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

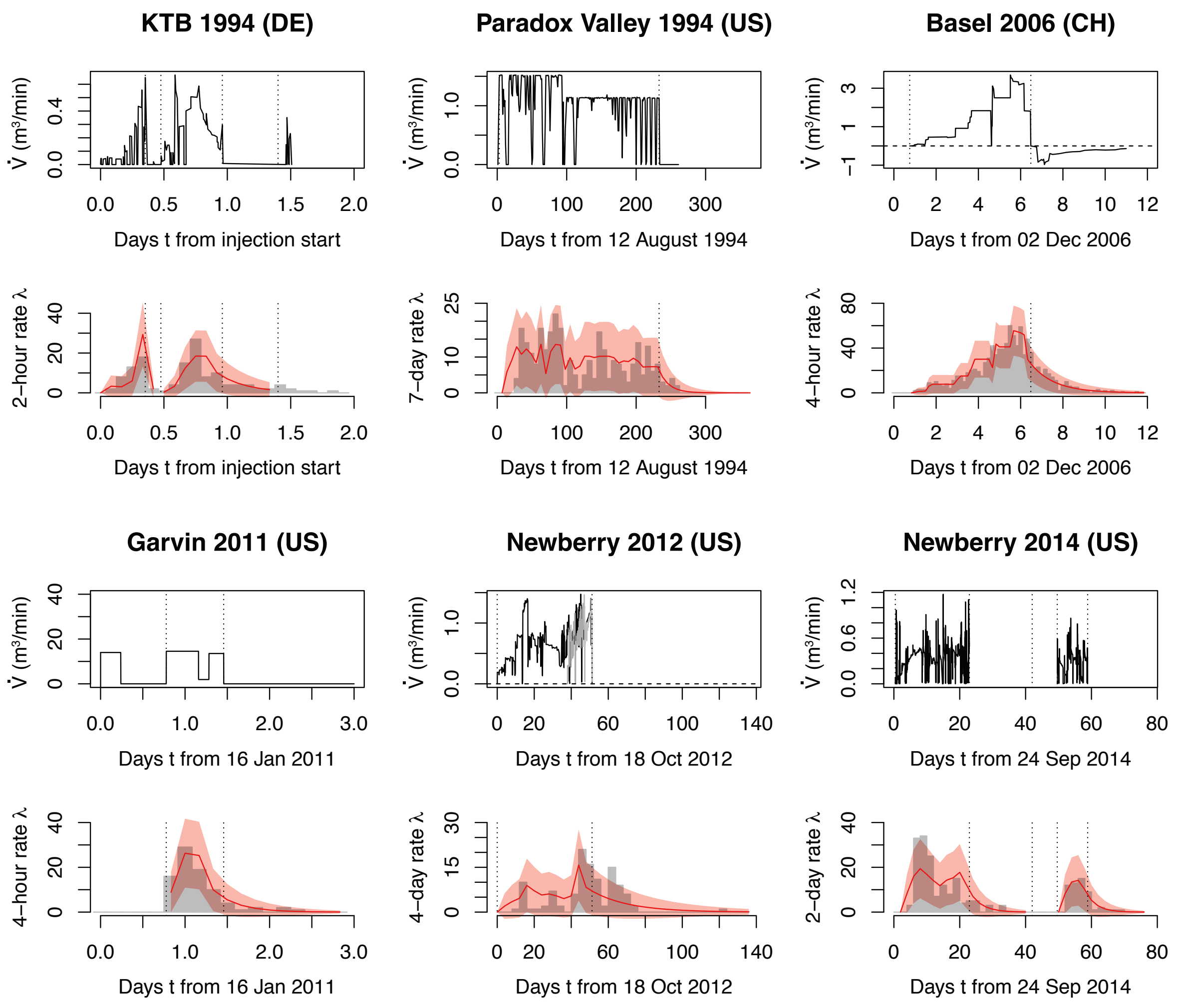
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

A. Mignan
arnaud.mignan@sed.ethz.ch

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

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 risk 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, criticality) to a reductionist approach (top-down loading, non-criticality) 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



Model

The following statistical model explains induced seismicity timeseries (red curve):

$$\lambda(t, m \geq m_0; \boldsymbol{\theta}) = \begin{cases} 10^{a_{fb}-bm_0}\dot{V}(t) & ; t \leq t_{shut-in} \\ 10^{a_{fb}-bm_0}\dot{V}(t_{shut-in})\exp\left(-\frac{t-t_{shut-in}}{\tau}\right) & ; t > t_{shut-in} \end{cases}$$

Such model can be based on simple physics with *K* the bulk modulus, $\Delta\sigma_*$ the background stress amplitude range and δ_+ the seismicity activation density (*Mignan*, 2016), such that:

$$a_{fb} \propto \log_{10}\left(\frac{\delta_+ K}{\Delta\sigma_*}\right) + bm_0$$

The exponential decay is representative of normal diffusion. Cases where the stretched exponential function fits post-injection data better can be explained by subdiffusion in a fractal network of static traps (e.g., *Grassberger & Proccacia*, 1982; *Mignan*, 2015),

Postulate (*Mignan*, 2012)

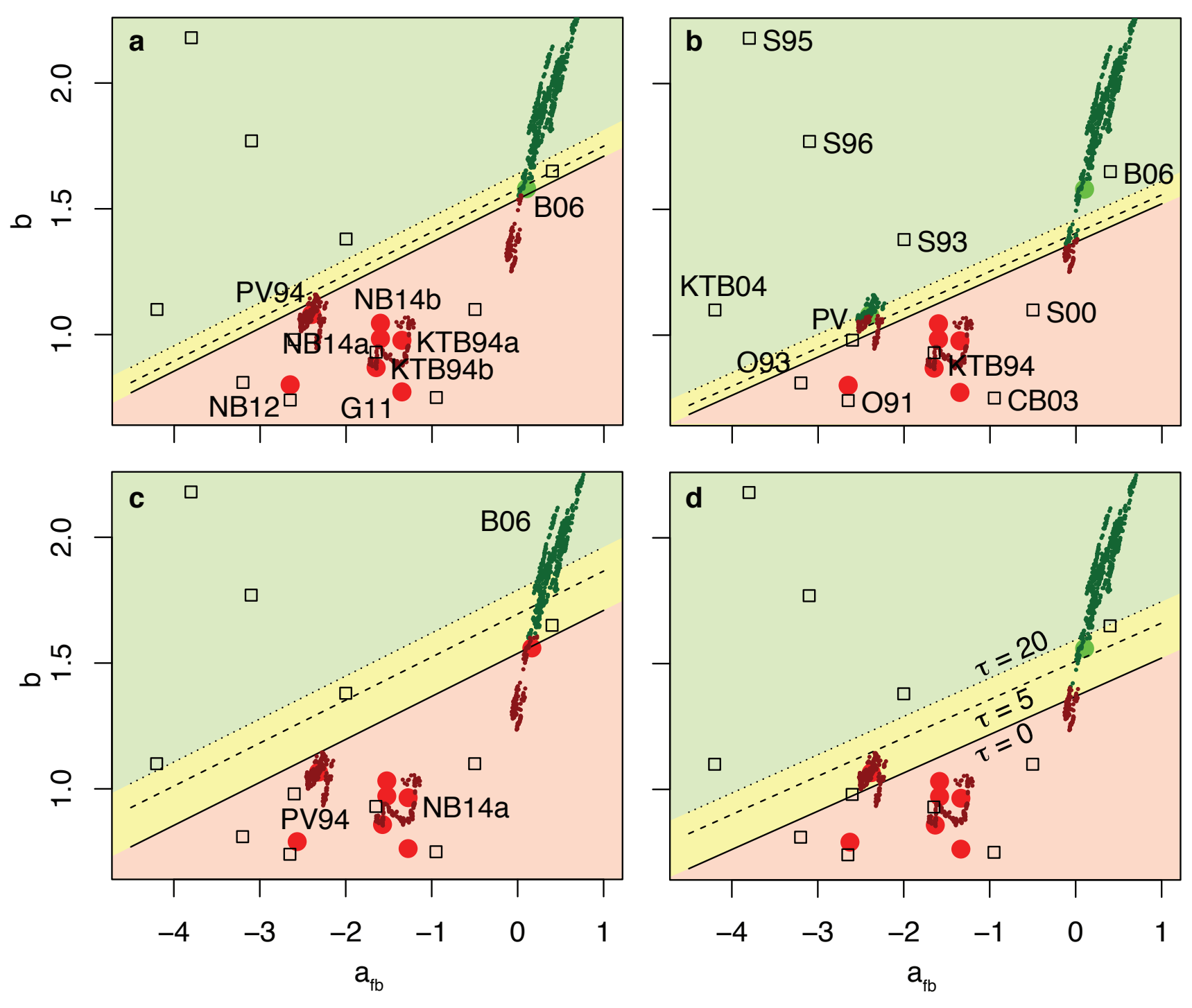
Seismicity densities δ_0, δ_+ and δ_- (background, activation, quiescence) are controlled by the static stress step function:

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

Against Complexity

1) No proof of power-law universality (e.g. diffusion)
2) Power-laws can also be explained by geometry (*King*, 1983; *Mignan*, 2012)
3) No proof that rock lab. experiments can be extrapolated to crust behaviour (different topologies)
4) Fails to predict observed seismicity control by *a*-value (volume change; predicts *b*-value control by increase of correlation length that is not observed)
5) Tendency for model complexification (hybrids...)
6) Parameters often elusive

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



3-parameter set scattering in fluid injection experiments & impact on project validation for different fluid injection scenarios (different mean flow rates & distances-to-borehole).

Safety criterion

Fixed with respect to different safety metrics, such as individual risk (IR), economic loss, building damage or level of nuisance. Here, the safety criterion is fixed to IR ≤ 10^{-6} (i.e. the probability that a statistically average individual dies for the introduced hazard). This safety criterion can be converted in the magnitude space into a time-varying adaptative TLS threshold, *Y*, which will ensure that the acceptable level of risk is preserved at all time:

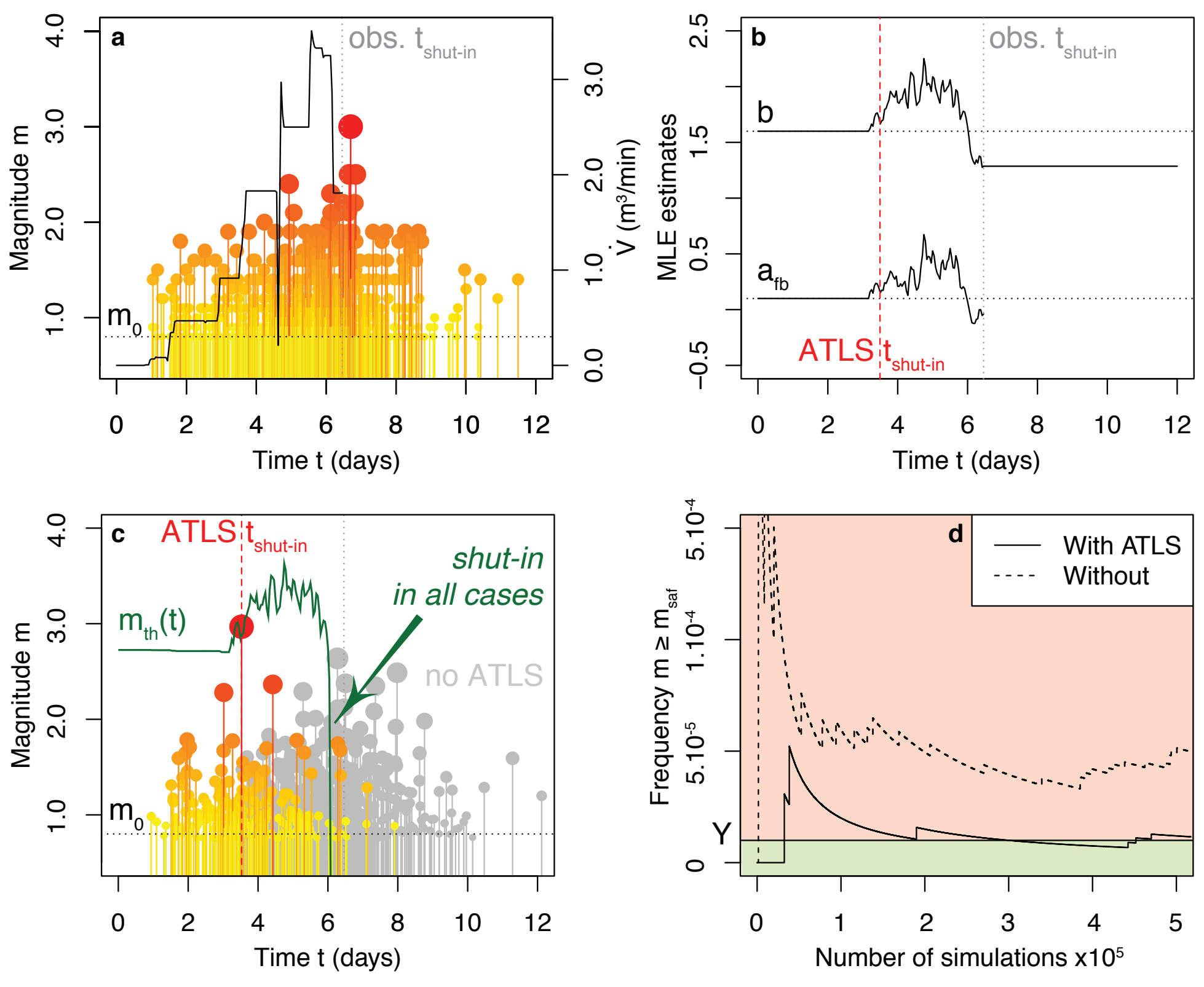
$$\Pr(m \geq m_{saf}) = 1 - \exp\{-10^{a_{fb}-bm_{saf}}[V(t_{shut-in}) + \tau\dot{V}(t_{shut-in})]\} = Y$$

Decision variable

A threshold earthquake magnitude m_{th} is used as decision variable. In particular, m_{th} is defined as the magnitude value for which mitigating actions (here stopping injection) must be taken, i.e.

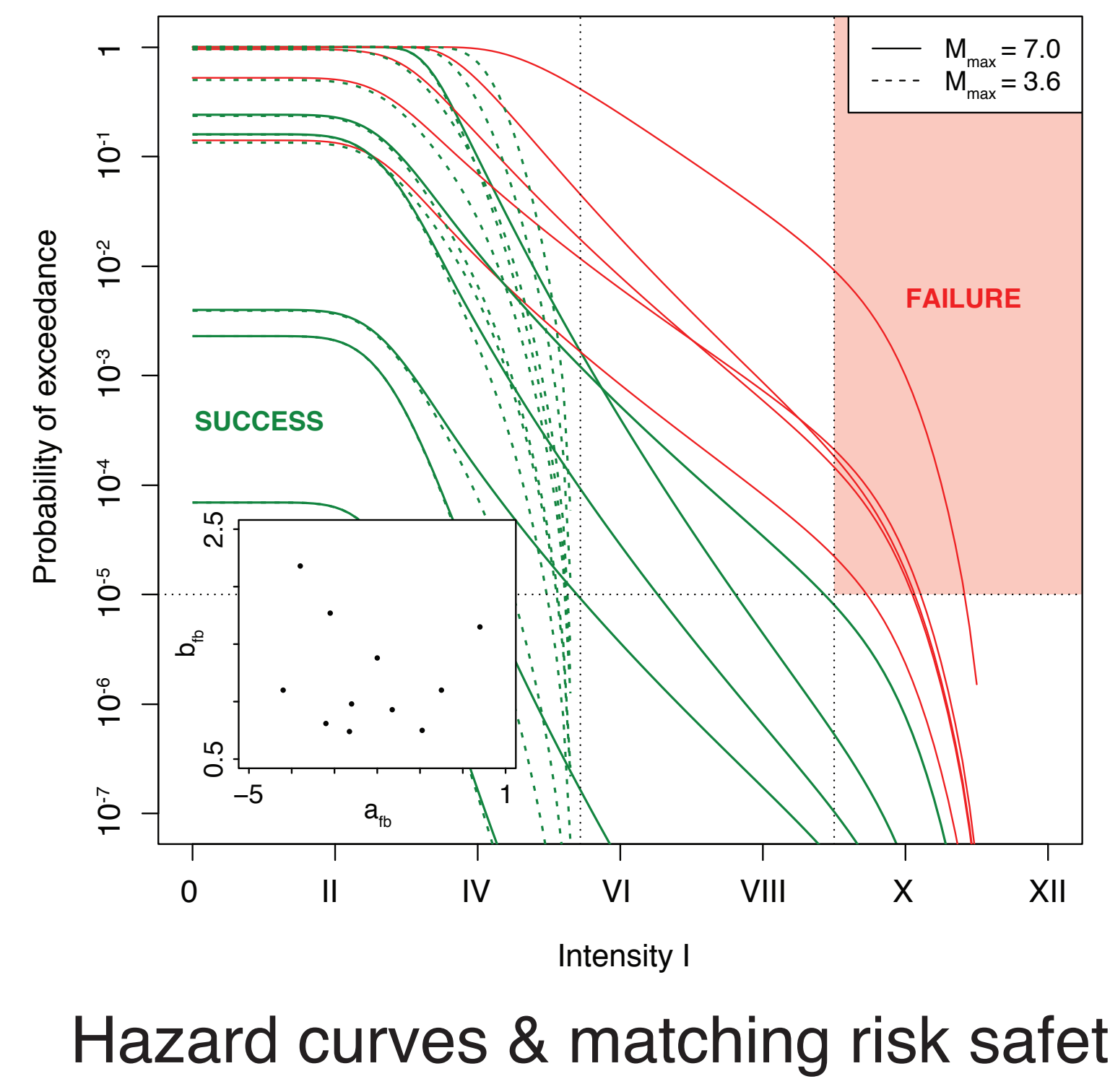
$$m_{th} = \frac{1}{b}\log_{10}[Y - 10^{a_{fb}-bm_{saf}}\tau\dot{V}(t_{shut-in})] + m_{saf}$$

See also poster by Broccardo et al., "*A hierarchical bayesian model for controlling induced seismicity associated with geothermal exploration*"

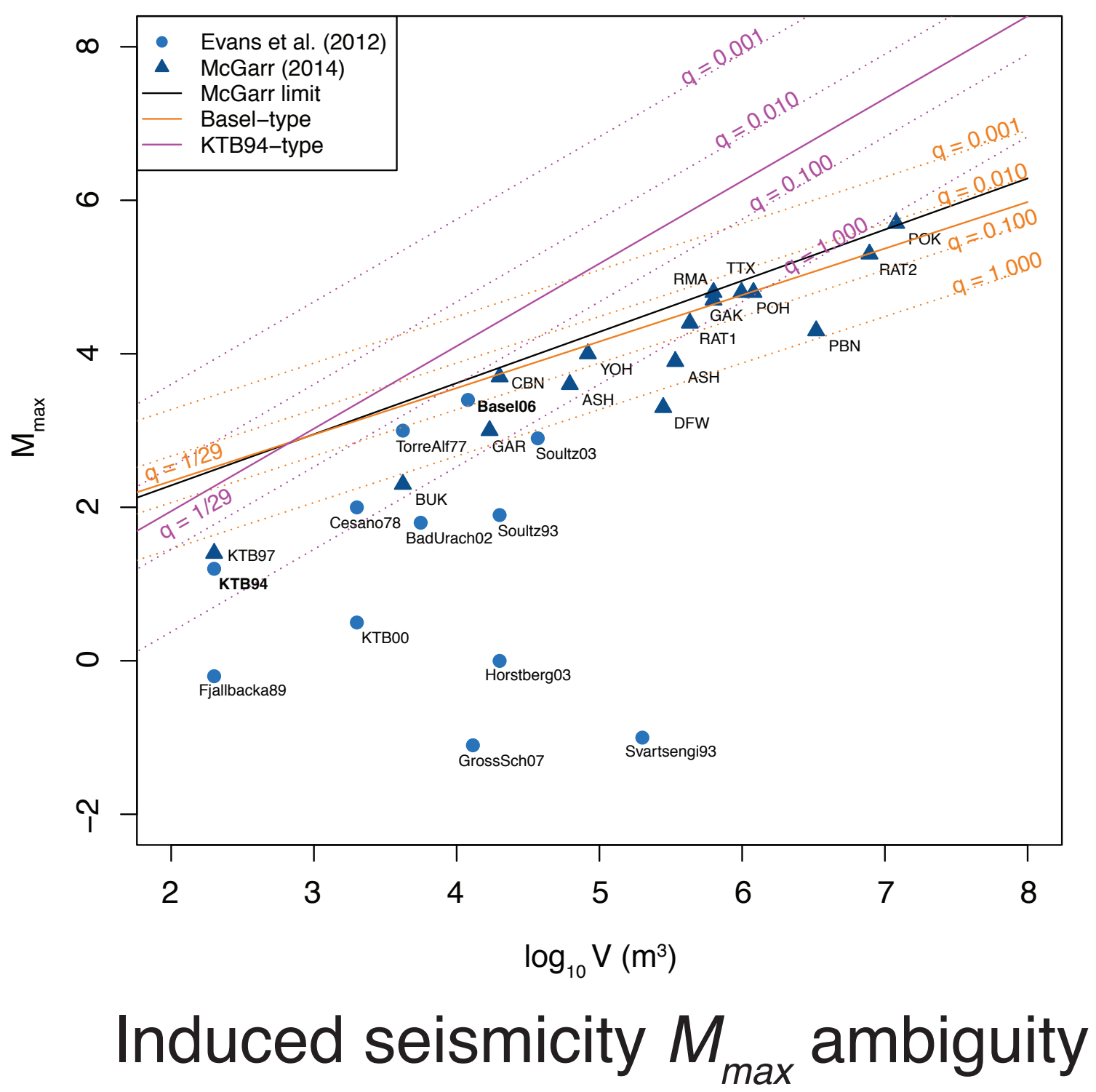


a. Observed (Basel); b. MLE values of ground parameters over time; c. Simulated version of Basel time series (in grey) and shorten (colored) when the TLS is applied; d. TLS validation over many simulations.

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



Hazard curves & matching risk safety criterion for a planned EGS project: Should the project go ahead?



Induced seismicity M_{max} ambiguity: McGarr deterministic value (M_{max} 3.6) or tectonic null-hypothesis (M_{max} 7.0)?

Cost-benefit analysis for EGS life cycle (simplified case)

Drilling costs of $11 million/well, earnings of $24 million (1.5MW, 30 years, 7¢/kWh)
Life cycle: 1. injection well, 2. stimulation+TLS (pass/fail), 3. production well, 4. production

Tools of decision-making under uncertainty (simplified case)

Uncertainty on a_{fb} can be reduced to second-order probability while M_{max} represents pure uncertainty (not reducible)
Actions a_1 (cancel) and a_2 (approve project) combined to states s_1 (safety criterion respected) and s_2 (not respected) lead to the outcomes (million $): $a_1(s_1) = 0$, $a_1(s_2) = 0$, $a_2(s_1) = 2$ (i.e., final profit) and $a_2(s_2) = -11$ (i.e., project stopped before second drilling phase)

For a risk-neutral stakeholder (linear utility function), maximizing expected value leads to a_2 for M_{max}=3.6 fixed and a_1 for M_{max}=7.0 fixed. To take into account M_{max} ambiguity, an ambiguity-averse stakeholder would use the maximin method, leading to a_1 while the maximax method (ambiguity-seeking stakeholder) would lead to a_2, showing how subjectivity influences the decision process.

References

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