(1) Earthquake triggering by stress changes: Observations and modelling using the rate and state friction law

(2) Seismic monitoring of Sechilienne rockslide, french Alps

Earthquake triggering by stress changes: Observations and modelling using the rate and state friction law

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Earthquake triggering

Obervations of aftershocks:

when? where? scaling with mainshock size?

Rate and state model :

relation between stress change and seismicity

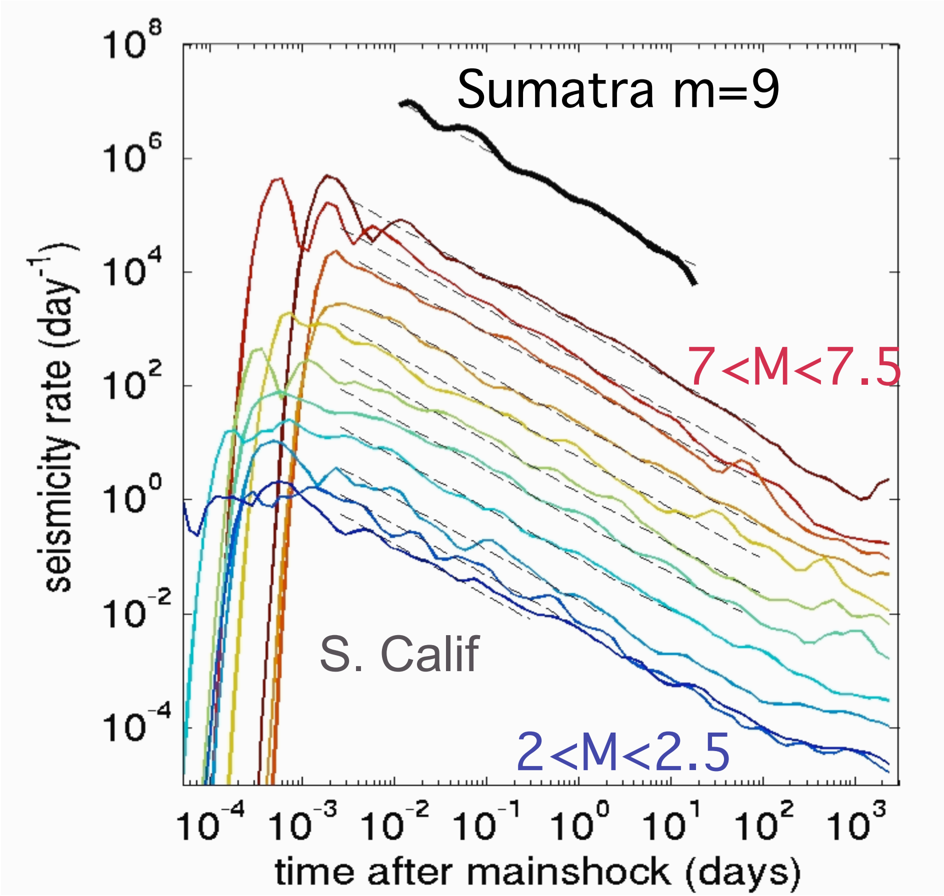
Applications:

triggering by heterogeneous static stress change

afterslip and slow earthquakes triggered by stress changes

aftershocks triggered by afterslip

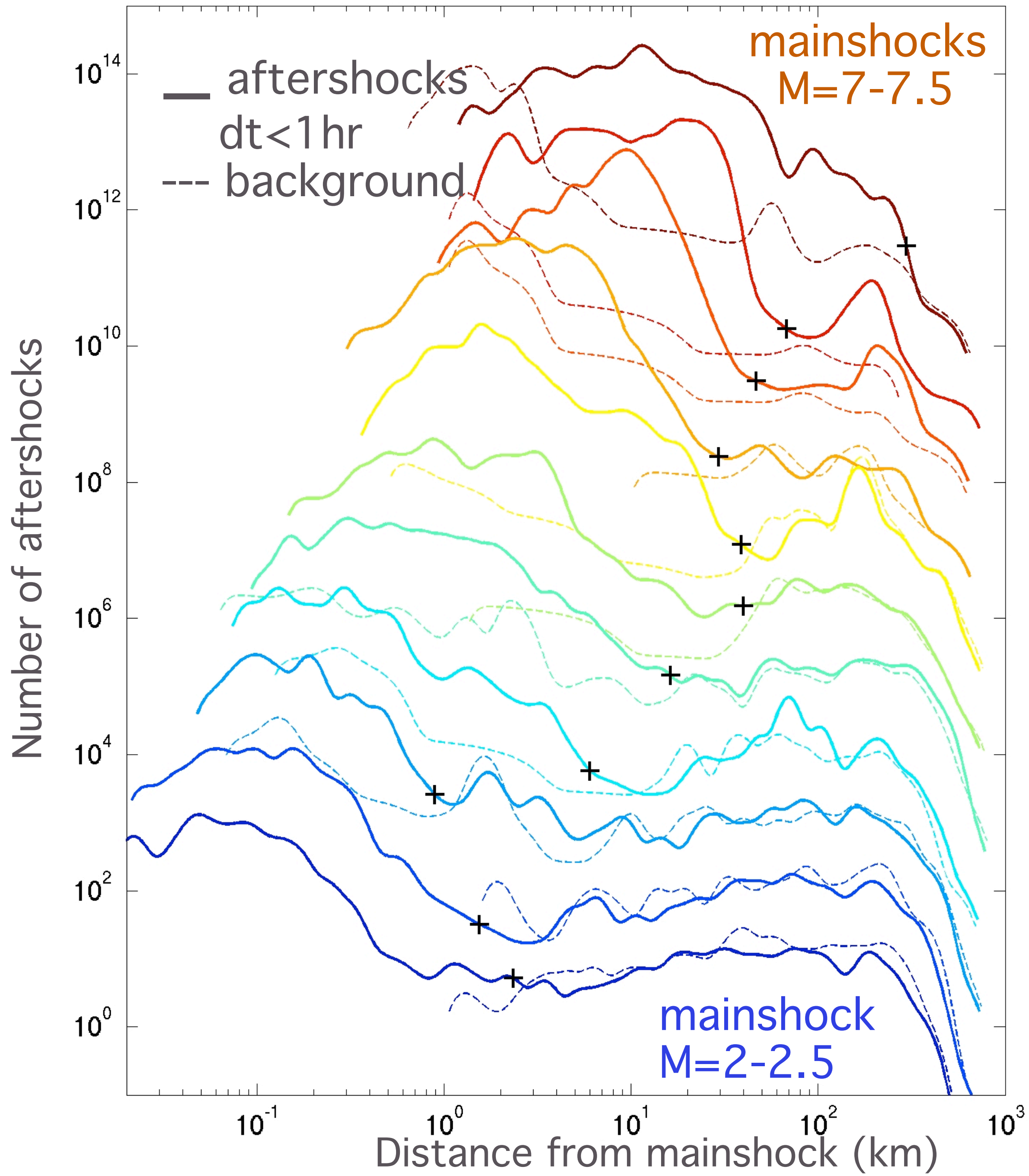
Observations of aftershock sequences



[*Helmstetter et al.* 2005]

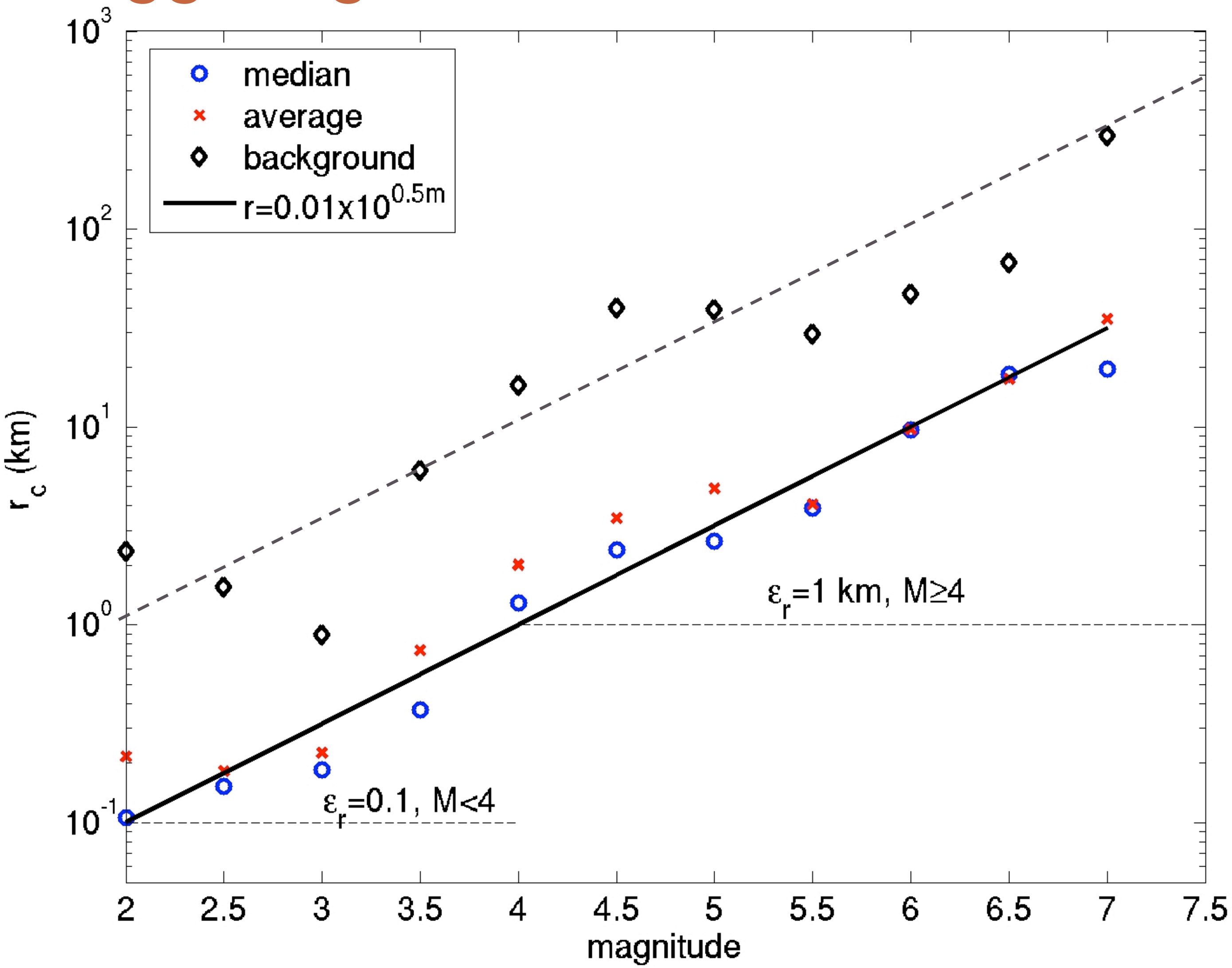
- aftershock rate : $R(t,M) \sim 10^M / t^p$
  - 10^M: rupture area
  - $/ t^p$: Omori law, p≈0.9
- duration ≈ 10 yrs indep of M
- short-time cutoff for t≈ 1mn = catalog incompleteness?

Spatial distribution of aftershocks



- relocated catalog for Southern California *[Shearer et al., 2004]*
- triggering distance increases with M
- max triggering distance: R ~ 7 rupture lengths ~ $0.07 \times 10^{m/2}$ km

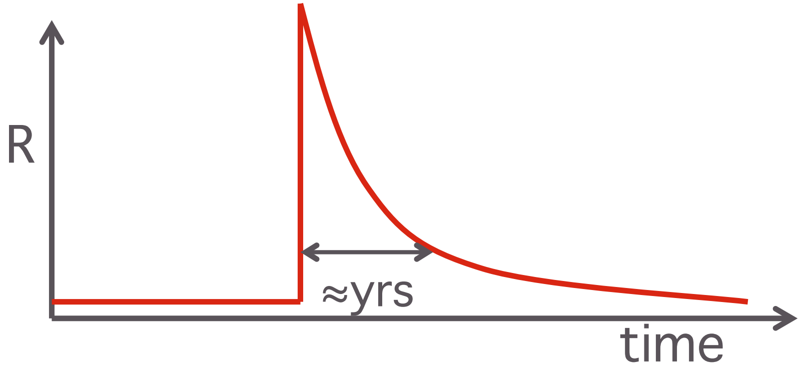
Triggering distance as a function M



- mean triggering distance d(m) ≈ $0.01 \times 10^{0.5m}$ km ~ rupture length
- max distance ≈ 7L

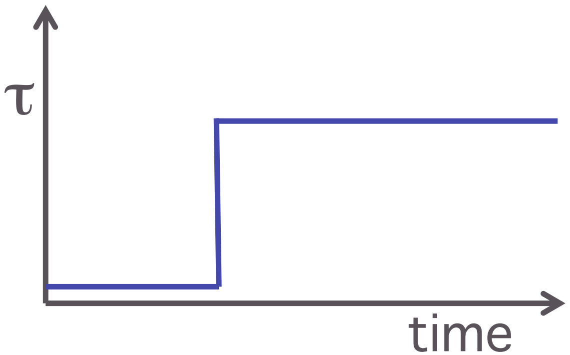
Earthquake triggering by stress changes

seismicity rate
after a mainshock

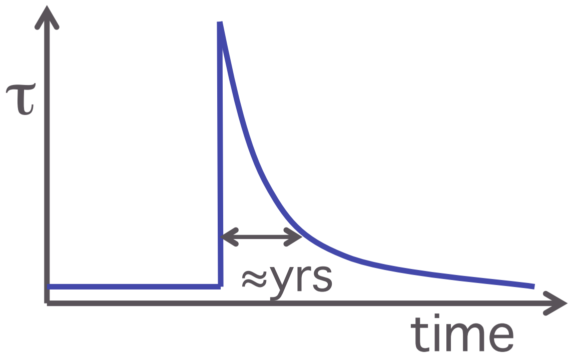


Aftershocks triggered by:

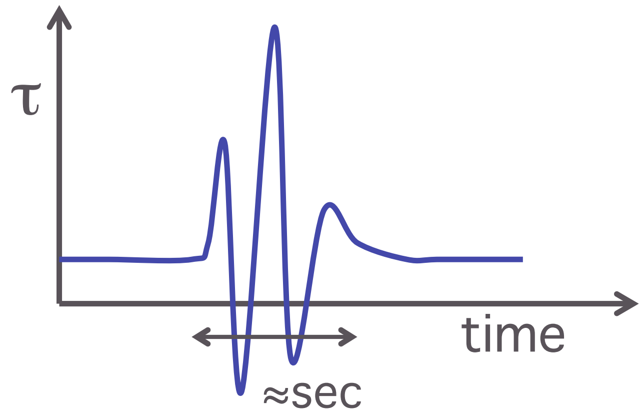
Static stress changes?



Afterslip?



Dynamic stress changes?



Earthquake triggering by stress changes

Static stress change

☺ permanent change → easy to explain long time triggering

☹ fast decay with distance ~ $1/r^3$ → how to explain distant aftershocks?

Dynamic stress change

☺ slower decay with distance ~ $1/r$ → better explains distant aftershocks

☹ short duration → how to explain long time triggering?

Secondary aftershocks or permament change in permeability? (Brodsky and others)

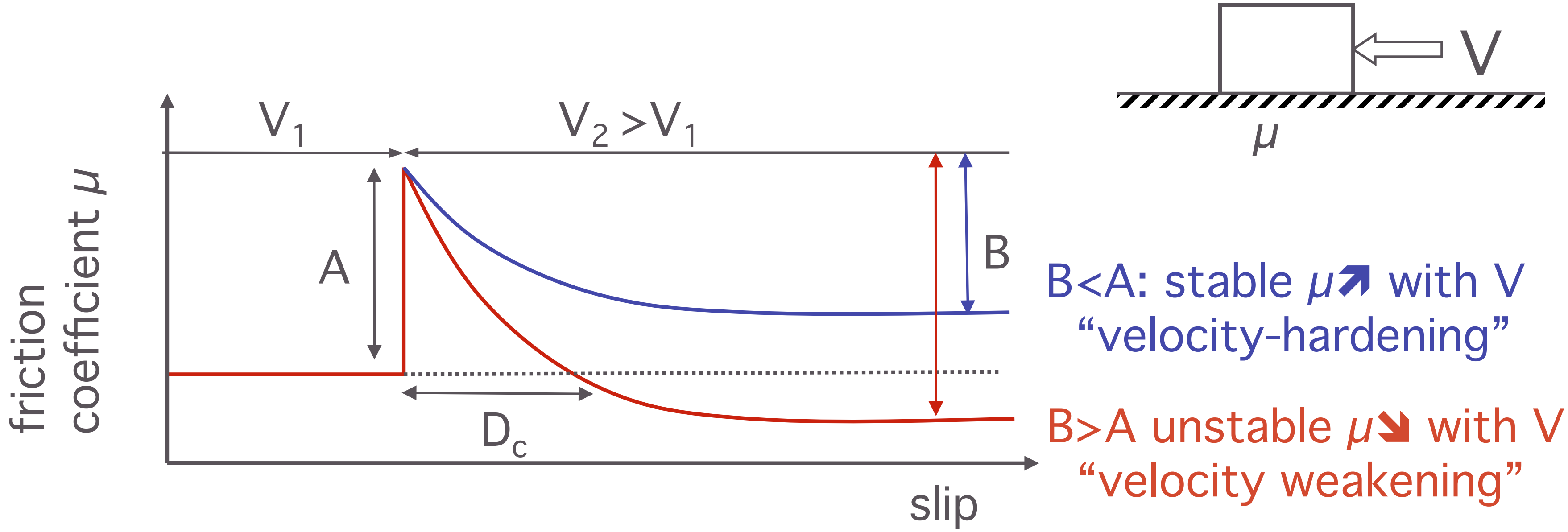
Postseismic relaxation

Afterslip, fluid flow, viscoelastic relaxation ...

☺ Slow decay with time, ~ seismicity rate → easy to explain Omori law

☹ Smaller amplitude than coseismic stress change

Rate-and-state friction law



- friction law

$$\frac{\tau}{\sigma} = \mu = \mu_0 + A\ln\left(\frac{V}{V^*}\right) + B\ln\left(\frac{\theta}{\theta^*}\right)$$

[Dieterich, 1979]

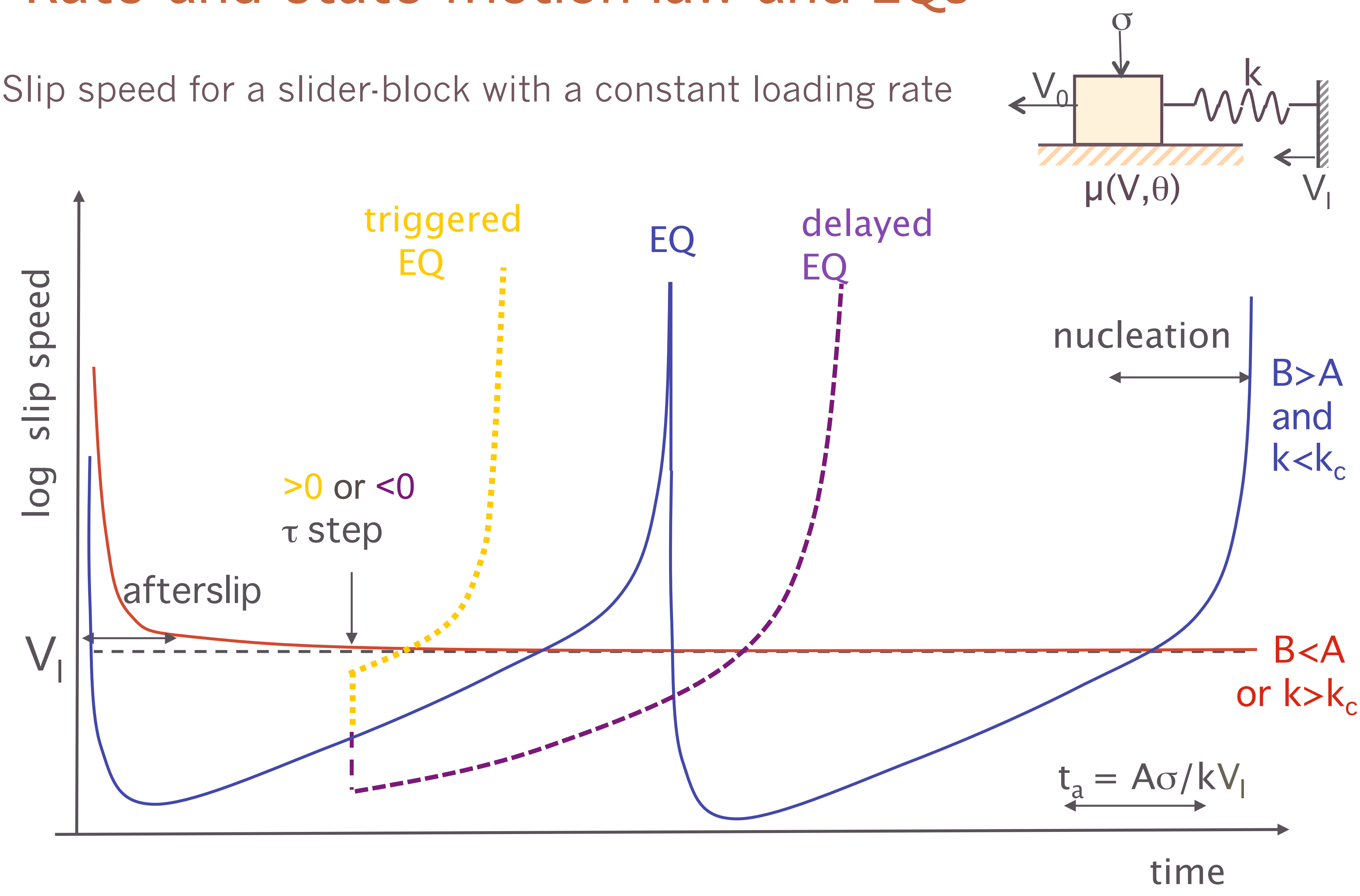
- state variable θ ≈ age of contacts

$$d\theta/dt = 1 - V\theta/D_c$$

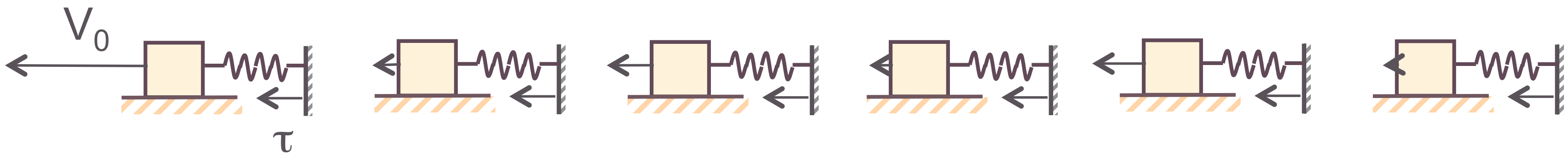
- lab :
  - A≈B≈0.01, depend on T, stress, gouge thickness, strain...
  - D_c ≈1-100μm, depends on roughness and gouge thickness

Rate-and-state friction law and EQs

Slip speed for a slider-block with a constant loading rate



Relation between stress and seismicity



- rate & state friction law
- 1 fault = slider block, stick slip regime
- infinite population of independent faults
- stress changes modify the slip rate and advance or delay the failure time
- time advance/ delay function of stress change and initial slip rate
- relation between seismicity rate and any stress history *[Dietrich, 1994]*

Relation between stress and seismicity

- *Dieterich* [2004] model is equivalent to

R: seismicity rate
$R_0 = R(t=0)$
$N(t)=\int^t R(t)dt$
r: ref seismicity rate
for $d\tau/dt = \tau'_r$
τ : coulomb stress
change (=0 at t=0)
t_a: nucleation time
$= A\sigma/\tau_r'$

$$A\sigma \ln\left(\frac{R}{R_0}\right) + \frac{N\dot{\tau}_r}{r} = \tau$$

short-times regime

for $T \ll t_a$

$R \sim R_0 \exp(\tau/A\sigma)$

(tides, ...)

long-times regime

for $T \gg t_a$

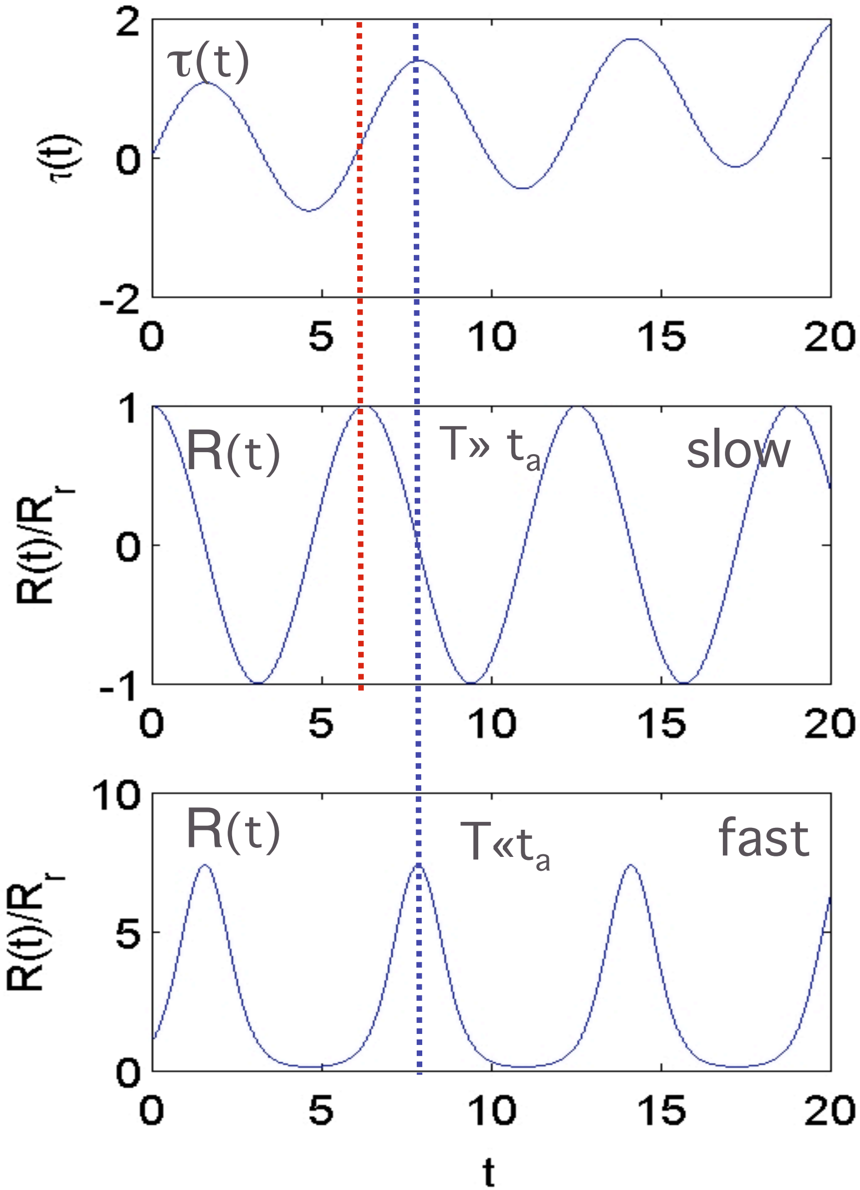
$R \sim d\tau/dt$

(tectonic loading, ...)

Example periodic stress change

$$A\sigma \ln\left(\frac{R}{R_0}\right) + \frac{N\dot{\tau}_r}{r} = \tau$$

- $\tau(t) = \cos(2\pi t/T) + \tau'_r\, t$
- If $T \gg t_a$ $\quad$ $R(t) \sim d\tau/dt$
- If $T \ll t_a$ $\quad$ $R(t) \sim \exp(\tau/A\sigma)$
- In general there is not « simple » relation between stress change and seismicity!



Seismicity rate following a static stress change

[Dieterich, 1994]

- For a stress increase

  Omori law for c « t « t_a

  R~ rupture area ~10^M

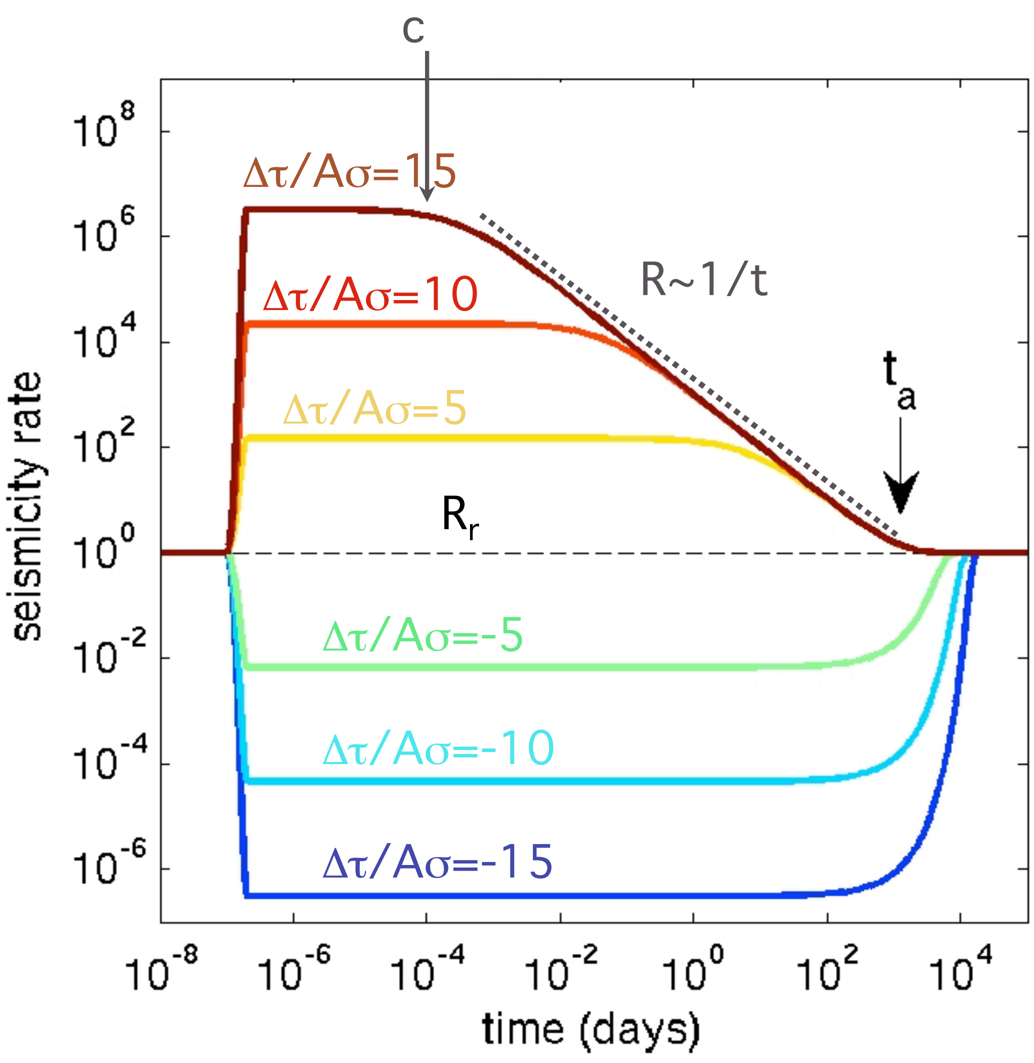
  realistic aftershock duration

- Requires very large stress !

  σ=100MPa

  A=0.01 (lab)

  $\Delta\tau$=15MPa >> EQ stress drop!

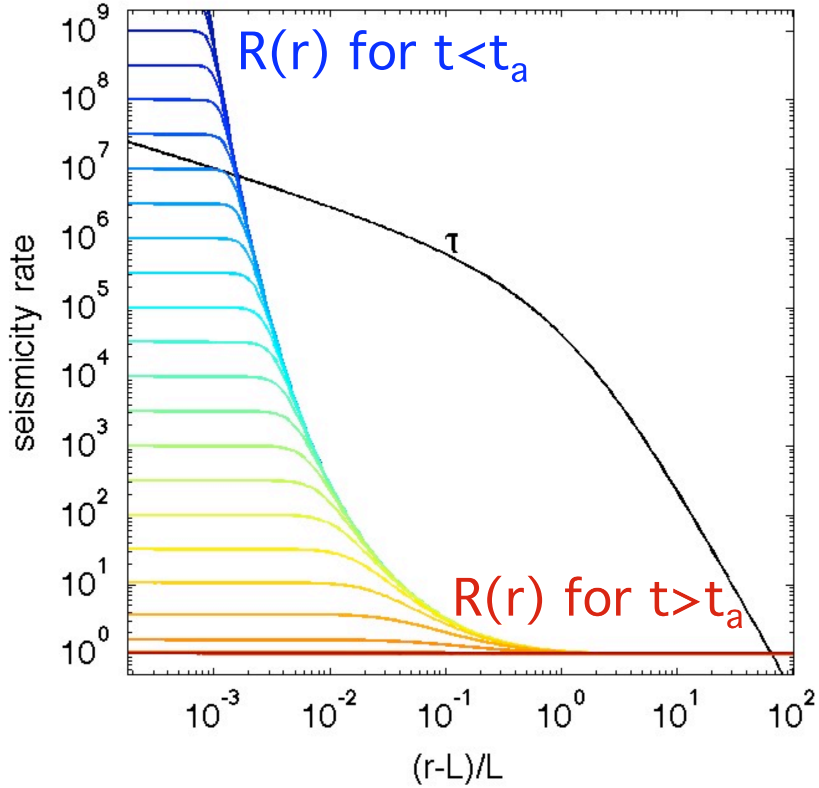


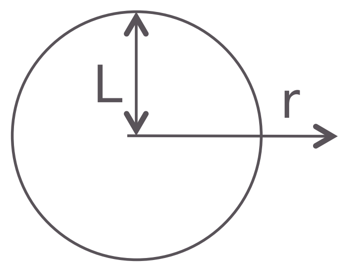
$$t_a = \frac{A\sigma}{\dot{\tau}_r}$$

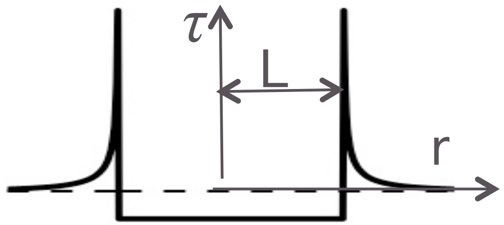
c=t_a exp($\Delta\tau/A\sigma$)

Static stress changes and aftershocks

- stress change dislocation of length L: $\tau(r) \sim (1-(L/r)^3)^{-1/2} - 1$





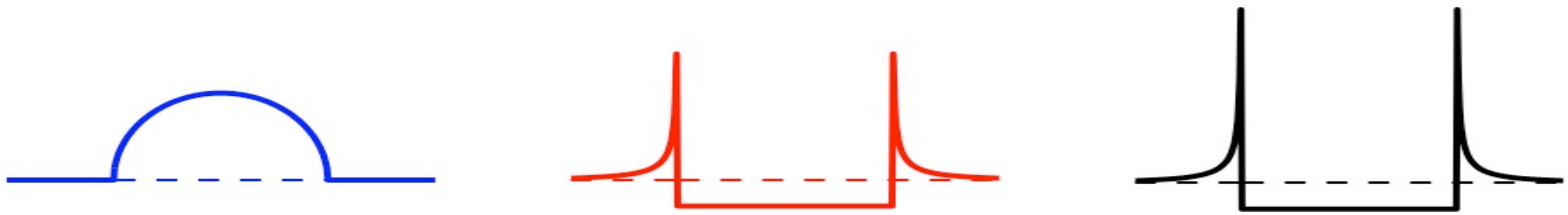


- Very few events for r>2L
- «diffusion» of aftershocks with time
- Shape of R(r) depends on time, very # from $\tau(r)$
- Difficult to guess triggering mechanisms from the decrease of R(r)

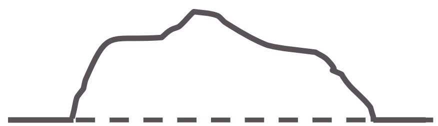
Coseismic slip, stress change, and aftershocks:

- Model: planar fault, uniform stress drop, and R&S model

slip shear stress seismicity rate

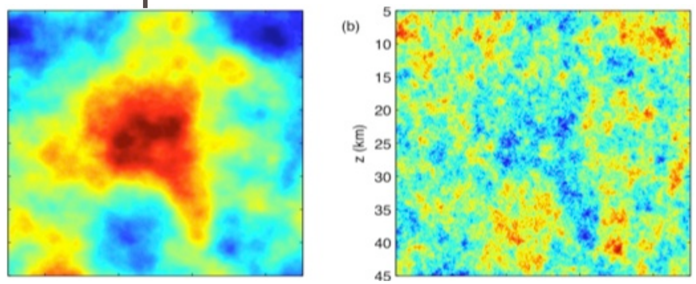


- Real data: most aftershocks occur on or close to the rupture area



➔ Slip and stress must be heterogeneous to produce an increase of stress and thus R on parts of the fault

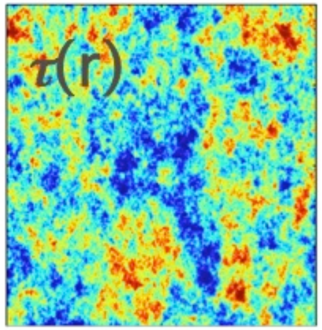
slip stress

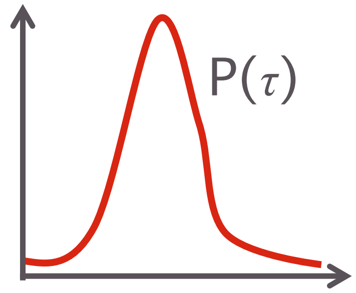


Seismicity rate and stress heterogeneity

Seismicity rate triggered by a heterogeneous stress change on the fault

$$R(t) = \int R(t, \tau(\vec{r}))\, d\vec{r} = \int_{-\infty}^{\infty} R(t,\tau)\, P(\tau)\, d\tau$$

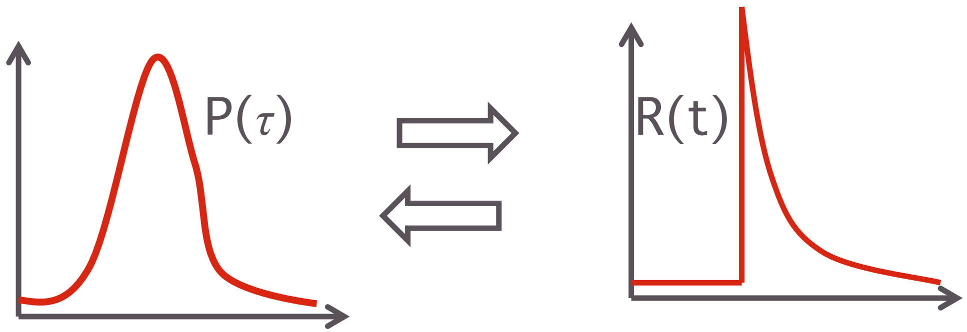




- R(t, τ) : R&S model, unif stress change *[Dieterich 1994]*
- P(τ) : stress distribution (due to slip heterogeneity or fault roughness)

Goals

- seismicity rate R(t) produced by a realistic P(τ)
- inversion of P(τ) from R(t)

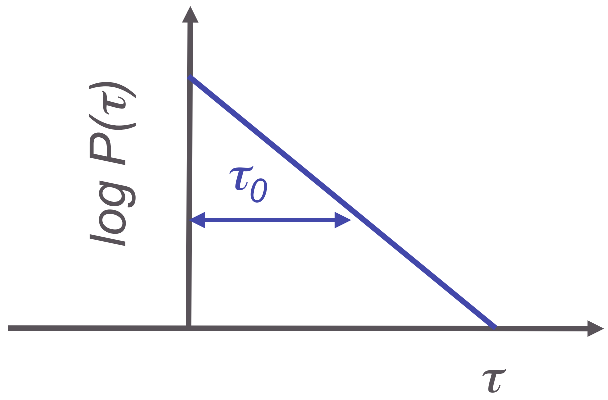


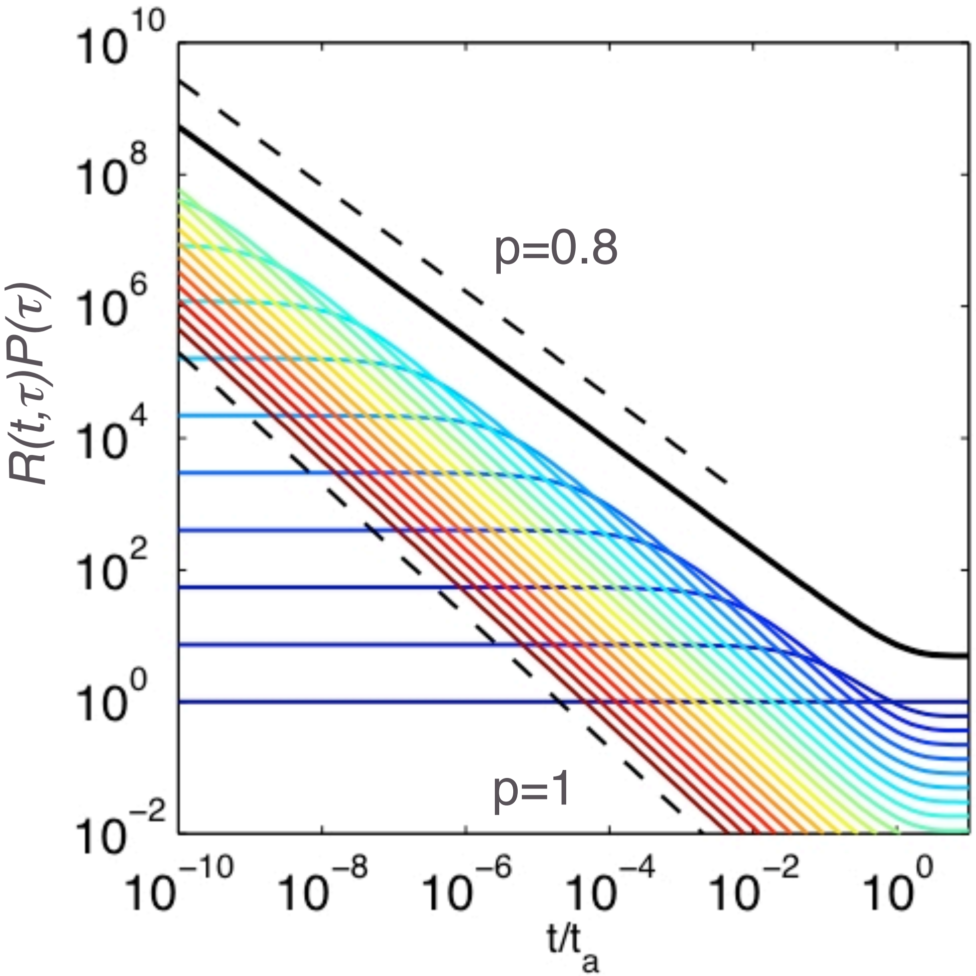
Stress heterogeneity and aftershock time decay

- For an exponential pdf $P(\tau) \sim e^{-\tau/\tau_o}$

➔ Omori law $R(t) \sim 1/t^p$ with $p = 1 - A\sigma/\tau_o$

- $p \leq 1$, ↗ if «heterogeneity» τ_o ↗





- colored lines:

EQ rate for a uniforme τ

$R(t,\tau)P(\tau)$

from τ=0 to τ=50 MPa

- black: global EQ rate,

heterogeneous τ:

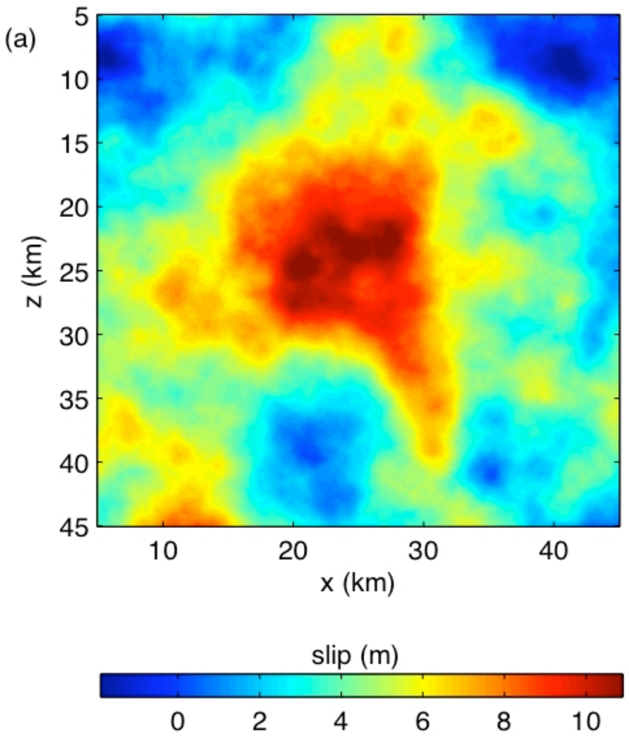
$R(t) = \int R(t,\tau)P(\tau)d\tau$

with $\tau_o/A\sigma = 5$

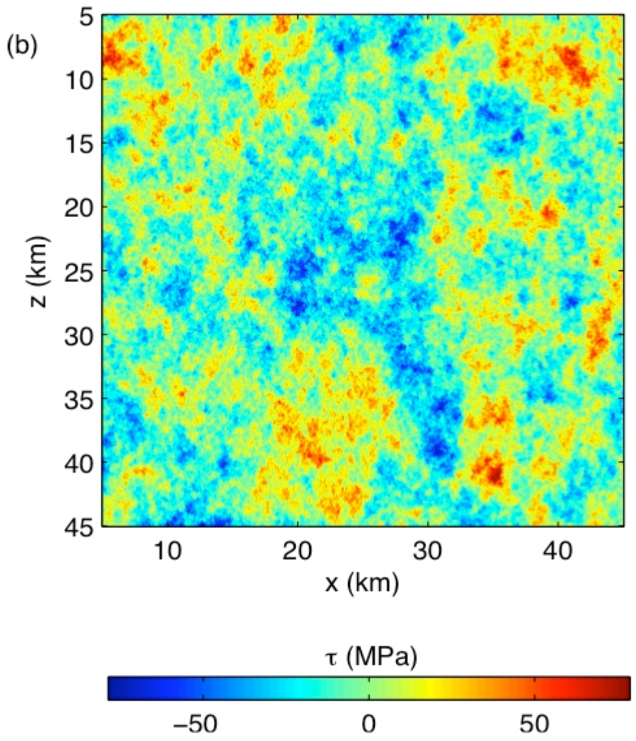
Slip and shear stress heterogeneity, aftershocks

Modified « k^2 » slip model: *$U(k) \sim 1/(k+1/L)^{2.3}$* *[Herrero & Bernard, 1994]*

slip

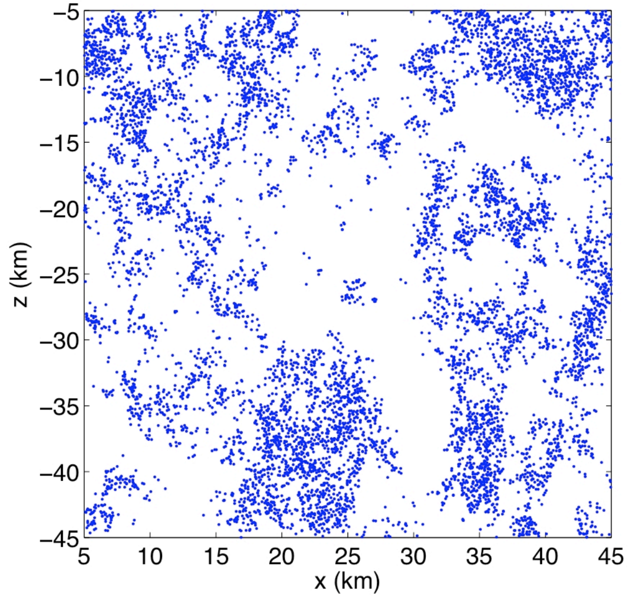


shear stress
stress drop σ_0 =3 MPa



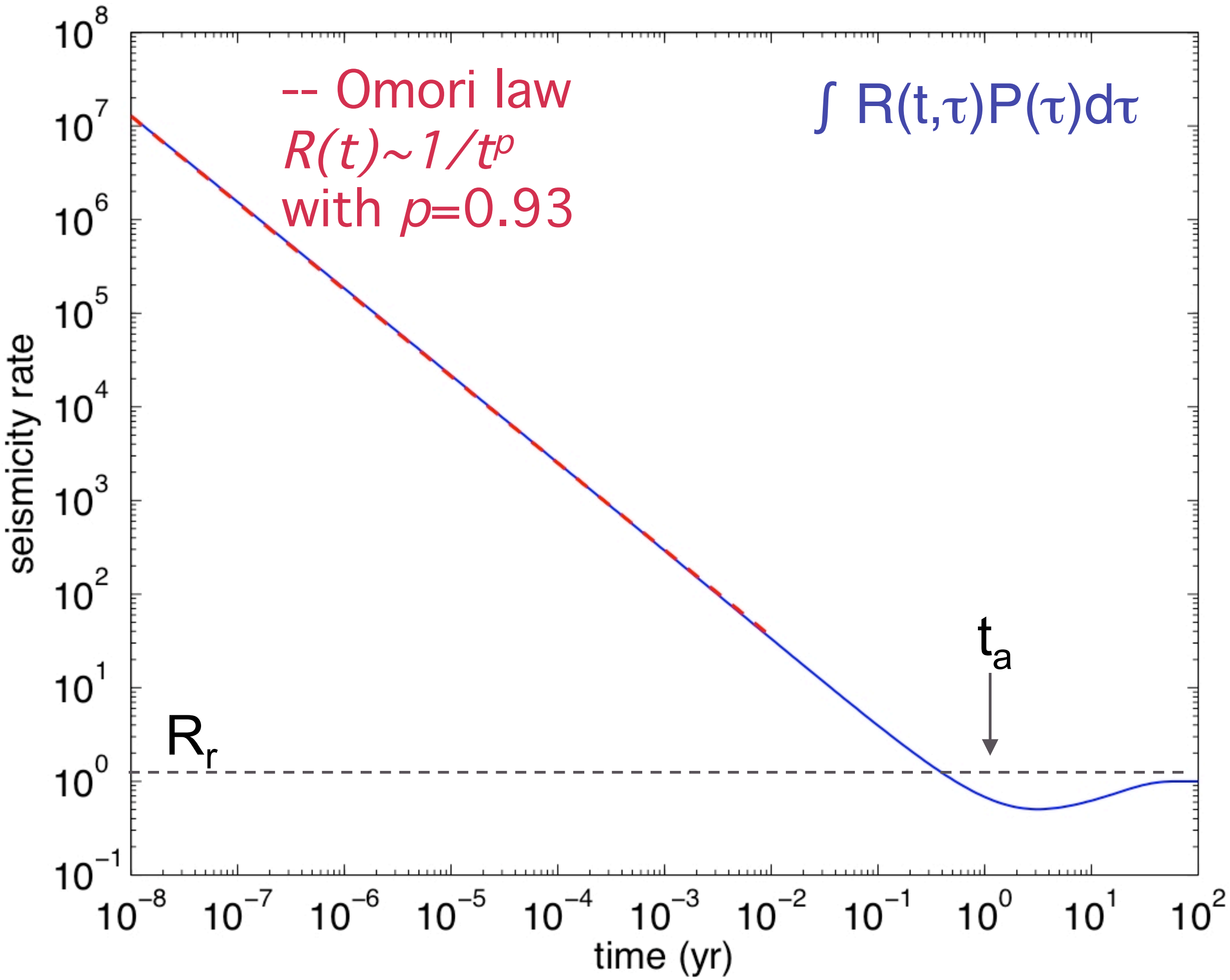
mean stress σ_0

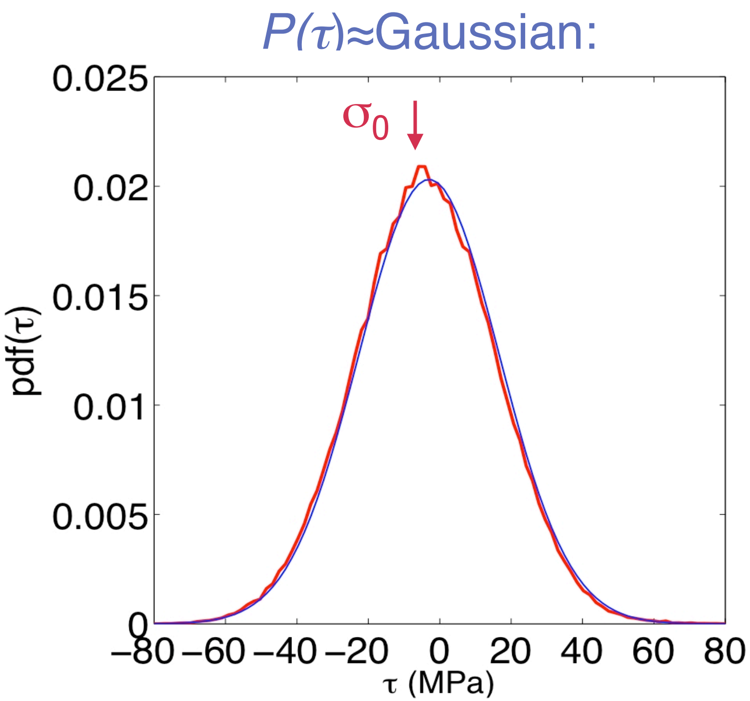
aftershock map
synthetic catalog
R&S model



Stress heterogeneity and aftershock time decay

Aftershock rate on the fault with R&S model for modified k^2 slip model



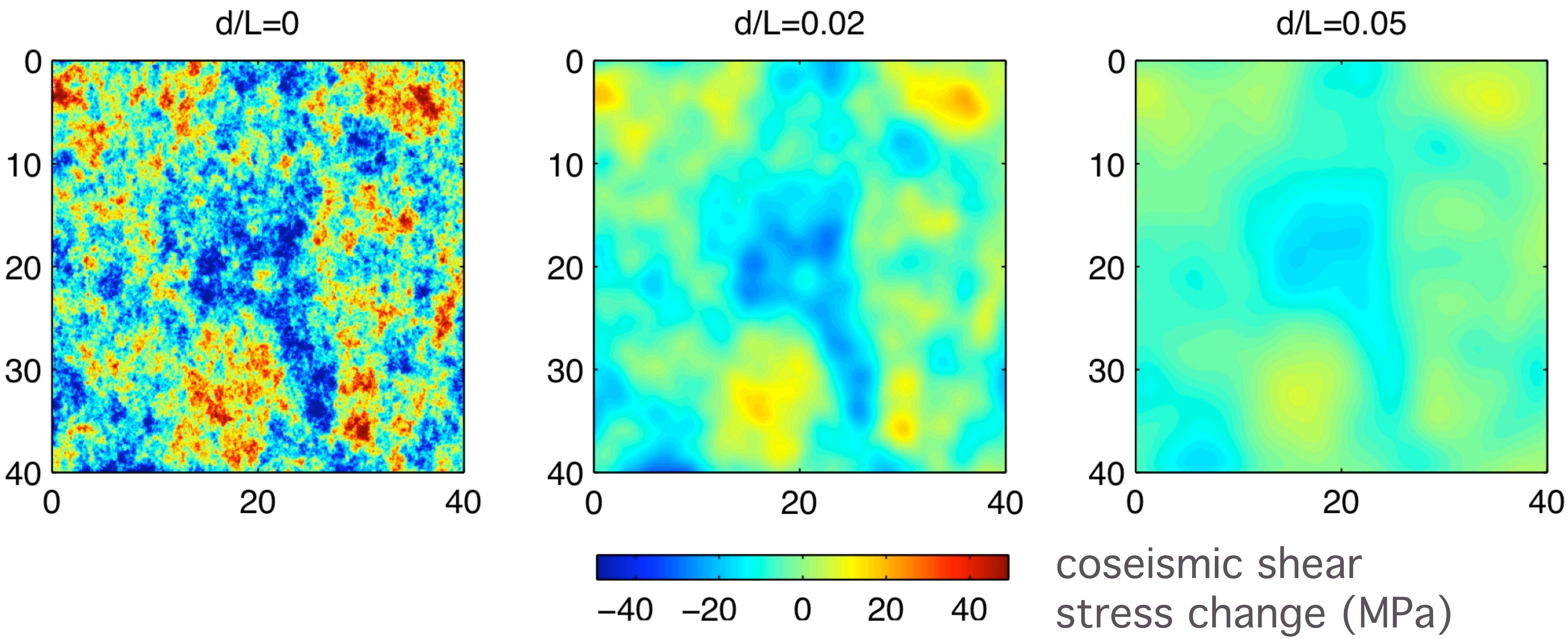


Short times $t \ll t_a$: apparent Omori law with $p \leq 1$

Long times $t \approx t_a$: stress shadow $R(t) < R_r$

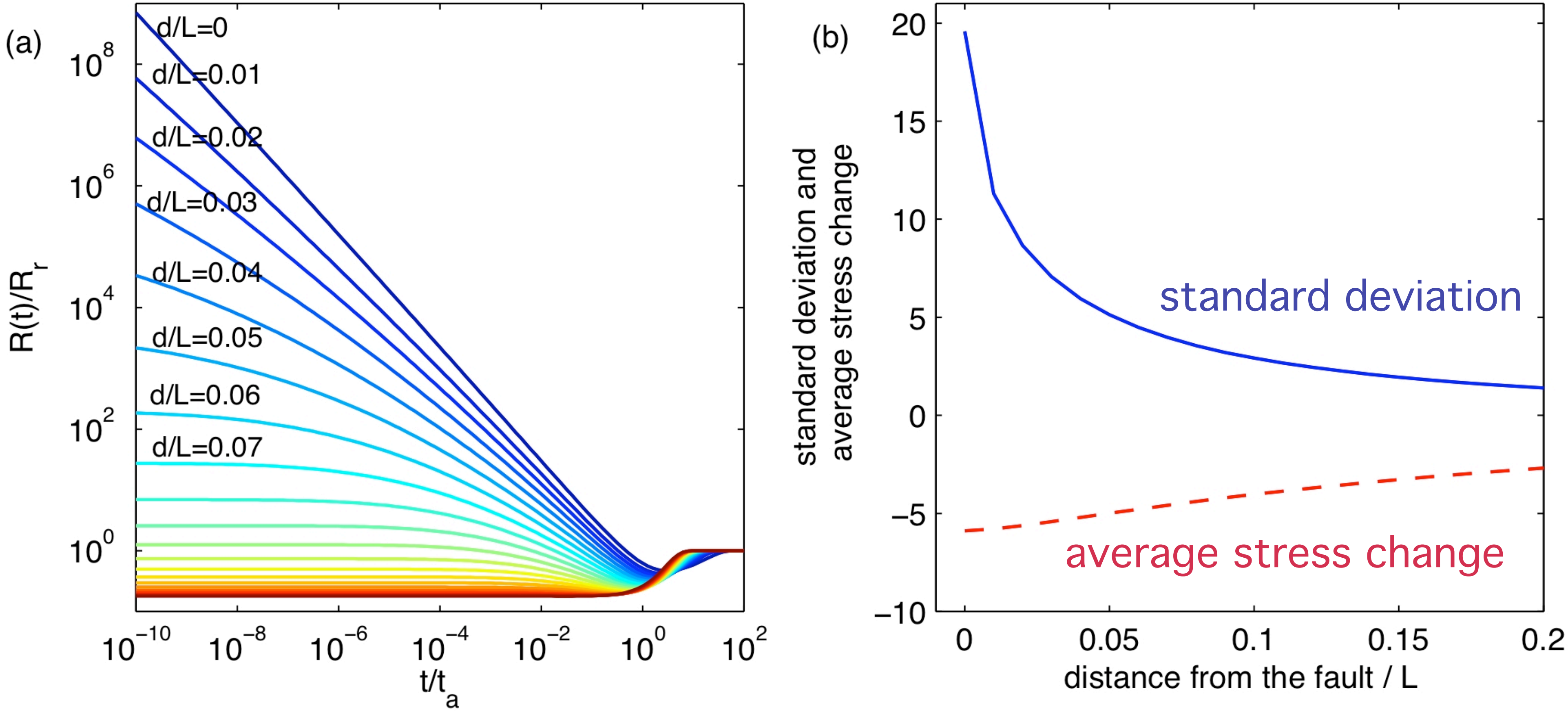
Modified k^2 slip model, off-fault stress change

- distance $d<L$ from the fault: $\tau(k,d) \sim \tau(k,0)e^{-kd}$ for $d \ll L$
- fast attenuation of high frequency τ perturbations with distance



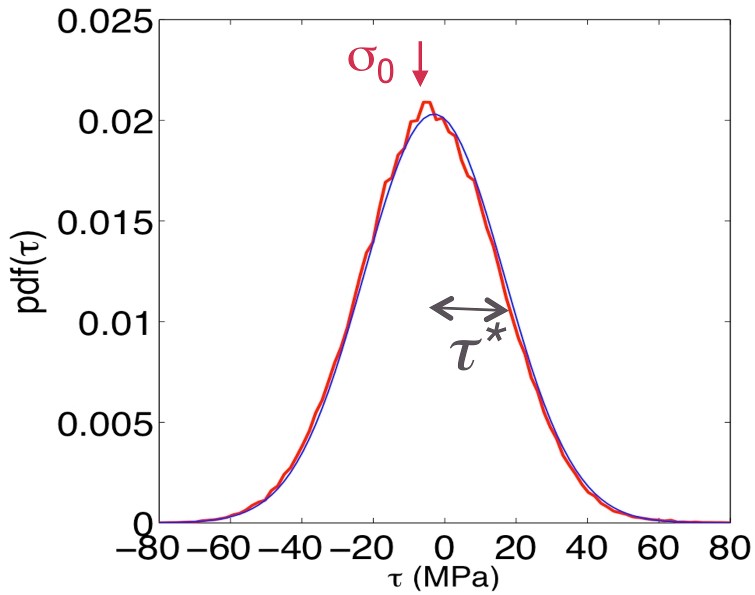
Modified k^2 slip model, off-fault aftershocks

- seismicity rate and stress change as a function of *d/L*
- quiescence for d >0.1L

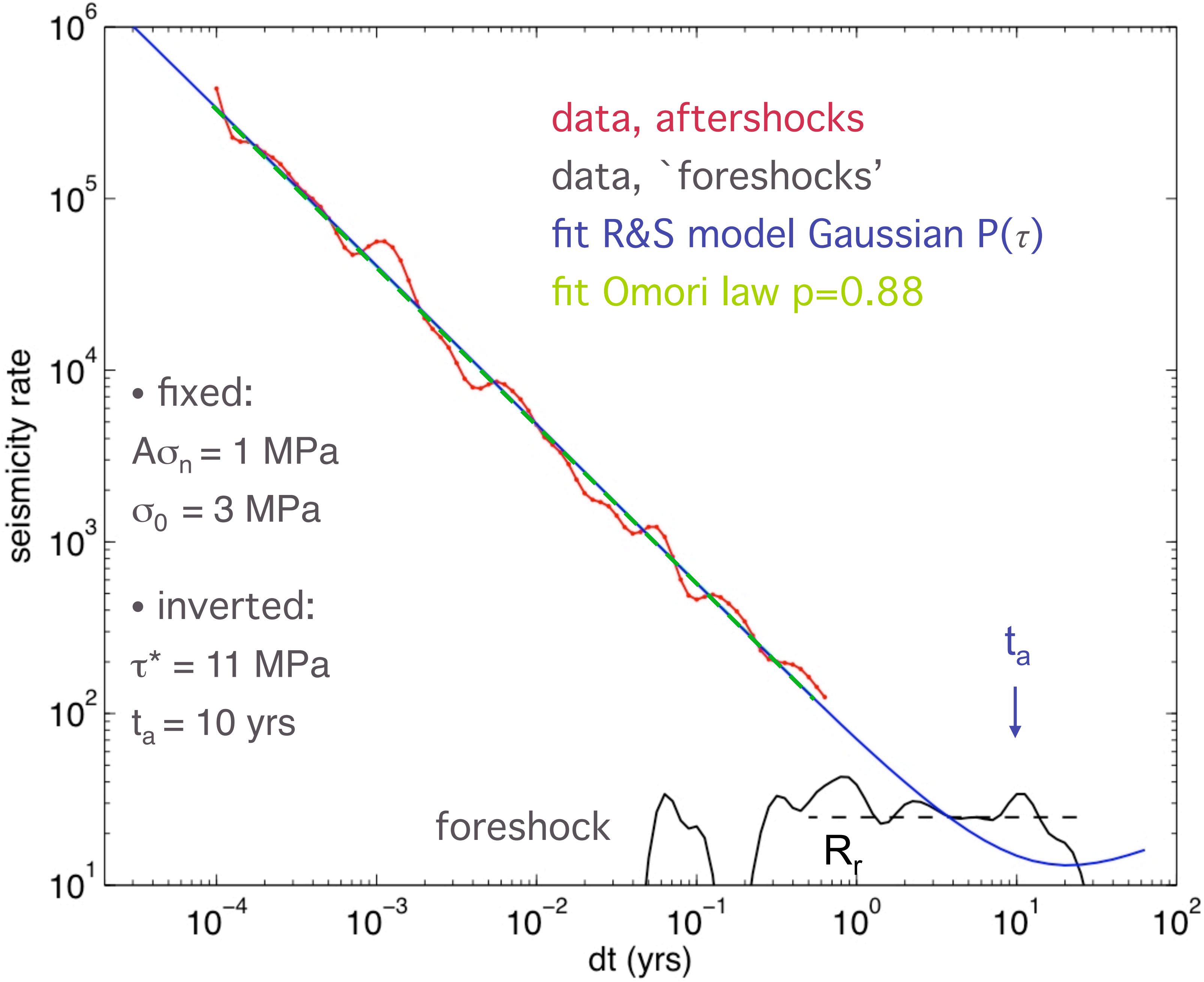


Inversion of stress distribution from aftershock rate

- We invert for $P(\tau)$ from $R(t)$ for individual aftershocks sequences in California and stacked sequences in Japan
- select aftershocks close to fault plane
- assume $P(\tau)$ is gaussian
- stress drop σ_0 fixed to 3 MPa
- $A\sigma = 1$ MPa
- invert for t_a and standard deviation τ^*



Parkfield 2005 M=6 aftershock sequence



Inversion of P(τ) for real sequences

Sequence	p	τ^* (MPa)	t_a (yrs)
Morgan Hill M=6.2, 1984	0.68	6.2	78.
Parkfield M=6.0, 2004	0.88	11.	10.
Stack, 3<M<5, Japan*	0.89	12.	1.1
San Simeon M=6.5 2003	0.93	18.	348.
Landers M=7.3, 1992	1.08	**	52.
Northridge M=6.7, 1994	1.09	**	94.
Hector Mine M=7.1, 1999	1.16	**	80.
Superstition-Hills, M=6.6,1987	1.30	**	**

* *[Peng et al., 2007]*

** we can't estimate τ^* because $p>1$

Conclusion - triggering by heterogeneous static stress changes

R&S model with stress heterogeneity explains

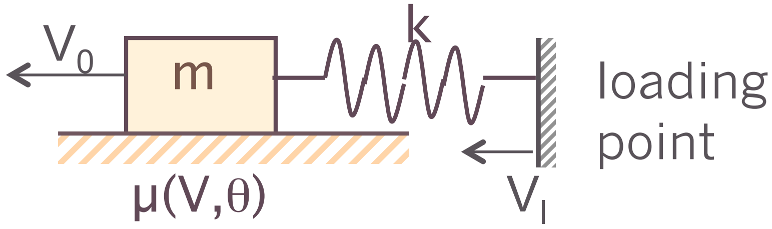
- short-times triggering
  - Omori law with $p \leq 1$
  - p decreases with stress variability
- Long times quiescence for $t \approx t_a$
- in space : clustering on/close to the rupture area

Problems:

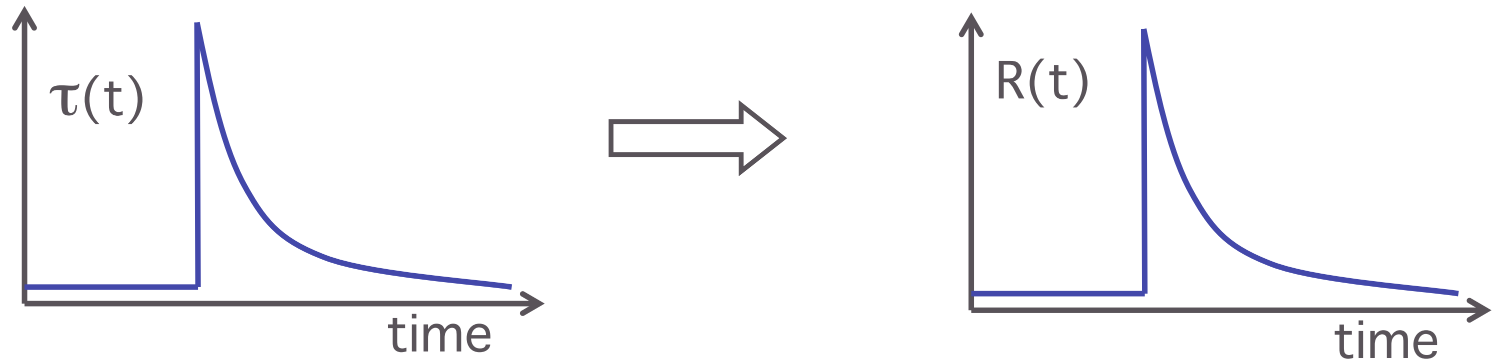
- inversion: stress drop not constrained if catalog too short
- we don't know $A\sigma$: 0.01 or 1MPa??
- secondary aftershocks?
- can't explain $p>1$: post-seismic stress relaxation?

Earthquakes triggering by aseismic stress changes (afterslip, viscous relaxation, fluid flow,...)

- Modelling afterslip and slow slip events with a simple slider-block model and R&S friction

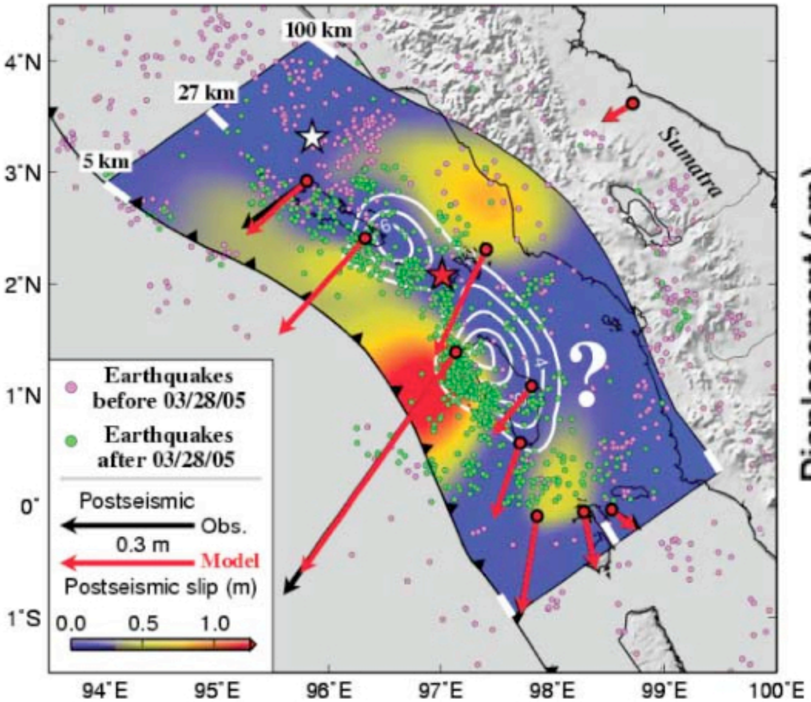


- Triggering of aftershocks by afterslip

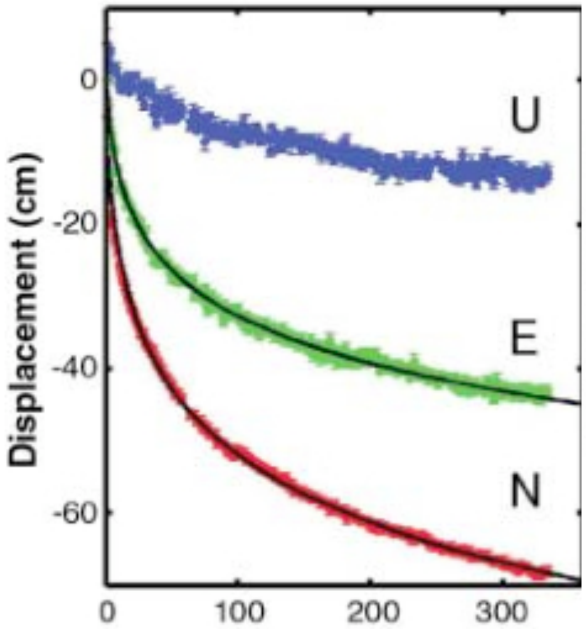


Observations: example for 2005 m=8.7 Nias EQ

Co- and after- slip

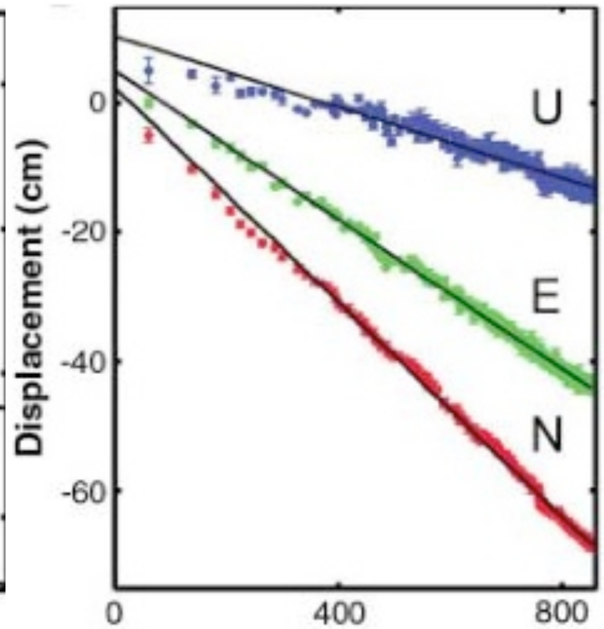


Afterslip (time)



Days after Nias earthquake

Afterslip and
# of aftershocks



Cumulative number of aftershocks

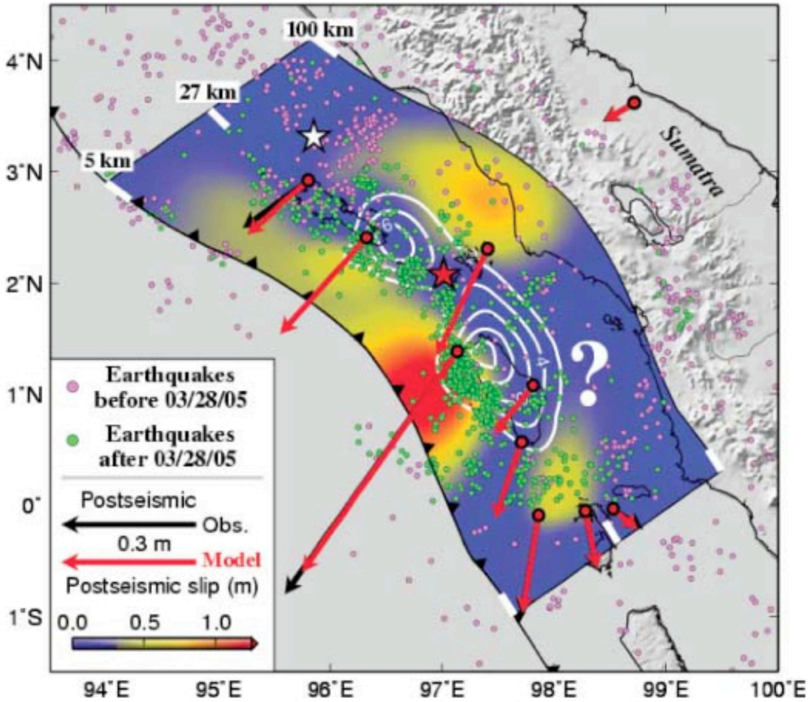
[Hsu et al, Science 2006]

Interactions between afterslip and aftershocks

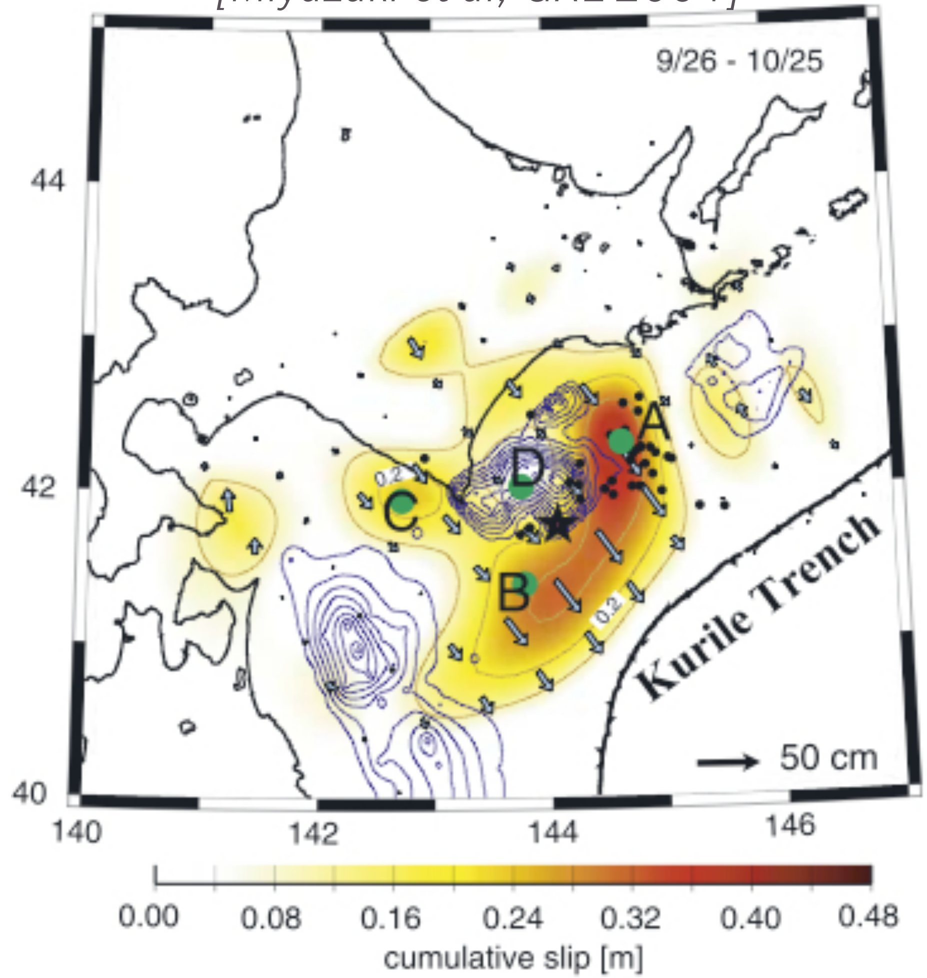
- relation between coseismic and postseismic slip?
- can we use afterslip to constrain the rheology of the crust (stable/unstable)?
- relation between afterslip and aftershocks?
- mechanisms for aftershock triggering?

Observations of postseismic behavior

2005 m=8.7 Nias
[Hsu et al, 2006]

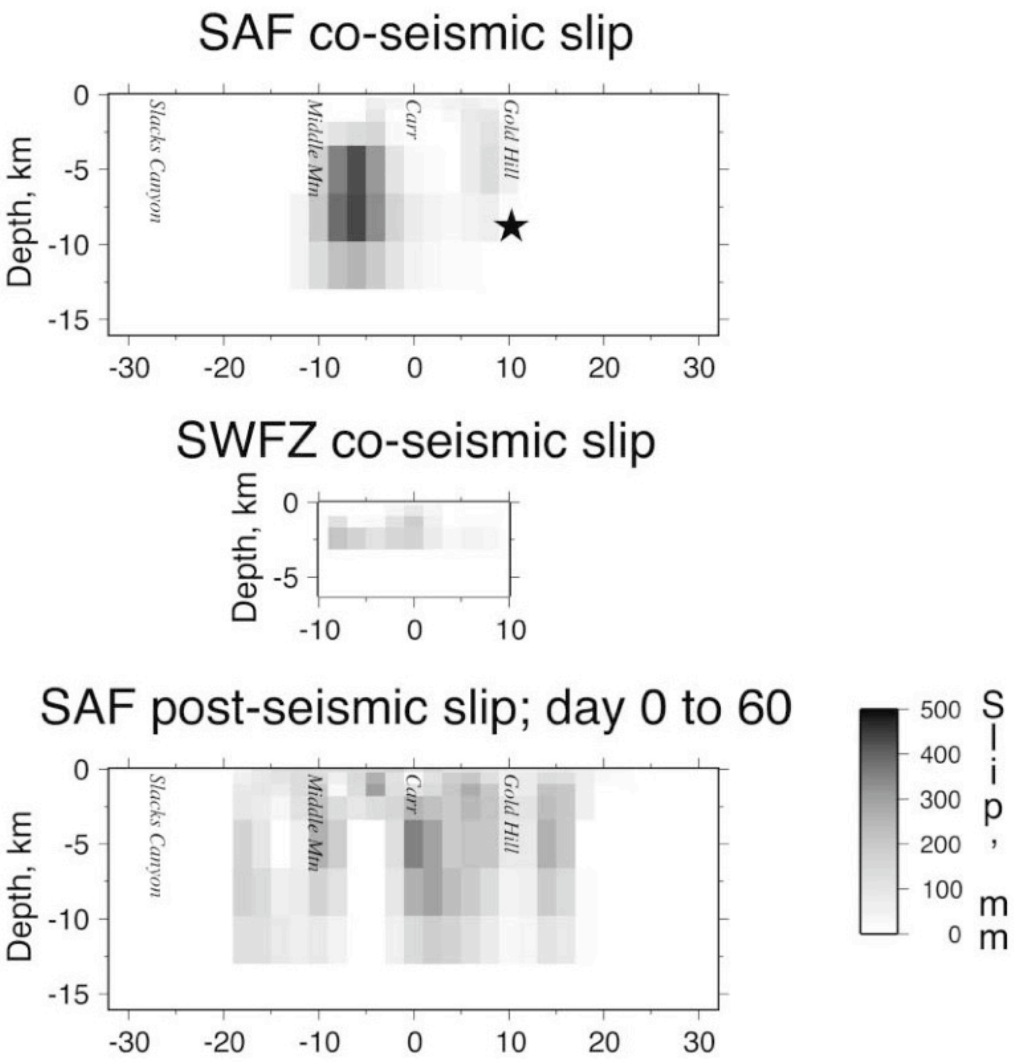


2003 m=8 Tokachi
[Miyazaki et al, GRL 2004]

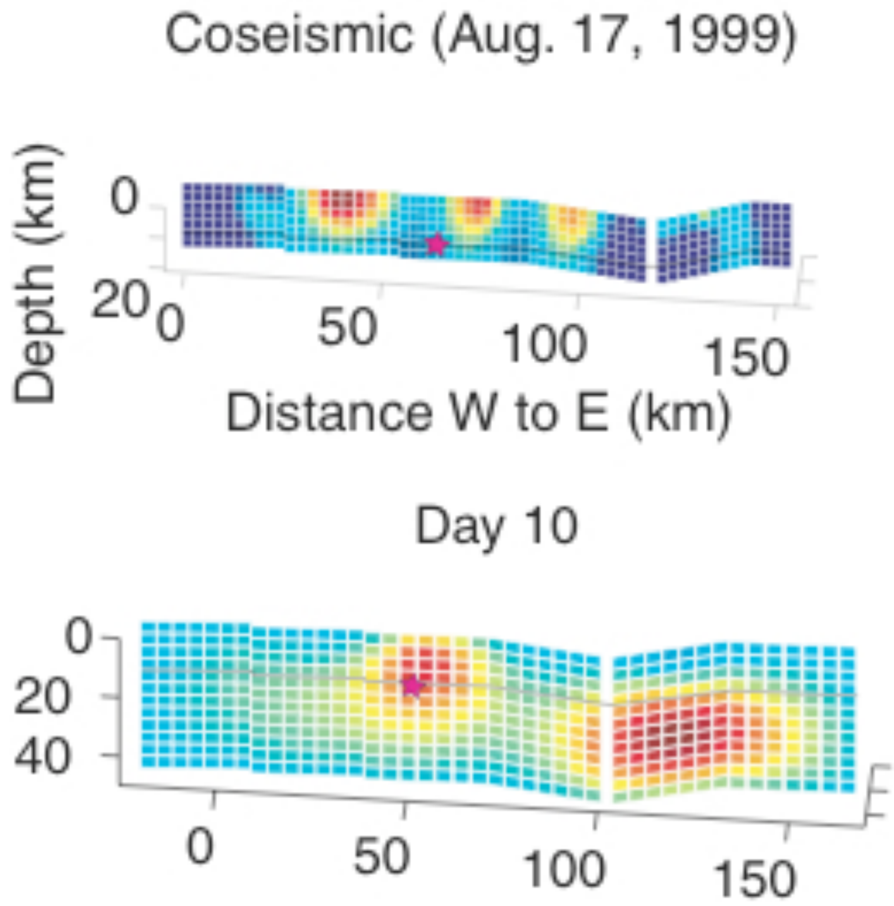


Observations of postseismic behavior

Parkfield 2004, M=6
[Langbein et al 2006]

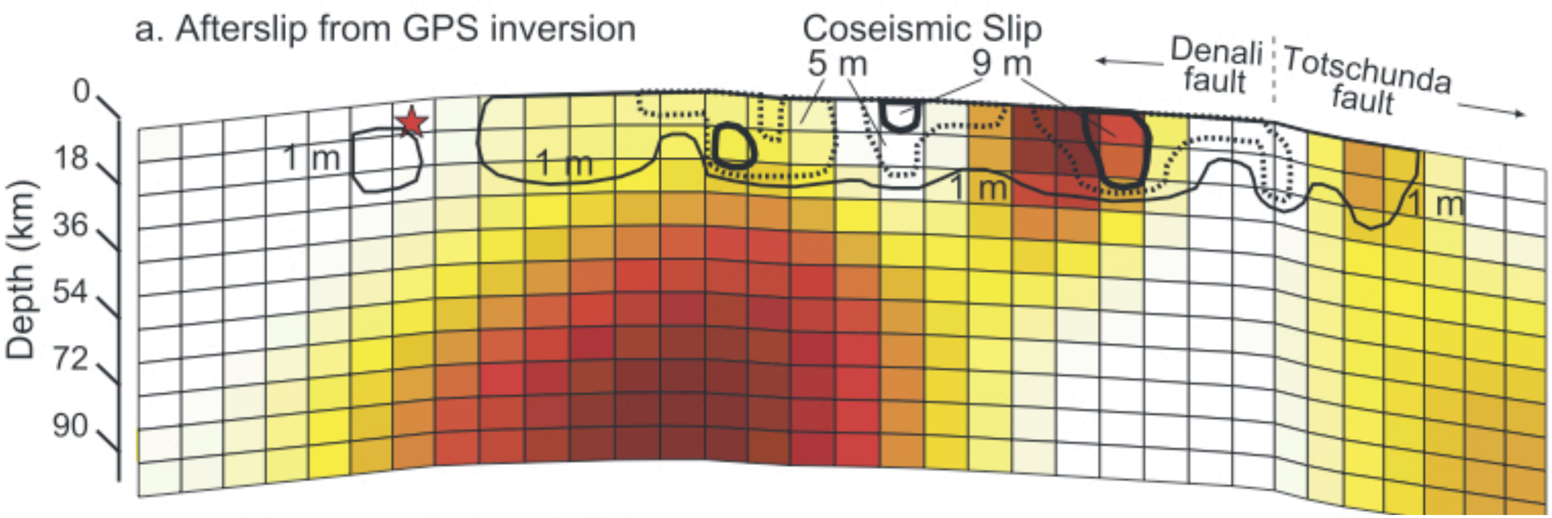


Izmit 1999, M=7.6
[Burgmann, 2002]



Spatial distribution of afterslip and aftershocks

2002 m=7.8 Denali *[Freed et al, JGR 2006]*



Observations of afterslip

- afterslip on average scales with co-seismic slip
- afterslip moment is usually a few % of coseismic
- But it may be larger than coseismic moment (eg, Parkfield 2004)
- Slip rate usually decays as 1/t

  … but hard to distinguish from exponential decay
- Afterslip is usually associated with velocity-hardening faults and earthquakes associated to velocity weakening?

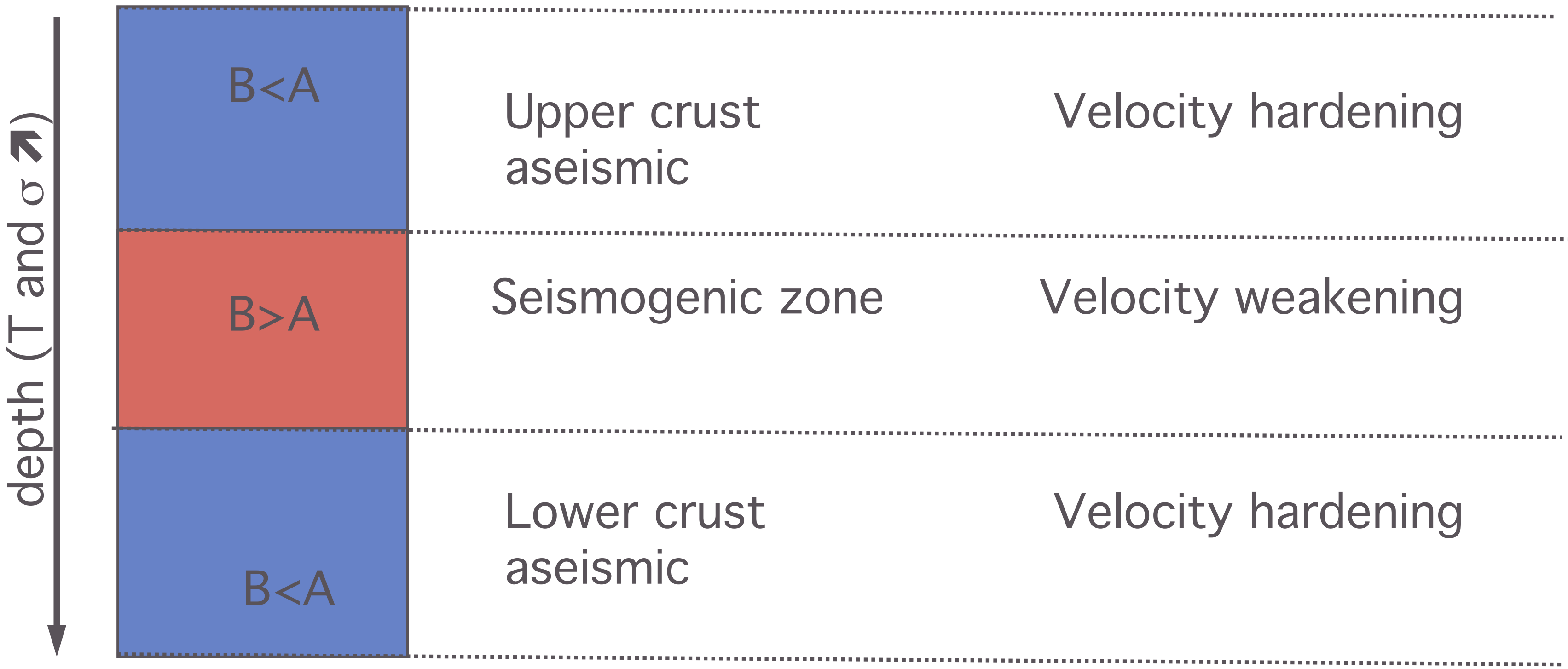
  [Marone et al 1991, Perfettini and Avouac 2003, …]
- Some overlap between aftershocks, co- and post-seismic slip

➔ temporal or spatial changes in the friction law parameters?

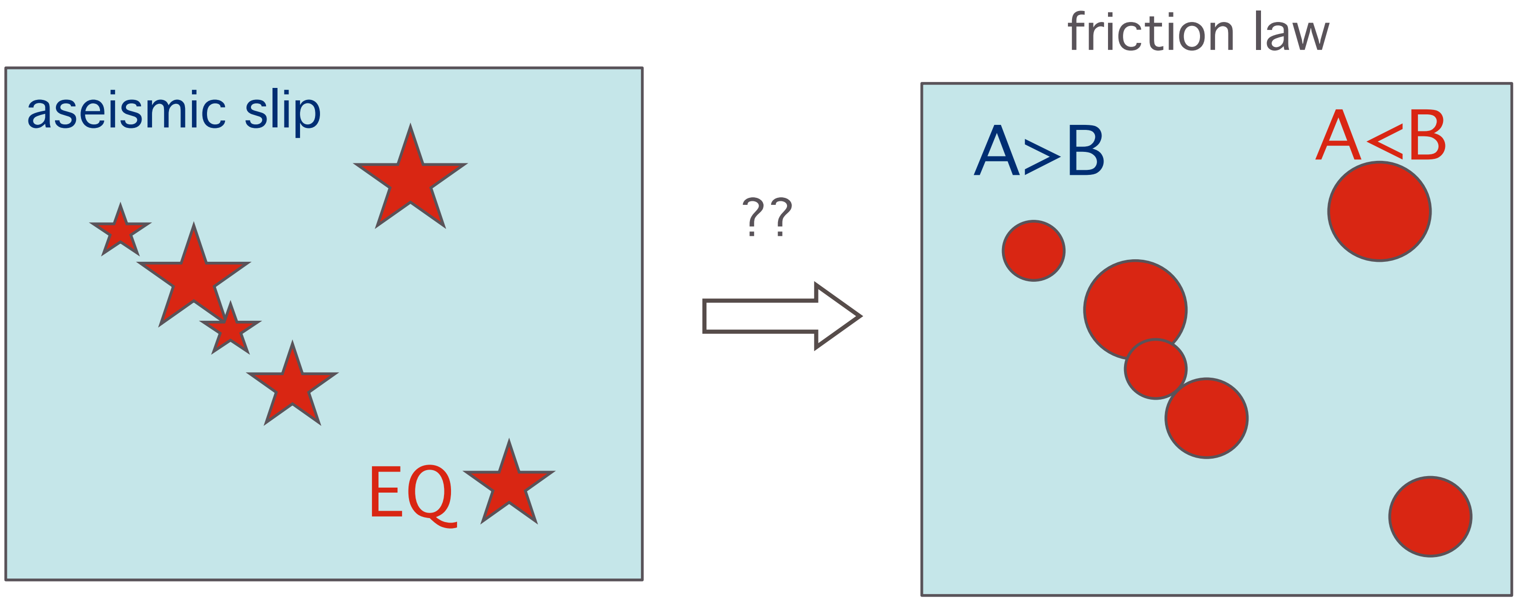
Rate-and-state friction and fault dynamics

From lab experiments, A and B are expected to vary with T and σ

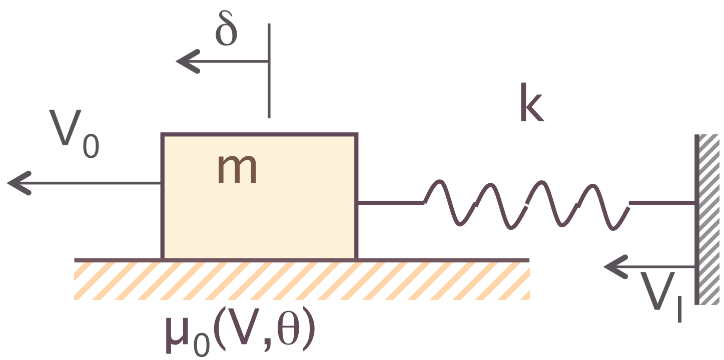
Variations of B/A can explain the distribution of seismicity with depth

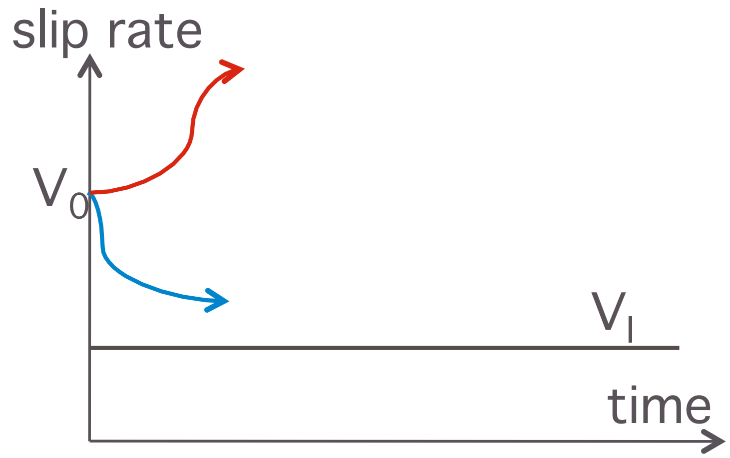


Rate & state friction and fault behavior



Rate-and-state friction law and afterslip





- friction law [*Dieterich*, 1979]

$$\mu = \mu_0 + A \log(V/V_0) + B \log(\theta/\theta_0) = \mu_0 - k(\delta - V_l t)/\sigma$$

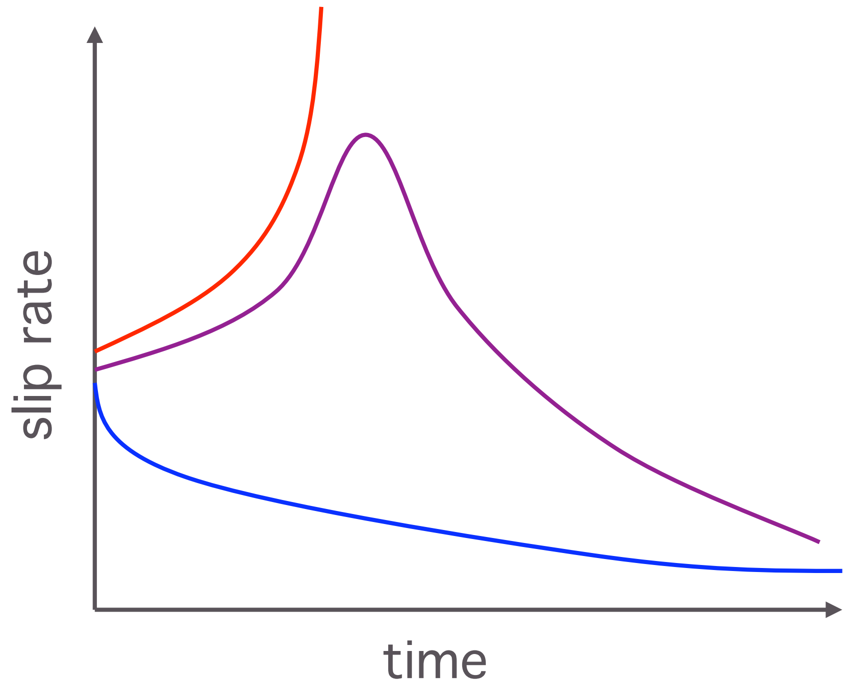
$$d\theta/dt = 1 - V\theta/D_c$$

- relaxation or nucleation of a slip instability after a stress step
- inertia and tectonic loading negligible:

$V_l \ll V \ll$ coseismic slip rate

Numerical & analytical analysis
Fault behavior after a stress step

Different behaviors are observed in numerical simuations as a function of friction parameters *B/A*, stiffness k/k_c and stress μ:



Aftershock:
Slip instability triggered by stress change

Slow EQ
Slip rate increase followed by relaxation

Afterslip
Relaxation toward background rate

Fault behavior – phase diagram

Fault behavior controlled by *B/A*, stiffness *k* and stress ($V \gg V_l$) *[Helmstetter and Shaw, 2009]*

- slip accelerations

if $k<k_B$ and $\mu>\mu_a>\mu_{ss}$

- slip instabilities

if $k<k_c$ and $\mu>\mu_l>\mu_{ss}$

- steady-state

$d\theta/dt=0$

$V= D_c/\theta=\text{const}$

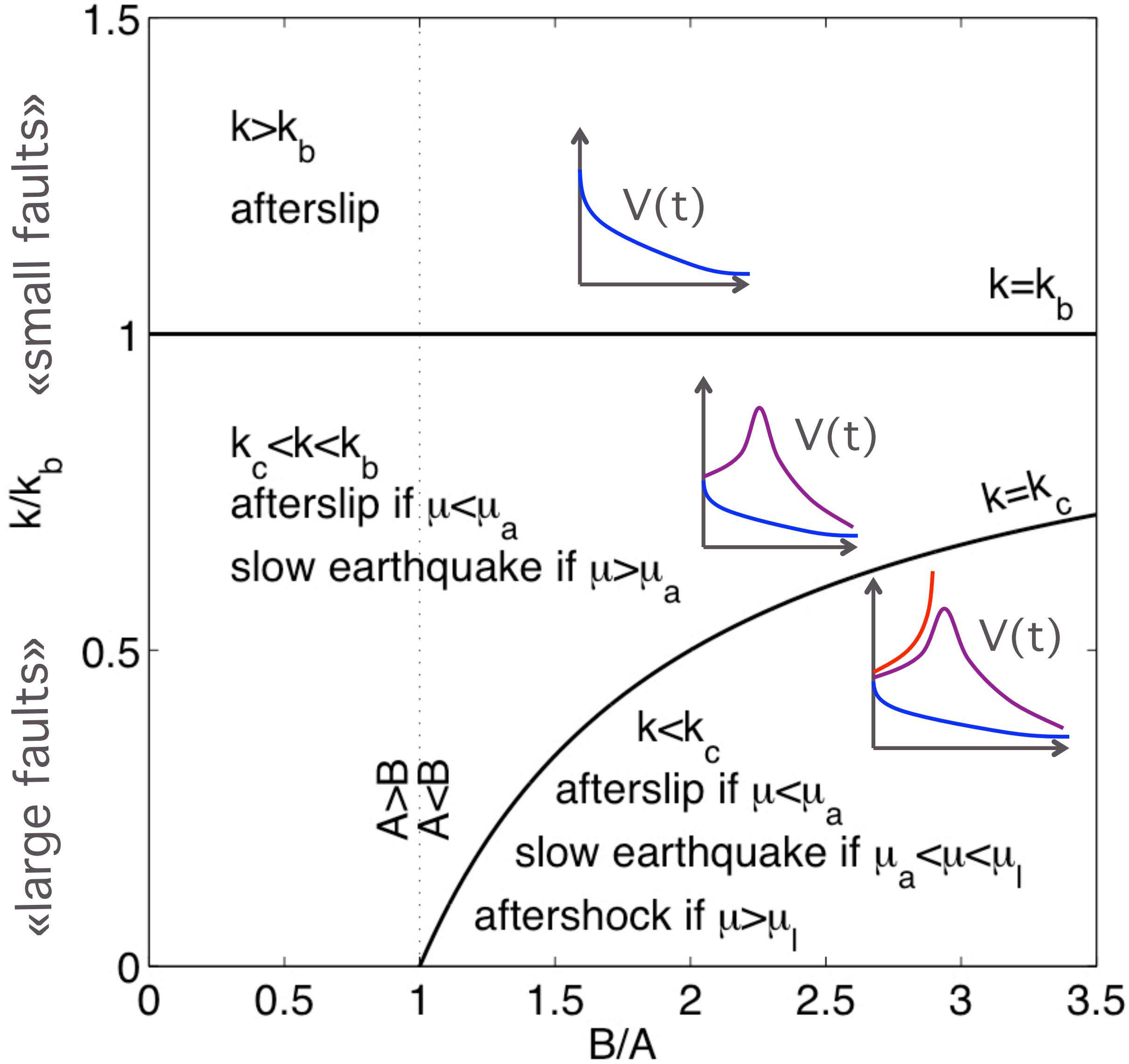
$\mu_{ss} = \mu_0 +(B-A)\ \ln(V/V_0)$

$k_B = B\sigma/D_c$

$k_c=(B-A)\sigma/D_c$

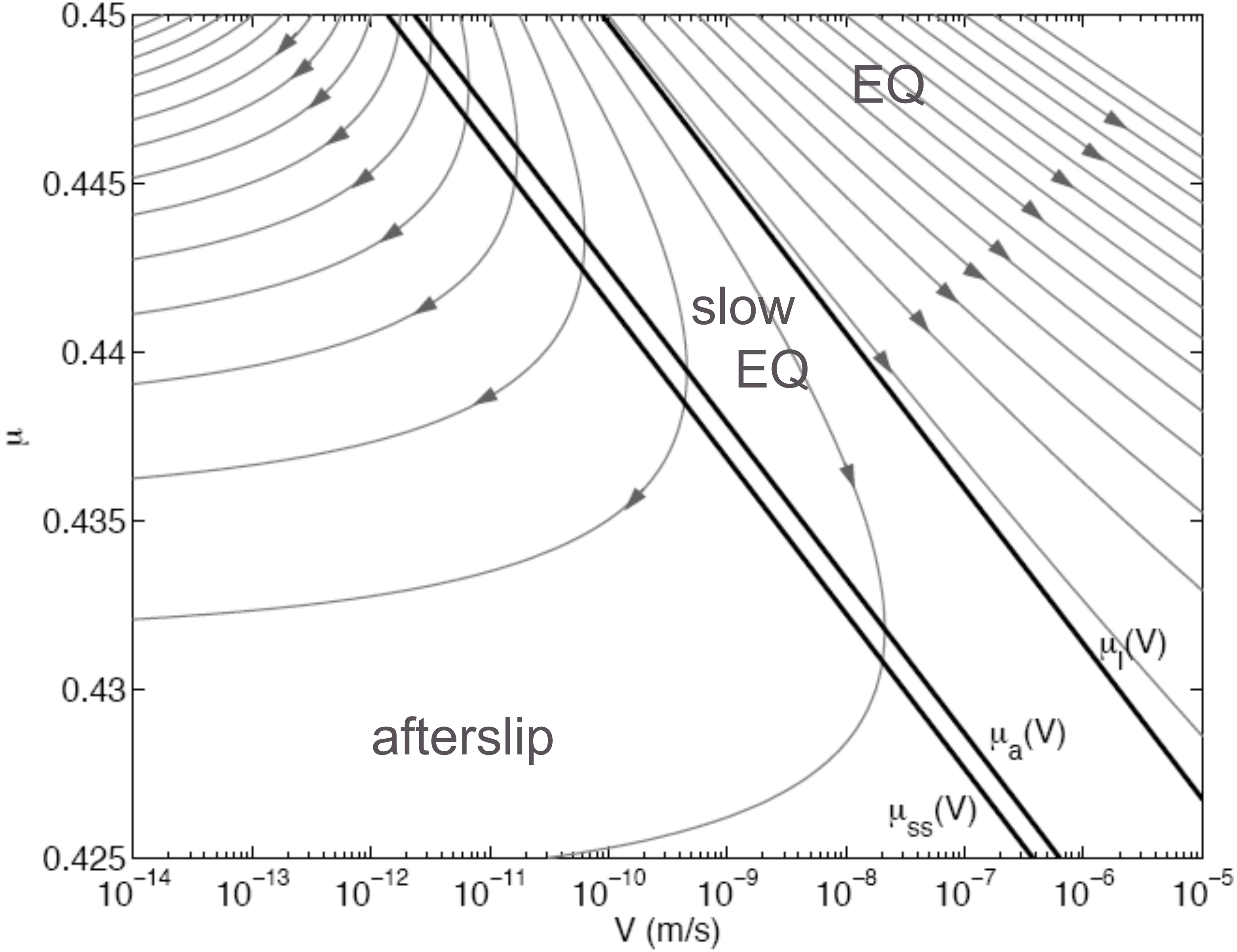
$\mu_l = \mu_{ss}-B\ \ln(1-k/k_c)$

$\mu_a = \mu_{ss}-B\ \ln(1-k/k_B)$



Fault behavior

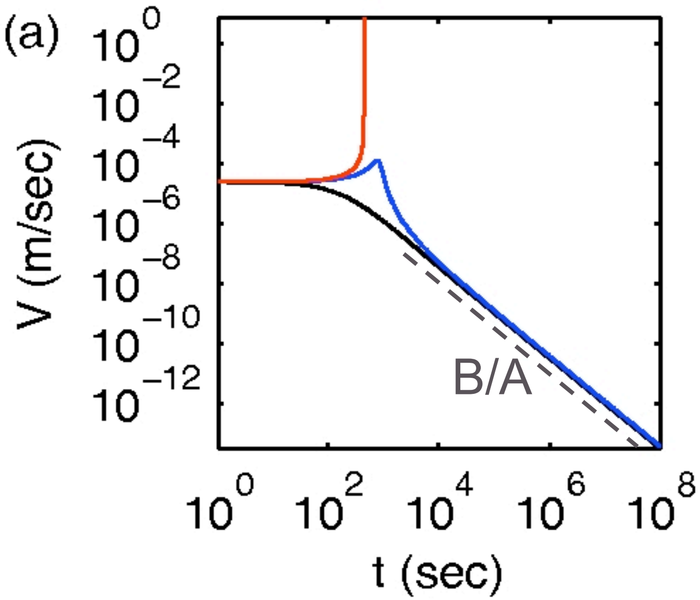
Fault behavior for $B > A$ and $k < k_c$ ($V \gg V_l$)



Slip rate history

- **# behaviors**: aftershocks, slow EQ, and afterslip
- **# afterslip regimes,** with slope exponent=*B/A* or1
- **# characteristic times *t****
- analytical solutions for μ », « or ≈ μ_{ss}

[Helmstetter and Shaw, 2009]



Unstable case:

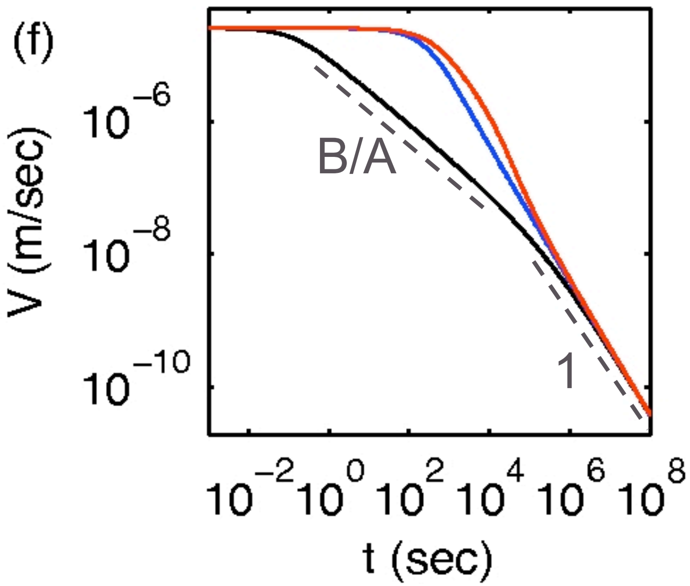
B=1.5A

$k=0.8k_c$

$\mu_0>\mu_l$: aftershock

$\mu_l>\mu_0>\mu_a$: slow EQ

$\mu_0<\mu_a$: afterslip



Stable case

B=0.5A

$k=2.5|k_c|$

only afterslip

$\mu_0>\mu_{ss}$

$\mu_0=\mu_{ss}$

$\mu_0<\mu_{ss}$

Slip history - 1D model and afterslip data

Data:

- GPS and creep-meter for 2004 m=6 Parkfield [Langbein et al , 2006]
- GPS data for 2005 Nias m=8.5 [Hsu et al , 2006]
- GPS data for 2002 Denali m=7.8 [Freed et al, 2006]

Models : each dataset fitted individually with

- Omori law: $V=V_0/(t/c+1)^p + V_l$
- Rate-dependant frictin law friction law : $\mu = \mu_0 + (B\text{-}A)\ \ln(V/V_0)$

[Marone et al., 1991; Hsu, 2006; Perfettini et al, 2004, 2007, ...]

$$V = V_0/[1+\exp(-t/t_r)(1/d-1)] + V_l$$

- Full R&S friction law with constant tectonic rate :

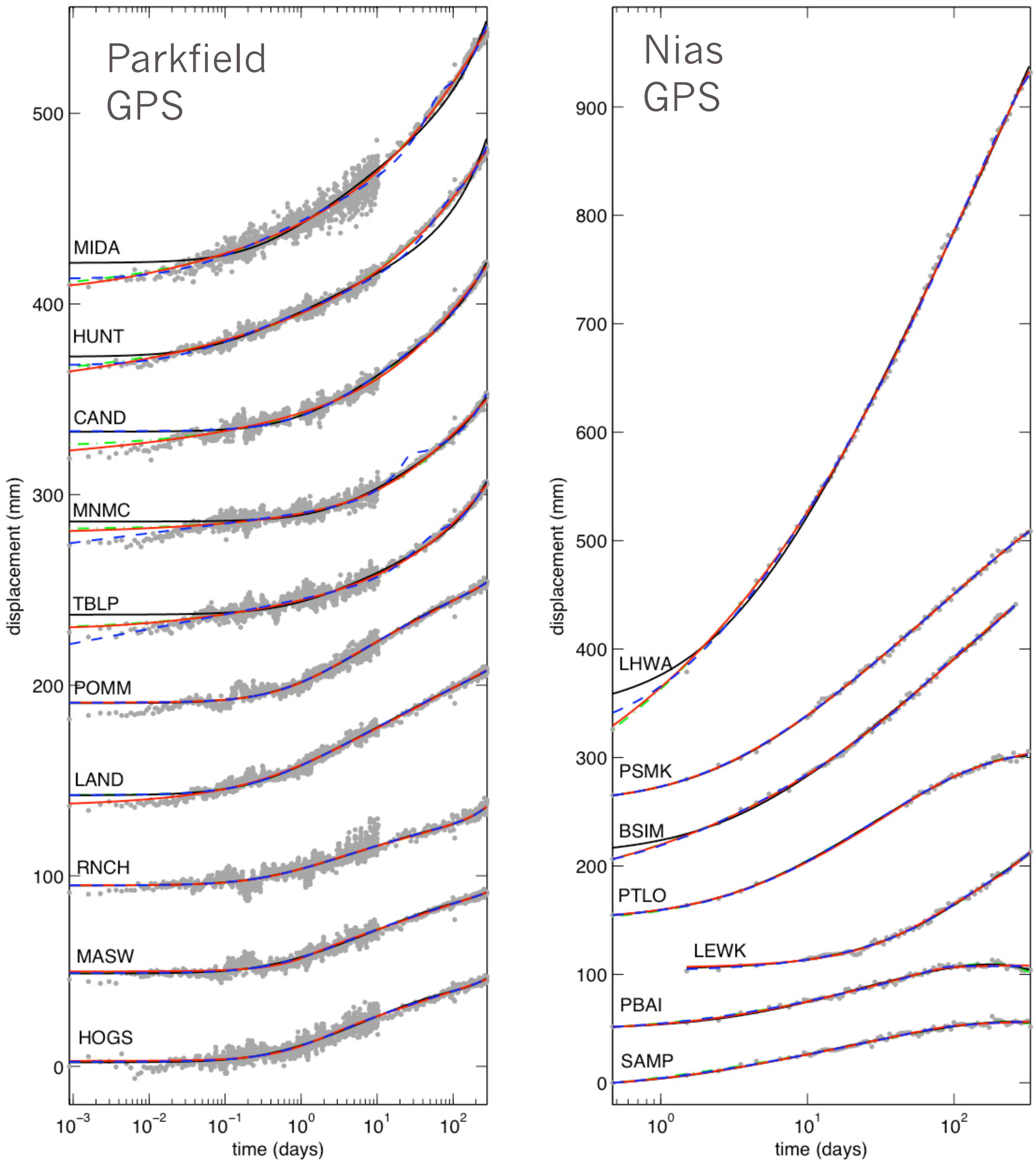
invert for A, B, k, D_c, V_l, V_0 and μ_0

-- Omori

_ R friction

_ R&S friction
with A>B

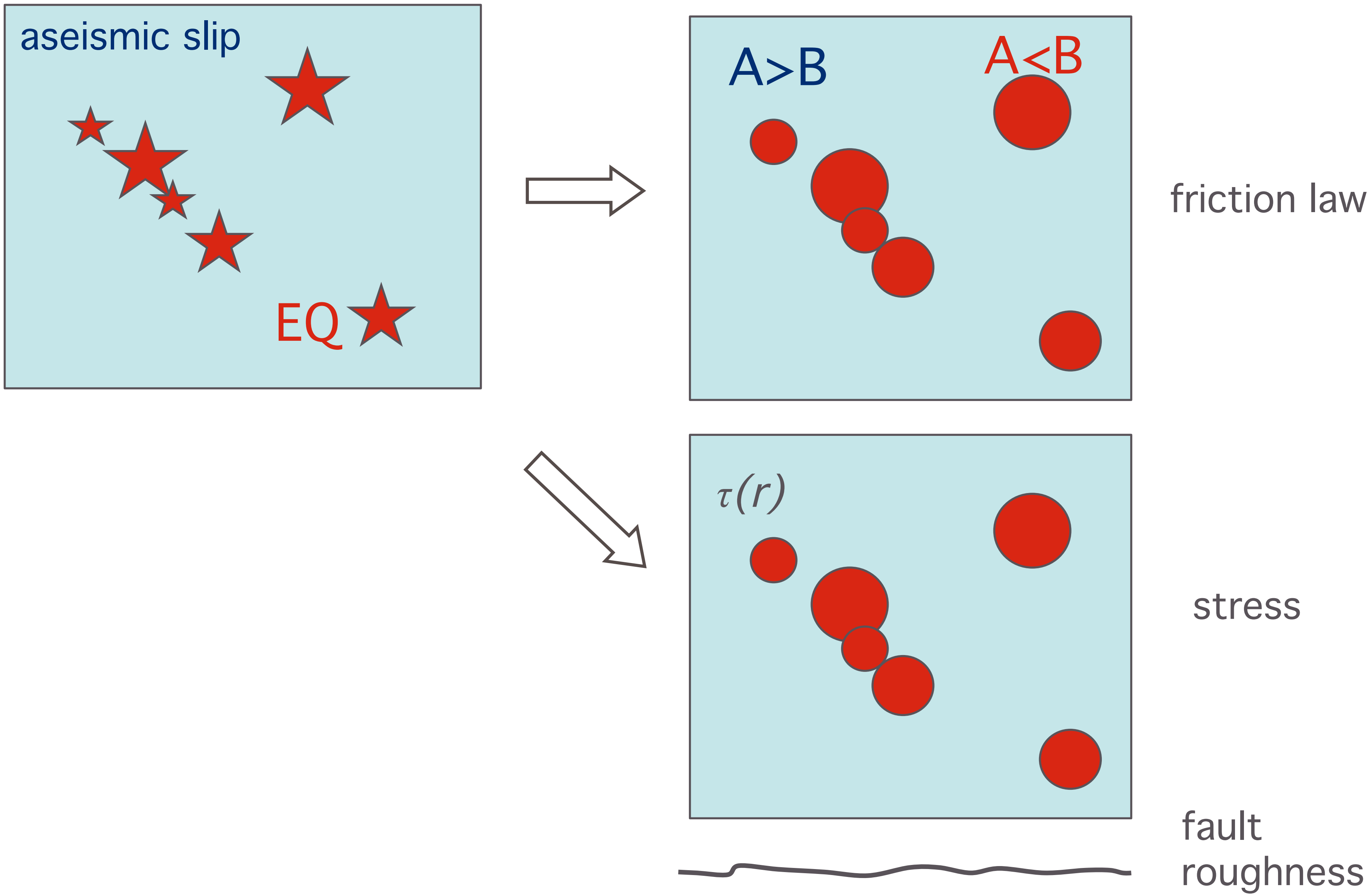
-- R&S friction
with A<B



Results - 1D model and fit of afterslip data

- All models provide a good fit to the data for the 3 EQs
- full R&S friction law usually gives a better fit than rate-dependant friction or than Omori law, but with more inverted parameters
- Inversion is not constrained: many very # models give similar slip history and very good fits, but sometimes unphysical values (A=100000, D_c=1km, ...)
- Models with A>B or B>A often provide similar fit

Conclusions : rate & state and fault behavior



Afterslip and aftershocks

- mainshock ⇨ coseismic stress change ⇨ afterslip ⇨ postseismic reloading ⇨ aftershocks?

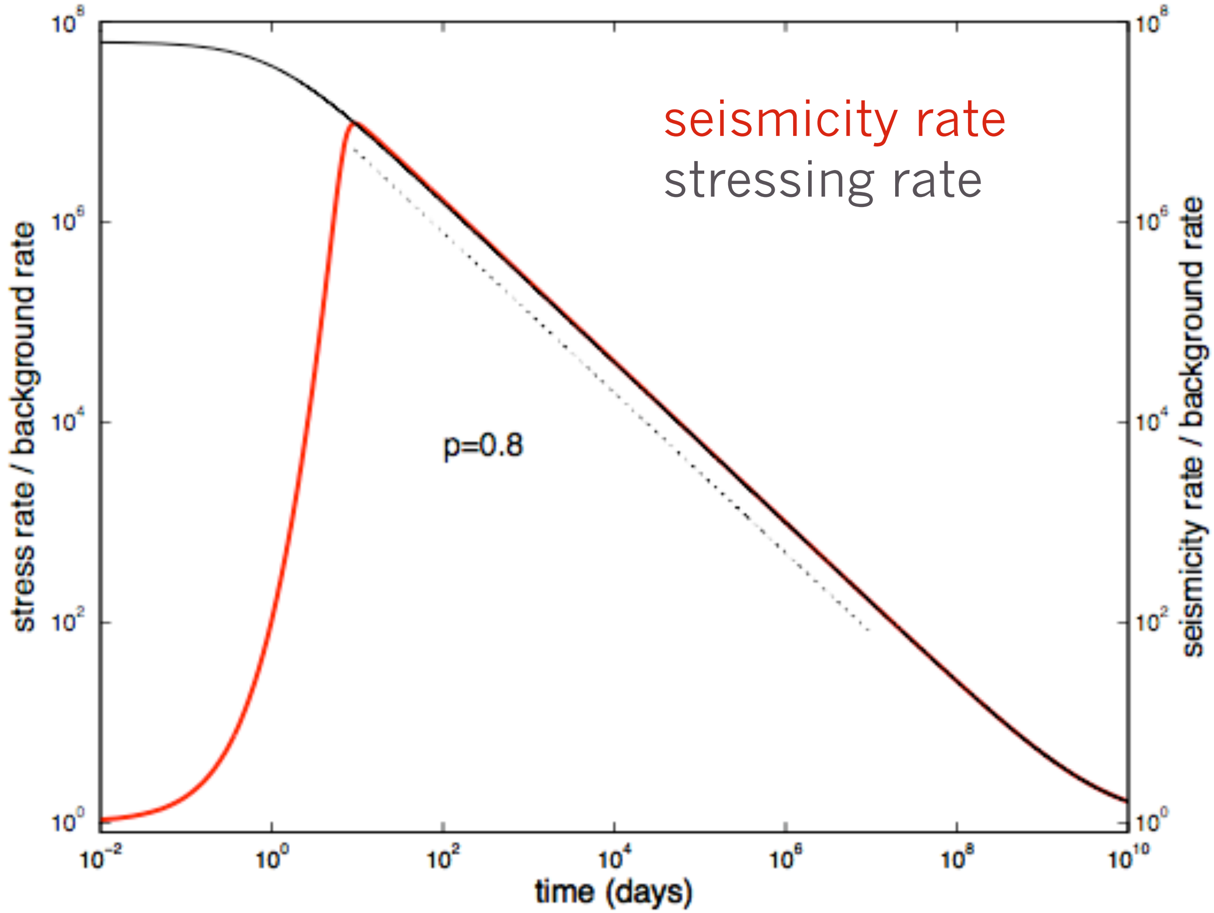
[Rice and Gu, 1983, Dieterich 1994, Schaff et al 1998, Perfettini and Avouac 2004, 2007; Wennerberg and Sharp 1997, Hsu et al 2006, Savage 2007a,b, ...]

- Afterslip also unloads other parts of the fault and modifies aftershock time decay
- we use the R&S model of *Dieterich [1994]* to model triggering due to afterslip ~ $d\tau/dt$

$$A\sigma \ln\left(\frac{R}{R_0}\right) + \frac{N\dot{\tau}_r}{r} = \tau$$

Aftershocks triggered by afterslip

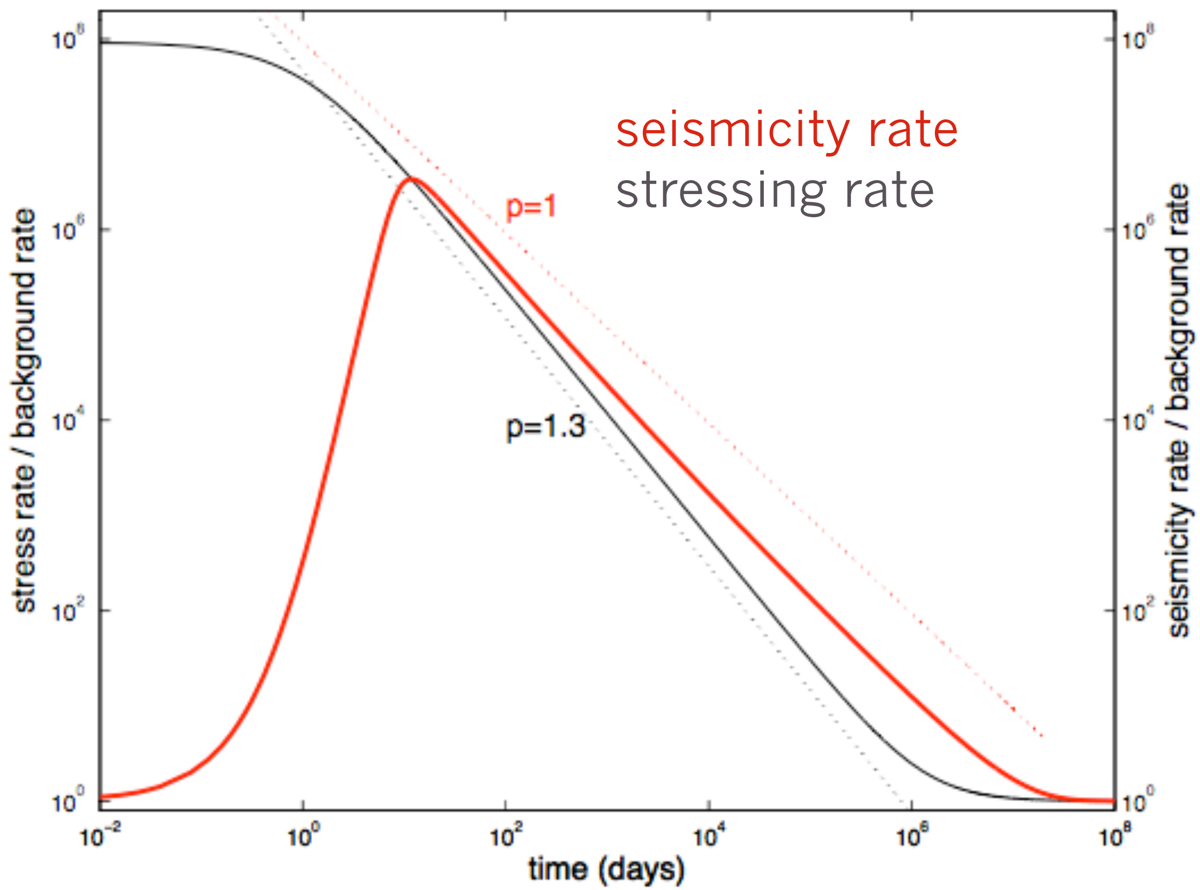
- numerical solution of R-τ relation assuming reloading by afterslip
- Stress rate $d\tau/dt \sim 1/(1+t/t^{*})^{q} + \tau'_{r}$ with q=0.8



- when p<1, R(t) ~ $d\tau/dt$ for «large times»

Aftershocks triggered by afterslip

- Afterslip reloading $d\tau/dt \sim \tau'_0/(1+t/t^*)^q$ with q=1.3



- apparent Omori exponent p(t) decreases from 1.3 to 1

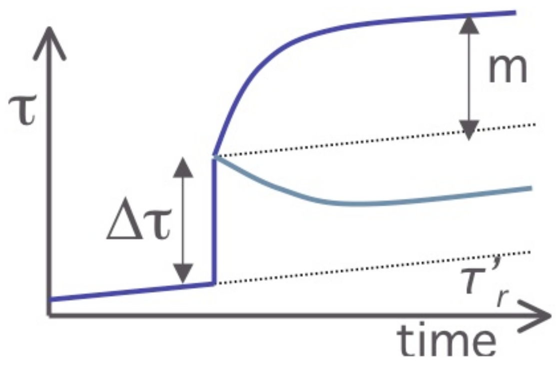
Aftershocks triggered by afterslip

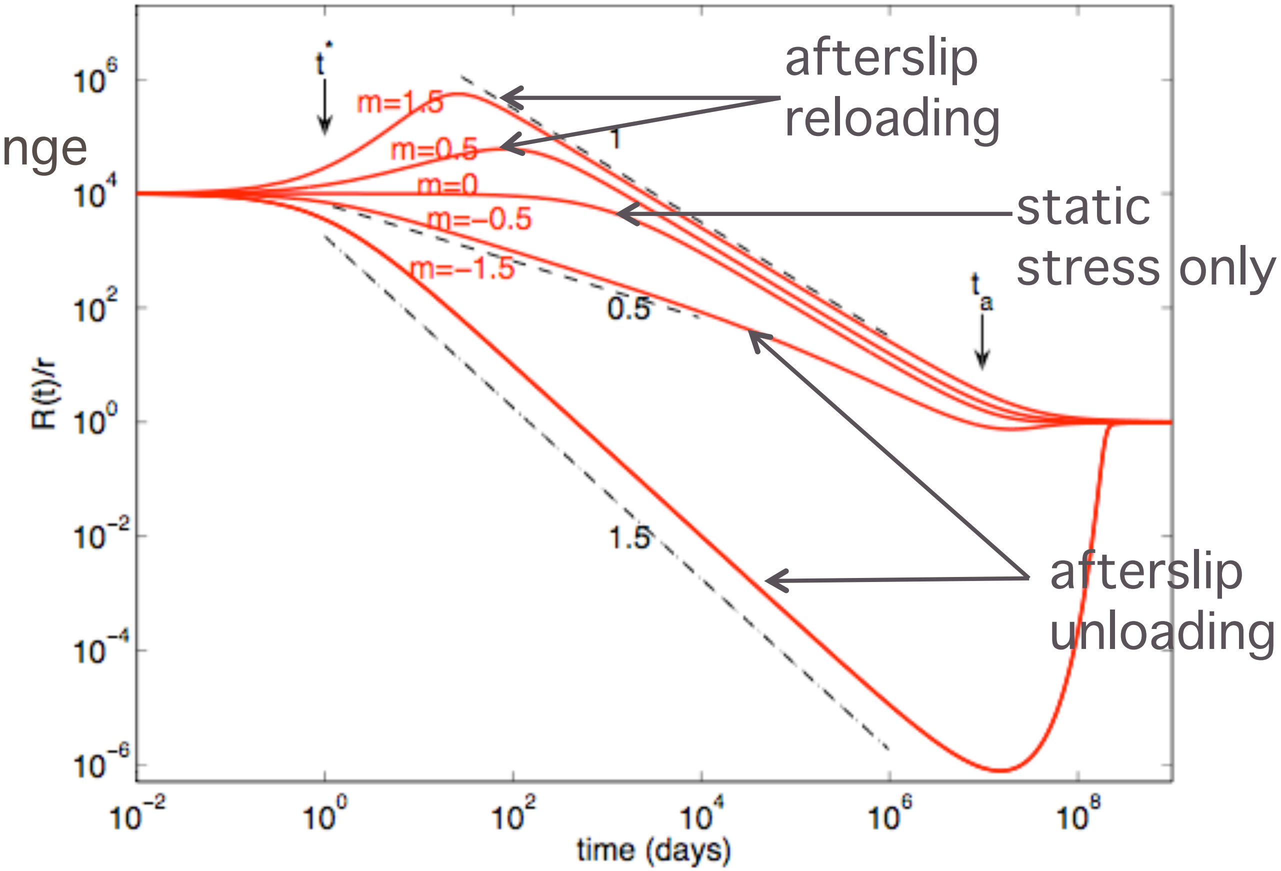
- coseismic stress step + unloading or reloading by afterslip
- afterslip stress rate

  $d\tau/dt \sim \tau'_0/(1+t/t^*)$

- total afterslip stress change

  $m=\tau'_0 t^*/A\sigma$





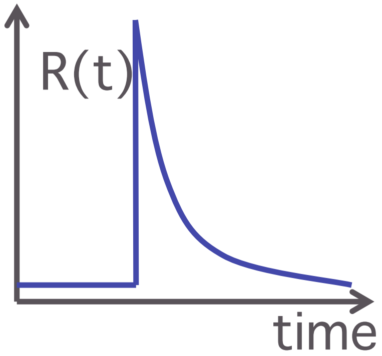
- afterslip reloading (m>0) : p=1 *[Dieterich 1994]*
- afterslip unloading (m<0) : p=-m *[Dieterich 1994]*

Conclusions: aftershocks triggered by afterslip

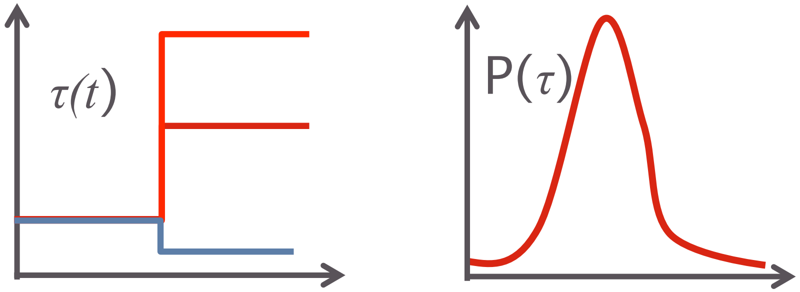
- R&S friction law can be used to model aftershock rate
- afterslip is likely a significant mechanism for aftershock triggering
- but less important than static stress changes, because slip (and σ) is smaller

! EQ rate does not scale with stress rate

Conclusions: EQ triggering and R&S model



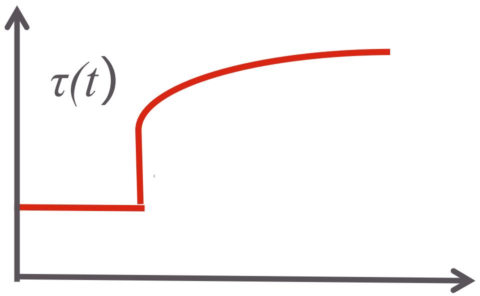
heterogeneous stress step



→ short=time triggering p<1, depends on stress heterogeneity

→ long time quiescence

afterslip (+coseismic step)



→ Triggering or quiescence

→ Omori law decay with p< or >1, depends on amplitude and time decay of stress-rate

Conclusions

☺ **Rate & state fits well observations**

aftershock rate (t,r), afterslip, slow slip events

☹ **little constrain on mechanisms and parameters**

static / afterslip triggering?

stress change?

velocity weakening / strengthening?

☹ **complex behavior, yet very simplistic model**

1 slider block / continuous model

no inertia

no heterogeneity of friction law parameters

no secondary aftershocks