The Static Behaviour of Induced Seismicity

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Schatzalp Workshop

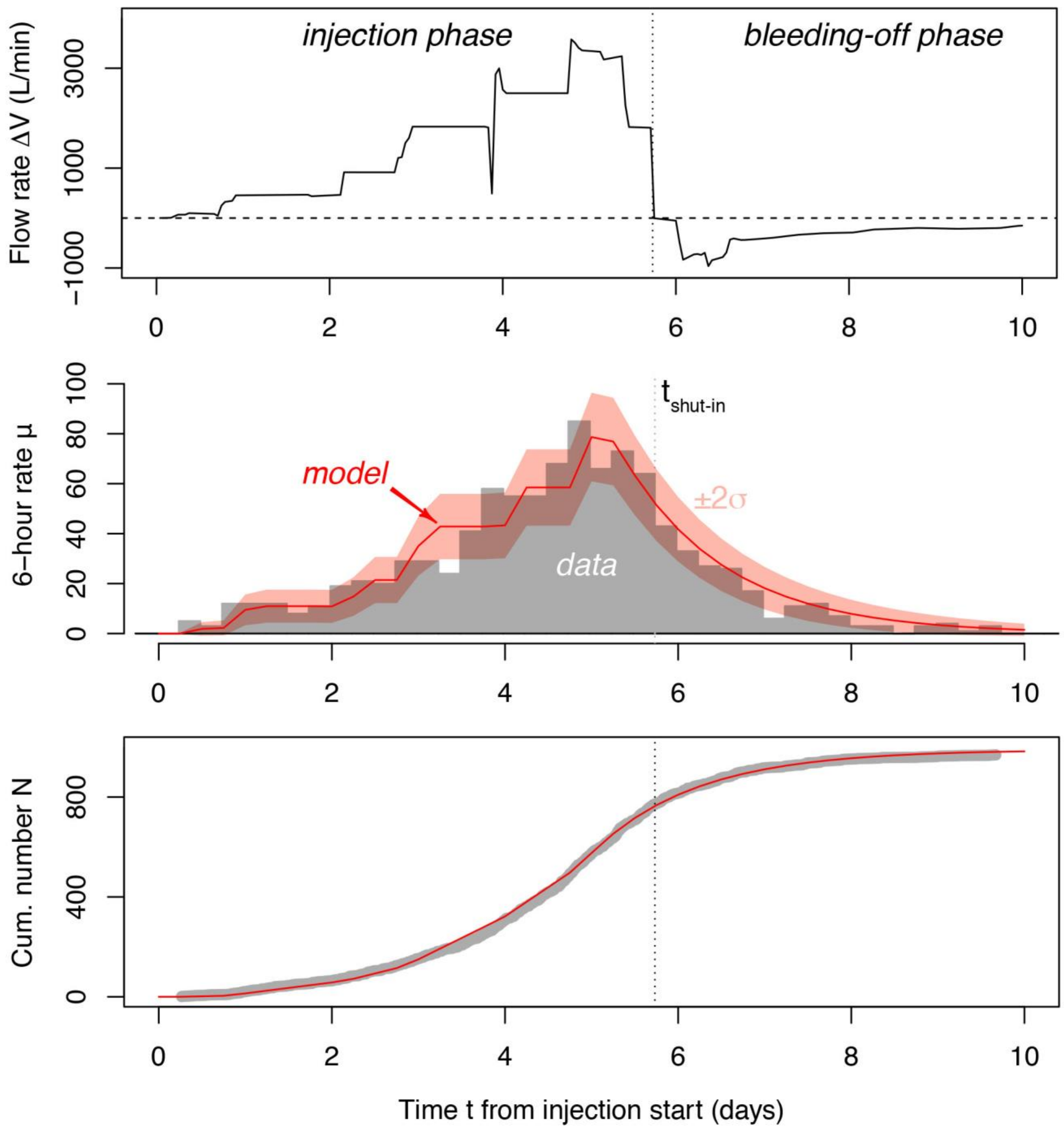
Understanding and Modeling of Induced Seismicity (II)

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

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

The 2006 Basel EGS textbook example



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

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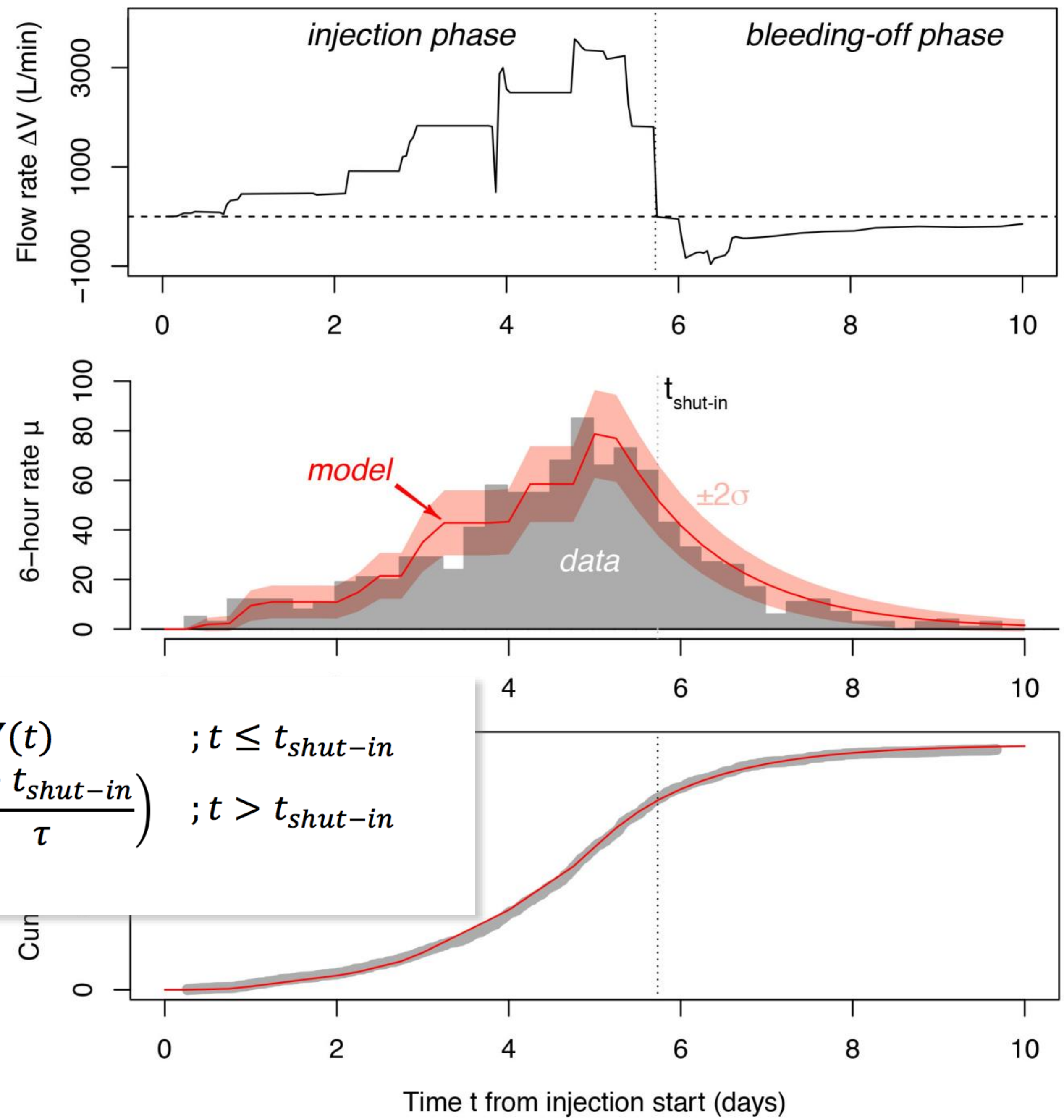

$$\begin{cases} \mu(t) = 10^{a_{fb}} 10^{-bM_c} \Delta V(t) & ; t \le t_{shut-in} \\ \mu(t) = \mu(t_{shut-in}) \exp\left(-\dfrac{t - t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases}$$

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Very reasonable results obtained quite systematically with very SIMPLE MODEL

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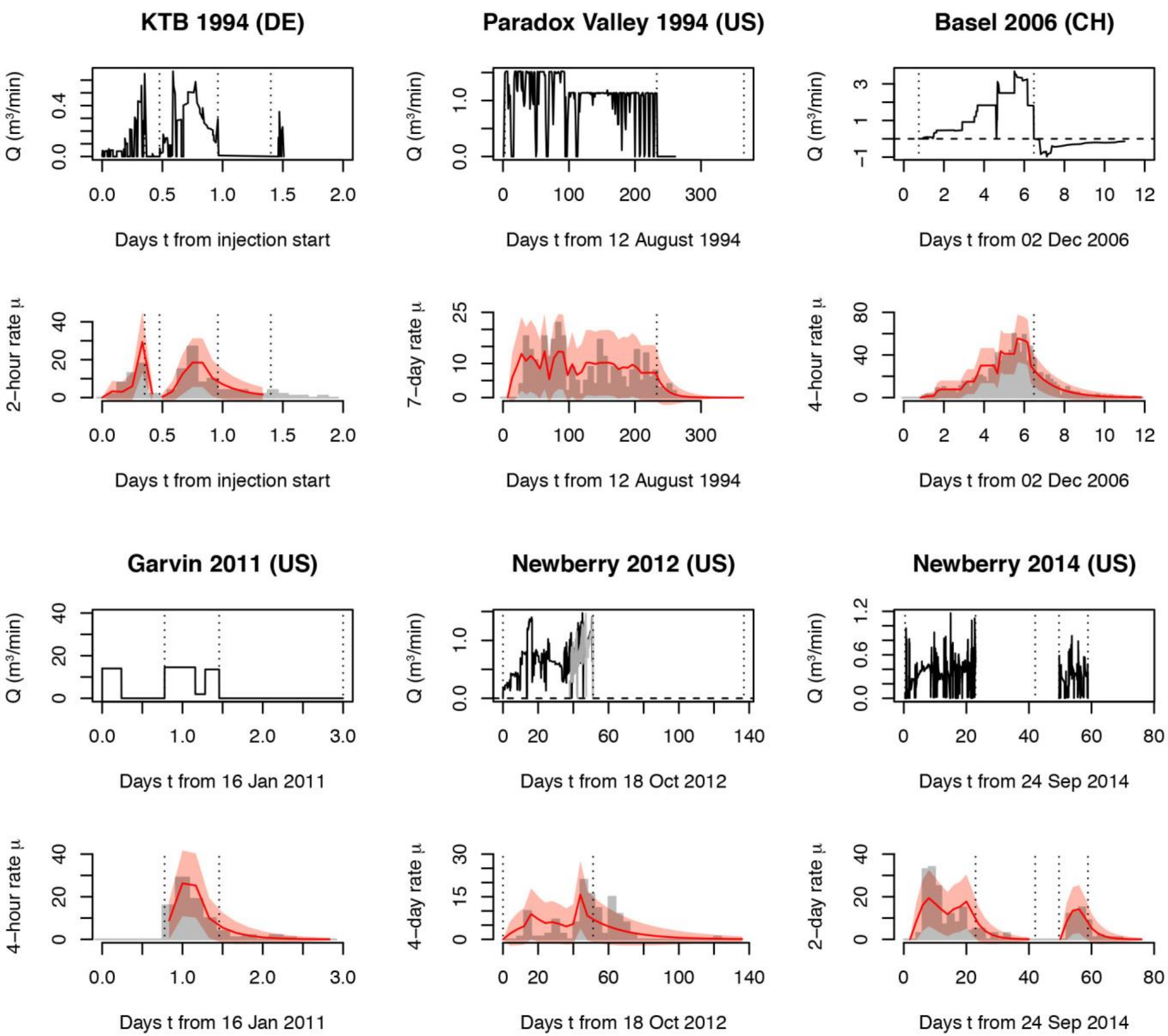


Linear relationship $\mu \approx \Delta V$

✓Empirical

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

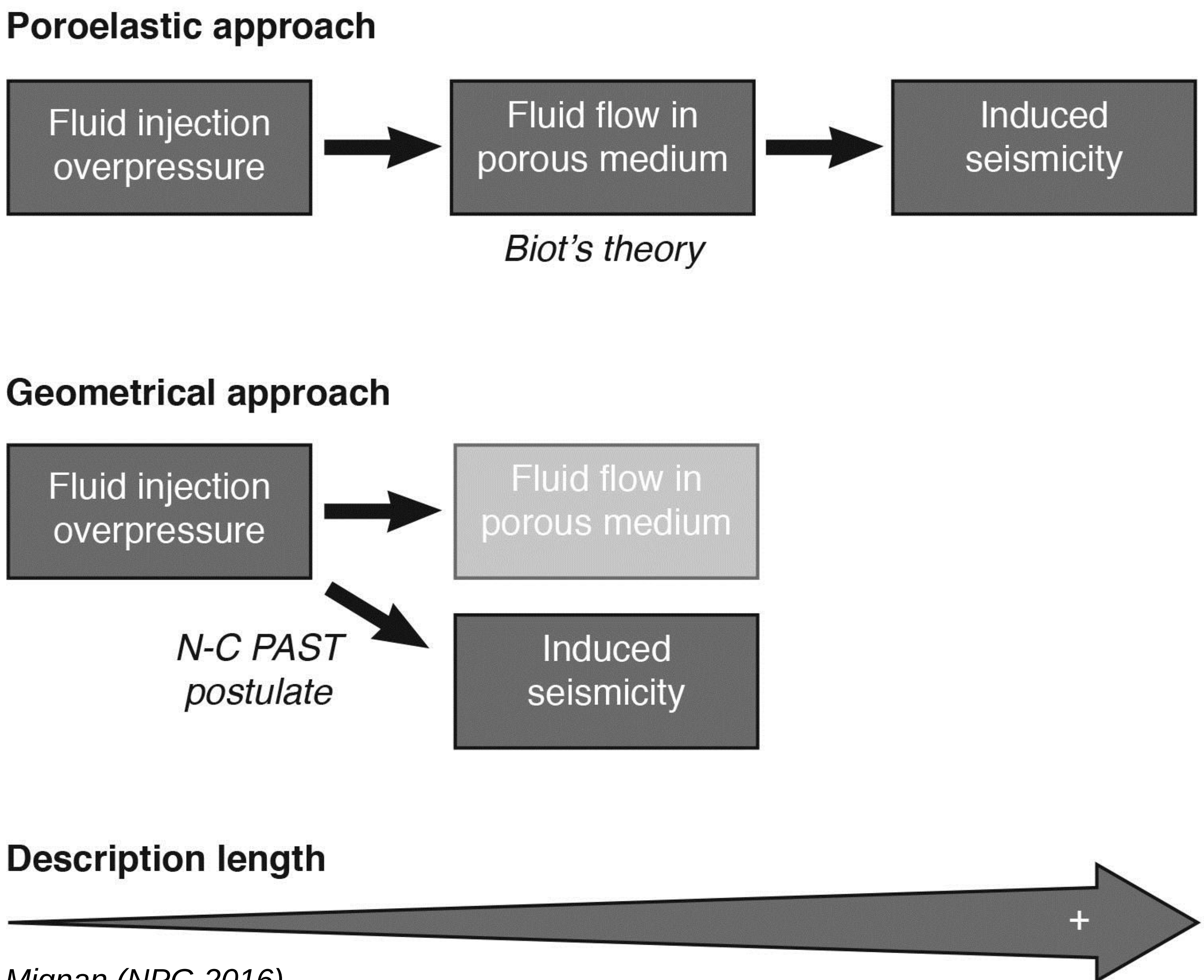
Normal diffusion

✓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*)

Source: Mignan et al. (sub.)

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



Source: Mignan (NPG 2016)

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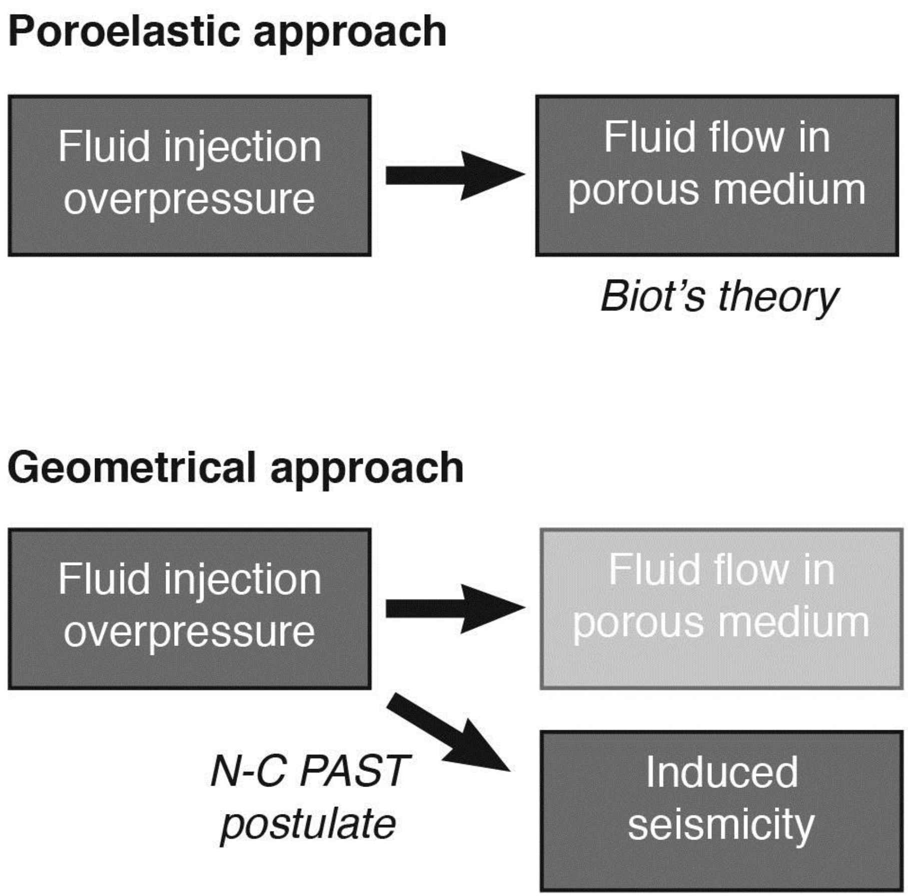
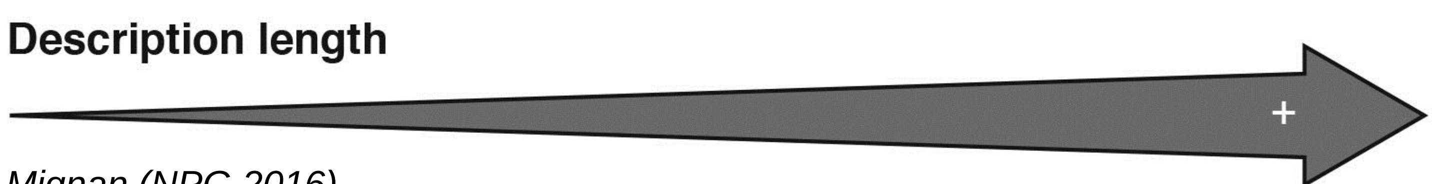


- ✓ Algebraic model (**INTEGRABLE** in analytical risk management, e.g., closed-form TLS)
- ✓ Few physical parameters (**PARSIMONIOUS**)
- ✓ Same physics as tectonic earthquakes (**UNIFYING**)



Source: Mignan (NPG 2016)

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)

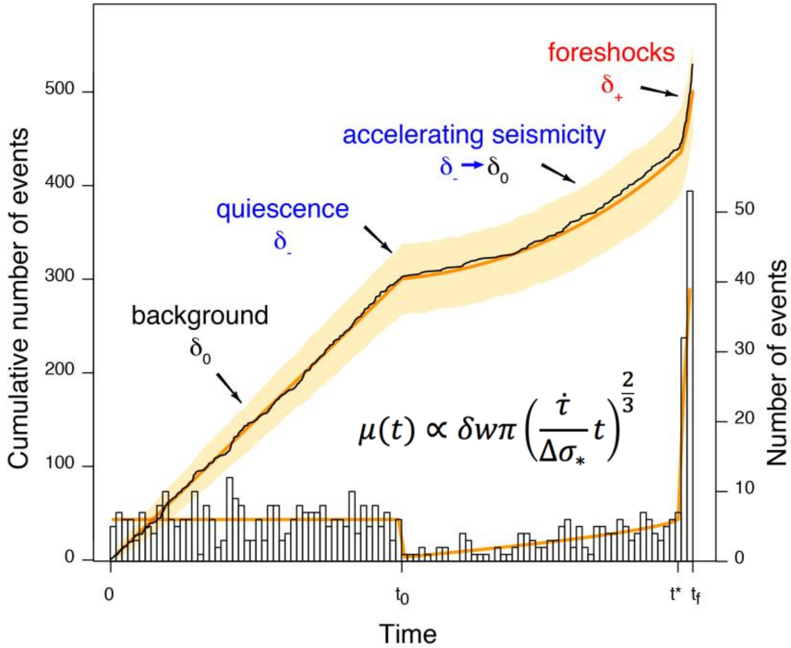
- ✓ **Postulate.** *Seismicity is strictly categorized into three regimes of constant spatiotemporal densities – background δ_0, quiescence δ_- and activation δ_+ (with $\delta_- < \delta_0 < \delta_+$) – and depends on the static stress step function $\delta(\sigma)$ with $\Delta\sigma_*$ the background static stress amplitude range*

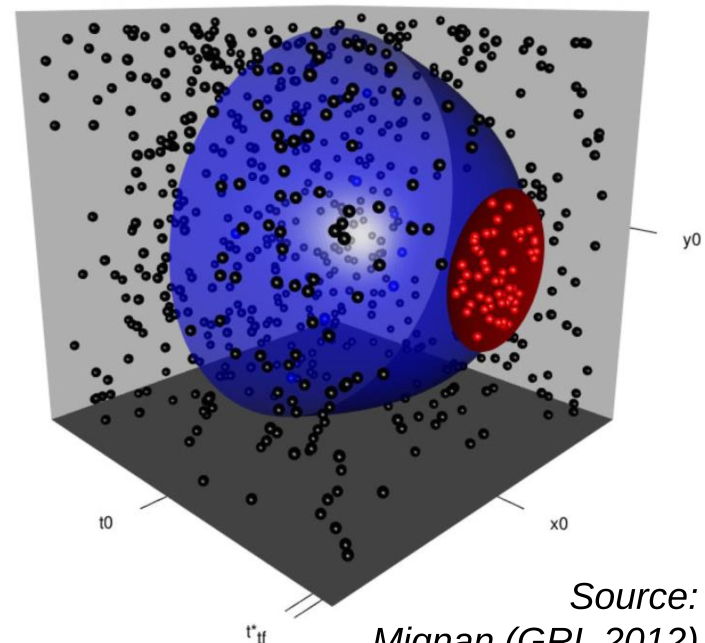
$$\delta(\sigma) = \begin{cases} \delta_- & \text{if } \sigma < -\Delta\sigma_* \\ \delta_0 & \text{if } \sigma \leq |\Delta\sigma_*| \\ \delta_+ & \text{if } \sigma > \Delta\sigma_* \end{cases}$$

- ✓ **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)

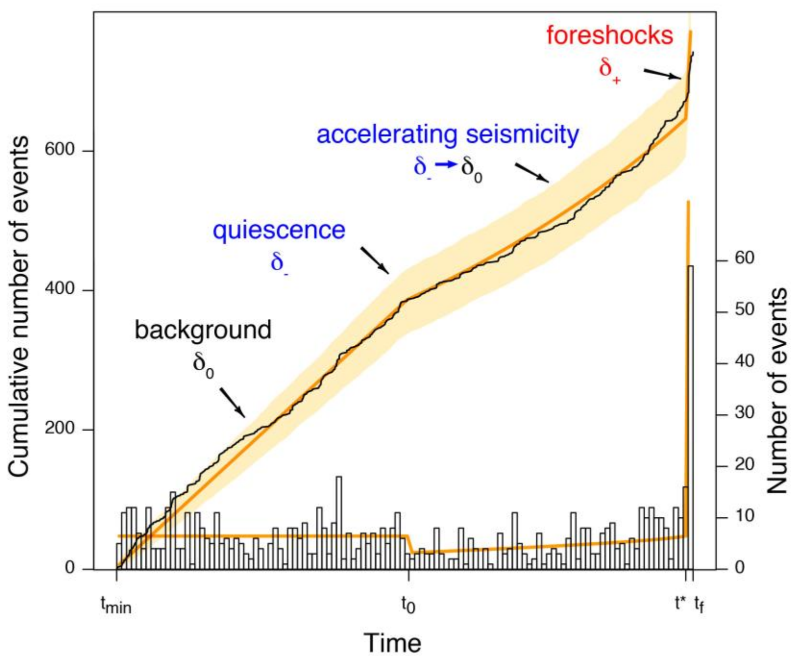
Simulations of precursory seismicity from algebraic model

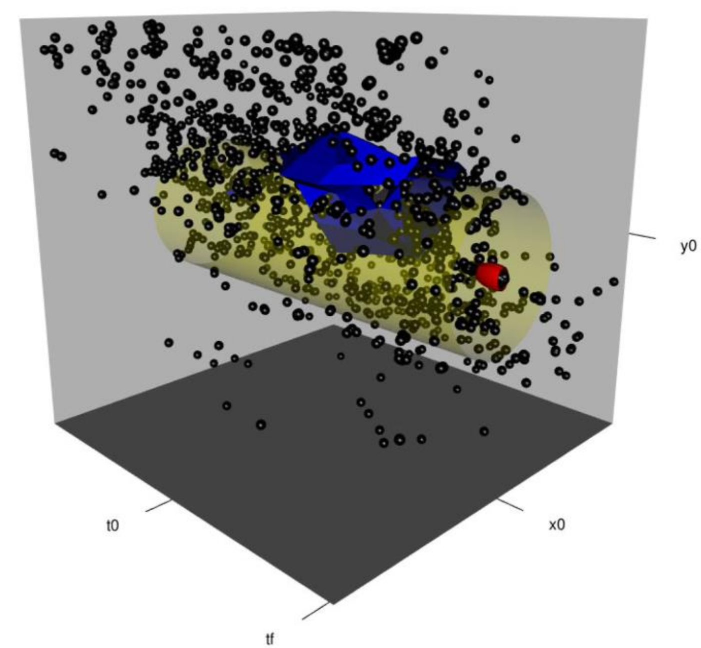




Source: Mignan (GRL 2012)

Observations (2009 L'Aquila mainshock)



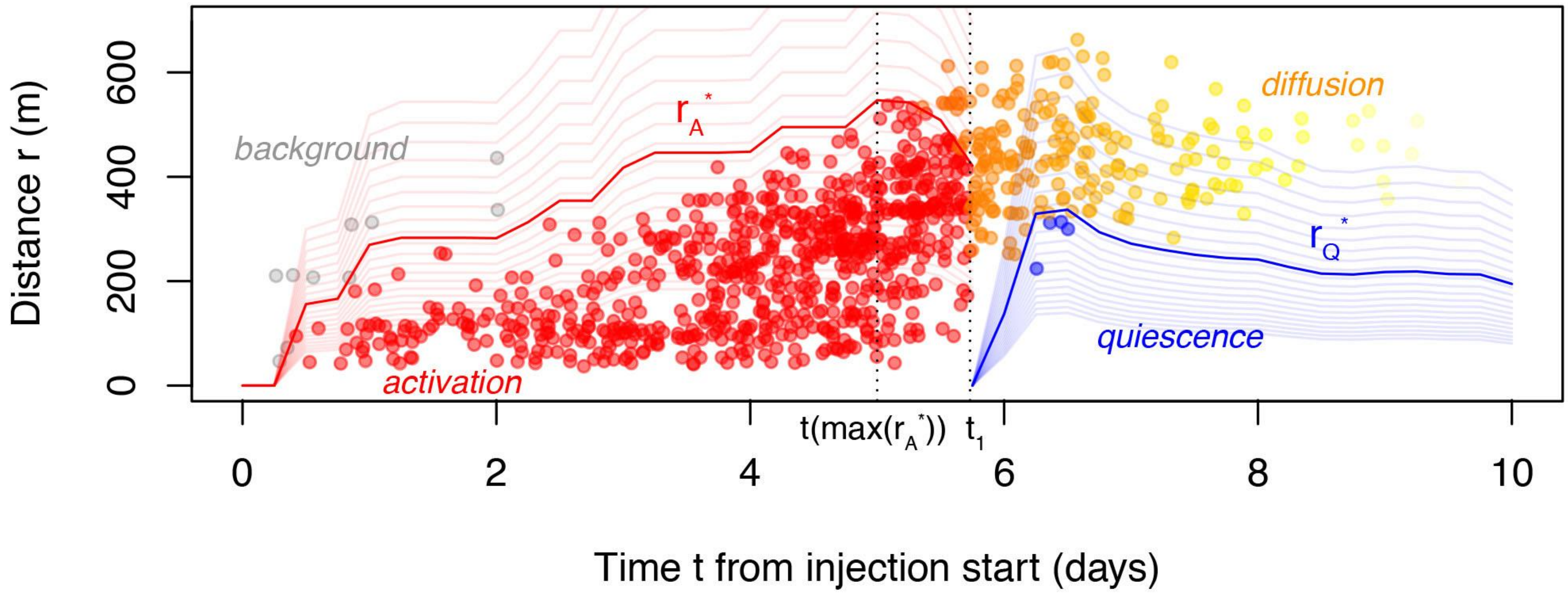


“N-C PAST Postulate” also explains parabolic spatial front & linear relationship μ≈ΔV

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)

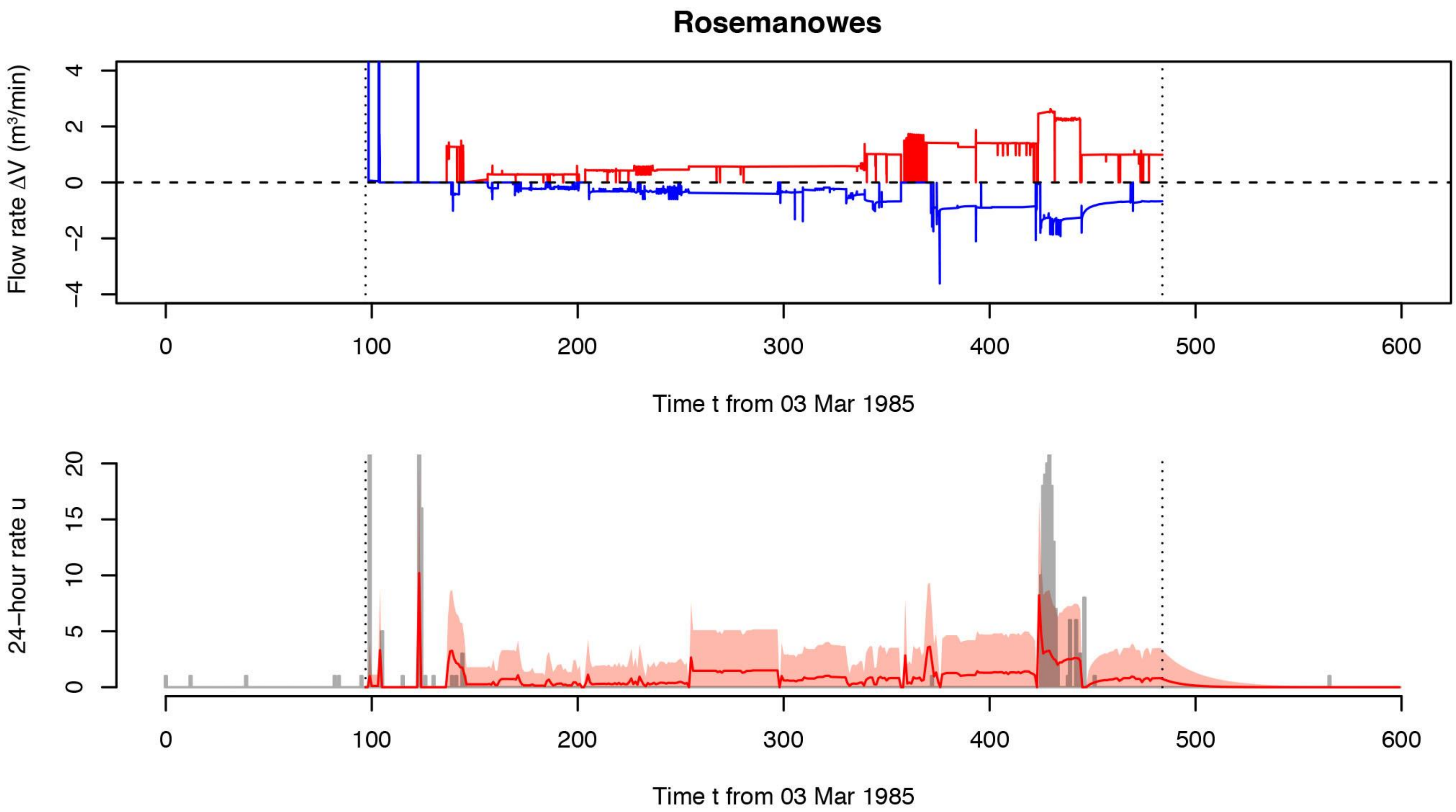


2. Linear relationship between induced seismicity rate & flow rate = direct consequence of 1

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

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

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

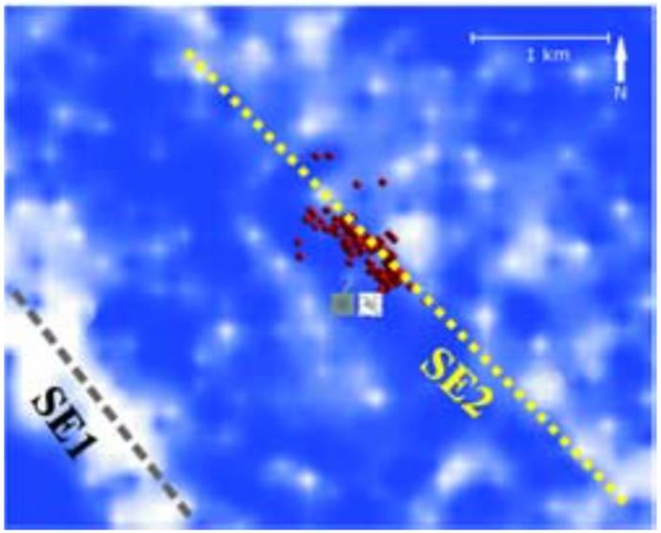


More complicated cases (stem of "complicated" meaning "folded")

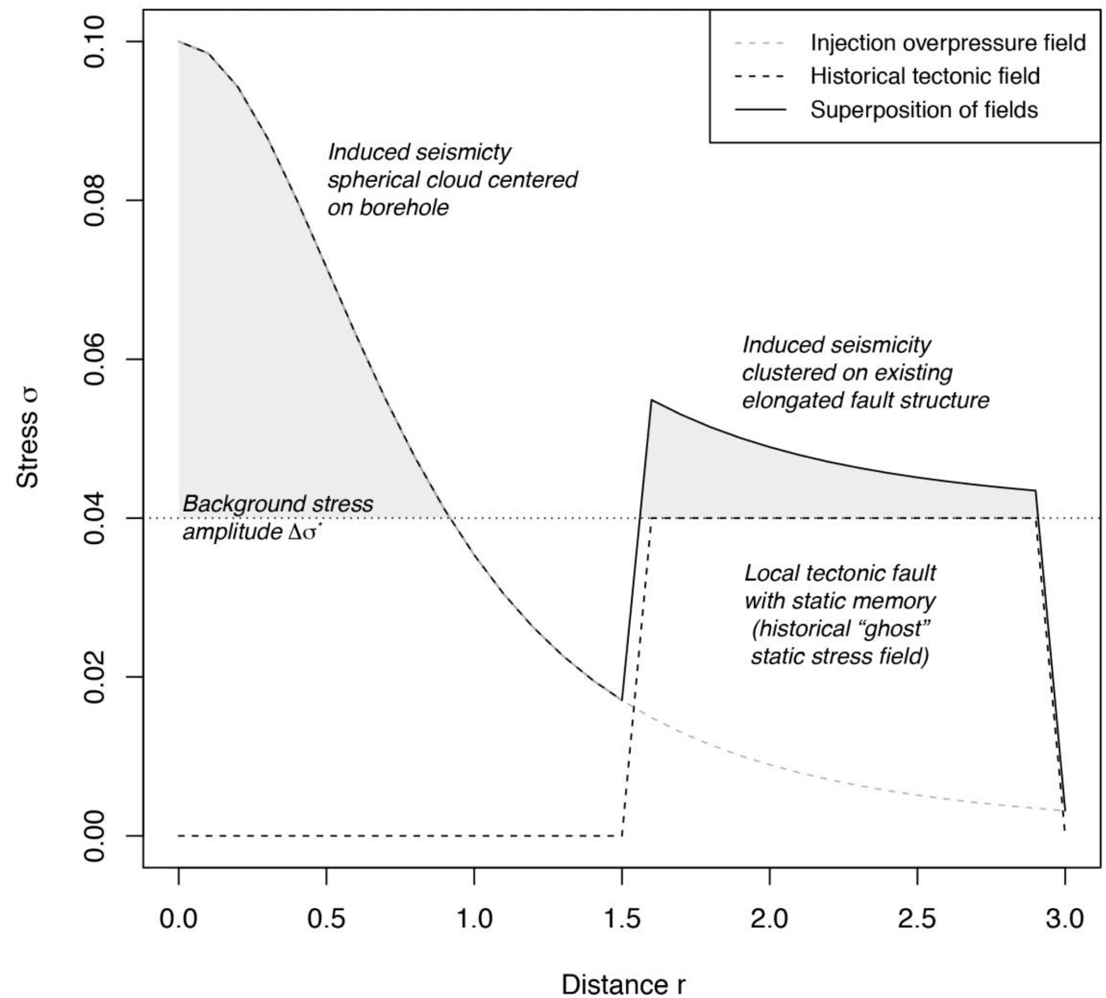
1. **Sum of two pressure fields**, e.g. overpressure + underpressure in production phase

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

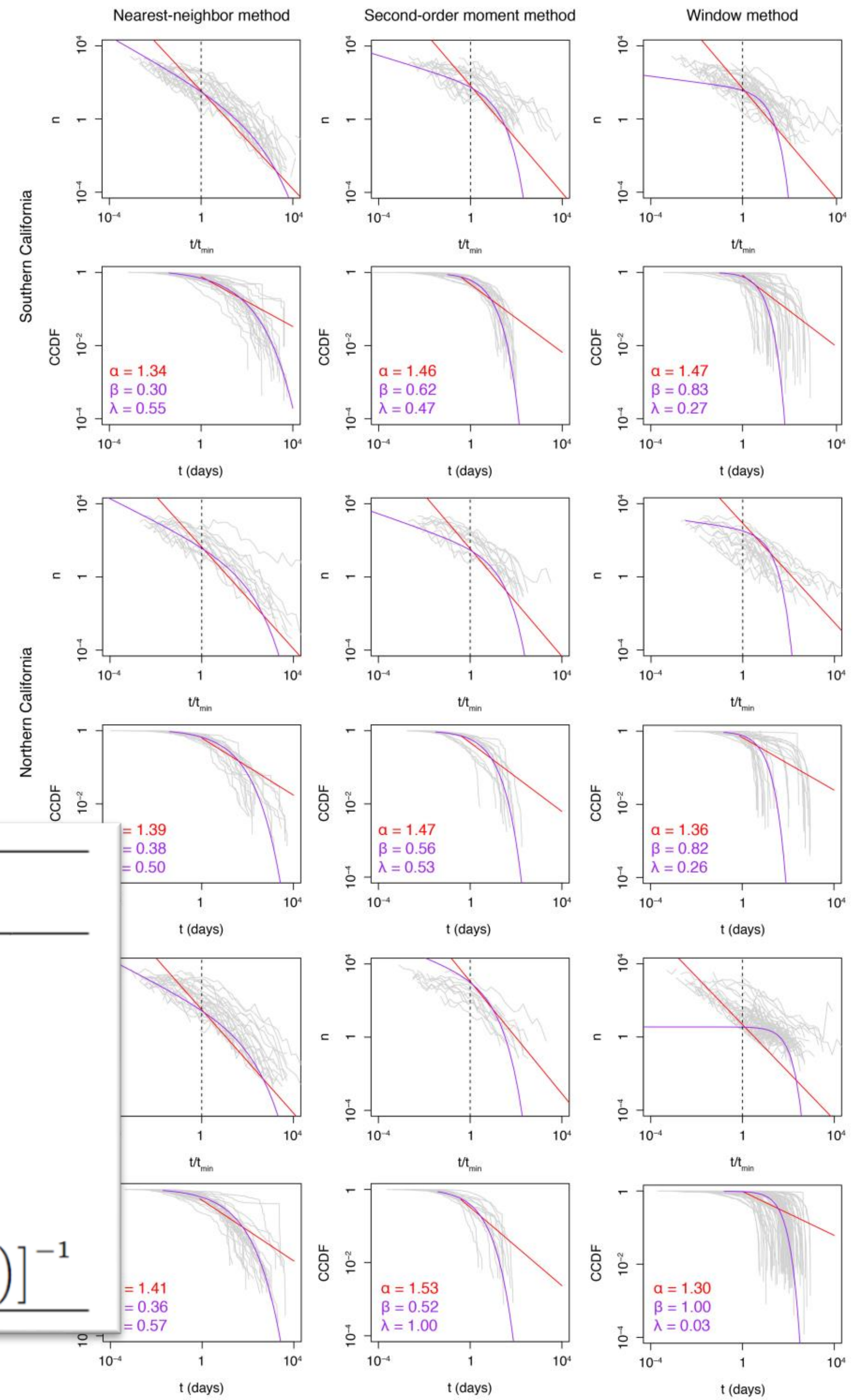


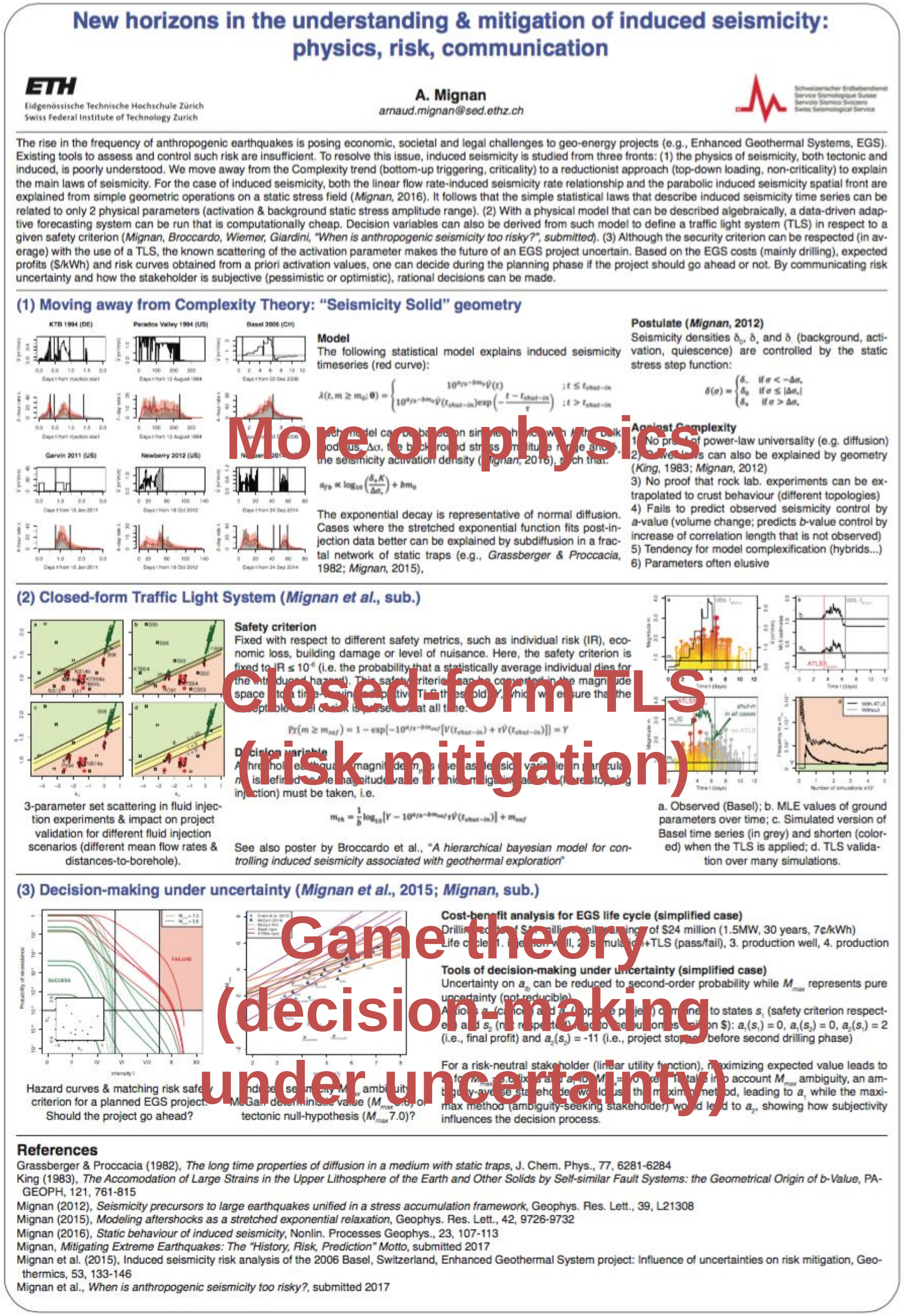
Note on Aftershocks & post-injection relaxation

- ✓ **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	$\frac{1}{x}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]$	$\sqrt{\frac{2}{\pi\sigma^2}}\left[\operatorname{erfc}\left(\frac{\ln x_{\min}-\mu}{\sqrt{2}\sigma}\right)\right]^{-1}$

Source: Clauset et al. (2009)





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

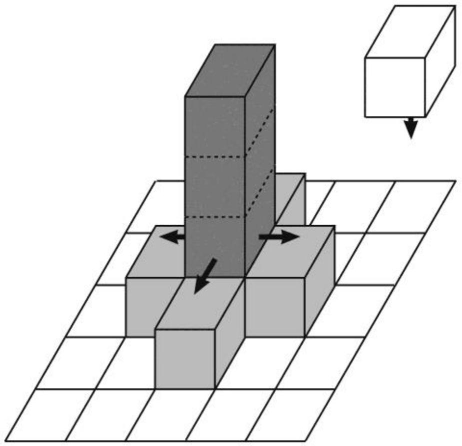
Mignan, A. (2012), Seismicity precursors to large earthquakes unified in a stress accumulation framework, Geophys. Res. Lett., 39, doi: 10.1029/2012GL053946

Mignan, A. (2015), Modeling aftershocks as a stretched exponential relaxation, Geophys. Res. Lett., 42, doi: 10.1002/2015GL066232

Poster P2-11

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

✓ Holistic – Bottom-up triggering – Dynamic – Critical



Local interactions lead to system behaviour

Source: Mignan (Tectonophysics 2011)

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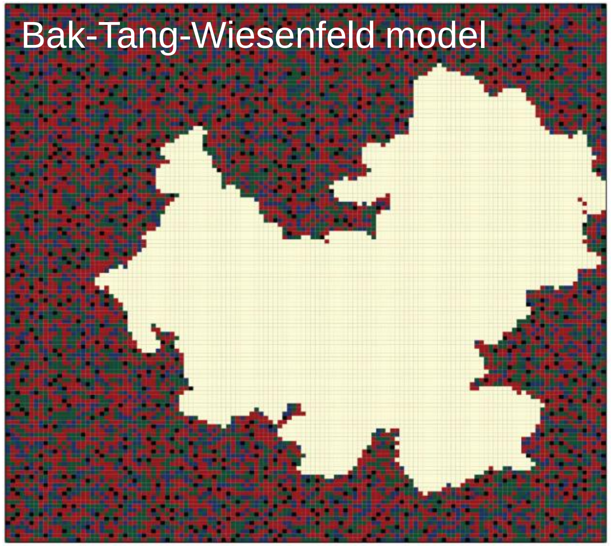
- ✓ Holistic – Bottom-up triggering – Dynamic – Critical
- ✓ Self-Organized Criticality (SOC) gives power-law freq.-size distr.



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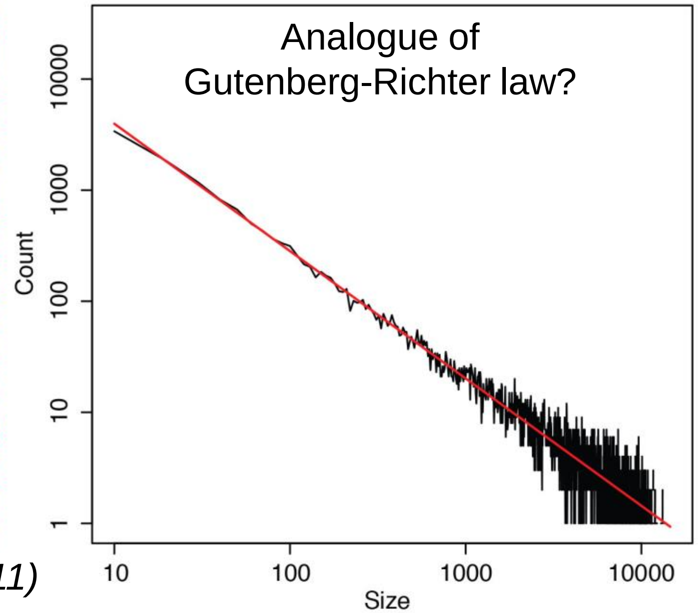

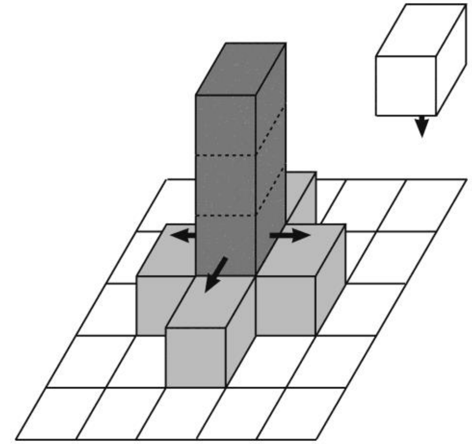

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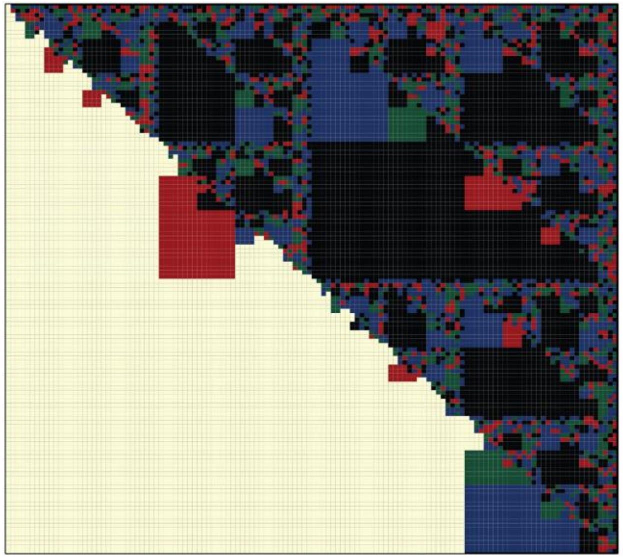

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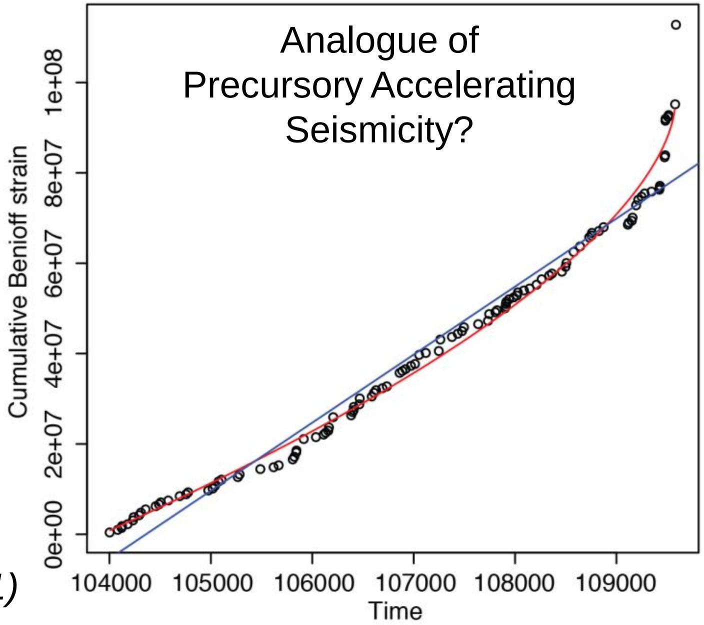

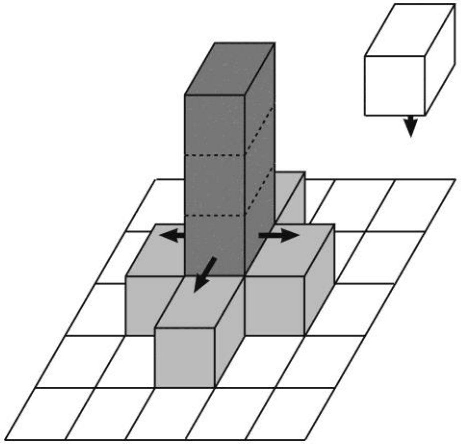

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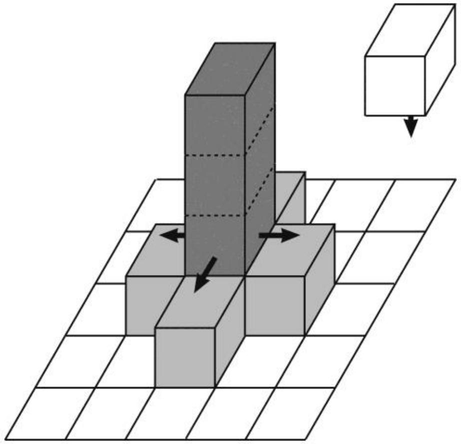
- ✓ **Propositional fallacy**. ***the fact that critical processes lead to power-laws does NOT mean that the presence of power-laws is the proof that critical processes are in play. Indeed:*** ***GEOMETRY also explains GR law (King 1983) & precursors (Mignan 2012)***



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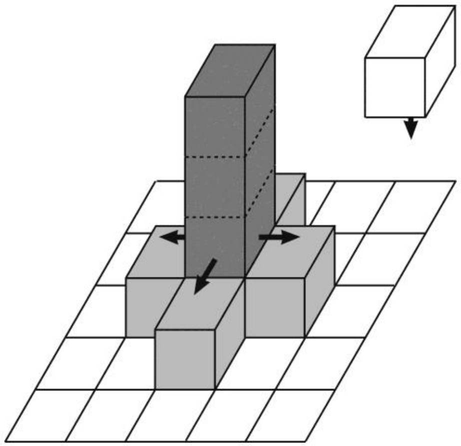
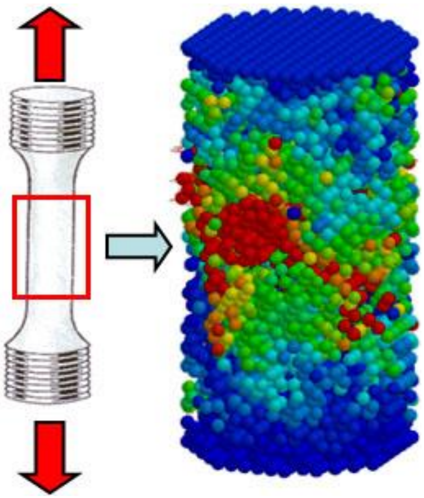


Local interactions lead to system behaviour

- ✓ 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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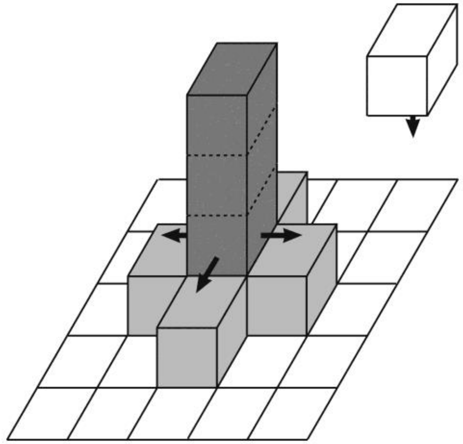

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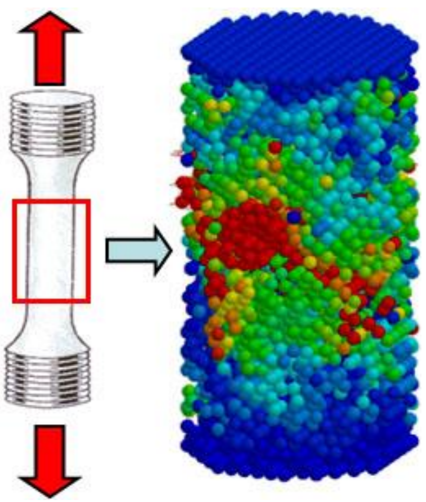
  - ✓ **In terms of GEOMETRY: can we really extrapolate results from a confined cylindrical rock sample to a spherical layer with free surface (crust)? Different TOPOLOGIES**



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