Earthquake triggering, stress changes

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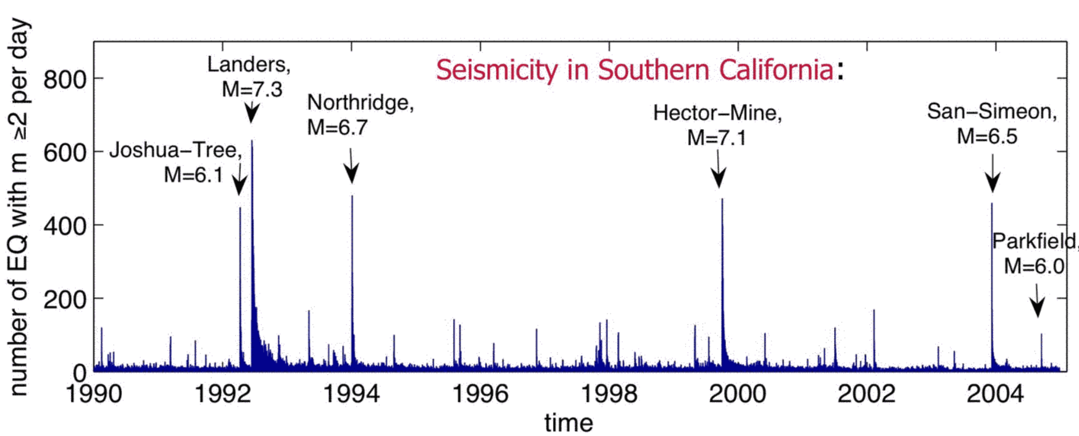
Outline



- Observations earthquake triggering:

  When? Where? How? What size?

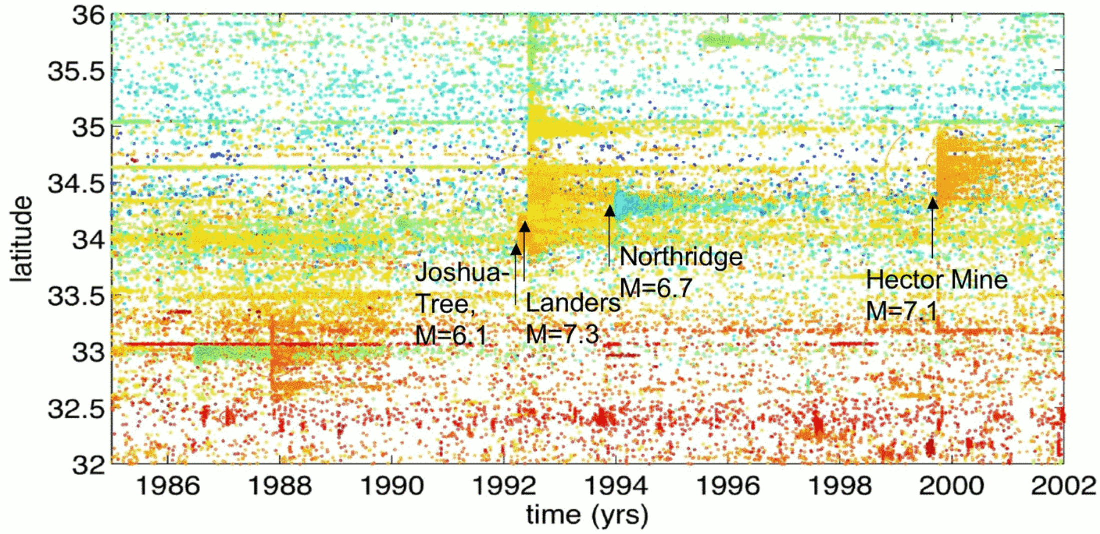
- Models:

  ETES, Rate-and-State

- Estimating stress changes from triggered earthquakes?

Earthquake clustering

- Seismicity in Southern California with m≥2
- Symbol size ~ rupture area ~ 10^m
- Color represents longitude [-120 -116]



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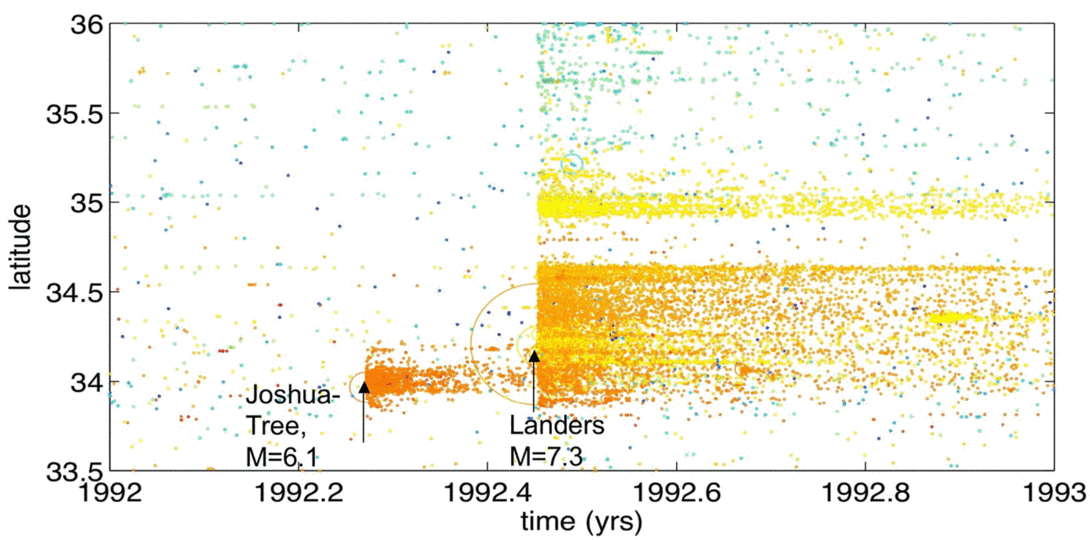
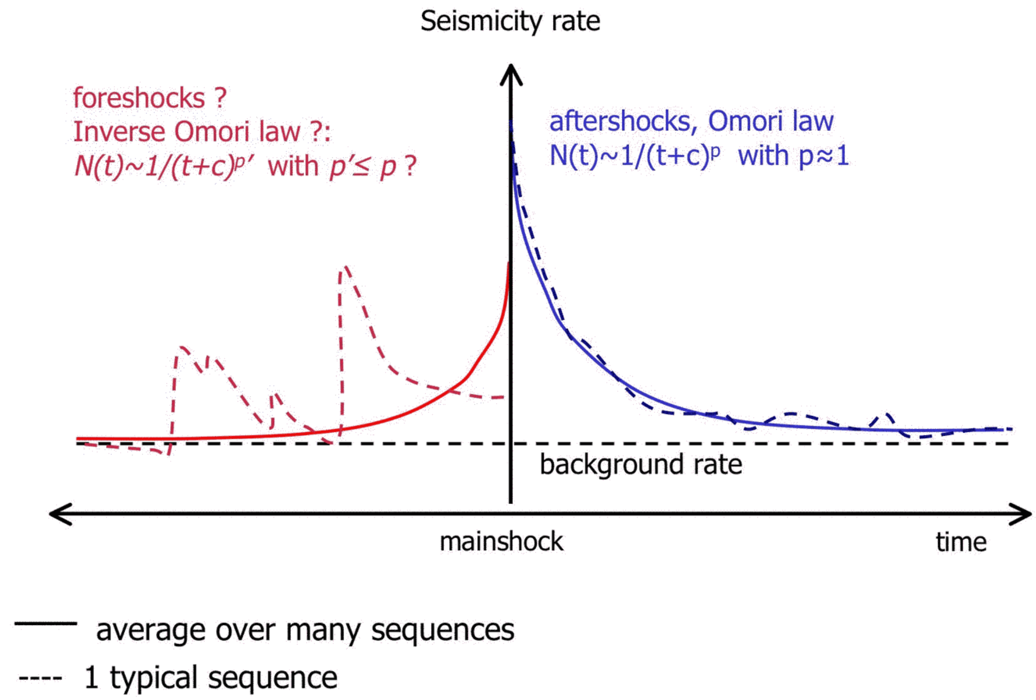


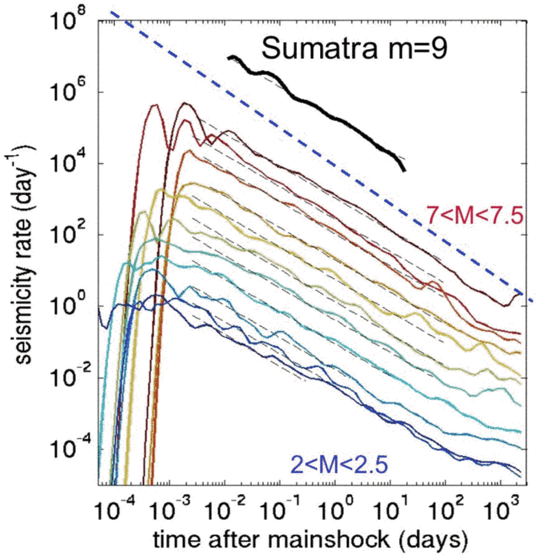
"Foreshocks", "mainshocks", "aftershocks"

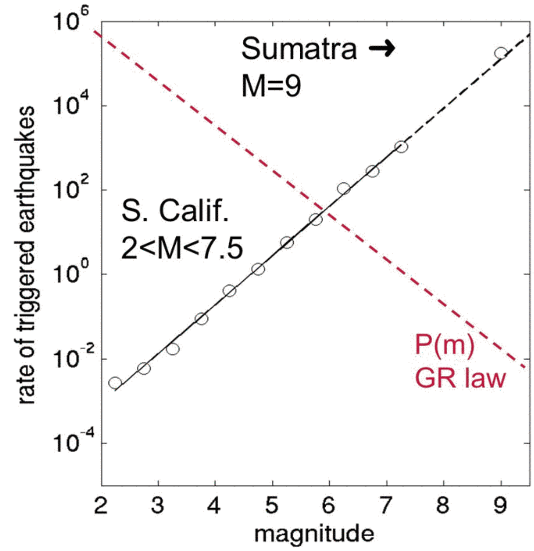


!! Non-conventional definition of "mainshocks" and "aftershocks"

- Mainshock = any "isolated" EQ
- Aftershock = EQ within the "influence zone" (T,R) of the mainshock can be LARGER than the mainshock
- Motivation: can we explain the triggering of a 'large' EQ by a smaller one using the same laws as for a small EQ triggered by a larger one?

When : Relaxation of number of aftershocks with time and scaling with mainshock magnitude M

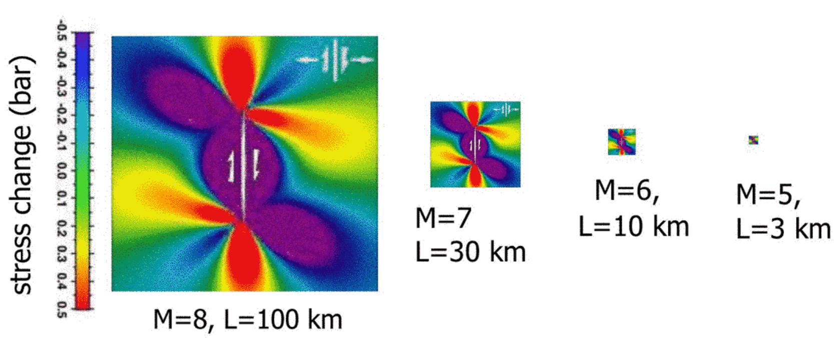




- Aftershock rate decays with time as $N \sim 1/t^{0.9}$ for all M ("Omori law")
- Only the number of aftershocks increases with M, N~ rupture area $\sim 10^M$

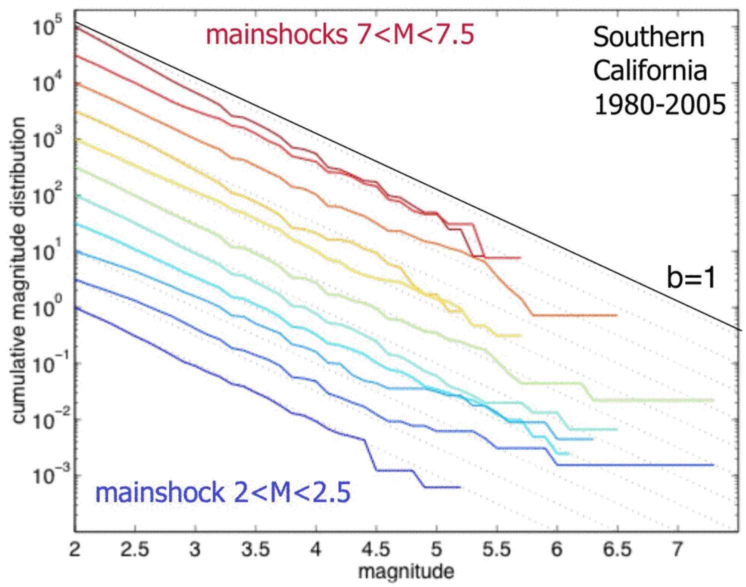
How are large EQs # from smaller ones?

- … they're larger: $L \sim 10^{0.5m}$
- but same stress drop
- static coulomb stress change $\sigma(r/L,\theta)$



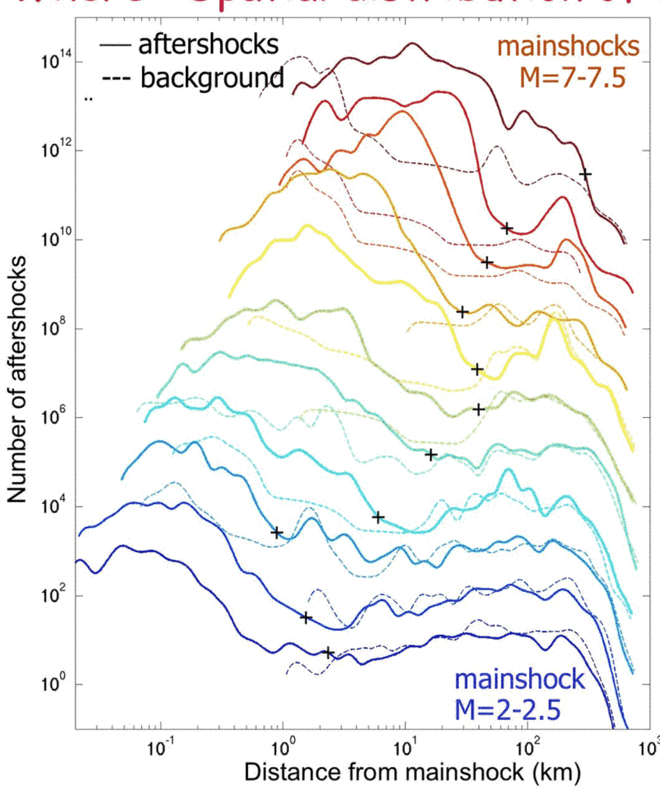
- so the number of aftershocks ~ fault area ~ $L^2 \sim 10^m$ as observed
- small and 'large' EQS collectively as important for triggering and for stress transfers between EQS if $P(m) \sim 10^m$ (GR law)

How big are triggered events: Distribution of aftershocks magnitudes for different mainshock size M



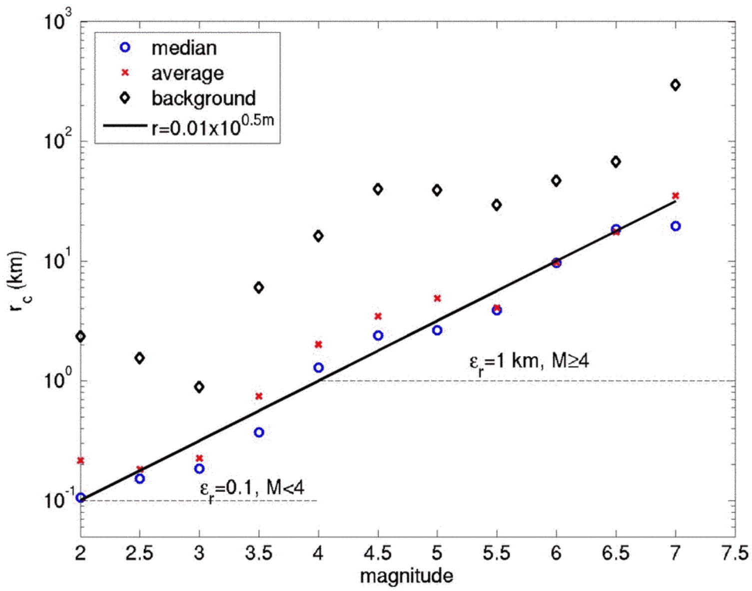
- Same mag distribution for all M
- Only the number of aft increases with M

Where : Spatial distribution of aftershocks



- relocated catalog for Southern Califorina *[Shearer et al., 2004]*
- Triggering distance increases with M
- Max triggering distance: R ~ 2* rupture length ~ $0.02 \times 10^{m/2}$ km

Where: Triggering distance as a function M



- triggering distance $d(m) \approx 0.01 \times 10^{0.5m}$ km ~ rupture length

Summary: earthquake triggering, observations

- Aftershock rate decays as $N \sim 1/t^{0.9}$, for t between a few sec and several yrs, independently of the mainshock magnitude M.
- The number of aftershocks increases as $N \sim 10^M \sim L^2$, for 0<M<9.
- Small EQs collectively as important as larger ones for EQ triggering
- The size of a triggered event is not constrained by the mainshock size
- The typical triggering distance = $L = 0.01 \times 10^{M/2}$ km.

  The maximum triggering distance is 2L
- These observations can be explained by several models of earthquake triggering by static stress changes, such as the "rate-and-state" model of Dieterich [1994].

How:

- static (permanent) coseismic stress change **+** "stress weakening"
  - rate-and-state friction *[Dieterich, 1994]*
  - subcritical crack growth *[Das & Scholz, 1981; Shaw, 1993]*
  - damage rheology *[Ben-Zion & Lyakhovsky, 2005]*
- or stress relaxation with time
  - fluid diffusion [*Nur & Booker, 1972*]
  - postseismic slip + asperities [*Schaff et al., 1998*]
  - viscous relaxation (?) [*Mikumo and Miyatake, 1979*]
- dynamic stress changes (seismic waves) ?
  - does not explain long-time triggering

  [Gomberg, 1997; Brodsky et al., 1998, 2003]

Models for EQ triggering and forecasting

"Epidemic Type EQ Sequence" (ETES)

- [Kagan and Knopoff, 1981; Ogata, 1988]
- Empirical model, based on Omori law & GR law
- Seismicity rate depends on time, location and mag of past EQs

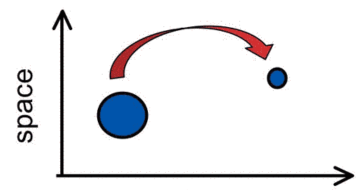
"Rate-and-State"

- [Dieterich, 1994]
- Physical model based on rate-and-state friction law
- Seismicity rate as a function of stress history rate-and-state friction

Epidemic Type Earthquake Sequence (ETES) model

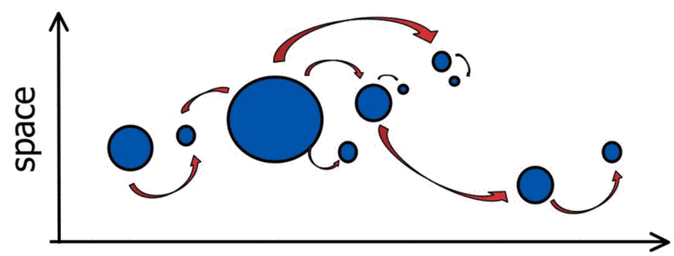
- Input :

  Probability that an EQ *(t,x,m)* triggers another *(t′,x′,m′)*



- Results :

  Multiple interactions between EQs



Definition of ETES model

- Seismicity rate = "background" + "aftershocks":

$$\lambda(t,\vec{r},m) \sim P(m)[\mu(\vec{r}) + \sum_{t_i<t} \phi_{m_i}(t-t_i,\vec{r}-\vec{r}_i)]$$

- Magnitude distribution: G.R. law

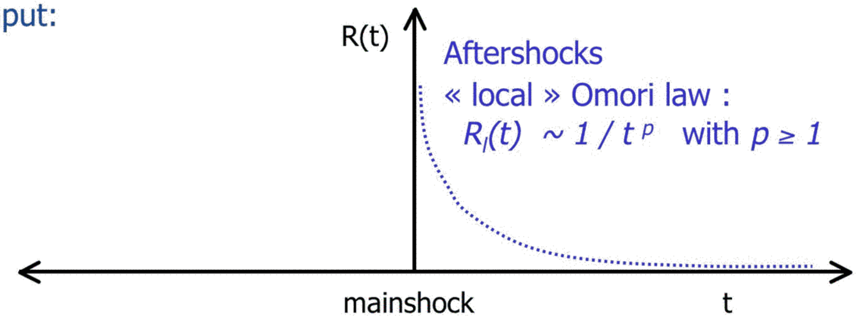
$$P(m) \sim 10^{-b(m-m_0)}$$

- Aftershocks: Omori law and increase of aftershock # with magnitude

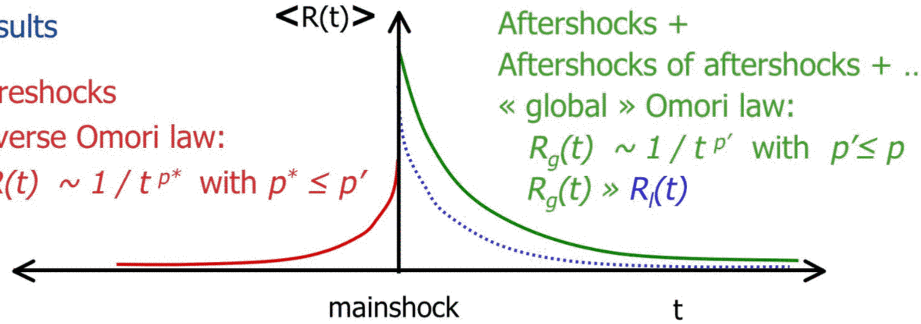
$$\phi_m(t,\vec{r}) = \frac{K\ 10^{\alpha(m-m_0)}}{(t+c)^{1+\theta}}\ f(\vec{r})$$

ETES model, foreshocks and aftershocks

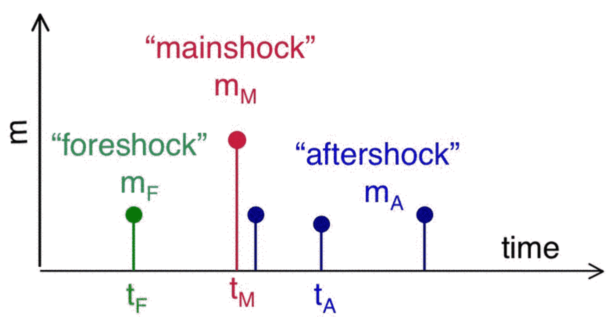
- Input:

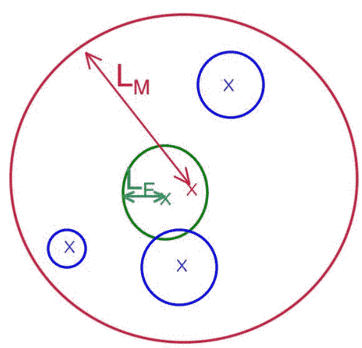


- Results



Foreshock, mainshocks , aftershocks





- same properties F⇨M and M⇨A
  - in time: Omori, aftershock duration and p exponent indep. of m_M
  - in space : $|r_M - r_F| \sim L_F$; $|r_A - r_M| \sim L_M$
  - in magnitude : $P(m_A)$ = G.R. law indep. of m_M
    $N_A(m_M) \sim 10^{\alpha m}$
- same physical mechanisms for F⇨M and M⇨A

from nucleation, "critical point" model, or rupture experiments

"Rate-and-state" friction law

- Friction law *[Dieterich, 1979; Ruina, 1983]*

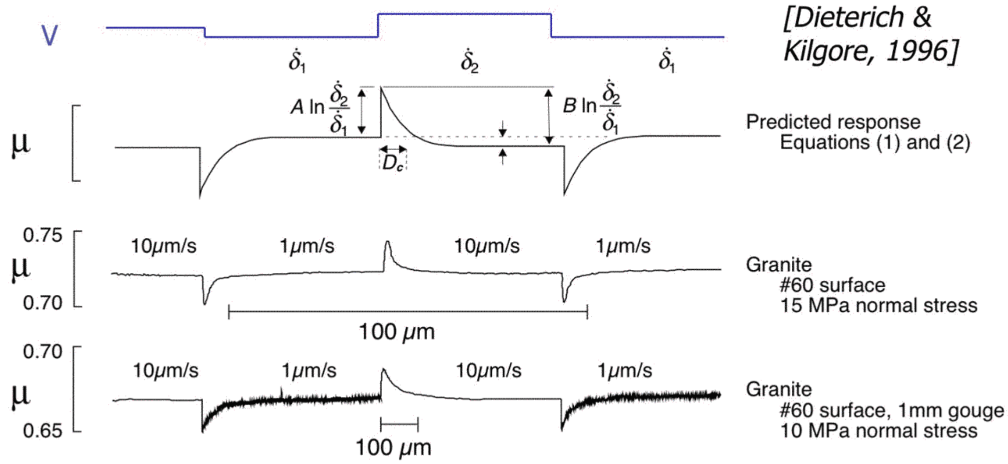
  $\mu = \mu_0 + A \ln(V) + B \ln(\theta)$

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

- steady state:

  $\mu = \text{const.} + (A-B) \ln(V)$

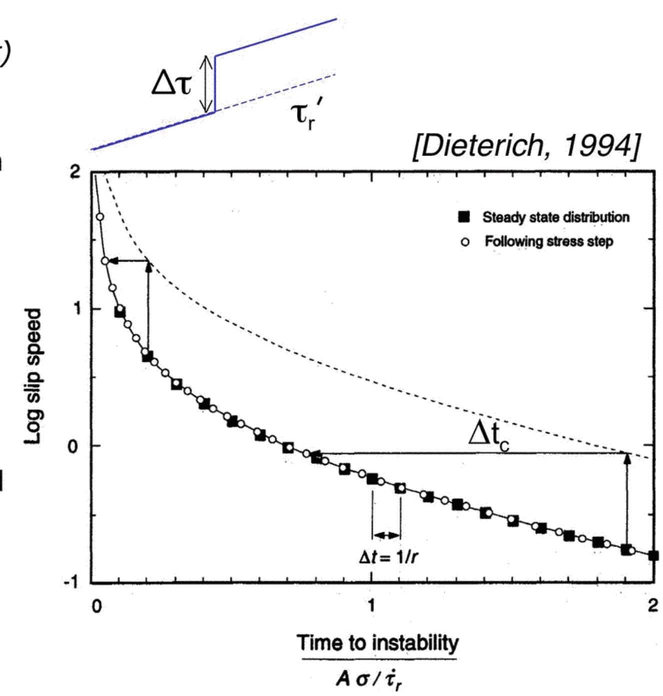
- stable if A>B ; EQs: A<B



[Dieterich & Kilgore, 1996]

"Rate-and-state" friction law and EQ triggering by a static stress change

- without perturbation $V \sim 1/(t_c - t)$ (nucleation phase)
- Initial population of faults with uniform pdf of rupture time
- $\Delta\tau$ increases V and moves the fault closer to failure
- Clock change Δt_c depends on initial state
- Increase of seismicity rate and Omori law decay



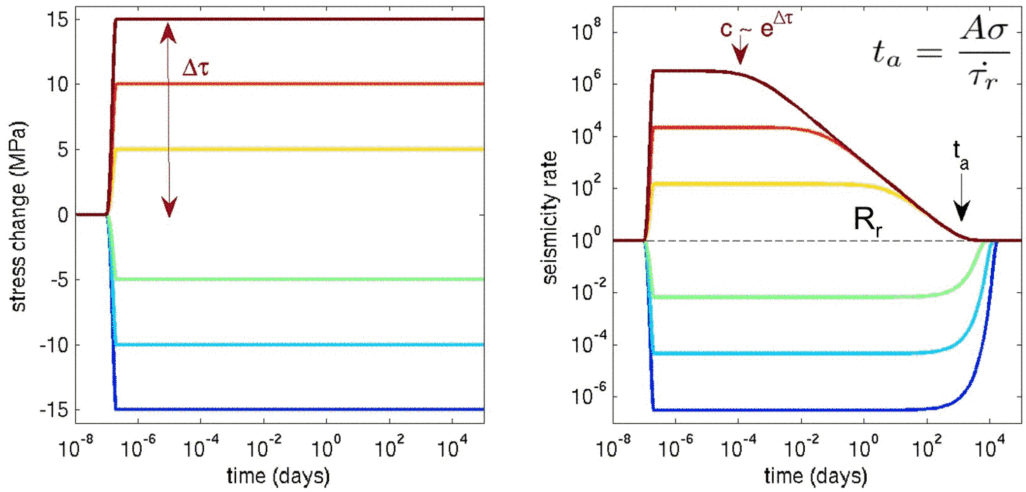
[Dieterich, 1994]

"Rate-and-state" model of seismicity *[Dieterich 1994]*

- Relation between seismicity rate R and (Coulomb) stress history

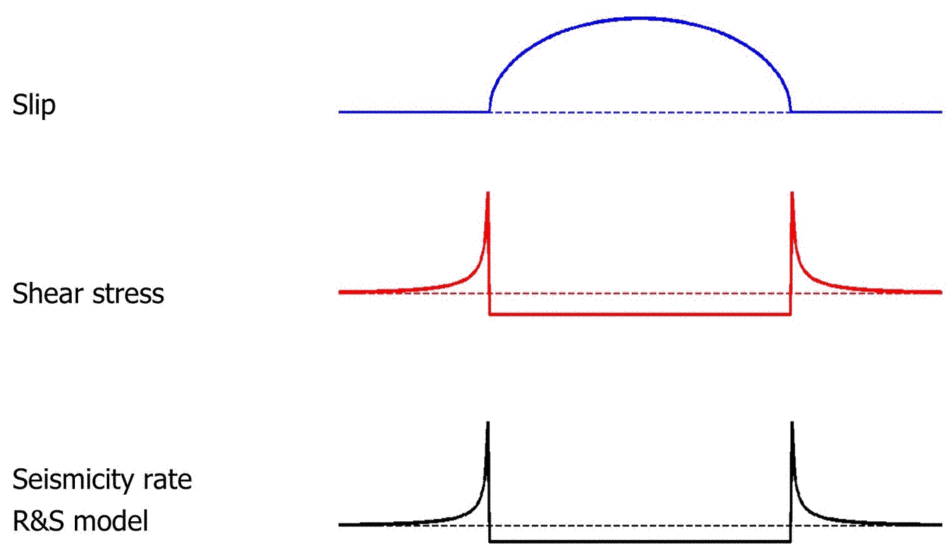
$$\partial\gamma = \frac{1}{A\sigma}[\partial t - \gamma\partial\tau]. \quad \text{and} \quad R(t) = \frac{R_r}{\gamma(t,\tau)\dot{\tau_r}},$$

- For a static stress change + constant tectonic loading rate:



Coseismsic slip, stress change, and aftershocks:

Planar fault, uniform stress drop



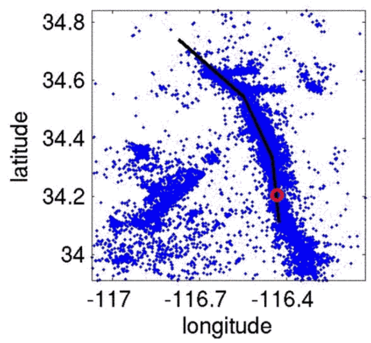
Spatial distribution of aftershocks:

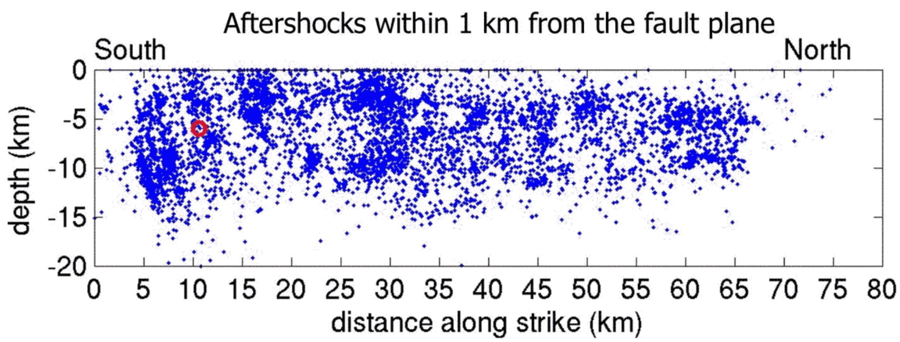
Map aftershocks

Landers, 1992, M=7.3

S. California

t<1yr





Spatial distribution of aftershocks

- Most aftershocks occur "on" or "close" to the fault plane, where the shear stress change decreases on average

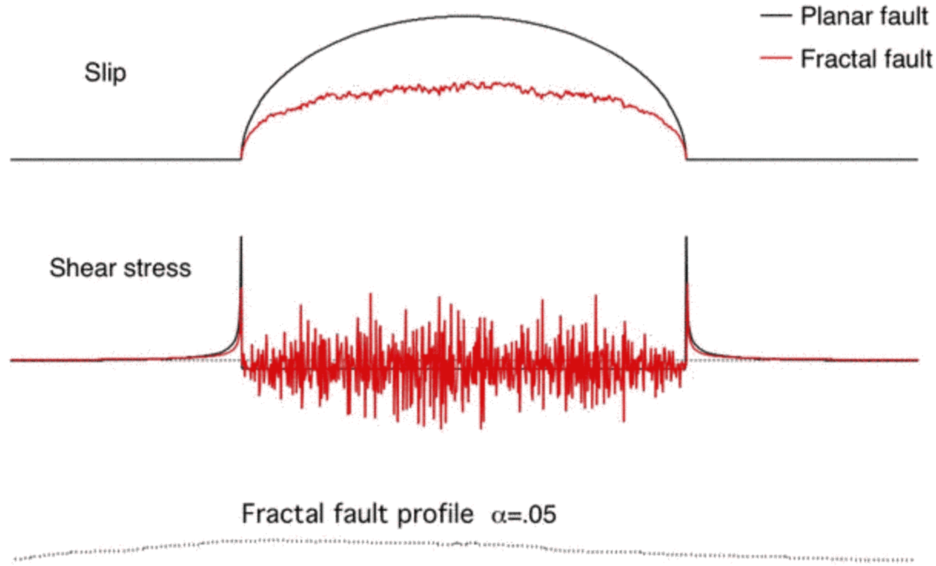
- Shear stress change must be very heterogeneous to explain on fault aftershock triggering with the rate-and-state model

  - fault roughness [Dieterich, 2005]

  - slip heterogeneity

Shear stress heterogeneity due to fault geometry

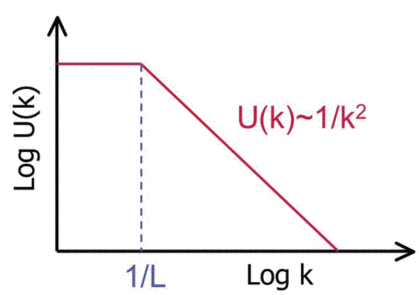
[Dieterich, 2005]



Slip and shear stress heterogeneity

- Stochastic scale-invariant kinematic slip model [Herrero and Bernard, 1994]
- Large $k>1/L$: $U(k) \sim 1/k^2$

  Large EQ = sum of small ones
- Small $k<1/L$: $U(k) = \text{const.}$
- Random phase

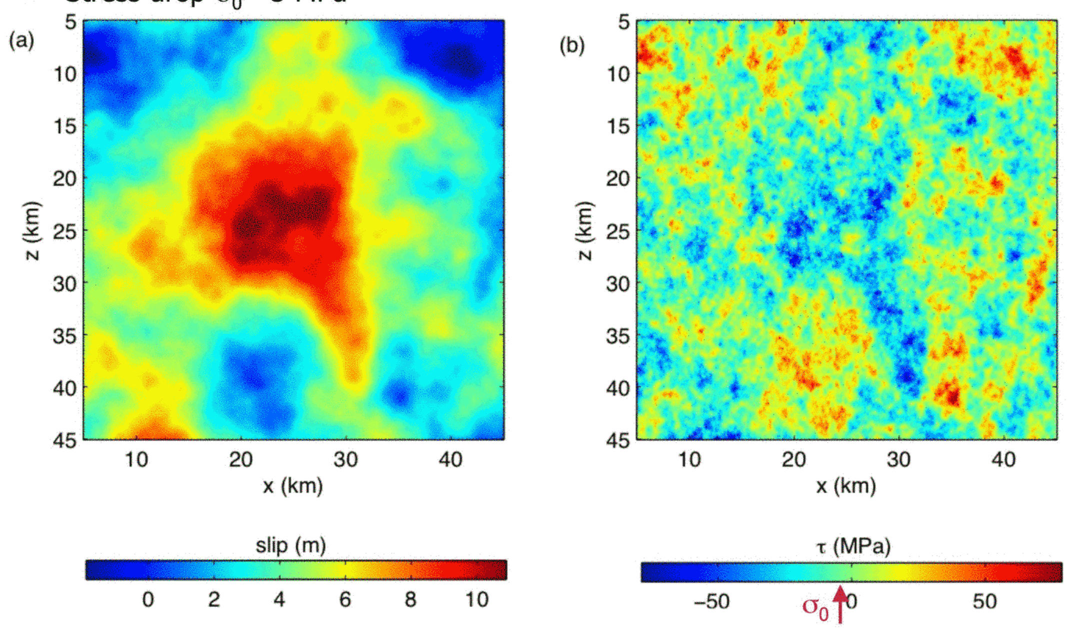


- Reproduces the $1/f^2$ power spectrum seismogramms (displacement) for $f>f_c$
- Shear stress power-spectrum: $\tau(k) \sim 1/k$ for $k>1/L$

  - infinite standard deviation!
  - small scale cutoff
  - or $U(k) \sim 1/k^n$ with $n>2$

Slip and shear stress heterogeneity

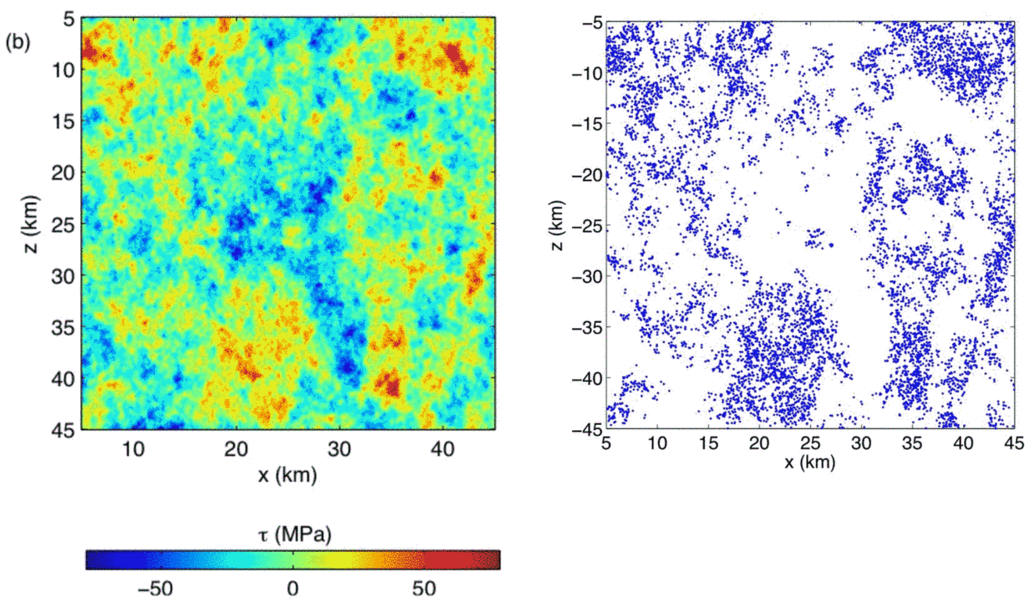
- Modified « k^2 » slip model: $U(k) \sim 1/(k+1/L)^{2.3}$
- Stress drop σ_0 =3 MPa



Slip and shear stress heterogeneity + R&S model

- Synthetic aftershock catalog generated using Dieterich [1994] model

(without multiple interactions between aftershocks)

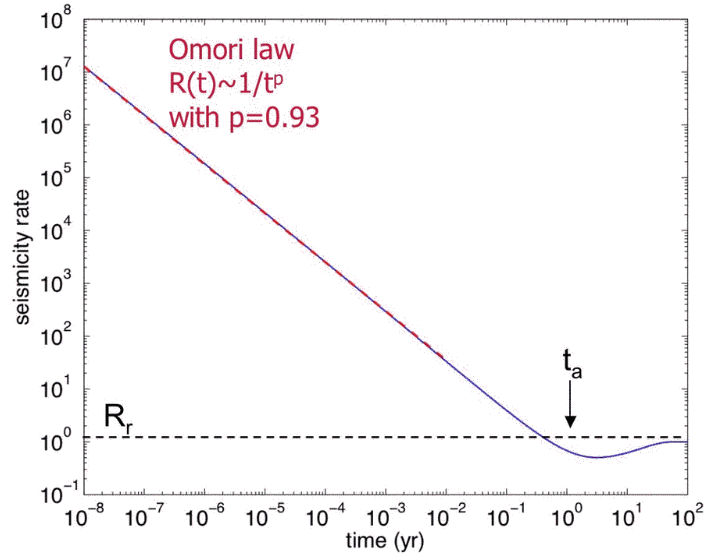


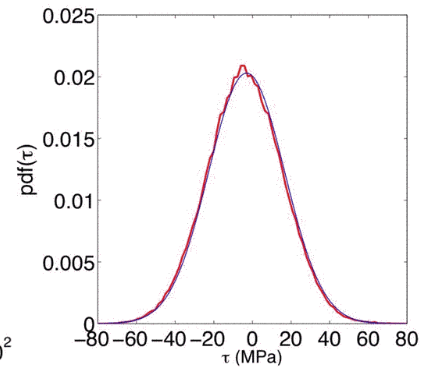
Stress heterogeneity and aftershock decay with time

- Aftershock rate from R&S model with modified k^2 slip model

$$R(t) = \int_{fault} R(t,\tau)\, P(\tau)\, d\tau$$

assuming $A\sigma_n$ = 1 MPa

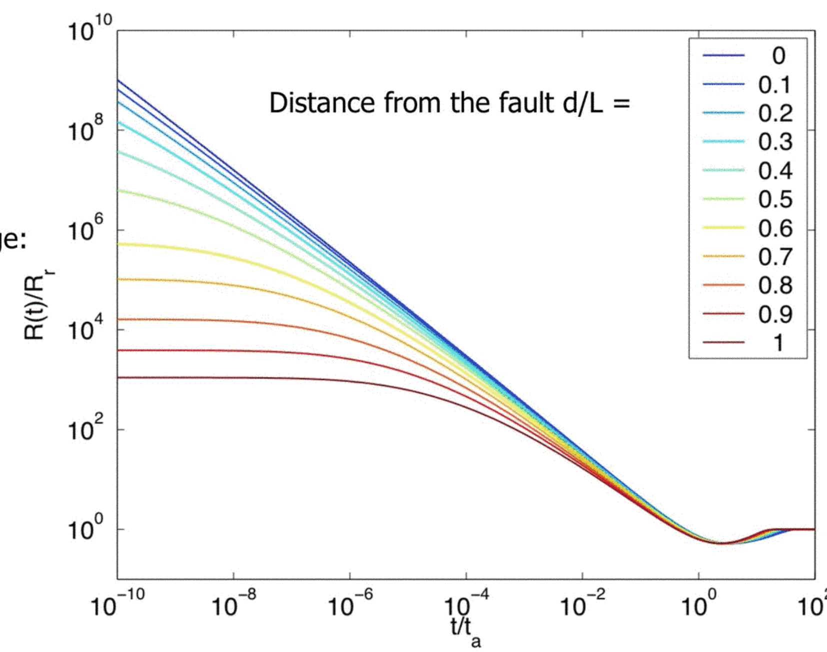




Modified k^2 slip model, Off-fault aftershocks

- On fault:
- for k>1/L
- slip:
$U(k) \sim 1/k^{2.3}$
- shear stress change:
$\tau(k) \sim 1/k^{1.3}$

- Distance d<L from the fault:
$\tau(k) \sim \exp(-kd)/k^{1.3}$

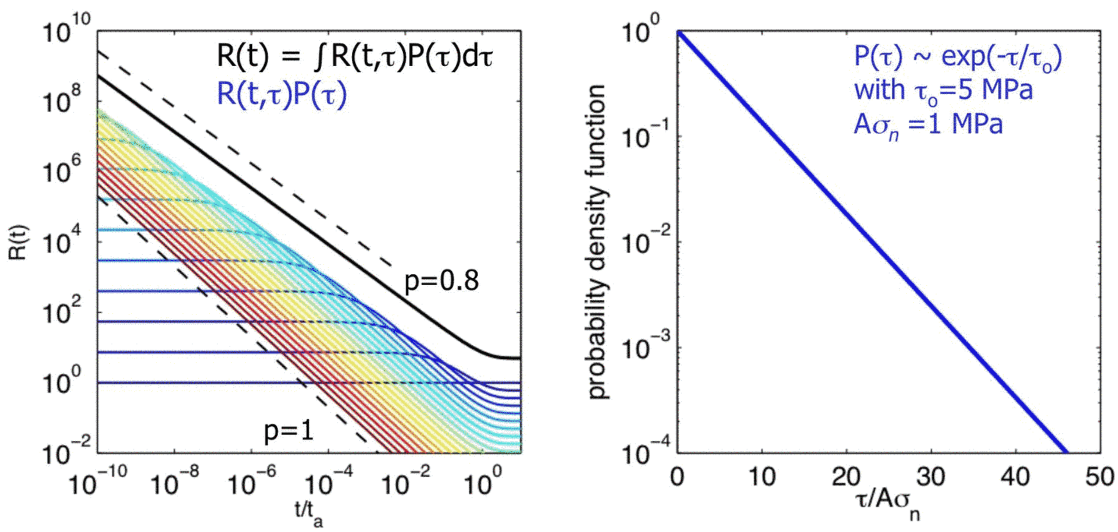


Stress heterogeneity and aftershock decay with time

- R&S model produces Omori law with $p \le 1$ for an exponential pdf $P(\tau)$

$P(\tau) \sim exp(-\tau/\tau_o)$

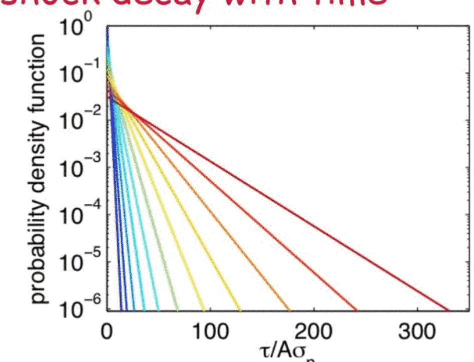
$R(t) = \int R(t,\tau)\, P(\tau)\, d\tau \sim 1/t^p$ for $t \ll t_a$ with $p = 1 - A\sigma_n/\tau_o$

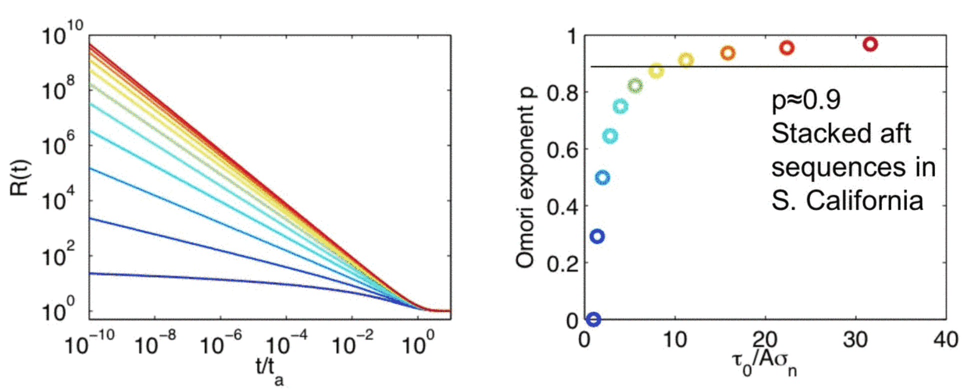


Stress heterogeneity and aftershock decay with time

- Aftershock rate for $P(\tau) \sim exp(-\tau/\tau_o)$
- $p = 1 - A\sigma_n/\tau_o$ for $t \ll t_a$

p decreases if « heterogeneity » τ_o increases





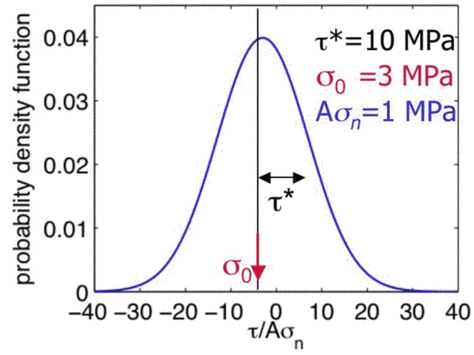
Aftershock decay for a Gaussian stress distribution

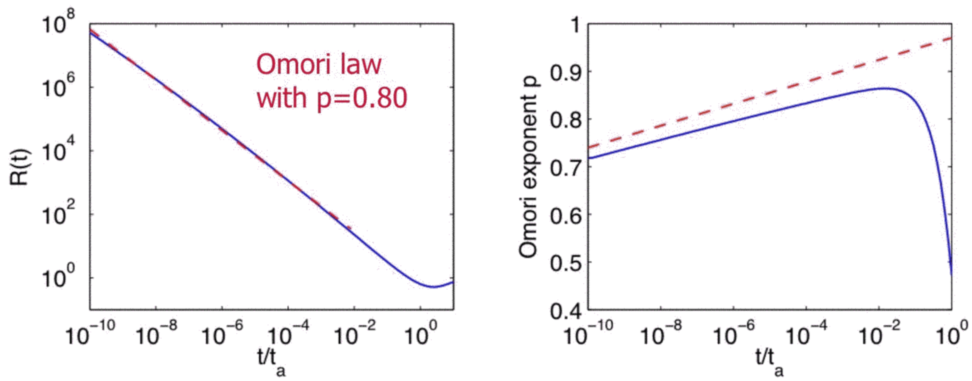
- stress distribution

  $P(\tau) \sim \exp[-(\tau-\sigma_0)^2 / 2\tau^{*2}]$

- aftershock rate close to Omori law with effective exponent

$p \approx 1 - [A \sigma_n \sigma_0 - A^2 \sigma_n^2 \log(t/t_a)] / \tau^{*2}$





Inversion of stress changes from aftershock rate

Deviations from Omori law with p=1 due to

- stress decrease / increase with time
  [Dieterich, JGR 1994; Nature 2000]
- or heterogeneity of coseismic stress change, due to
  - fault geometry [Dieterich, 2005]
  - heterogeneity of coseismic slip
- hard to distinguish between small scale stress heterogeneity and temporal variation

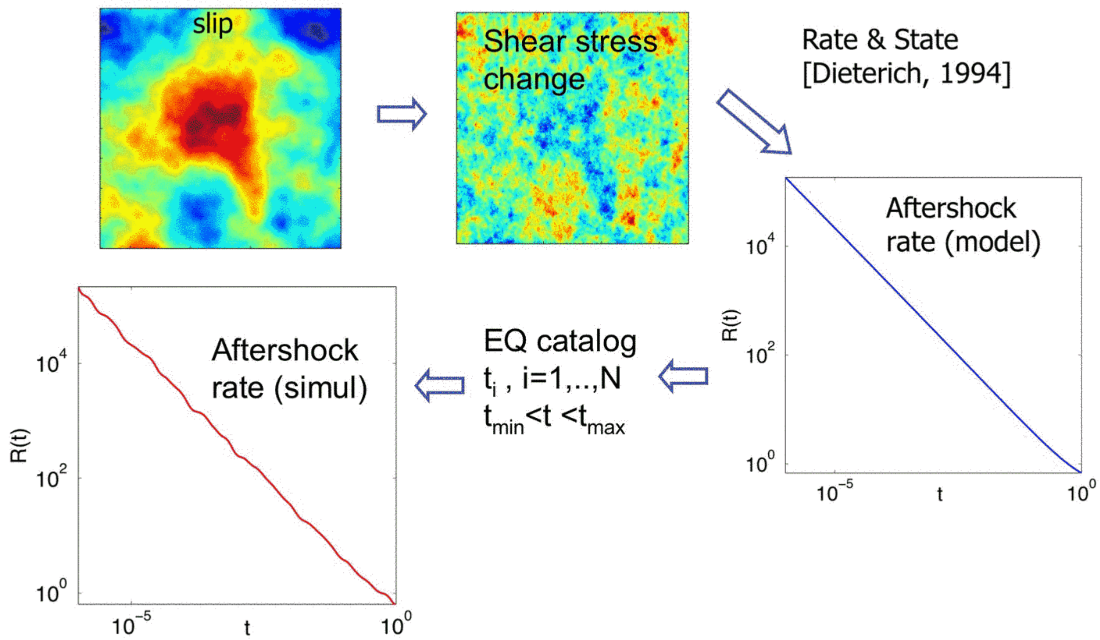
We invert for $P(\tau)$ from aftershocks rate $R(t)$

- Solve $R(t) = \int R(t,\tau)\, P(\tau)\, d\tau$
- assuming stress does not change with time
- problem: R&S model with instantaneous stress change can't explain p>1

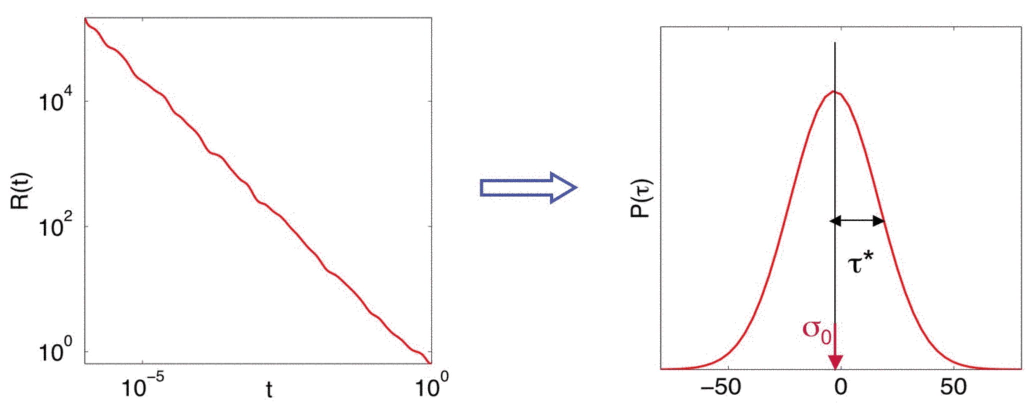
Inversion of stress pdf from aftershock rate

Test on synthetic R&S catalogs

modified k^2 model



Inversion of stress pdf from aftershock rate



- Complete distribution $P(\tau)$
  - solution of $R(t) = \int R(t,\tau)\, P(\tau)\, d\tau$
  - fixed t_a, R_r, $A\sigma_n$
- Gaussian $P(\tau)$
  - fixed $A\sigma_n$, R_r
  - invert for τ^*, σ_0 and t_a

Inversion of stress pdf from aftershock rate

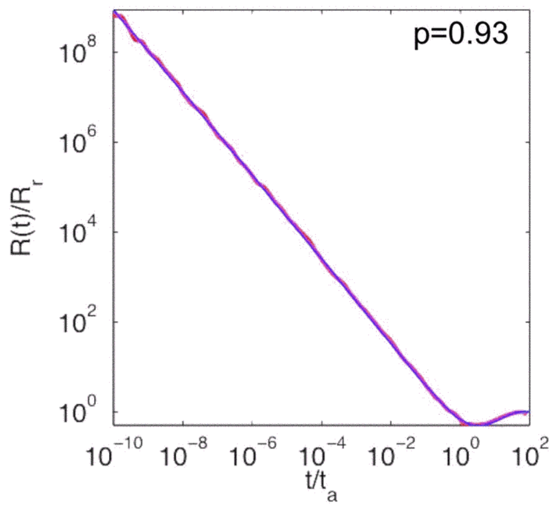
Synthetic R&S catalog

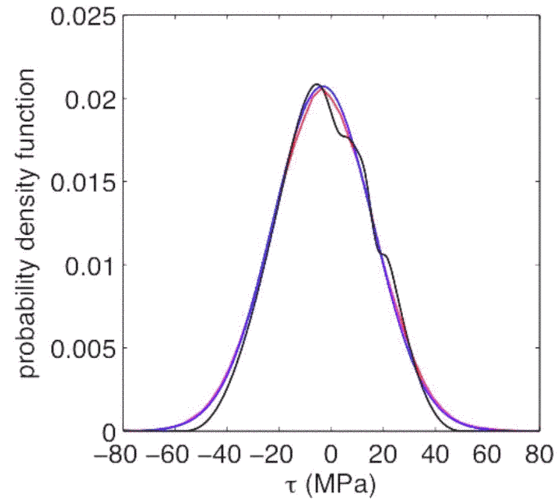
N=150000

$A\sigma_n$=1 MPa

σ_0 = 3 MPa; τ^*=20 MPa

- input $P(\tau)$
- inverted $P(\tau)$, fixed $A\sigma_n$, R_r and t_a
- Gaussian $P(\tau)$
  fixed $A\sigma_n$ and R_r, invert for t_a, σ_0 and τ^*





Inversion of stress pdf from aftershock rate

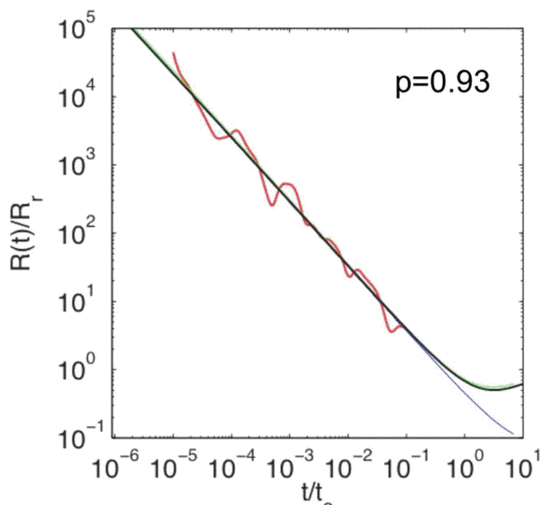
Synthetic R&S catalog

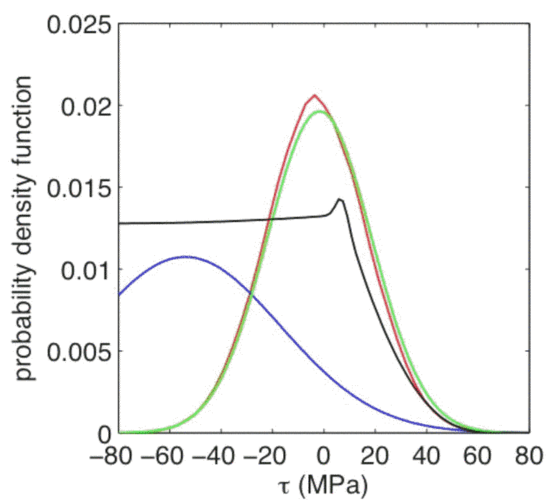
N=230

$A\sigma_n$=1 MPa

σ_0 = 3 MPa; τ^*=20 MPa

- input $P(\tau)$
- inverted $P(\tau)$, fixed $A\sigma_n$, R_r and t_a
- Gaussian $P(\tau)$, fixed $A\sigma_n$ and R_r, invert for t_a, σ_0 and τ^*
- Gaussian $P(\tau)$, fixed $A\sigma_n$, σ_0 and R_r, invert for t_a and τ^*





Inversion of stress pdf from aftershock rate

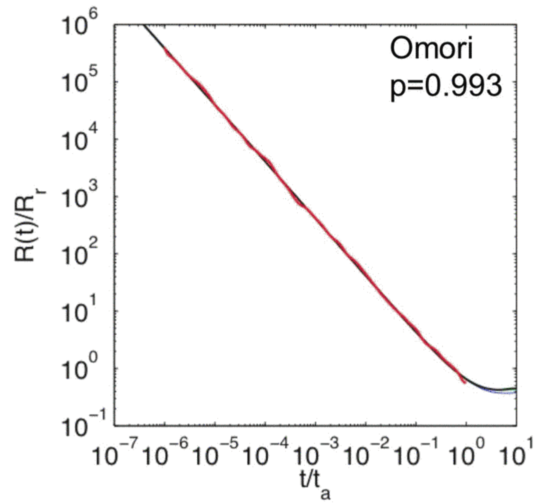
Synthetic R&S catalog

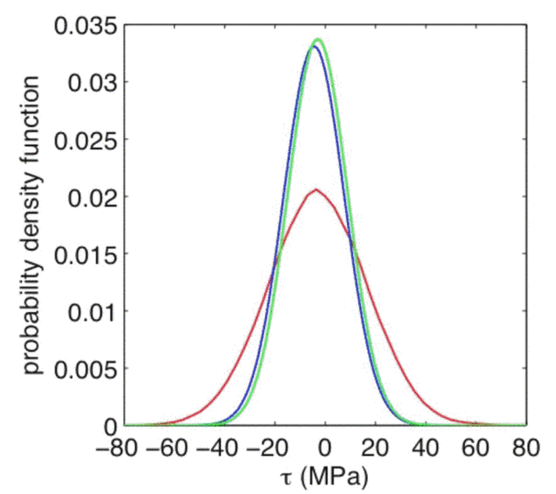
N=3857

$A\sigma_n$=0.1 MPa

σ_0 = 3 MPa; τ^*=20 MPa

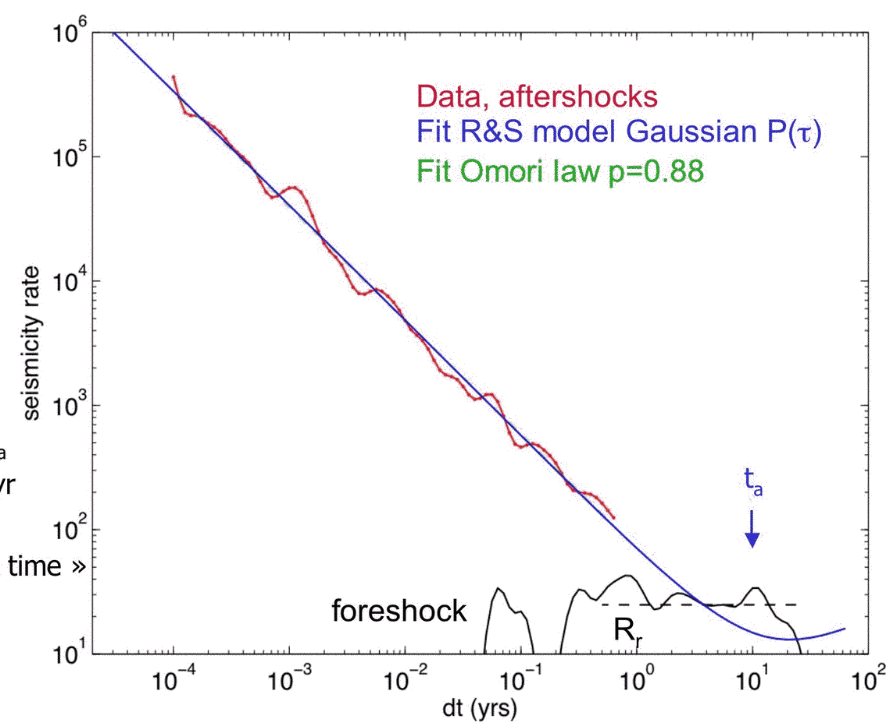
- input $P(\tau)$
- inverted $P(\tau)$: not constrained
- Gaussian $P(\tau)$, fixed $A\sigma_n$ and R_r , invert for t_a, σ_0 and τ^*
- Gaussian $P(\tau)$, fixed $A\sigma_n$, σ_0 and R_r , invert for t_a and τ^*





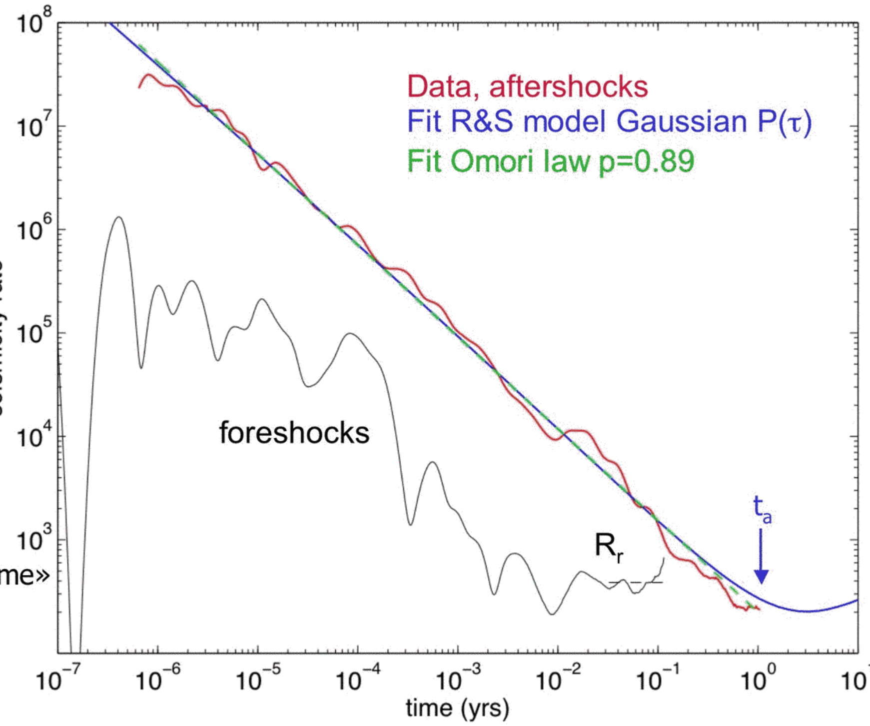
Parkfield 2005 m=6 aftershock sequence

- Fixed:
  $A\sigma_n$ = 1 MPa
  σ_0 = 3 Mpa
- Inverted:
  τ^* = 11 MPa
  t_a = 10 yrs
- Loading rate
  $d\tau/dt = A\sigma_n / t_a$
  = 0.1 MPa/yr
- « Recurrence time »
  $t_r = t_a \sigma_0 / A\sigma_n$
  = 30 yrs



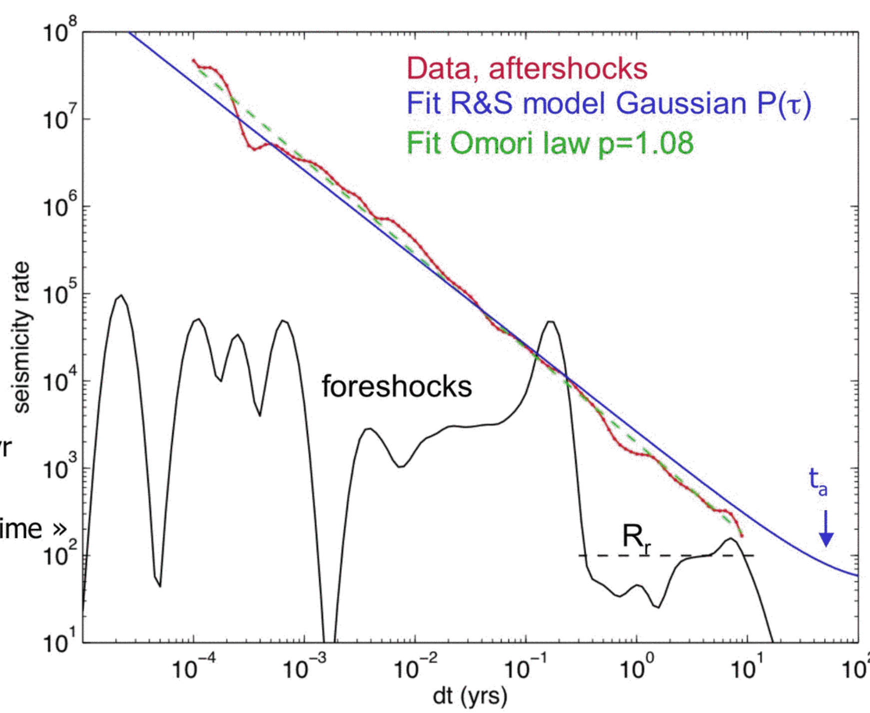
Stacked aftershock sequences, Japan (80, 3<M<5, z<30)

- Fixed:
  $A\sigma_n$ = 1 MPa
  σ_0 = 3 Mpa
- Inverted:
  τ^* = 12 MPa
  t_a = 1.1 yrs
- Loading rate
  $d\tau/dt = A\sigma_n / t_a$
  = 0.9 MPa/yr
- «Recurrence time»
  $t_r = t_a \sigma_0/A\sigma_n$
  = 3.4 yrs



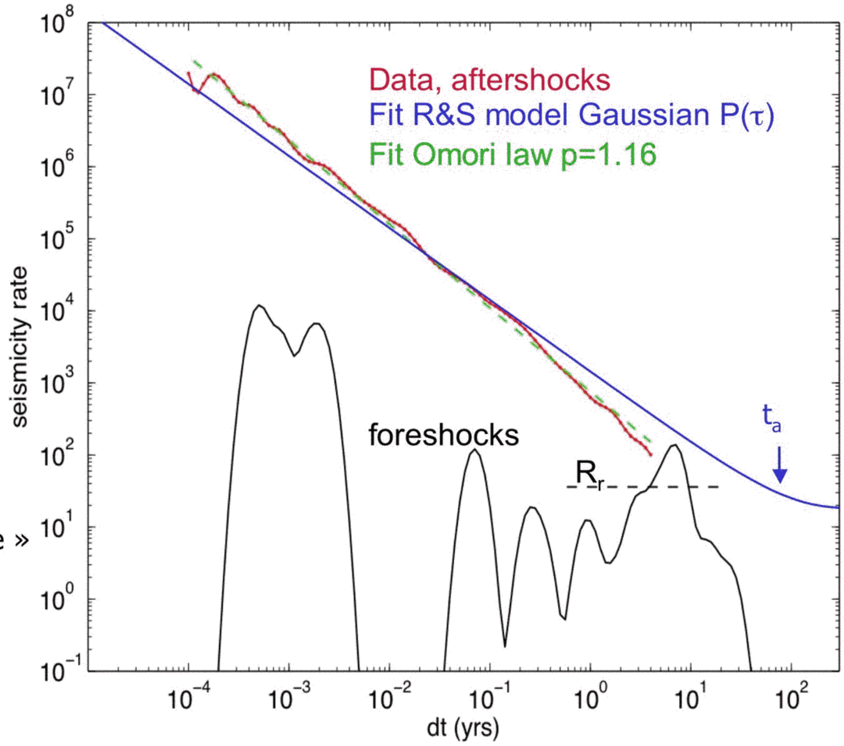
Landers, 1992, M=7.3, aftershock sequence

- Fixed:
  $A\sigma_n$ = 1 MPa
  σ_0 = 3 Mpa
- Inverted:
  τ^* = 2350 MPa
  t_a = 52 yrs
- Loading rate
  $d\tau/dt = A\sigma_n / t_a$
  = 0.02 MPa/yr
- « Recurrence time »
  $t_r = t_a \sigma_0/A\sigma_n$
  = 156 yrs



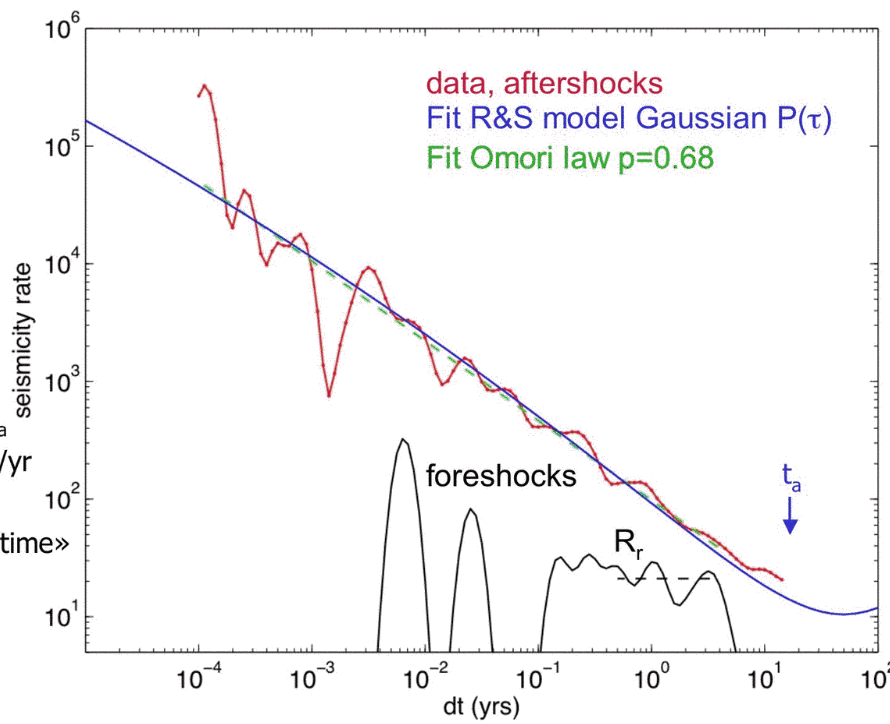
Hector Mine 1999 M=7.1 aftershock sequence

- Fixed:
  $A\sigma_n = 1$ MPa
  $\sigma_0 = 3$ MPa
- Inverted:
  $\tau^* = 438$ MPa
  $t_a = 80$ yrs
- Loading rate
  $d\tau/dt = A\sigma_n / t_a$
  $= 0.012$ MPa/yr
- « Recurrence time »
  $t_r = t_a \sigma_0 / A\sigma_n$
  $= 240$ yrs



Morgan Hill, 1984 M=6.2, aftershock sequence

- Fixed:
  $A\sigma_n = 1$ MPa
  $\sigma_0 = 3$ Mpa
- Inverted:
  $\tau^* = 6.2$ MPa
  $t_a = 26$ yrs
- Loading rate
  $d\tau/dt = A\sigma_n / t_a$
  $= 0.04$ MPa/yr
- «Recurrence time»
  $t_r = t_a \sigma_0 / A\sigma_n$
  $= 78$ yrs



Inversion of stress - Conclusion

- Stress drop not constrained if catalog too short
- We can estimate τ^* (width of $P(\tau)$) for a limited catalog if $p<1$
- And if we know $A\sigma_n$
    - $A\sigma_n$ = 1 MPa ? A=0.01 (Lab experiments, Dieterich and Kilgore 1996)
      σ_n=100 MPa (lithostatic pressure at 5km)
    - $A\sigma_n$ = 0.1 MPa ? (relation between t_a and recurrence time [Dieterich, 1994])
- Effect of secondary aftershocks?
    - increase ref EQ rate R_r [Ziv and Rubin, 2003], but does not change p or τ^* ?
- Heterogeneity of $A\sigma_n$? (does not change R(t) if $A\sigma_n$ less heterogeneous than $\Delta\tau$)
- Post-seismic stress relaxation?