Erice, 2007

Recurrence-time statistics of large earthquakes resulting from stochastic rupture nucleation and fault interaction

Sebastian Hainzl

Gert Zöller

in collaboration with: Licia Faenza, Nicolas Kühn, Frank Scherbaum, Yehuda Ben-Zion, Matthias Holschneider

Questions:

(1) Do large earthquakes occur quasi-periodically on fault segments?
Existence of seismic cycles?

… contradictory evidence for seismic gaps from rare observational data

(2) What is the impact of the Gutenberg-Richter type background activity on the regularity of the recurrence of the mainshocks?

(3) Does fault coupling destroy any "natural" cycling?

→ Impact on seismic hazard estimations?

Outline:

(1) Introduction

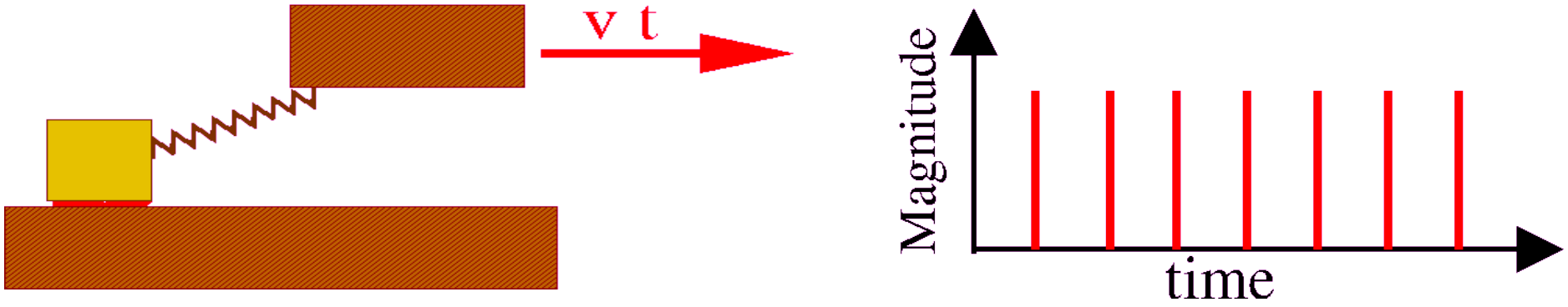
(2) Stochastic earthquake models:
Stress Release Model & Brownian Oscillator

(3) Results of model simulations
... for isolated faults
... for a coupled fault network

(4) Summary & Conclusions

Introduction

Simplified theory *Reid's elastic rebound theory (1910)*



... leads to periodic recurrence of earthquakes

However, real earthquake processes include:

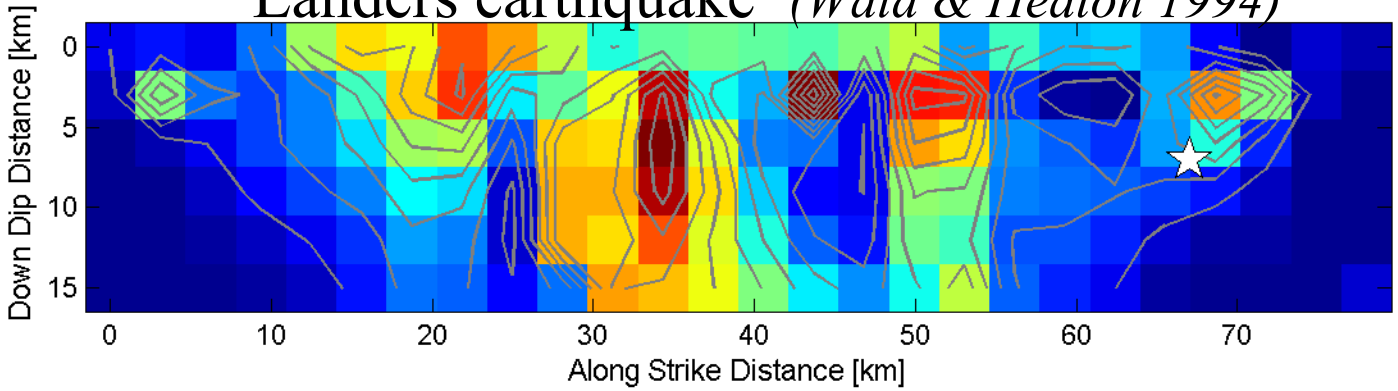
- **stochastic rupture nucleation & propagation**

Introduction

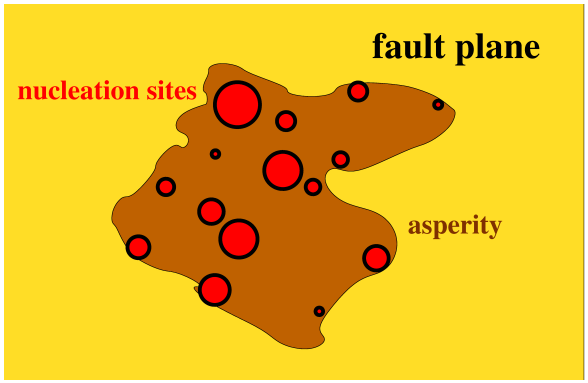
Stochastic rupture nucleation & propagation

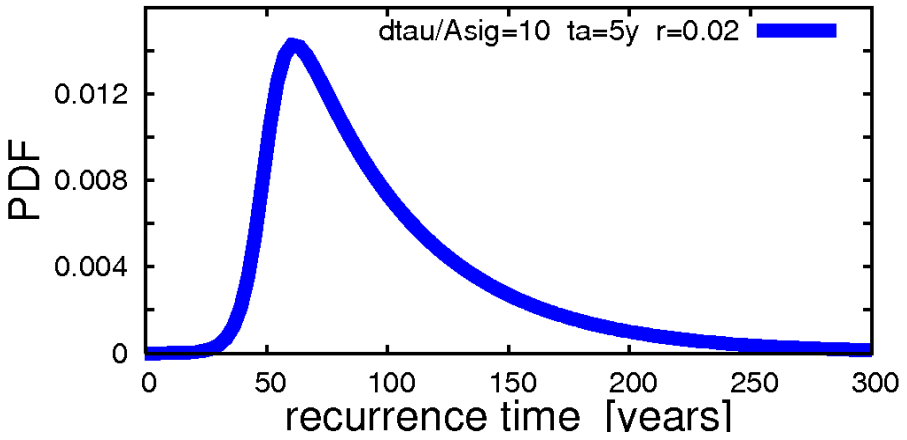
slip

Landers earthquake *(Wald & Heaton 1994)*



nucleation



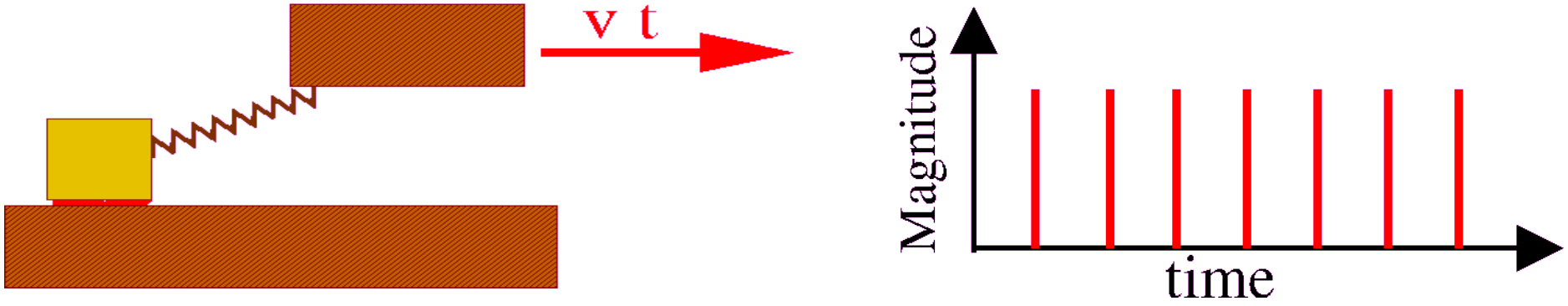


Population of independent nucleation sites *(Dieterich, 1994)*

$$p(t) = re^{\frac{rt_a\triangle\tau}{A\sigma}}\left[1+(e^{\frac{\triangle\tau}{A\sigma}}-1)e^{-\frac{t}{t_a}}\right]^{-1-rt_a}\cdot e^{-rt}$$

Introduction

Simplified theory *Reid's elastic rebound theory (1910)*



... leads to periodic recurrence of earthquakes

However, real earthquake processes include:

- stochastic rupture nucleation & propagation
- **occurrence of small to intermediate size events**

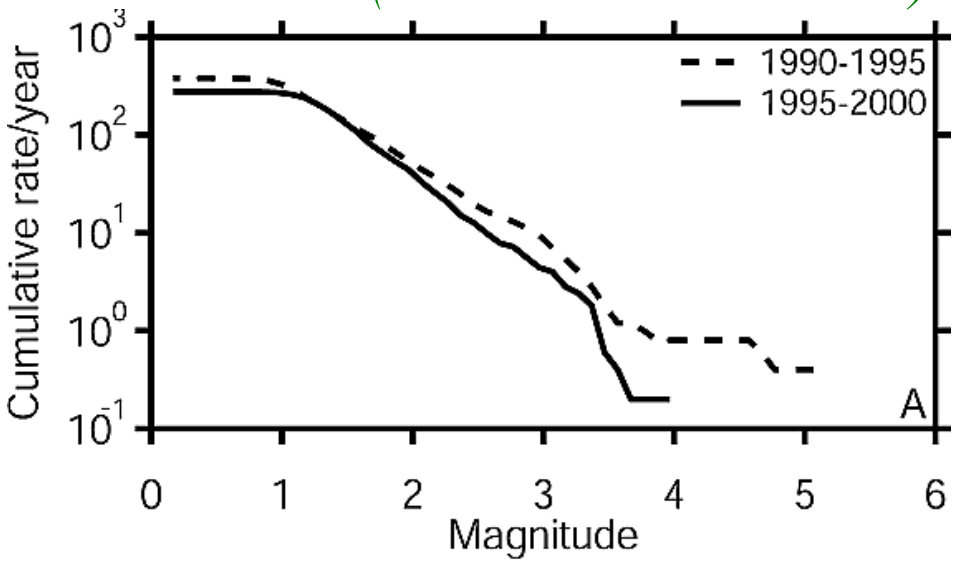
Occurrence of small to intermediate size events

Gutenberg-Richter law

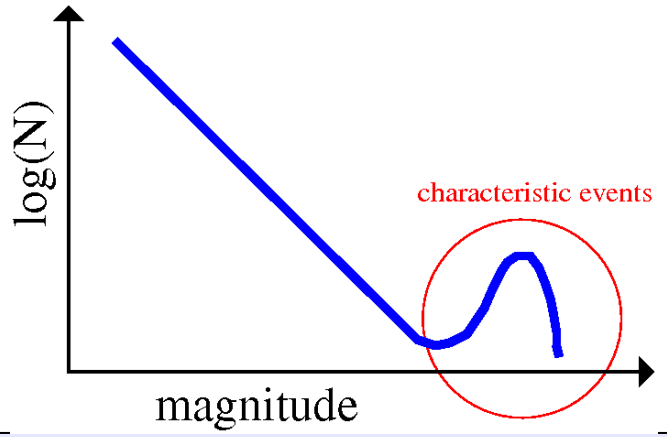
is almost universal

... also for on-fault seismicity

Parkfield *(Schorlemmer et al. 2004)*

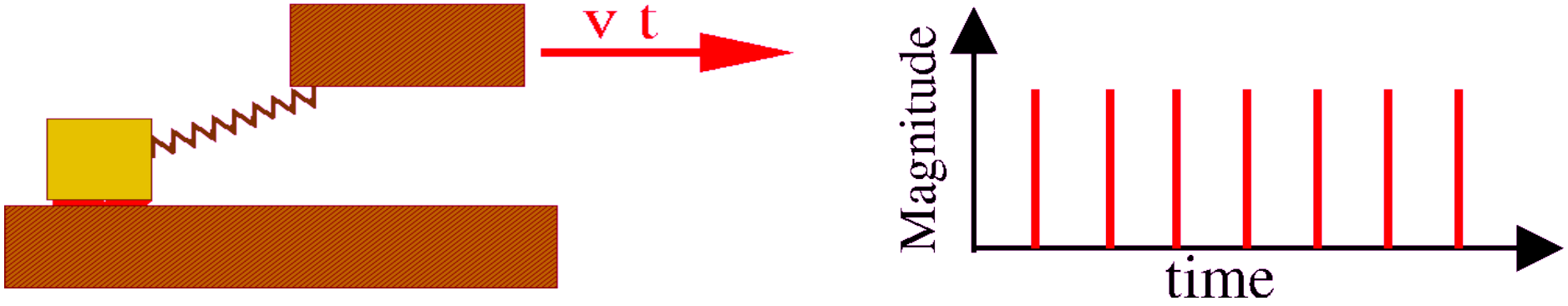


... only weak indications for characteristic size distribution



Introduction

Simplified theory *Reid's elastic rebound theory (1910)*



... leads to periodic recurrence of earthquakes

However, real earthquake processes include:

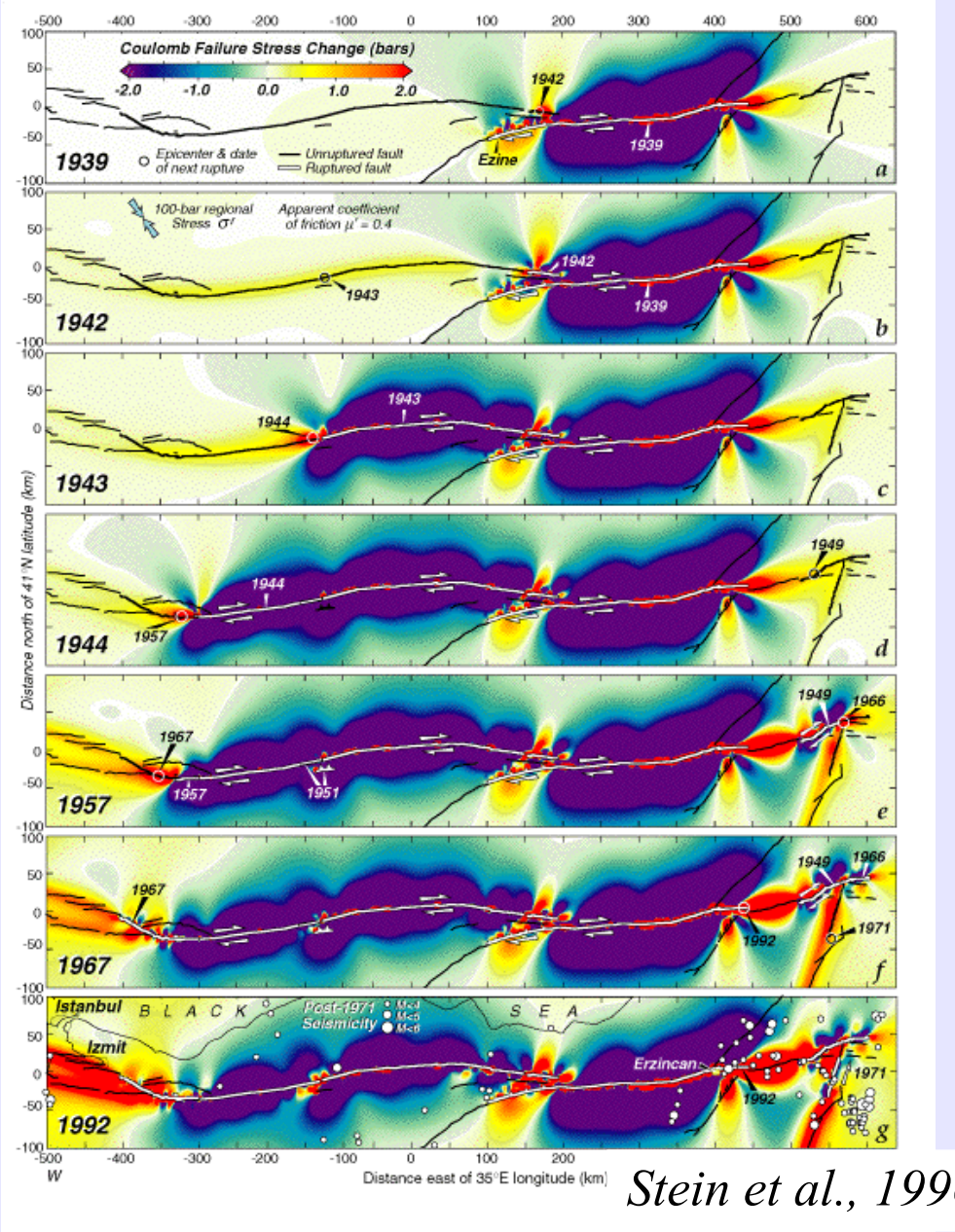
- stochastic rupture nucleation & propagation
- occurrence of small to intermediate size events
- **fault interactions**

Fault interactions

faults are seldom isolated and are usually part of a **fault-network**

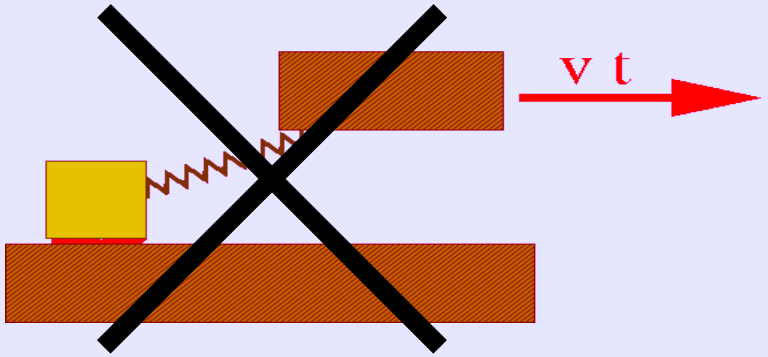
communication by e.g. **Coulomb-stress interactions**

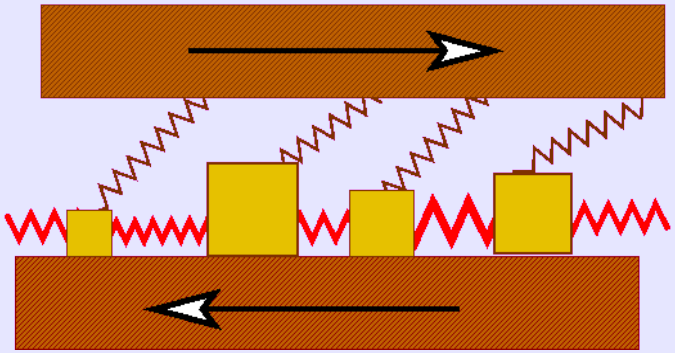
example: *North Anatolia*



Stein et al., 1996

Randomization of the recurrence of mainshocks?





heterogeneous nucleation & ruptures

\+ effect of small to intermediate earthquakes

\+ fault interactions

? ... leads to SOC (self-organized criticality)

to completely randomized mainshock occurrence ?

Stochastic earthquake models

... can parameterize unresolvable small-scale properties and dynamics by stochastic components

... are hoped to capture the fundamental processes

... can simulate thousands of seismic cycles in extended fault networks

We study the following “mainshock” models:

(A) **Stress-Release model** *(Vere-Jones, 1978)*

(B) **Brownian Relaxation model** *(Matthews et al. 2002)*

Stress Release model

Assumptions:

- scalar "stress" state S which changes by

(a) tectonic loading: $dS = \rho\, dt$

(b) earthquakes of magnitude M: $dS = -10^{h M}$

where the maximum magnitude is limited by available "stress"

→ **S(t) = S(0) + loading − sum of stress drops**

- hazard function / local earthquake rate

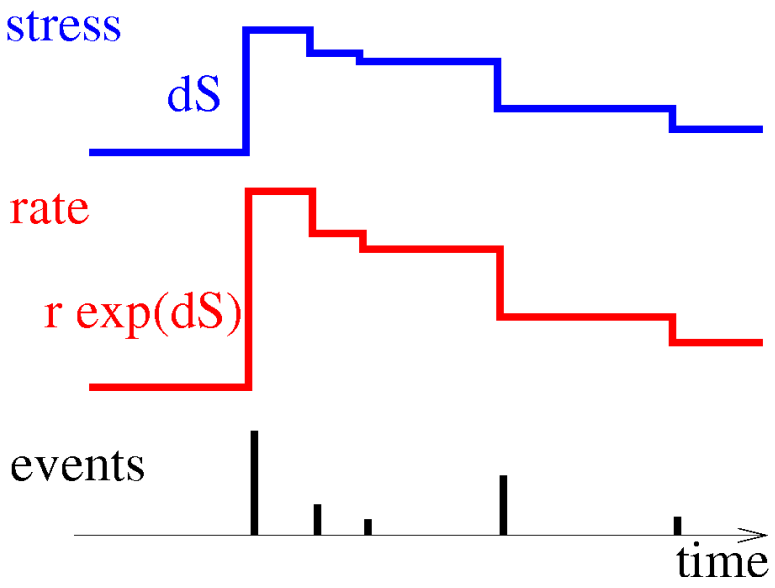
$$r(t) = r_0 \exp [c\, S(t)]$$

Stress Release model

stress jump dS leads to change of

rate = r exp(c dS)

in agreement with response of a fault population with rate-state friction (Dieterich, 1994)



By using the frequency-magnitude distribution as independent information (a, b, and M_{max}), most parameters can be fixed and the only free parameters are:

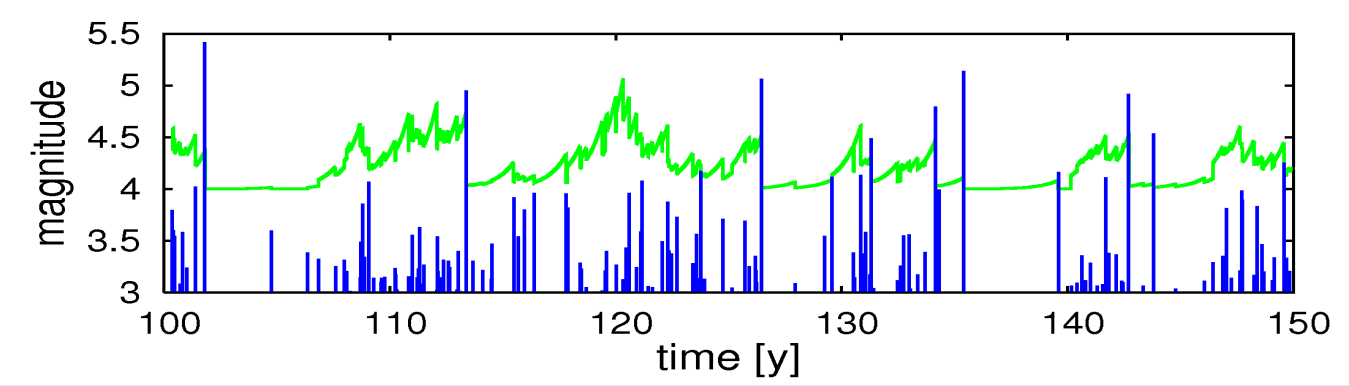
h scaling between "stress"-change and earthquake magnitude

c relative importance of earthquake stress redistribution

Stress Release model: Isolated fault

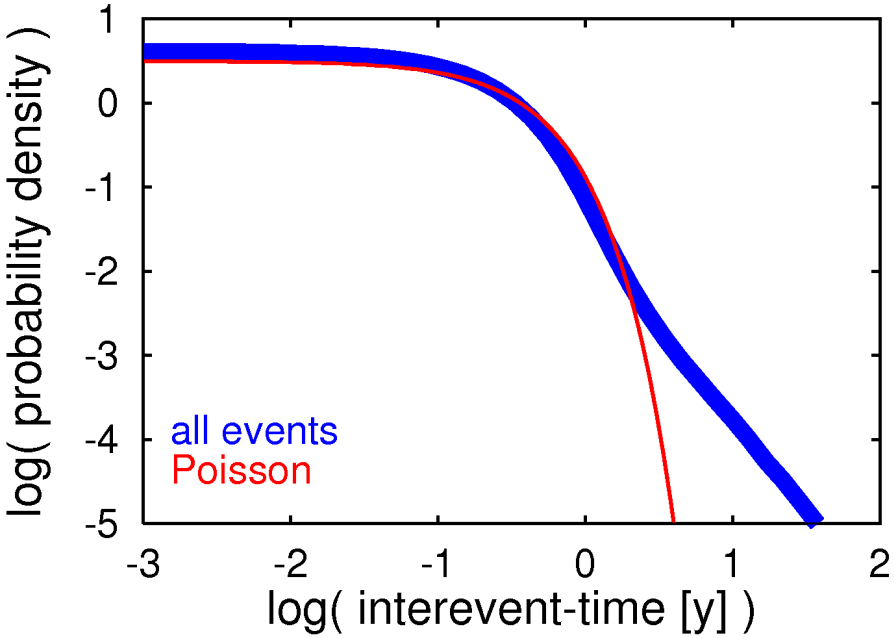
(Kühn et al., sub.)

Example:

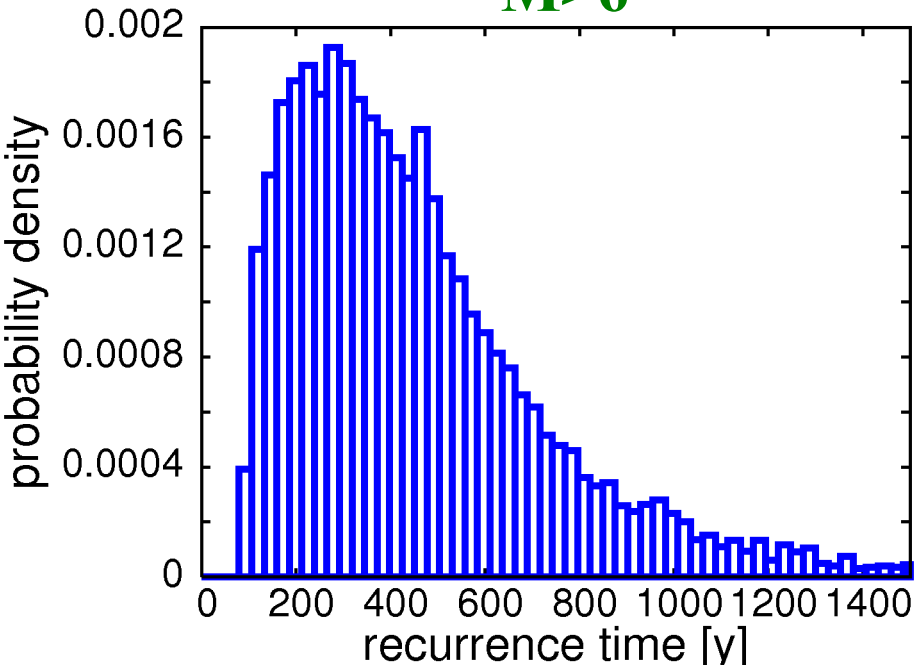


Distribution of Recurrences:

all events



M>6

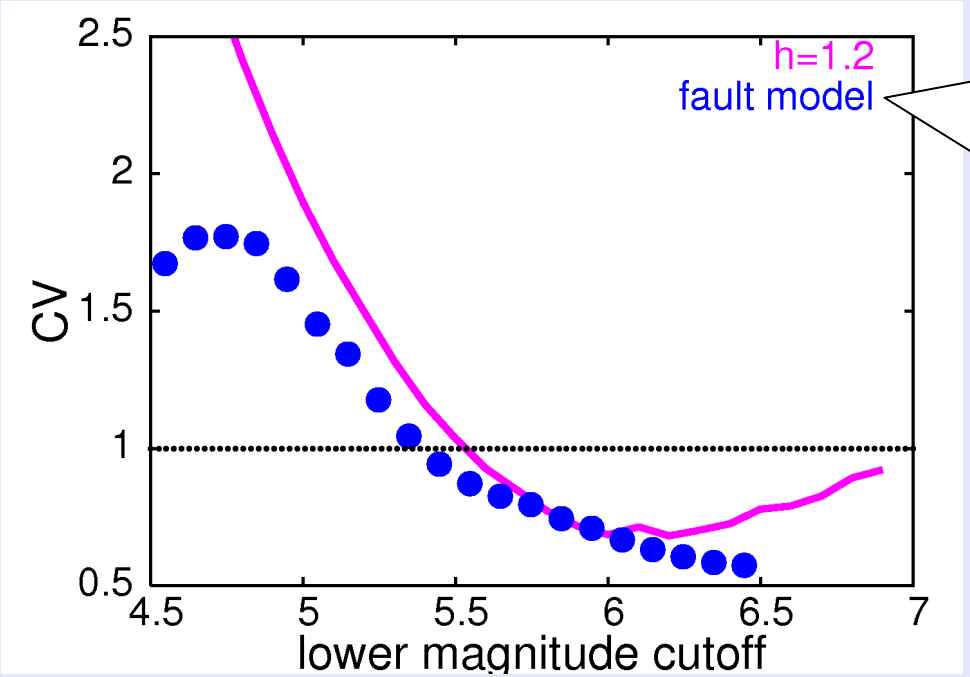


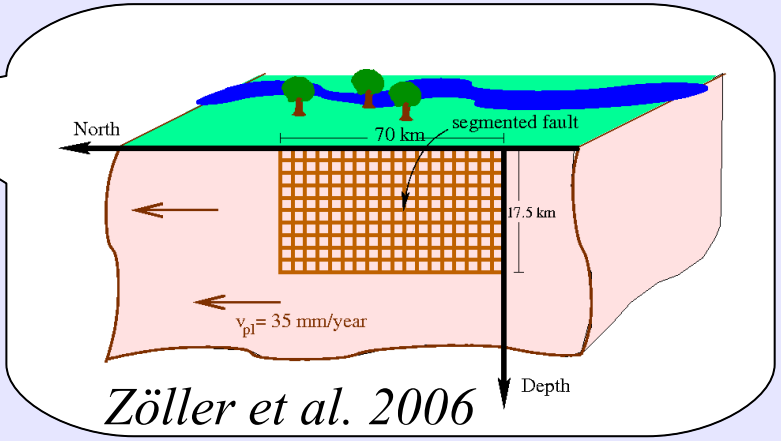
Stress Release model: Isolated fault

(Kühn et al., sub.)

Coefficient of variation ("aperiodicity"): **CV = std / mean**

CV = 0	periodic
CV < 1	quasi-periodic
CV = 1	random (Poisson-process)
CV > 1	clustering



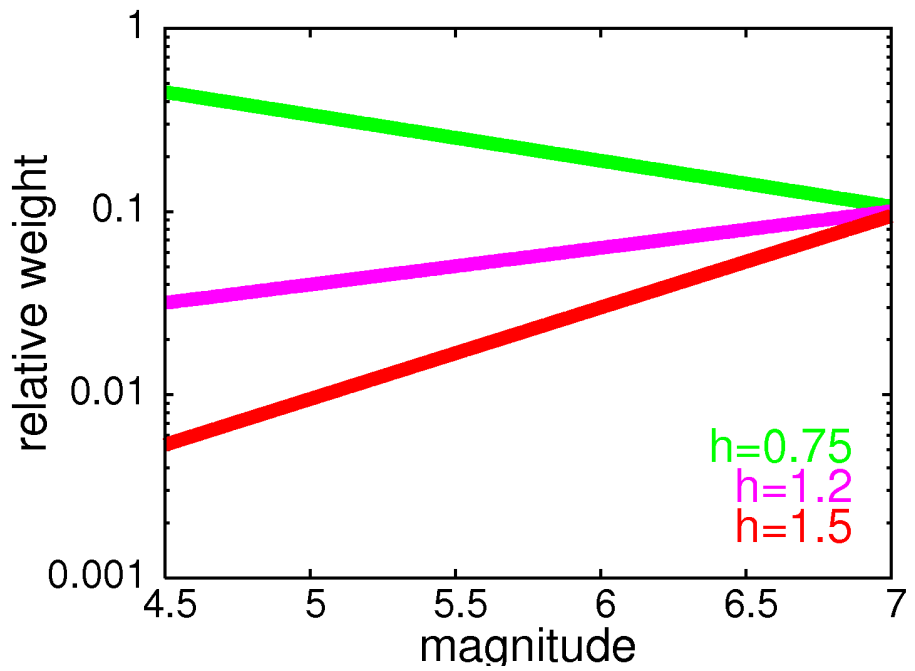


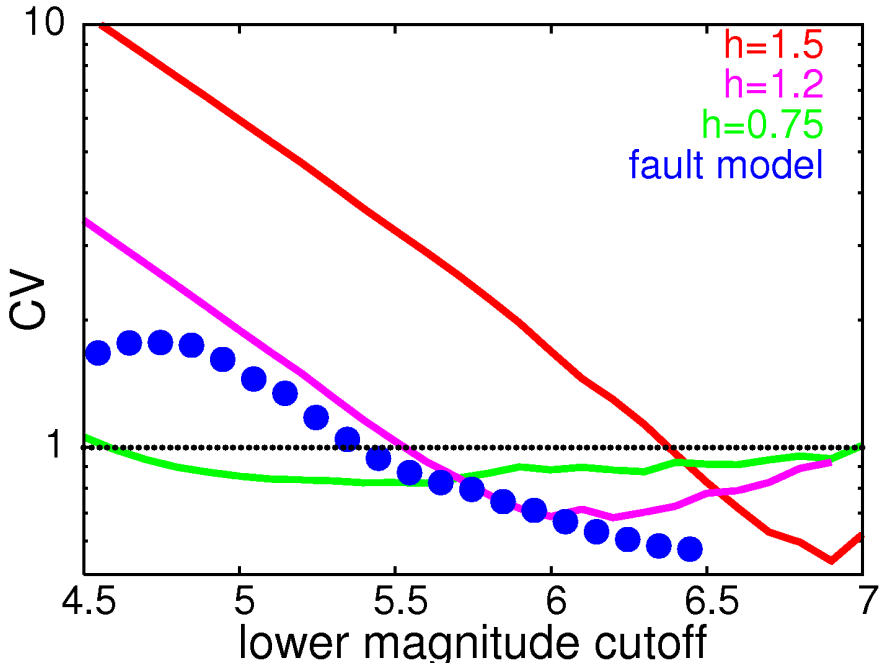
Zöller et al. 2006

Stress Release model: Isolated fault

(Kühn et al., sub.)

Degree of "quasi-periodicity" of large events depend on **parameter h** which determines the relative importance of smaller events for stress redistribution...





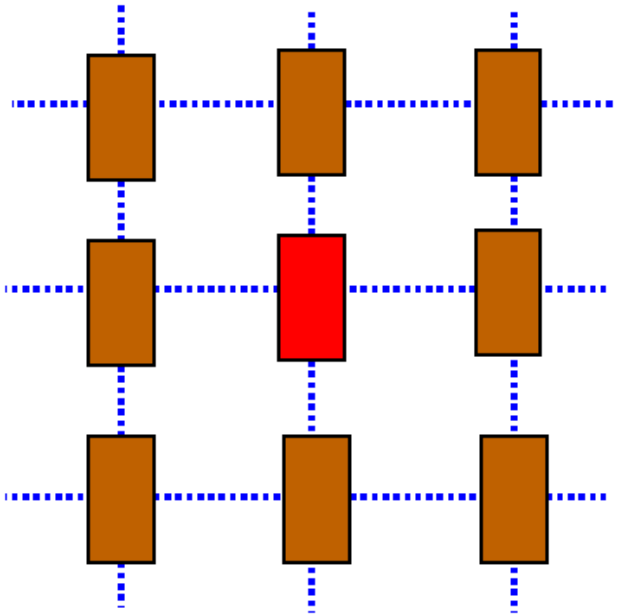
However, **weak seismic cycles occur** even in the case of the dominance of small magnitude events!

Stress Release model: FAULT NETWORK

$$S^{(i)}(t) = S^{(i)}(0) + \rho^{(i)}\, t - \sum_j \hat{\tau}_{ij}\ sumS^{(j)}(t)$$

sumS(j) = cumulative "stress"-release by earthquakes in region (j)

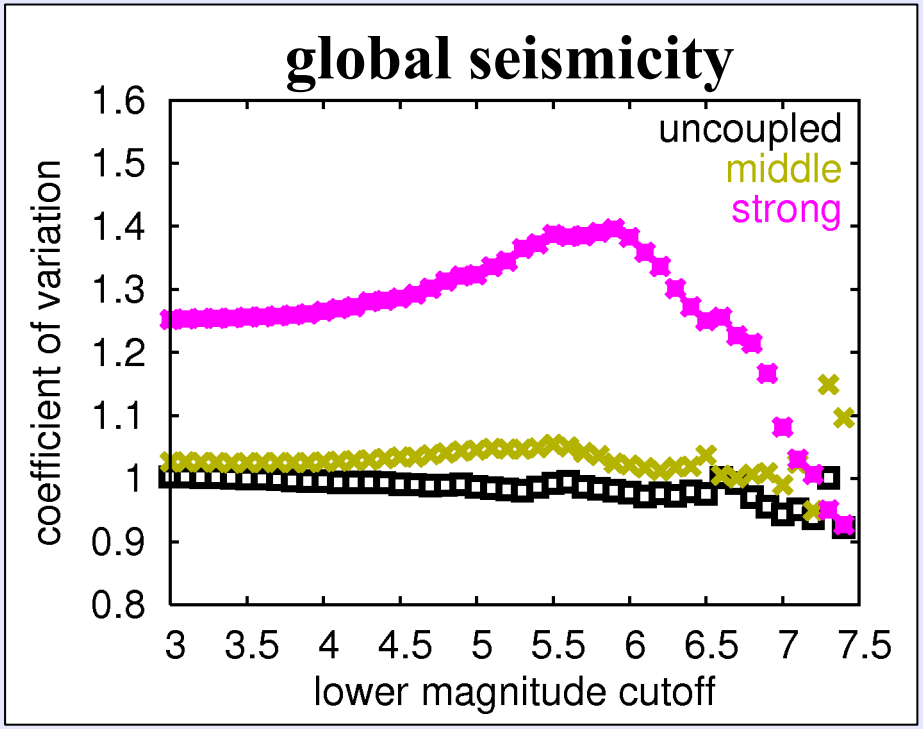
tau$_{ij}$ = coupling between (i) and (j)
condition: sum$_{ij}$ x tau$_{ij}$ < 0

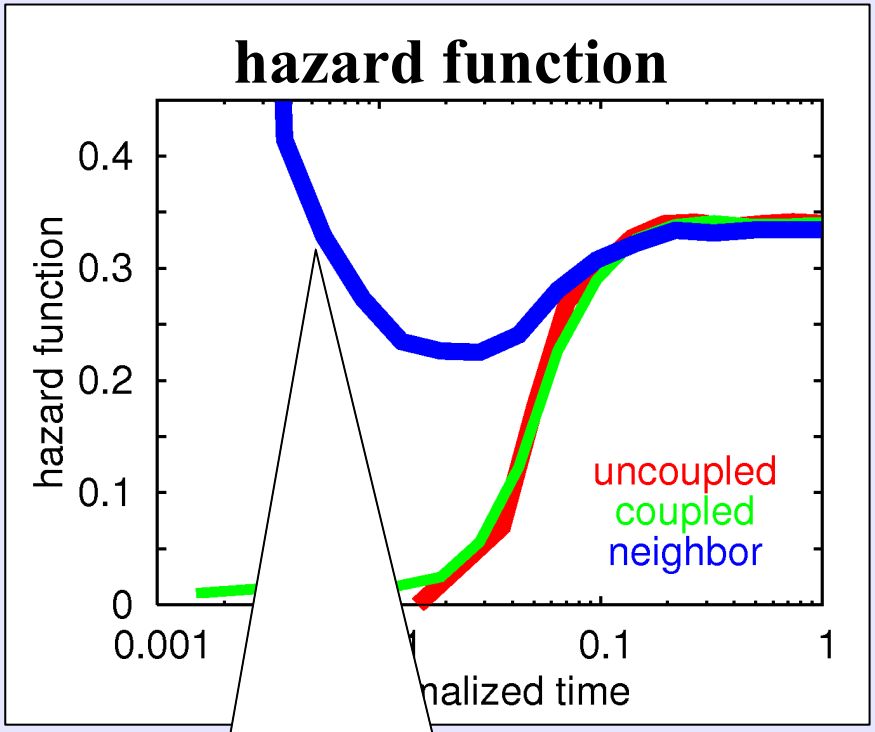


Examples will be shown for: - 10 x 10 regions
- nearest neighbor interactions

Stress Release model: FAULT NETWORK

(Kühn et al., sub.)



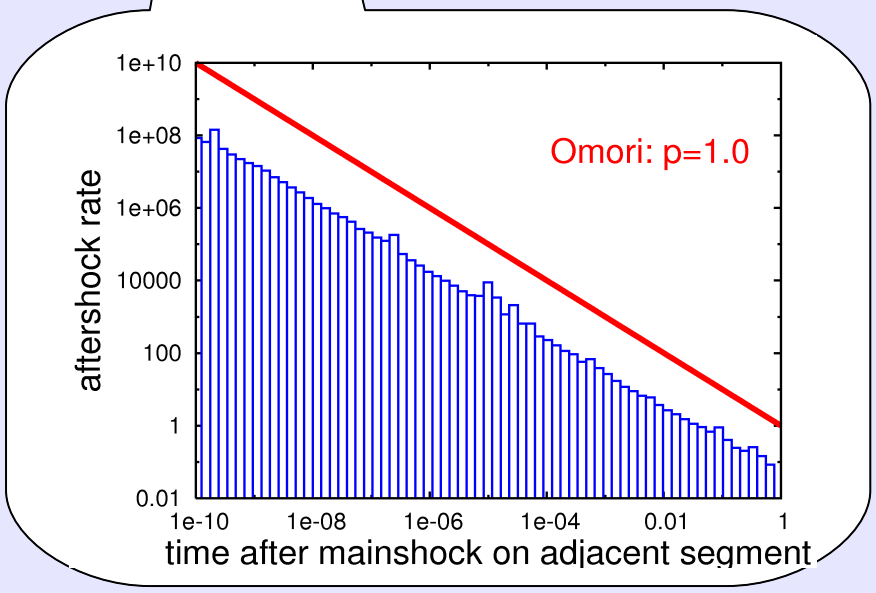


global seismicity: **clustering**

local seismicity: **cycles**

after mainshocks:
increased hazard in coupled regions

"Omori-type" mainshock triggering



Brownian Relaxation Model

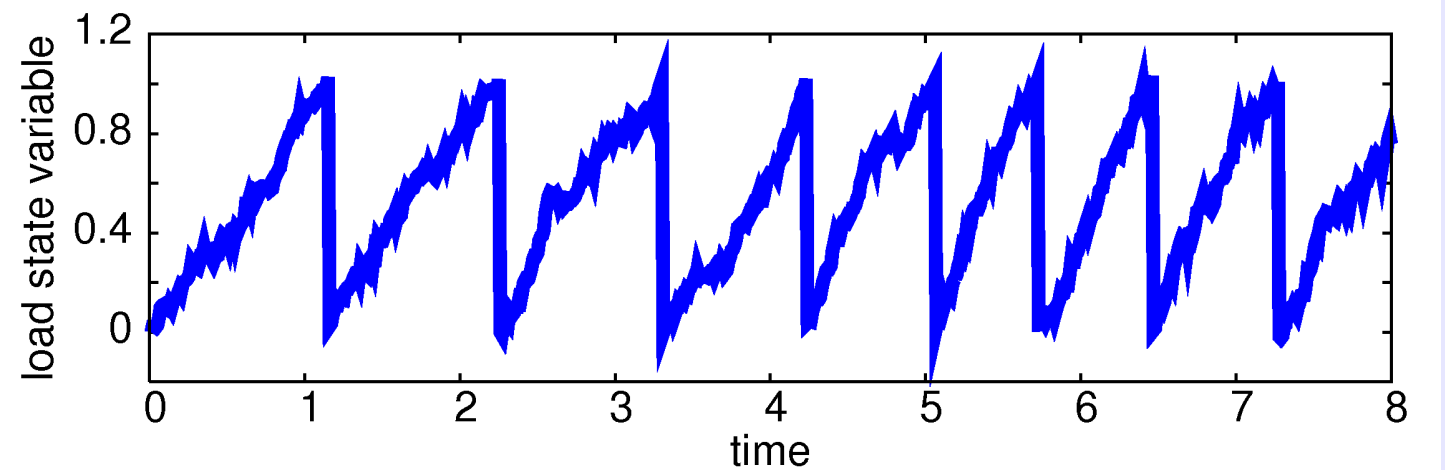
Assumptions:

- scalar "stress" state S which changes by

  (a) tectonic loading: **dS = rho dt**

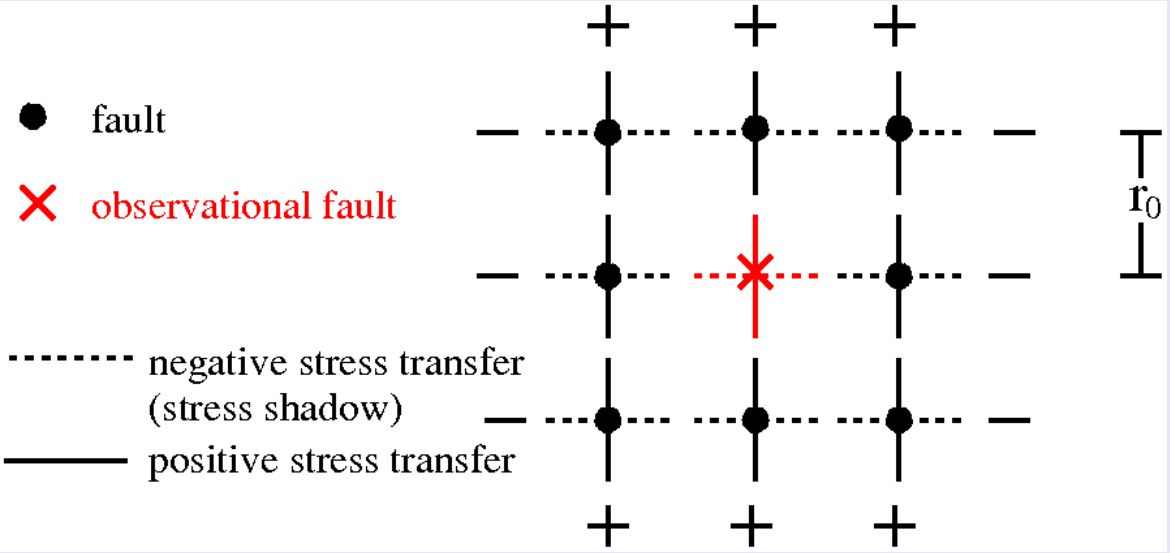
  (b) Brownian walk (accounting for sub-scale processes)
  noise ~ **sigma**

- static stress threshold where mainshocks occur and
  all stress is relaxed



Brownian Model: FAULT NETWORK

(Zöller & Hainzl, 2007)



coupling strength:

tau < 0.5

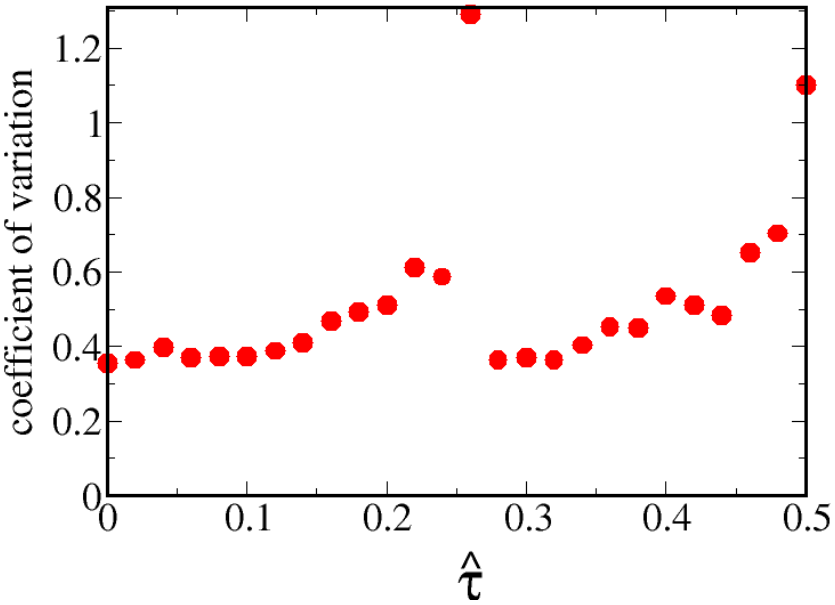
Seismic cycles:

(1) CV ~ noise level

(2) CV increases with tau

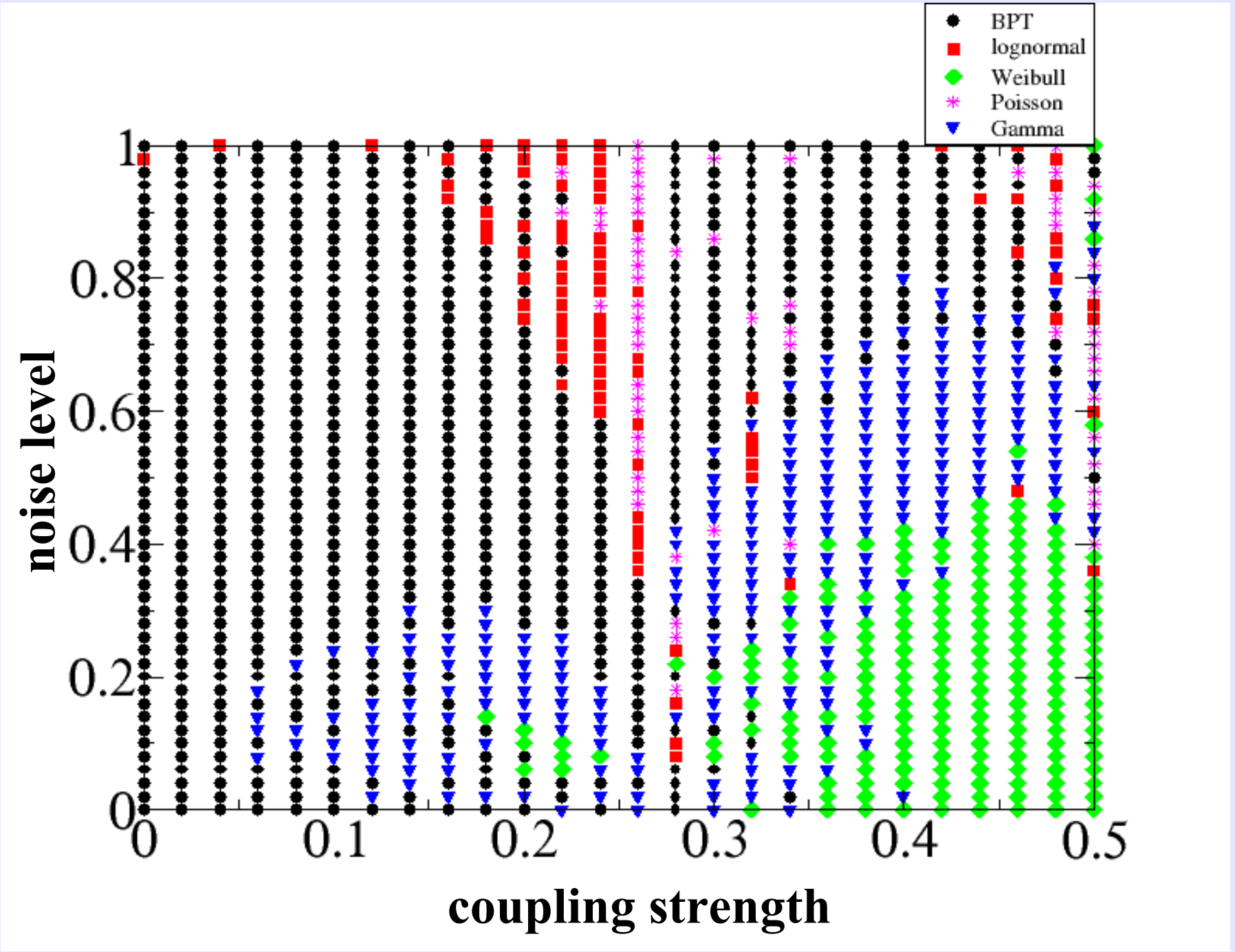
(3) two regimes:

tau < 0.25 & tau > 0.25



Brownian Model: FAULT NETWORK

(Zöller & Hainzl, 2007)



Brownian Model

Brownian Passage-Time distribution

$$f(t;\mu,\sigma) = \sqrt{\frac{\mu^3}{2\pi t^3\sigma^2}}\exp\left\{-\frac{(t-\mu)^2\mu}{2t\sigma^2}\right\}$$

Lognormal distribution

$$f(t;\bar{y},\sigma_y) = \frac{1}{\sqrt{2\pi}t\sigma_y}\exp\left\{-\frac{(\log t-\bar{y})^2}{2\sigma_y^2}\right\}$$

with $\mu = \exp\left(\bar{y}+\frac{1}{2}\sigma_y^2\right)$ and $\sigma_T = \mu\sqrt{(e^{\sigma_y^2}-1)}$

Weibull distribution

$$f(t;\gamma,\beta) = \frac{\beta}{\gamma}\left(\frac{t}{\gamma}\right)^{\beta-1}\exp\left\{-\left(\frac{t}{\gamma}\right)^{\beta}\right\}$$

with $\mu = \gamma\Gamma(1+1/\beta)$ and $\sigma_T = \gamma\sqrt{\Gamma(1+2/\beta)-[\Gamma(1+1/\beta)]^2}$

Gamma distribution

$$f(t;\alpha,\delta) = \frac{t^{\delta-1}\exp\left(-\frac{t}{\alpha}\right)}{\alpha^{\delta}\Gamma(\delta)}$$

with $\mu = \alpha\delta$ and $\sigma_T = \alpha\sqrt{\delta}$

Summary & Conclusions

Our simulations of stochastic nucleation and rupturing on coupled fault systems indicate that:

- **seismic cycles occur on individual fault segments**,
  even for strong coupling and
  dominance of small earthquakes

- **mainshock-mainshock triggering on adjacent fault segments**:
  "Omori-like"

- **the shape of recurrence time distributions changes**:
  "Weibull-distribution fits best for strong coupling"

→ **... poster** of **Zöller et al.**

→ **impact on seismic hazard?**
... discussion on the **poster** of **Faenza et al.**