{cases}$$

- ✓ **Building of “seismicity solids”:**

- ✓ Permanent static stress field

$$\sigma(r, t) \propto \frac{\Sigma(t)}{r^3}$$

- ✓ Seismicity solid envelope

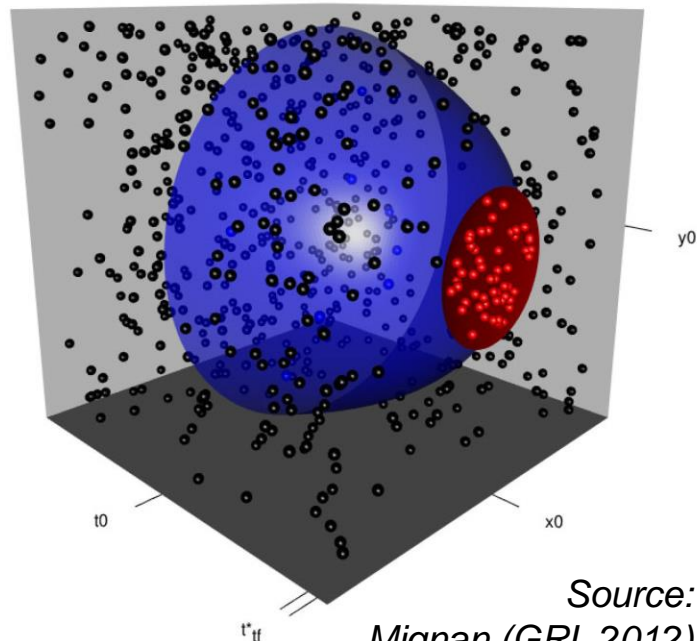
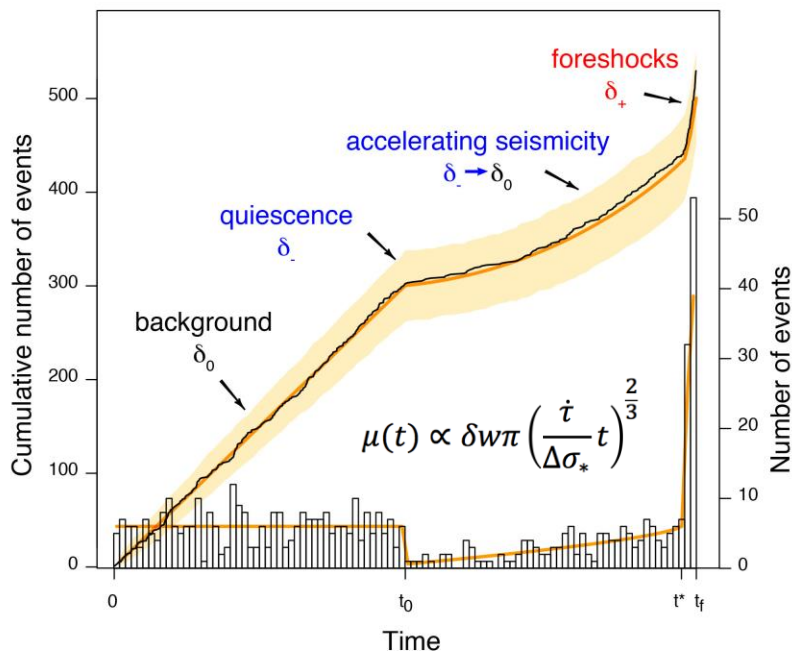
$$r_*(t) \propto \left( \frac{\Sigma(t)}{\Delta\sigma_*} \right)^{\frac{1}{3}}$$

- ✓ Seismicity rate function

$$\mu(t) \propto \delta k r_*(t)^d$$

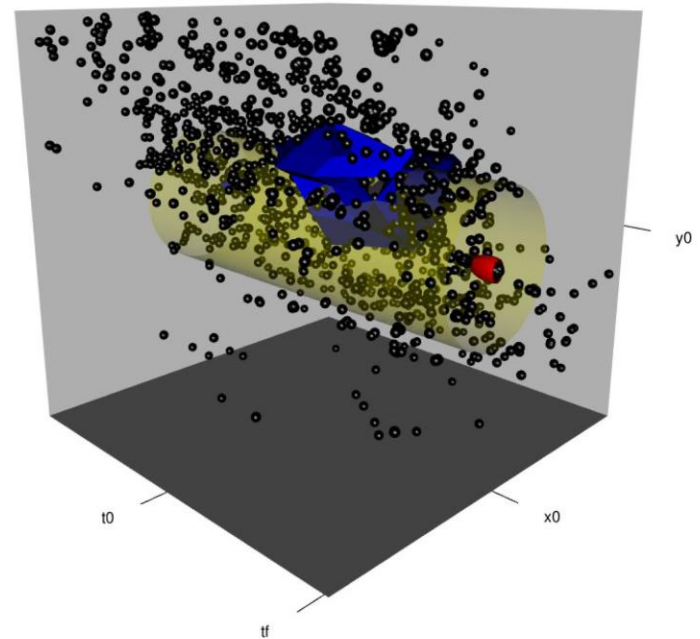
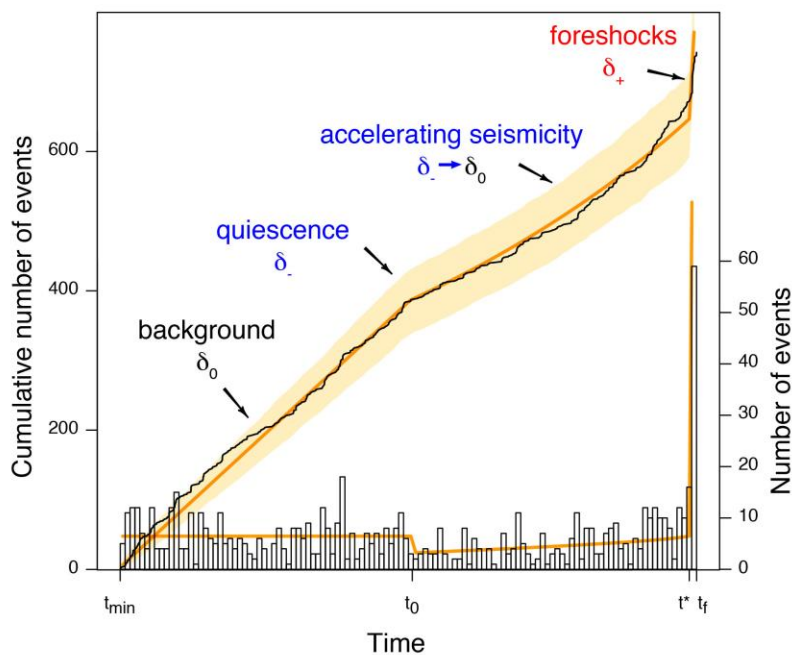
# Originally coined **NON-CRITICAL** precursory accelerating seismicity theory (N-C PAST)

*Simulations of precursory seismicity from algebraic model*



Source:  
Mignan (GRL 2012)

*Observations (2009 L'Aquila mainshock)*



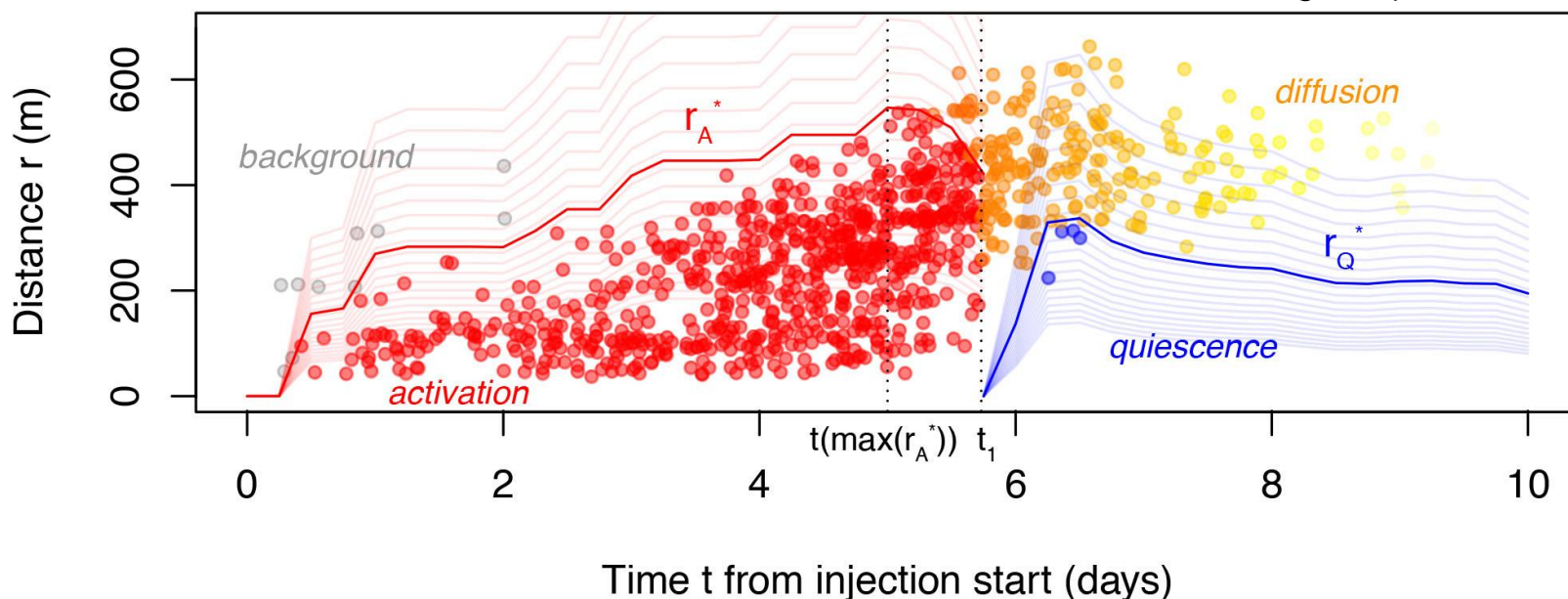


## “N-C PAST Postulate” also explains parabolic spatial front & linear relationship $\mu \approx \Delta V$

1. Parabolic front of induced seismicity = **Activation solid** driven by borehole overpressure

$$r_*(t) \propto \left( \frac{K \Delta V(t)}{\Delta \sigma_*} \right)^{\frac{1}{3}}$$

Source: Mignan (NPG 2016)

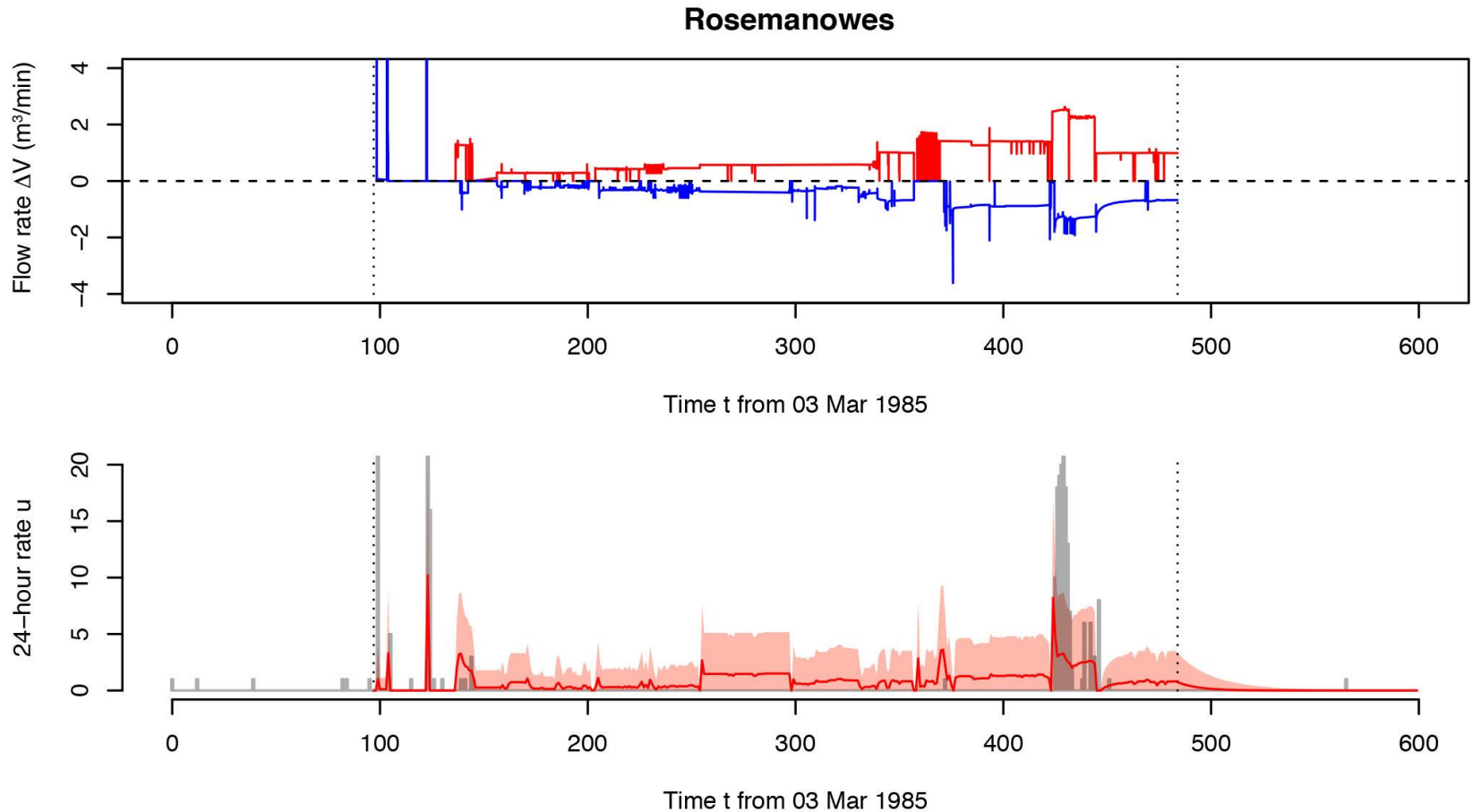


2. Linear relationship between induced seismicity rate & flow rate = direct consequence of 1

$$\mu(t) \propto \delta_+ \frac{4\pi K}{3 \Delta \sigma_*} \Delta V(t)$$

# More complicated cases (stem of “COMPLICATED” meaning “FOLDED”)

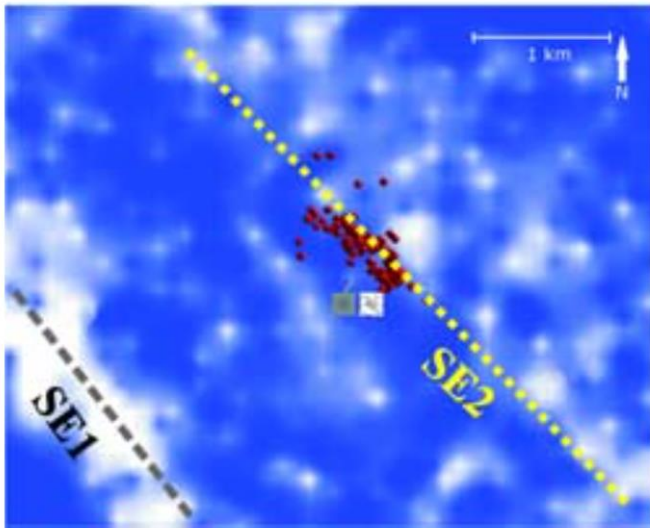
## 1. Sum of two pressure fields, e.g. overpressure + underpressure in production phase



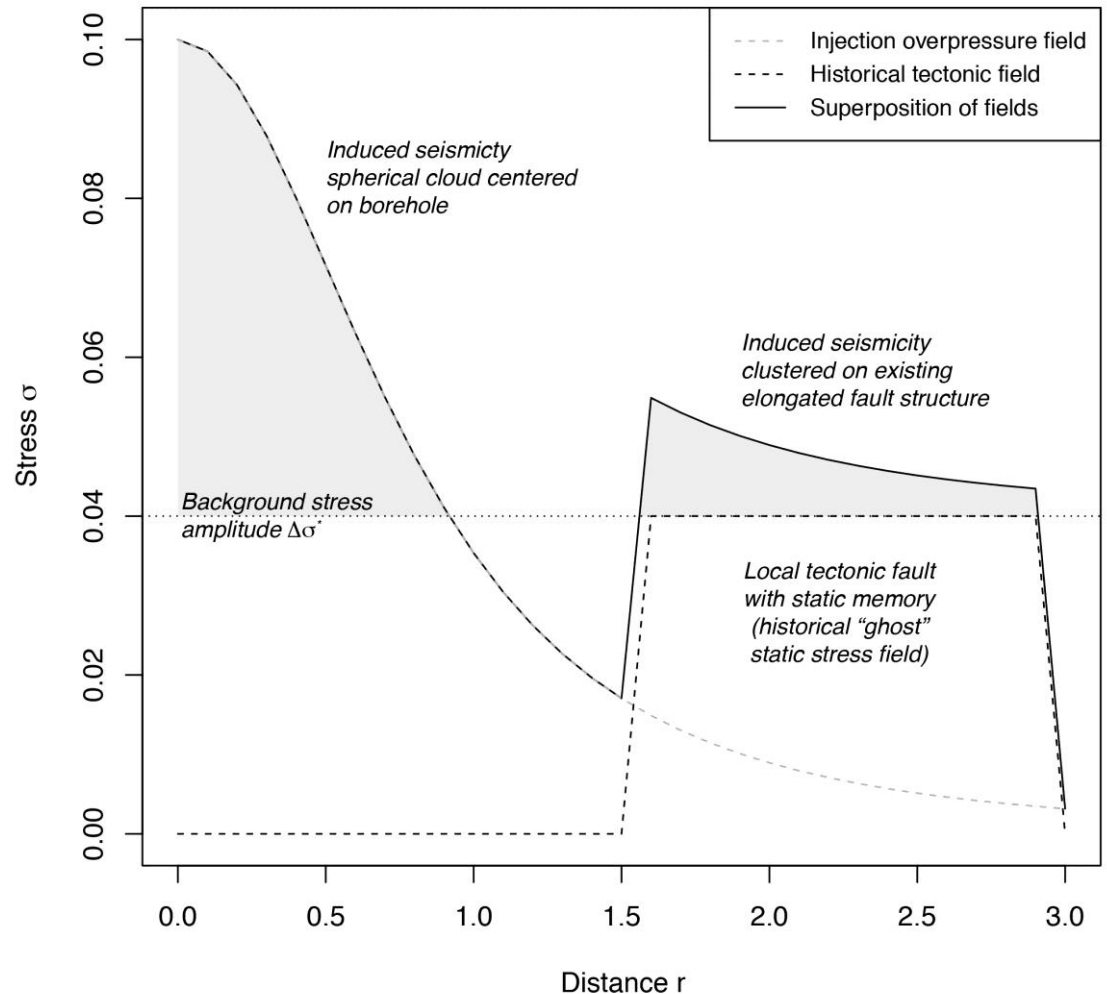
## More complicated cases (stem of “complicated” meaning “folded”)

1. Sum of two pressure fields, e.g. overpressure + underpressure in production phase
2. Sum of overpressure field + remnant of permanent static stress field of an active fault

Source: Mignan (NPG 2016)



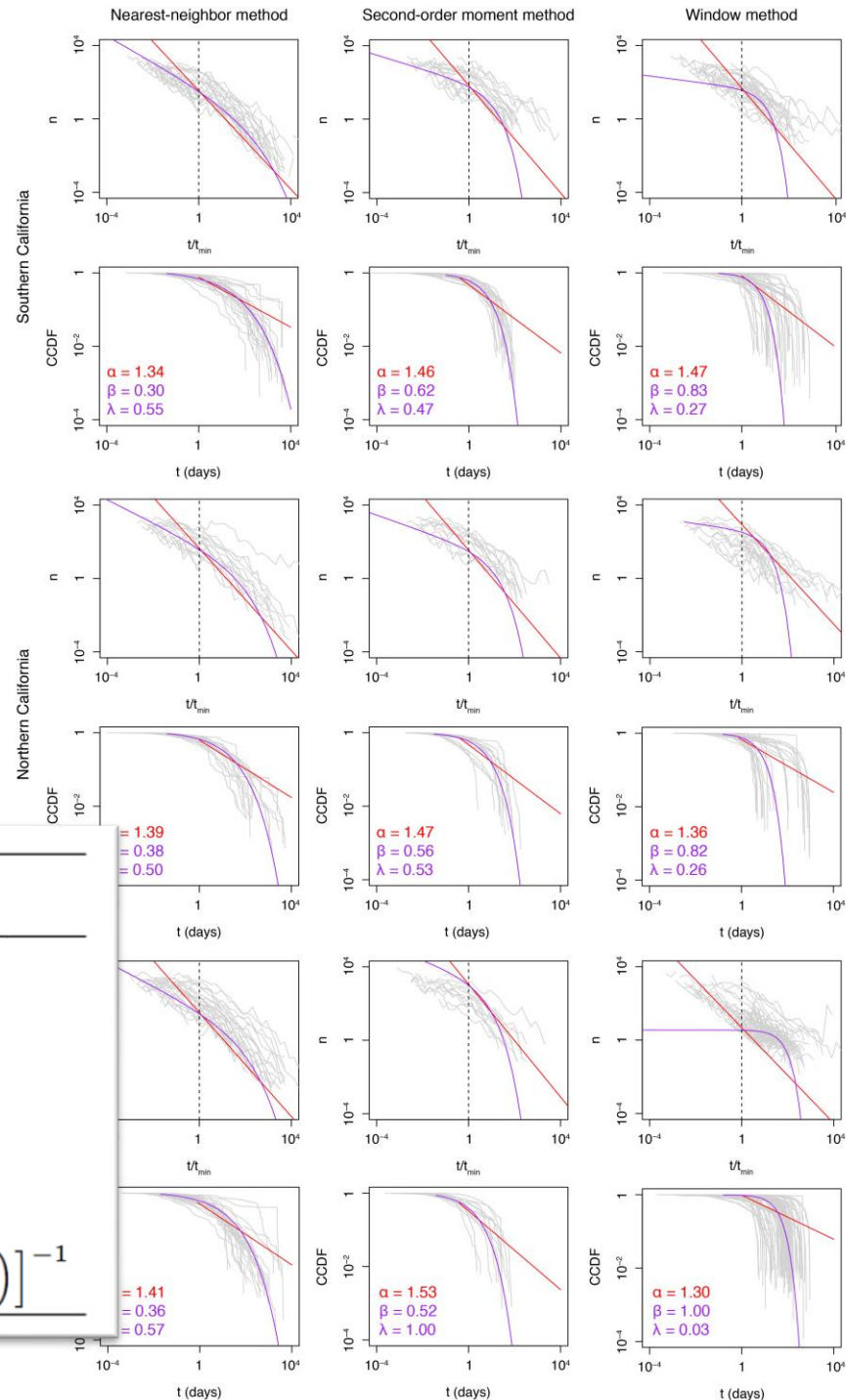
Source: Shapiro et al. (GRL 2006), KTB 2004/5 anisotropy



## Note on Aftershocks & post-injection relaxation

- ✓ **Omori law (power law) ill-defined:**  $c > 0$  infers that singularity occurs before mainshock (*Kagan & Houston 2005*)
- ✓ A **stretched exponential function** fits aftershocks better than a standard power-law (*Mignan, GRL 2015*); similar for post-injection cases (against complexity?)
- ✓ **Subdiffusion** explainable by **STATIC trap model** (*Grassberger & Procaccia 1982*) with stretching explained by **TOPOLOGY** of traps (fractal fault network)

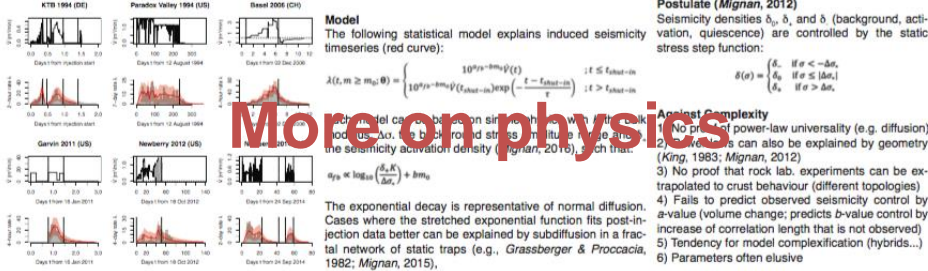
	Name	Distribution $p(x) = Cf(x)$	
		$f(x)$	$C$
Continuous	Power law	$x^{-\alpha}$	$(\alpha - 1)x_{\min}^{\alpha-1}$
	Power law with cutoff	$x^{-\alpha}e^{-\lambda x}$	$\frac{\lambda^{1-\alpha}}{\Gamma(1-\alpha, \lambda x_{\min})}$
	Exponential	$e^{-\lambda x}$	$\lambda e^{\lambda x_{\min}}$
	Stretched exponential	$x^{\beta-1}e^{-\lambda x^{\beta}}$	$\beta\lambda e^{\lambda x_{\min}^{\beta}}$
	Log-normal	$\frac{1}{x} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$	$\sqrt{\frac{2}{\pi\sigma^2}} \left[\operatorname{erfc}\left(\frac{\ln x_{\min} - \mu}{\sqrt{2}\sigma}\right)\right]^{-1}$



**New horizons in the understanding & mitigation of induced seismicity:  
physics, risk, communication**

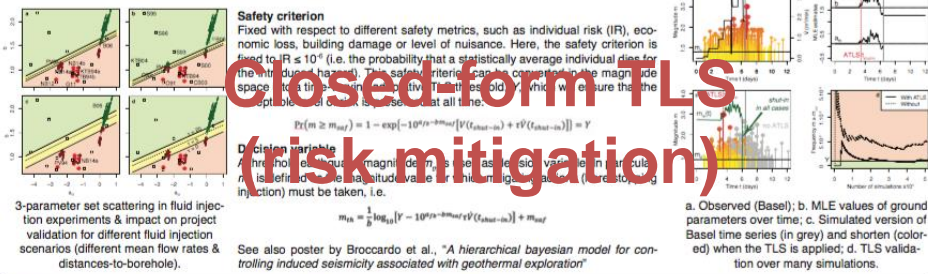
The rise in the frequency of anthropogenic earthquakes is posing economic, societal and legal challenges to geo-energy projects (e.g., Enhanced Geothermal Systems, EGS). Existing tools to assess and control such risks are insufficient. To resolve this issue, induced seismicity is studied from three fronts: (1) the physics of seismicity, both tectonic and induced, is poorly understood. We move away from the Complexity trend (bottom-up triggering, critically) to a reductionist approach (top-down loading, non-critically) to explain the main laws of seismicity. For the case of induced seismicity, both the linear flow rate-induced seismicity rate relationship and the parabolic induced seismicity spatial front are explained from simple geometric operations on a static stress field (Mignan, 2016). It follows that the simple statistical laws that describe induced seismicity time series can be related to only 2 physical parameters (activation & background static stress amplitude range). (2) With a physical model that can be described algebraically, a data-driven adaptive forecasting system can be run that is computationally cheap. Decision variables can also be derived from such model to define a traffic light system (TLS) in respect to a given safety criterion (Mignan, Broccardo, Wiemer, Giardini, "When is anthropogenic seismicity too risky?", submitted). (3) Although the security criterion can be respected (in average) with the use of a TLS, the known scattering of the activation parameter makes the future of an EGS project uncertain. Based on the EGS costs (mainly drilling), expected profits (\$/kWh) and risk curves obtained from a priori activation values, one can decide during the planning phase if the project should go ahead or not. By communicating risk uncertainty and how the stakeholder is subjective (pessimistic or optimistic), rational decisions can be made.

**(1) Moving away from Complexity Theory: "Seismicity Solid" geometry**



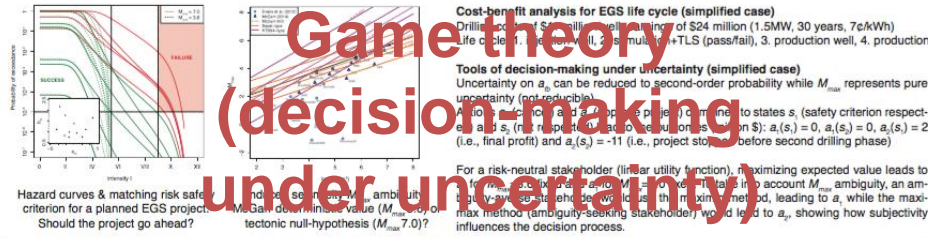
**More on physics**

**(2) Closed-form Traffic Light System (Mignan et al., sub.)**



**Closed-form TLS (Risk mitigation)**

**(3) Decision-making under uncertainty (Mignan et al., 2015; Mignan, sub.)**



**Game theory (decision-making under uncertainty)**

**References**  
Grassberger & Procaccia (1982), *The long time properties of diffusion in a medium with static traps*, J. Chem. Phys., 77, 6281-6284  
King (1983), *The Accommodation of Large Strains in the Upper Lithosphere of the Earth and Other Solids by Self-similar Fault Systems: the Geometrical Origin of b-Value*, PA-GEOPH, 121, 781-815  
Mignan (2012), *Seismicity precursors to large earthquakes unified in a stress accumulation framework*, Geophys. Res. Lett., 39, L21308  
Mignan (2015), *Modeling aftershocks as a stretched exponential relaxation*, Geophys. Res. Lett., 42, 9726-9732  
Mignan (2016), *Static behaviour of induced seismicity*, Nonlin. Processes Geophys., 23, 107-113  
Mignan, *Mitigating Extreme Earthquakes: The "History, Risk, Prediction" Motto*, submitted 2017  
Mignan et al. (2015), *Induced seismicity risk analysis of the 2006 Basel, Switzerland, Enhanced Geothermal System project: Influence of uncertainties on risk mitigation*, Geothermics, 53, 133-146  
Mignan et al., *When is anthropogenic seismicity too risky?*, submitted 2017

**Induced seismicity references:**

Mignan, A. et al. (2015), *Induced seismicity risk analysis of the 2006 Basel, Switzerland, Enhanced Geothermal System project: Influence of uncertainties on risk mitigation*, Geothermics, 53, doi: 10.1016/j.geothermics.2014.05.007  
Mignan, A. (2016), *Static behaviour of induced seismicity*, Nonlin. Processes Geophys., 23, doi: 10.5194/npg-23-107-2016

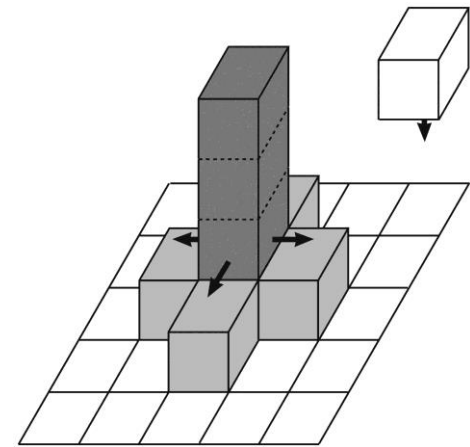
**See also on geometric origin of seismicity:**

Mignan, A. (2011), *Retrospective on the Accelerating Seismic Release (ASR) hypothesis: Controversy and new horizons*, Tectonophysics, 505, doi: 10.1016/j.tecto.2011.03.010  
Mignan, A. (2012), *Seismicity precursors to large earthquakes unified in a stress accumulation framework*, Geophys. Res. Lett., 39, doi: 10.1029/2012GL053946  
Mignan, A. (2015), *Modeling aftershocks as a stretched exponential relaxation*, Geophys. Res. Lett., 42, doi: 10.1002/2015GL066232



## AGAINST Complexity Theory (stem of complex meaning “intertwined”)

- ✓ Holistic – Bottom-up triggering – Dynamic – Critical



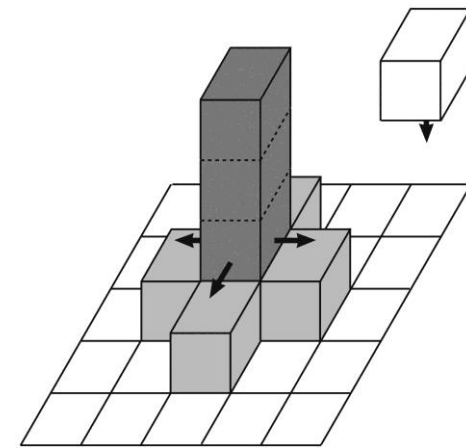
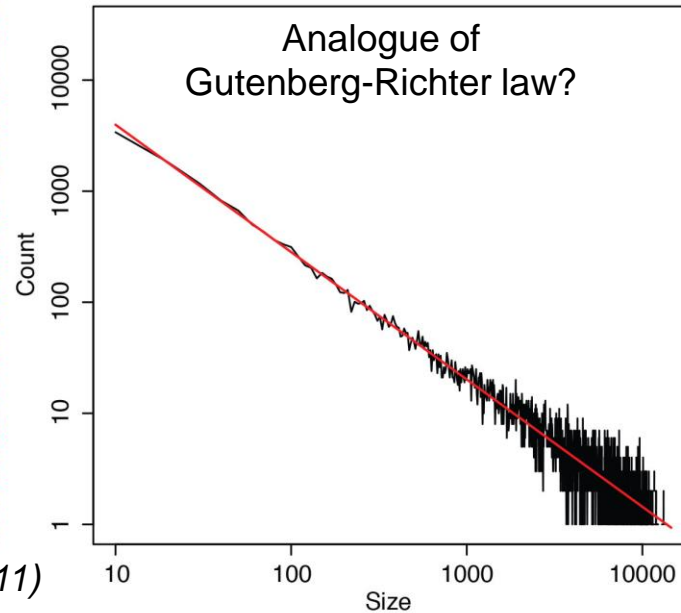
Local interactions lead  
to system behaviour

## AGAINST Complexity Theory (stem of complex meaning “intertwined”)

- ✓ Holistic – Bottom-up triggering – Dynamic – Critical
- ✓ Self-Organized Criticality (SOC) gives power-law freq.-size distr.



Source: Mignan (*Tectonophysics* 2011)

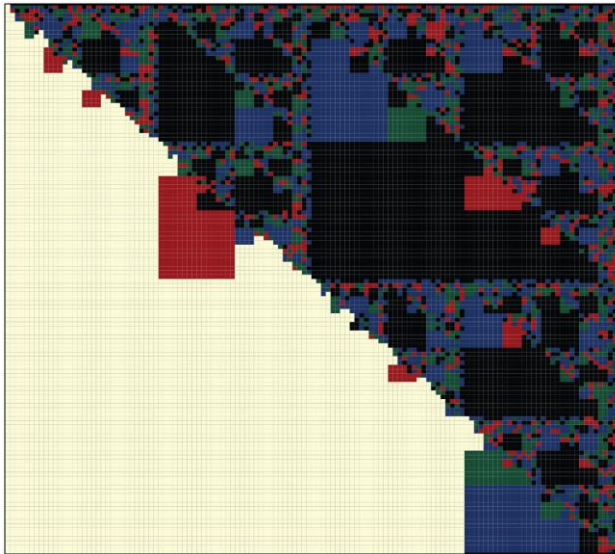


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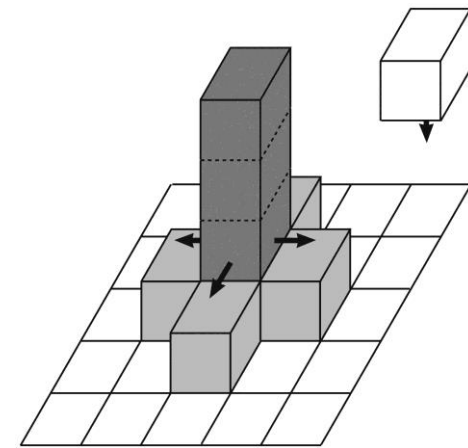
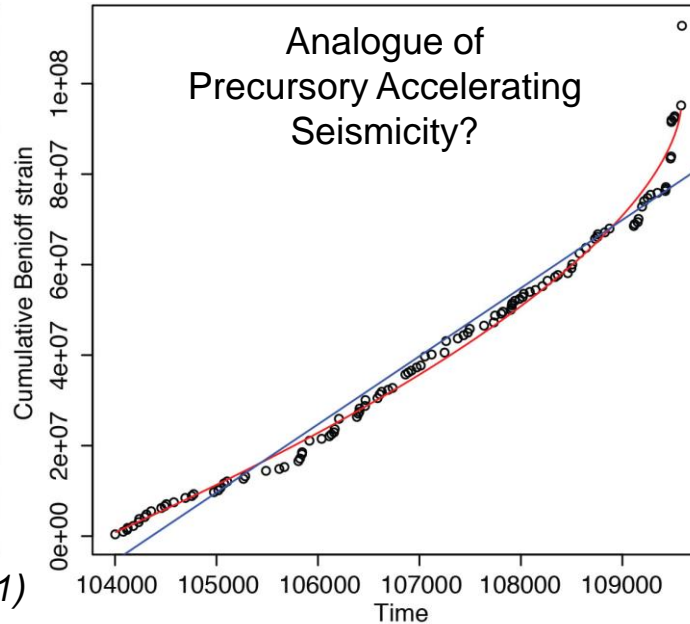


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- ✓ Holistic – Bottom-up triggering – Dynamic – Critical
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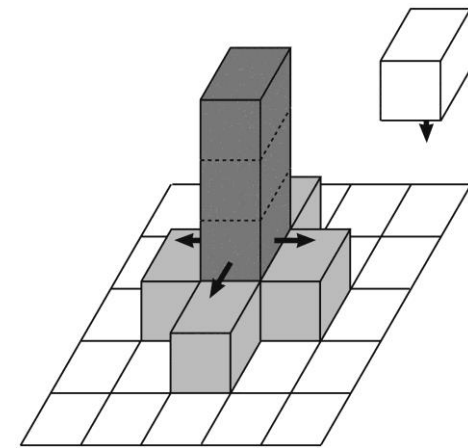
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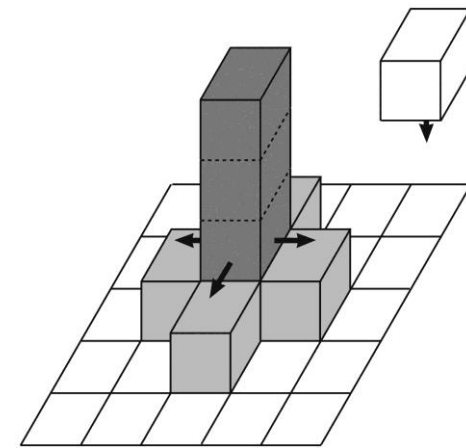
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- ✓ **Propositional fallacy. *the fact that critical processes lead to power-laws does NOT mean that the presence of power-laws is the proof that critical processes are in play. Indeed: GEOMETRY also explains GR law (King 1983) & precursors (Mignan 2012)***



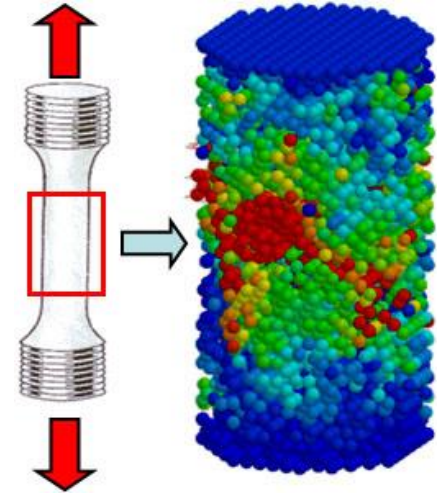
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- ✓ Movable Cellular Automata mimic rock lab experiments
  - ✓ CA where laws of physics are implemented (e.g., Hooke’s law, friction’s laws)
  - ✓ Extrapolating lab results to crust behaviour makes sense in Complexity paradigm (bottom-up process, scale-invariant)



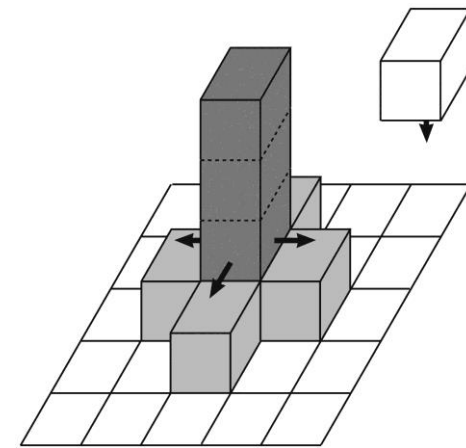
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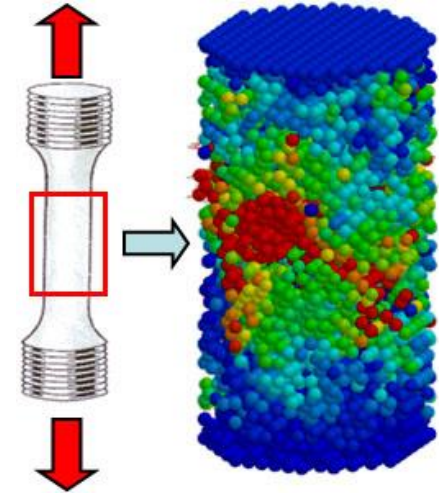
Source: Wikipedia

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  - ✓ Extrapolating lab results to crust behaviour makes sense in Complexity paradigm (bottom-up process, scale-invariant)
  - ✓ In terms of **GEOMETRY**: can we really extrapolate results from a confined cylindrical rock sample to a spherical layer with free surface (crust)? **Different TOPOLOGIES**



Local interactions lead to system behaviour



Source: Wikipedia