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Multifractal Omori–Utsu Law for Earthquake Triggering

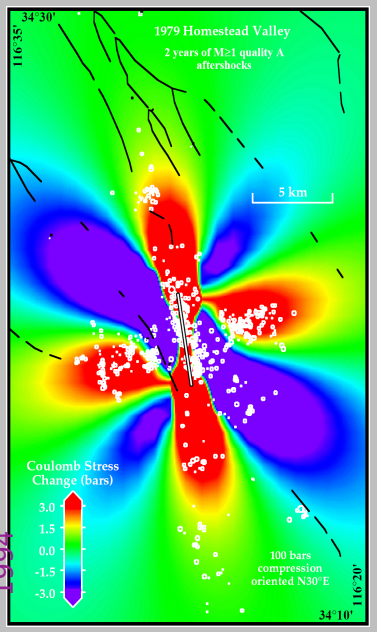
Theory and empirical tests

Single body approach

1

Single body approach

1



Stein et al, 1994

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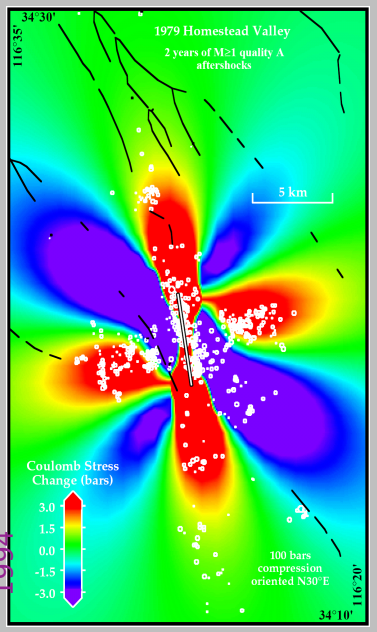

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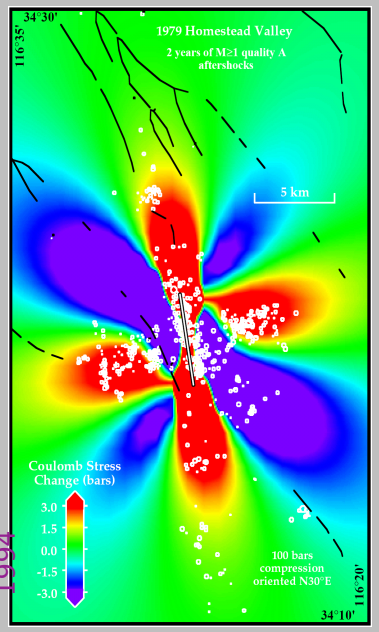

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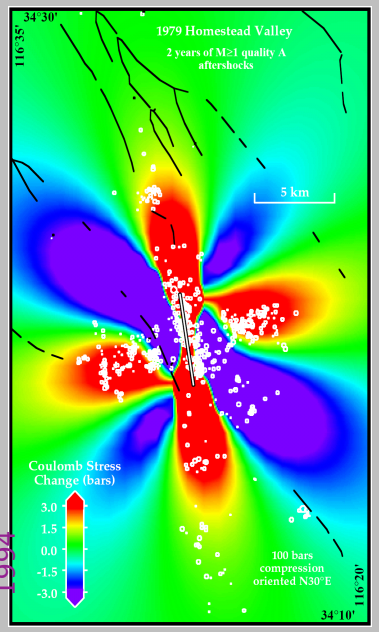

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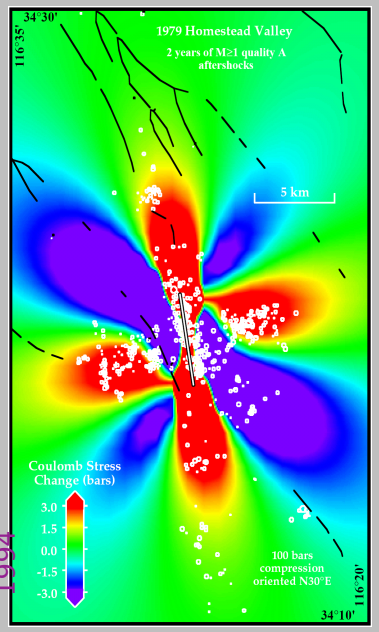

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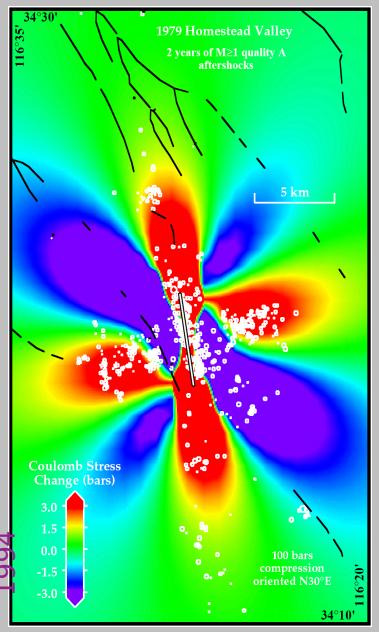

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Omori law with p=1 independent of M

The need of a manybody approach

2

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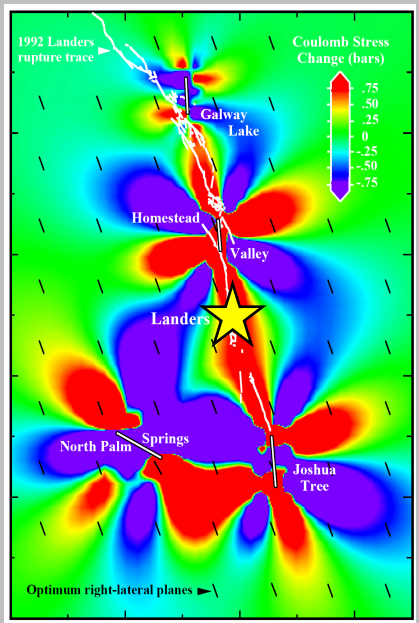

Complex previous history with known or unknown rupture parameters

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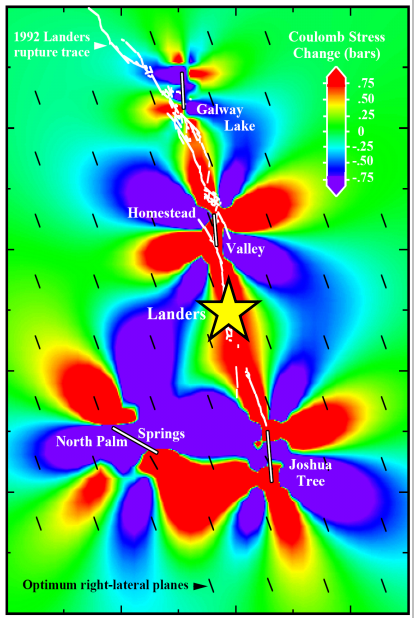
The need of a manybody approach



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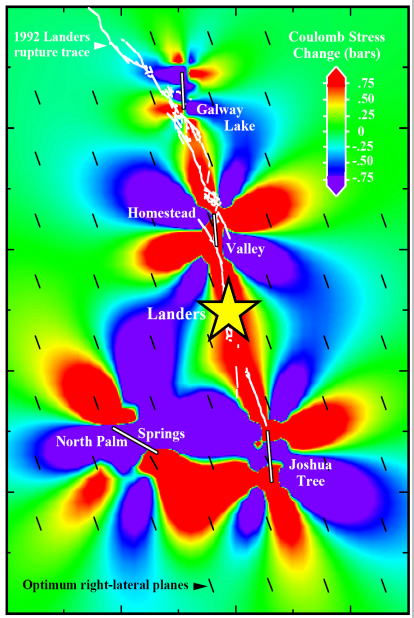

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The physical model : thermal activation driven by stress

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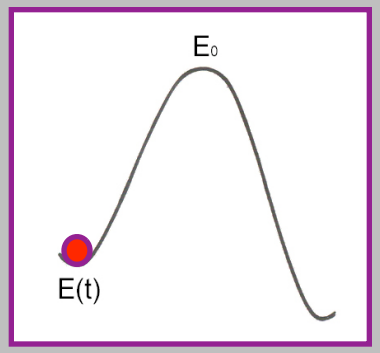
Before the shock



The physical model : thermal activation driven by stress

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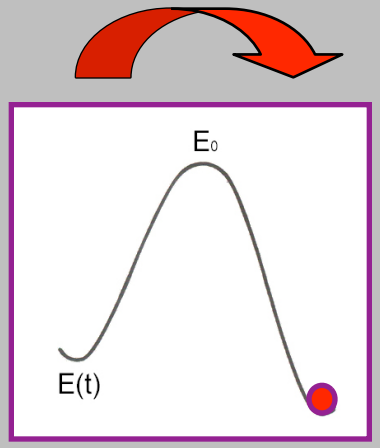

After the shock

Energy barrier = $E_0 - E(t)$

The physical model : thermal activation driven by stress

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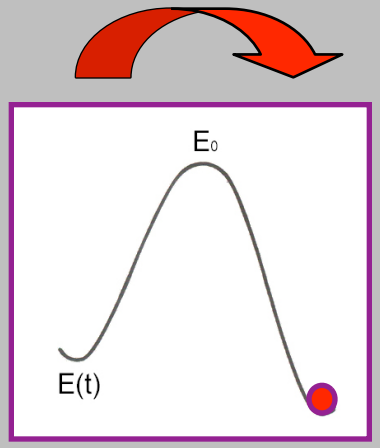

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Energy barrier = $E_0 - E(t)$

Arrhenius law for the activation rate:

$$\lambda(t) = \lambda_0 \exp\left(-\frac{E_0 - E(t)}{kT}\right)$$

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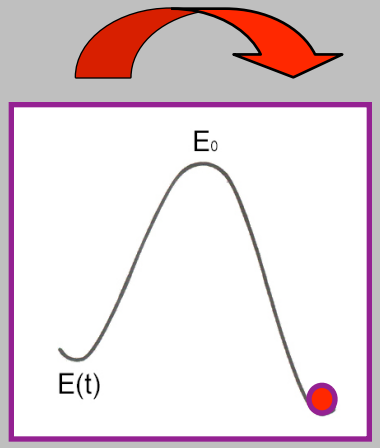

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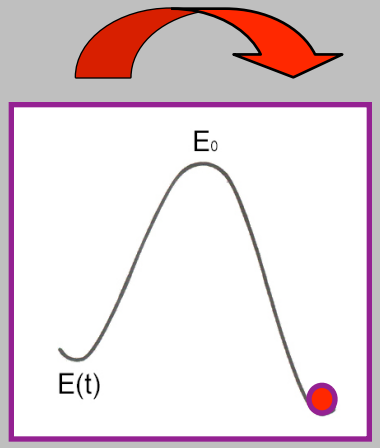

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Compatible with state-and-rate friction, stress corrosion, …

$\lambda(t)$: instantaneous rate

λ_0 ~ average nucleation rate

σ_0 : material strength

$\sigma(t)$: applied stress

V : activation volume

T : temperature

k : Boltzmann constant

Taking account of history and boundary conditions

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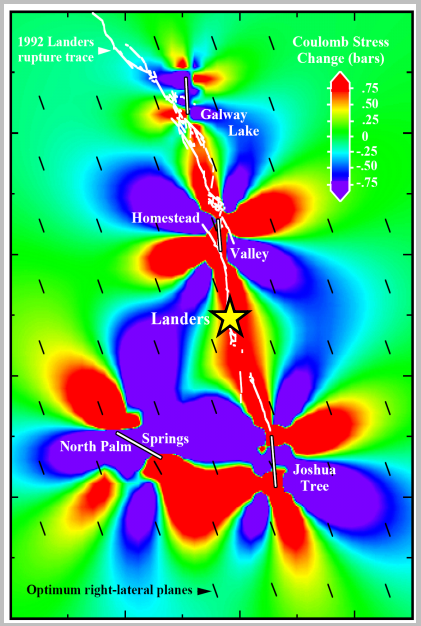

Stress is assumed to be a scalar for the sake of simplicity

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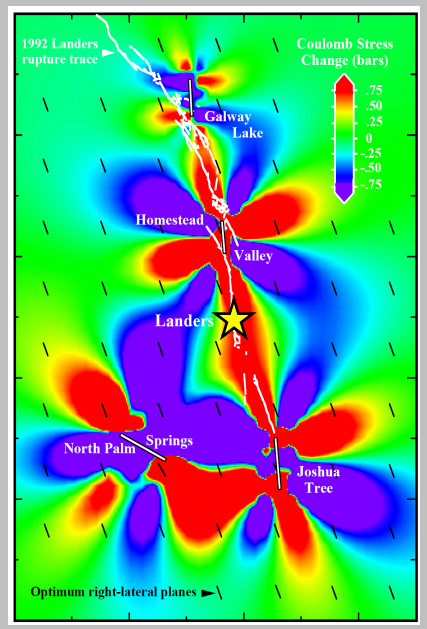

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$$\sigma(\vec{r},t) = \sigma(\vec{r})_{far\ field} + \int_{-\infty}^{t} \int_{space} dN\left[d\vec{\rho} \times d\tau\right] \Delta\sigma(\vec{\rho},\tau)\, G(\vec{r}-\vec{\rho}, t-\tau)$$

local stress

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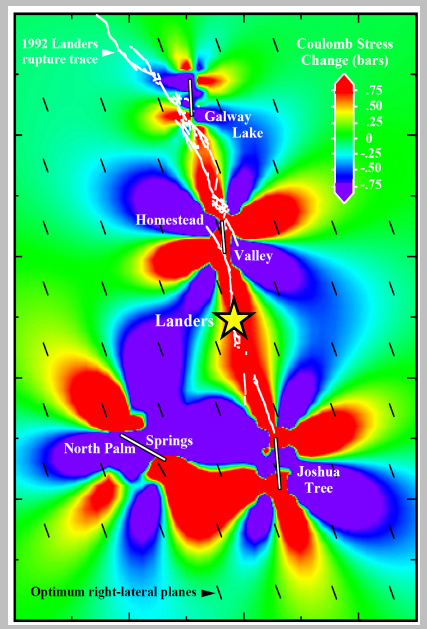

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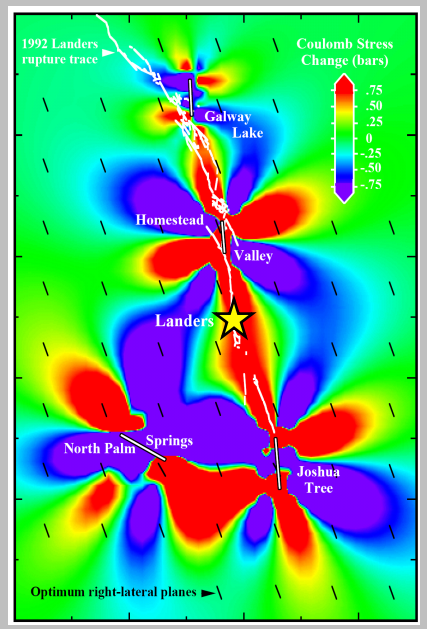

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Stress fluctuations induced by all past events in the system

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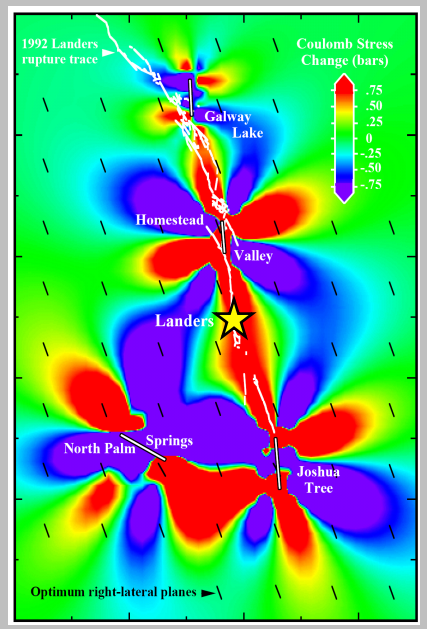

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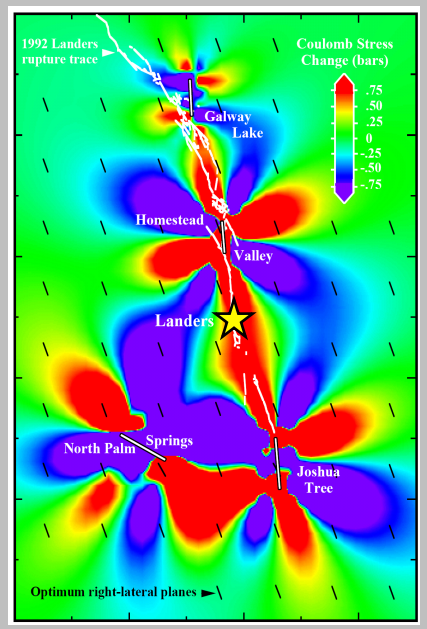

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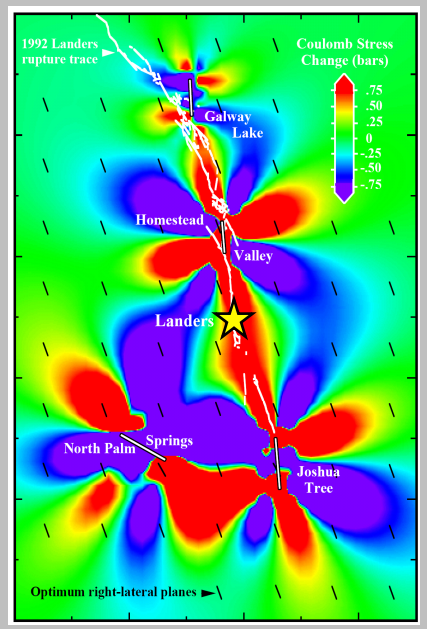

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Time and space distribution of past sources

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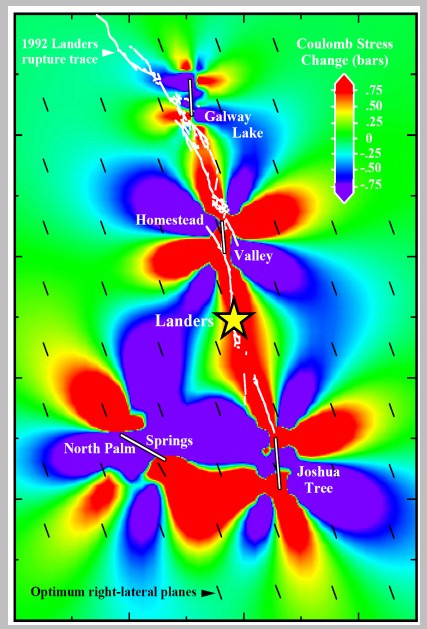

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Time and space distribution of past sources

Stress fluctuations at sources

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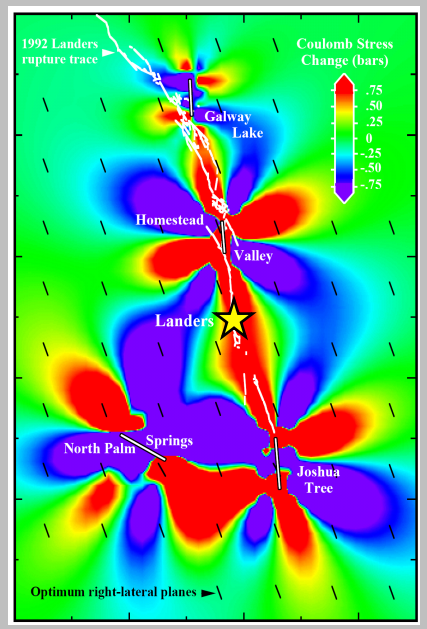

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local stress

tectonic loading

Time and space distribution of past shocks

Stress fluctuations at sources

Green function for stress transfer

A few working hypotheses

5

A few working hypotheses

5

Every shock is activated by stress and temperature according to Arrhenius law

A few working hypotheses

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Every shock is activated by stress and temperature according to Arrhenius law

Every shock of magnitude M triggers instantaneously 10^{qM} aftershocks (ETAS-like productivity law)

A few working hypotheses

Every shock is activated by stress and temperature according to Arrhenius law

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Separation of variables : $\boxed{G(\vec{r},t) = f(\vec{r}) \times h(t)}$

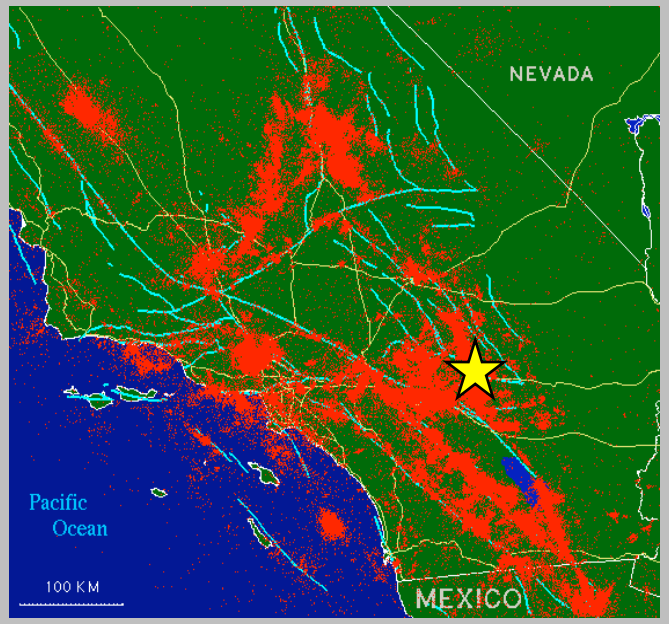
A few working hypotheses

Every shock is activated by stress and temperature according to Arrhenius law

Every shock of magnitude M triggers instantaneously 10^{qM} other events

Separation of variables : $G(\vec{r},t) = f(\vec{r}) \times h(t)$

Stress fluctuations at ☆ depend on the location of events (red dots), their rupture geometry, and on the spatial decay of the Green function. Most of these parameters are unknown, and some events even not recorded at all. Those fluctuations are thus considered as realizations of a random variable.



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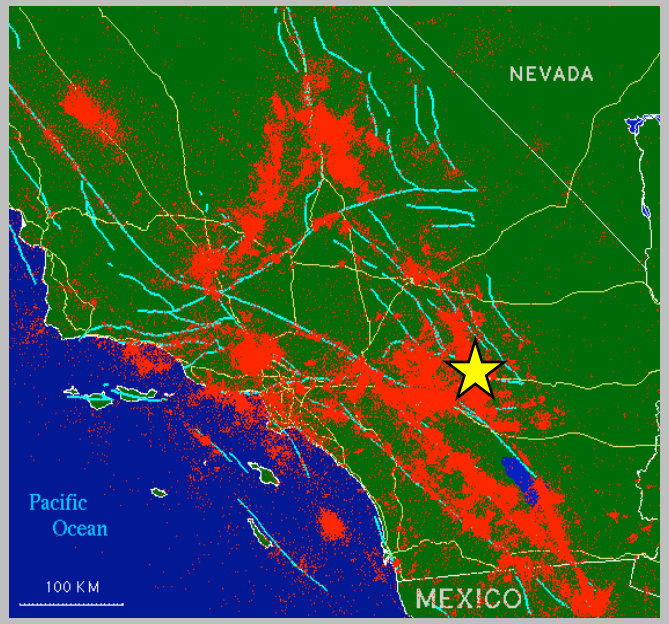
Stress fluctuations at location ☆ due to previous events :

$$P(\sigma_{fluc})\, d\sigma_{fluc} \approx \frac{C}{(\sigma_{fluc} + \sigma_{f1})^{+\mu}}\, d\sigma_{fluc}$$

Exponent μ depends on (and encapsulates) the spatial structure of the fault pattern, the GR law, as well as ***f(r)***.



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Elastoviscoplastic rheology

$$h(t) = \frac{h_0}{(t + t_1)^{1+\theta}} \exp\left(-\frac{t}{\tau_M}\right)$$

Maxwell time τ_M >> time scale of observations

h(t) : dislocations motion and unresolved seismicity

Relaxation after a magnitude M event

6

Relaxation after a magnitude M event

We re-write in discrete form after spatial averaging :

$$\lambda(t) = \lambda_{tec} \exp\left[\frac{V}{kT} \sum_{past} \sigma_{fluc}(t_i) h(t - t_i)\right]$$

cf Ouillon and Sornette, JGR, 2005

λ_{tec} is the average seismicity rate, modulated by a time-varying activation term. The formulation is thus non-linear.

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$$if \quad \mu(1+\theta) = 1$$

$$\lambda(t) \propto t^{-p(M)} \qquad p(M) = aM + b$$

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$$h(t) = \frac{h_0}{(t + t_1)^{1+\theta}} \exp\left(-\frac{t}{\tau_M}\right)$$

Power-law relaxation rate of aftershocks increases with the size of energy fluctuations => multifractality

Multifractal Stress Activation model

Probable meaning of multifractality

7

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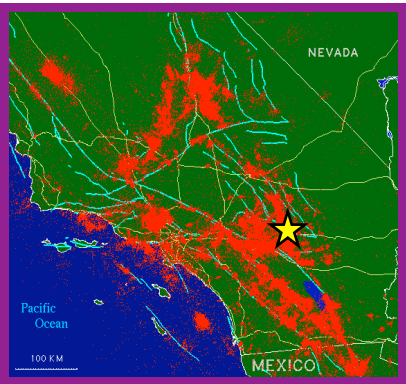

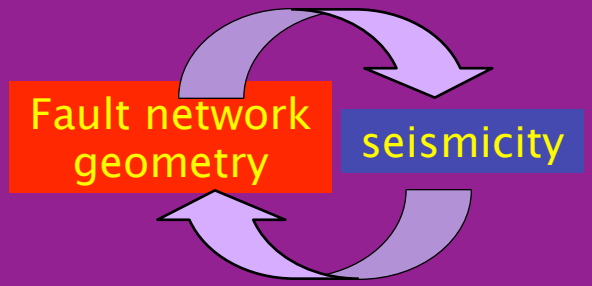

μ :

Spatial self-organization of the fault pattern

Probable meaning of multifractality

7

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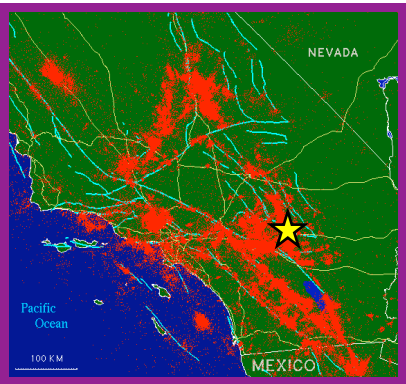
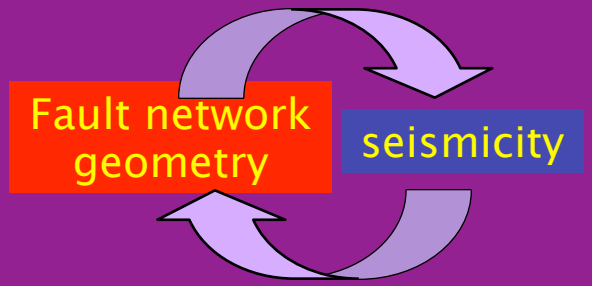




$$h(t) = \frac{h_0}{(t+t_1)^{1+\theta}} \exp\left(-\frac{t}{\tau_M}\right)$$

θ :

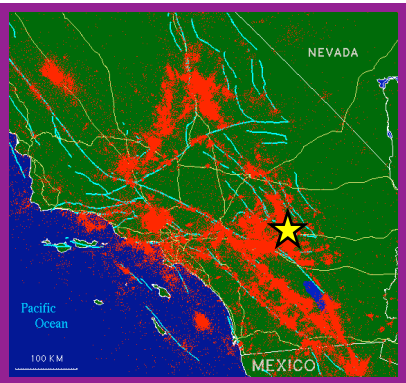
temporal self-organization of the fault pattern

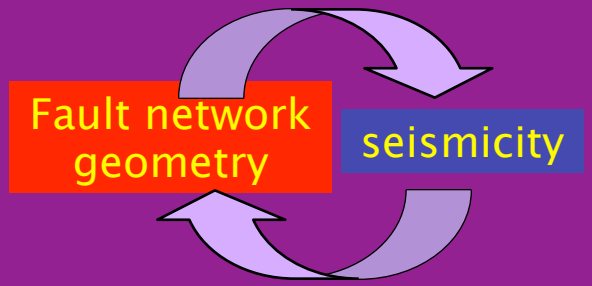
Probable meaning of multifractality

$$h(t) = \frac{h_0}{(t+t_1)^{1+\theta}} \exp\left(-\frac{t}{\tau_M}\right)$$

$$\mu(1+\theta) = 1$$

$$P(\sigma_{fluc})\,d\sigma_{fluc} \approx \frac{C}{(\sigma_{fluc}+\sigma_{f1})^{1+\mu}}\,d\sigma_{fluc}$$





$\mu(1+\theta) = 1$:

Spatio-temporal self-organization of the fault pattern

Building aftershocks time series

8

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The Scaling Function Analysis (SFA)

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The background term is regular

$$\boxed{B(t) = b_0 + b_1 \times t + b_2 \times t^2 + \ldots + b_n \times t^n}$$

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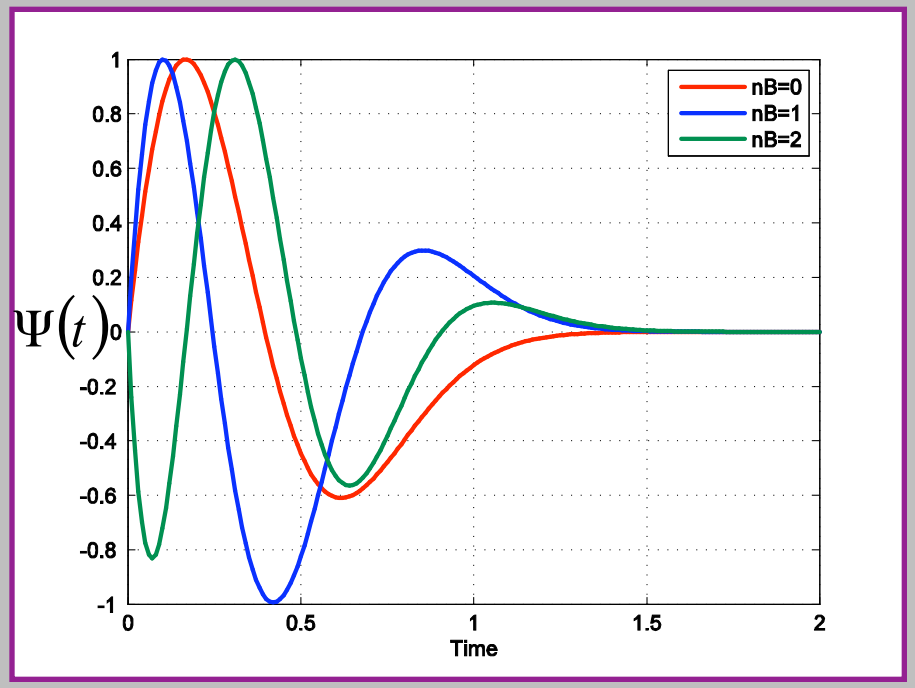

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$$C(s) \propto s^{1-p}$$

An example on a real catalog

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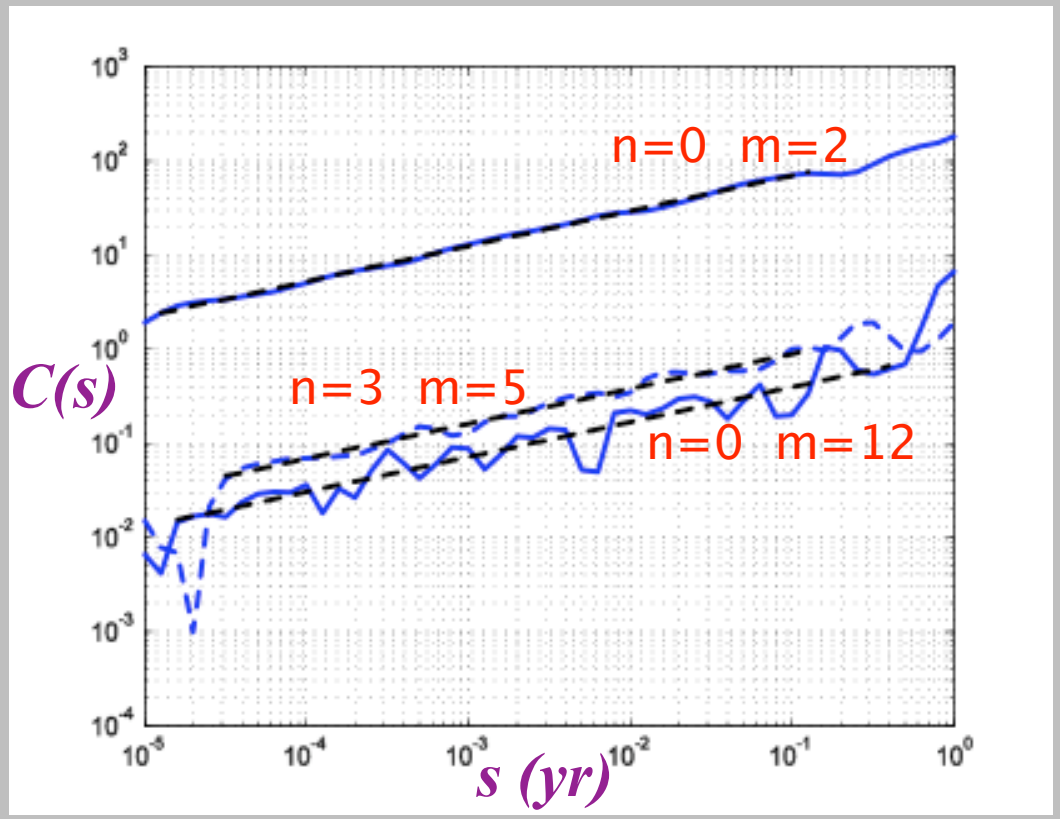
Ouillon et al, 2007 submitted to GJI

3 different scaling functions yield power law scaling with the same value of p.

SCEC – M[2.5;3.0] – p=0.63



Results on real catalogs

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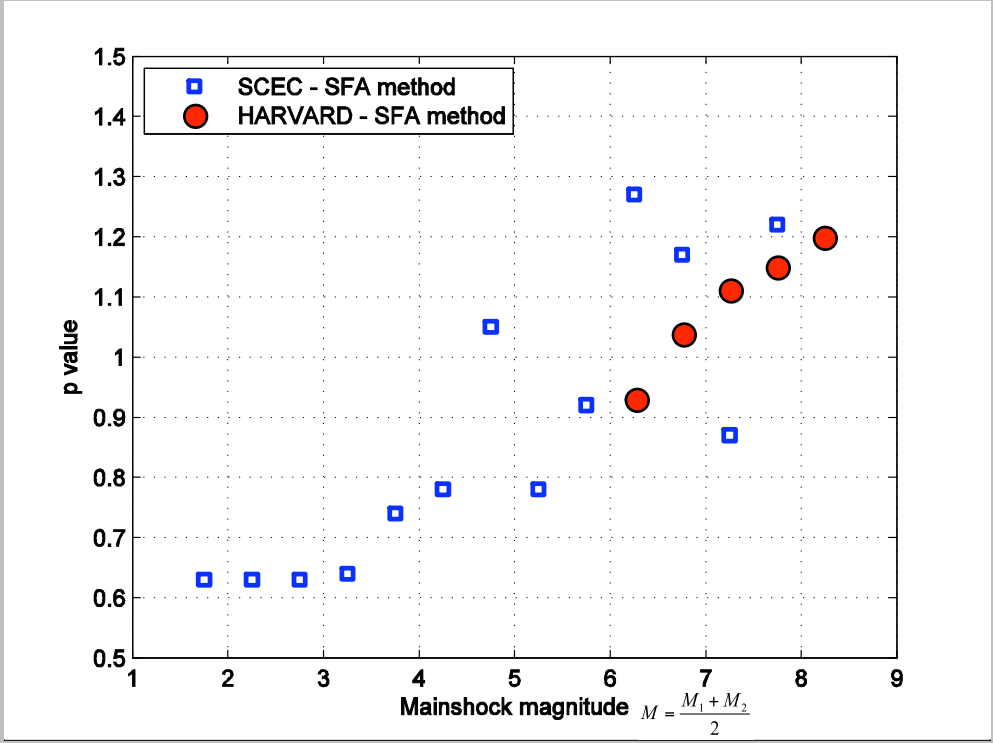
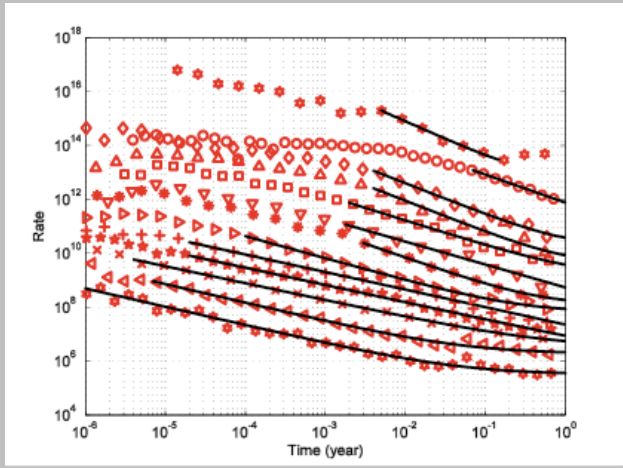


Results on real catalogs

Construction of standard bined time series and least squares fits.



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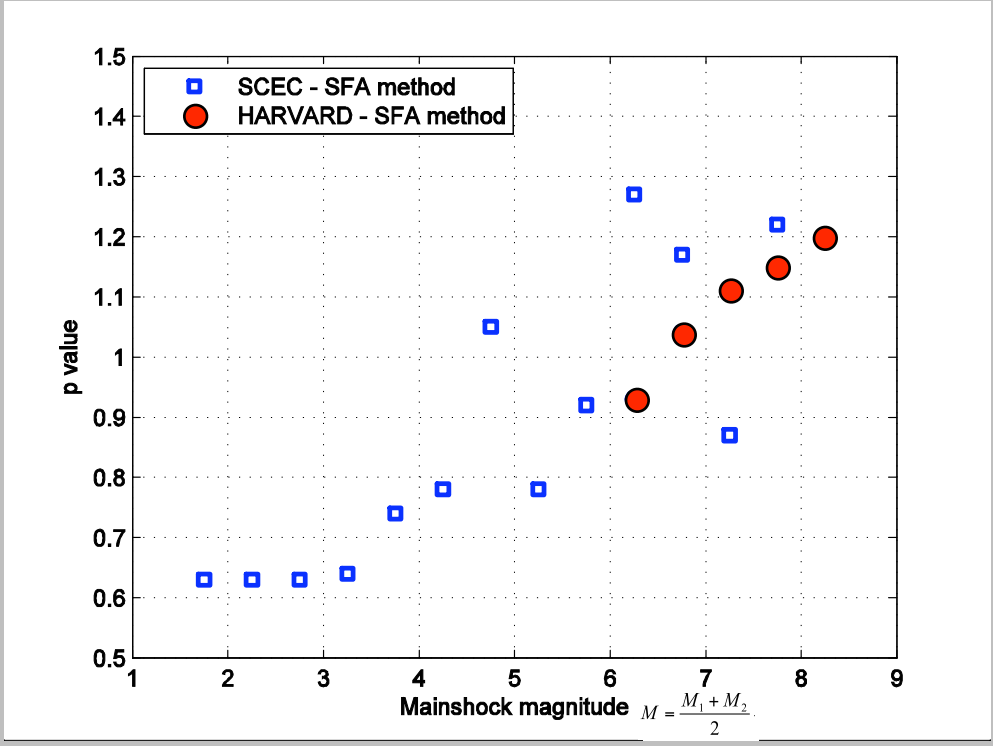

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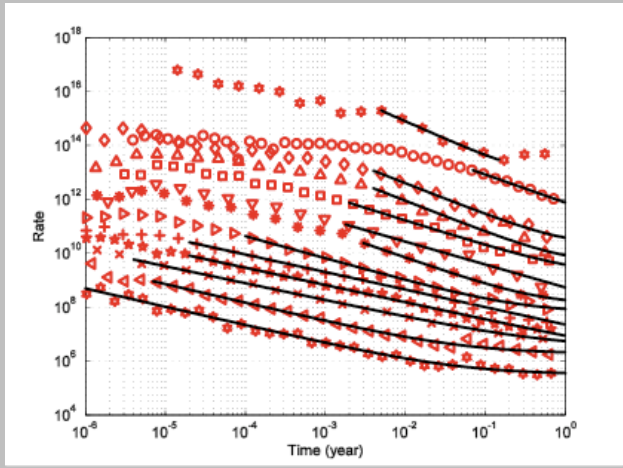

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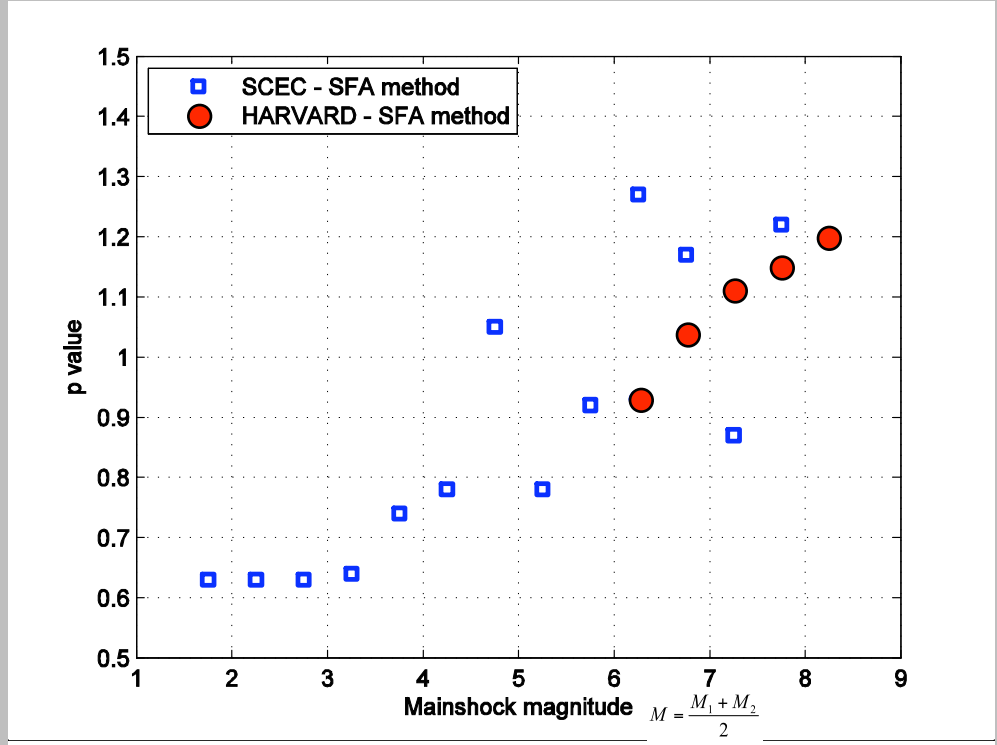

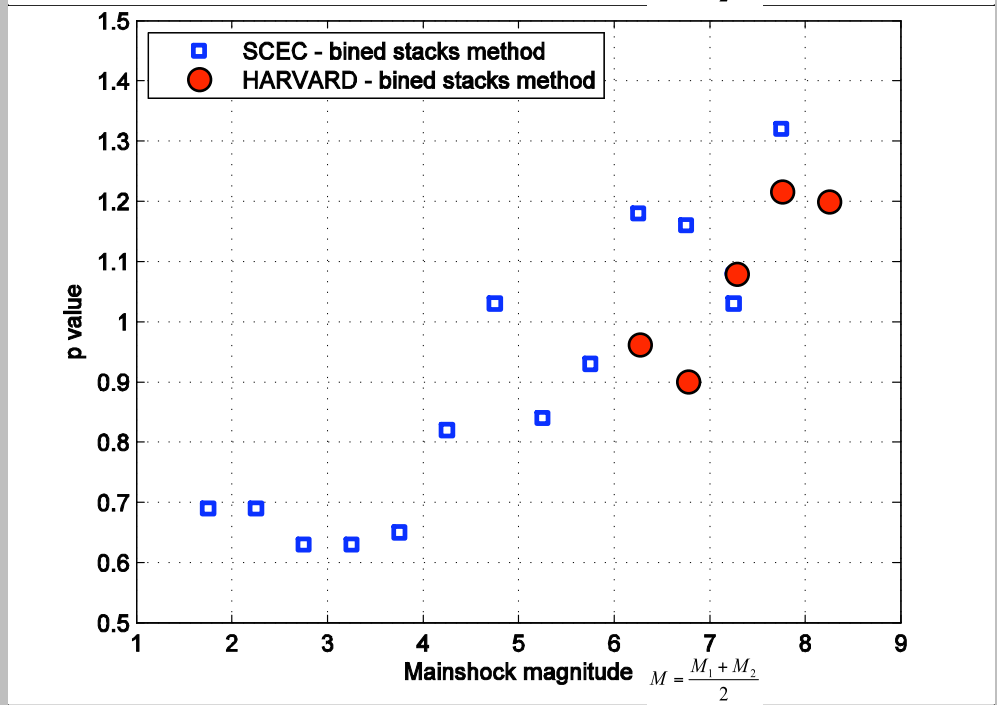

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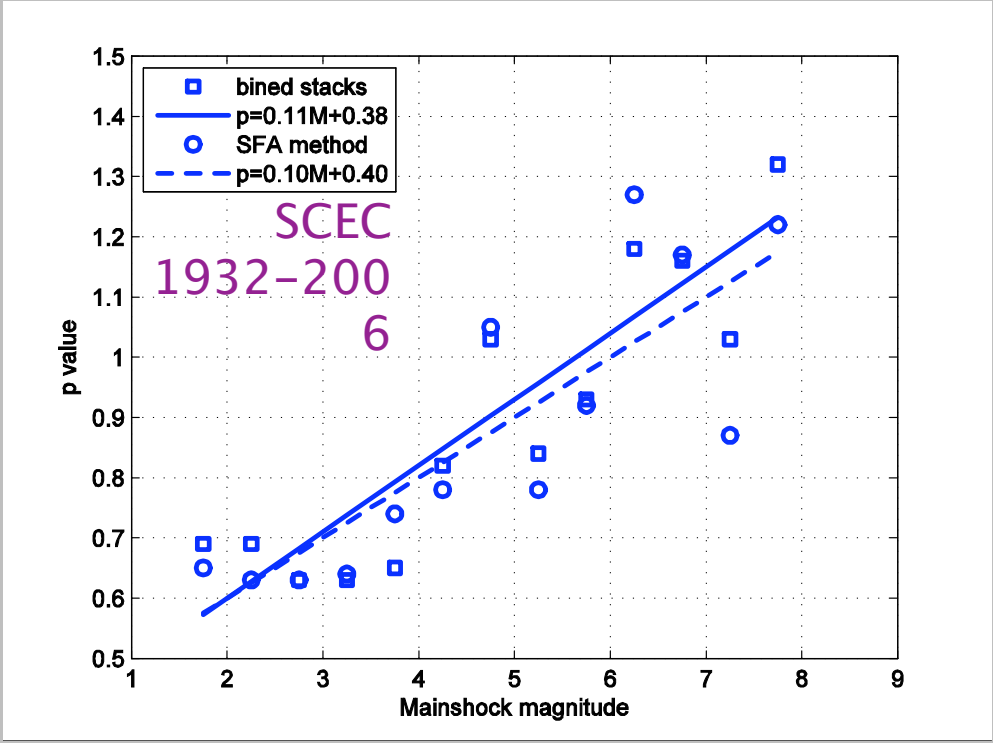

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Bins : p(M)=0.10M +0.40

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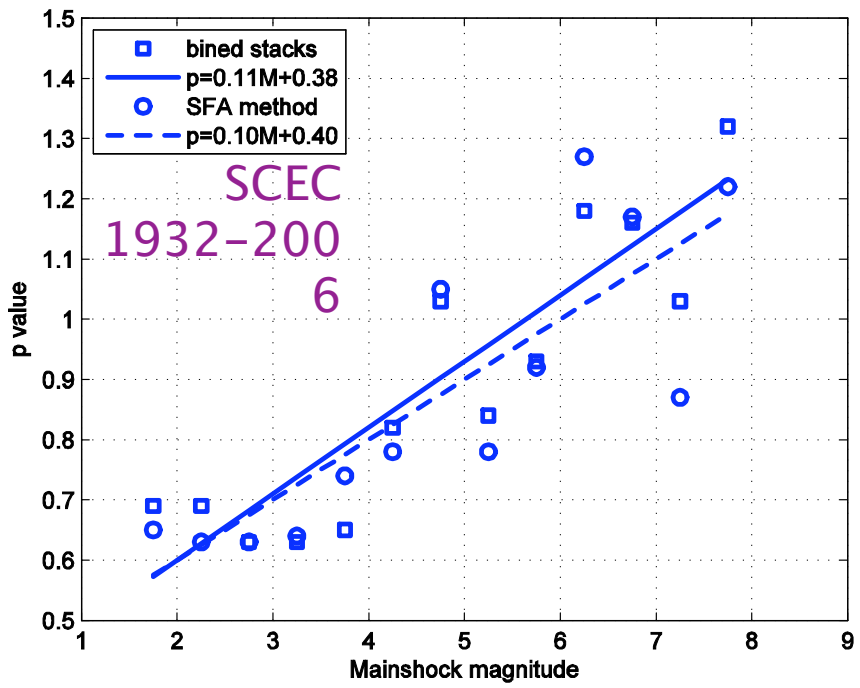

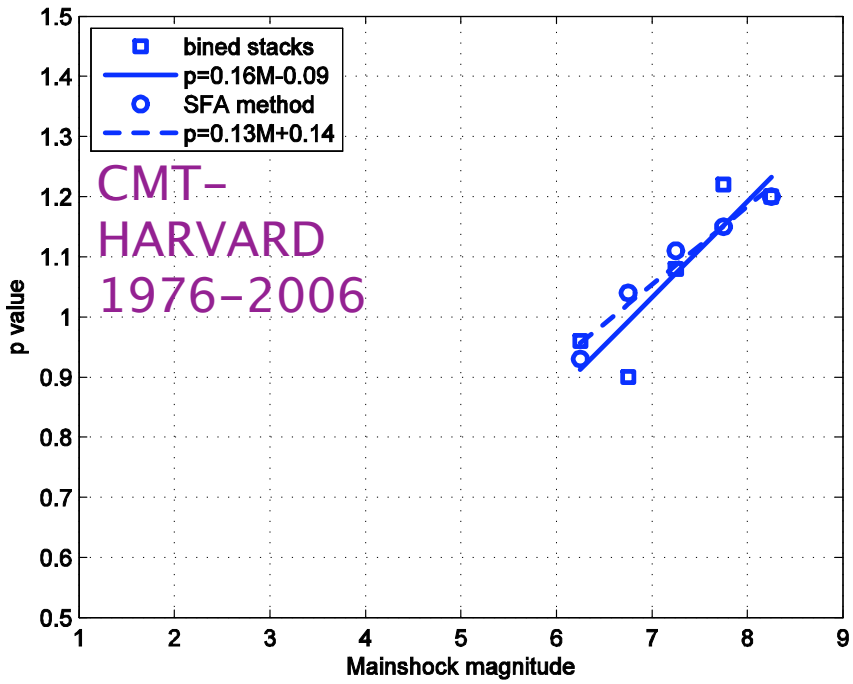

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Summary

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Mechanical model taking account of interactions between all events

Seismicity rate depends exponentially on applied stress

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Multifractality stems from the spatio-temporal self-organization of the fault pattern ($\mu(1+\theta)=1$)