Coulomb stress change and its correlation with aftershocks

Static versus dynamic Coulomb stresses

Ramifications: will a big quake trigger other big quakes? Will the Japan quake increase the chance of a Cascadia M 9 or other large quake in BC?

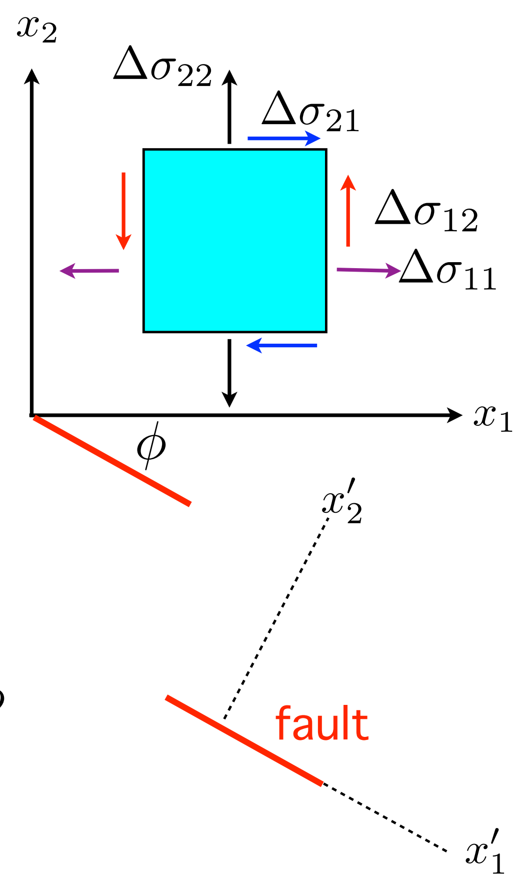
$$\begin{bmatrix} \Delta\sigma_{11} & \Delta\sigma_{12} \\ \Delta\sigma_{21} & \Delta\sigma_{22} \end{bmatrix}$$

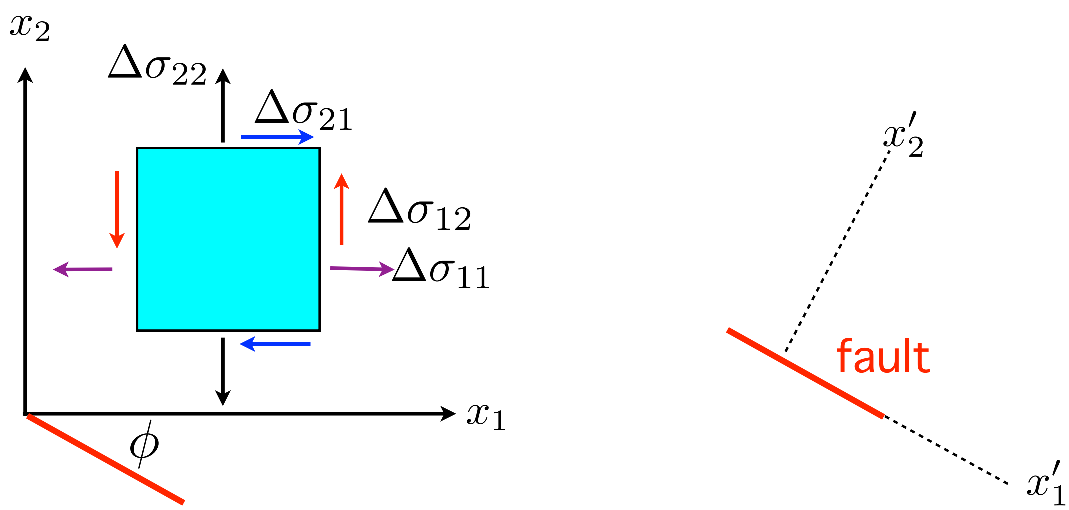
What are

$\Delta\tau$ and $\Delta\sigma_e$

on a fault of arbitrary orientation?

Say it's on a plane rotated ϕ from the x_2 -normal plane

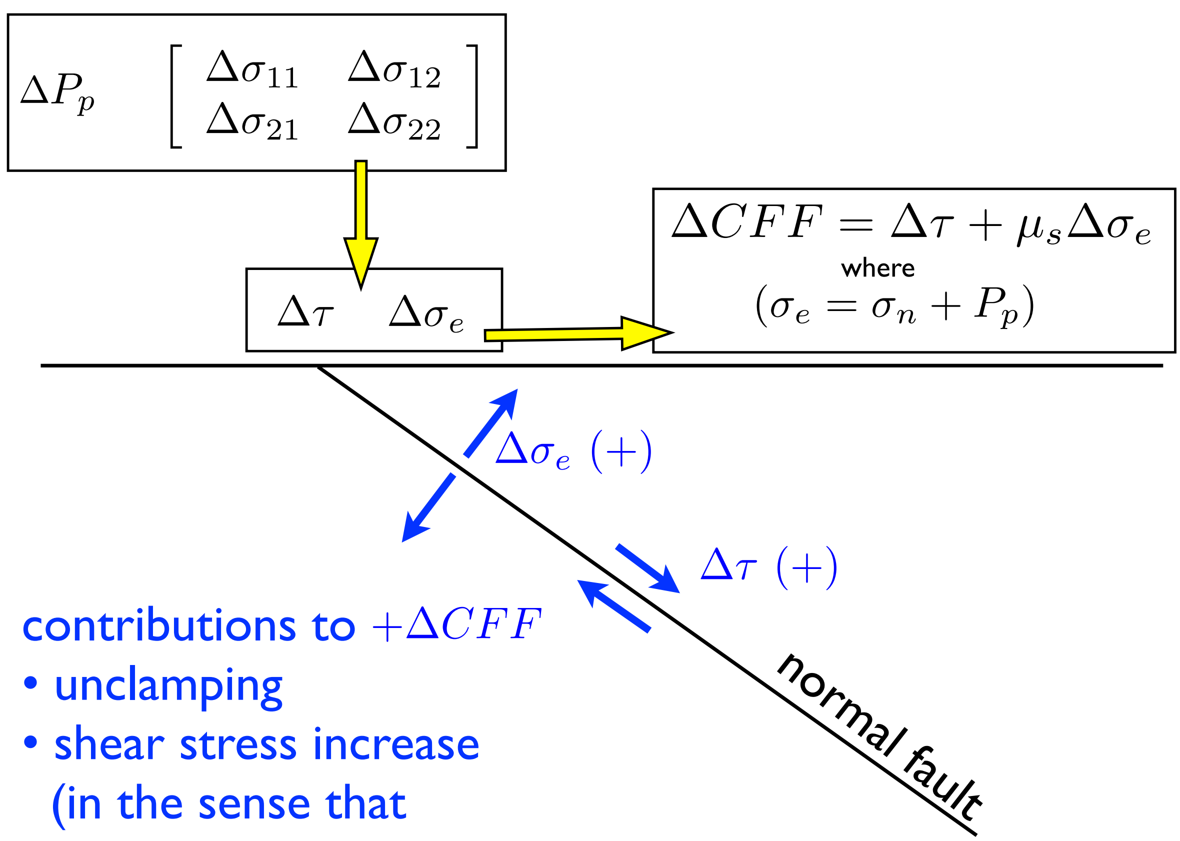




$$\Delta\tau = -(\frac{\Delta\sigma_{11} - \Delta\sigma_{22}}{2})sin2\phi \ + \Delta\sigma_{12}cos(2\phi)$$

$$\Delta\sigma_n = (\frac{\Delta\sigma_{11} + \Delta\sigma_{22}}{2}) - (\frac{\Delta\sigma_{11} - \Delta\sigma_{22}}{2})cos2\phi \ - \Delta\sigma_{12}cos(2\phi)$$

If pore fluid is present then induced pore pressure change is the pressure change times the Skempton's coefficient B (usually between 0 and 1).
To get $\Delta\sigma_e$ we must add ΔP_p to $\Delta\sigma_n$.
Remember the sign difference. If P_p increases then this should act to reduce the magnitude of the effective normal stress.



contributions to $+\Delta CFF$

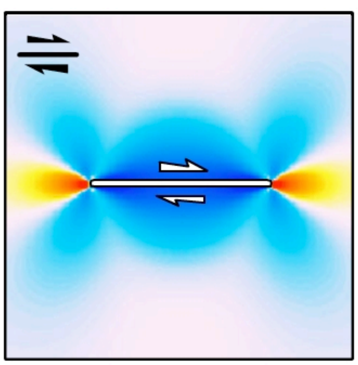
- unclamping
- shear stress increase (in the sense that drives the fault slip)

Coulomb stress changes from large earthquakes can be sufficient to trigger other earthquakes

This is the main reason for aftershocks

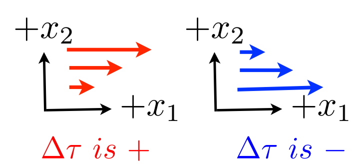
How the Coulomb Stress Change is Calculated

Stress Rise Drop



Shear stress change

$\Delta\tau_s$

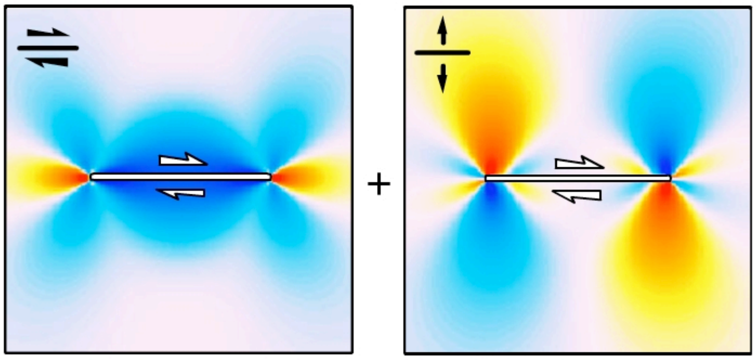


- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

How the Coulomb Stress Change is Calculated

Stress Rise Drop



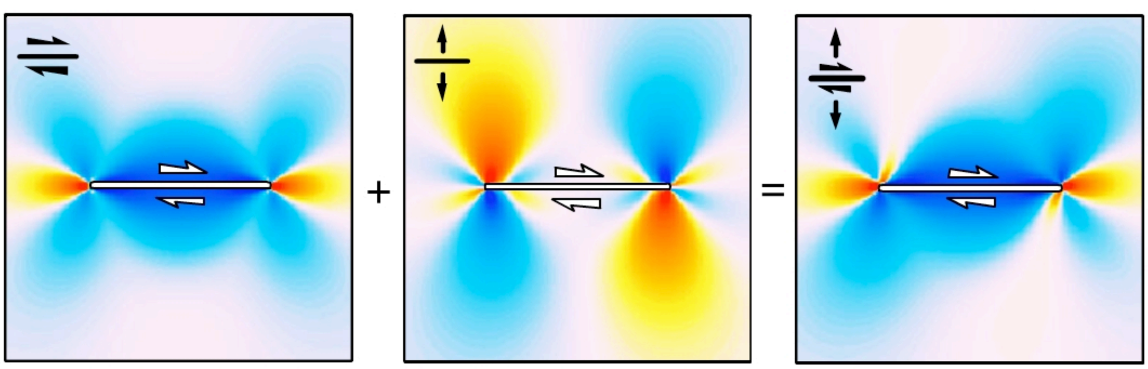
Shear stress change	+	Friction coefficient **x** normal stress change
$\Delta\tau_s$	+	$\mu' (\Delta\sigma_n)$

• Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

How the Coulomb Stress Change is Calculated

Stress Rise Drop

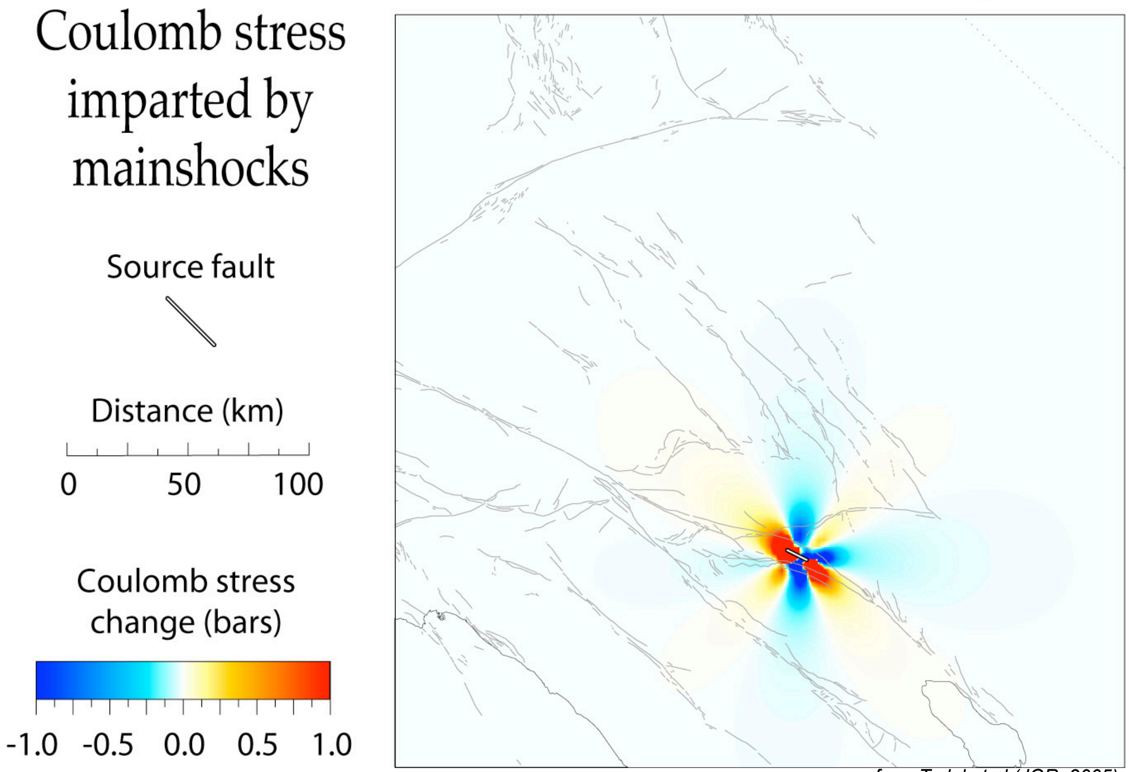


Shear stress change	+	Friction coefficient **x** normal stress change	=	Coulomb failure stress change
$\Delta\tau_s$	+	$\mu' (\Delta\sigma_n)$	=	$\Delta\sigma_f$

• Example calculation for faults parallel to master fault

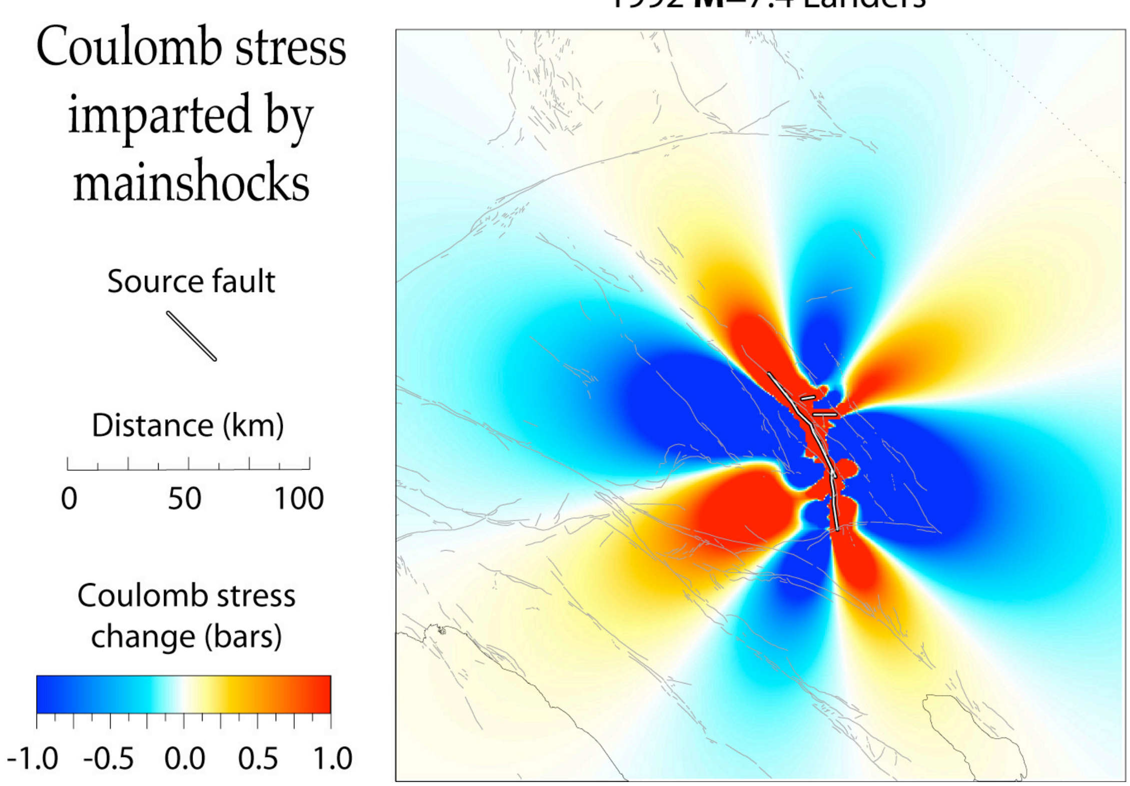
From King et al (BSSA, 1994)

1986 **M**=6.0 North Palm Springs

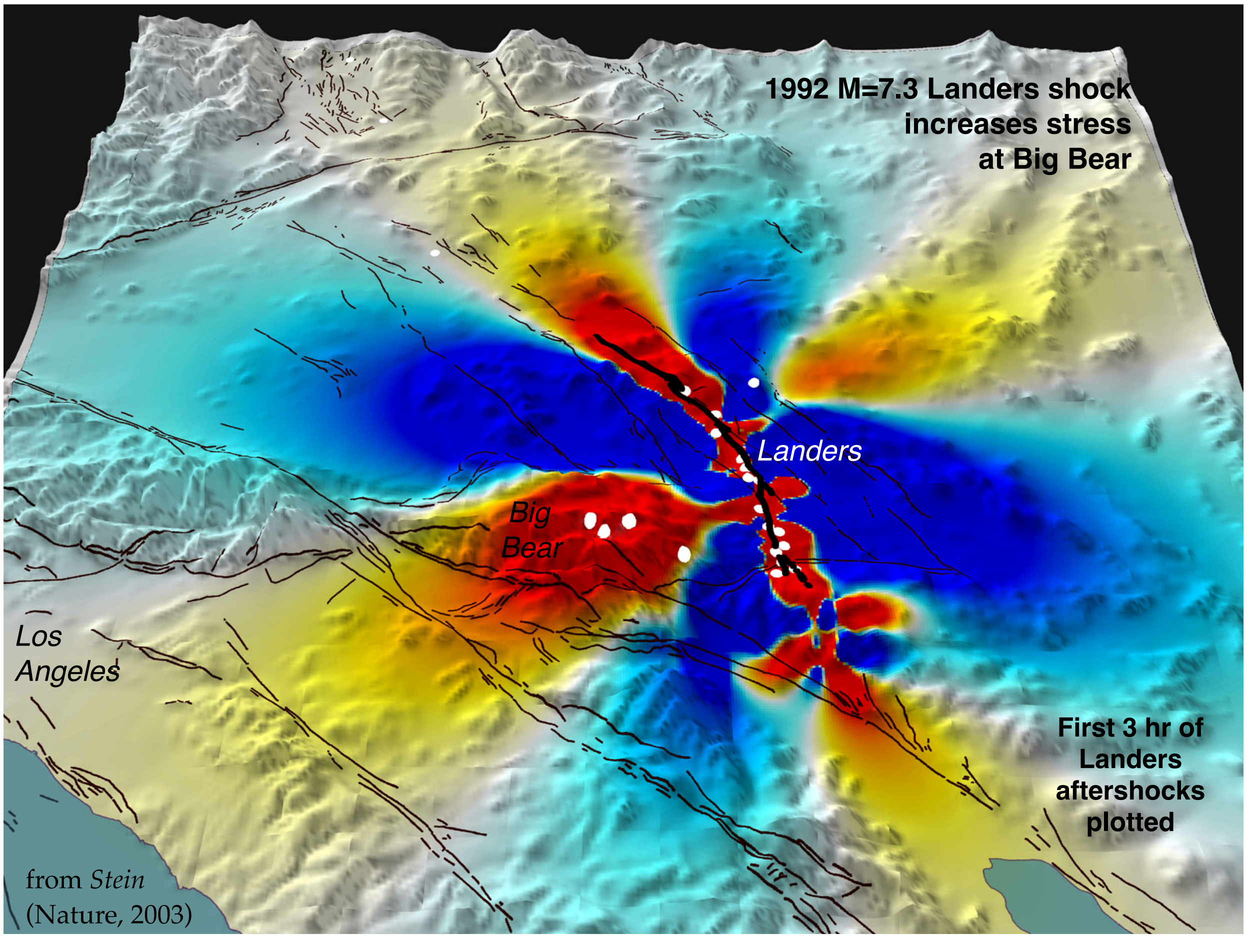


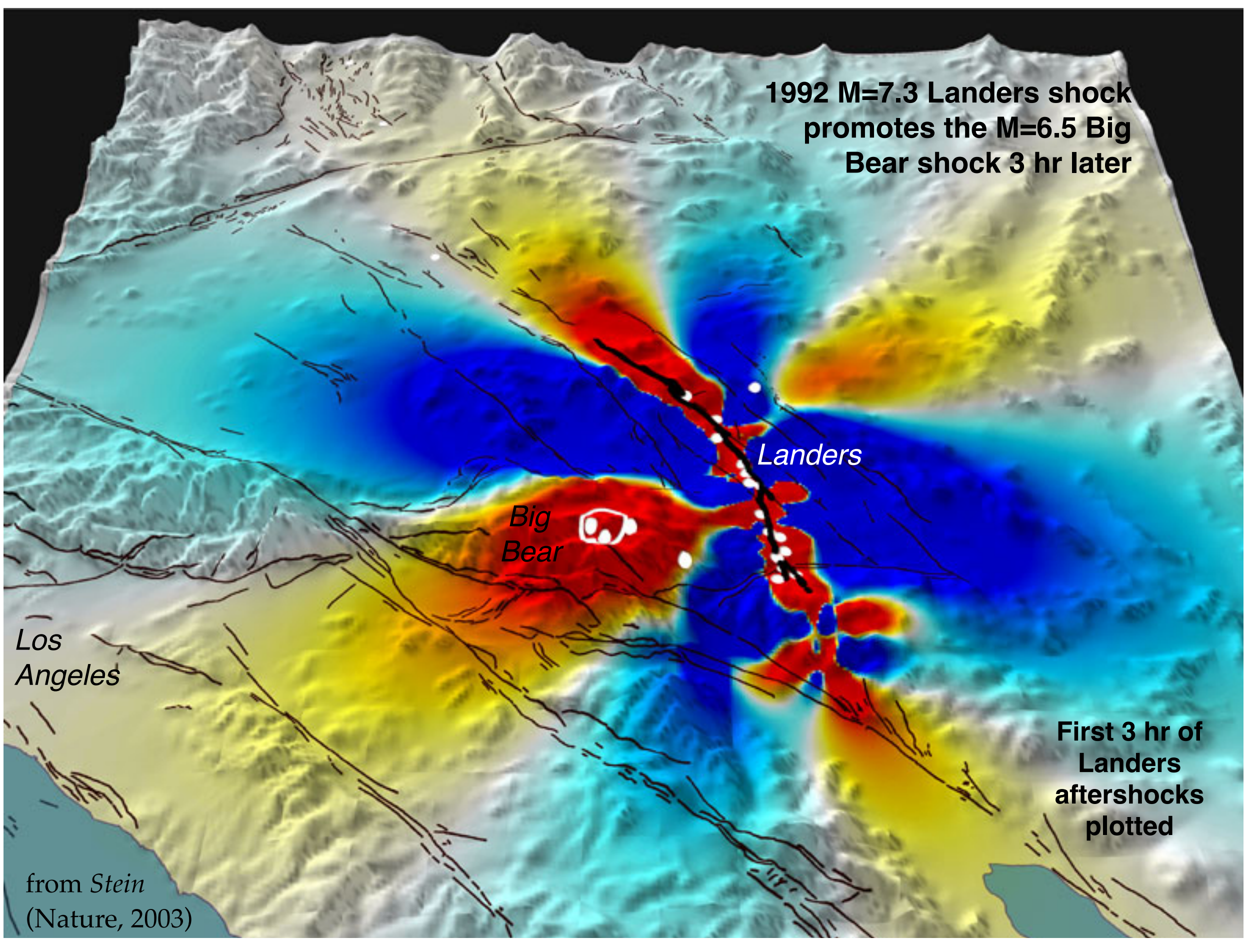
from Todal et al (JGR, 2005)

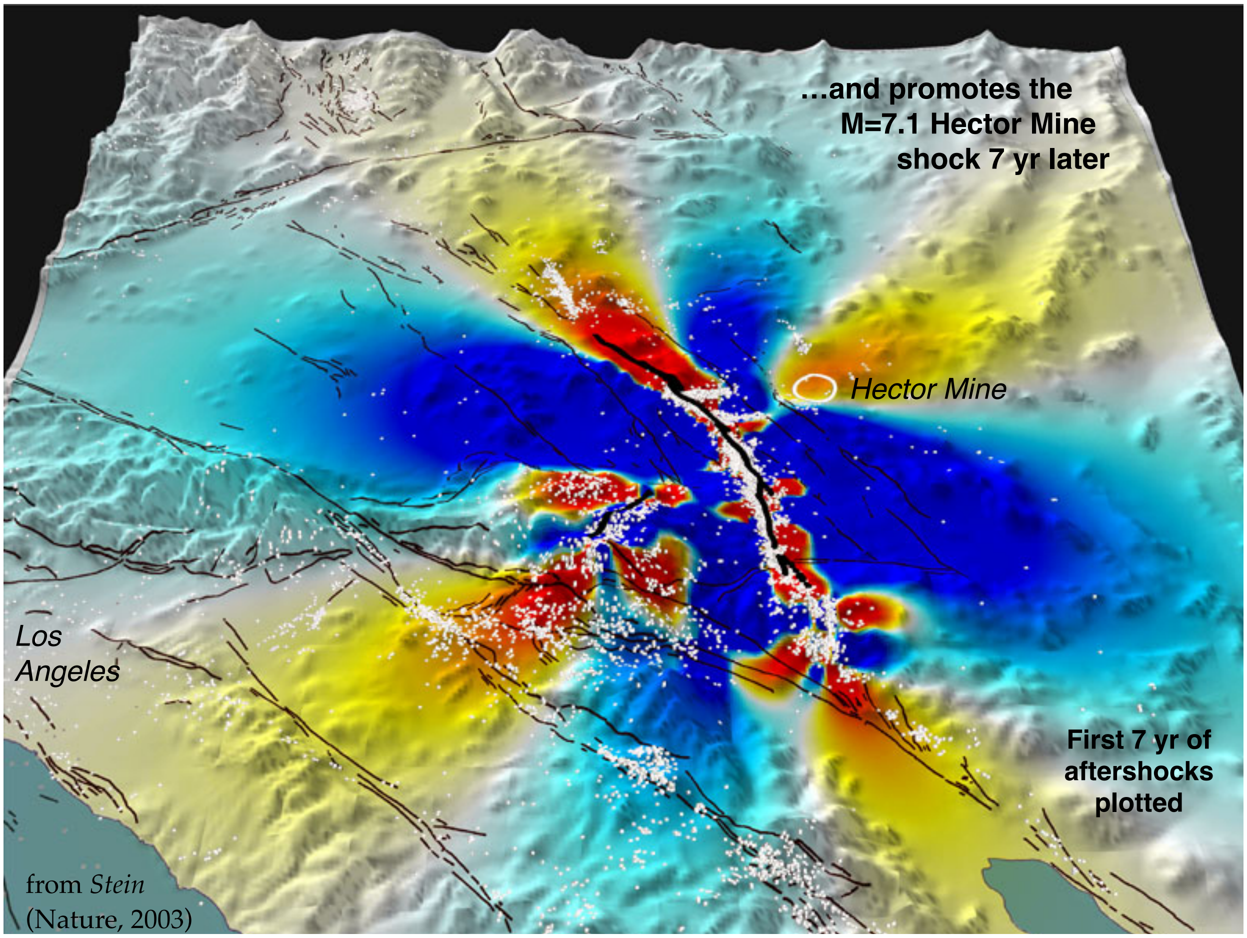
1992 **M**=7.4 Landers

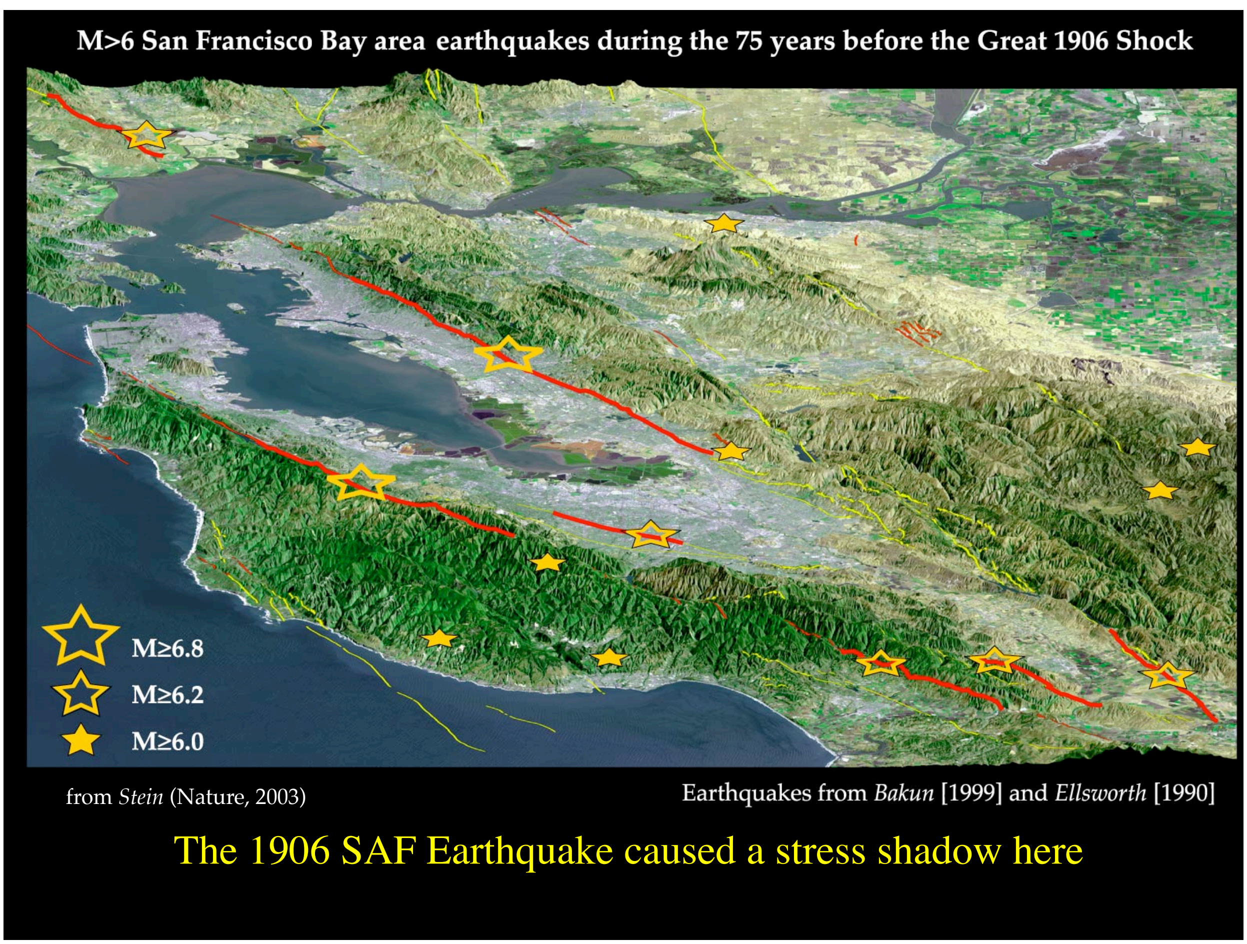


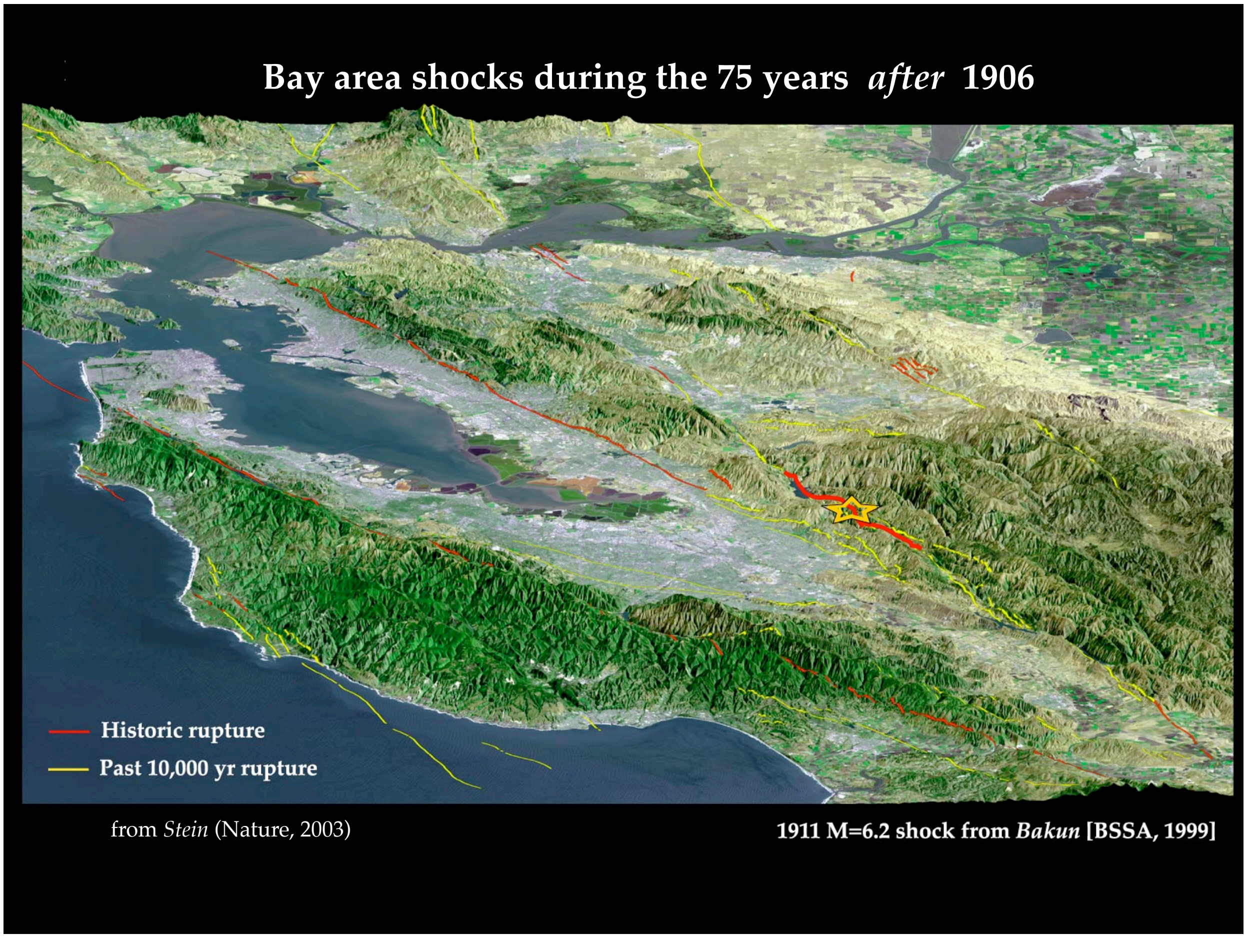
from Todal et al (JGR, 2005)


1992 M=7.3 Landers shock
increases stress
at Big Bear
Landers
Big
Bear
Los
Angeles
First 3 hr of
Landers
aftershocks
plotted
from Stein
(Nature, 2003)

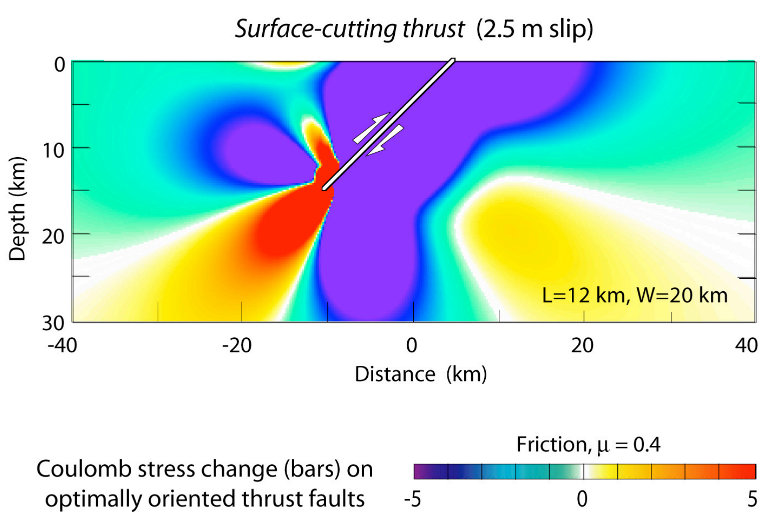

1992 M=7.3 Landers shock
promotes the M=6.5 Big
Bear shock 3 hr later
Landers
Big
Bear
Los
Angeles
First 3 hr of
Landers
aftershocks
plotted
from Stein
(Nature, 2003)


...and promotes the
M=7.1 Hector Mine
shock 7 yr later
Hector Mine
Los
Angeles
First 7 yr of
aftershocks
plotted
from *Stein*
(Nature, 2003)

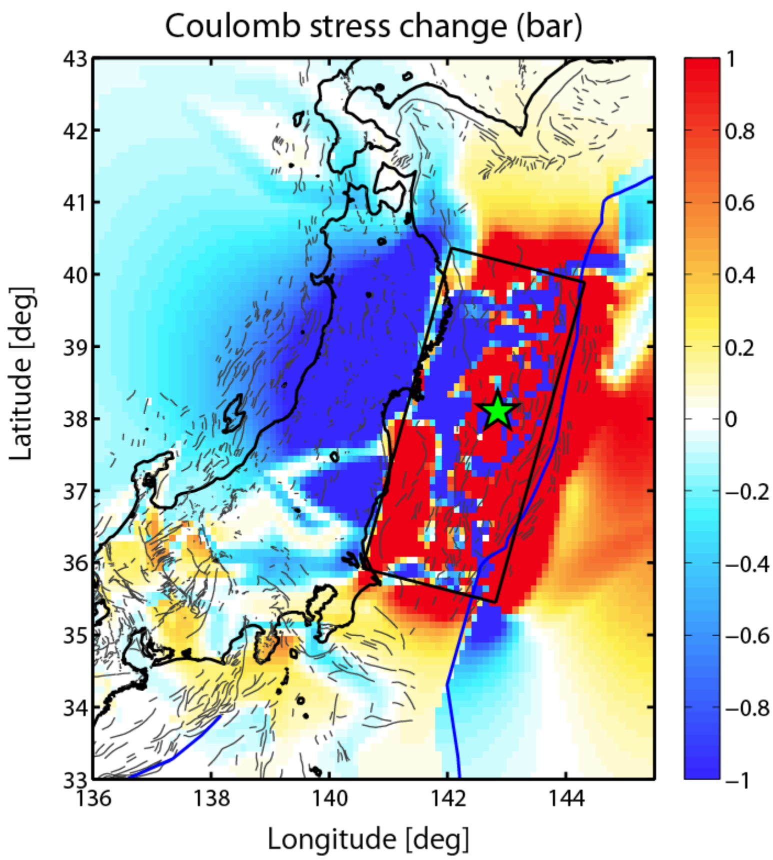

M>6 San Francisco Bay area earthquakes during the 75 years before the Great 1906 Shock
M≥6.8
M≥6.2
M≥6.0
from *Stein* (Nature, 2003)
Earthquakes from *Bakun* [1999] and *Ellsworth* [1990]
The 1906 SAF Earthquake caused a stress shadow here



Surface-cutting thrusts drop the stress in the upper crust



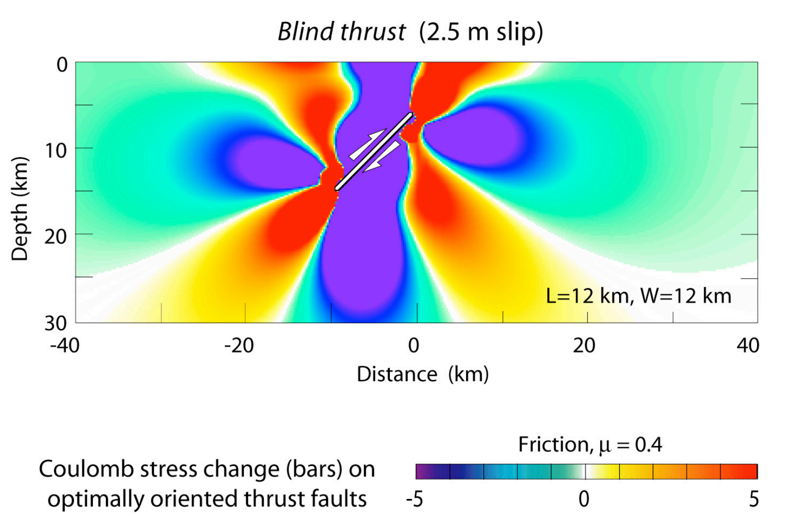
from *Lin & Stein* (JGR, 2004)



Coulomb stress change, assuming spatially variable fault planes and sense of slip based on geology.

Most of the reverse faults in the Tohoku region show a stress shadow (blue). Relatively large positive stress changes can be seen at the north and south extremities of the mainshock fault, as well as in the outer rise characterized by normal faulting. Some regions in southwest Japan have been also brought closer to failure (positive stress changes of up to about 0.6 Bar).

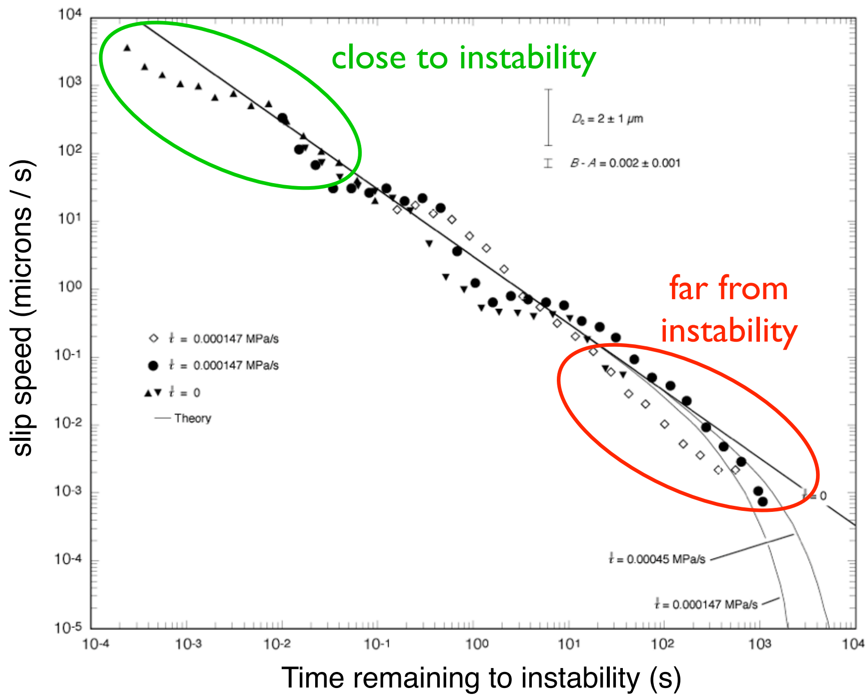
Blind thrusts raise the stress in parts of the upper crust



from *Lin & Stein* (JGR, 2004)

Random population of creeping but not YET unstable fault patches (all have shear stress = friction coeff. times effective normal stress, but have not reached their critical size)

Colloquium Paper: Dieterich and Kilgore Proc. Natl. Acad. Sci. USA 93 (1996) 3791



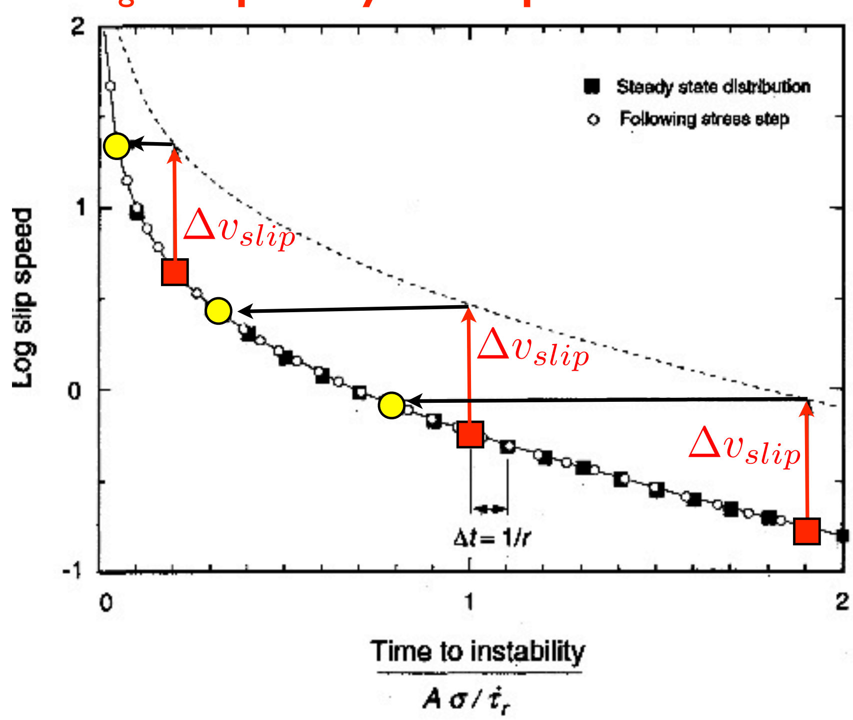
the tiny patches slip very slowly

slip speed increases as the slipping patches grow

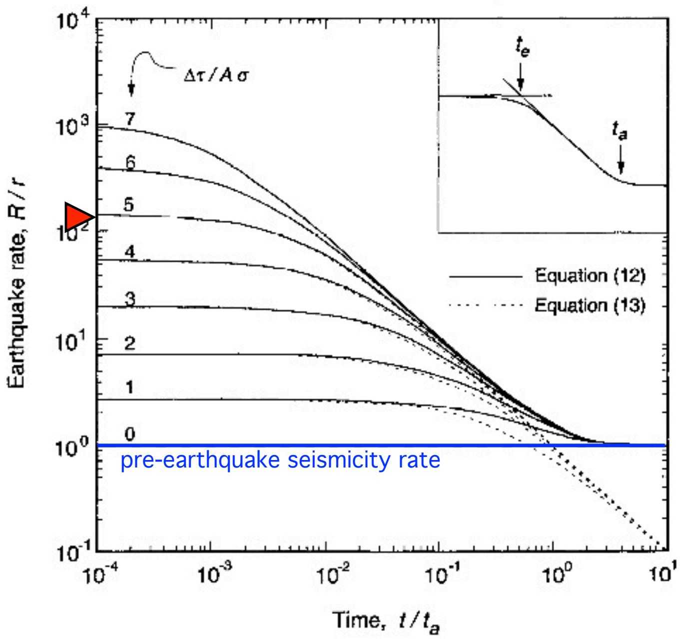
as they slip faster the patches grow even larger, and the time to instability becomes short...

Suppose a Coulomb stress change happens to all of these patches.
This boosts slip speed of all them by Δv_{slip}

Because faster slipping patches are so much closer to failure, small stress change **temporarily** causes a **profound** increase in seismicity



Note: we did not go into how to compute Δv_{slip} . You are not responsible for knowing this.



0.01? 10 MPa?

typical $a\sigma_e$:
1 bar?

$\Delta\tau = 5\ bar$

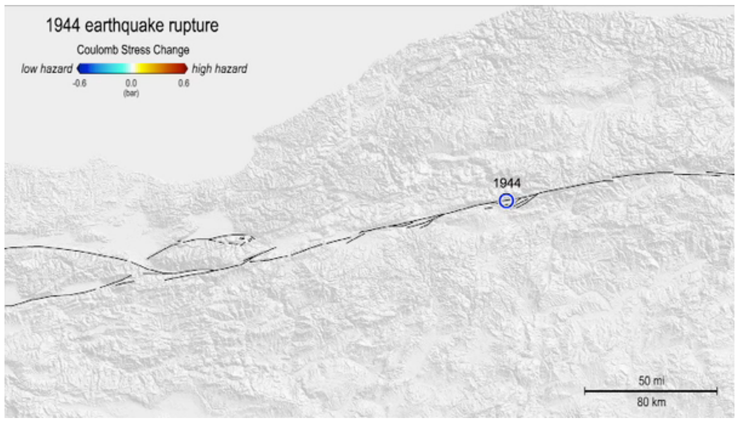
150 times as many earthquakes as before: aftershocks

earthquake rate decreases as 1/t

Static triggering

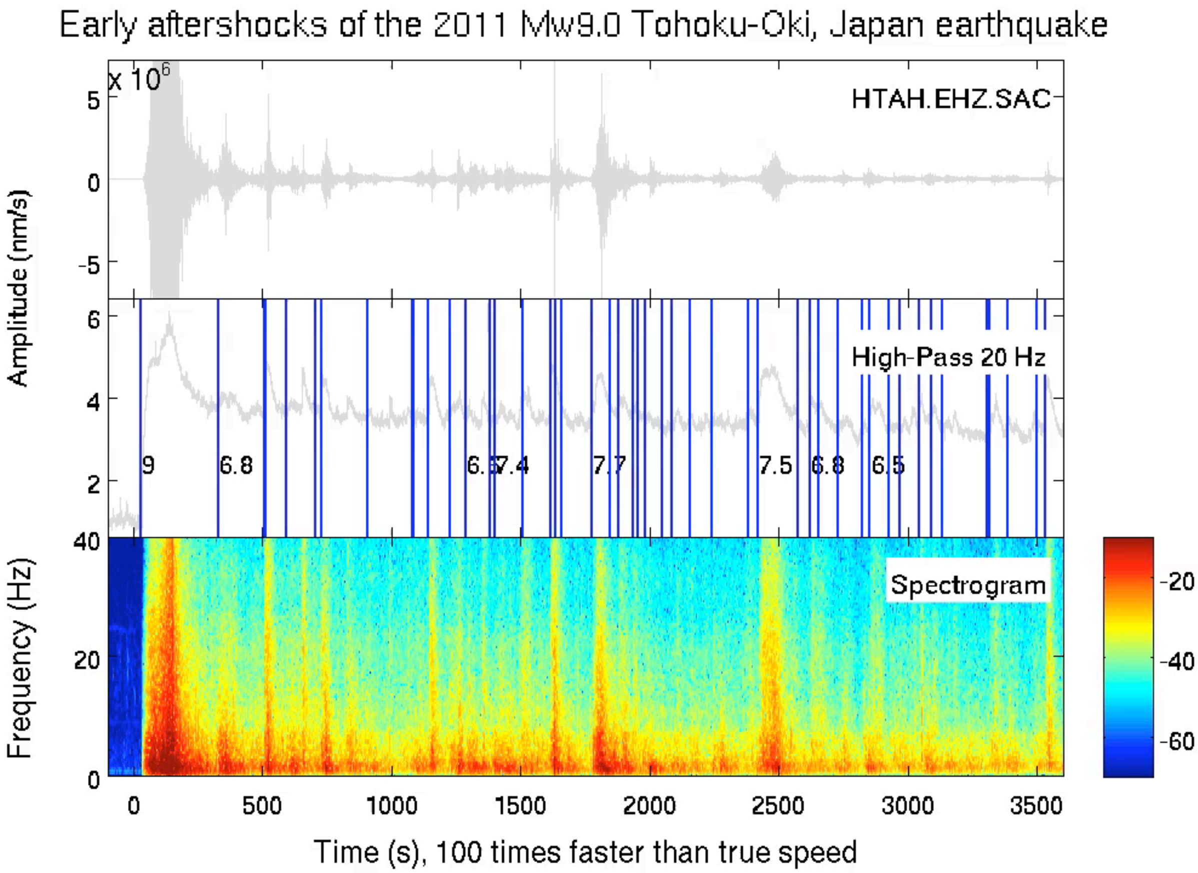
- local
- can last for years

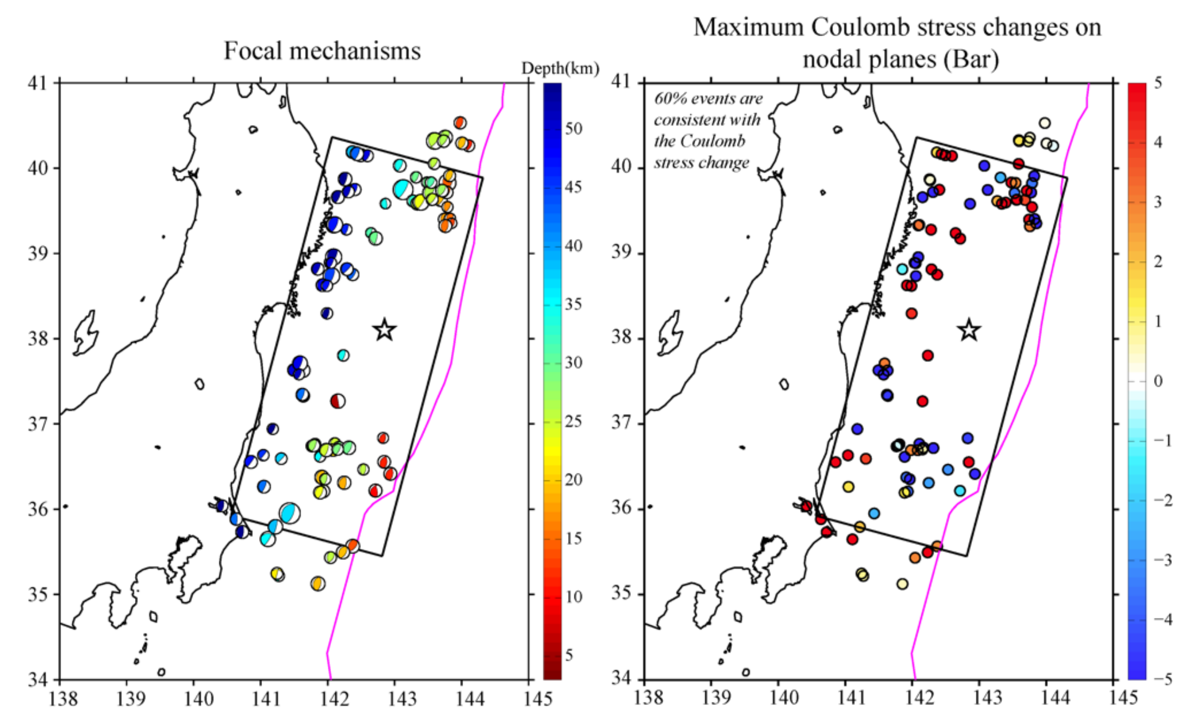
Dynamic and static Coulomb stress change



Dynamic triggering

- large region (sometimes global)
- only while waves are passing (minutes)
- restricted to volcanic or geothermal areas





a) Focal mechanism solutions of aftershocks of the 2011 Tohoku earthquake, which are similar to the mechanism of the mainshock. To separate these events, Asano et al. (2011) have used the 3-D rotation angle of Kagan (GJI, 1991); b) Maximum Coulomb stress change on the nodal planes of the aftershocks shown in (a). About 60% procent of all events have occurred in a stress-increase regime (red colors). Due to their proximity to the fault plan of the mainshock (the similarity of the focal mechanisms sugests this also), the correlation between the Coulomb stress changes and the occurence of the aftershocks is more influenced by the plate geometry and slip uncertainties.

Occurrence of large earthquakes worldwide: Do great quakes trigger other large quakes worldwide?