Advanced Structural Geology, Fall 2022

Static stress changes--Coulomb

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Static Stress Changes and the Triggering of Earthquakes

by Geoffrey C. P. King, Ross S. Stein, and Jian Lin

Key concepts:

- •Source faults
- •Receiver faults
- •Optimally oriented faults
- •Assume receiver faults are close to failure
- •Triggering lag time is a problem

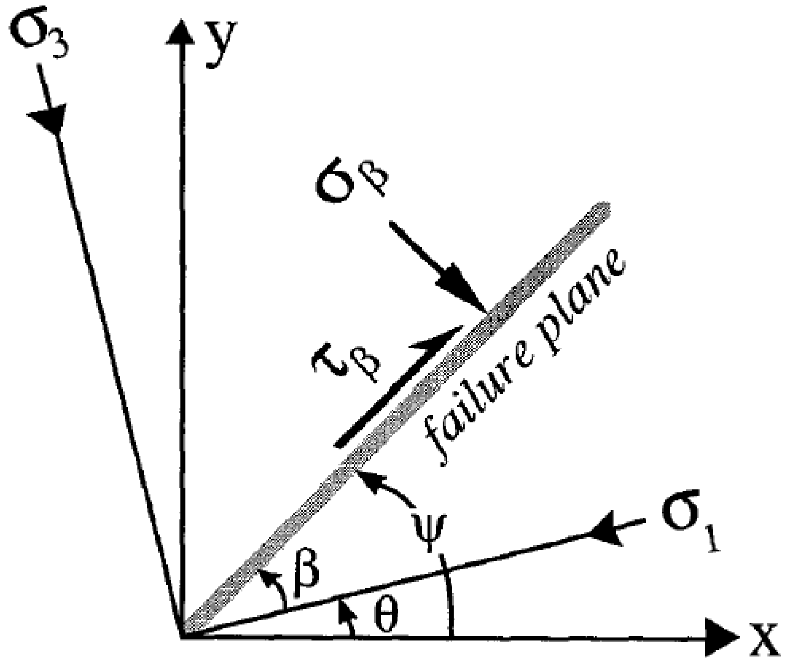
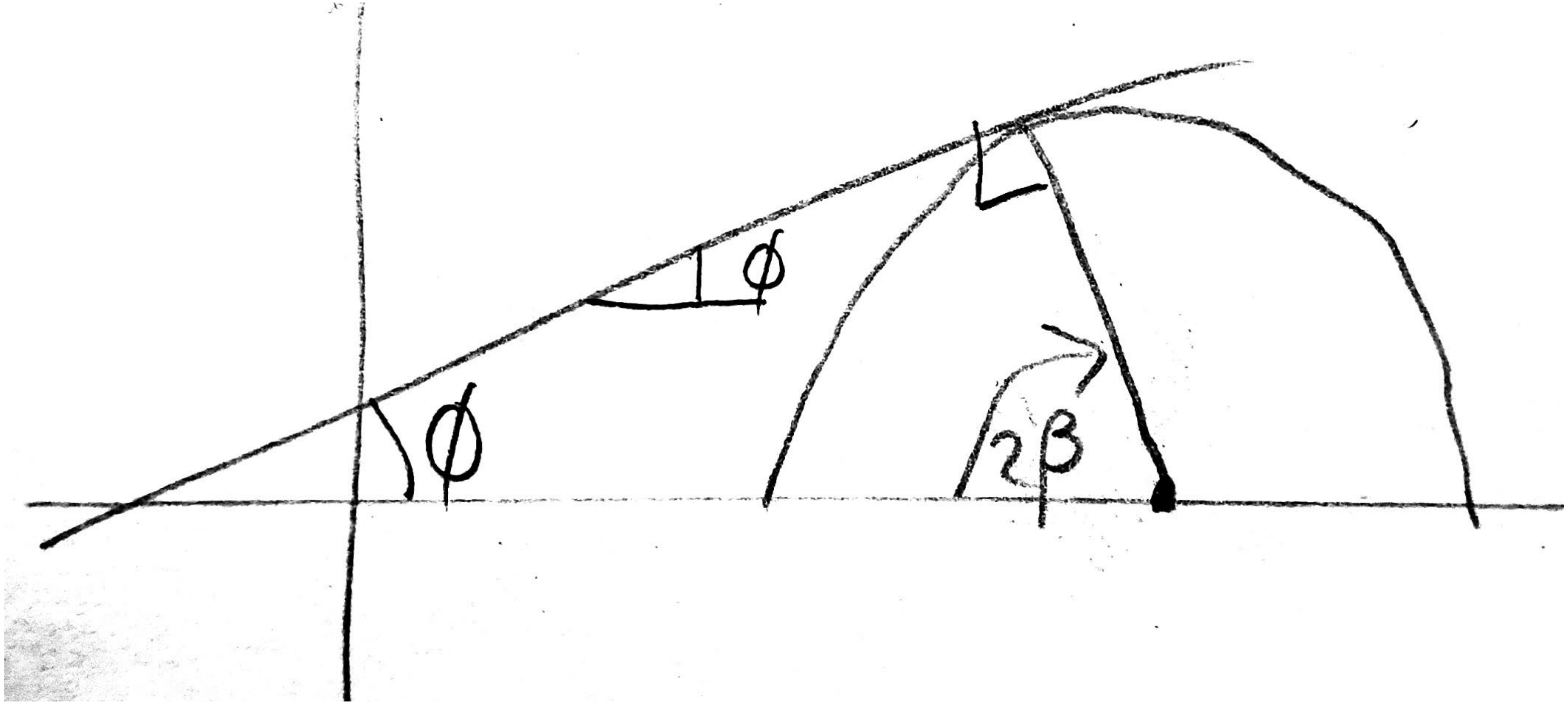


Figure 1. The axis system used for calculations of Coulomb stresses on optimum failure planes. Compression and right-lateral shear stress on the failure plane are taken as positive. The sign of τ_β is reversed for calculations of right-lateral Coulomb failure on specified failure planes.

Coulomb failure and optimal orientation of fault planes

Optimal orientation; $\phi + 90 + 2\beta = 180$



Change of coulomb stress on faults of specified orientation (see next lecture)

Can change spatially
Remote: S_{ij}^{r}

Induced: S_{ij}^{f}

Total: $S = S_{ij}^{r} + S_{ij}^{f}$

Given $\mathbf{S}$ principal stress tensor with orientation $x'y'z'$

Rotate to N-S, E-W components

$$\mathbf{R} = \begin{bmatrix} l & l' & l'' \\ m & m' & m'' \\ n & n' & n'' \end{bmatrix} \text{ where } \begin{aligned} l &= x * x' \\ l' &= x * y' \\ l'' &= x * z' \\ &\ldots \end{aligned}$$

$$\mathbf{S}' = \mathbf{R}^T \mathbf{S} \mathbf{R}$$

And given plane with normal vector direction cosines $\mathbf{N}$ — Can change spatially

Traction $\mathbf{T} = \mathbf{S}' * \mathbf{N}$ (row and column multiplication)
$T = \sqrt{\mathbf{T}(1)^2 + \mathbf{T}(2)^2 + \mathbf{T}(3)^2}$ traction magnitude

$\sigma_n = \mathbf{T} \cdot \mathbf{N}$ dot product for normal traction magnitude

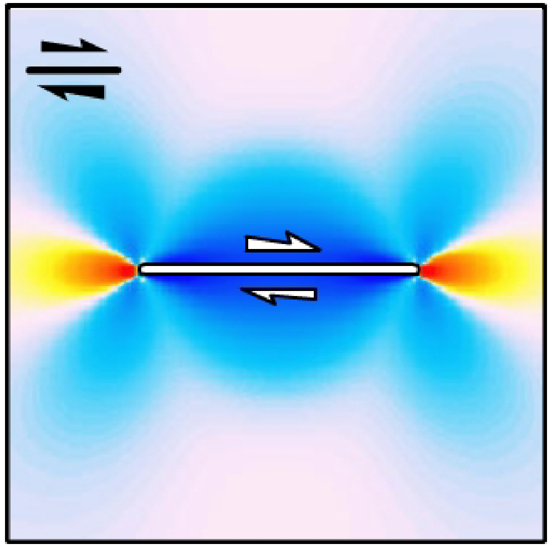
$\mathbf{B} = \mathbf{T} \times \mathbf{N}$ cross product for null vector
$B = \sqrt{\mathbf{B}(1)^2 + \mathbf{B}(2)^2 + \mathbf{B}(3)^2}$ $\mathbf{B}$ magnitude
$\mathbf{B}_{normalized} = \mathbf{B}./B$ normalize for orientation if necessary

$\mathbf{T_s} = \mathbf{N} \times \mathbf{B}$ cross product for shear traction vector
$\tau = \sqrt{\mathbf{T_s}(1)^2 + \mathbf{T_s}(2)^2 + \mathbf{T_s}(3)^2}$ shear traction magnitude
$\mathbf{T_s}_{normalized} = \mathbf{T_s}./\tau$ normalize for shear traction orientation

Coulomb failure function: $\Delta\sigma_f = \Delta\tau - (\mu - P)\Delta\sigma_n$

How the Coulomb Stress Change is Calculated

Stress Rise Drop



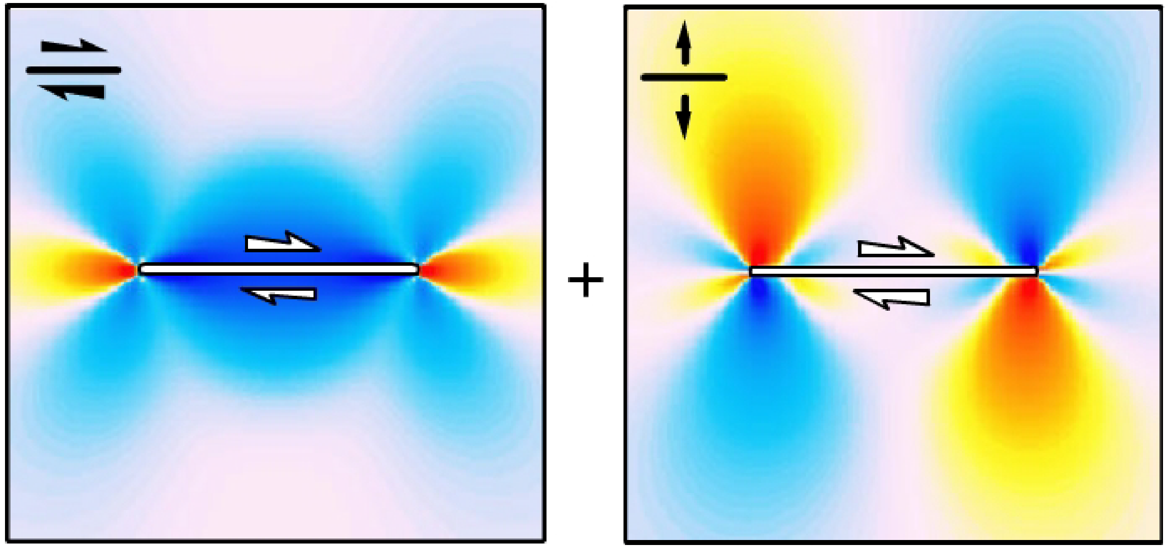
Shear stress change

$\Delta\tau_s$

- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

How the Coulomb Stress Change is Calculated



Shear stress change + Friction coefficient x normal stress change

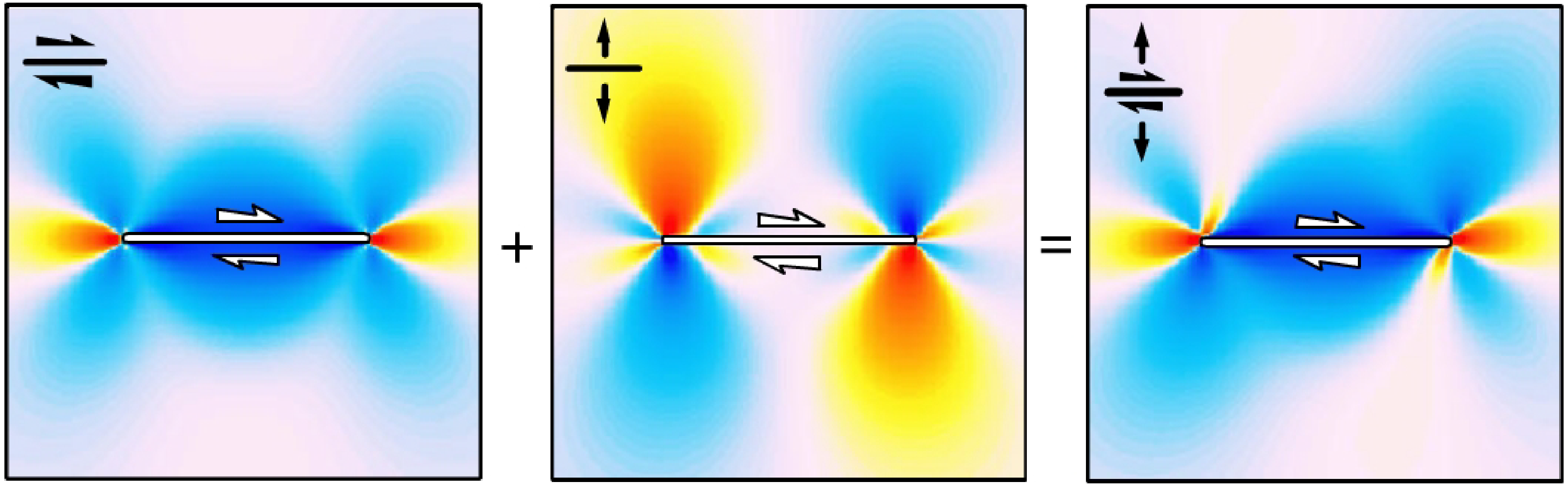
$\Delta\tau_s + \mu' (\Delta\sigma_n)$

- 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)

Change of coulomb stress on faults of optimal orientation

Mostly book keeping going from the stress tensor to the traction vector
β is orientation from σ_1 of optimal failure plane

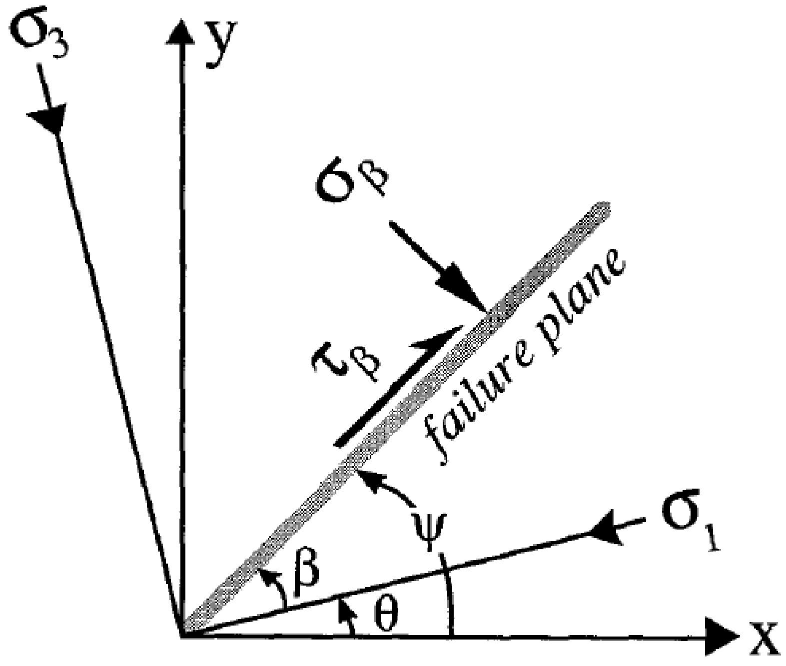


Figure 1. The axis system used for calculations of Coulomb stresses on optimum failure planes. Compression and right-lateral shear stress on the failure plane are taken as positive. The sign of τ_β is reversed for calculations of right-lateral Coulomb failure on specified failure planes.

Coulomb stress imparted by mainshocks

Source fault

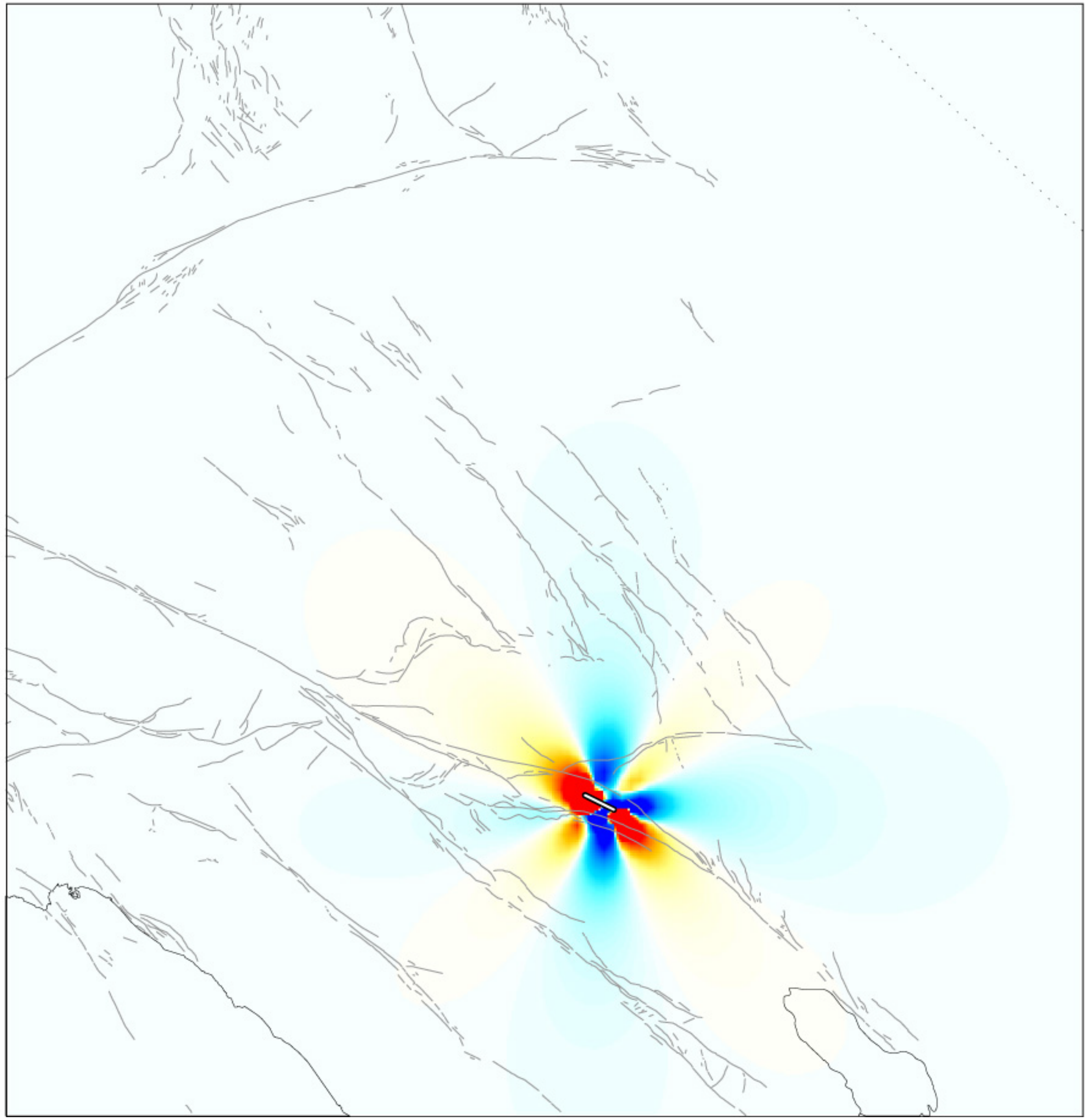
Distance (km)

0 50 100

Coulomb stress change (bars)

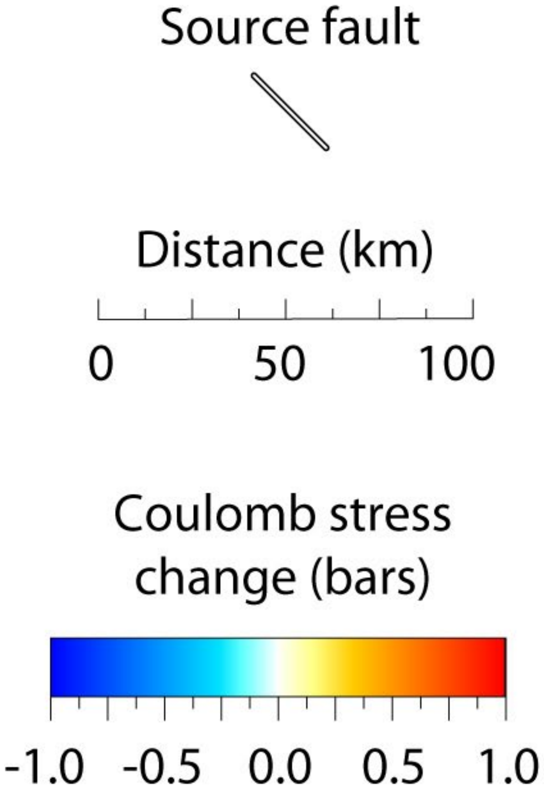
-1.0 -0.5 0.0 0.5 1.0

1986 **M**=6.0 North Palm Springs

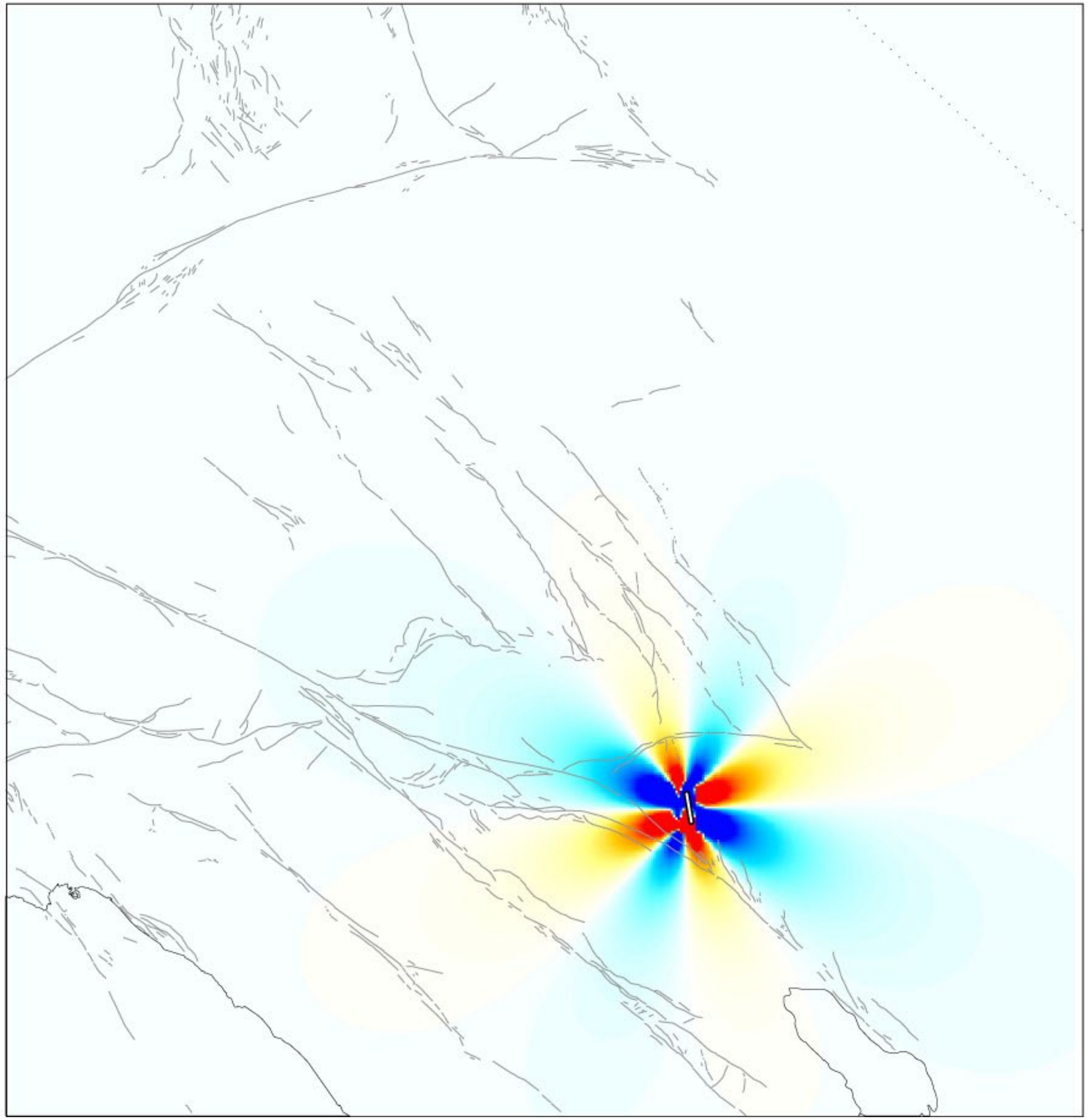


from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

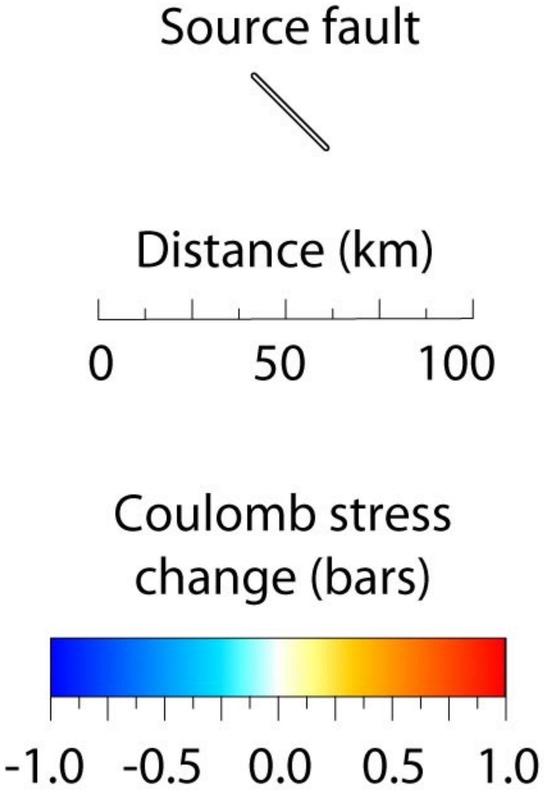


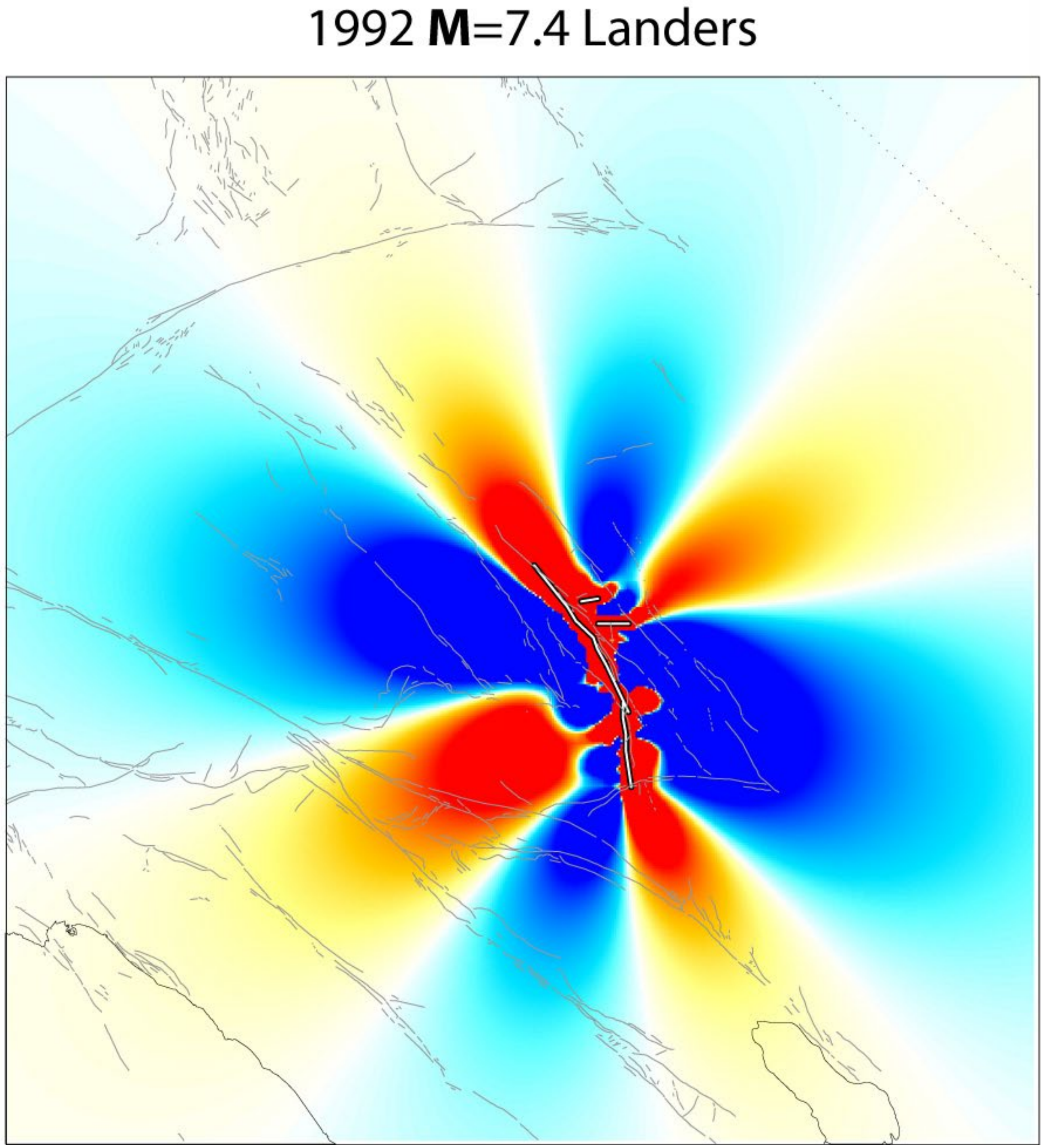
1992 **M**=6.2 Joshua Tree



from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

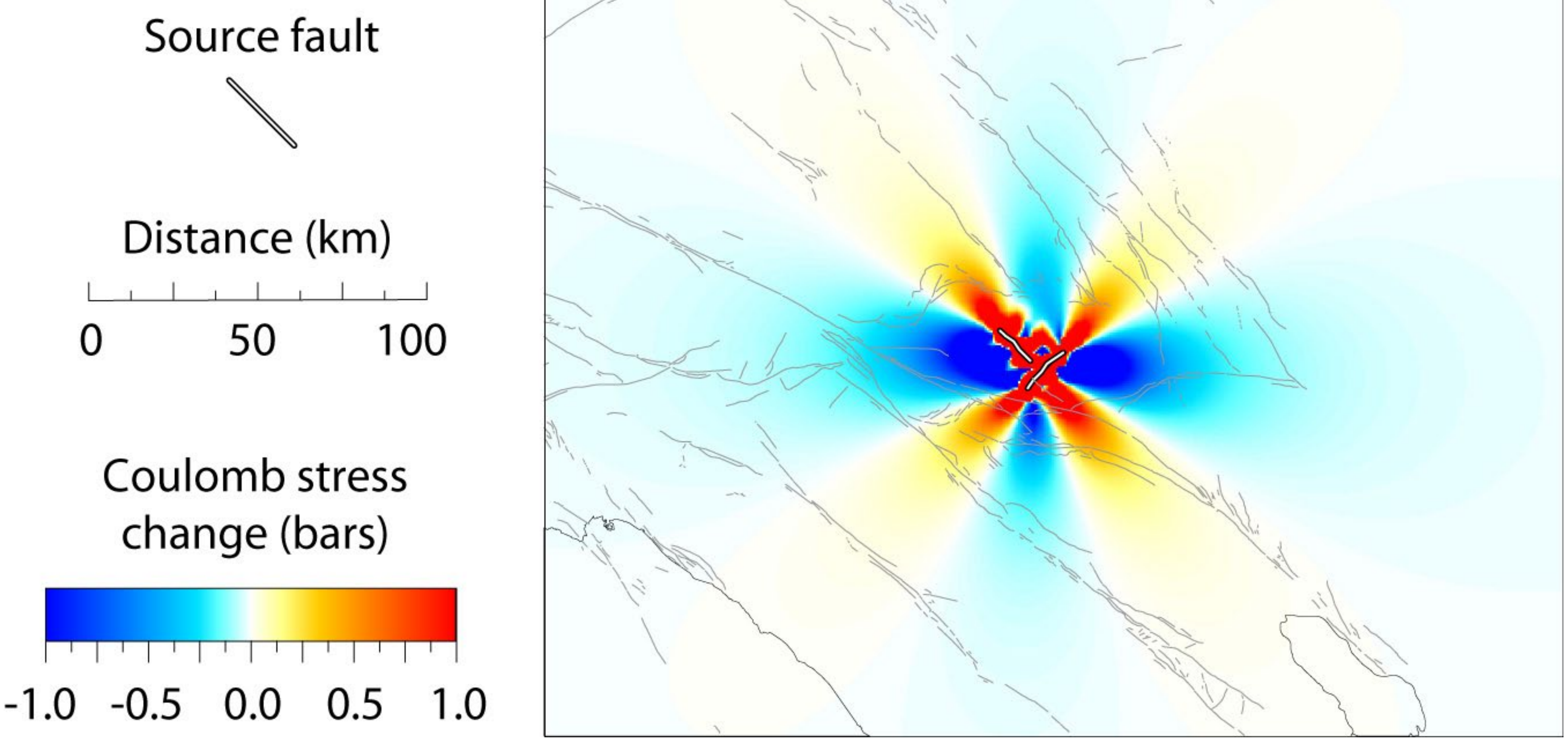




from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

1992 **M**=6.5 Big Bear



from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

Source fault

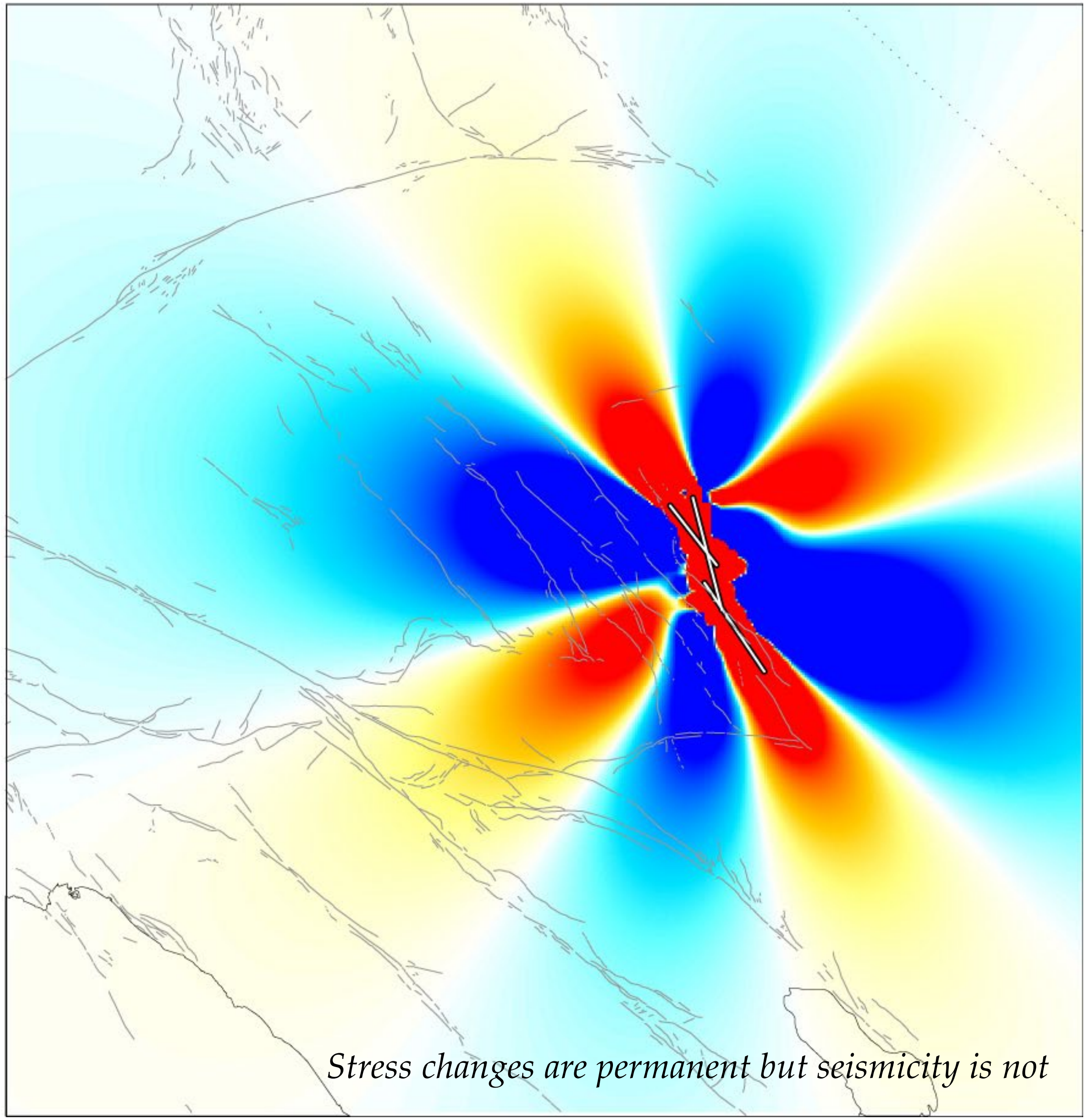
Distance (km)

0 50 100

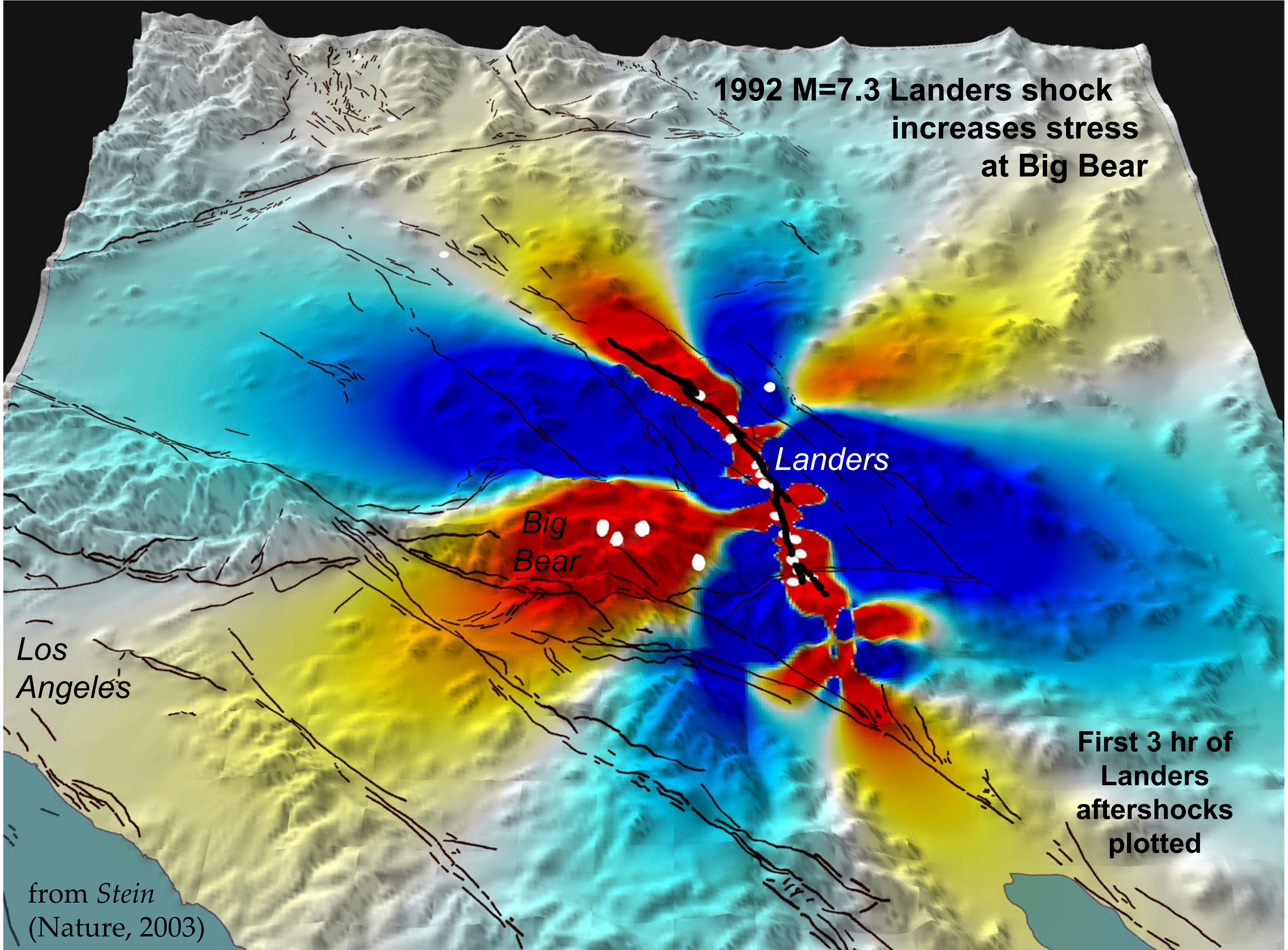
Coulomb stress change (bars)

-1.0 -0.5 0.0 0.5 1.0

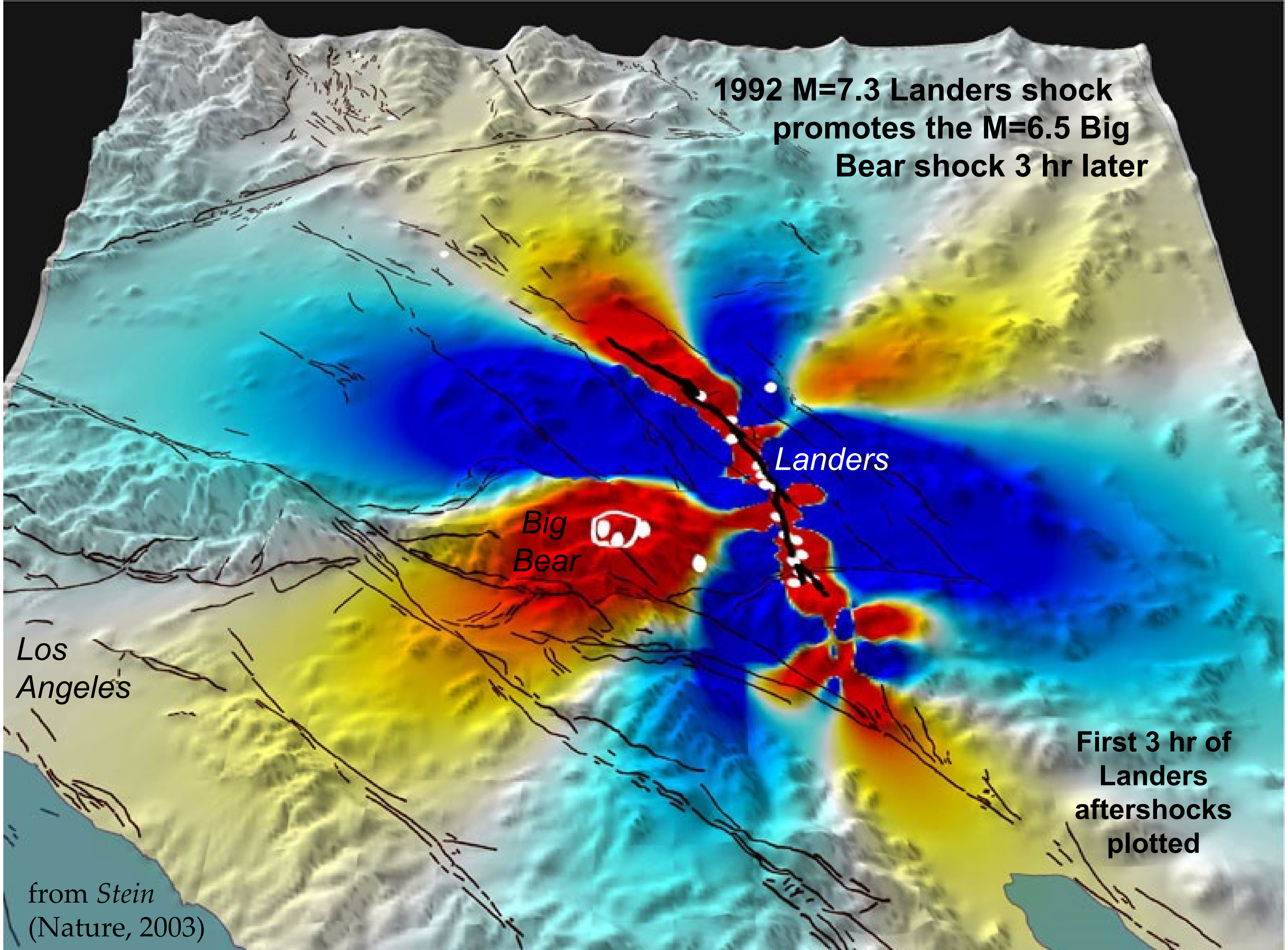
1999 **M**=7.1 Hector Mine

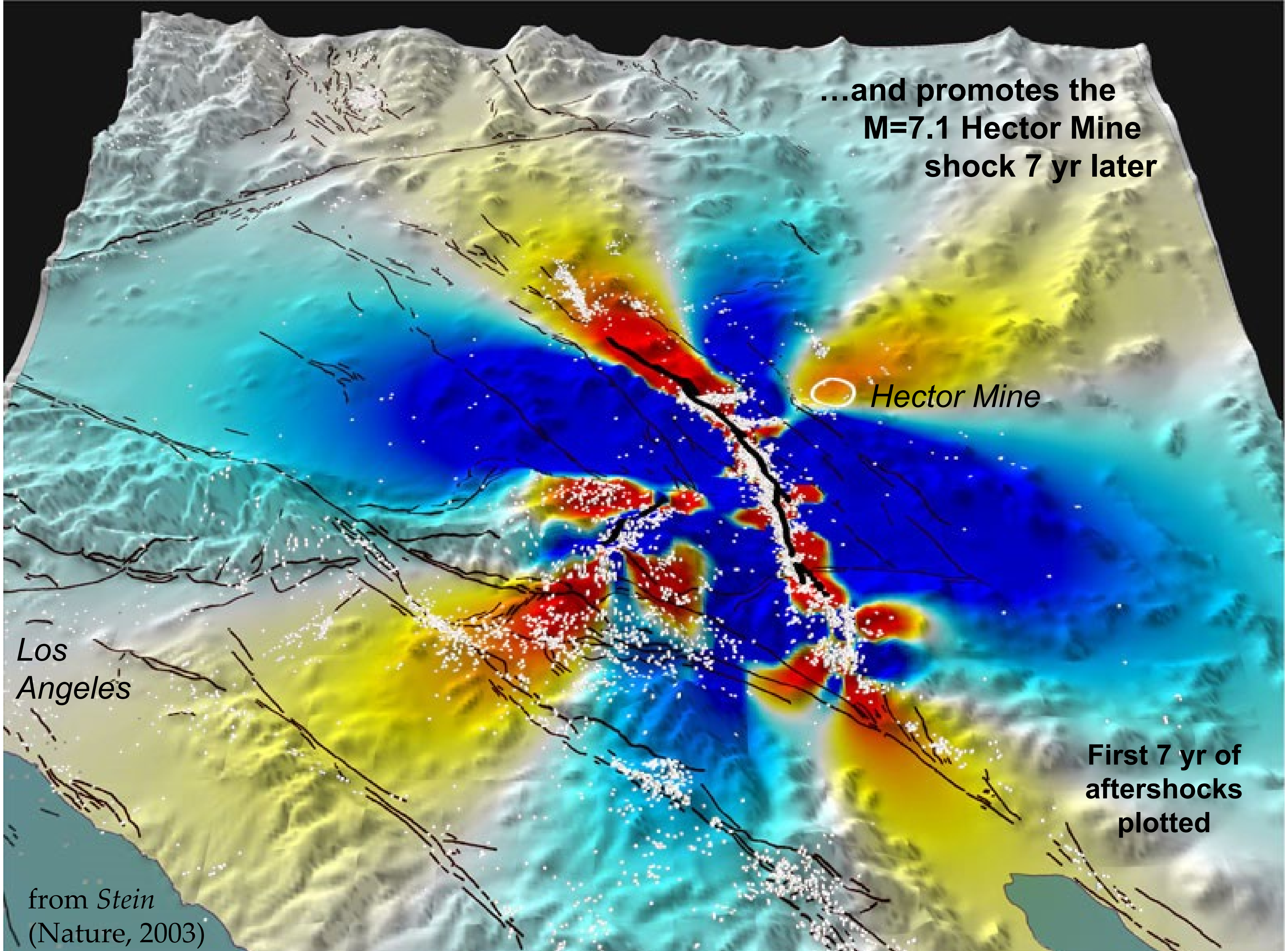


from Todal et al (JGR, 2005)

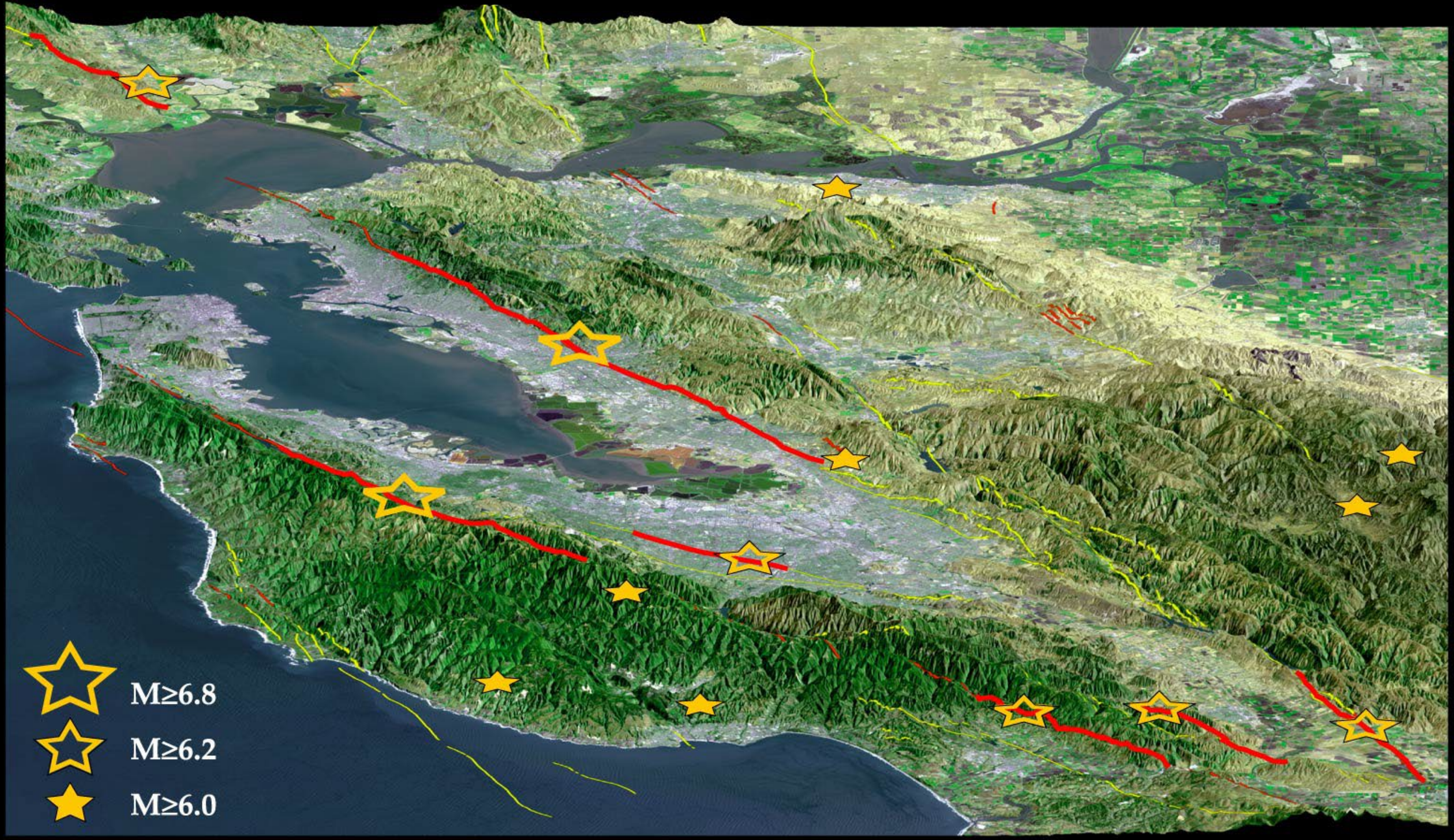


1992 M=7.3 Landers shock
increases stress
at Big Bear
Landers
Big
Bear
Los
Angeles
First 3 hr of
Landers
aftershocks
plotted
from *Stein*
(Nature, 2003)


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)

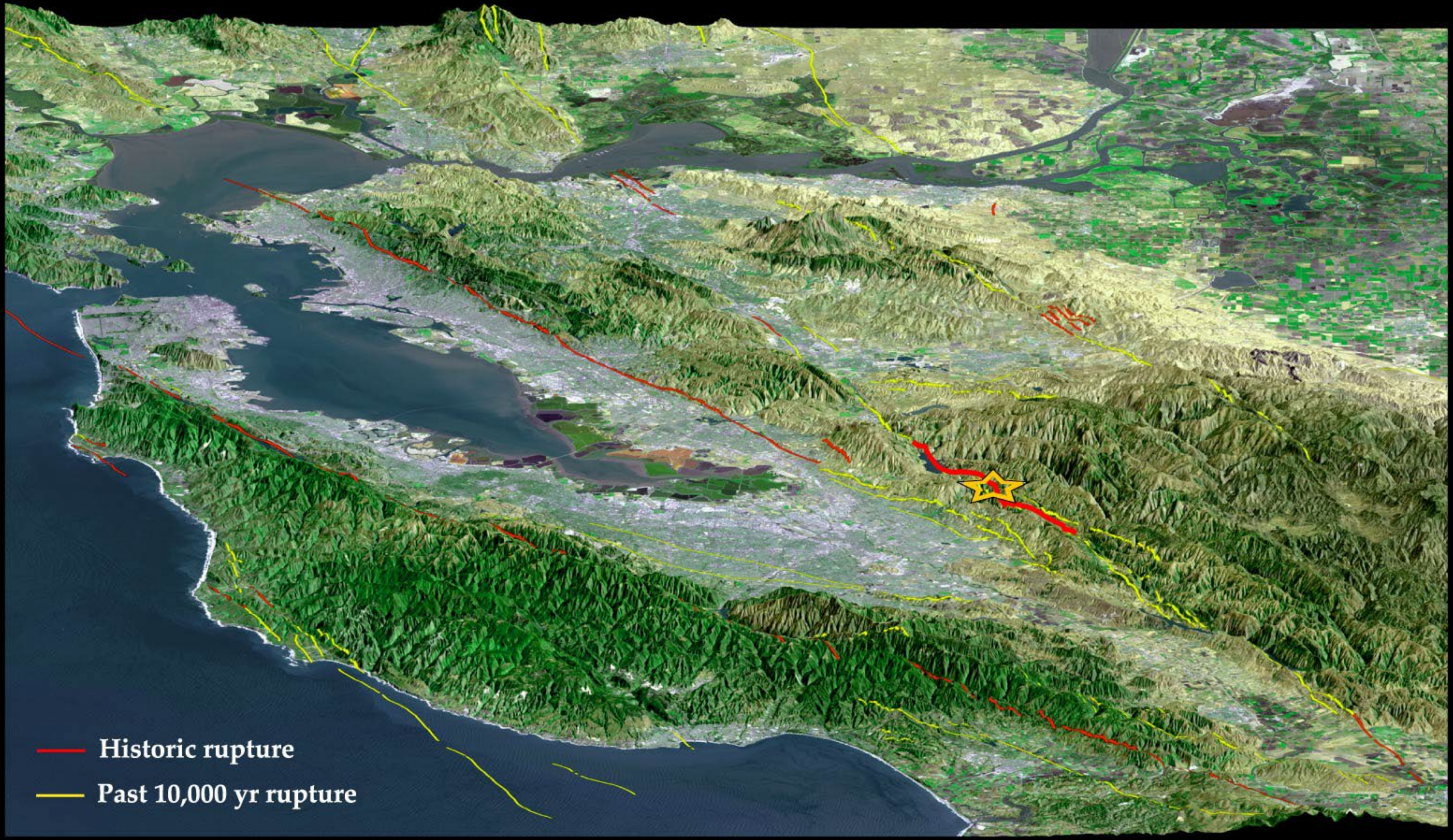
Bay area shocks during the 75 years *before* 1906



from *Stein* (Nature, 2003)

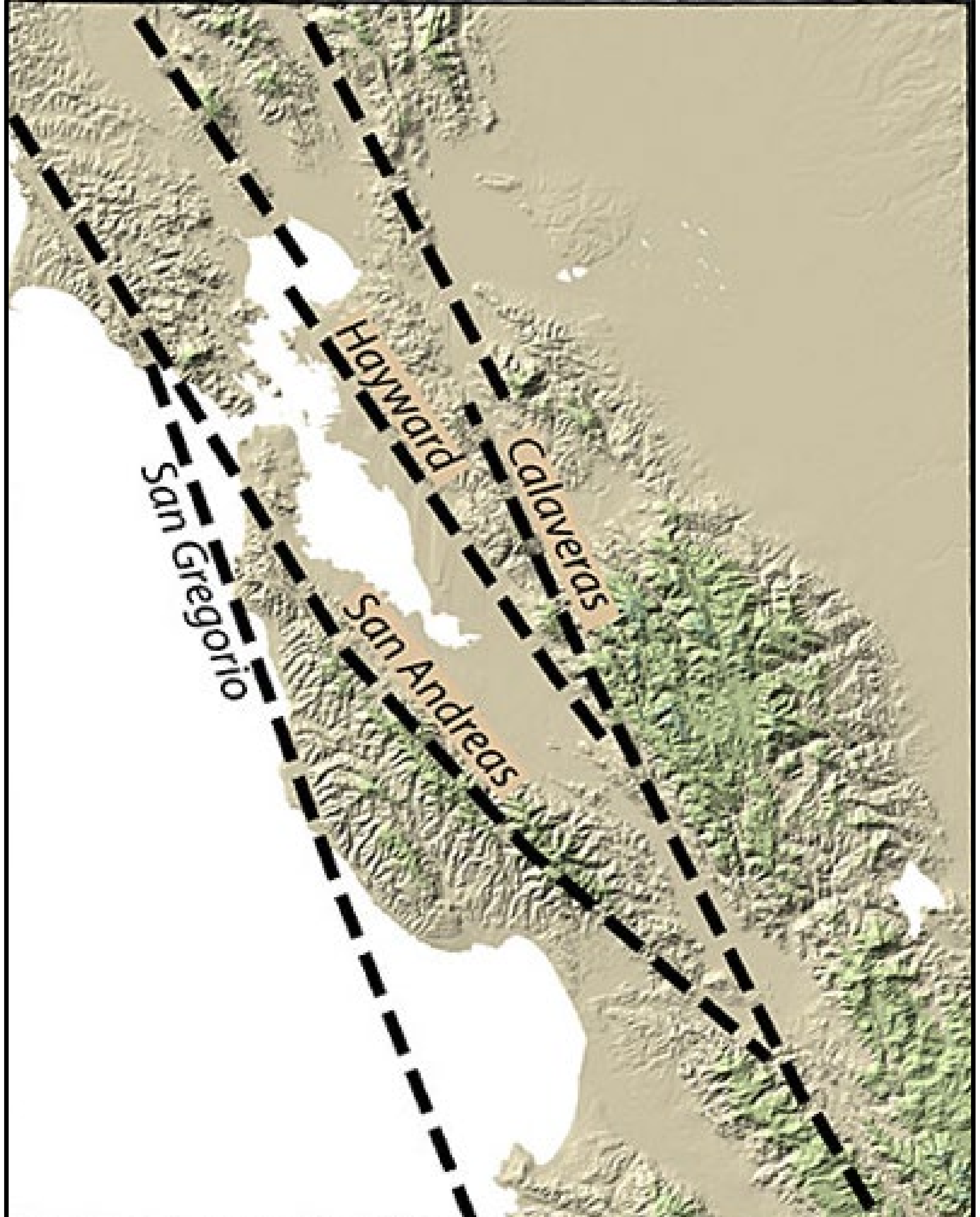
Earthquakes from *Bakun* [1999] and *Ellsworth* [1990]

Bay area shocks during the 75 years *after* 1906

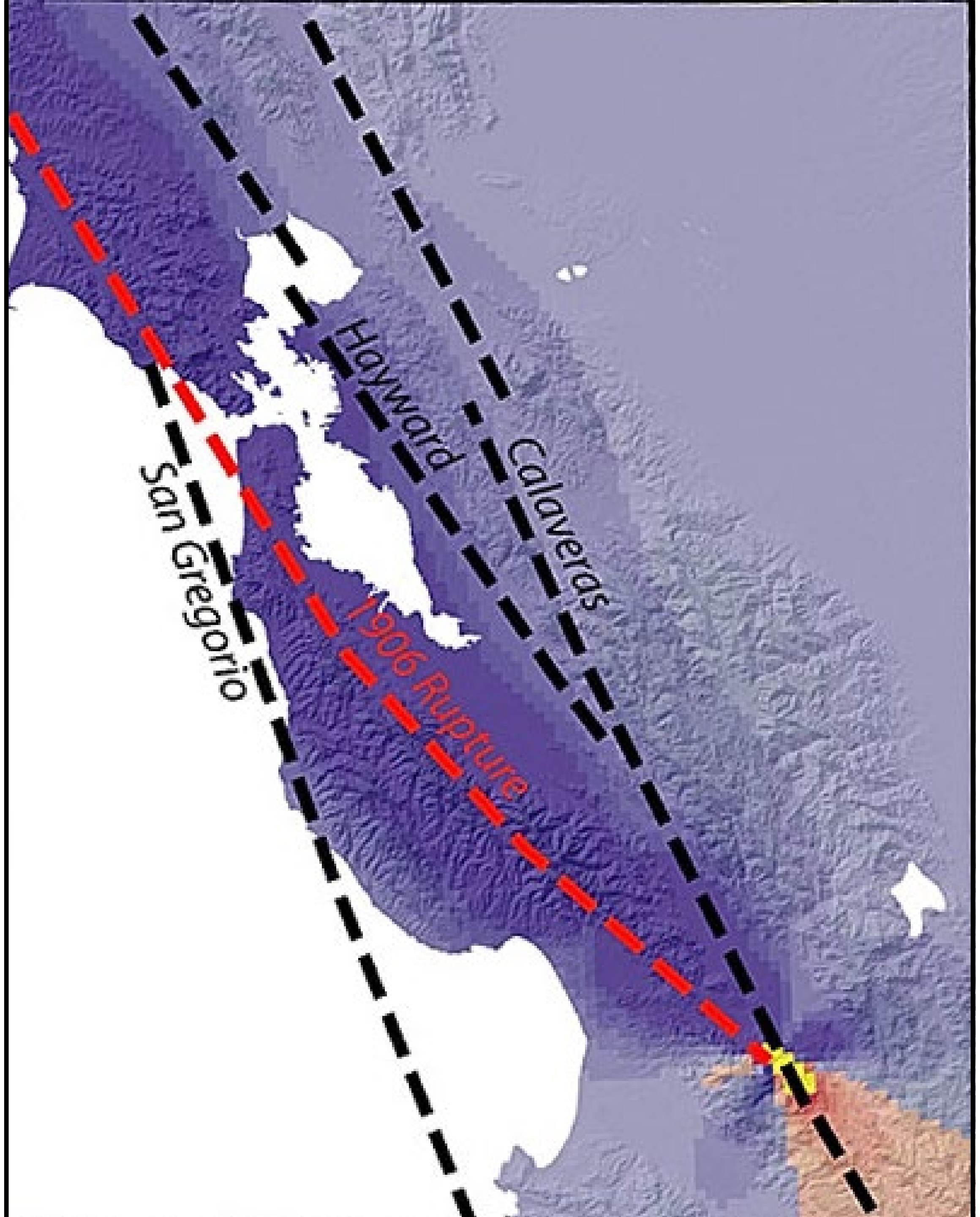


from *Stein* (Nature, 2003)

1911 M=6.2 shock from *Bakun* [BSSA, 1999]

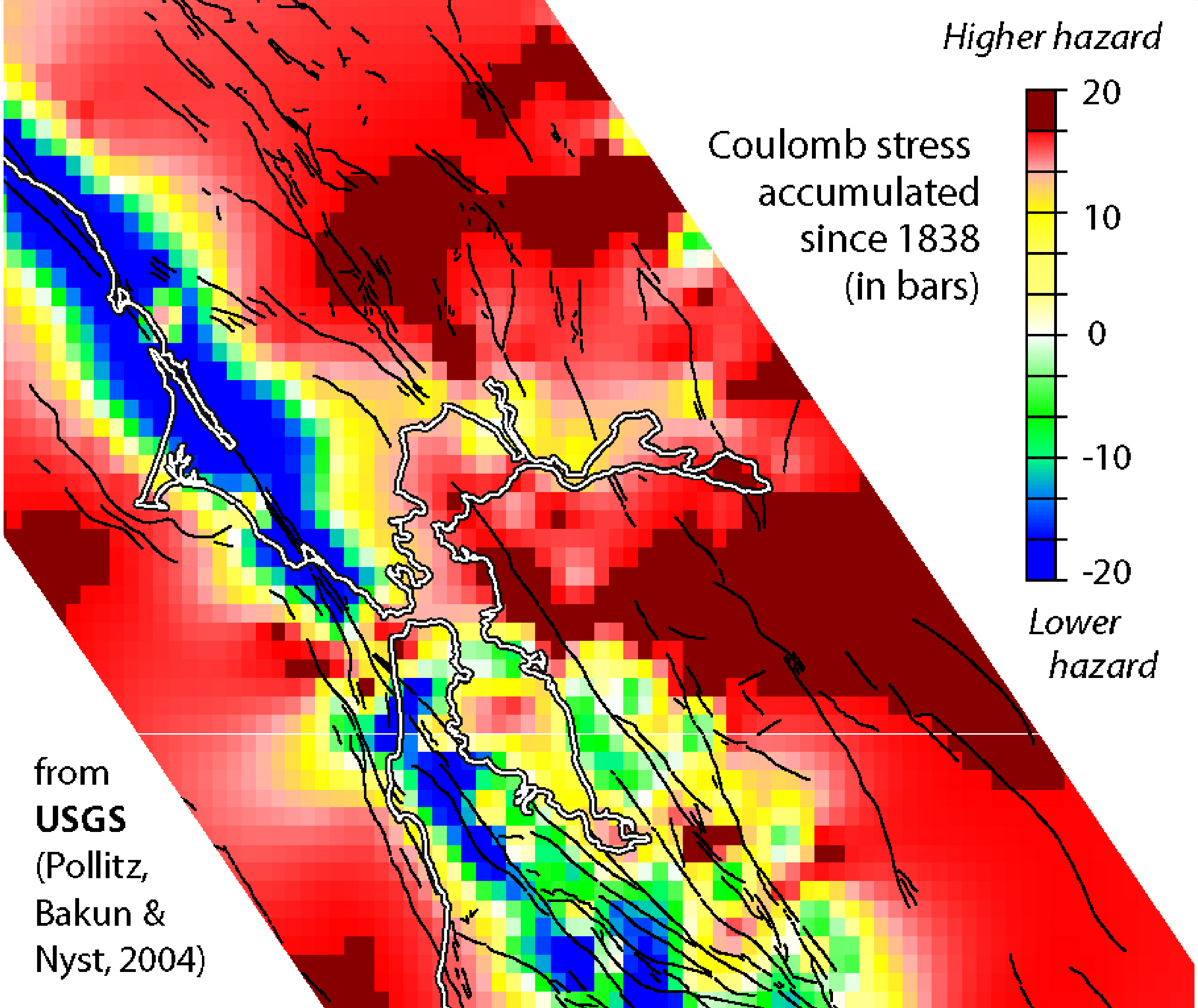


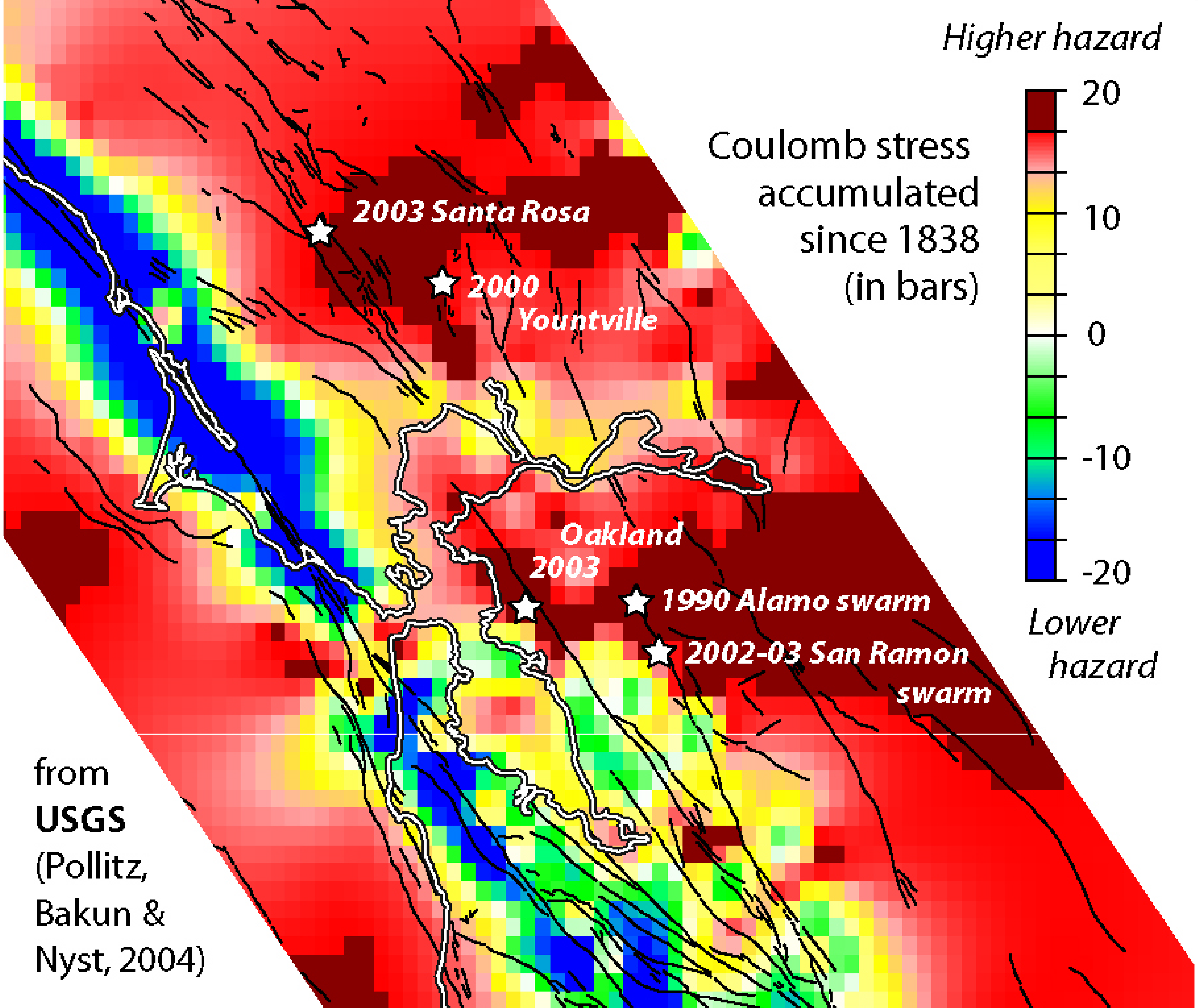
Bay area is a system of roughly parallel faults



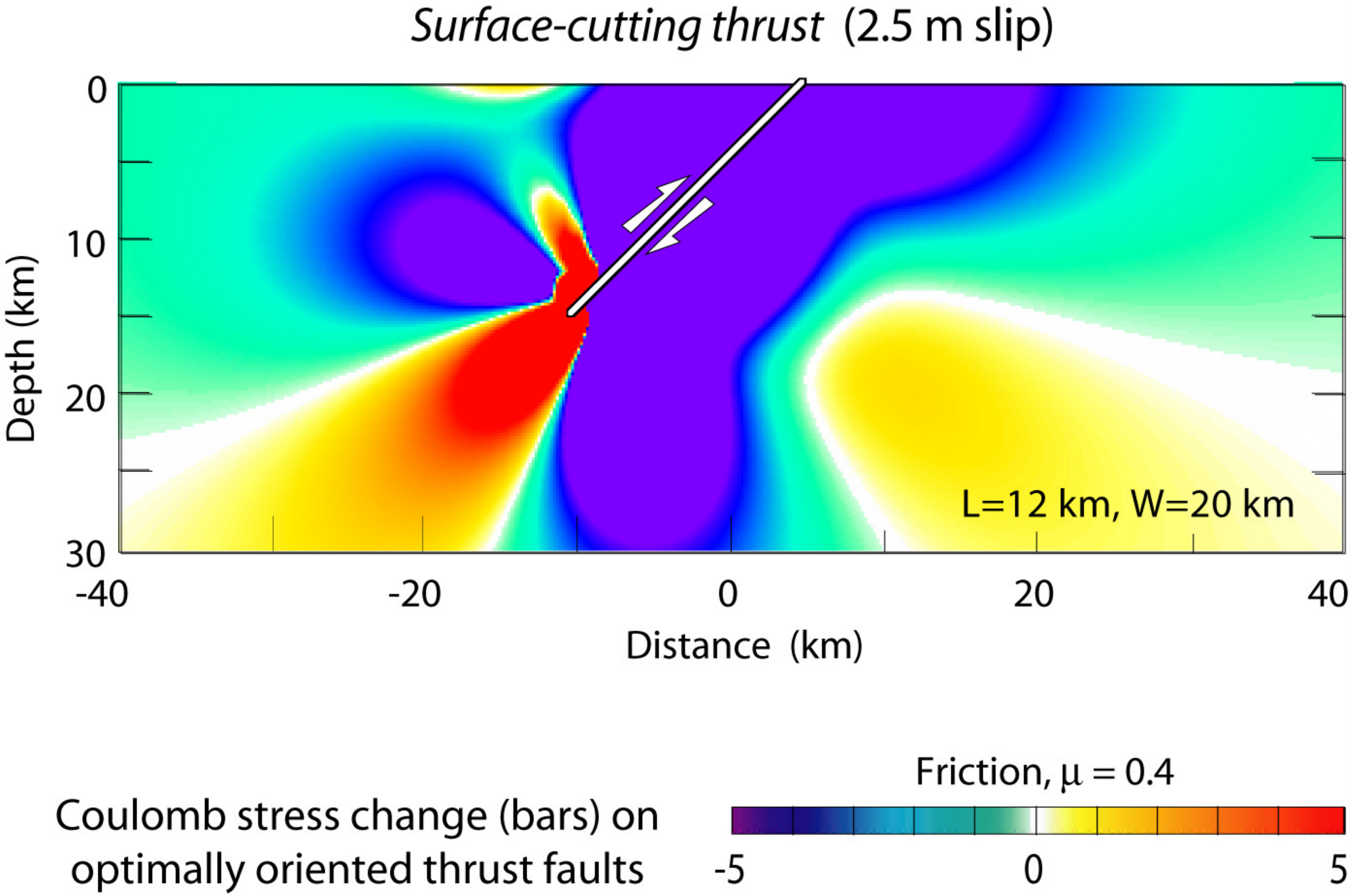
Bay area faults
may have
fallen under
a stress shadow
in 1906

from
Harris & Simpson
(1998) and *Parsons*
(2003)


Higher hazard
Coulomb stress accumulated since 1838 (in bars)
20
10
0
-10
-20
Lower hazard
from
USGS
(Pollitz, Bakun & Nyst, 2004)

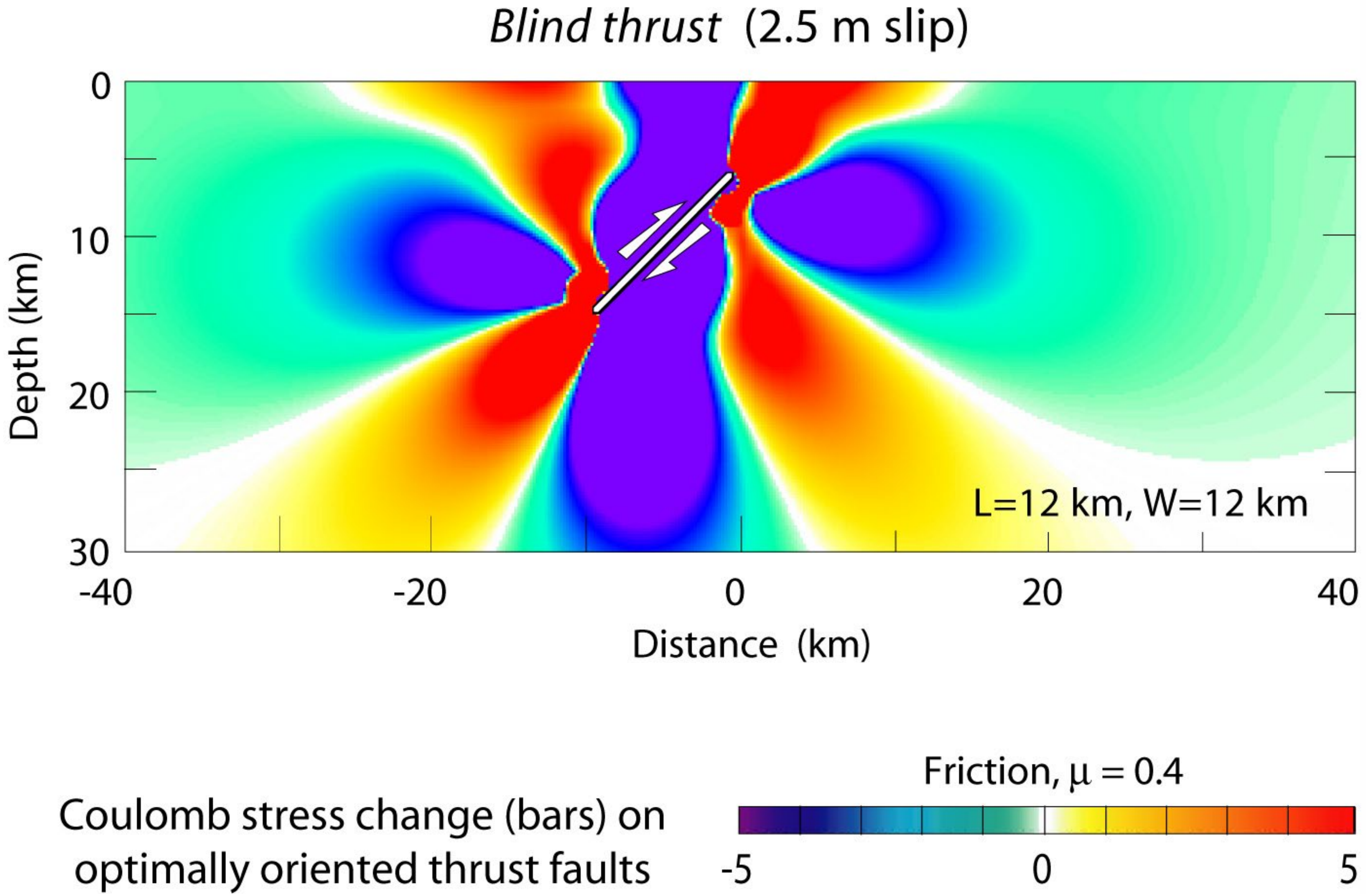

Higher hazard
20
Coulomb stress
accumulated
since 1838
(in bars)
10
0
-10
-20
Lower
hazard
2003 Santa Rosa
2000
Yountville
Oakland
2003
1990 Alamo swarm
2002-03 San Ramon
swarm
from
USGS
(Pollitz,
Bakun &
Nyst, 2004)

Surface-cutting thrusts drop the stress in the upper crust



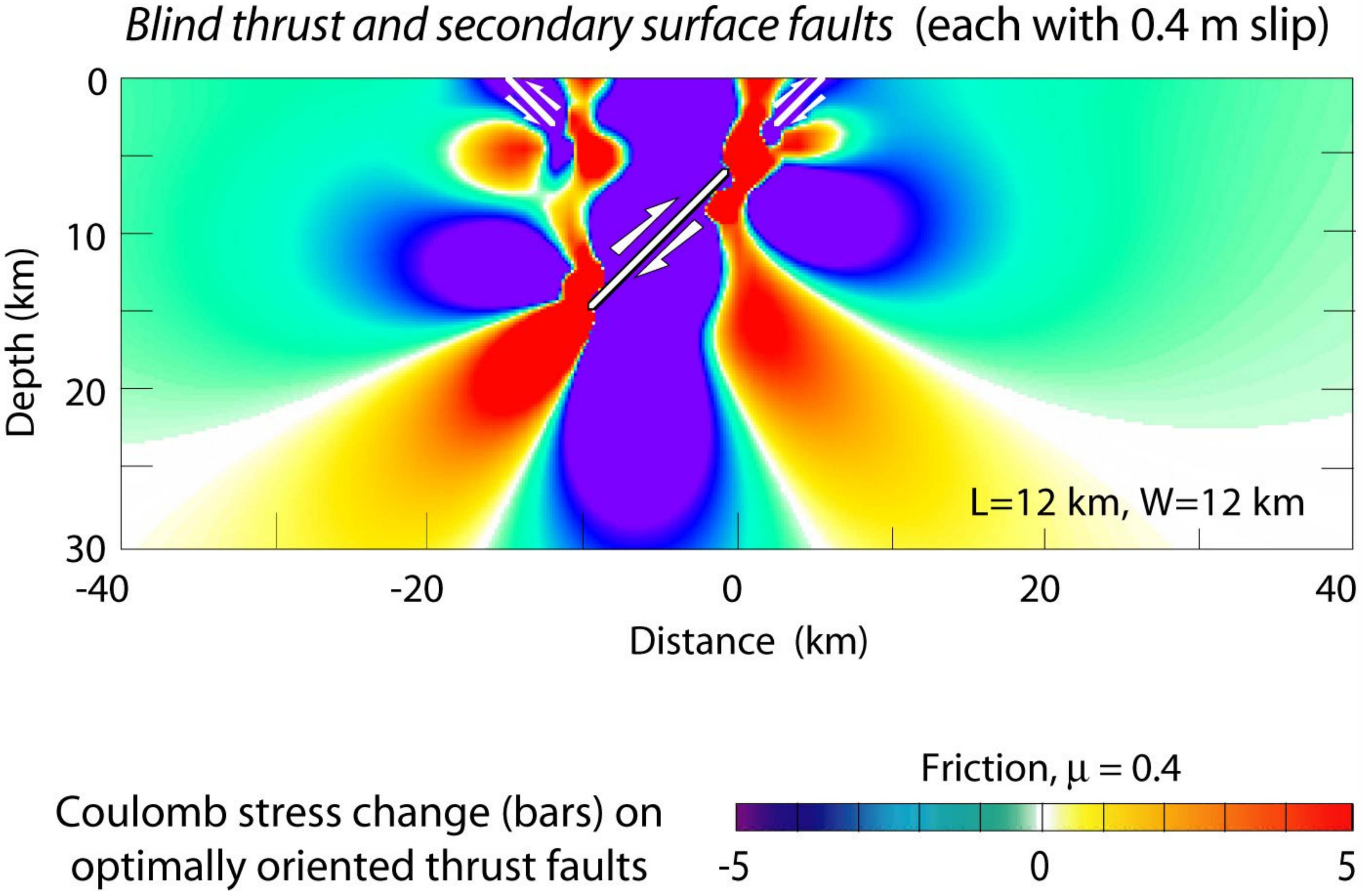
from *Lin & Stein* (JGR, 2004)

Blind thrusts raise the stress in parts of the upper crust



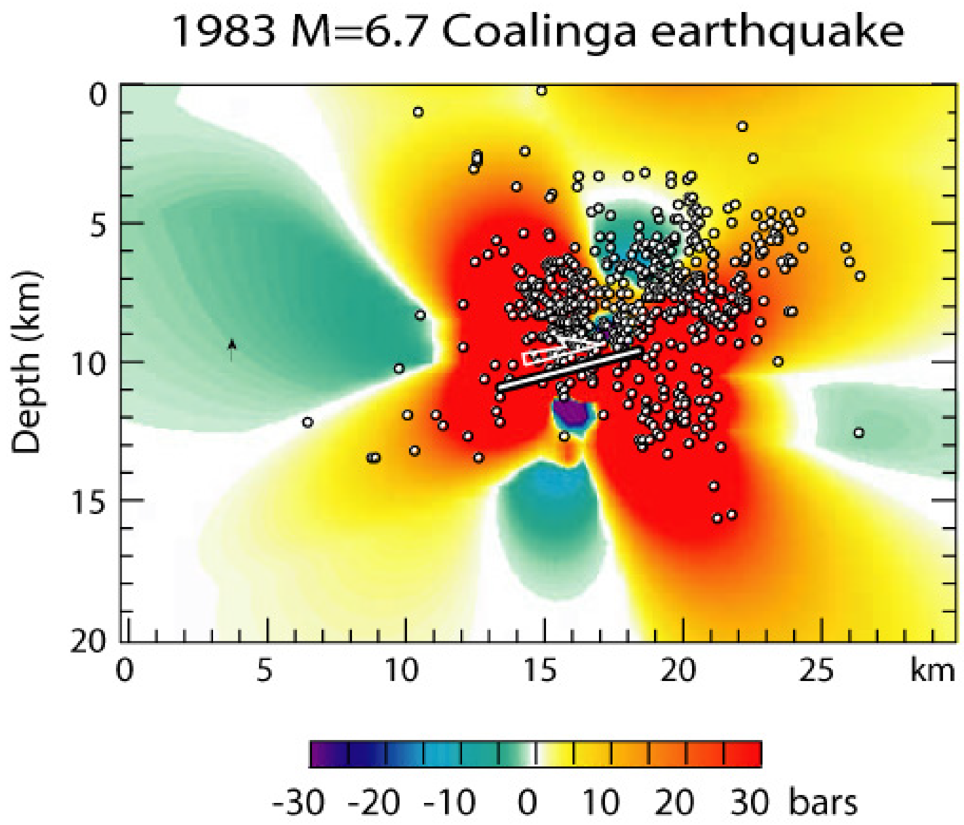
from *Lin & Stein* (JGR, 2004)

Secondary surface faults relieve the imparted stress

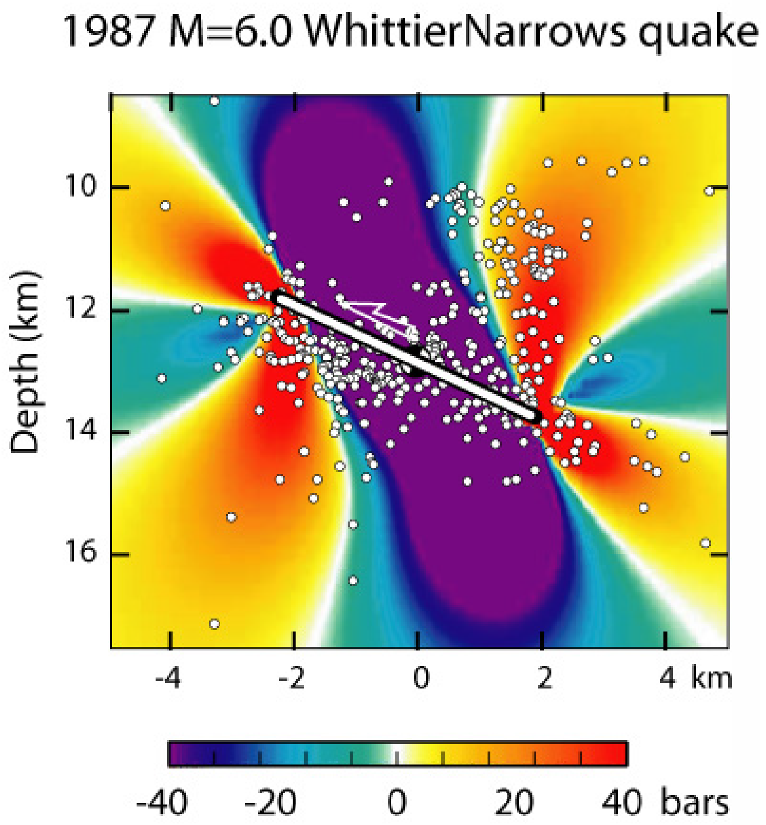


from *Lin & Stein* (JGR, 2004)

Diffuse aftershocks are characteristic of blind thrust events



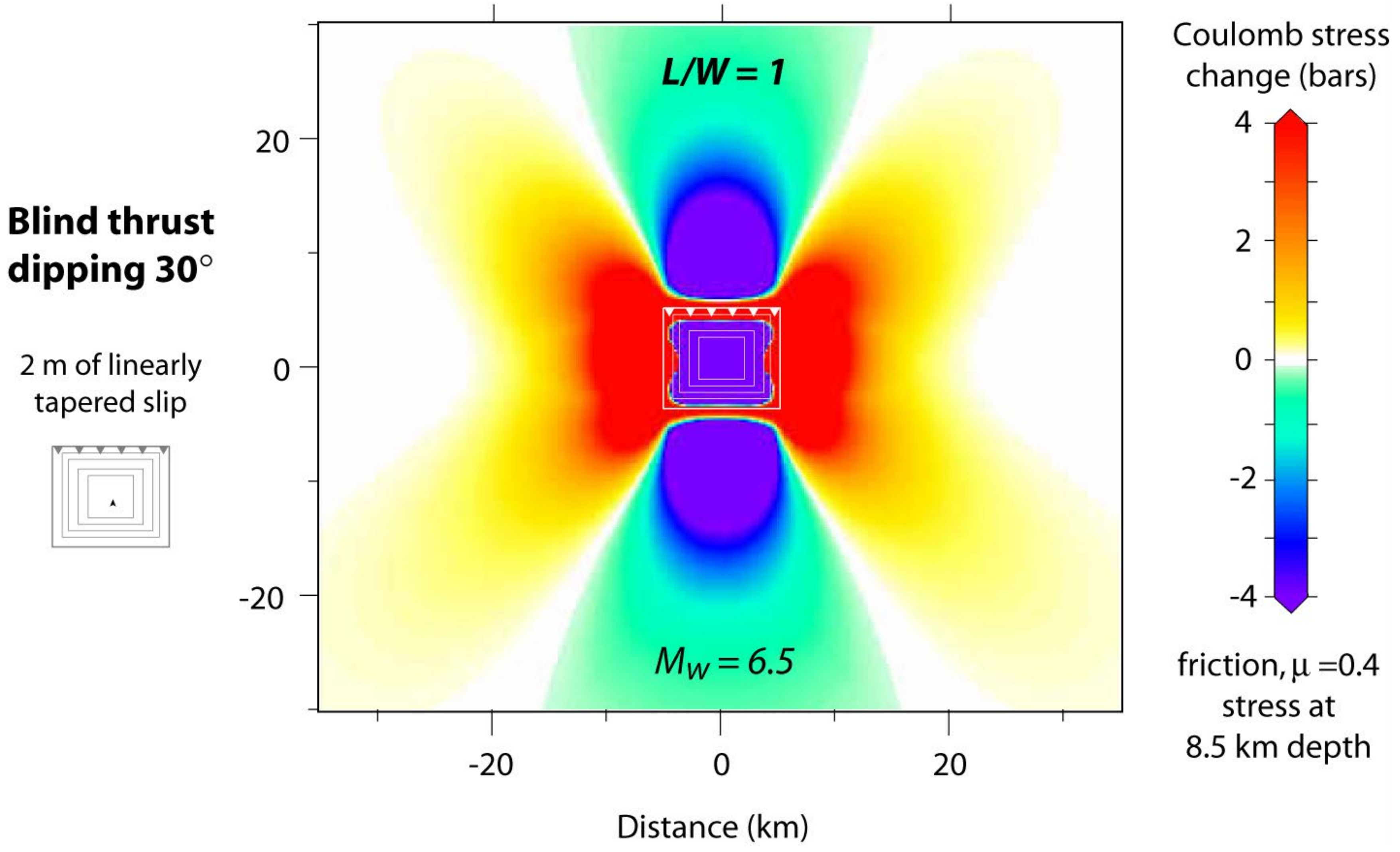
Coulomb Stress Change on optimally oriented thrust fault faults



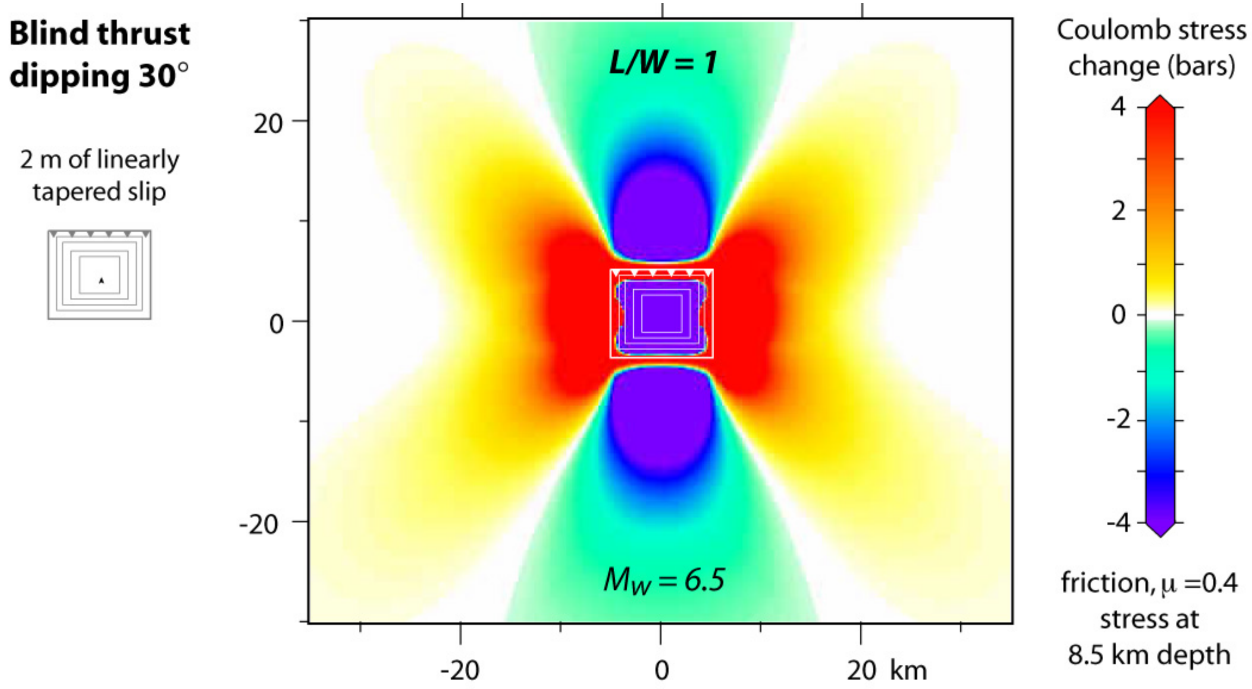
Coulomb stress change on thrust faults parallel to the source fault rutpure

from *Lin & Stein* (JGR, 2004)

Earthquake increases Coulomb stress in 'butterfly wings'

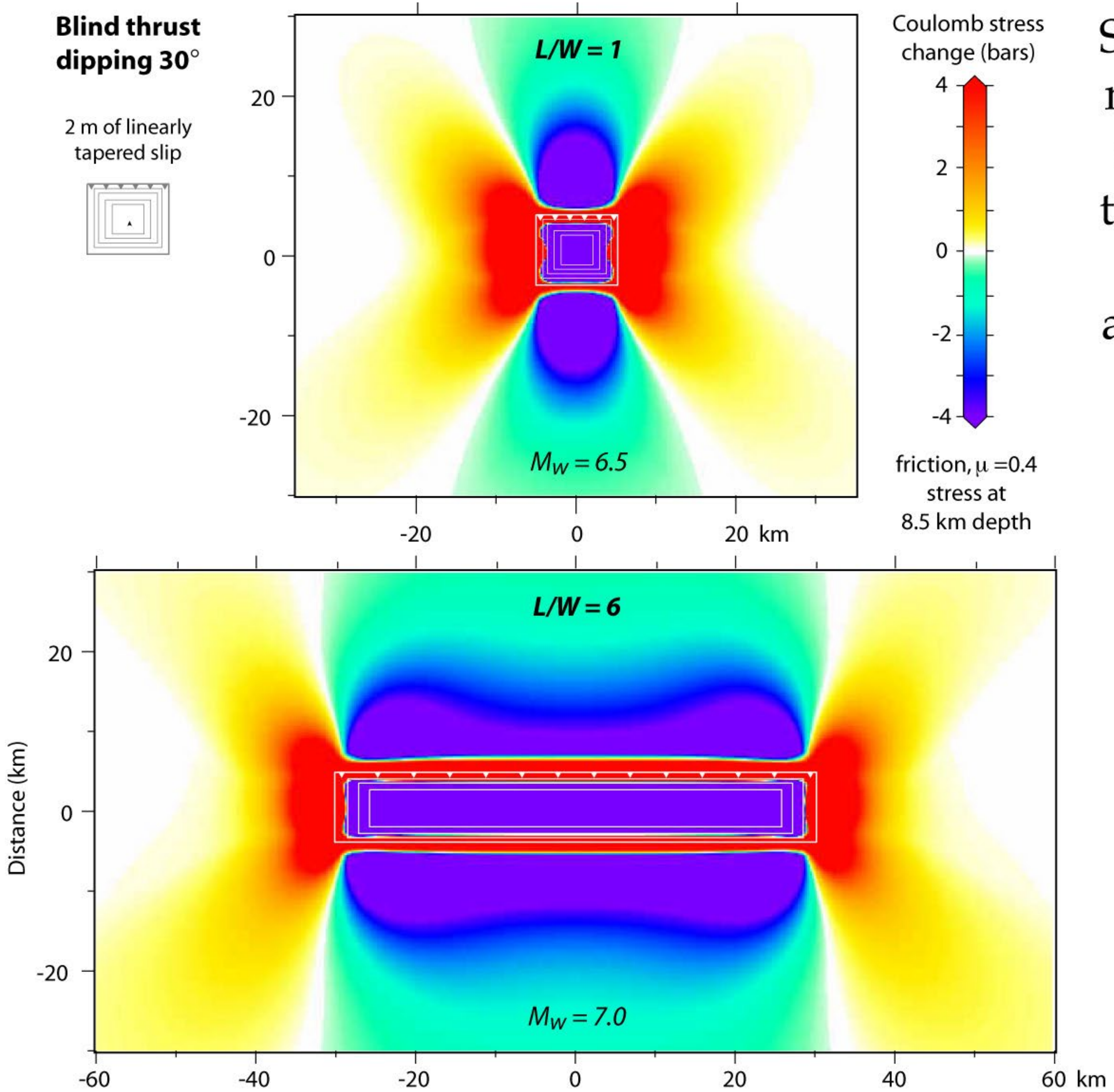


from *Lin & Stein* (JGR, 2004)



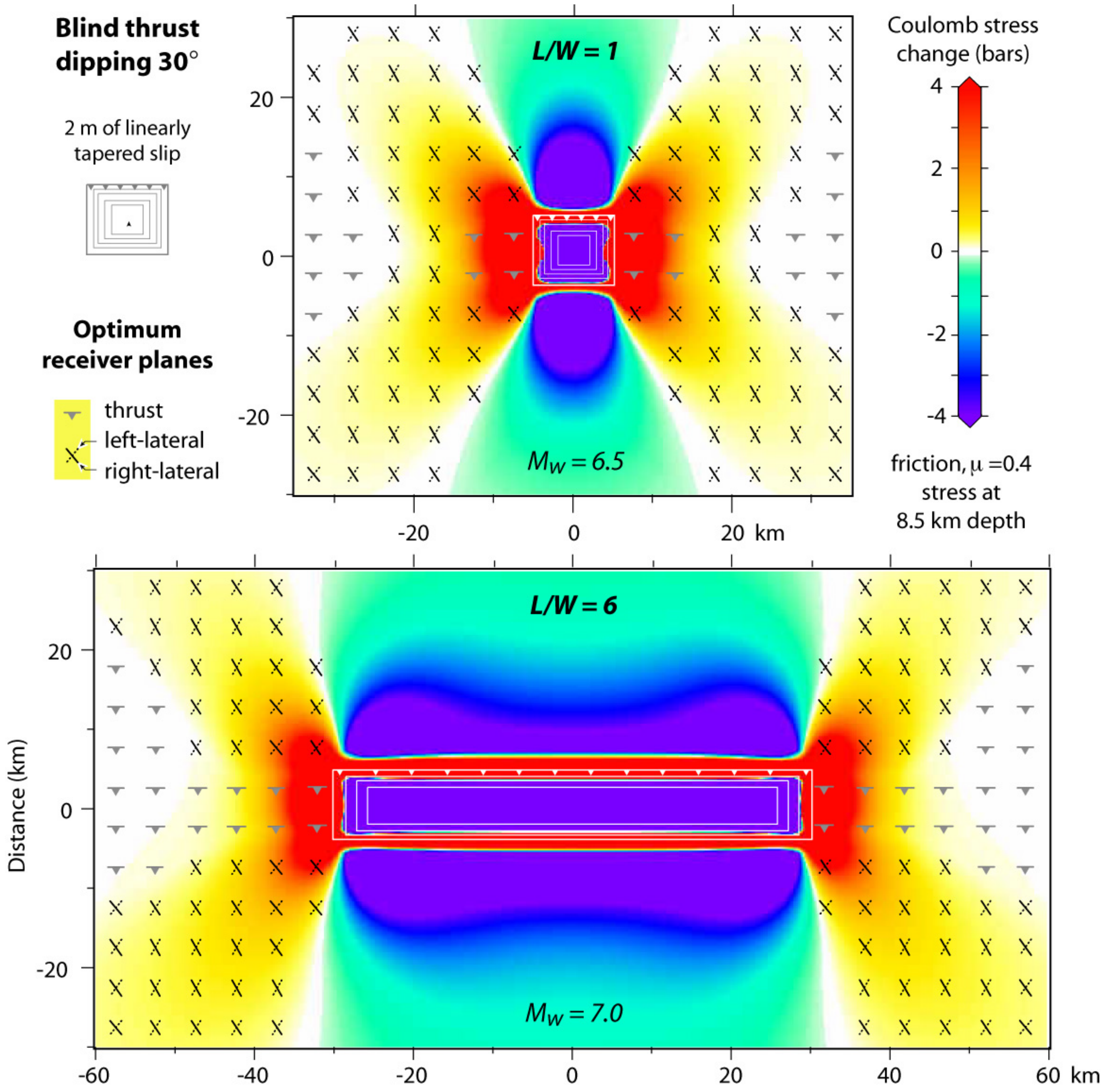
Stress is imparted to the 'butterfly wings'

from *Lin & Stein* (JGR, 2004)



Short thrust much more efficient at transferring stress along strike

from *Lin & Stein* (JGR, 2004)



Stress imparted to wings promotes strike-slip faulting

from *Lin & Stein*
(JGR, 2004)

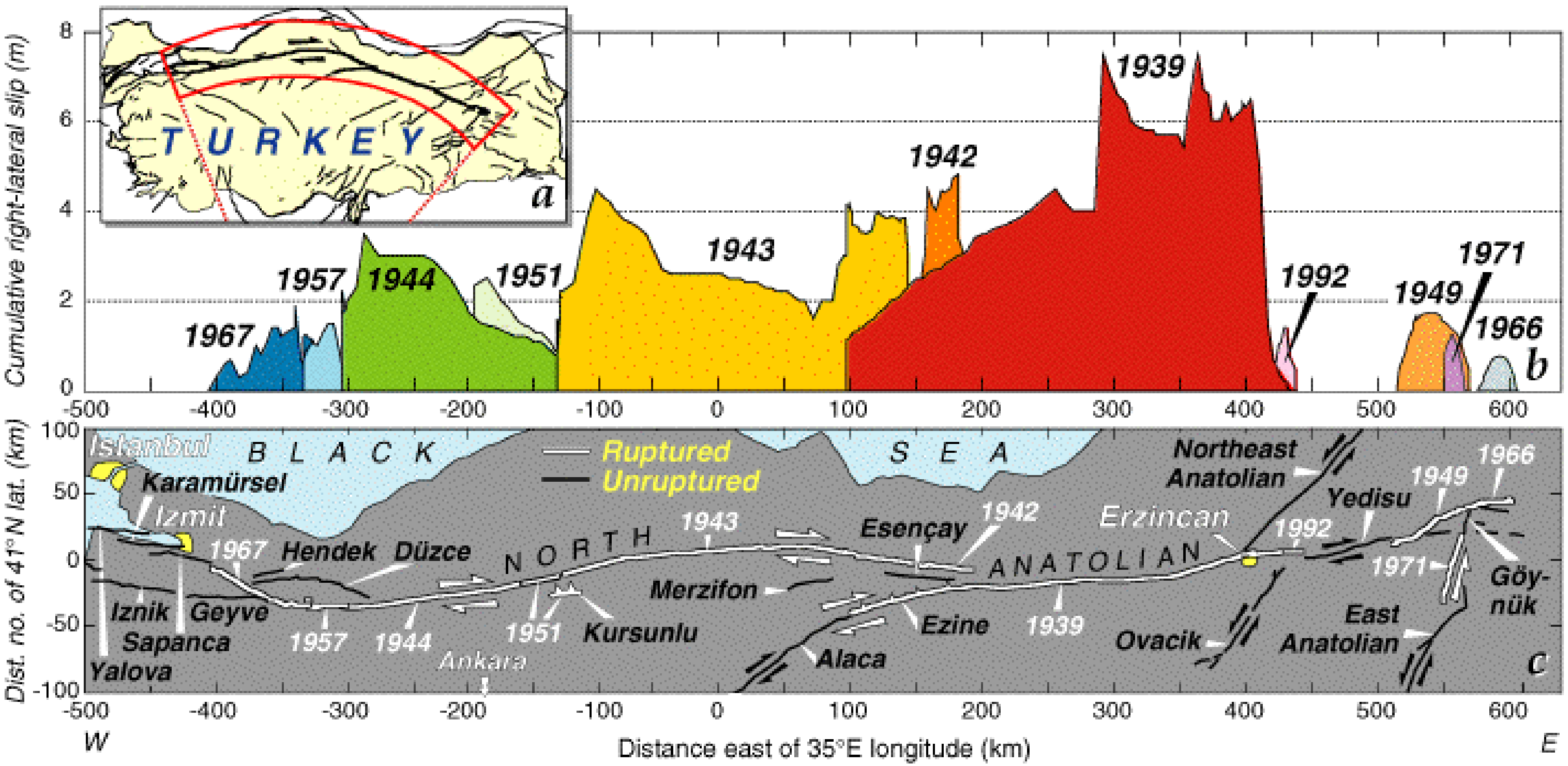


Figure 1 17 Oct 96 Stein et al.

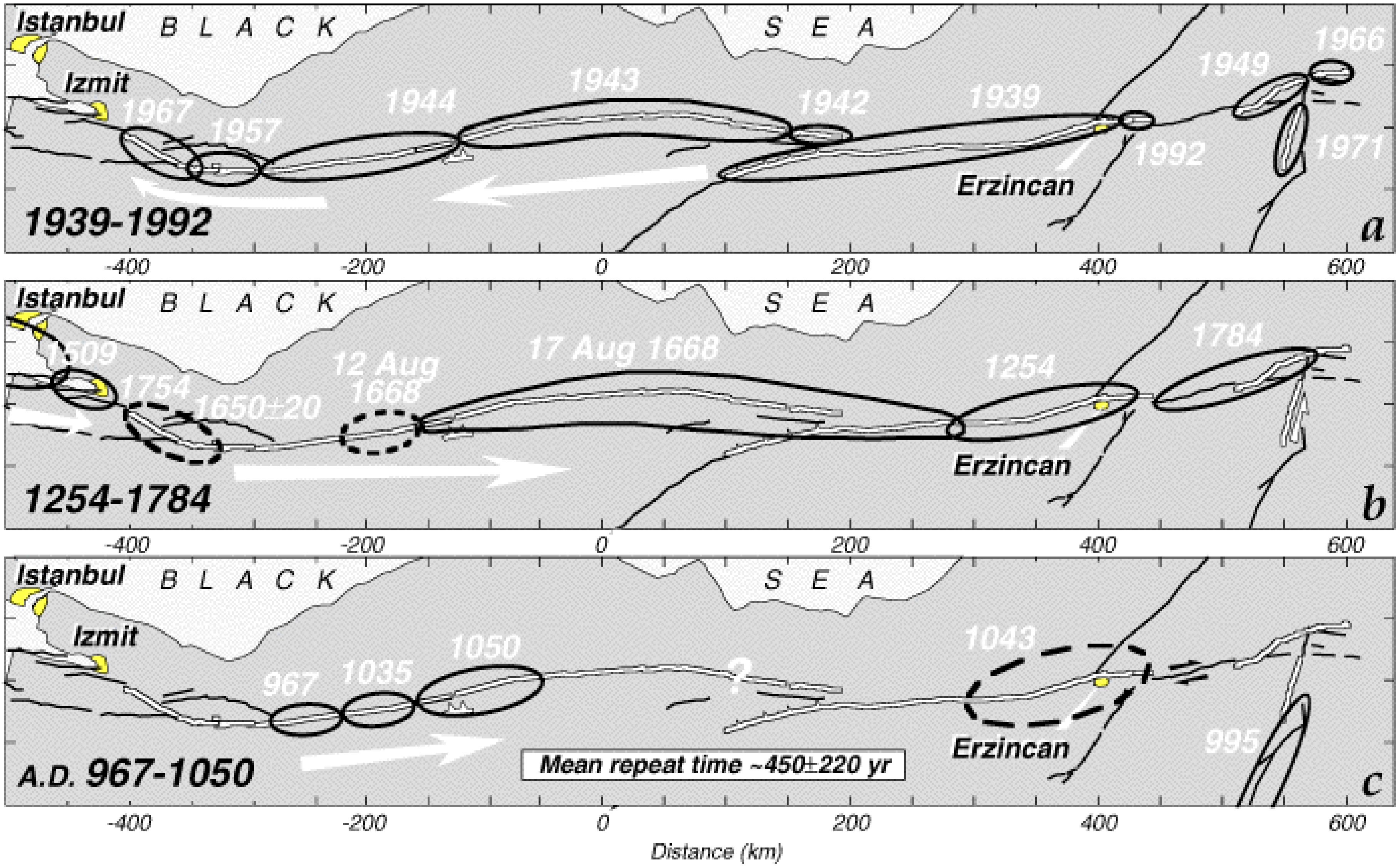
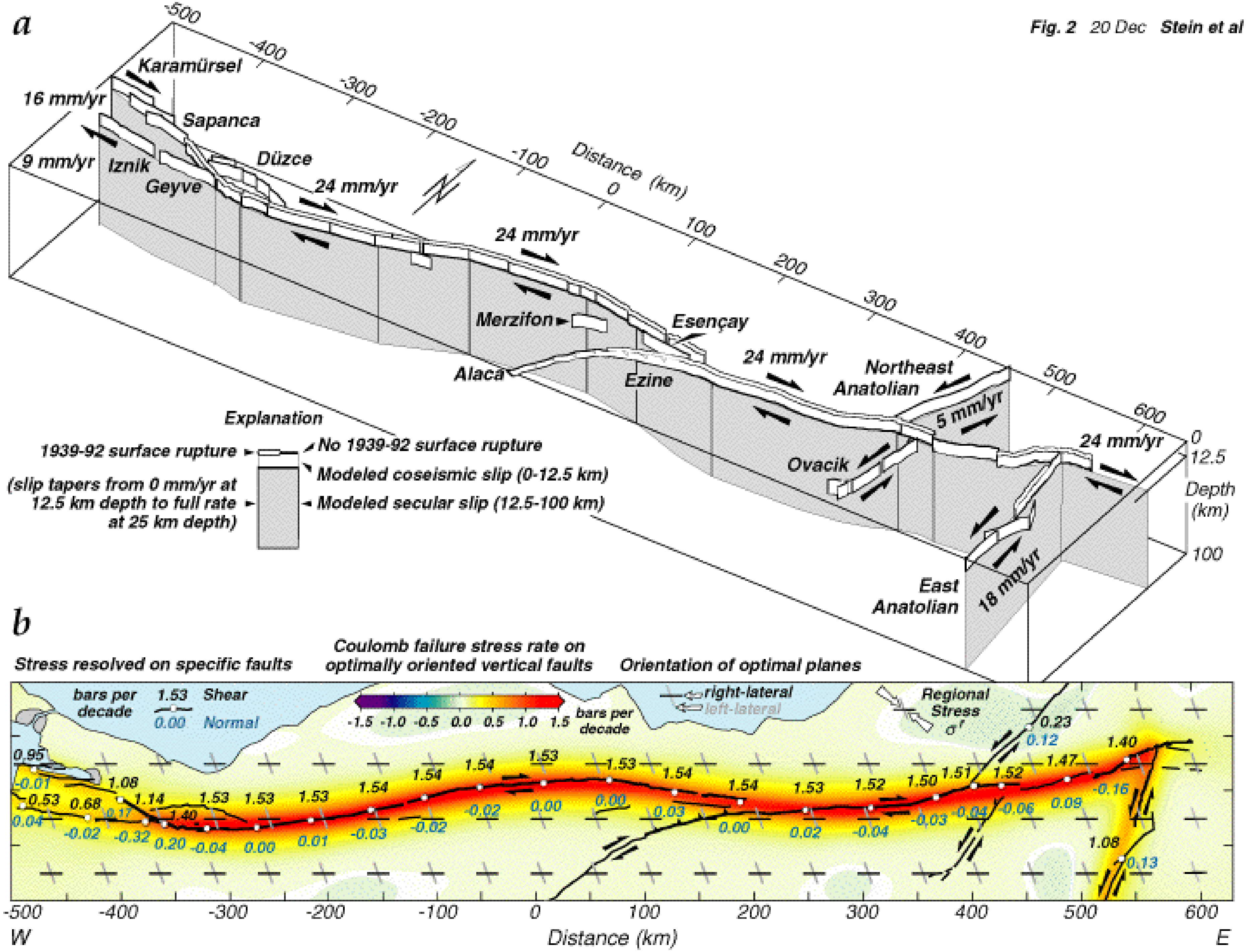


Fig. 7 17 Oct 96 Stein et al.


a
Karamürsel
16 mm/yr
Sapanca
9 mm/yr
Iznik
Geyve
Düzce
24 mm/yr
N
24 mm/yr
Distance (km)
Merzifon
Esençay
Alaca
Ezine
24 mm/yr
Northeast Anatolian
5 mm/yr
Ovacik
24 mm/yr
East Anatolian
18 mm/yr
Depth (km)
0
12.5
100
Explanation
1939-92 surface rupture
No 1939-92 surface rupture
Modeled coseismic slip (0-12.5 km)
(slip tapers from 0 mm/yr at 12.5 km depth to full rate at 25 km depth)
Modeled secular slip (12.5-100 km)
b
Stress resolved on specific faults
Coulomb failure stress rate on optimally oriented vertical faults
Orientation of optimal planes
bars per decade
1.53 Shear
0.00 Normal
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
bars per decade
right-lateral
left-lateral
Regional Stress
Distance (km)
W
E

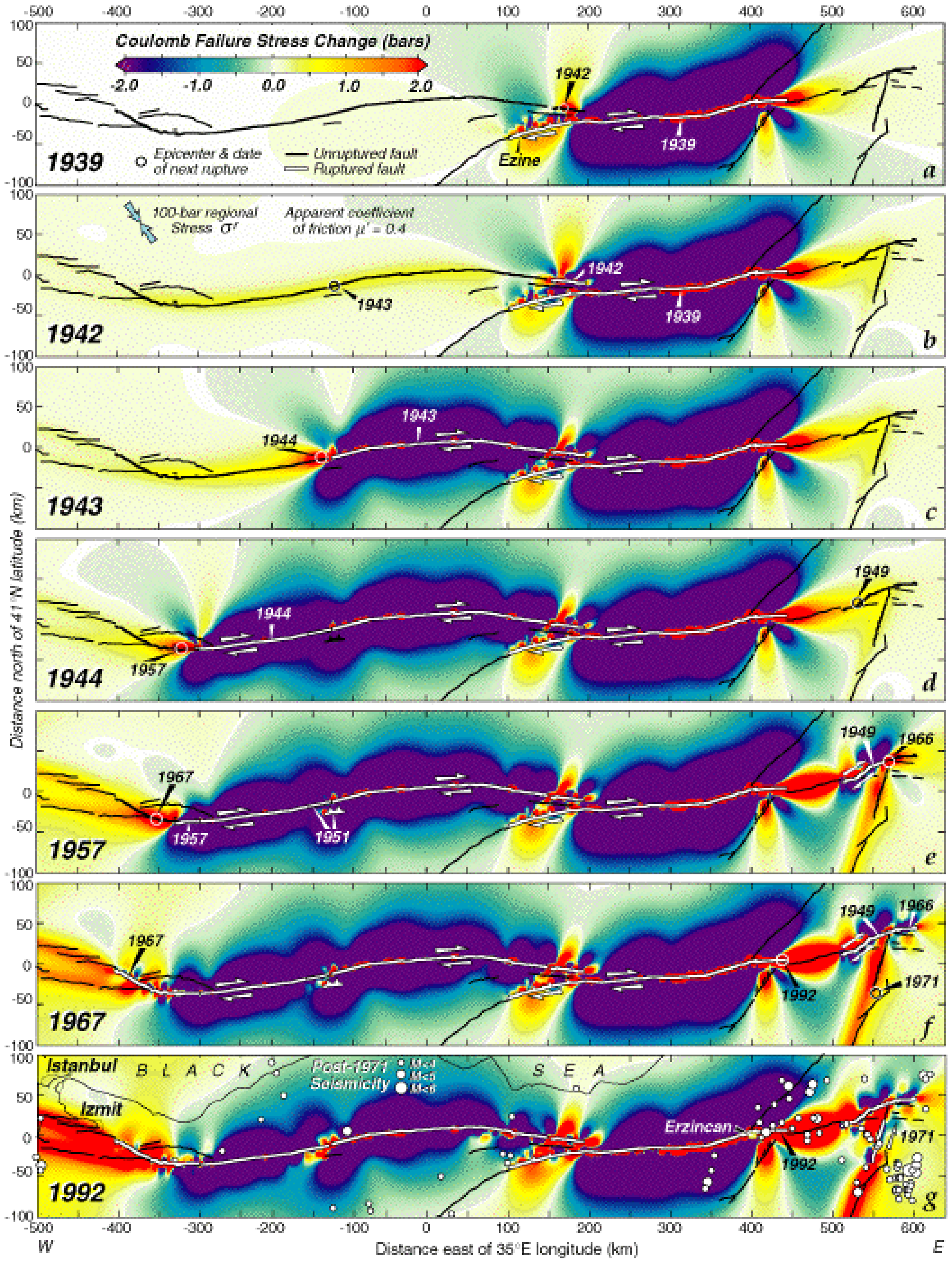


Figure 4 17 Oct 96 Stein et al.

From Stress Change to Earthquake Probability Change