Link between seismicity and deformation: Application to the postseismic phase

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Thanks to J.P. Avouac, J. Savage, Z. Peng and B. Enescu for their support on this work

Outline of the talk

1) The Coulomb failure stress ΔCFF
2) Coseismic Coulomb stress changes, aftershocks and optimally oriented planes
3) Is the Coulomb failure function compatible with more realistic friction laws, i.e., rate and state friction?
4) Dieterich's model of seismicity
5) Characteristics of afterslip
6) Afterslip model of seismicity
7) Case of the Landers earthquake
8) Case of the Tohoku earthquake
9) Conclusions

The Coulomb Failure Model

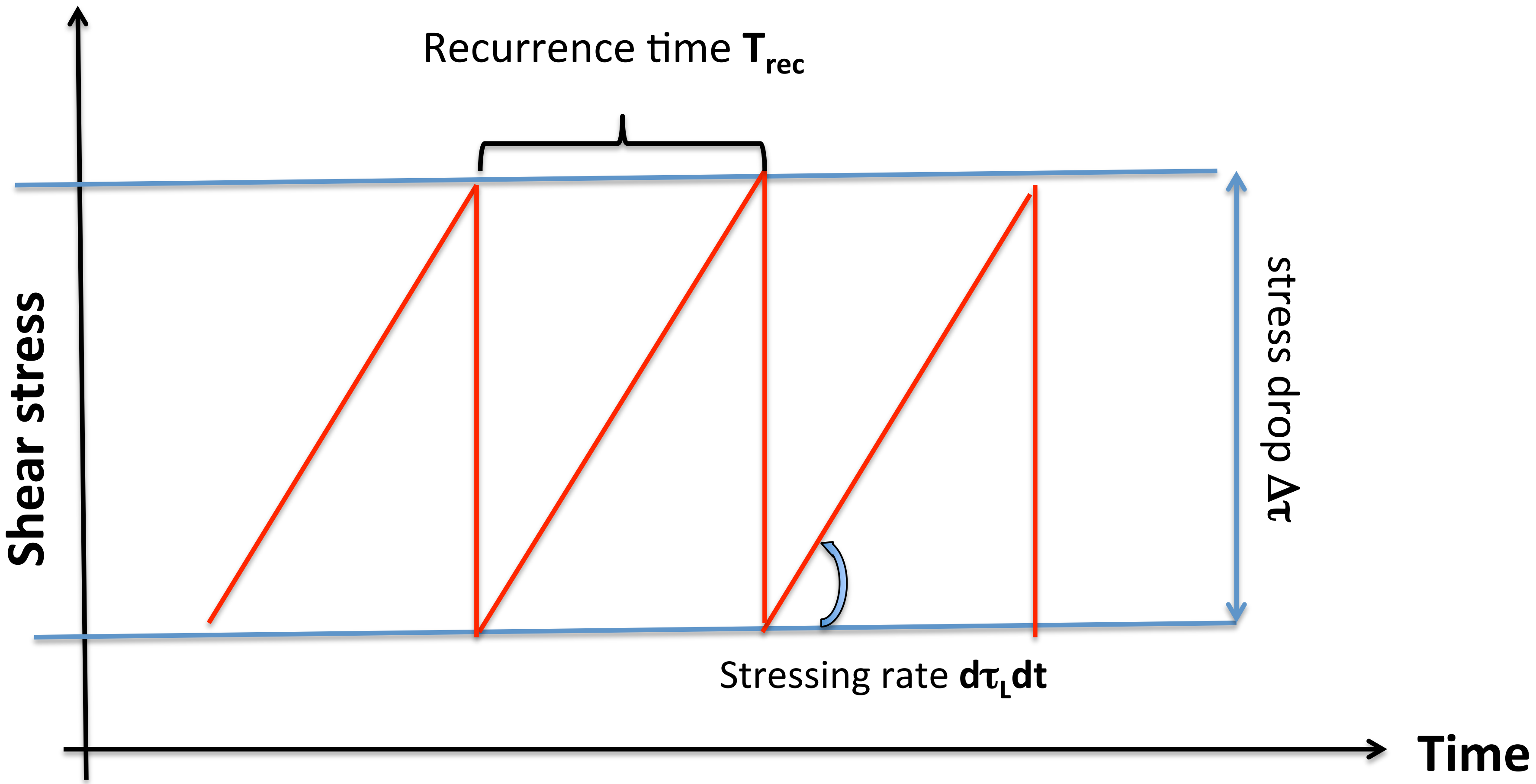
$$\Delta CFF = \Delta\tau - \mu\Delta\sigma$$

$\Delta\tau$: shear stress change

$\Delta\sigma$: normal stress change (<0 for unclamping)

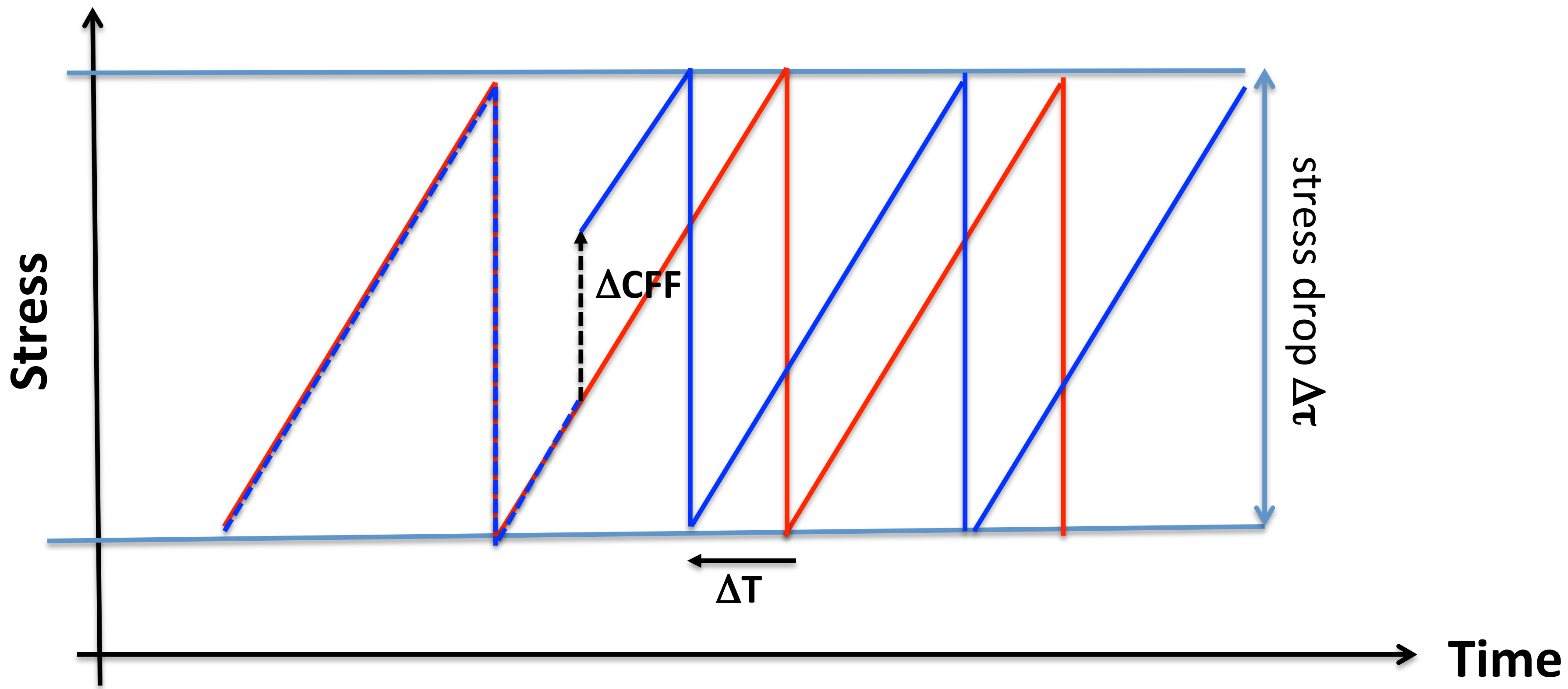
μ: (constant) friction coefficient

The Coulomb Failure Model: Clock Change



$$T_{rec} = \Delta\tau / (d\tau_L dt)$$

The Coulomb Failure Model: Clock Change (I)



Clock change: **$\Delta T = \Delta CFF/(d\tau_L dt)$**

Independent of the time of the applied perturbation

Instantaneous triggering if **$\Delta CFF > \Delta\tau$**

The Coulomb Failure Model: Clock Change (II)

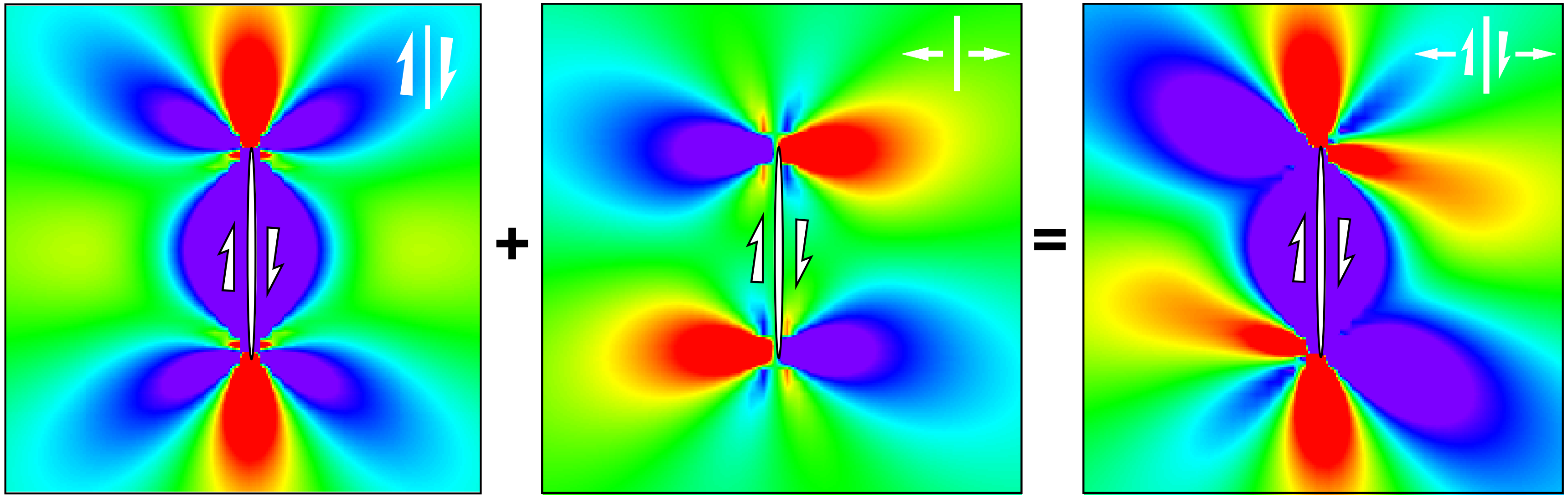
Clock change: $\Delta T = \Delta CFF/(d\tau_L dt)$

ΔCFF>0: Clock advance ➔ Triggering expected

ΔCFF<0: Clock delay ➔ Triggering not expected

The Coulomb Failure Model and Coseismic Stress Changes

A. Coulomb stress change for *right-lateral faults parallel to master fault* **Stress** **Rise** **Drop**



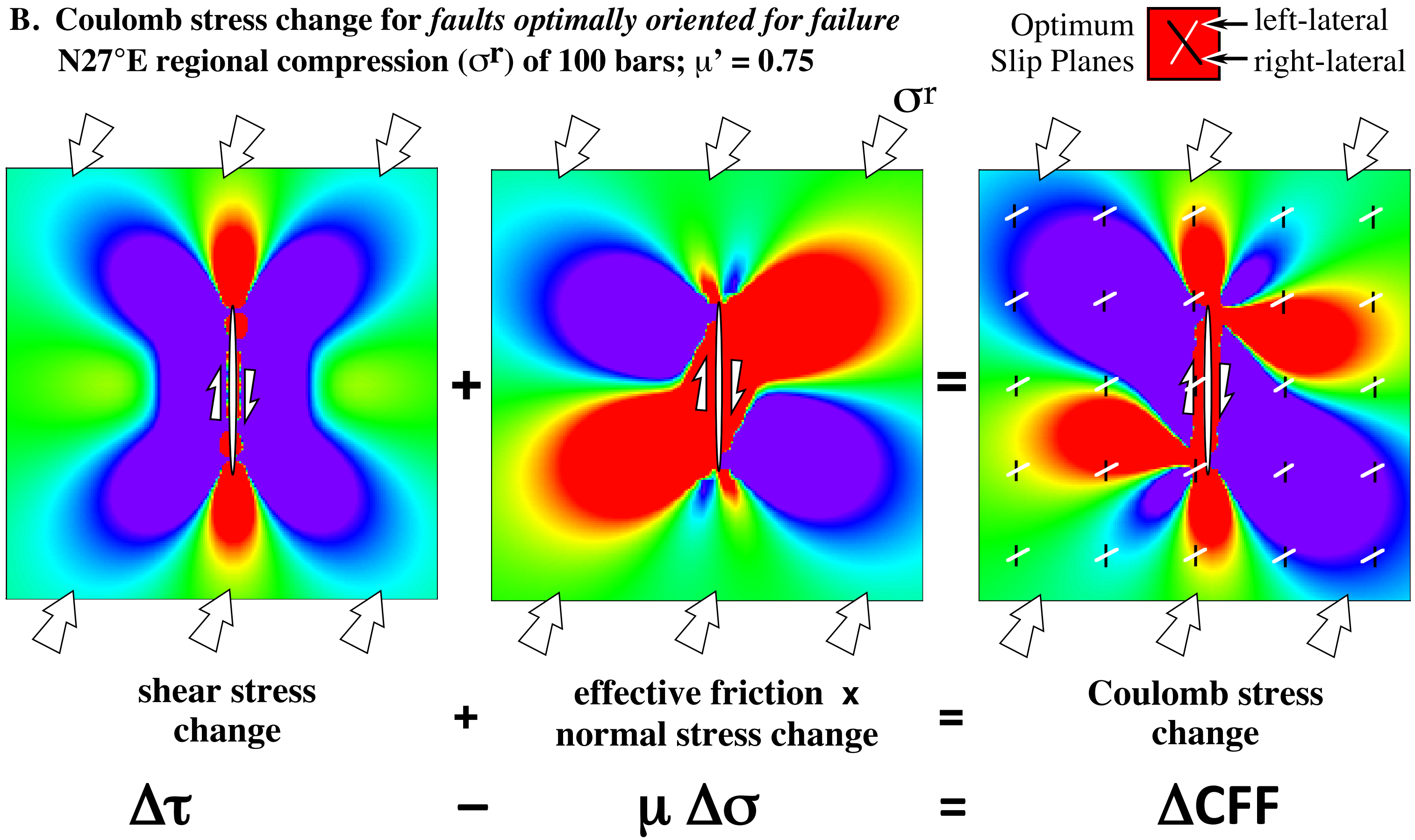
King et al., 1994

right-lateral shear stress change	+	effective friction x normal stress change	=	right-lateral Coulomb stress change

$$\Delta\tau \quad - \quad \mu\,\Delta\sigma \quad = \quad \Delta CFF$$

Coulomb stress computed assuming that each receiver fault (i.e., a grid point) is oriented as the main fault

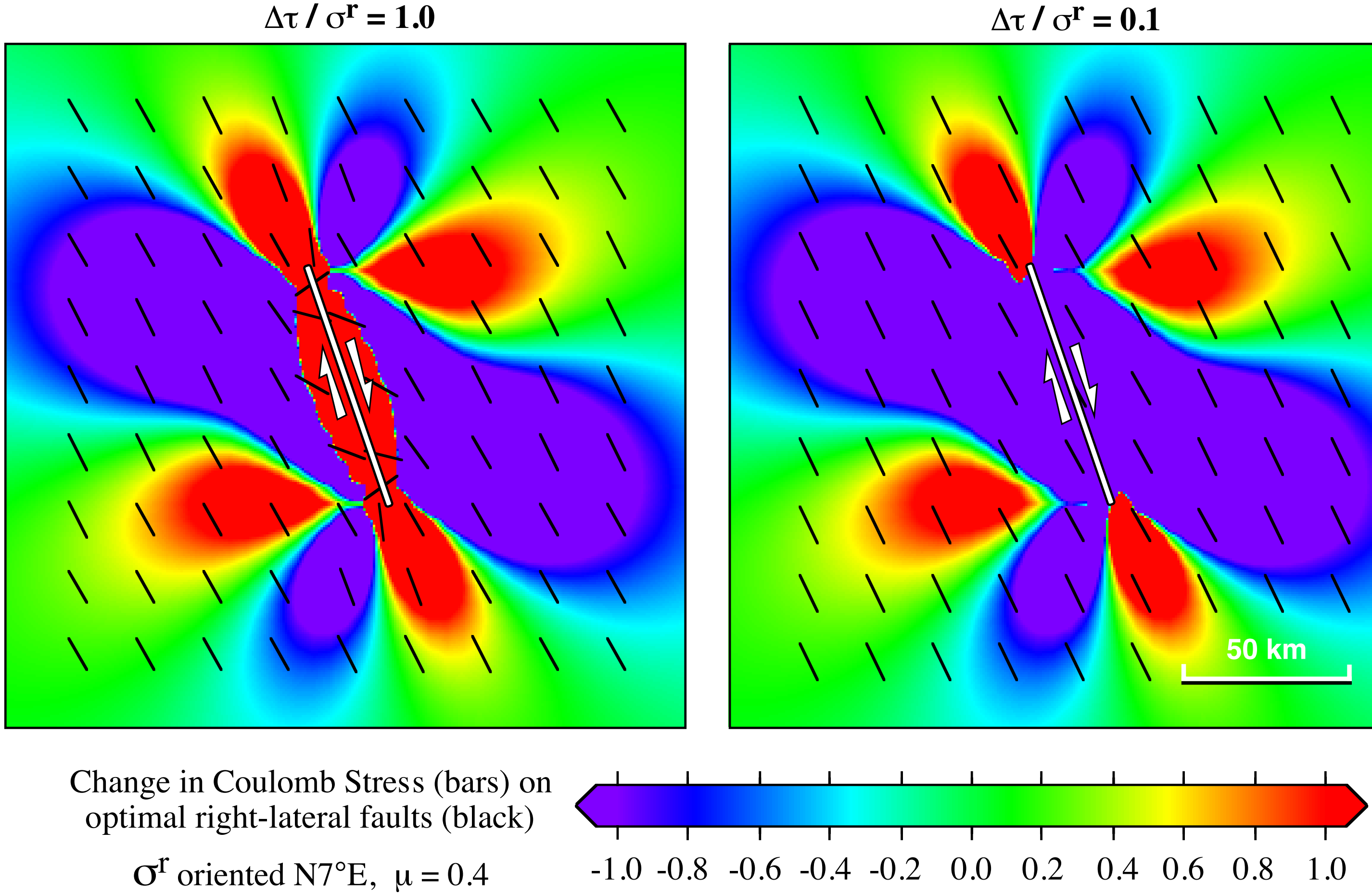
The Coulomb Failure Model and Coseismic Stress Changes: Optimally Oriented Planes



King *et al.*, 1994

Coulomb stress computed assuming that each receiver fault (i.e., a grid point) is oriented optimally to get the maximum **ΔCFF**

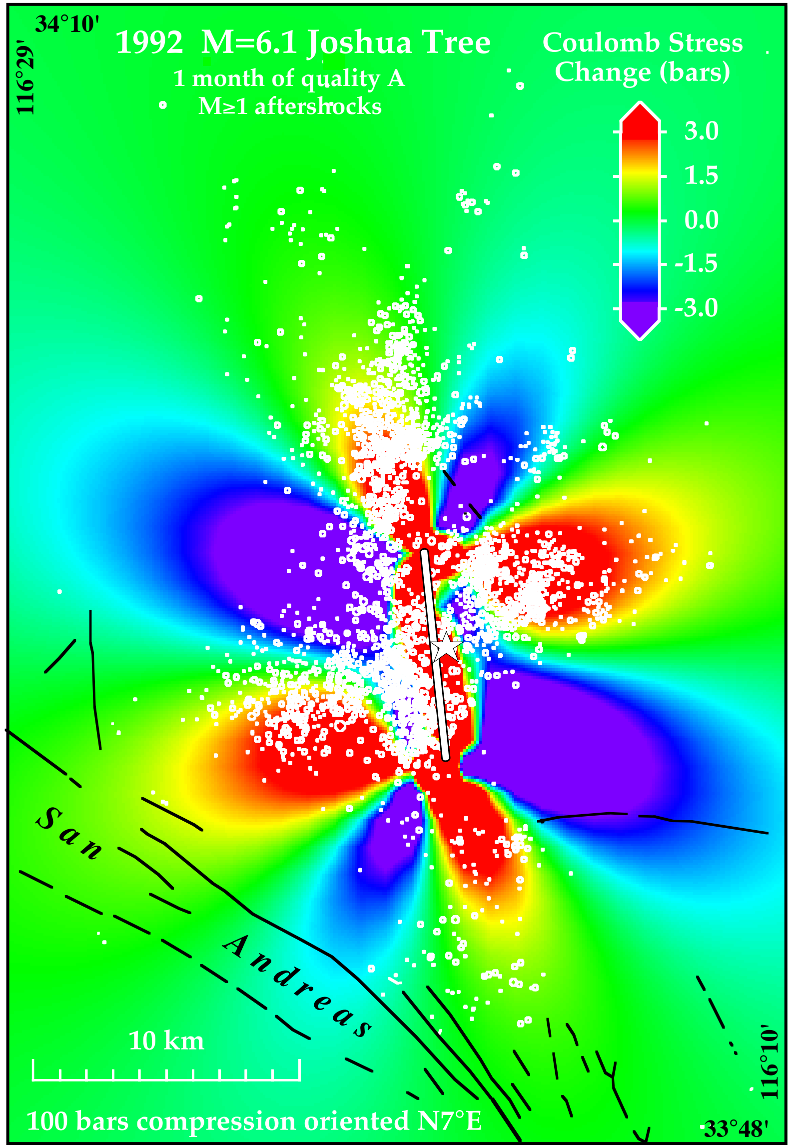
The Coulomb Failure Model and Coseismic Stress Changes: Optimally Oriented Planes



King et al., 1994

- In the far field, the OOP are oriented conformably to the tectonic field
- In the near field, they follow the coseismic stress field if $\boldsymbol{\Delta\tau >> \tau^r}$, where $\boldsymbol{\sigma^r}$ is the regional tectonic stress field

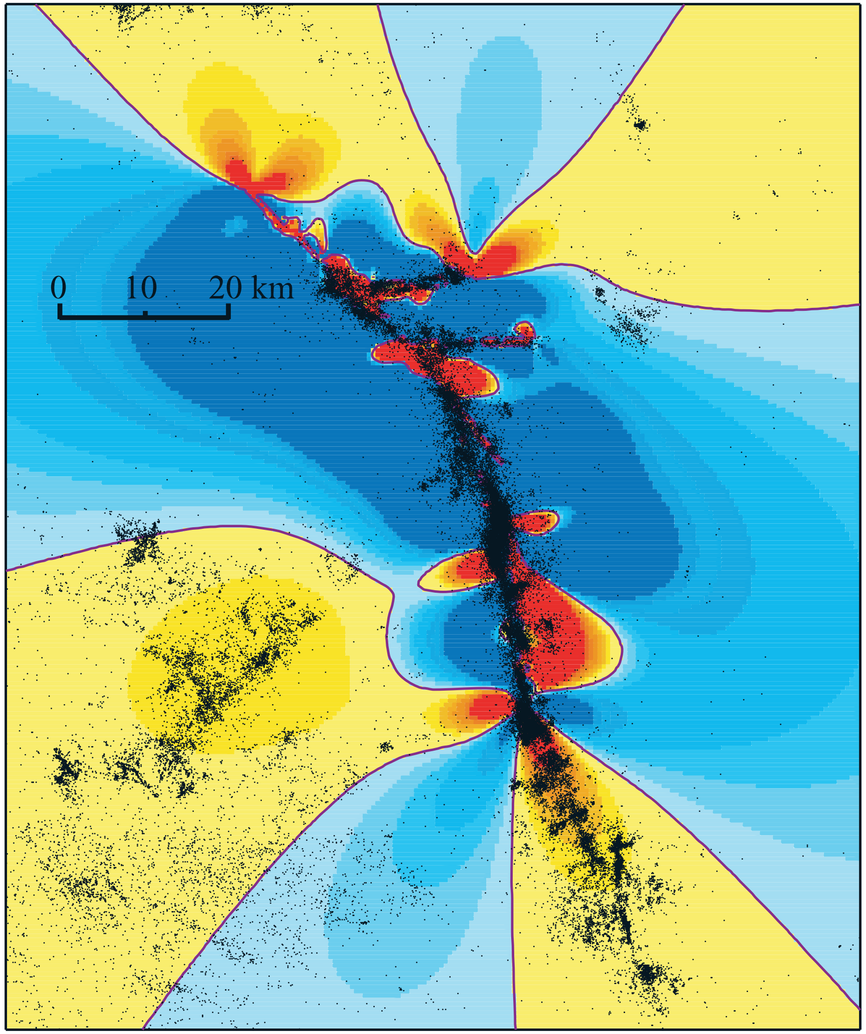
Application to the 1992, Mw7.3, Landers earthquake



King et al., 1994

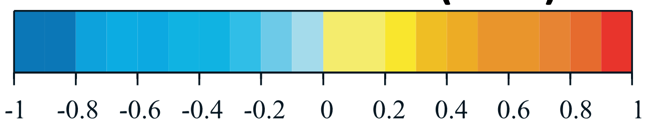
Good correlation between the distribution of aftershocks and the coseismic Coulomb stress change assuming the OOP

Application to the 1992, M_w7.3, Landers earthquake

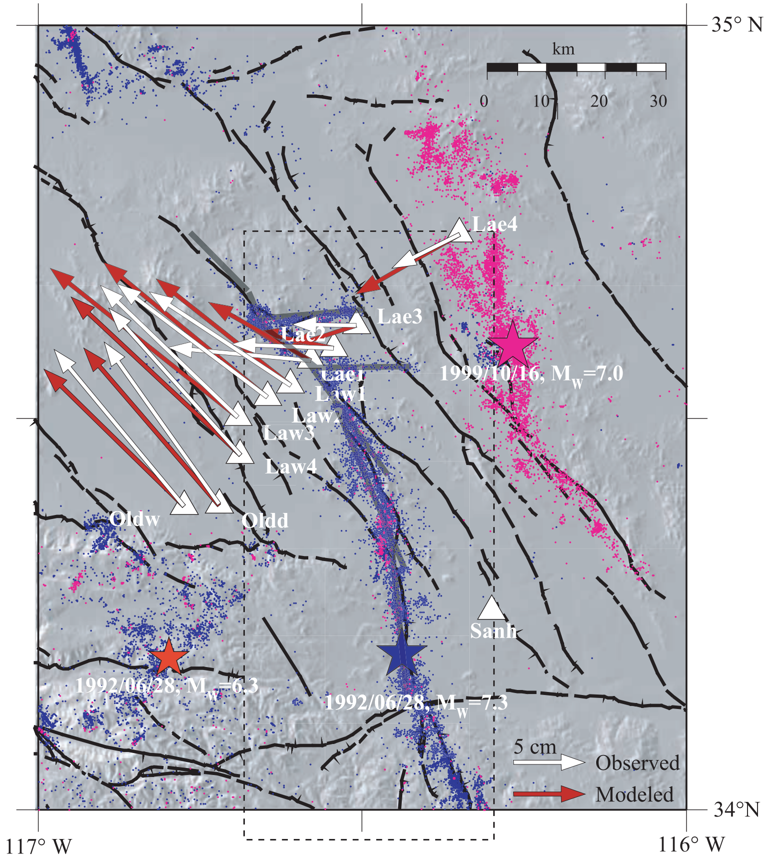


Perfettini and Avouac, 2007.

ΔCFF Coseismic (MPa)



- Weak correlation between the distribution of aftershocks and the coseismic Coulomb stress change assuming that all receiver faults are oriented parallel to the main fault
- The coseismic stress field near the fault highly depends on the details of the coseismic slip model



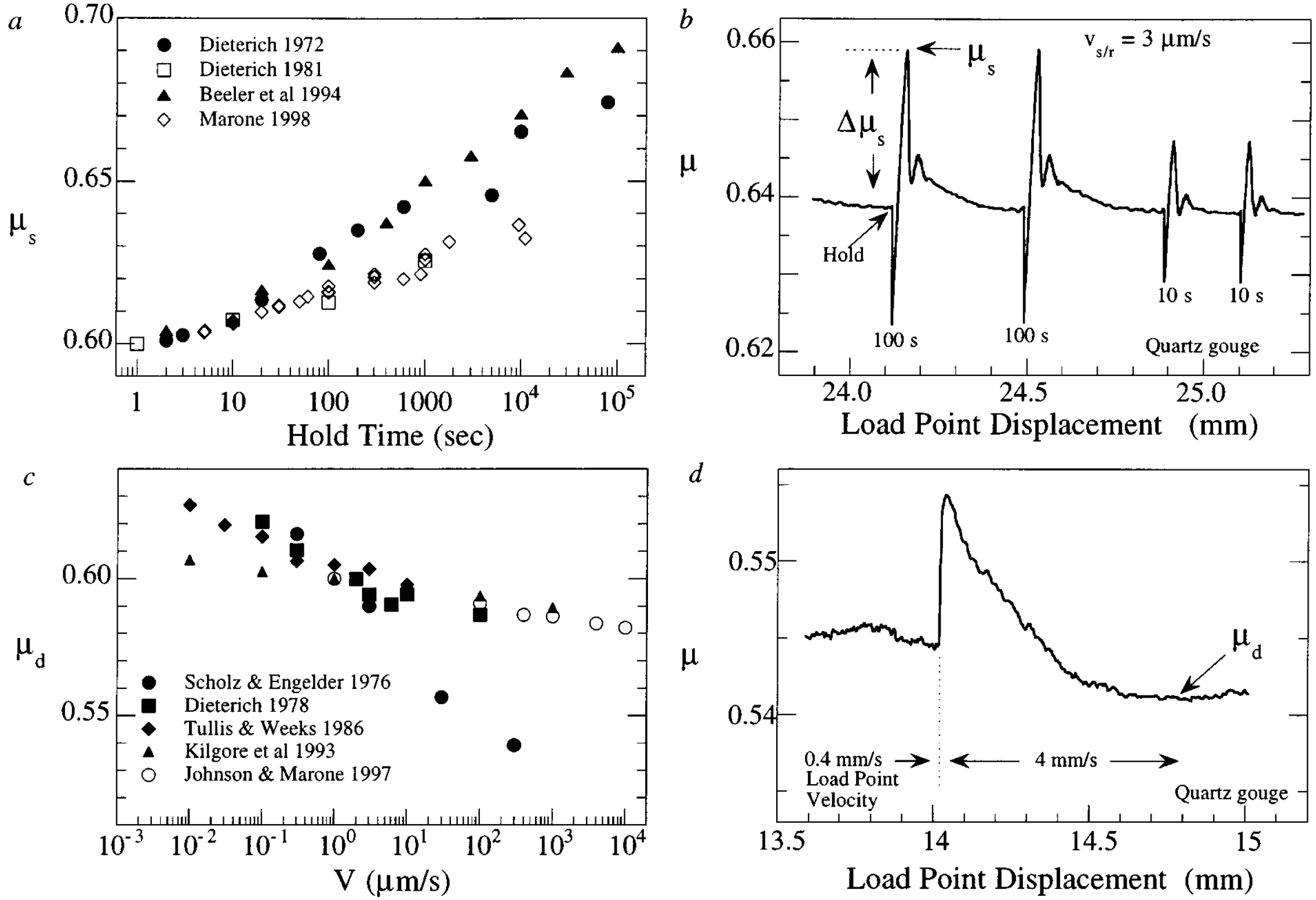
Perfettini and Avouac, 2007.

Optimally Oriented Planes

- The tectonic map of the Landers earthquake show that most of the structures are oriented as the main fault
- The focal mechanisms of the aftershocks show at most a 15^o variations from their pre-earthquake value

- Is it possible that new fault interface can be created knowing that a M_w4 earthquake corresponds to a radius of about 600m?
- Imagining that new faults are created, they would be created unloaded. Why should they re-rupture so quickly?
- The concept of OOP might be acceptable for small aftershocks (M_w<2) but not for large aftershocks

Rate and State friction



Marone, 1998.

- $\tau/\sigma=\mu=\mu_*+a \ln(V/V_*)+b \ln(\theta/\theta_*)$
  - $d\theta/dt=1-V\theta/d_c$ (aging law)
- Steady-state sliding: $\theta_{ss}= d_c/V \Rightarrow \mu_{ss}= \mu_*+(a-b) \ln(V/V_*)$

$$\mu_{ss}= \mu_*+(a-b)\ \ln(V/V_*)$$

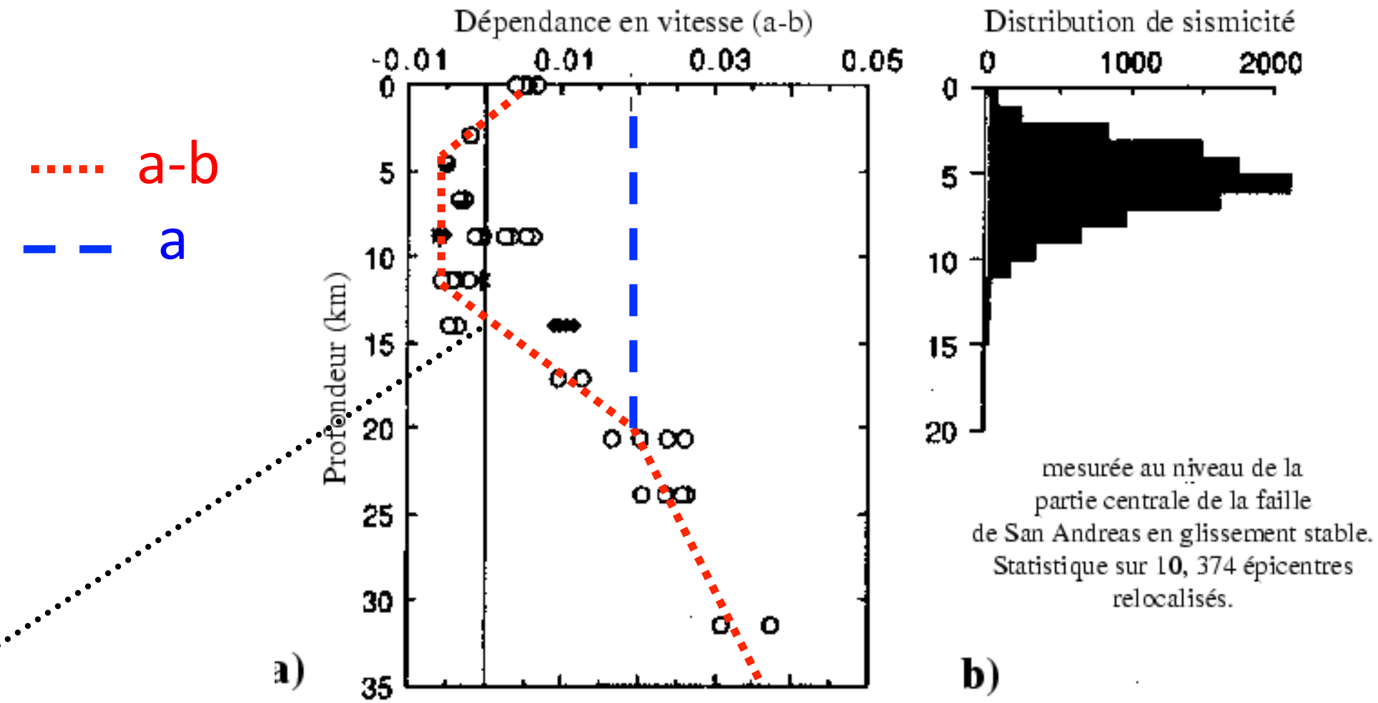
$a-b>0$

Stable slip: creeping faults

$a-b<0$

***Potentially* unstable slip:** unstable faults

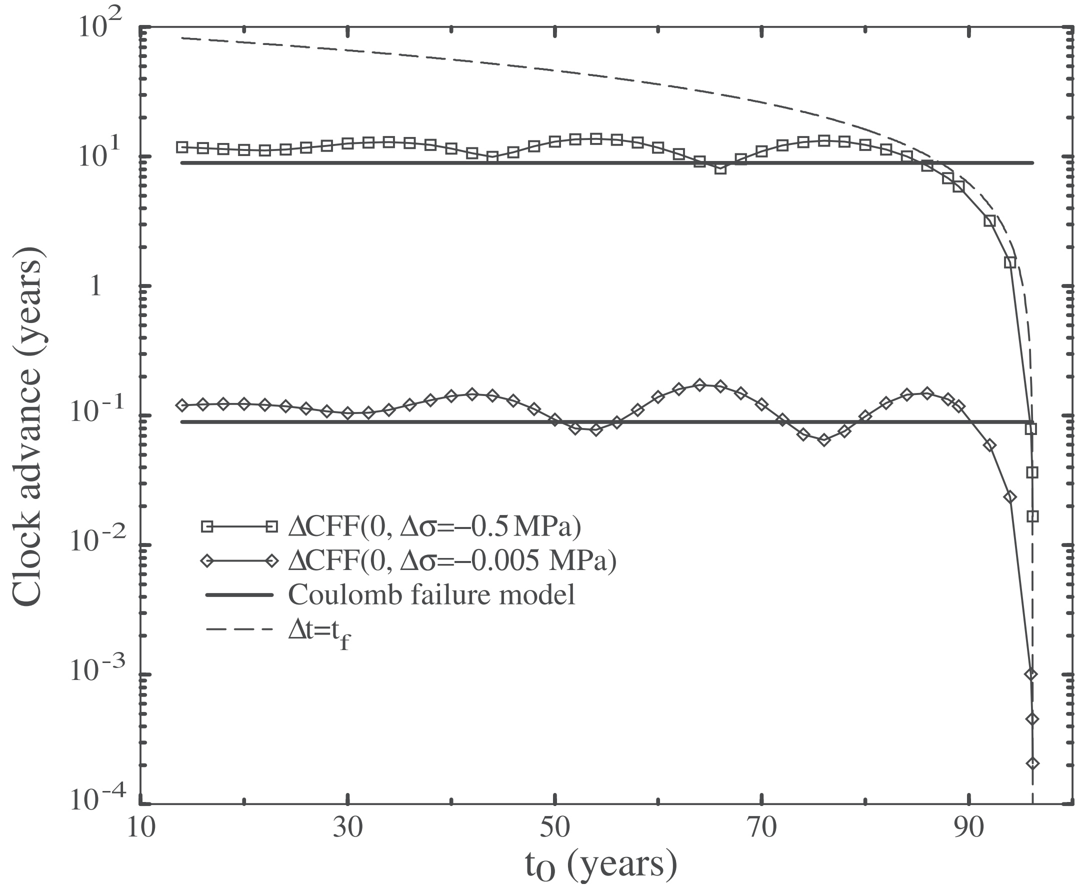
Explain the confinement of seismicity with depth



Correspond à T~350 °C

Blanpied et al., 1991.

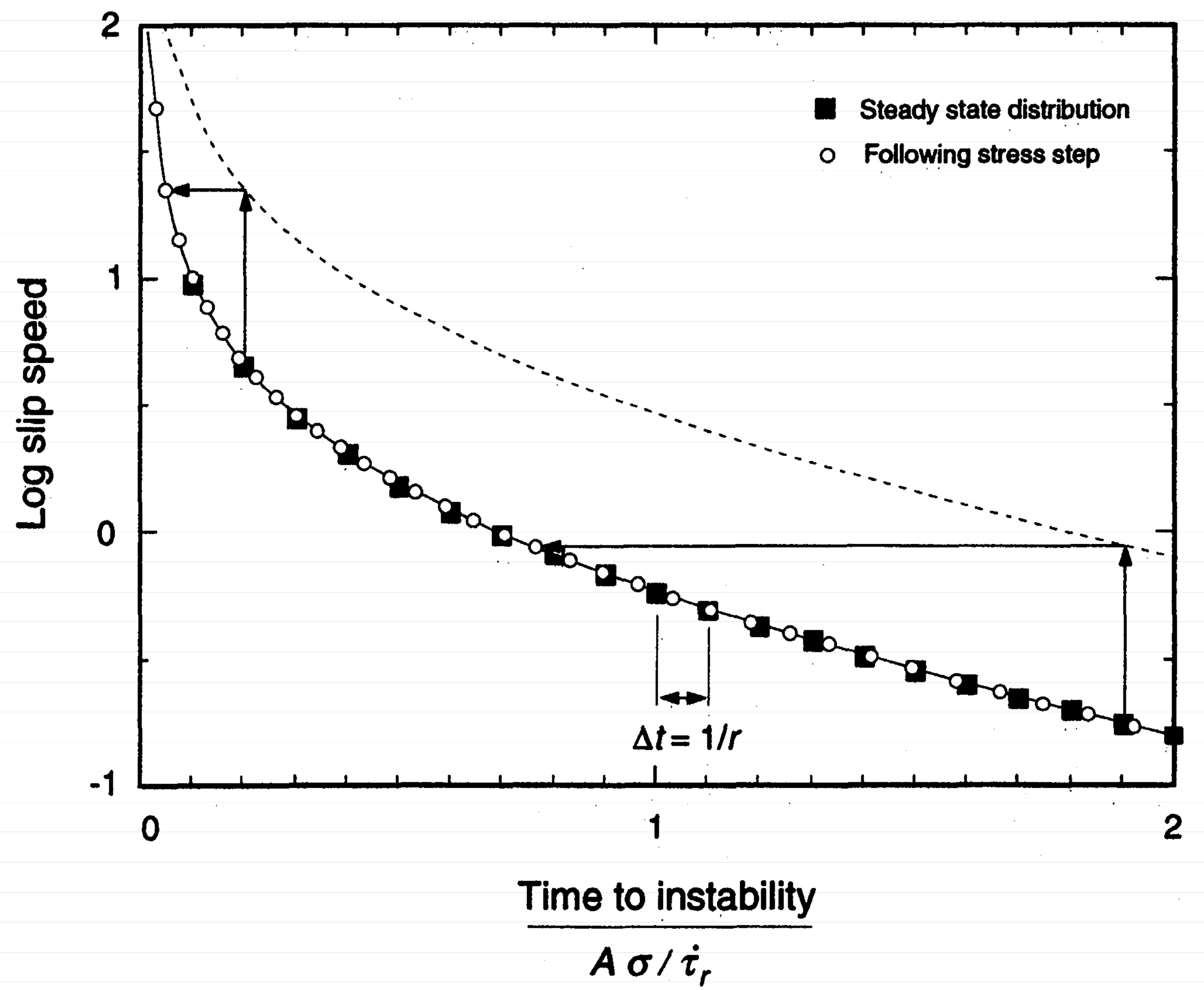
Clock change and agreement between Rate and State friction and the Coulomb Failure model



Perfettini et al., 2003.

- The Coulomb failure model agrees with the prediction of rate and state friction during most of the cycle, except at the end of the earthquake cycle, when nucleation is underway

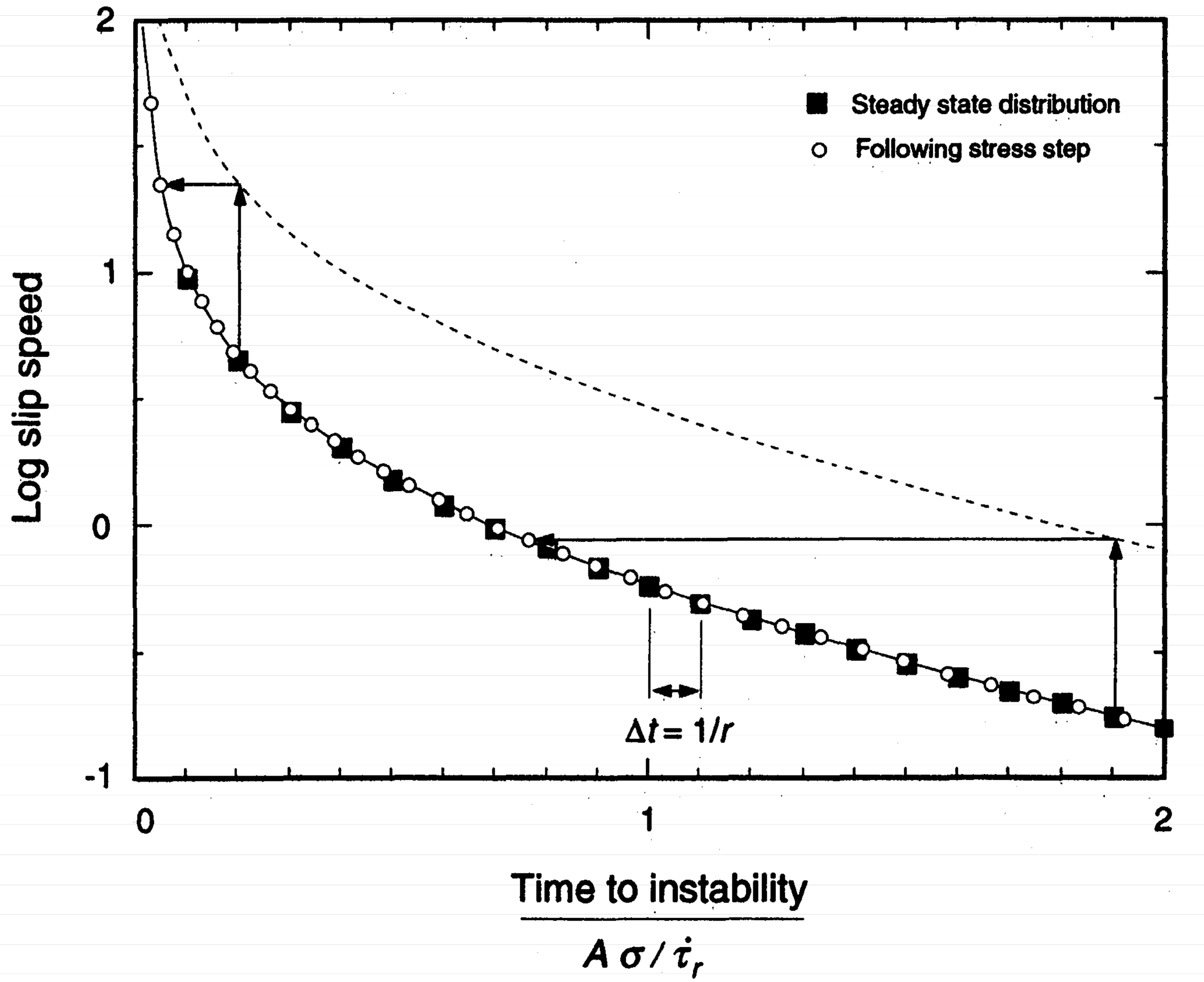
Dieterich's Model of Seismicity



Dieterich, 1994.

- Distribution of initial velocities built to result in a constant seismicity rate R_L in the case where ΔCFF=0
- Change of the nucleation time of a population of faults due a stress step that changes the sliding velocity: $\mathbf{V^+=V^- \exp(\Delta CFF/a\sigma)}$

Dieterich's Model of Seismicity



Dieterich, 1994.

- The stress change brings each elementary fault closer to failure
- The earlier in the cycle the perturbation is applied, the larger the clock advance
- The hypothesis of a constant seismicity rate is imposed and does not arise naturally

Dieterich's Model of Seismicity

$$R(t)=R_L/[\gamma(t)\, d\tau_L dt]$$
$$d\gamma/dt=(1-\gamma d\tau/dt)/(a\sigma)$$

R: seismicity rate
$d\tau_L dt$: long term loading rate
R_L: long term seismicity rate
a: rate and state parameter
σ: effective normal stress

- In steady-state: $\gamma=1/d\tau_L dt$ and $R=R_L$
- Surprisingly, the parameter **b**, responsible for instability in the rate and state framework disappear in Dieterich's model….
- Only the parameter **a**, responsible for the "viscous effect" of rate and state friction shows up…

Integral Formulation of Dieterich's Model

$$\Delta N(t)=N(t)-N(0)=R_L t_a \ln[1+(R(0)/R_L)(I(t)/t_a)]$$

with

$$R(0)=R_L/(\gamma(0)d\tau_L dt)$$

$$I(t)=\int_0^t dt' \exp[(\tau(t')-\tau(0))/A]$$

$$t_a=A/d\tau_L dt$$

with $\mathbf{A=a\sigma}$

The most general form for the evolution of the shear stress following a mainshock is

$$\tau(t)=\tau_0+d\tau_L dt\ .\ t+\Delta\tau_{cos}(t)+\Delta\tau_{post}(t)$$

Application to a coseismic step

$$\tau(t) = \tau_0 + d\tau_L dt \,.\, t + \Delta\tau_{cos} H(t)$$

H(t): Heaviside function (1 for t>0, 0 otherwise)

$$\Delta N(t) = N(t) - N(0) = R_L t_a \ln[1 + (R^+/R_L)(\exp(t/t_a) - 1)]$$

or

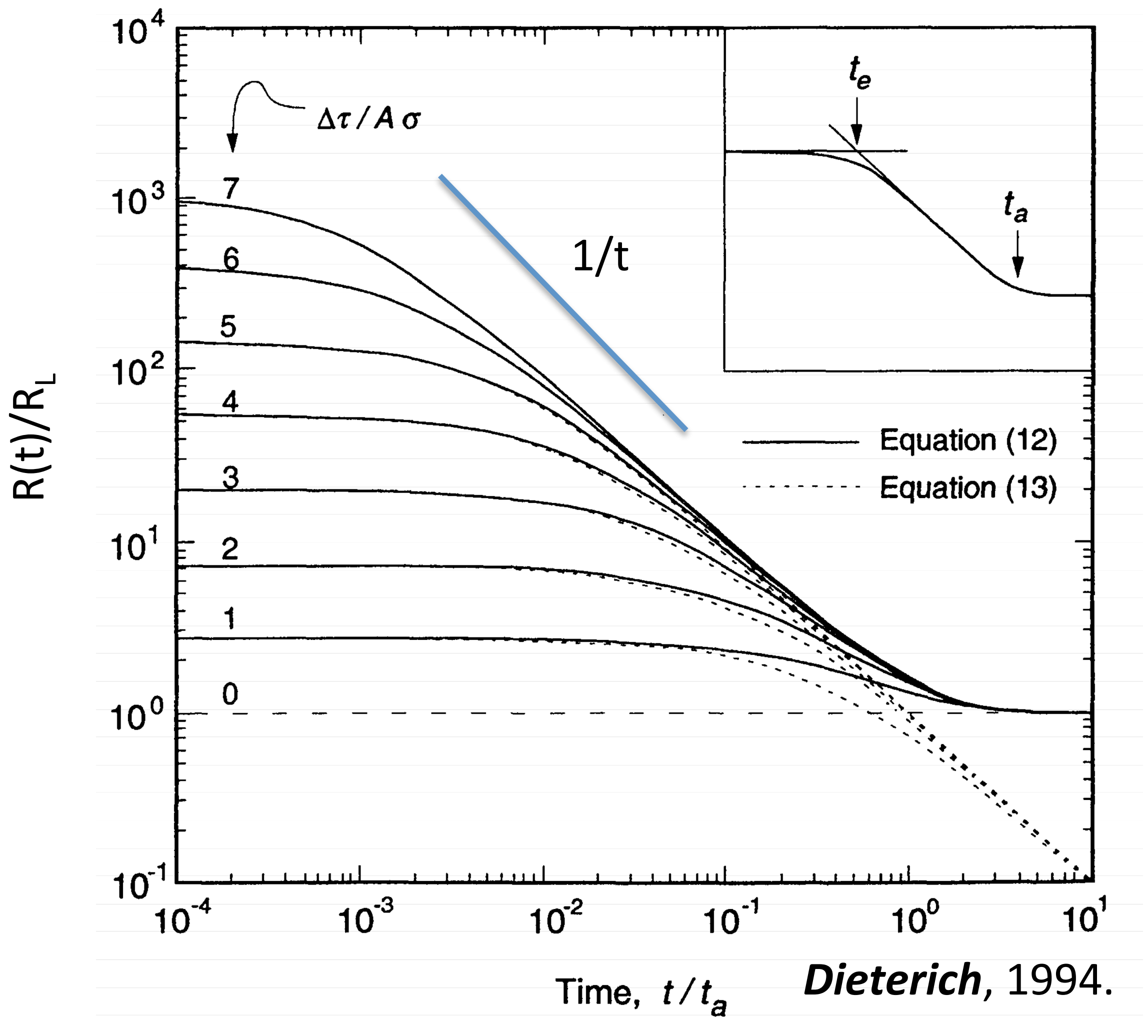
$$R(t) = R^+ \exp(t/t_a) / [1 + (R^+/R_L)(\exp(t/t_a) - 1)]$$

with

$R^+ = R(0)\exp(\Delta\tau_{cos}/A)$: Seismicity rate right at the end of the coseismic phase

Application to a coseismic step

$$R(t) = R^+ \exp(t/t_a)/[1+(R^+/R_L)(\exp(t/t_a)-1)]$$



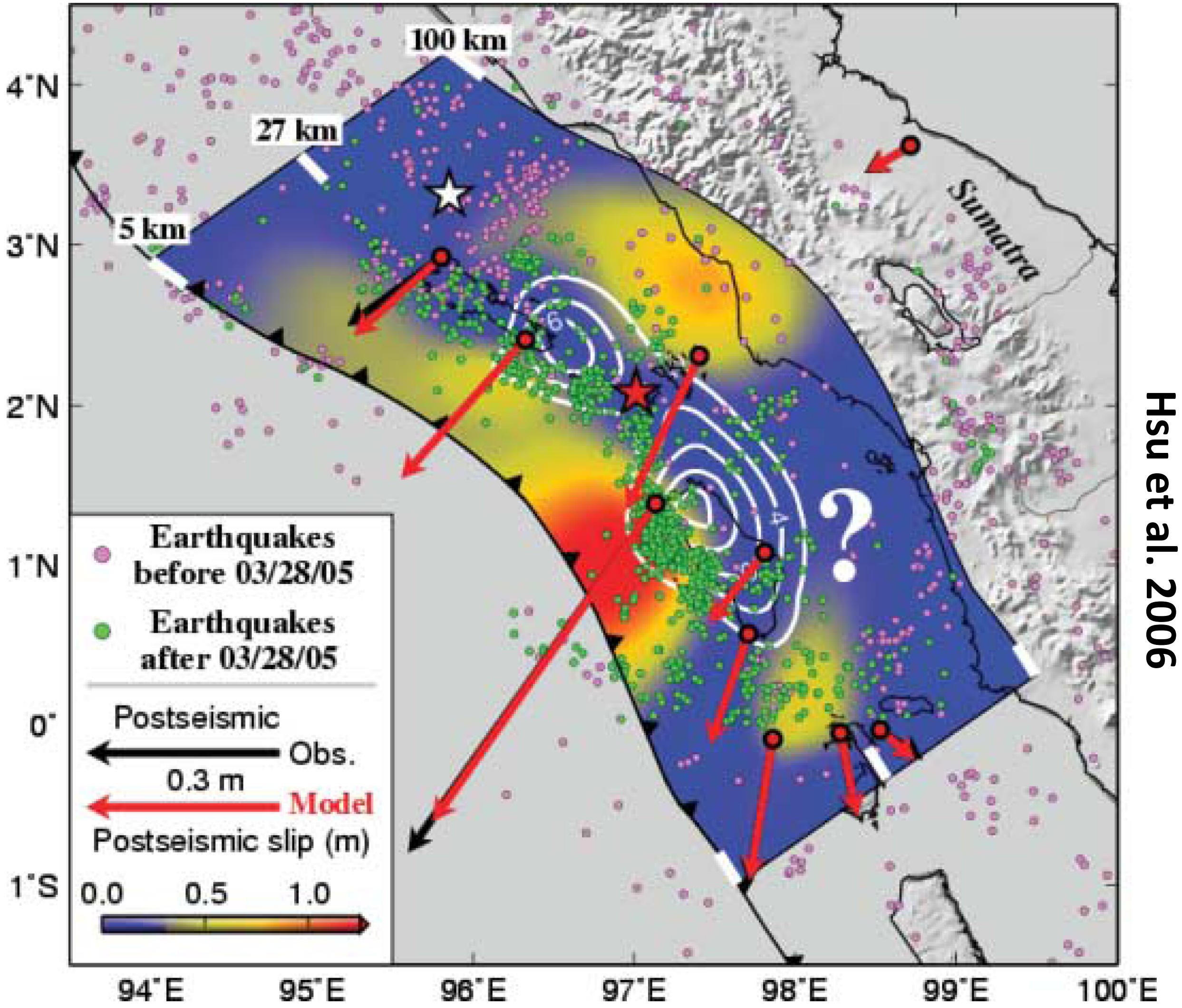
Dieterich, 1994.

- Seismicity rate jumps from R_L to R^+ at the time of the mainshock
- Decay as 1/time
- Omori law with an exponent of 1

Seismicity Model Based on Afterslip

Examples of Afterslip

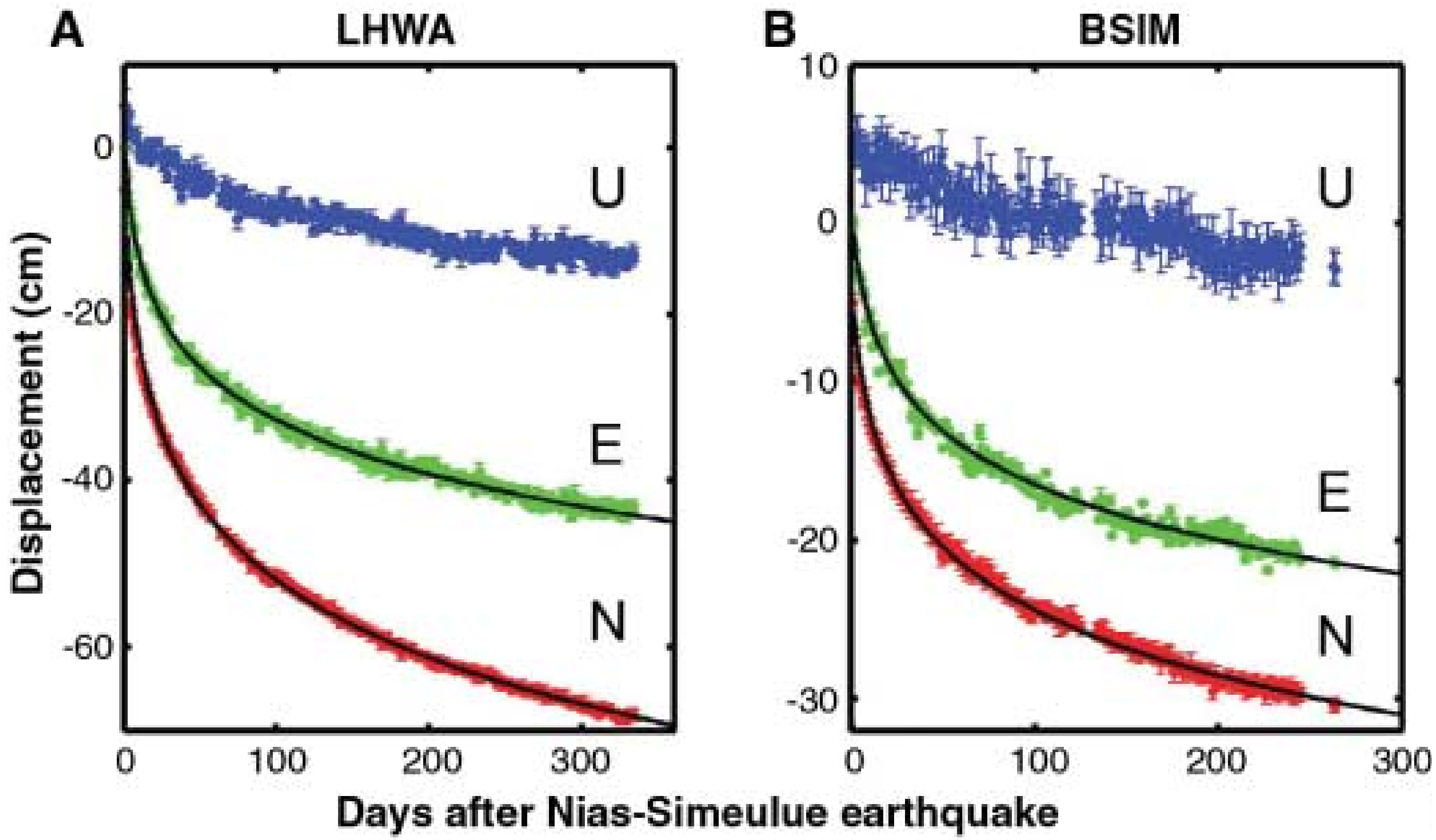
Afterslip of Nias (2005, M_w=8.7)



Hsu et al. 2006

- Anti-correlation between co- and postseismic slip
- Aftershocks occurs at the transition between co- and postseismic slip

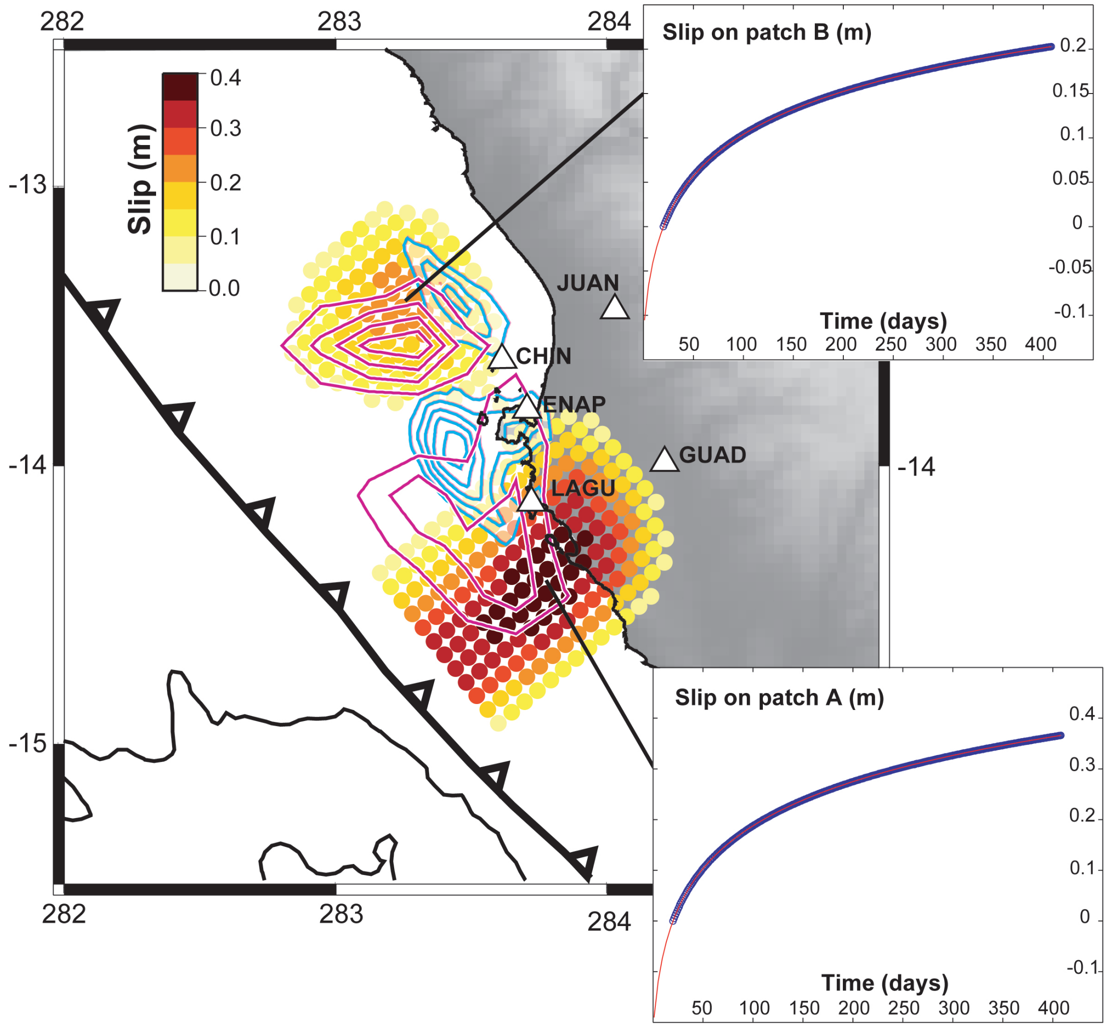
Afterslip of Nias (2005, M_w=8.7)



Hsu et al. 2006

Afterslip grows as the log(time)

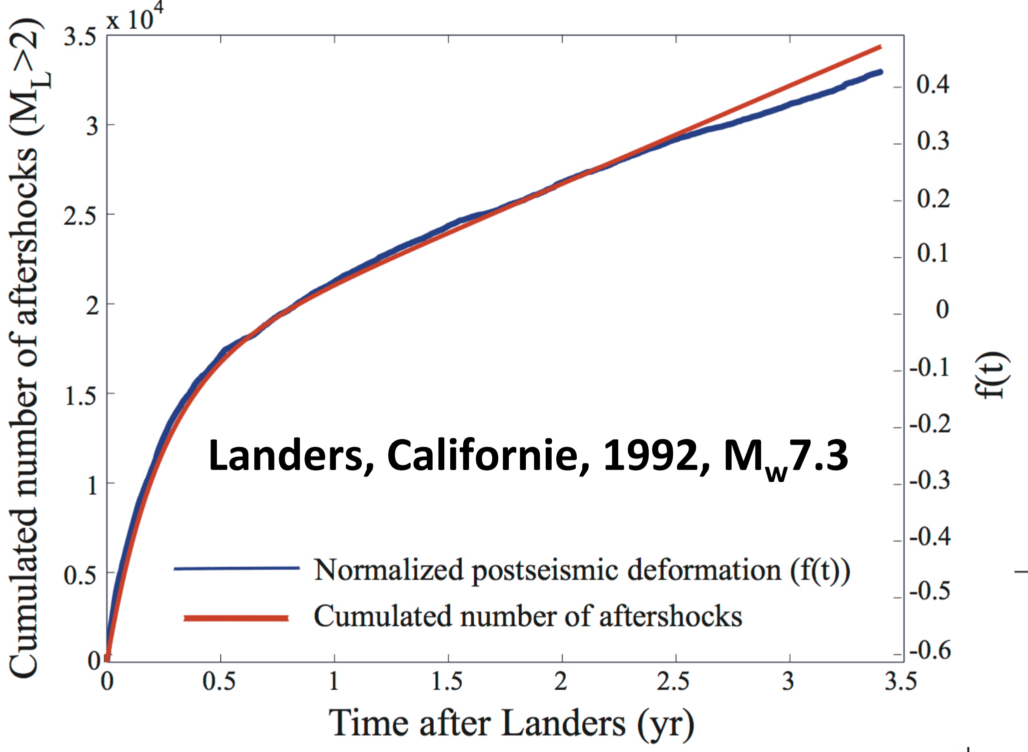
The Pisco Earthquake (2007, M_w8.0)



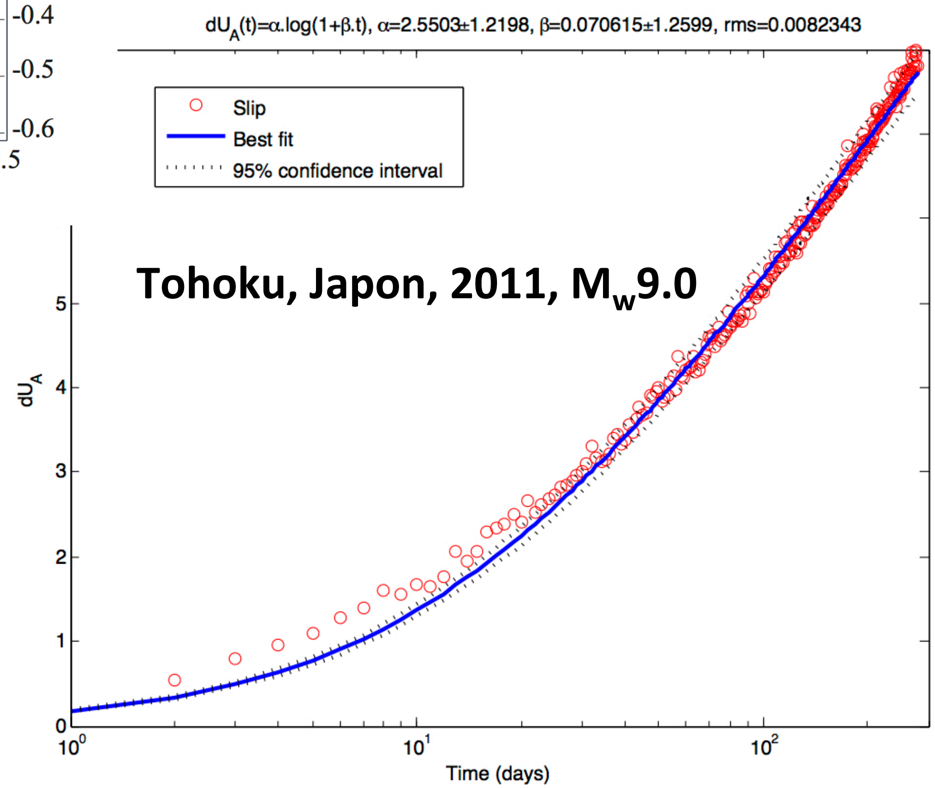
Perfettini et al. 2010

- Afterslip grows as the log(time)
- The distribution of seismicity follows the distribution of afterslip

Other Cases



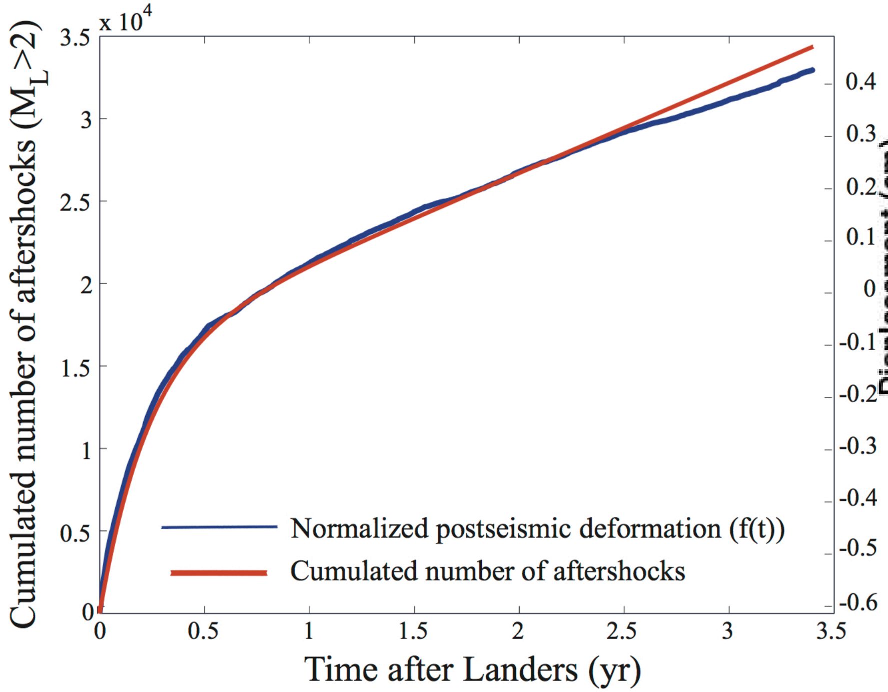
x 10^4
Cumulated number of aftershocks (M_L>2)
f(t)
Landers, Californie, 1992, M_w7.3
Normalized postseismic deformation (f(t))
Cumulated number of aftershocks
Time after Landers (yr)



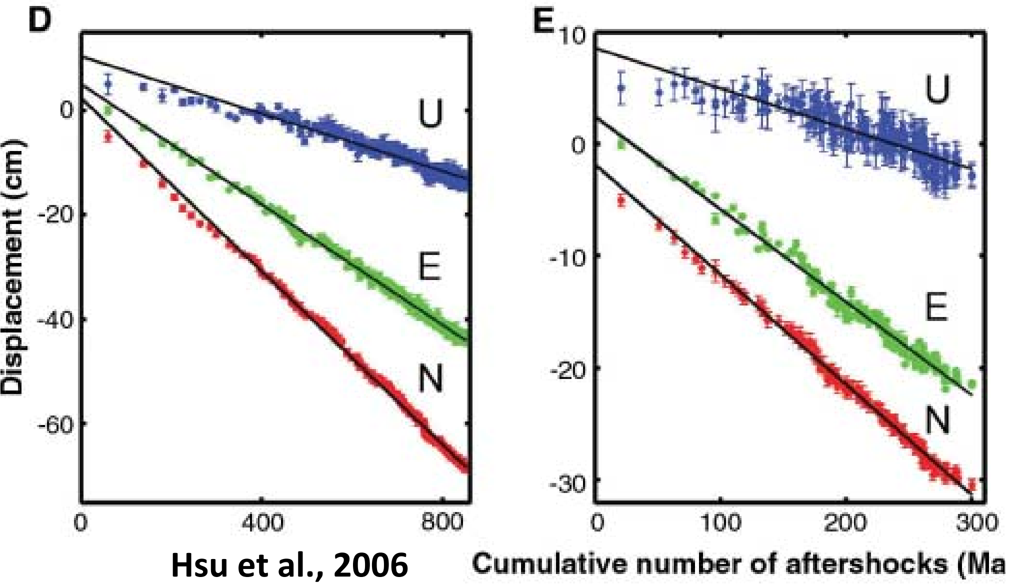
$dU_A(t)=\alpha.\log(1+\beta.t)$, $\alpha=2.5503\pm1.2198$, $\beta=0.070615\pm1.2599$, rms=0.0082343
Slip
Best fit
95% confidence interval
Tohoku, Japon, 2011, M_w9.0
dU_A
Time (days)

Link Between Afterslip and Seismicity

- Afterslip varies as the log(time) ➔ Slip rate~1/time
- Seismicity rate varies as 1/time (Omori law)
- Afterslip and seismicity seems to have the same temporal evolution (ex: Chi-Chi, Landers, Nias,…)

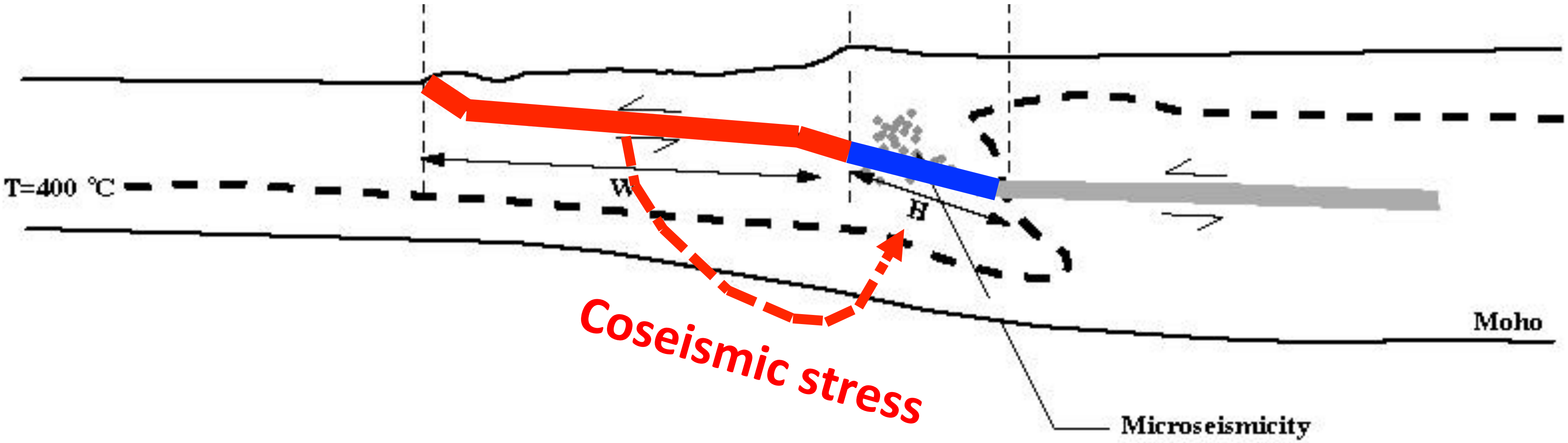


Perfettini and Avouac, 2007



Hsu et al., 2006

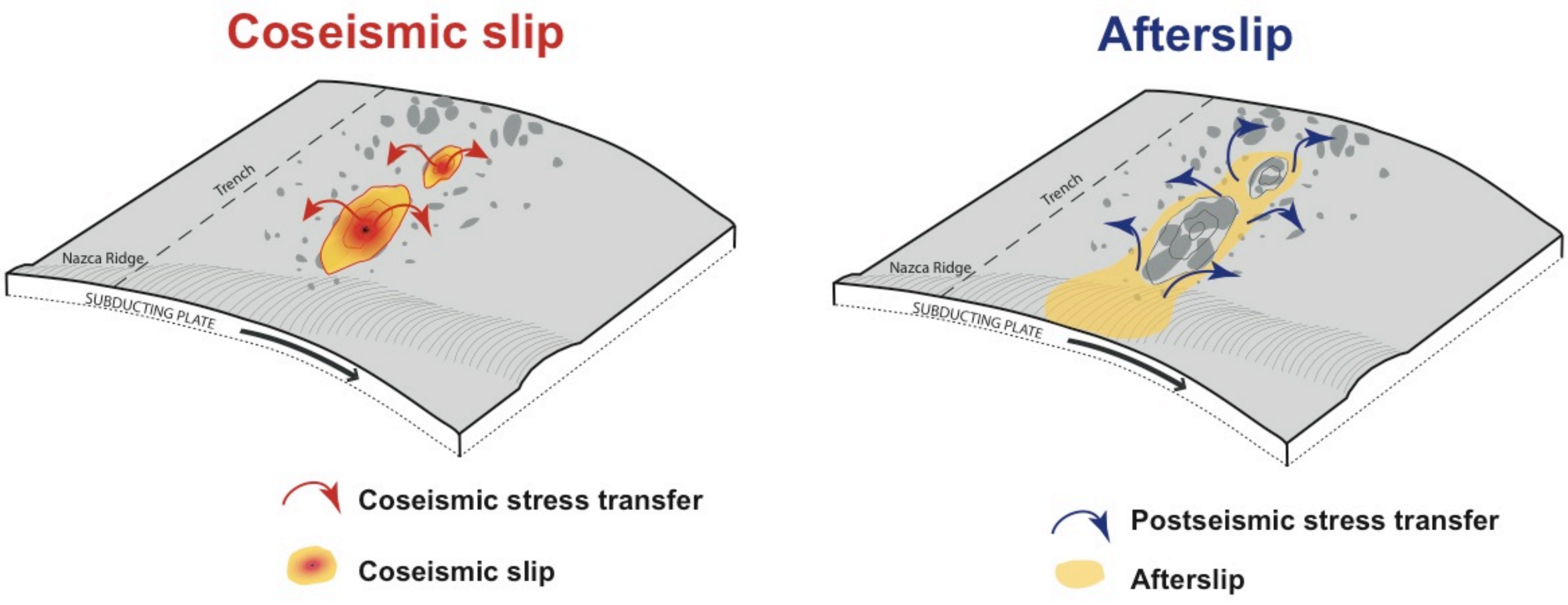
Response of a rate strengthening region to a stress step



Frictional stress: $\tau_f = \sigma[\mu_* + (a-b)\ln(V/V_*)]$

a-b>0: rate strengthening friction

Response of a rate strengthening region to a stress step



Frictional stress: $\boldsymbol{\tau_f = \sigma[\mu_* + (a-b)\ln(V/V_*)]}$

a-b>0: rate strengthening friction

Afterslip Model

$$\mathrm{slip}_{post}(t)=V_L t_r \log[1+ (V^+/V_L)\times (\exp(t/t_r)-1)]$$

$$V_{post}(t)=V^+ \exp(t/t_r)/[1+ (V^+/V_L)\times (\exp(t/t_r)-1)]$$

- **V_L**: long term sliding velocity
- **V^+**: sliding velocity at the end of the coseismic phase
- **t_r**: relaxation time of the postseismic phase

- **$t_r=(a-b)\sigma/(d\tau_L dt)$**
- **$a-b>0$**: parameters of the rate and state friction law
- **σ**: effective normal stress
- **$d\tau_L dt$**: long term stressing rate

- **$V^+=V_L \times \exp(\Delta\tau/(a-b)\sigma)$**
- **$\Delta\tau$**: coseismic shear stress step

The law: $\mathbf{slip_{post}(t)=V_L\, t_r\, log[1+ (V^+/V_L)\times (exp(t/t_r)-1)\ ]}$
can adjust postseismic slip following recent earthquake sequences (Chi-Chi, Arequipa, Nias, Pisco, Maule, Tohoku,…)

The parameter **(a-b)σ** is not varying too much with (**a-b)σ=1-10 bars**, suggesting either a low effective normal stress (high pore pressure?) and/or that the area of high postseismic response are close stability (a-b near 0)

Seismicity Model based on Afterslip

- We assume that the seismicity rate R(t) is proportional to the deformation rate, itself proportional to the afterslip rate:

$$\mathbf{R(t)=dN_{cum}/dt=c(t)V_{post}(t)}$$

$$\mathbf{N_{cum}(t)=\Big[C(t)U_{post}(t)-C(t)U_{post}(t)\Big]-\int_0^t U_{post}(t')[dc(t')/dt']dt'}$$

Since $\mathbf{U_{post}(0)=0}$:

$$\mathbf{N_{cum}(t)=c(t)U_{post}(t)-\int_0^t U_{post}(t')[dc(t')/dt']dt'}$$

We further assume that **c(t)=cste** (dc/dt=0):

$$\mathbf{N_{cum}(t)=c\,U_{post}(t)}$$

Seismicity Model based on Afterslip

Seismicity rate given by:

$$\mathbf{R(t)=R^{+}\,exp(t/t_r)/[1+\,(R^{+}/R_L)\times\,(exp(t/t_r)\text{-}1)\,]}$$

$\mathbf{R_L}$: long term seismicity rate
$\mathbf{R^+}$: seismicity rate at the end of the coseismic phase
$\mathbf{t_r}$: relaxation time of afterslip

$$\mathbf{t_r=(a\text{-}b)\sigma/(d\tau_L dt)}$$

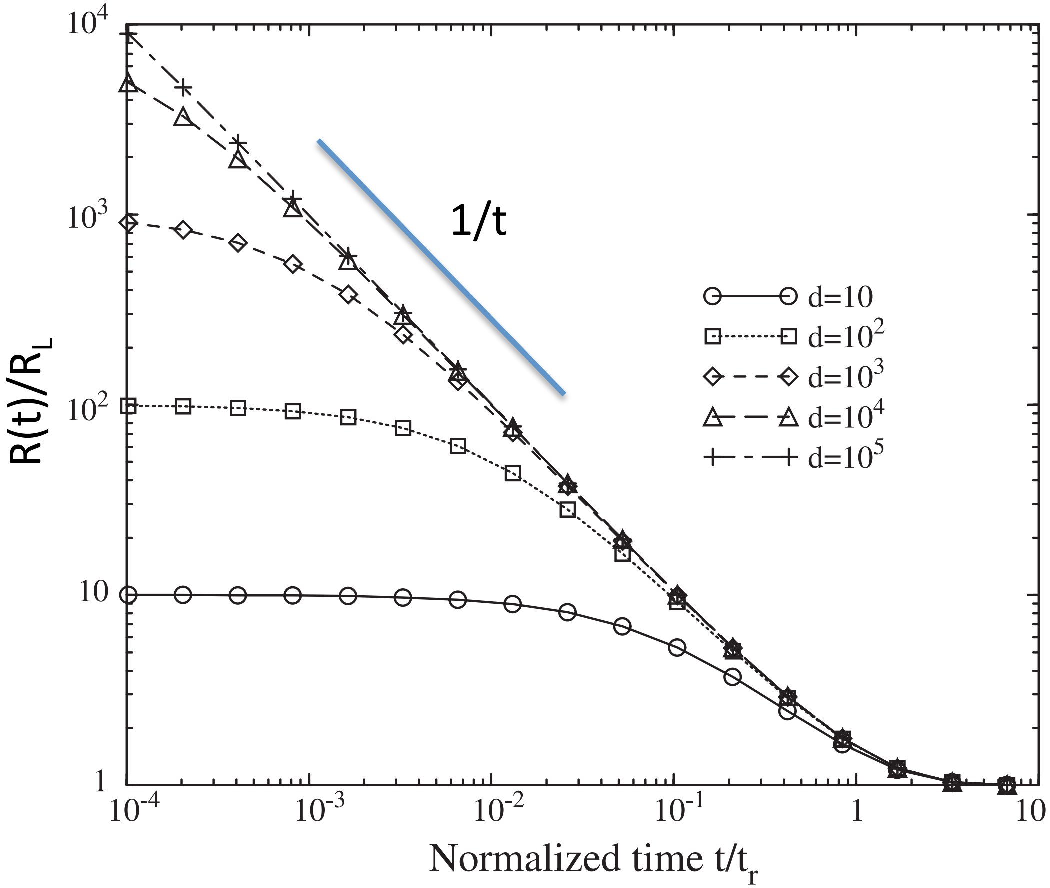
a-b>0: parameters of the rate and state friction law
$\boldsymbol{\sigma}$: effective normal stress
$\mathbf{d\tau_L dt}$: loading rate

$$\mathbf{R^+=R_L \times exp(\Delta\tau/(a\text{-}b)\sigma)}$$

$\boldsymbol{\Delta\tau}$: shear stress change

Seismicity Model

$$R(t)= R^{+}\exp(t/t_r)/[1+(R^{+}/R_L)(\exp(t/t_r)-1)]$$



Perfettini and Avouac, 2004.

- Seismicity rate jumps from $\mathbf{R_L}$ to $\mathbf{R^+}$ at the time of the mainshock
- Decay as **1/time**
- Omori law with an exponent of 1

Afterslip Model vs. Dieterich's Model

Afterslip: $R(t) = R^{+}\exp(t/t_r)/[1+(R^{+}/R_L)(\exp(t/t_r)-1)]$

Dieterich: $R(t) = R^{+}\exp(t/t_a)/[1+(R^{+}/R_L)(\exp(t/t_a)-1)]$

- Both models are identical mathematically

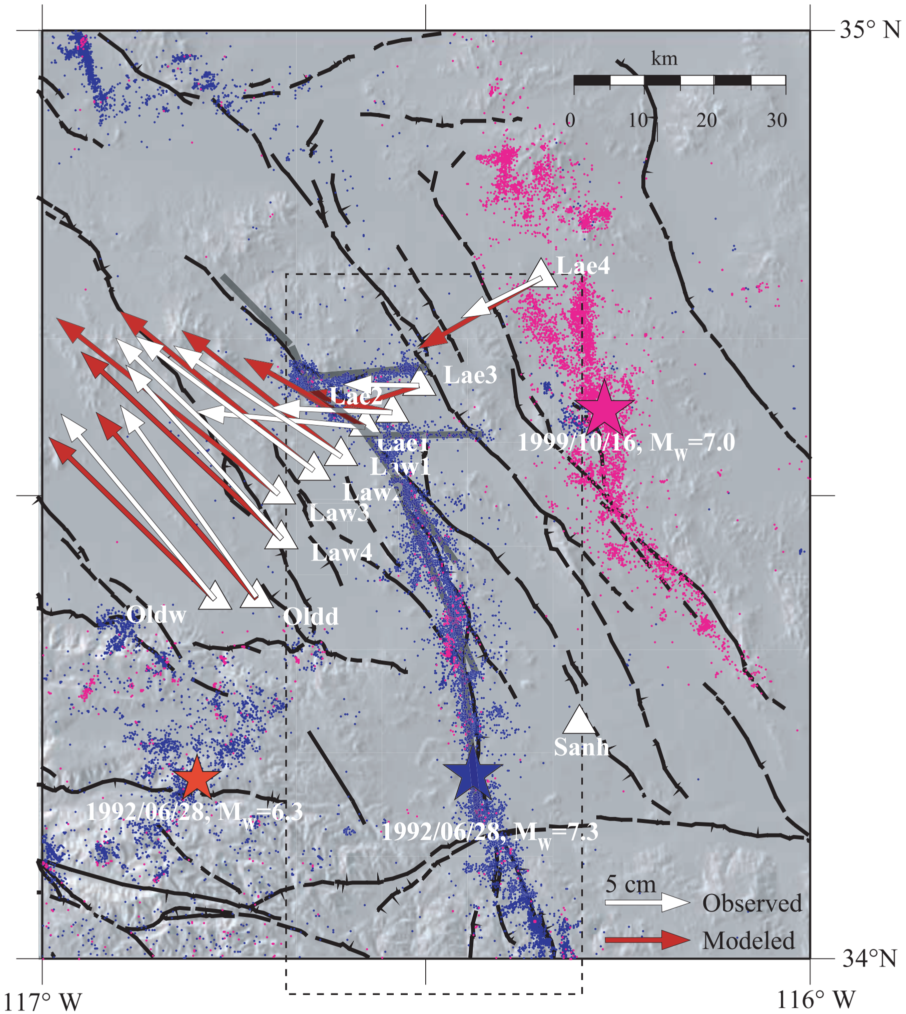
- The variable $\boldsymbol{\gamma(t)}$ of Dieterich's model is proportional to $\mathbf{1/V_{post}(t)}$ in the afterslip seismicity model

- The assumption of a constant seismicity rate in the afterslip model arises naturally because the creeping zone relaxes to the long term velocity

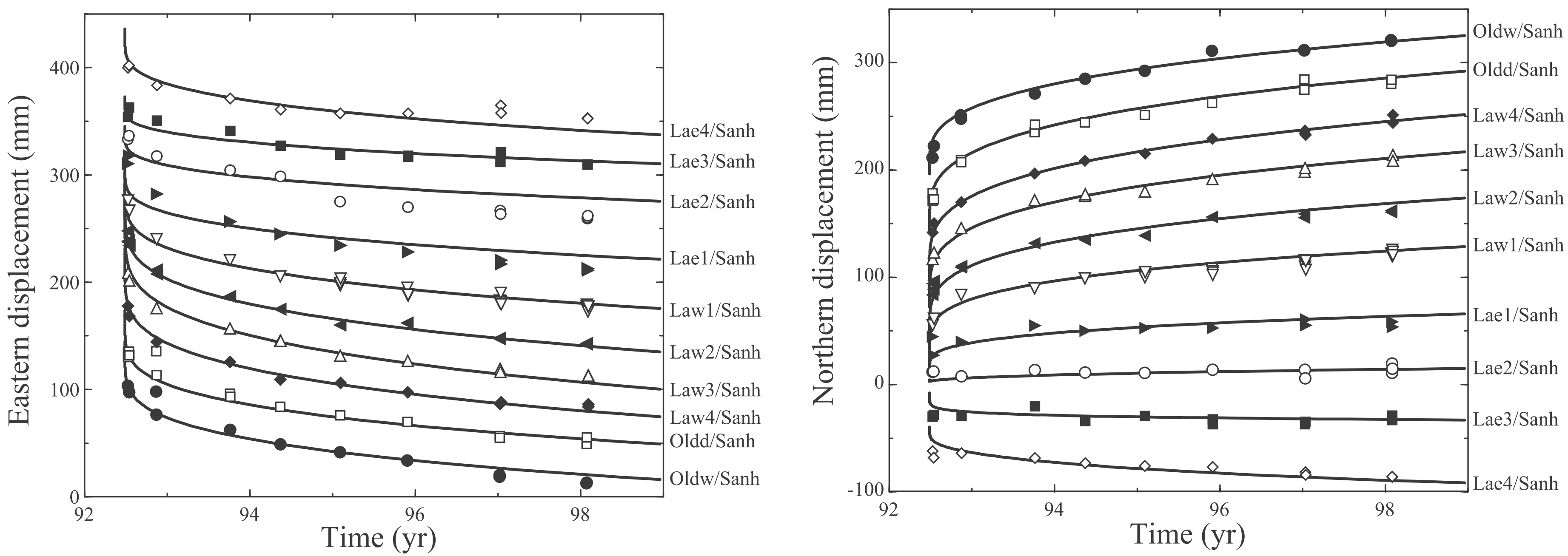
- The afterslip model has the additional constrain that $\mathbf{R(t)}$ is proportional to the afterslip velocity $\mathbf{V_{post}(t)}$

Case of the Landers Earthquake

Postseismic GPS data



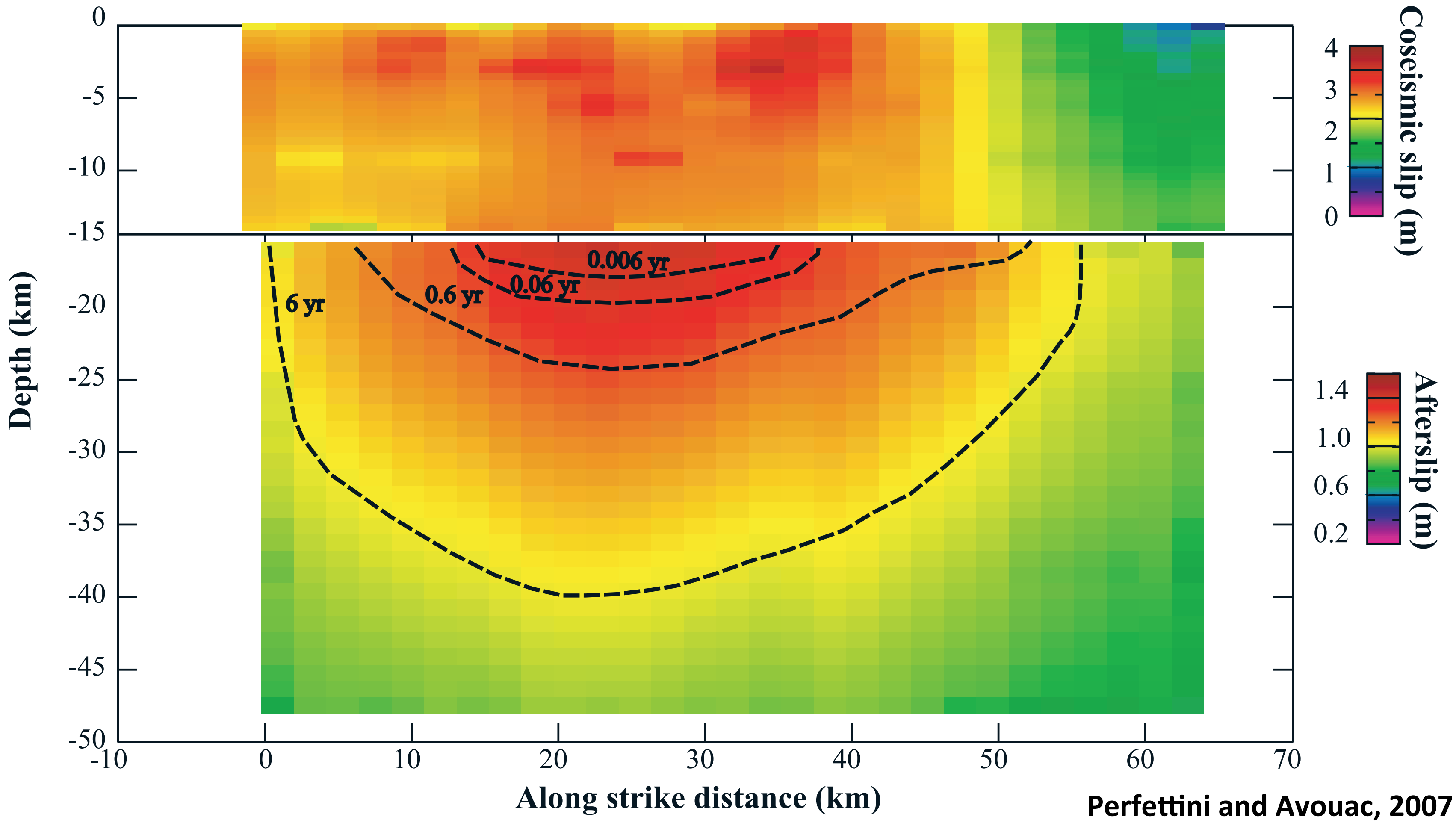
Postseismic GPS Time Series



Perfettini and Avouac, 2007

- The inverted afterslip distribution adjusts very well the observed time series
- The afterslip model is a quasi-dynamic model based on rate and state friction on a rate strengthening fault

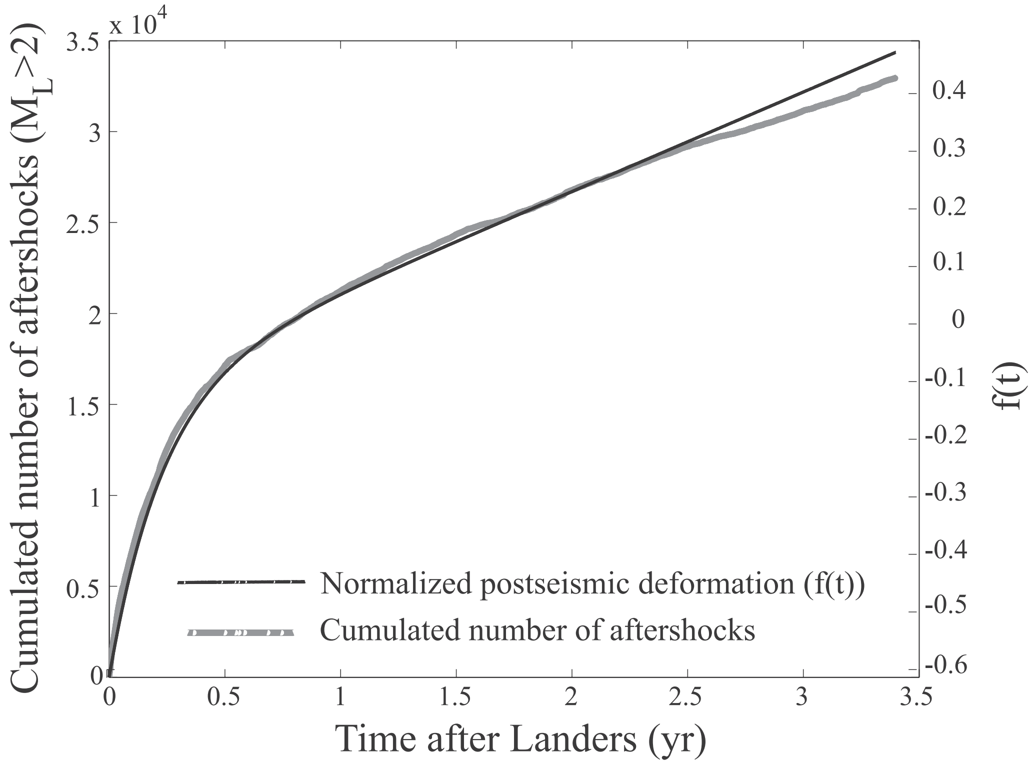
Afterslip Model of Landers



Perfettini and Avouac, 2007

- Afterslip is located below the seismogenic zone
- It is spreading with time but the spatial pattern remains the same

Seismicity Rate vs. Slip Rate

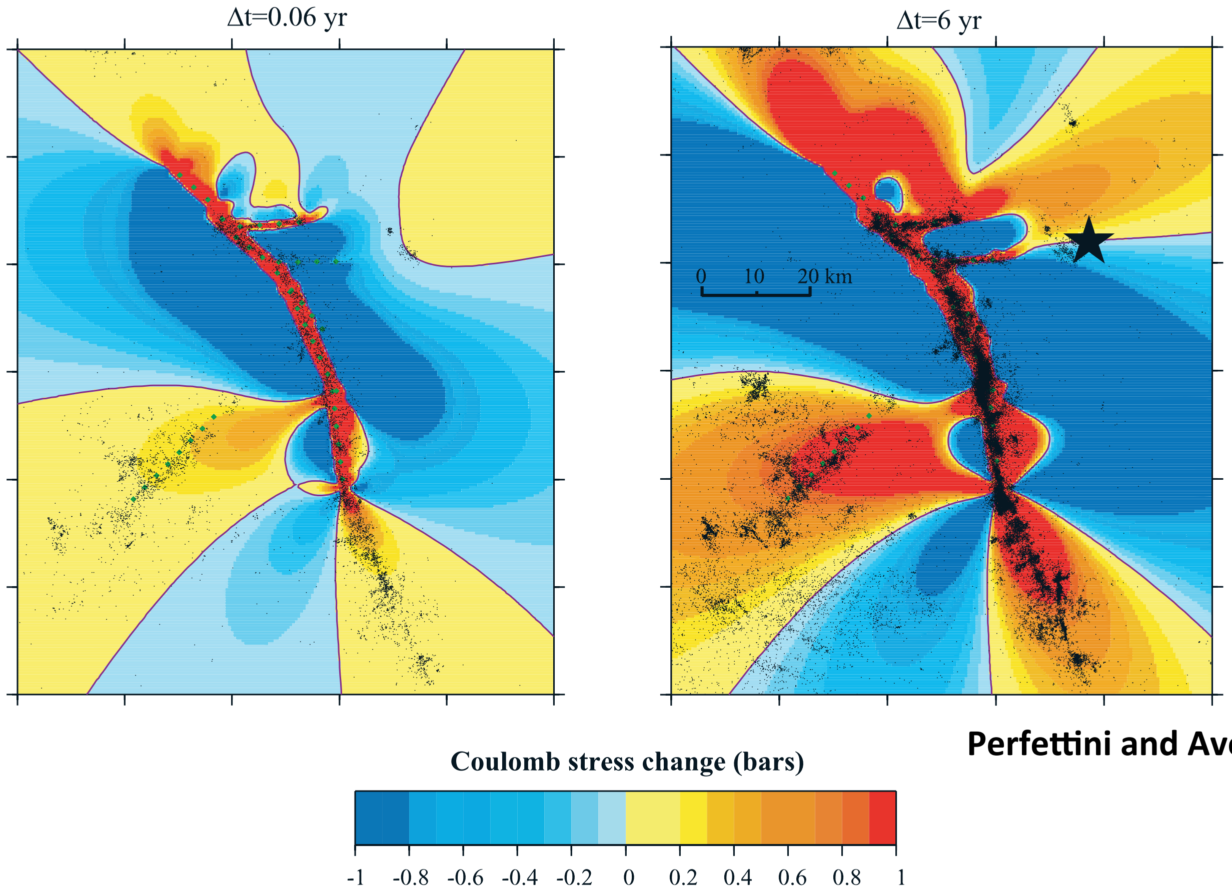


Perfettini and Avouac, 2007

In the case of the Landers earthquake, the cumulated number of aftershocks is proportional to the postseismic deformation inferred by GPS:

$$\mathbf{N_{cum}(t)=c\ U_{post}(t)}$$

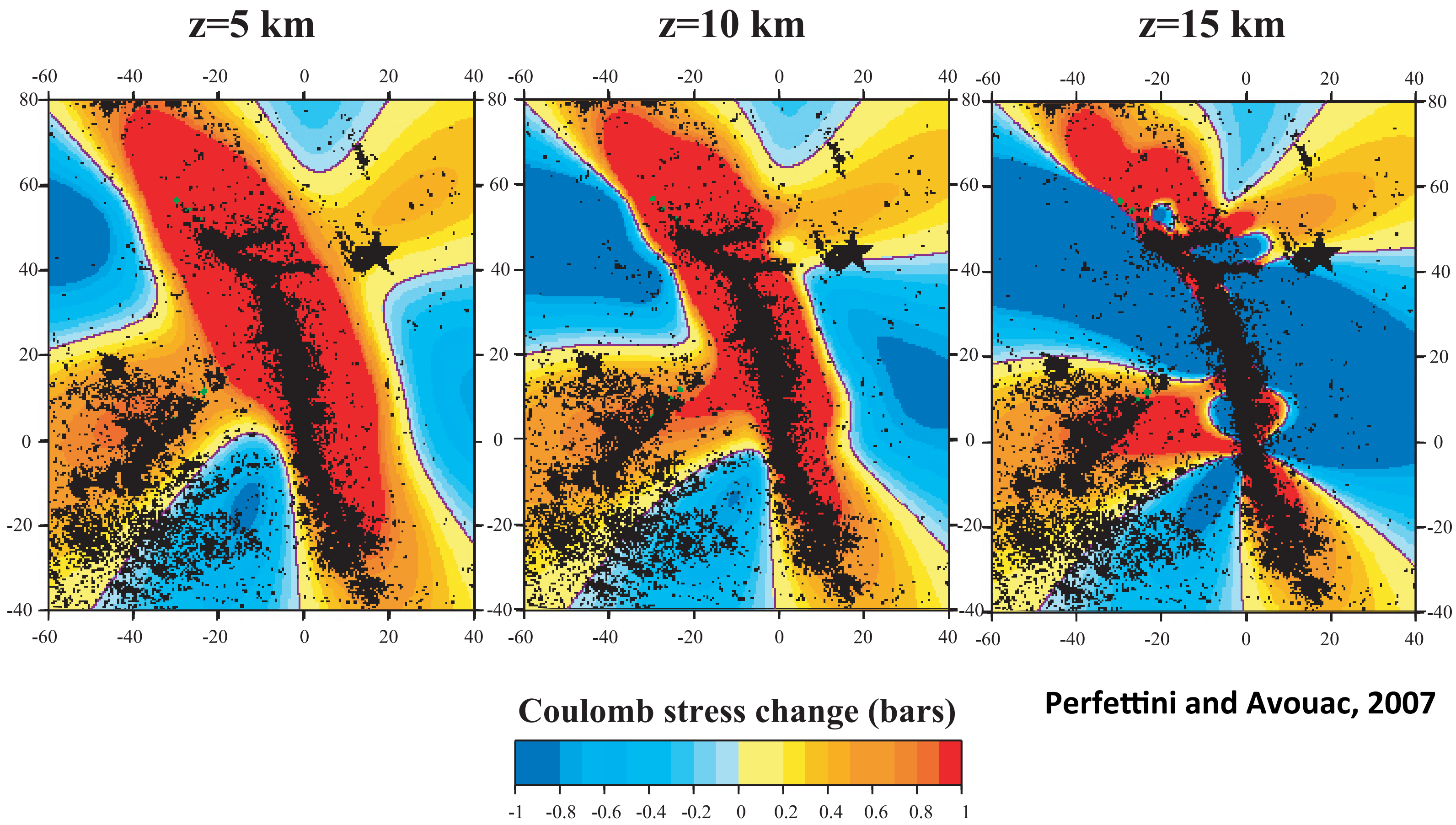
Postseismic Coulomb Stress at the base of the seismogenic zone



Perfettini and Avouac, 2007

- Postseismic Coulomb stress are always positive near the fault assuming receiver faults oriented as the regional tectonic trend
- Aftershocks are located in area of postseismic Coulomb stress increase

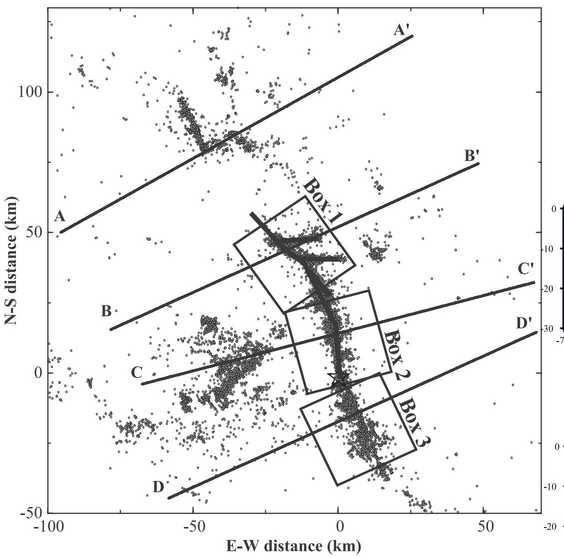
Postseismic Coulomb Stress



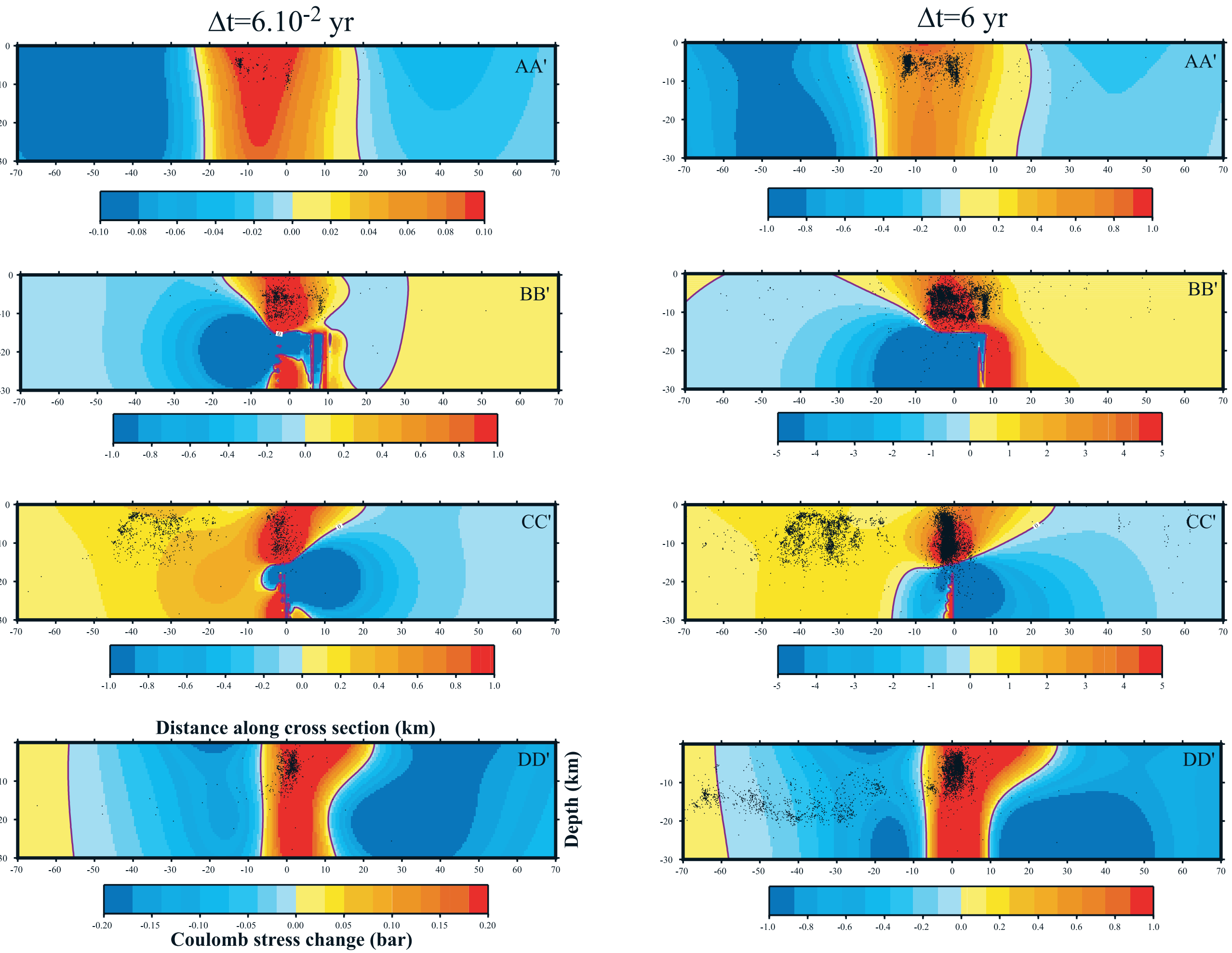
Perfettini and Avouac, 2007

Aftershocks are located in area of increased postseismic stress at all depths

Postseismic Coulomb Stress: Cross Sections

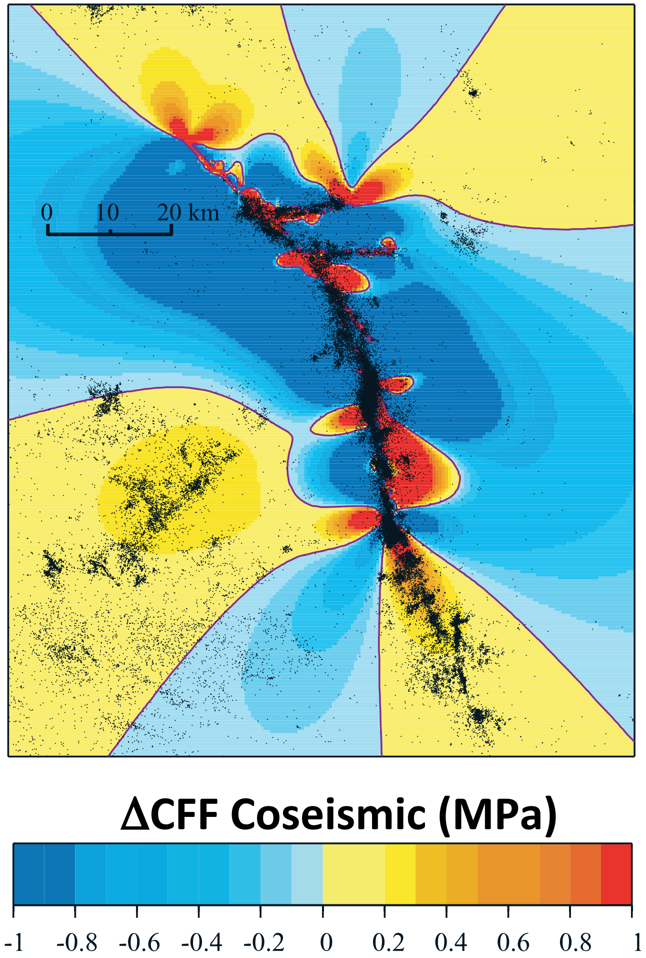


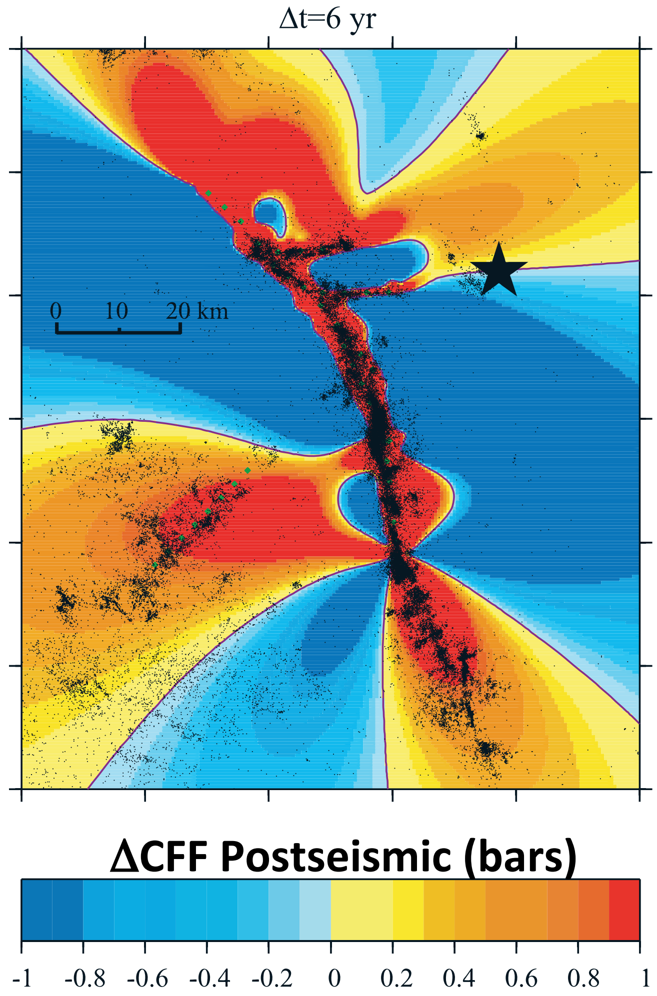
Perfettini and Avouac, 2007



The seismogenic fault zone is always loaded by postseismic stress

Coseismic vs. Postseismic Coulomb Stress

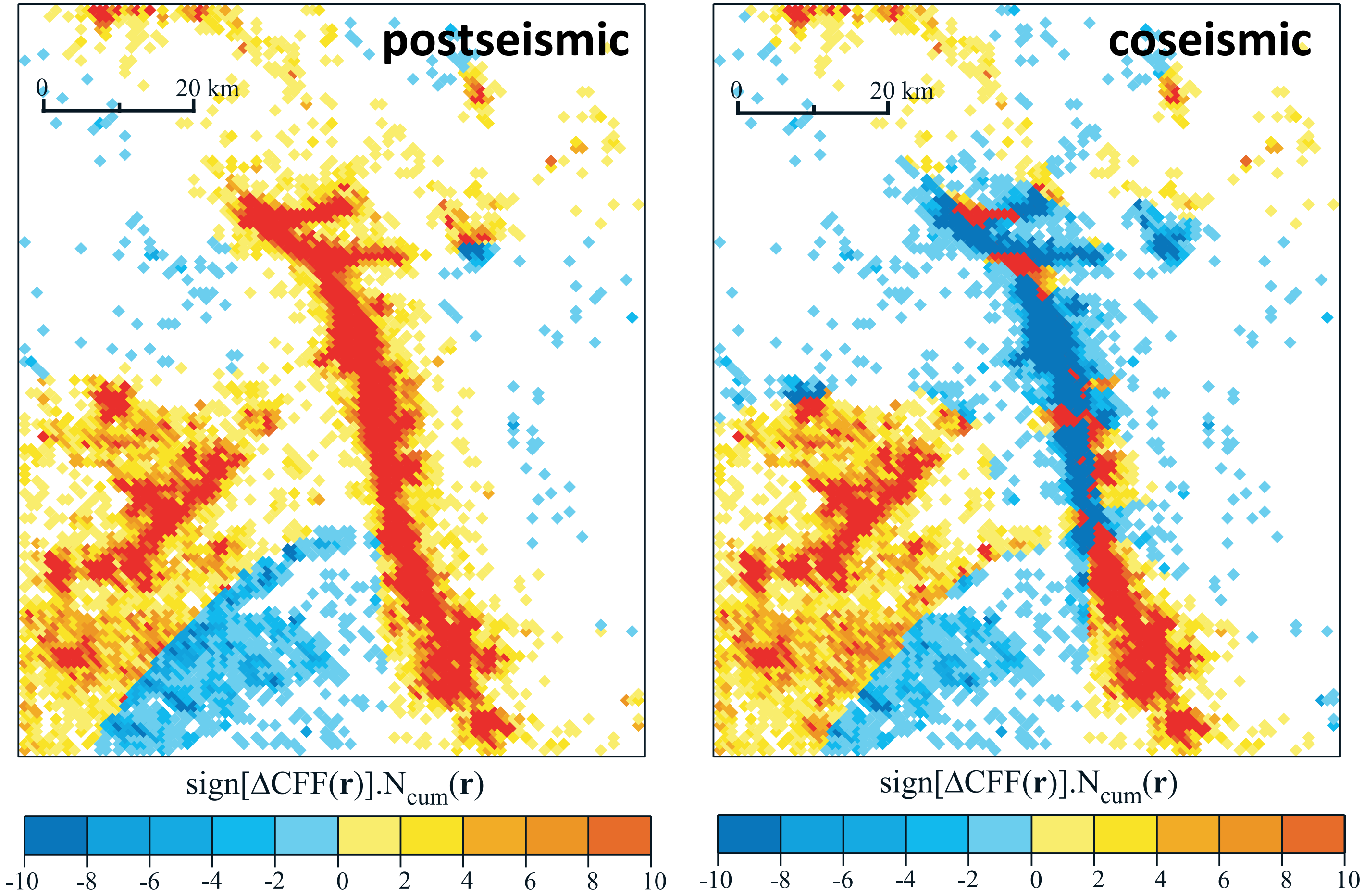




Perfettini and Avouac, 2007

- **Coseismic** Coulomb stress changes are mostly **negative** near the rupture plane
- **Postseismic** Coulomb stress changes are **positive** near the rupture plane

Coseismic vs. Postseismic Coulomb Stress

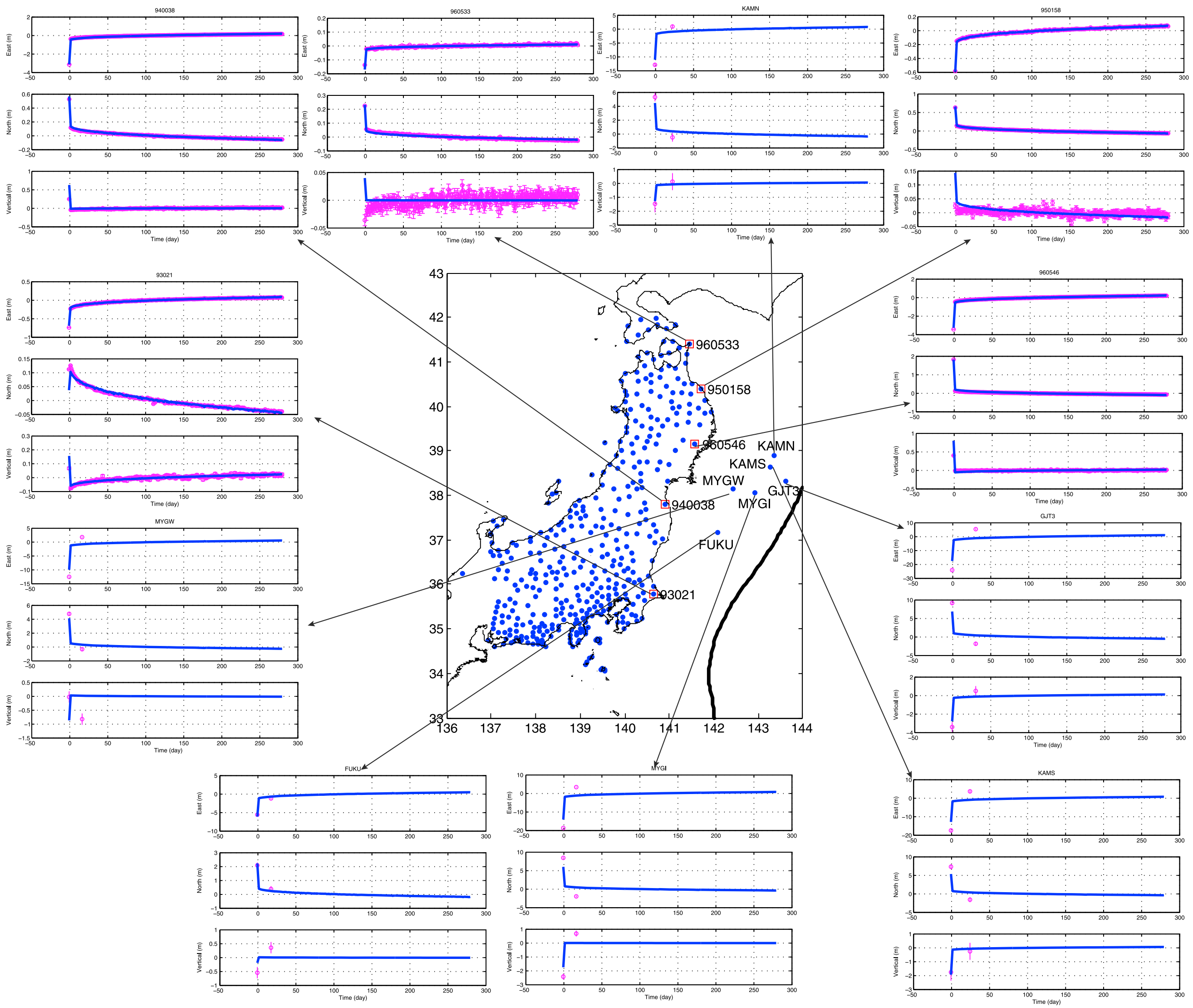


Perfettini and Avouac, 2007

- More than 95% of aftershocks correlated with areas of postseismic Coulomb stress increase
- This amount drops to about 50% when considering coseismic Coulomb stress

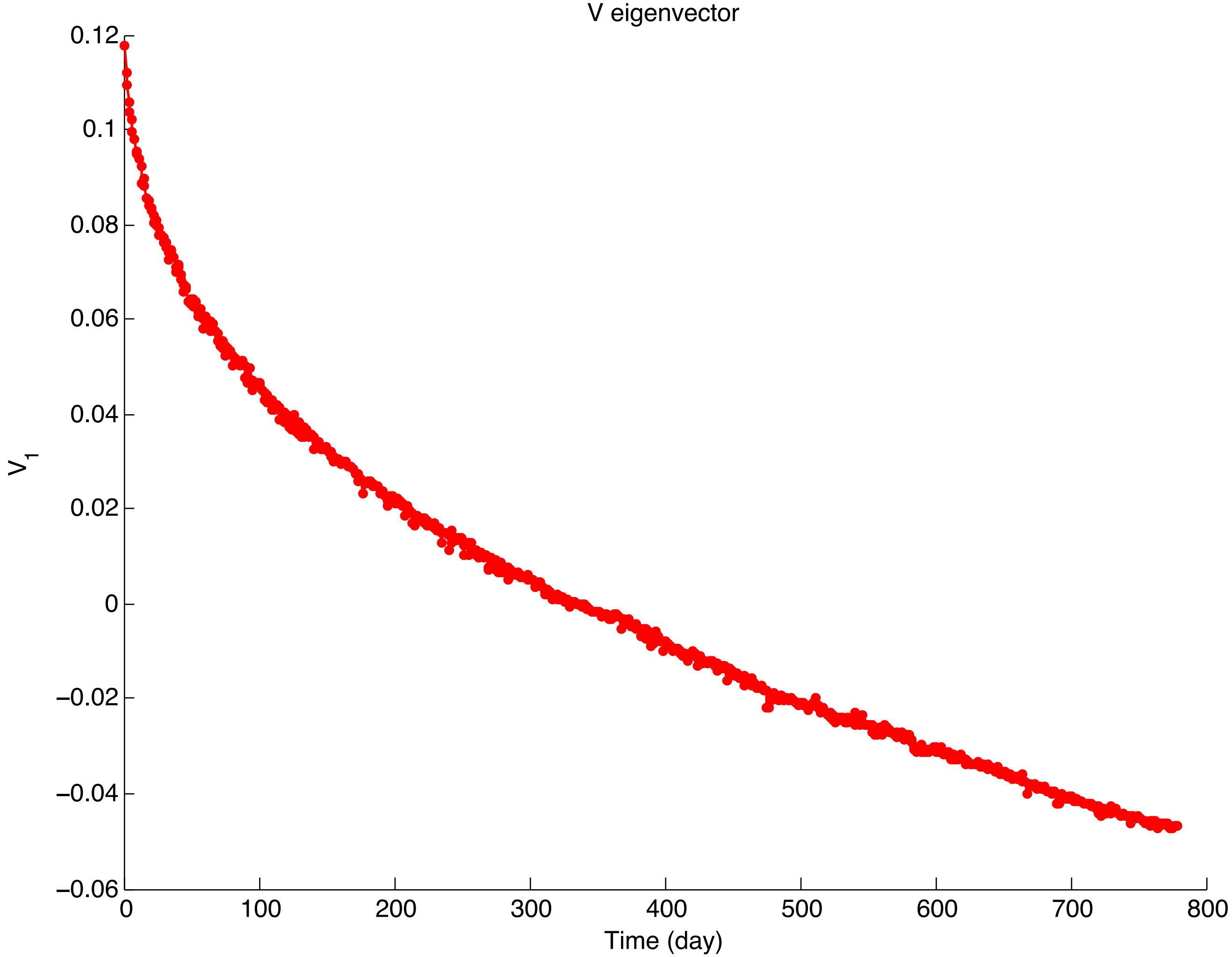
Case of the Tohoku-Oki Earthquake

Postseismic Deformation

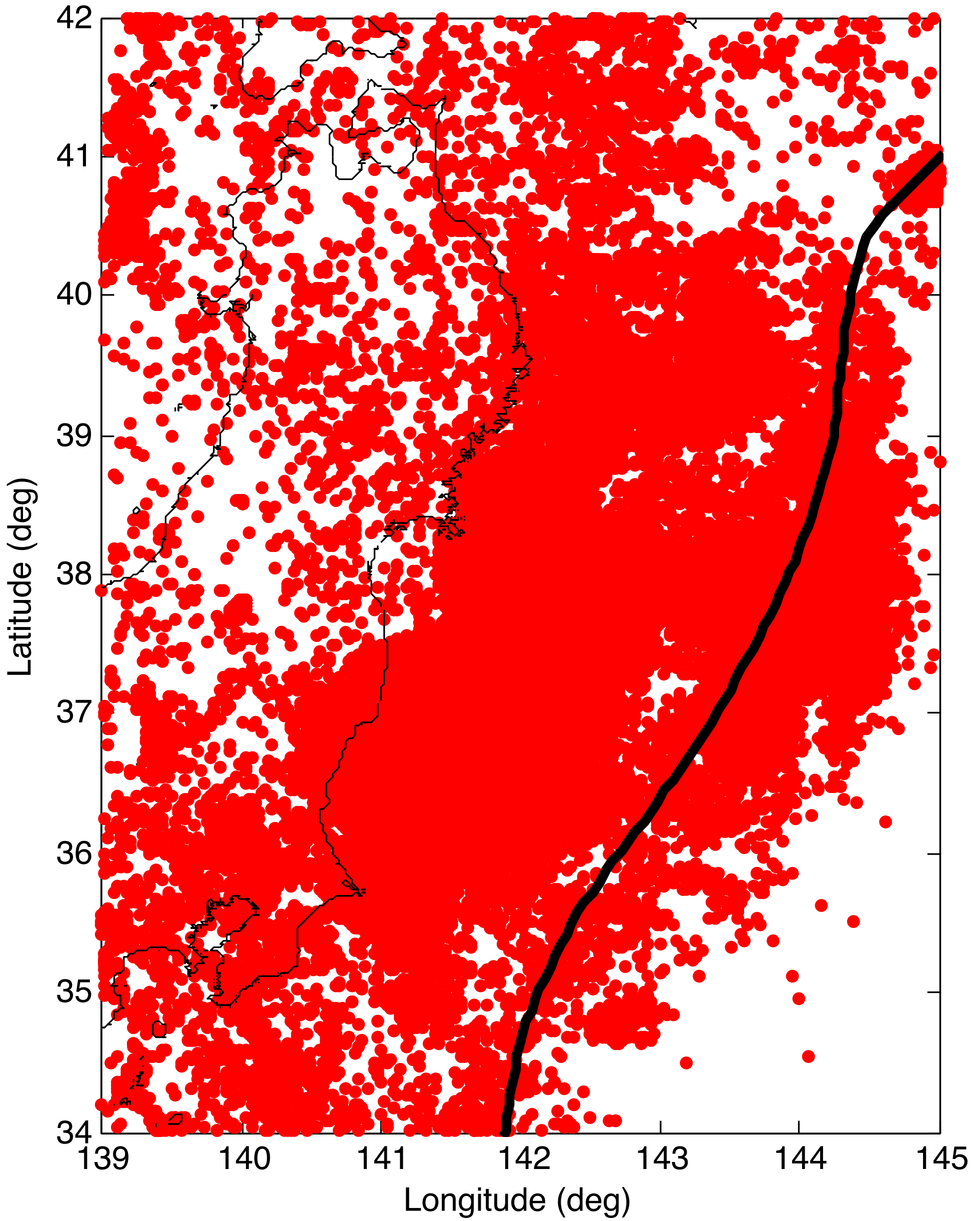


Exceptional set of 401 cGPS stations over 778 days

Postseismic Deformation: Temporal Evolution



- PCAIM decomposition: $\mathbf{X_{dat}=U_1\ S_1\ V_1}$
- One component alone explains 99.1% of the observations



Aftershocks

- JMA catalog with M_w>2
- About 126 000 aftershocks

Dieterich's Model with Postseismic Stress

$$\Delta N_{cum}(t)=R_L t_a \ln[1+(R^+/R_L)J(t)]$$

with

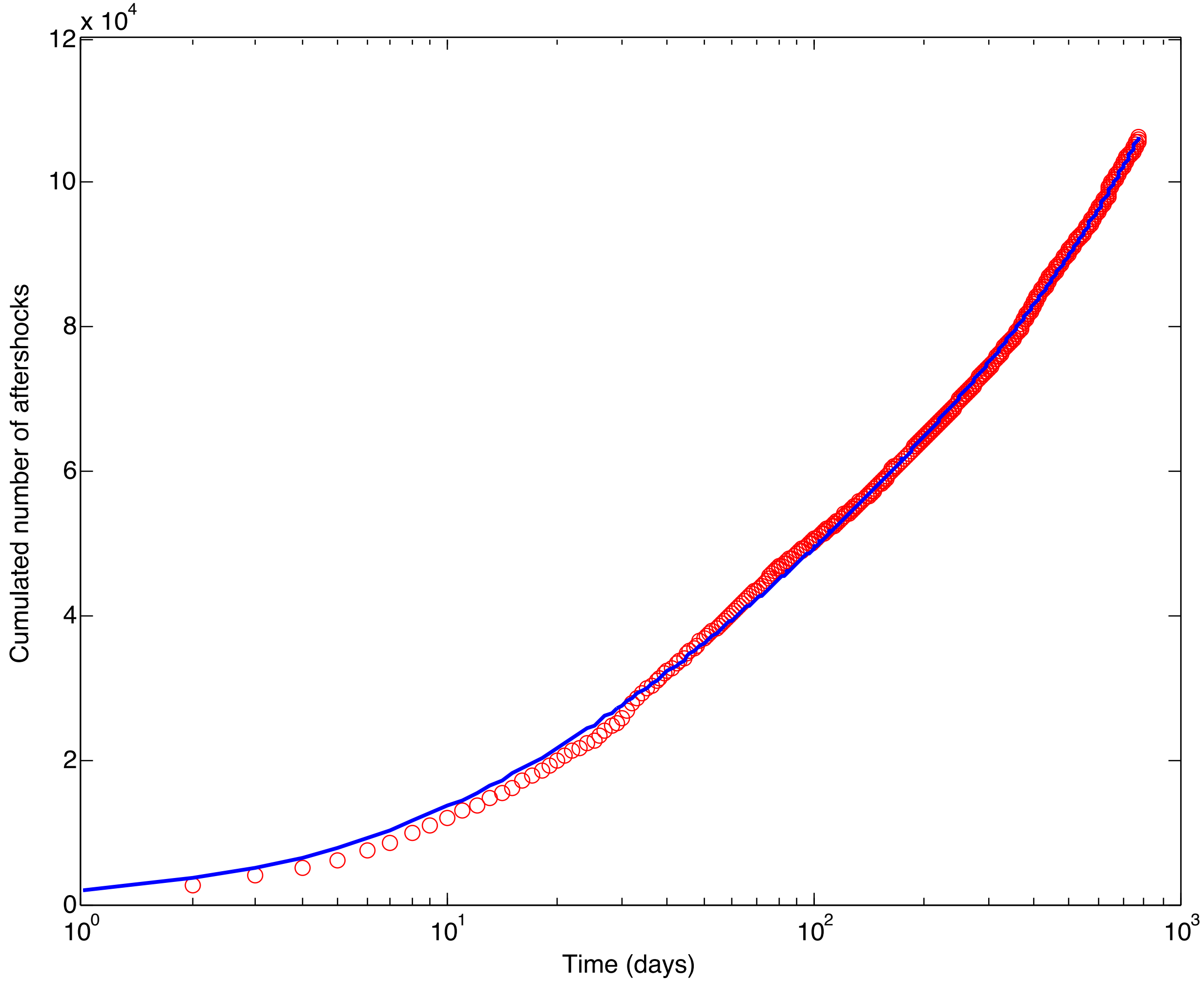
$$R^+=R(0)\exp(\Delta\tau_{cos}/A)$$

$$J(t)=(1/t_a)\,dt'\int_0^t \exp(t'/t_a)\,\exp[\Delta\tau_{post}(t')/A]$$

$$\Delta\tau_{post}(t)=cAV_1(t)$$

R_L, t_a, R^+ and **c** are **4 constants** to be adjusted

Dieterich's Model with Postseismic Stress



Very good fit to the data for:

- R_L=44.46 evts/day, R^+=1906 evts/day, t_a=451.5 days, c=3.586 10^{-10}
- The term involving postseismic stress is not required by the model (c≈0)

Afterslip Model

$$\Delta N_{cum}(t) = R_L t_r \ln[1 + (R^+/R_L) J(t)]$$

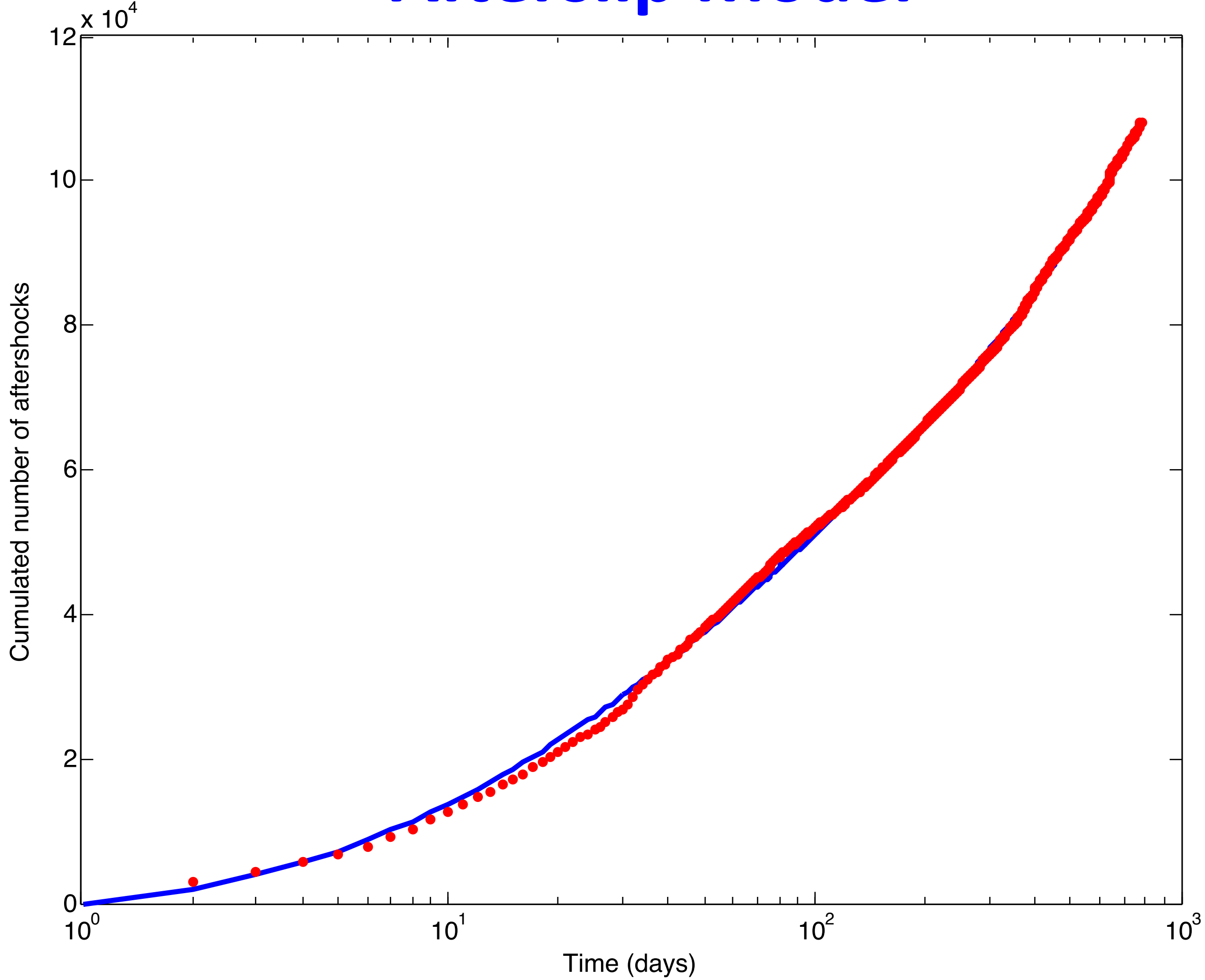
with

$$R^+ = R(0) \exp(\Delta\tau_{cos}/A)$$

$$J(t) = (1/t_a)\int_0^t dt' \exp(t'/t_a)$$

R_L, t_a, and R^+ are 3 constants to be adjusted

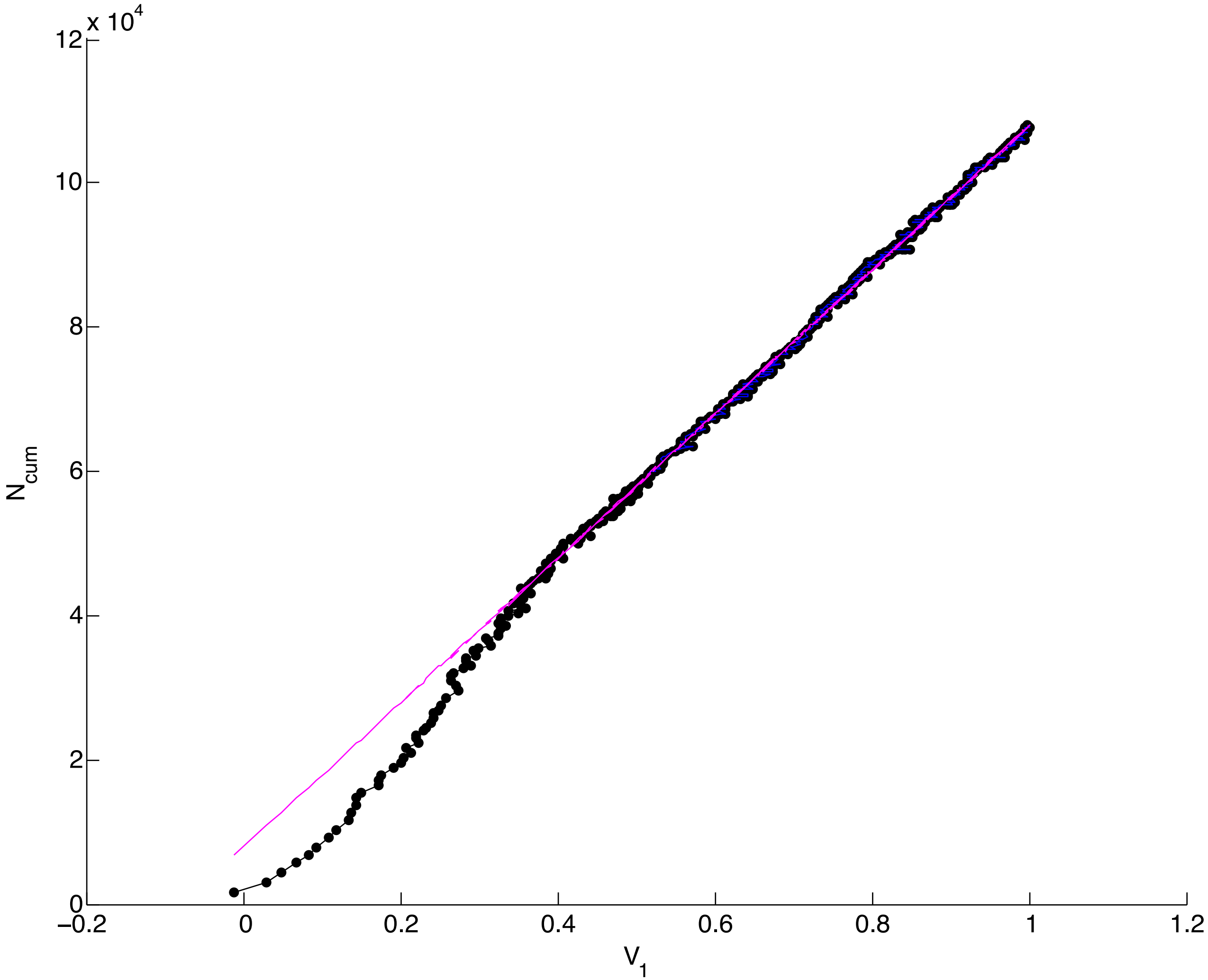
Afterslip Model



Very good fit to the data for:

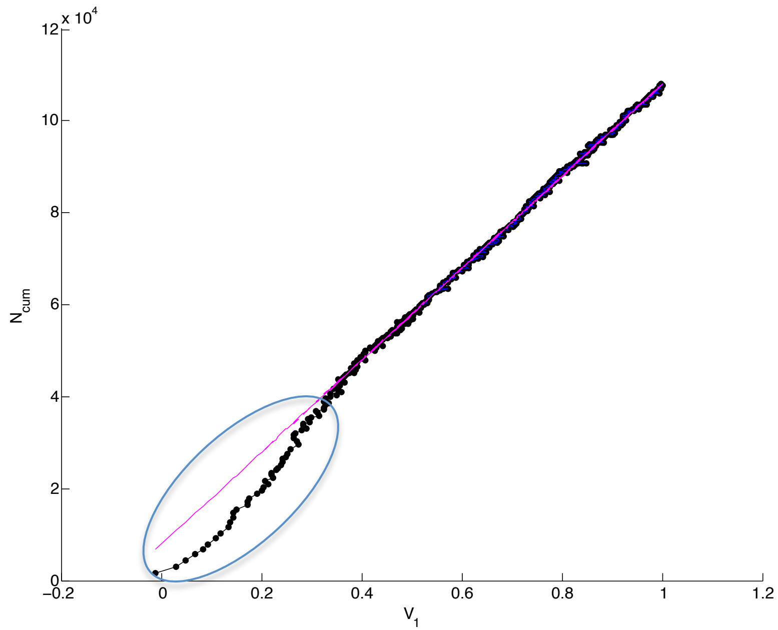
R_L=45.71 evts/day, R^+=2160 evts/day and t_a=432.4 days

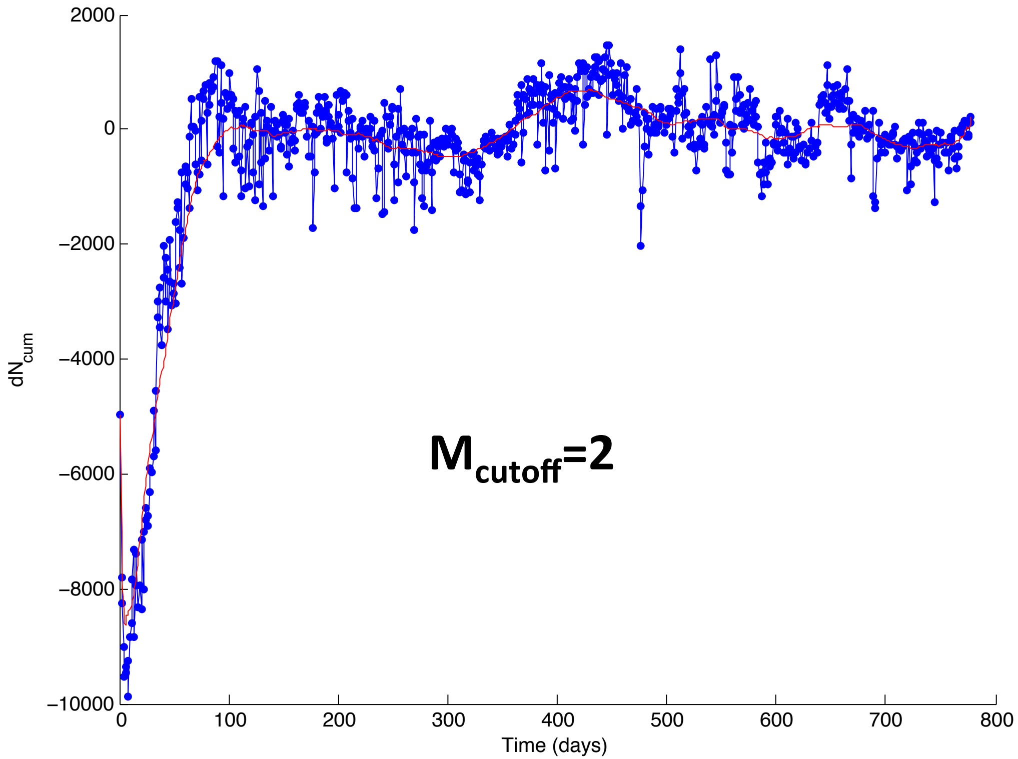
Postseismic Deformation vs. Aftershocks



- $N_{cum} \sim c\ V_1$
- Deviation at short times that decreases with time

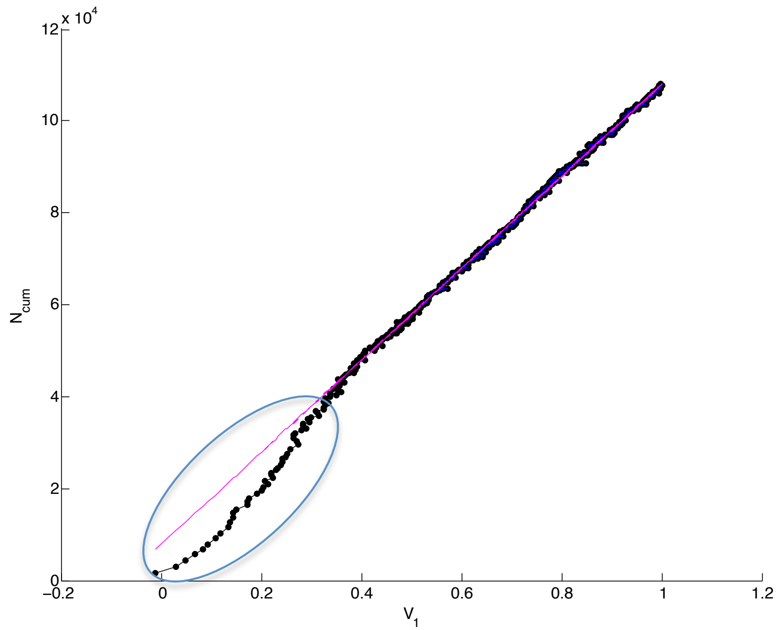
Postseismic Deformation vs. Aftershocks

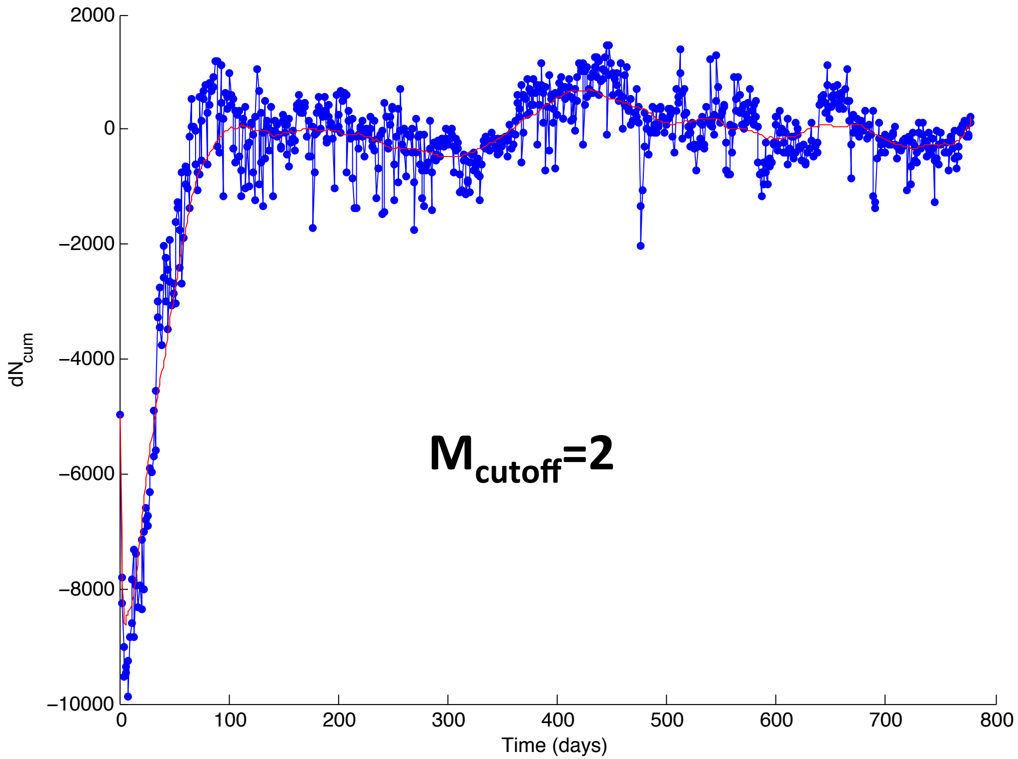




Deviation $\mathbf{dN_{cum}(t)=N_{cum}(t)\text{-}cV_1(t)}$ from linearity due to???

Postseismic Deformation vs. Aftershocks

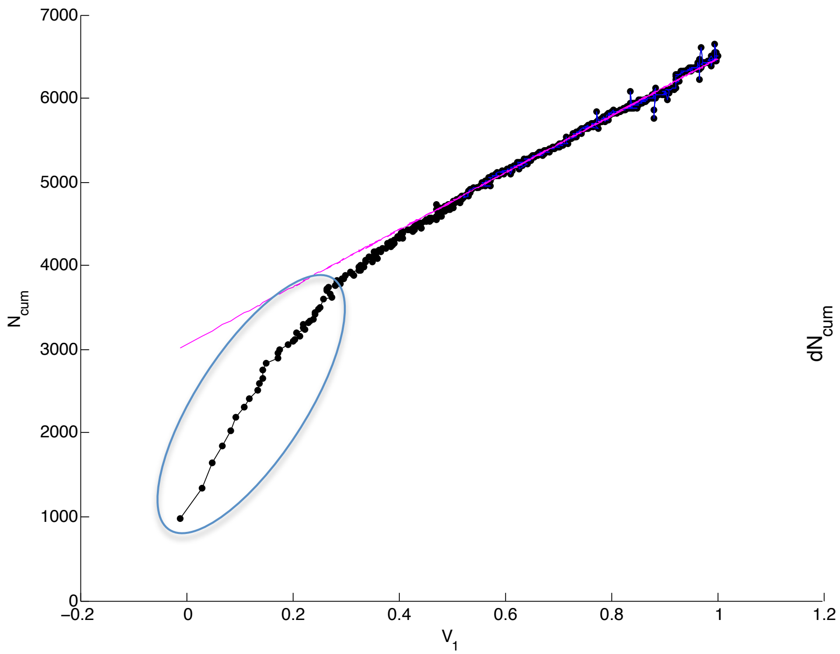


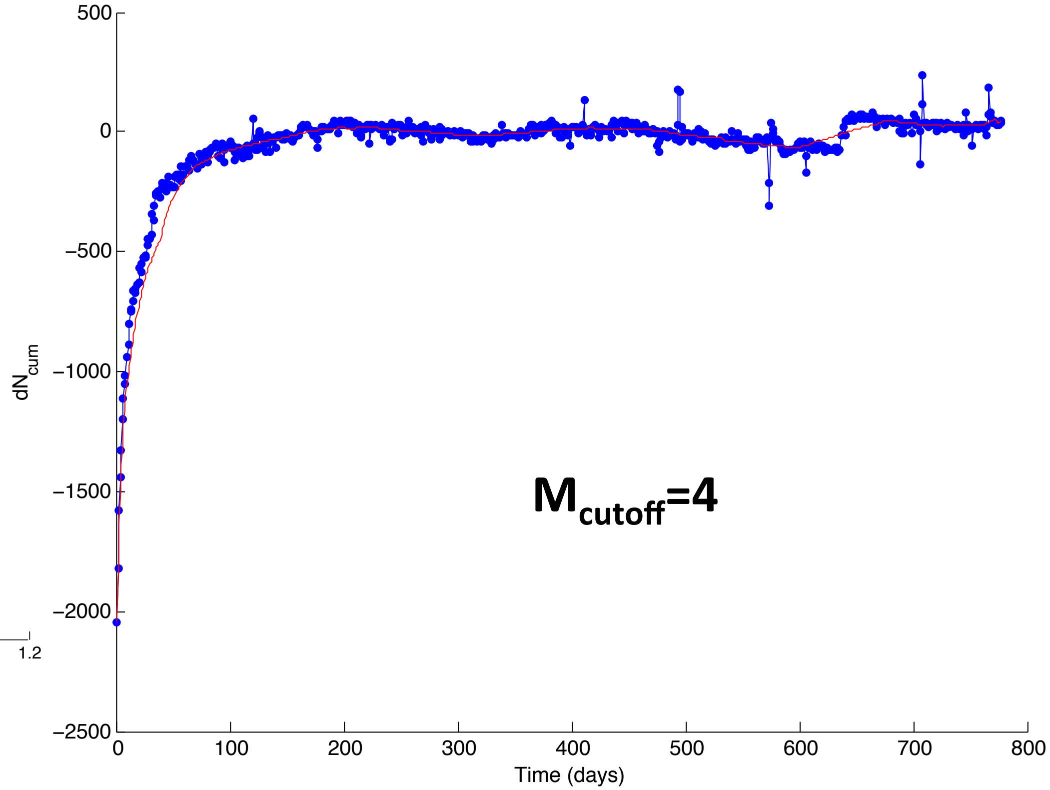


Deviation $\mathbf{dN_{cum}(t)=N_{cum}(t)-cV_1(t)}$ from linearity due to:

- Early missing aftershocks?
- The constant **c** relating $\mathbf{N_{cum}}$ and $\mathbf{V_1}$ is a function of time?
- Another mechanism controls early aftershocks?

Postseismic Deformation vs. Aftershocks





Deviation $\mathbf{dN_{cum}(t)=N_{cum}(t)\text{-}cV_1(t)}$ from linearity due to:

- 2000 events missing with M_w>4 implies that 2 events of M_w>7 must be missing ➔ The hypothesis of missing aftershocks looks reasonable (e.g., Kiser and Ishii, 2013)

Conclusions (I)

- In the case of the **Landers** earthquake, the distribution of aftershocks is **consistent** with **postseismic Coulomb stress changes**, assuming that aftershocks occur on faults oriented as the main fault

- In the case of the Landers earthquake, the distribution of aftershocks is **not consistent** with **coseismic** Coulomb stress changes, unless the concept of optimally oriented planes is used

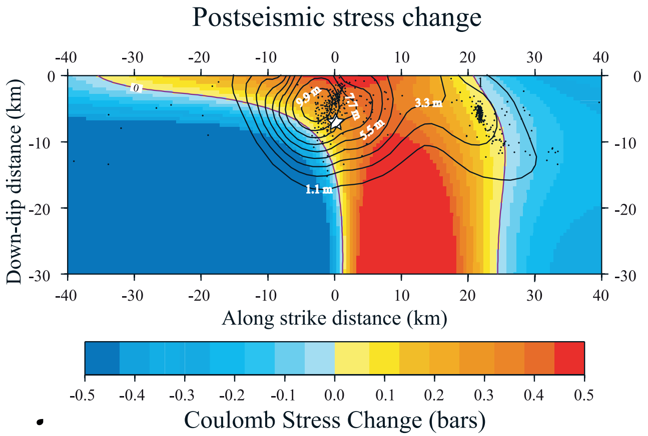
Conclusions (II)

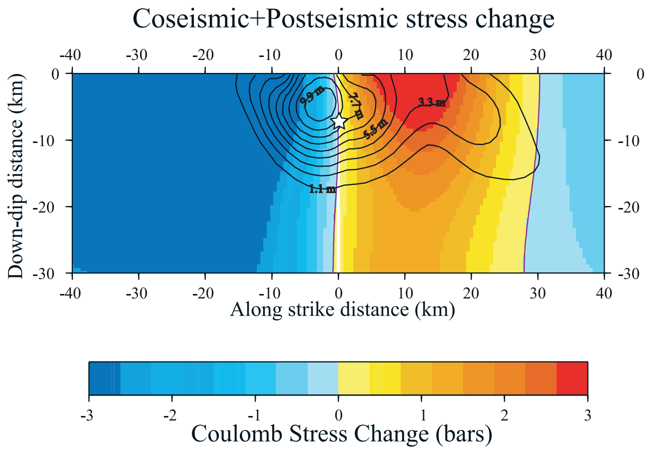
- Dieterich's model is **equivalent mathematically** to the afterslip seismicity model of *Perfettini and Avouac,* 2004

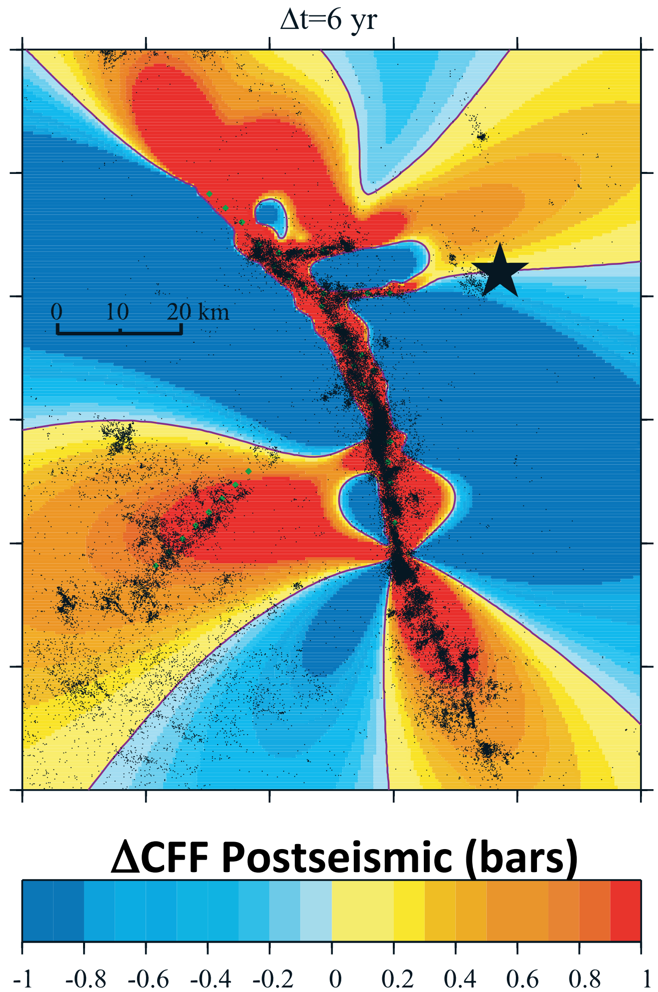
- The **afterslip model** has the **additional constrain** that **deformation** and **aftershocks** should be **linearly related**, with the idea that afterslip drives aftershocks

- **Seismicity** and **Deformation** seems to follow the **same temporal evolution** in the postseismic phase, in agreement with the hypothesis of the afterslip seismicity model

Triggering of the Hector Mine Earthquake







The location of the Hector Mine hypocenter has been increased by the postseismic Coulomb stress