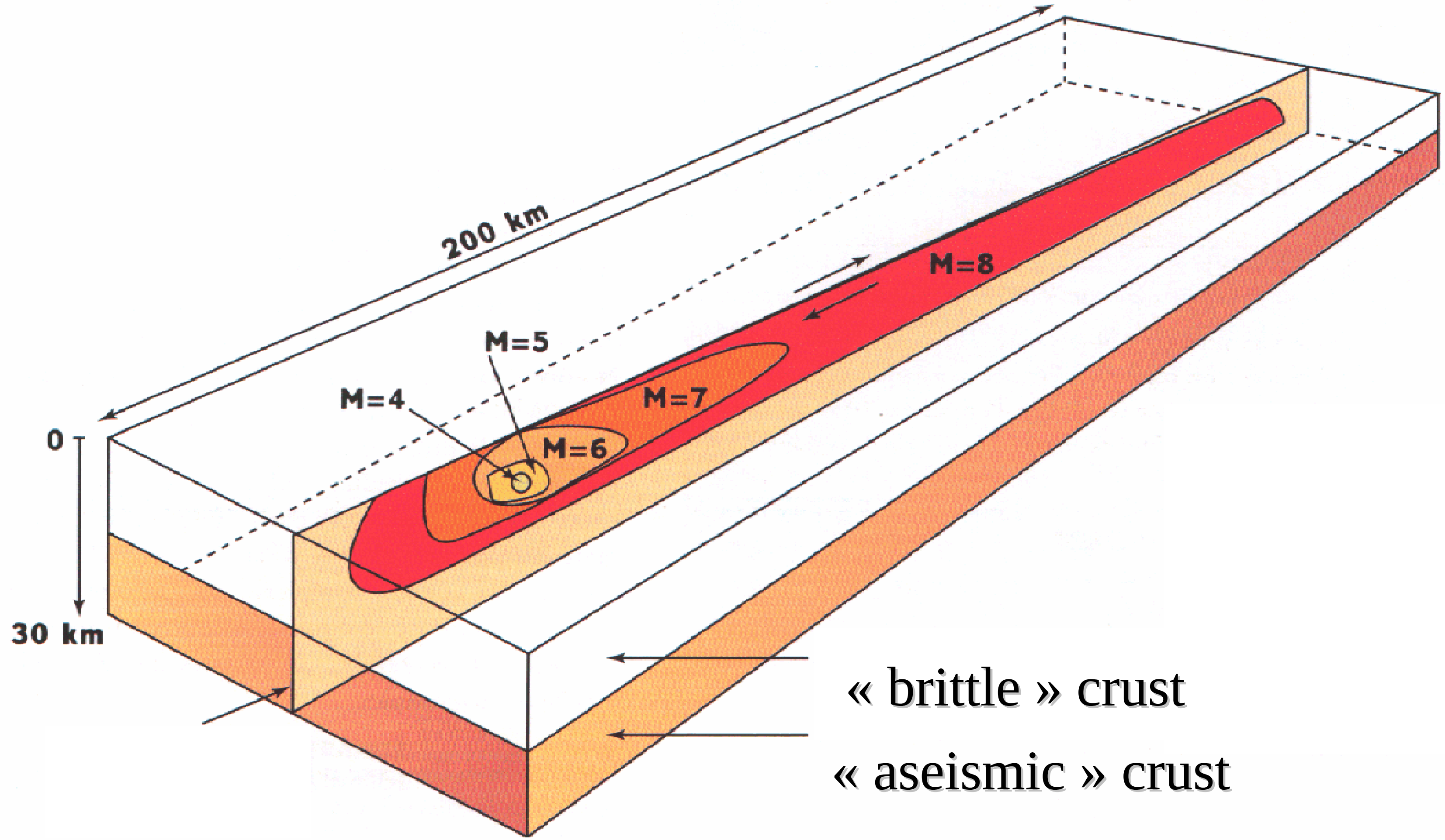
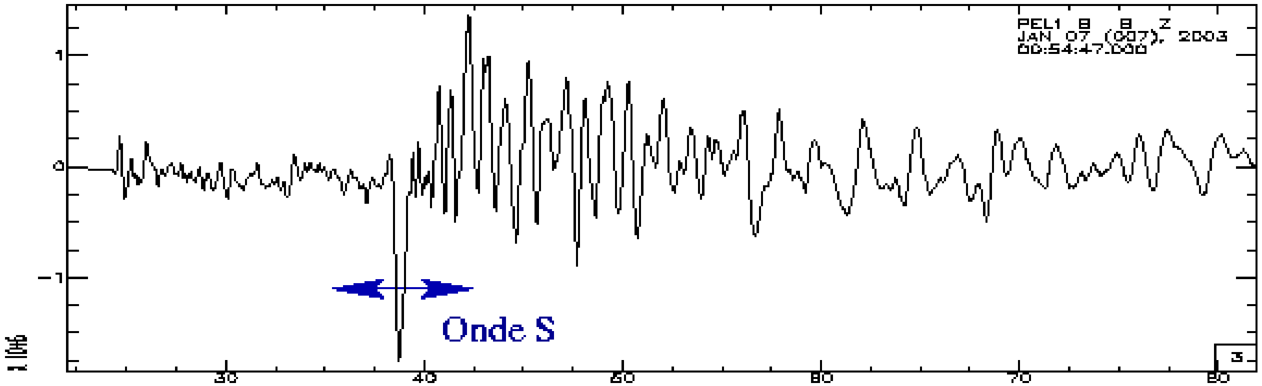
VI Lois d’échelles

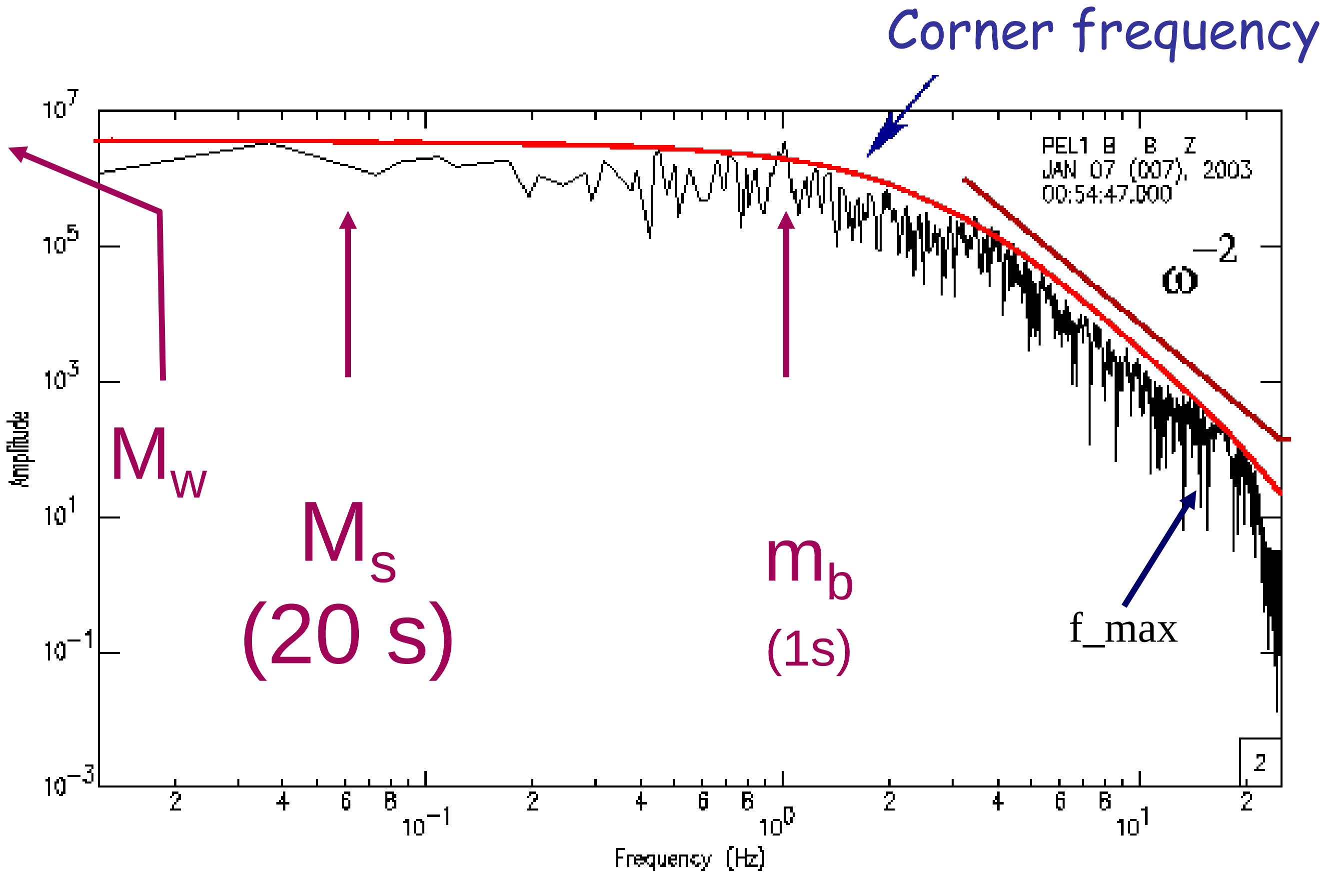
Taille de la rupture et magnitude

$M_w = \log(M_0)/1.5 - 10.73$: moment magnitude (Kanamori)



Typical spectral analysis of a displacement wave form





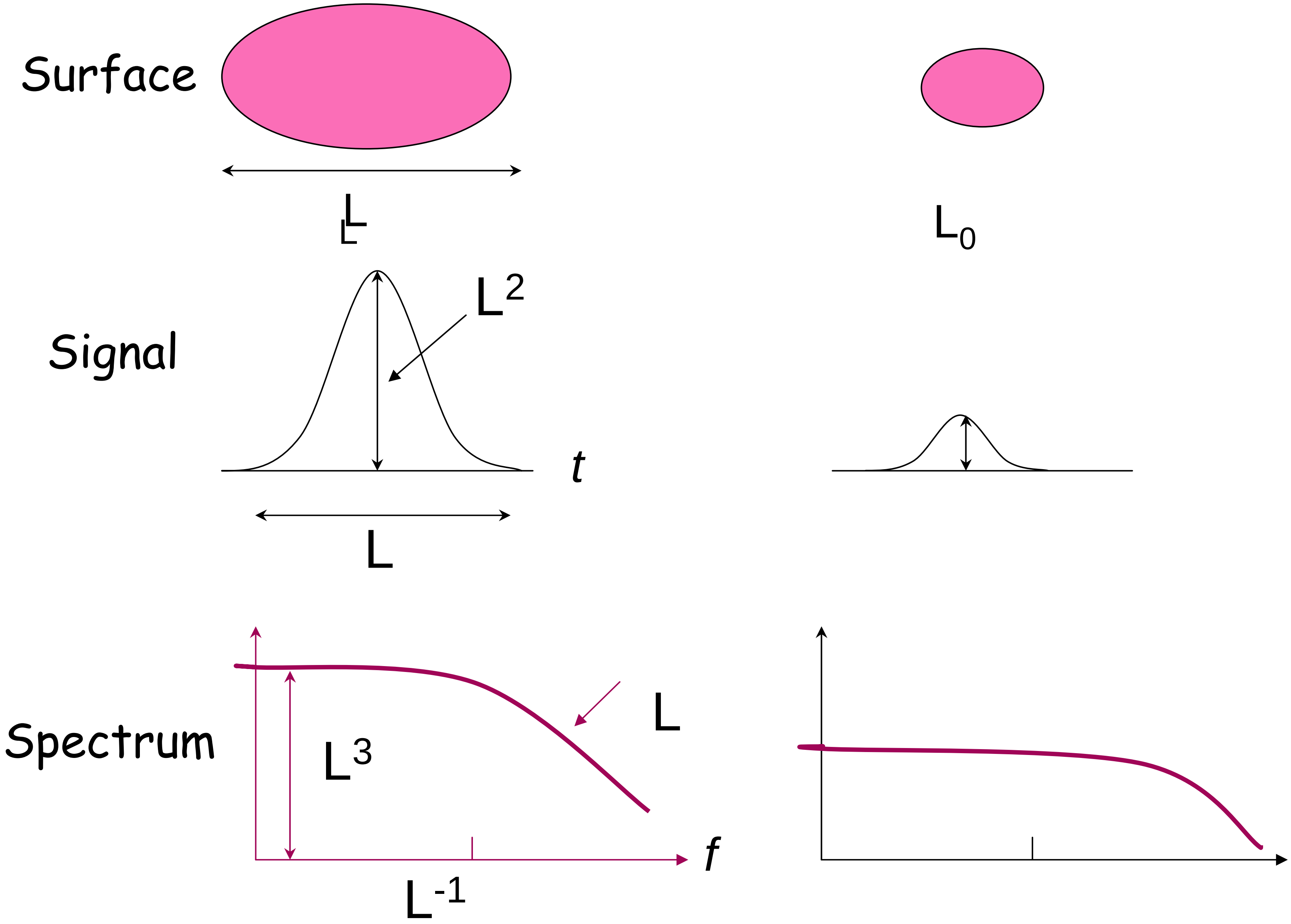
Station PEL
(Geoscope VBB)

7 Jan 2003

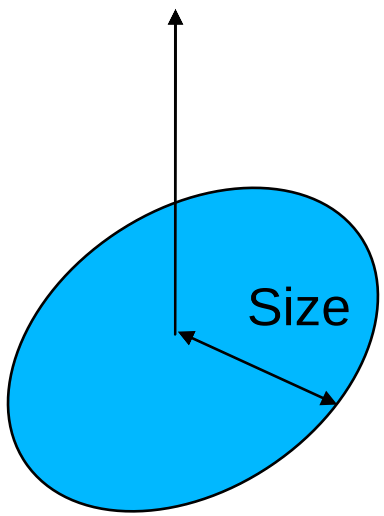
M=6
H=90 km
D=90 km

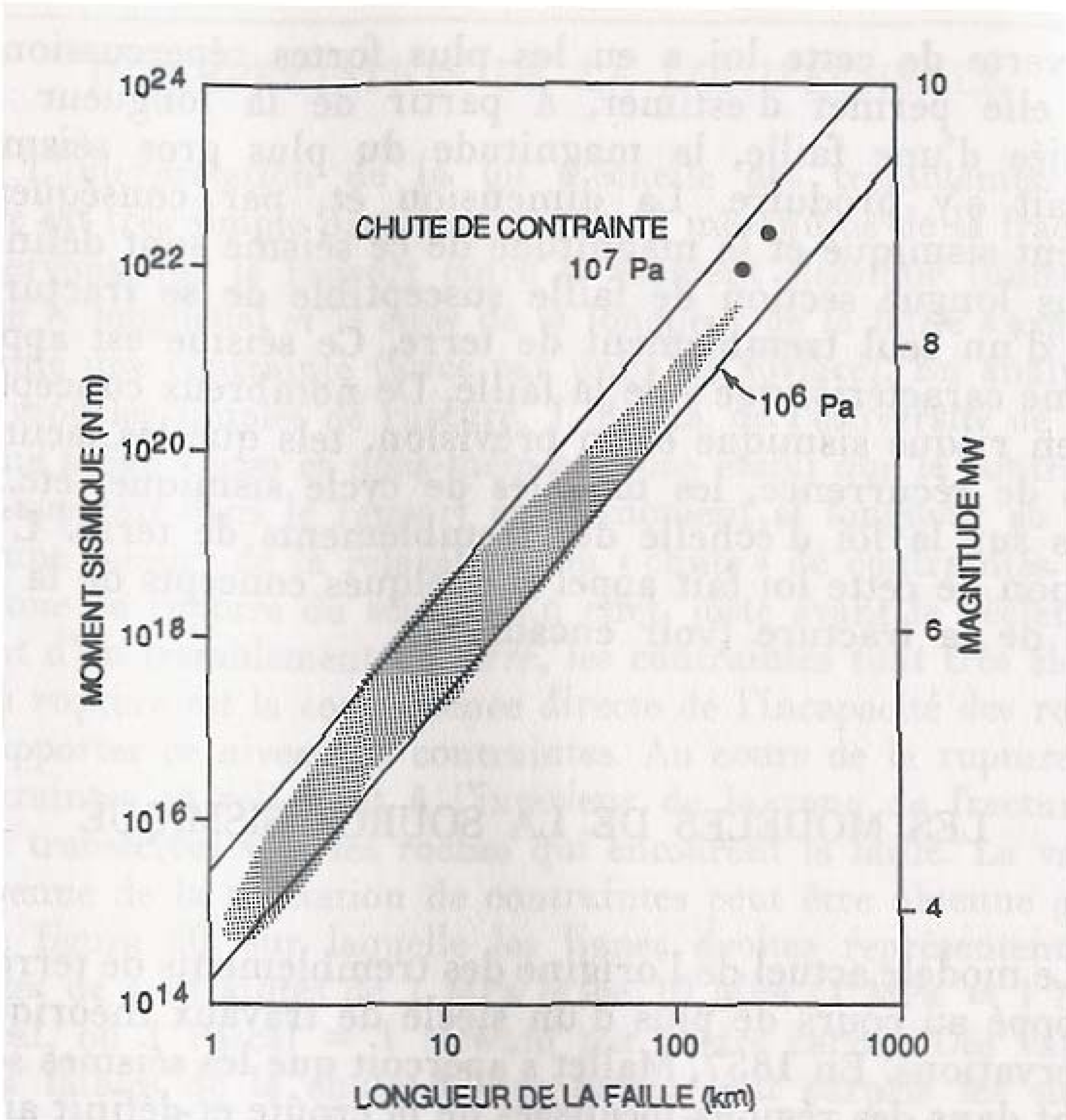
Vertical fault
slab pull
inside Nazca plate

Fundamentals of earthquake scaling



Earthquake scaling law

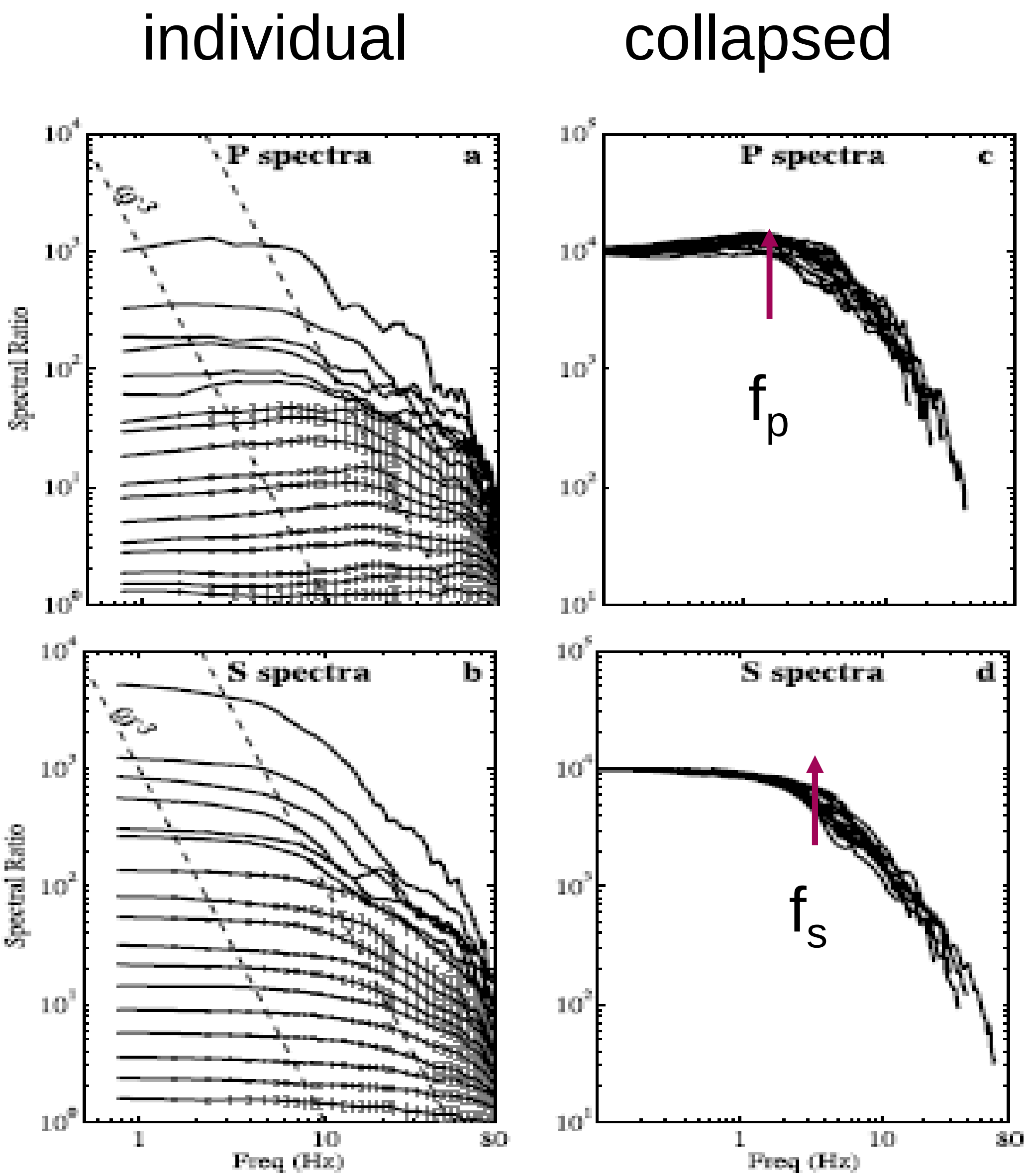




There is a single scale:

Earthquake size L

Modern test of earthquake scaling law



Test by Prieto et al
JGR, 2004

$$f_p / f_s = 1.6$$

Circular crack model

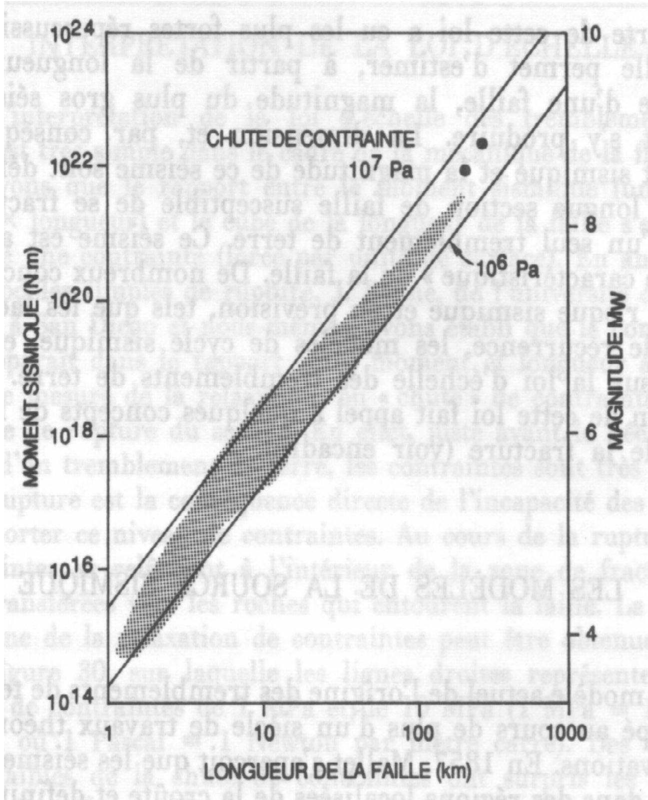
$$f_p / f_s = 1.7$$

(Madariaga, 76)

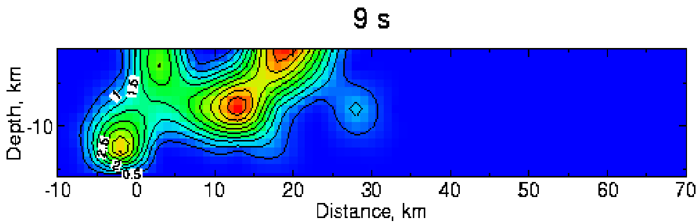
Lois d'échelle des ruptures sismiques

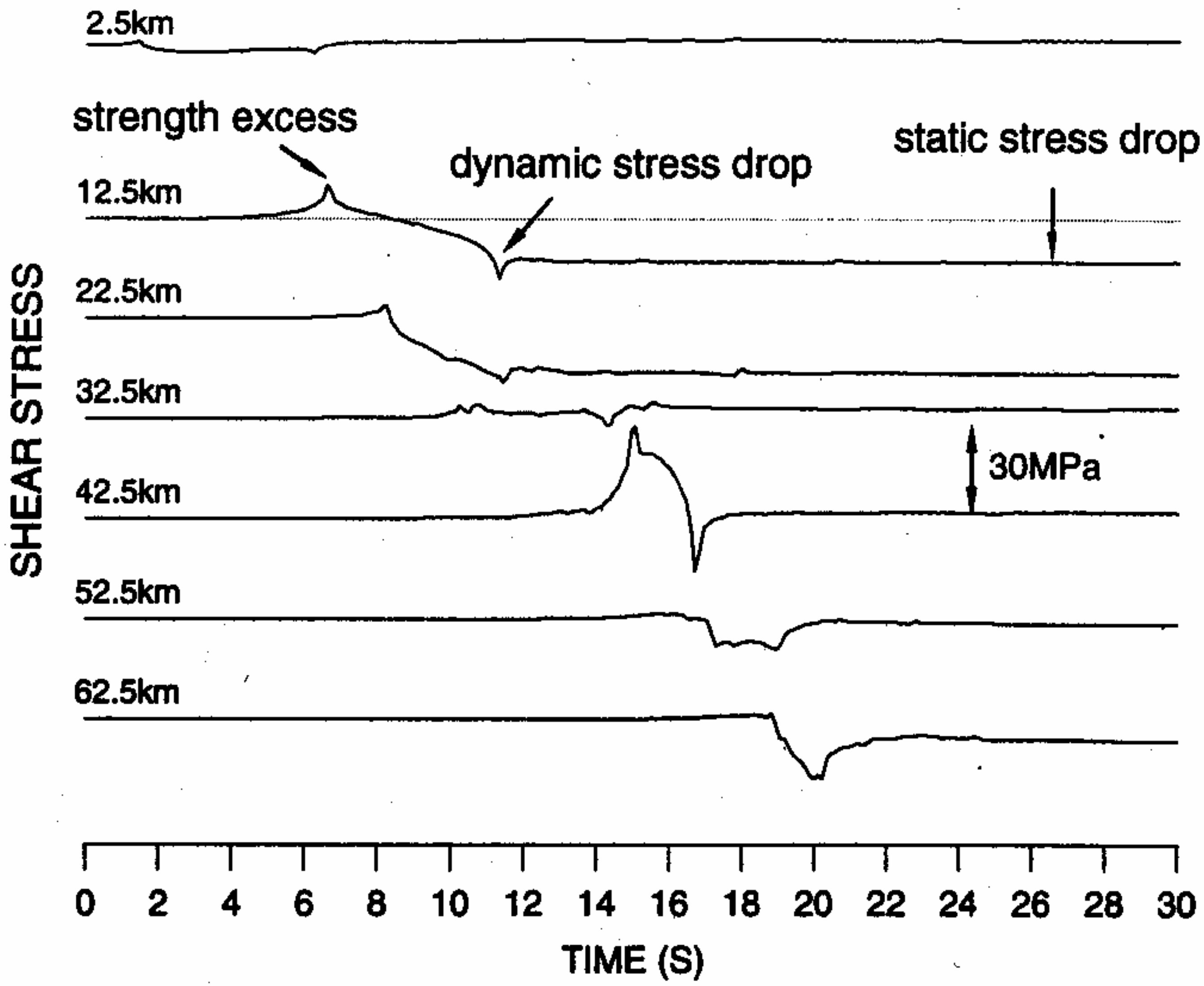
Magnitude	Longueur de faille	Coulissage moyen	Durée de rupture
9	800 km	15 m	250 s
8	200 km	5 m	60 s
7	50 km	1 m	15 s
6	10 km	20 cm	3 s
5	3 km	5 cm	1 s
4	1 km	1 cm	0,3 s

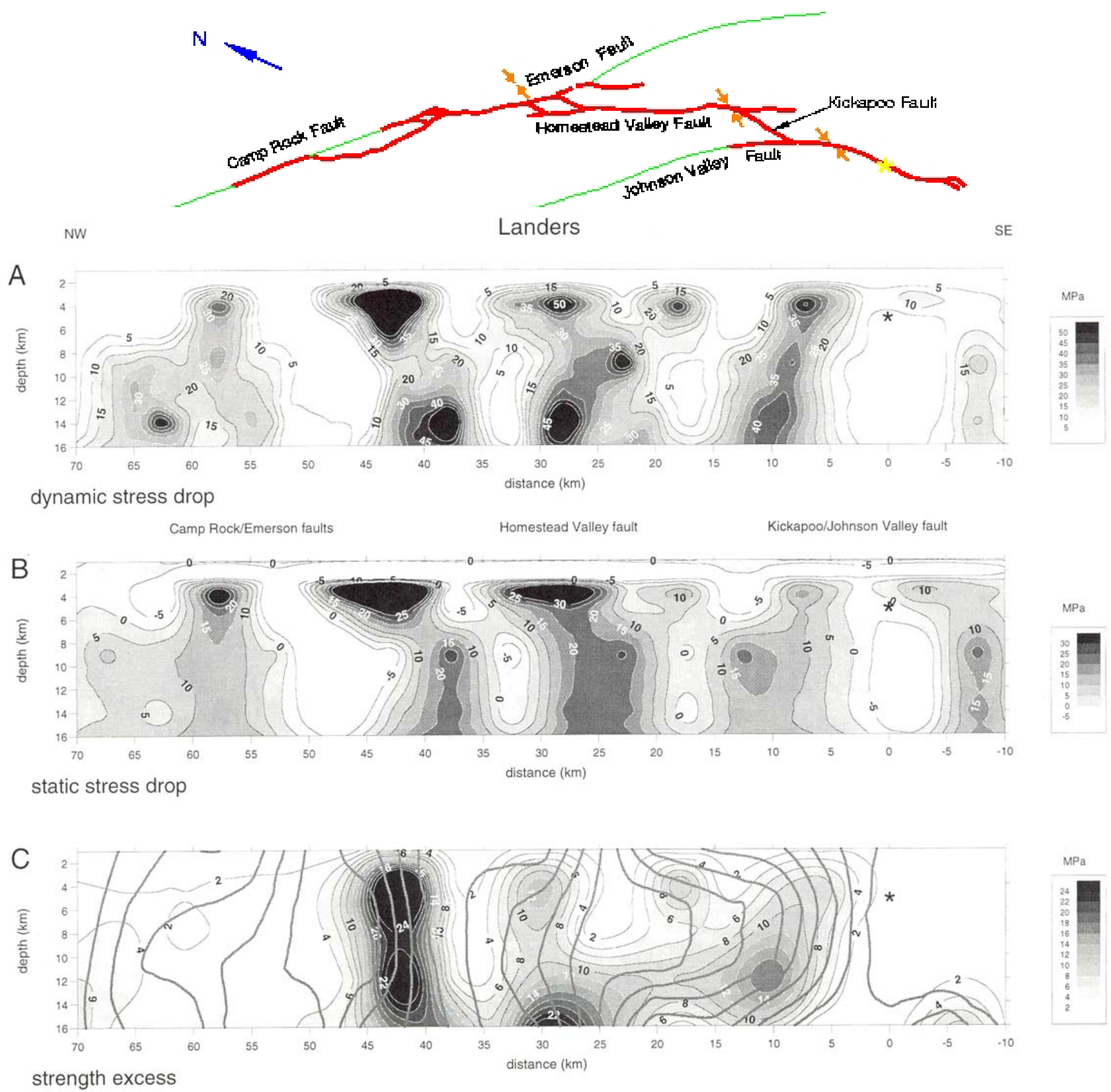
Variabilité : 50 %



Les tremblements de terre en France 1997, Madariaga et Perrier , 1991


9 s
Depth, km
-10
-10
0
10
20
30
40
50
60
70
Distance, km


2.5km
strength excess
12.5km
dynamic stress drop
static stress drop
22.5km
32.5km
30MPa
42.5km
52.5km
62.5km
SHEAR STRESS
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
TIME (S)


N
Emerson Fault
Camp Rock Fault
Homestead Valley Fault
Kickapoo Fault
Johnson Valley Fault
NW
Landers
SE
A
depth (km)
distance (km)
MPa
dynamic stress drop
Camp Rock/Emerson faults
Homestead Valley fault
Kickapoo/Johnson Valley fault
B
depth (km)
distance (km)
MPa
static stress drop
C
depth (km)
distance (km)
MPa
strength excess

A finite shear crack of radius a with uniform stress drop $\Delta\sigma$: static solution (Eshelby, 1957):

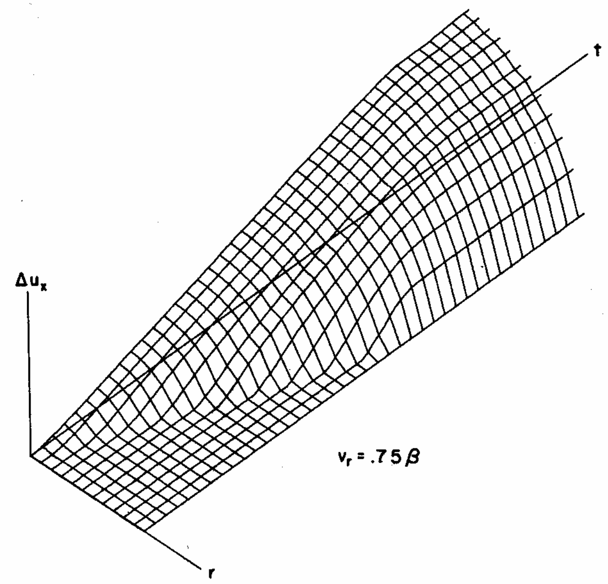
$$\Delta u(\xi) = \frac{7\pi}{12}\frac{\Delta\sigma}{\mu} a \sqrt{1 - \frac{\xi^2}{a^2}}$$

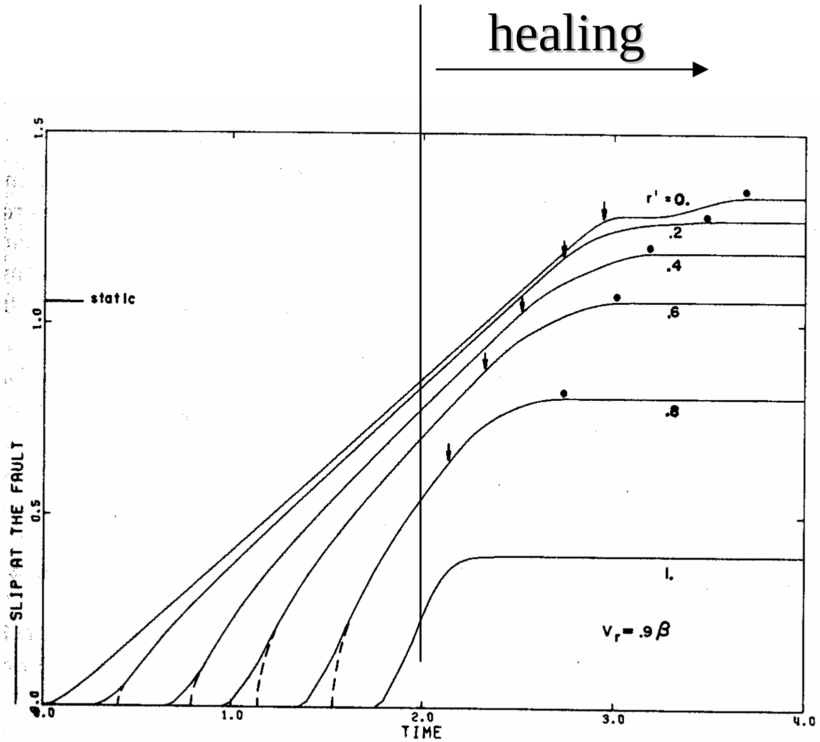
$\Rightarrow [u]_{max}$ or $[\bar{u}] \sim a$ at constant $\Delta\sigma$

$$M_0 = \mu[\bar{u}]\pi a^2 = \frac{16}{7}\Delta\sigma a^3$$

Kostrov’s self similar propagating crack: elliptical slip distribution

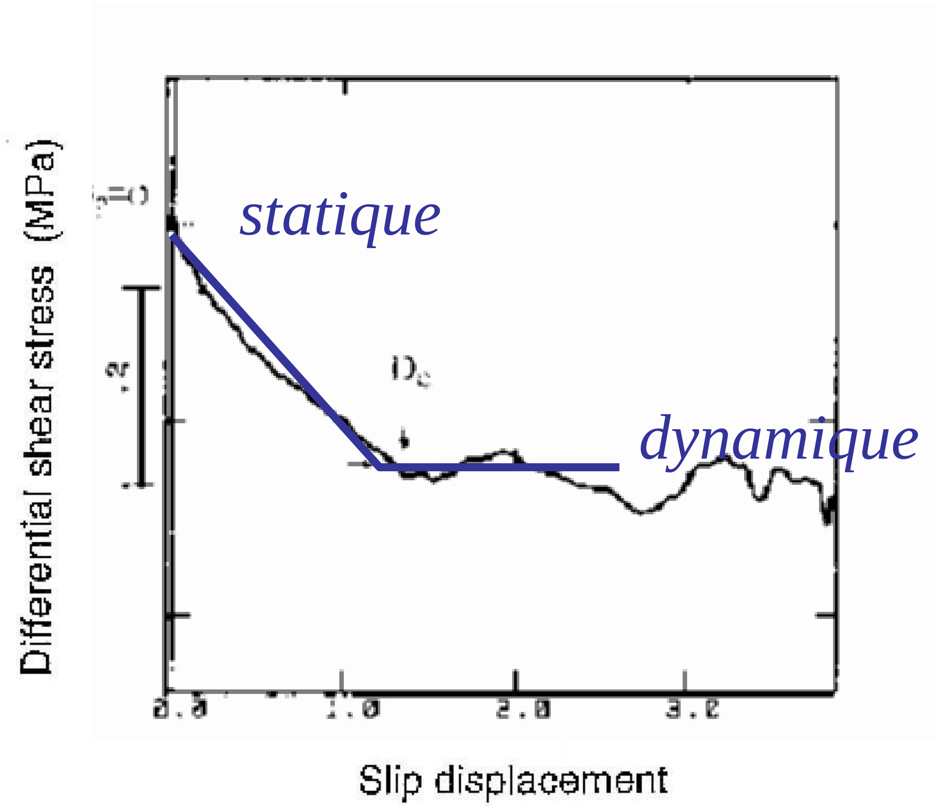
Madariaga (1976):
Numerical solution for a circular crack of finite size propagating at constant velocity.





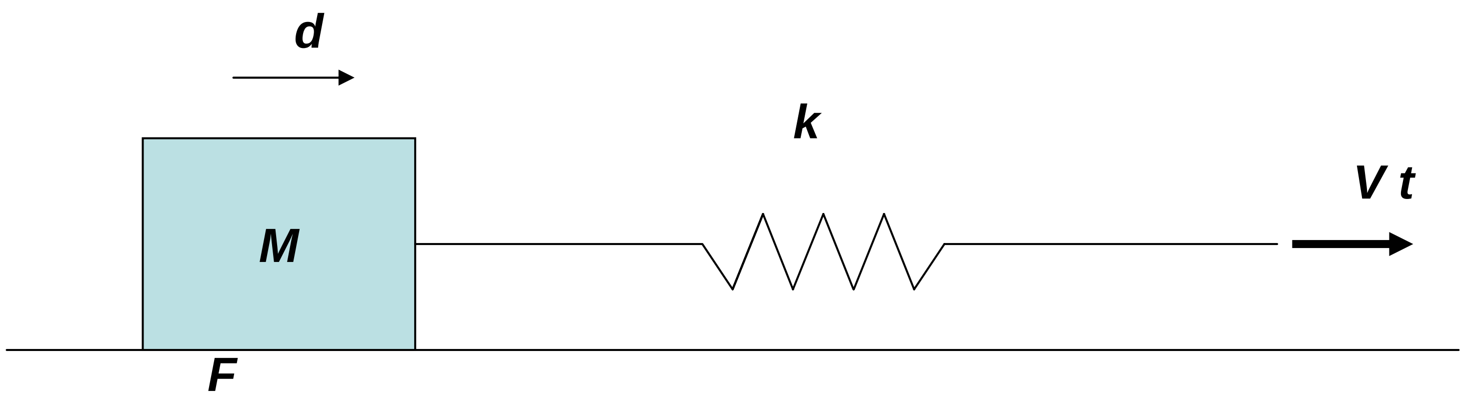
Loi de friction avec affaiblissement

Expérience de laboratoire



Taux d'affaiblissement

$$\alpha_c = \frac{-\sigma_{zz}^{\infty}(\mu_s - \mu_d)}{\rho v_s^2 L_c} = \frac{\sigma_s - \sigma_d}{G L_c}$$



$$M\frac{\partial^2 d}{\partial t^2} = k(l_0 + vt) - F; \quad F = Mg(\mu_s - \alpha d)$$

Autour de la position limite ($g = 0$):

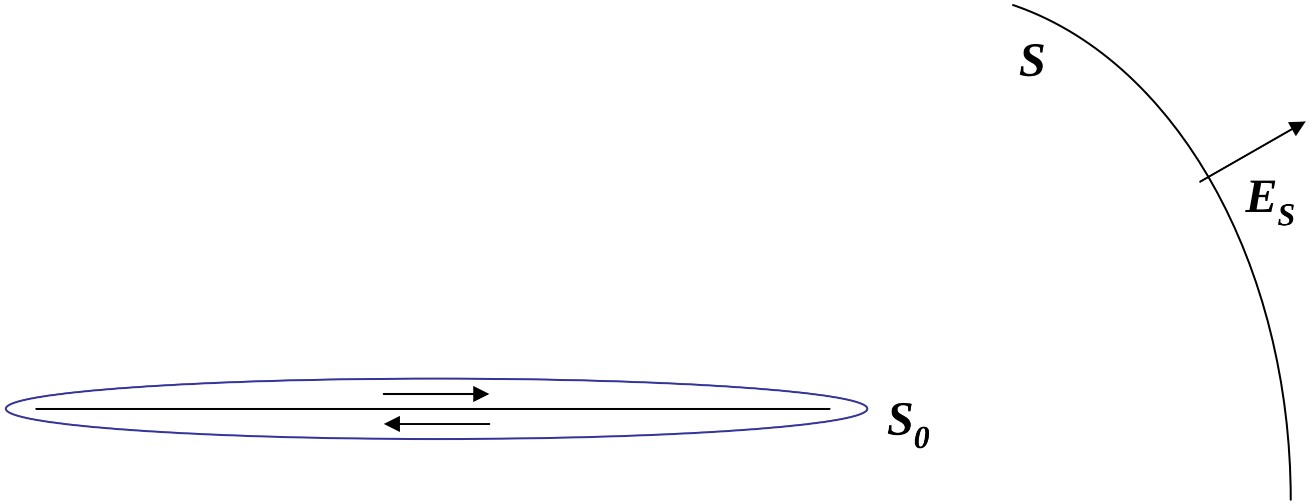
$$k(l_0 + vt) = F$$

$$\rightarrow M\frac{\partial^2 d}{\partial t^2} = kd - Mg\alpha d$$

Laplace: solution sous la forme $d = d_0 exp(\lambda t)$

$$M\lambda^2 d = (-k + Mg\alpha)d \rightarrow \lambda^2 = -\frac{k}{M} + g\alpha$$

si $g\alpha > \frac{k}{M} \rightarrow \lambda$ réel instabilité
si $g\alpha < \frac{k}{M} \rightarrow \lambda$ imaginaire stabilité



Bilan d'énergie d'un séisme

Energie totale: $E_T = \int_0^t dt \int_{S_0} \dot{D}\Delta\sigma dS_0$

- énergie sismique émise: E_S
- énergie de déformation statique: ΔW
- énergie de fracturation : $\int_{S_0} \gamma dS$

On peut mesurer l'énergie sismique

$$E_S = \int_0^t dt \int_S \dot{u}_i \Delta\sigma_{ij} n_j dS$$

$$E_S = E_T - \Delta W - \int_{S_0} \gamma dS$$

Calcul de ΔW

densité d'énergie = déformation $\times$ contrainte agissante

- contrainte

$$\sigma_a \approx <\sigma> - \sigma_f$$

$$<\sigma> \approx \frac{1}{2}(\sigma_0 + \sigma_f) \rightarrow \sigma_a \approx \frac{1}{2}(\sigma_0 - \sigma_f) = \frac{1}{2}\Delta\sigma$$

- déformation

$$\epsilon = \frac{D}{\delta z}$$

où δz est l'épaisseur de la faille.

$$\Delta W = \int_{V(S_0)} \frac{D}{\delta z} \frac{1}{2} \Delta\sigma dV$$

$$dV = \delta z dS \rightarrow \Delta W = \frac{1}{2} \int_{S_0} D\Delta\sigma dS \approx \frac{1}{2} E_T$$

$$E_S = E_T - \Delta W - \int_{S_0} \gamma dS = \Delta W - \int_{S_0} \gamma dS$$

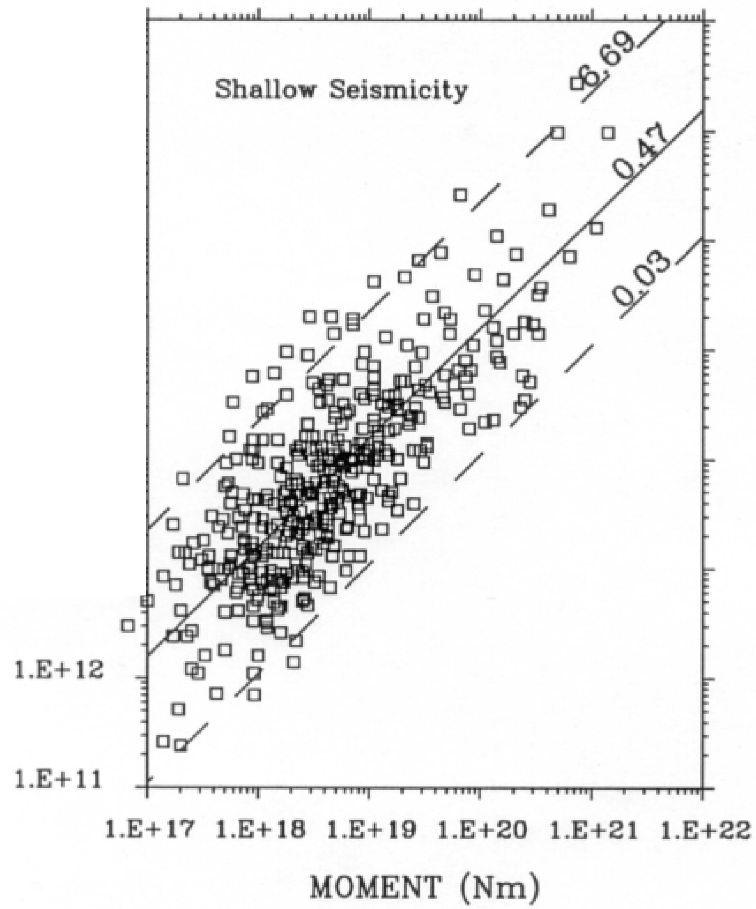
En supposant que $\Delta\sigma \approx$ constant:

$$E_S = (\frac{1}{2}\Delta\sigma < D > - < \gamma >)S$$

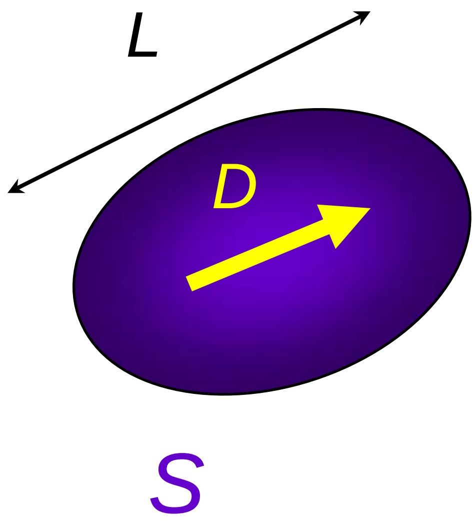
Pour les gros séismes:

$$< \gamma > << \frac{1}{2}\Delta\sigma < D >$$

$$E_S = \frac{1}{2}\Delta\sigma < D > S = \frac{1}{2\mu}\Delta\sigma M_0$$



Simple circular model



Moment

$$M_o = \mu\, DS \approx \mu L^3$$

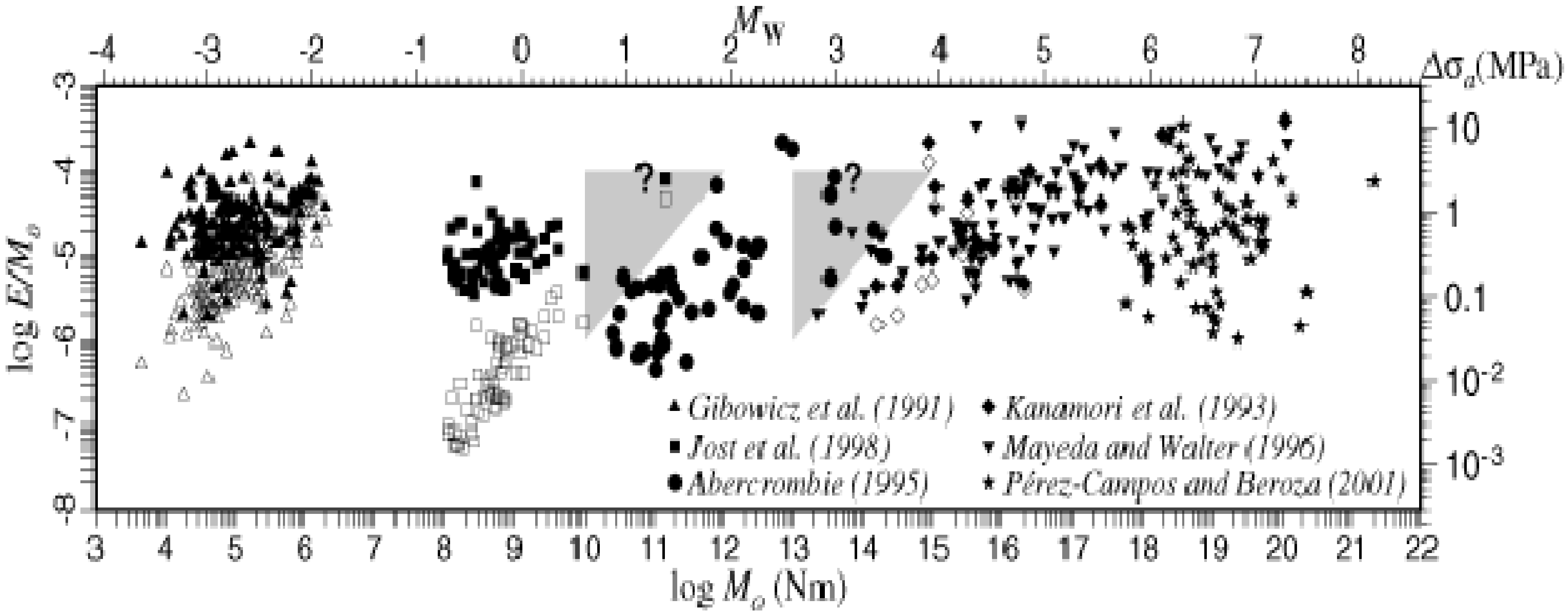
Seismic energy

$$E_S = \#\, \Delta\sigma\, D\, S \approx \Delta\sigma L^3$$

Energy moment ratio

$$\frac{E_s}{M_o} \approx \frac{\Delta\sigma}{\mu}$$

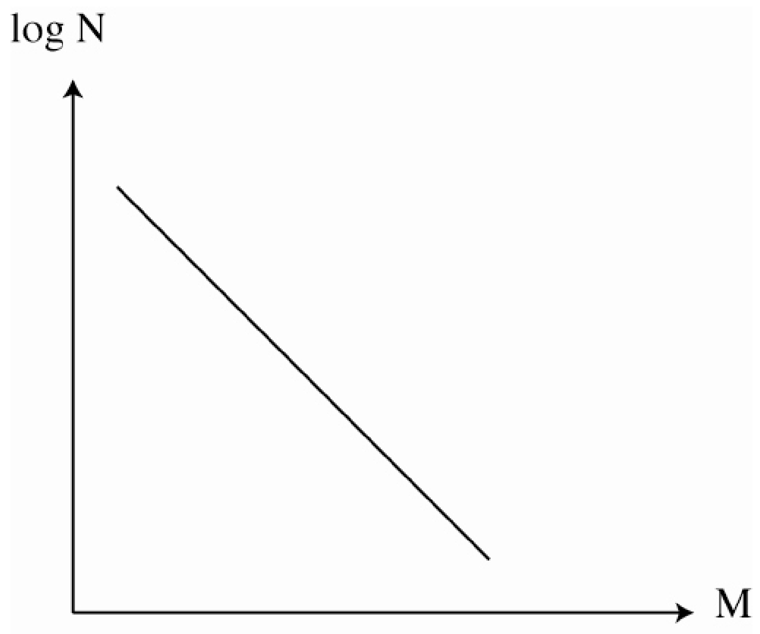
Summary of Observed Radiated Energy vs Moment



$$\log M_o = 1.5\, M_w + 9.6$$

Beroza et al, 2001

LOI DE GUTEMBERG ET RICHTER :



$$\log N = -bM + \log a$$

a : constante et b : constante

N : nombre de séismes par unités de temps de magnitude supérieure M.

On observe suivant les régions : $0.8 < b < 1.2$ (attention à la validité statistique!)

Pour la sismicité globale, b $\simeq$ 1.

Relation magnitude-moment:

$$\log M_0 = 1.5M + 9.1 = cM + d$$

$$M_0 \sim \Delta\sigma L^3 \;\Rightarrow\; \log M_0 = 3\log L + \log\Delta\sigma$$

$$\begin{aligned}\log N &= -bM + \log a \\ &= \frac{-b}{c}\left(\log M_0 - d\right) \\ &= \frac{-b}{c}\;3\log L + C^{ste}\end{aligned}$$

$$N = \beta L^{-\frac{3b}{c}} = \beta S^{-\frac{3}{2}\frac{b}{c}} \qquad ou \;\; S = L^2$$

avec $c = 1.5 \;\Rightarrow\; N = \beta\; L^{-2b}$

avec $b = 1 \;\Rightarrow N = \beta\; L^{-2} = \beta\; S^{-1}$

DEFINITION DE LA DIMENSION :

Exemple classique des côtes, topographies, fragmentations :
Fragmentation :
N : Nombre d'objets de dimension caractéristique $> r$
vérifie : $N = \frac{C}{r^D}$, C constante, D : dimension fractale

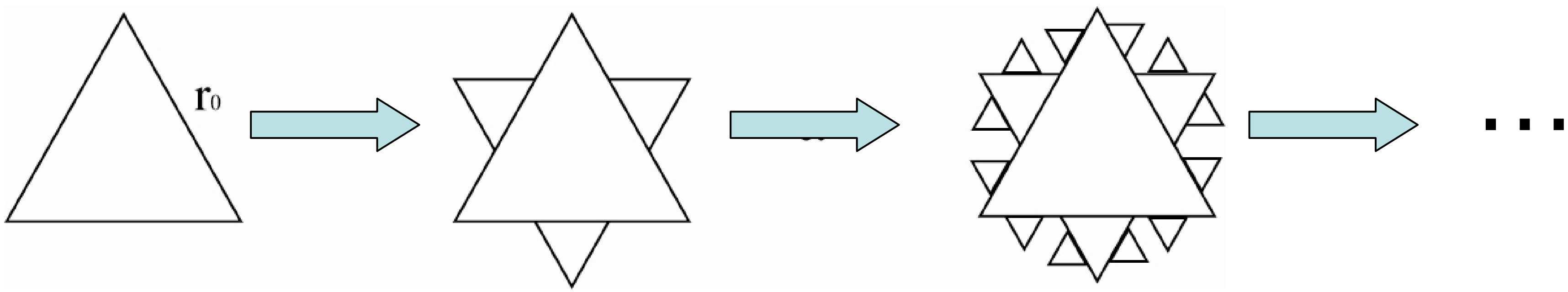
Exemples :

- d'un segment de droite : mesuré avec différentes règles . 10 fois plus de mm que de cm, etc... $\Rightarrow$ D=1
- d'un carré plein : mesuré avec diférents carrés de côtés variables. $\Rightarrow$ il en faut 100 fois plus avec $1mm^2$ qu'avec $1cm^2$ $\Rightarrow$ D=2

$\rightarrow$ peut être fractale : exemple longueur de la côtes $\rightarrow$ la longueur varie suivant la mesure utilisée $\Rightarrow$ D=1.25

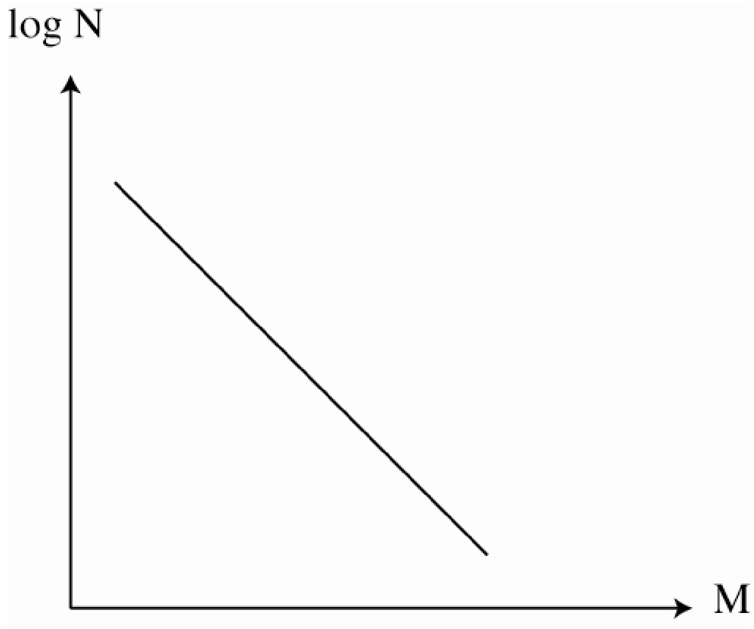
$\rightarrow$ Un modèle simple $\rightarrow$ périmètre de l'Ile de Koch

Sur chaque côté d'un triangle, on rajoute un triangle de côté $= \frac{r_0}{3}$



La croissance se fait dans une surface finie, la longueur du périmètre est infinie mais suit une loi puissance avec $D \simeq 1.262$.

$$logN = -bM + \log a$$



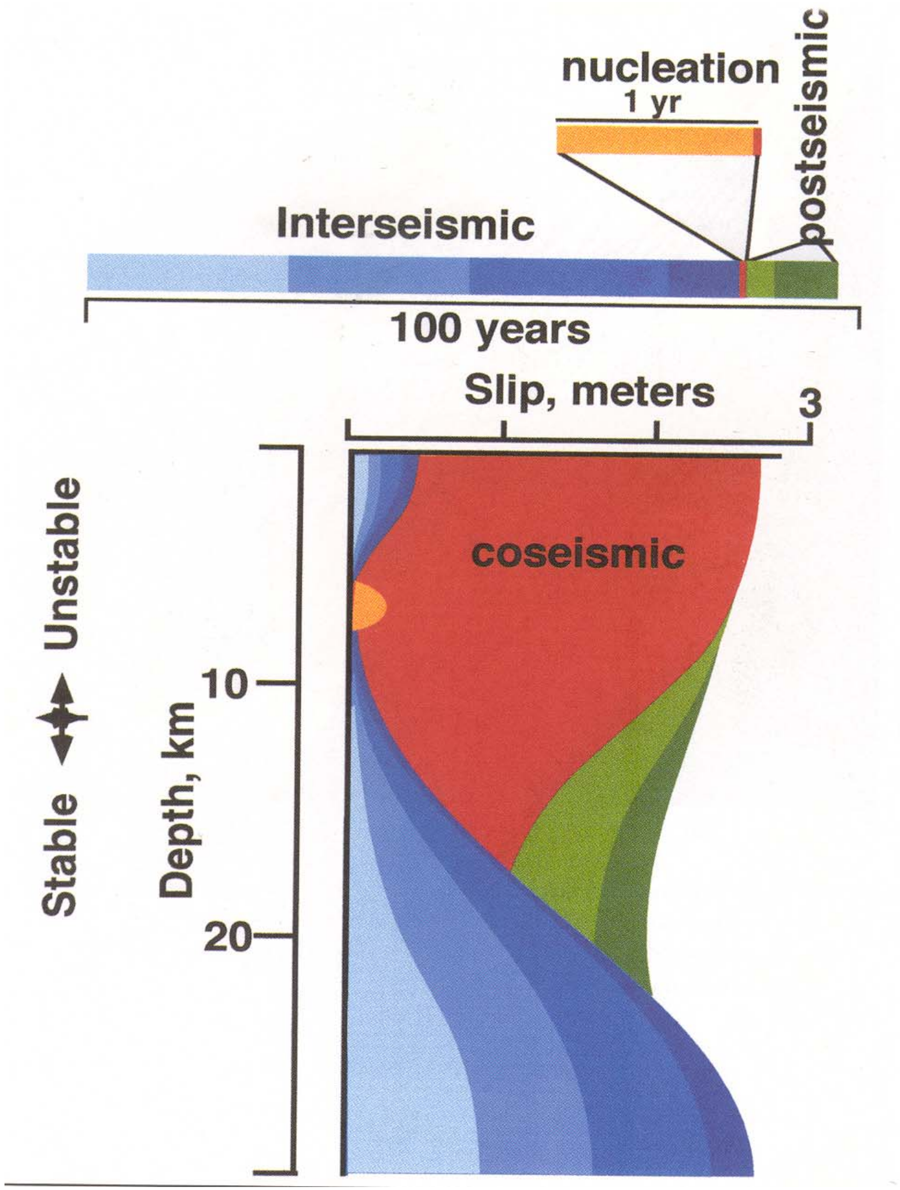
$$b = 1$$

L'ensemble de faille décrit par la sismicité a donc une "dimension" donnée par la loi de Gutemberg et Richter.

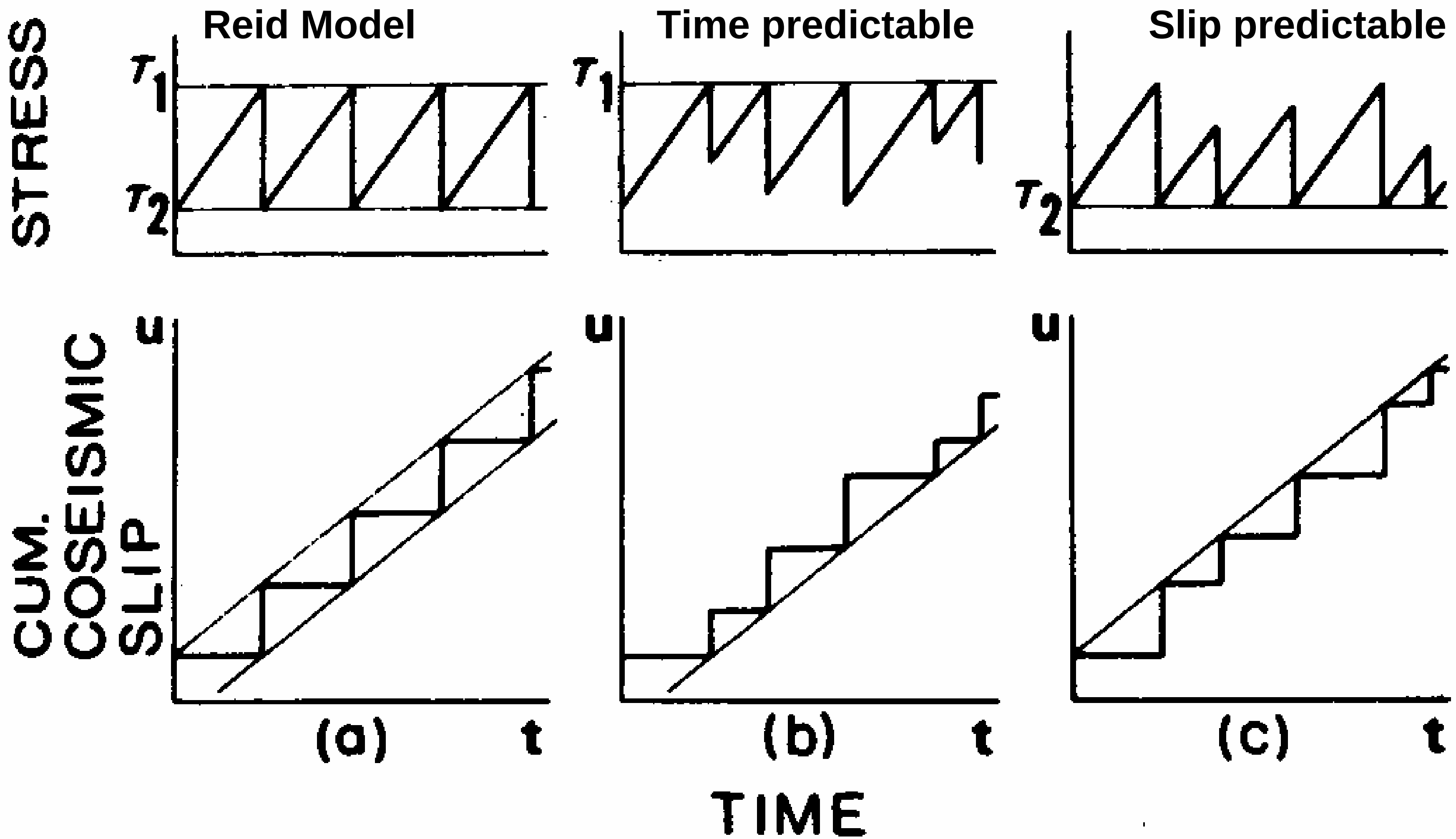
$$\Rightarrow \; N \simeq \beta L^2 \; \Rightarrow \boxed{D = 2.}$$

si $b \; < \; 1 \quad \Rightarrow \; D \; < \; 2 \; \Rightarrow$ "'surface lacunaire"'

$b \; > \; 1 \quad \Rightarrow \; D \; > \; 2 \; \Rightarrow$ "'source volumique"'



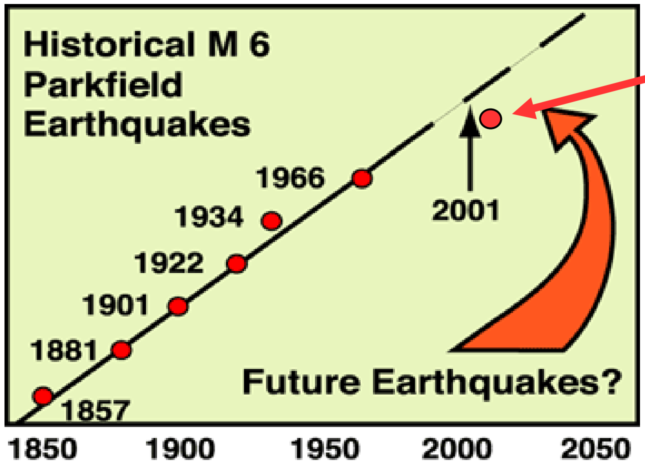
(Tse and Rice, 1997)


Reid Model
Time predictable
Slip predictable
STRESS
τ_1
τ_2
CUM. COSEISMIC SLIP
u
(a)
(b)
(c)
t
TIME

Scholz, 1989

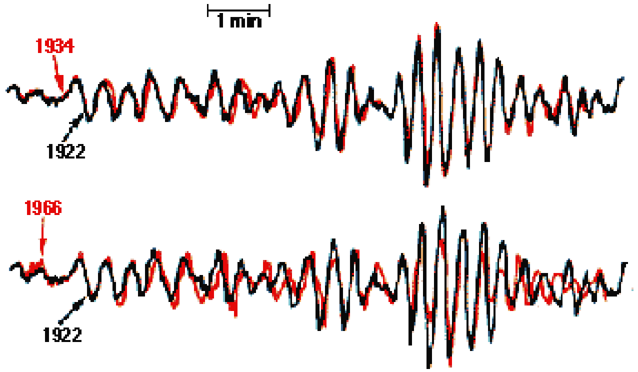
Parkfield

(Backun, McEvilly and Lindh, 1979, 1984, 1985)



28 September 2004, 18:17 GMT
M=6

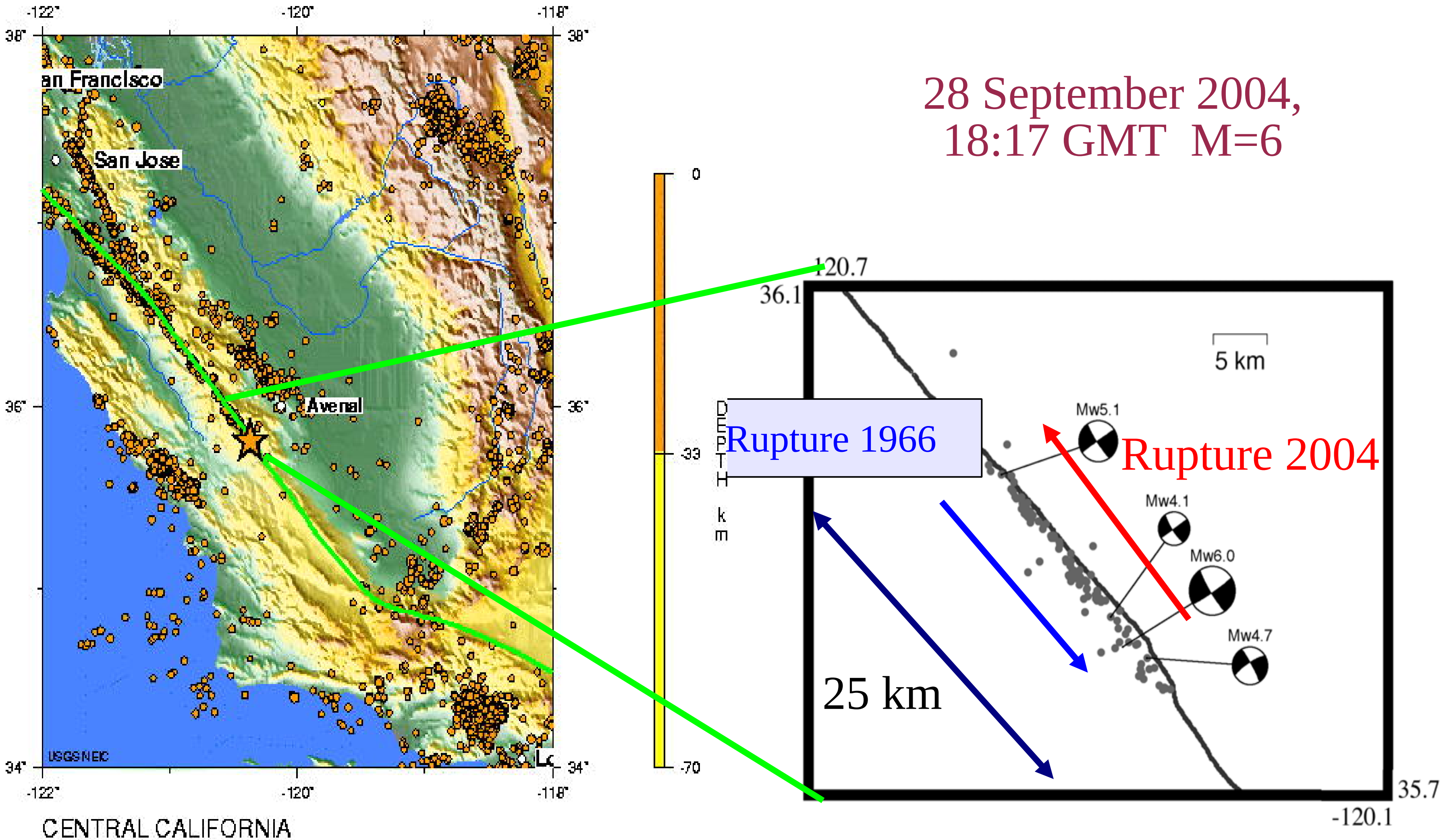
Since 1857
6 earthquakes de M 6 Parkfield



1922, 1934 et 1966 : same signal
At the station DBN

Parkfield : a characteristic earthquake ?

28 September 2004, 18:17 GMT M=6



CENTRAL CALIFORNIA

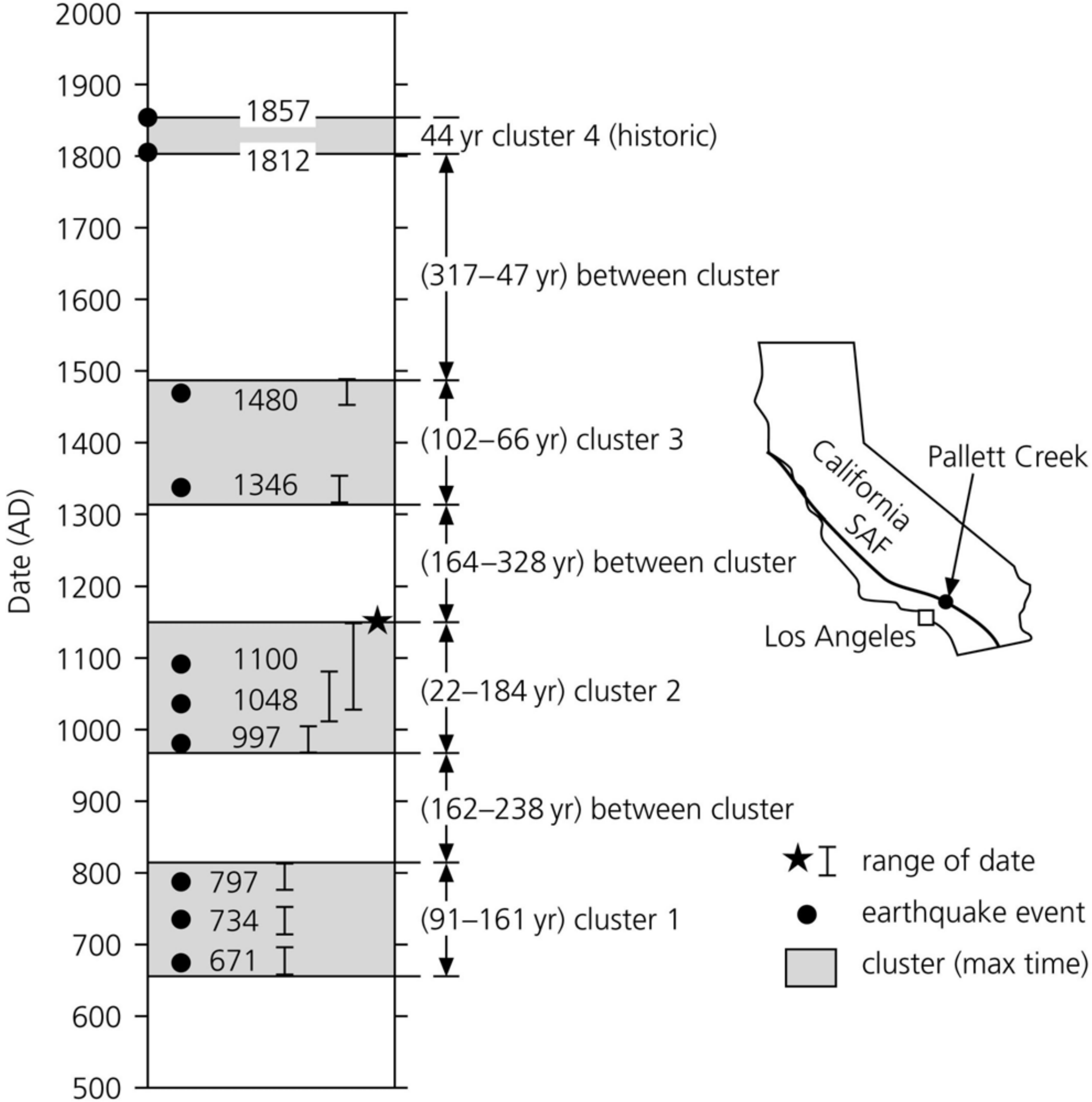
2004 09 28 17:15:24 UTC 35.81N 120.37W Depth: 8 km, Magnitude: 6.0

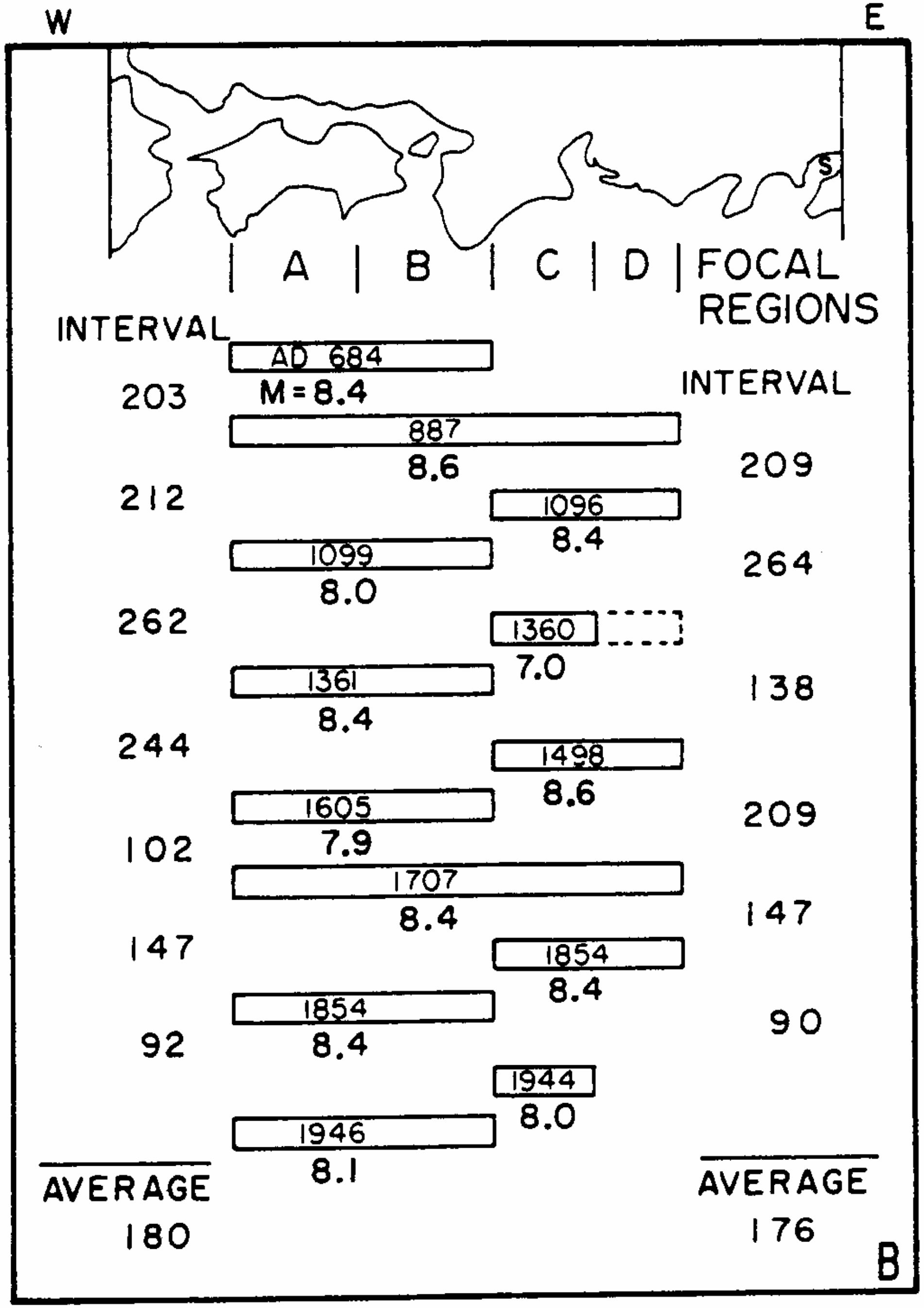
Seismicity 1990 to Present

Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green

USGS National Earthquake Information Center

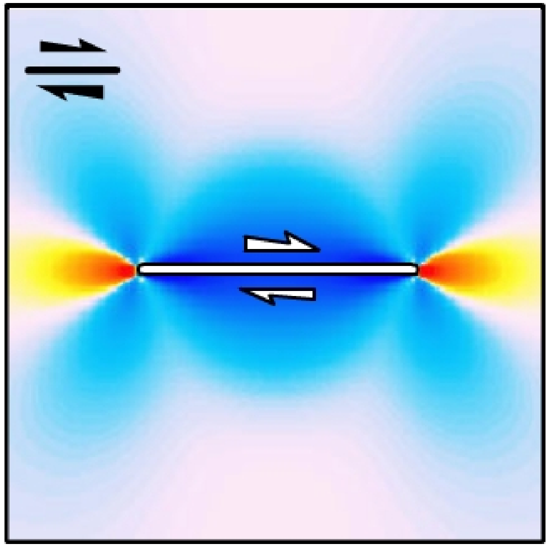
Figure 1.2-15: Paleoseismic time series for the San Andreas near Pallett Creek.




W
E
S
A
B
C
D
FOCAL REGIONS
INTERVAL
AD 684
M=8.4
203
887
8.6
209
212
1096
8.4
1099
8.0
264
262
1360
7.0
1361
8.4
138
244
1498
8.6
1605
7.9
209
102
1707
8.4
147
147
1854
8.4
1854
8.4
90
92
1944
8.0
1946
8.1
AVERAGE
180
AVERAGE
176
B

How the Coulomb Stress Change is Calculated

Stress Rise Drop



Shear stress change

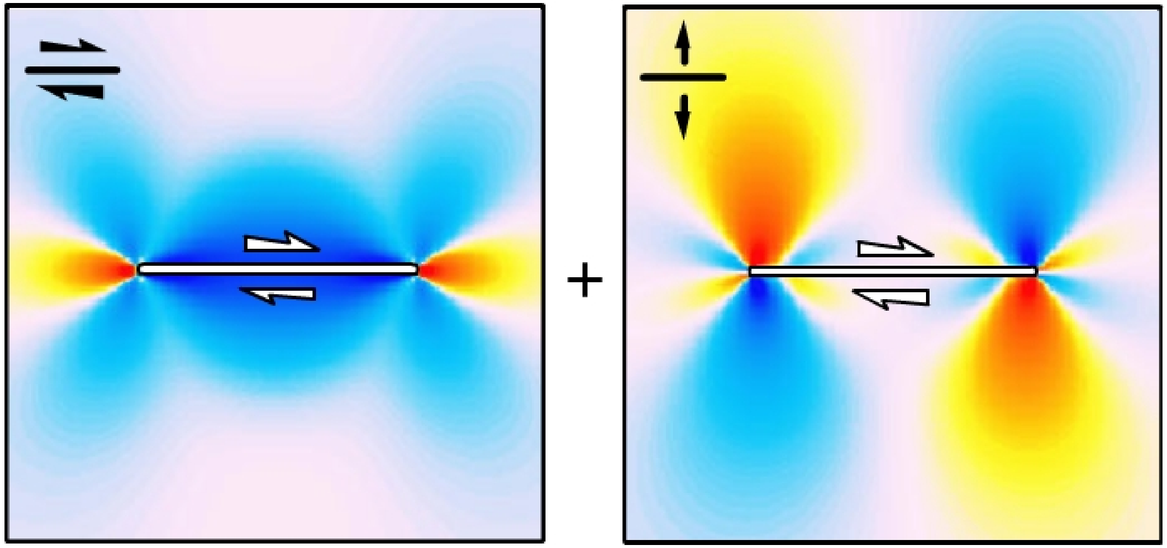
$\Delta\tau_s$

- 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

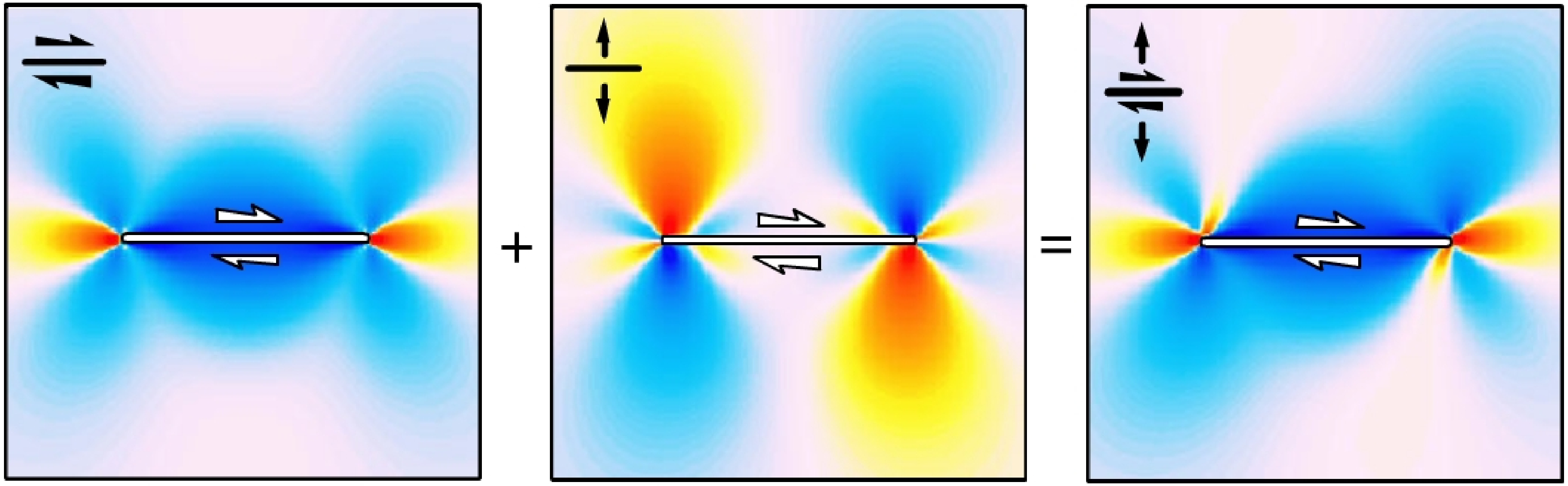
$\Delta\tau_s$ + $\mu' (\Delta\sigma_n)$

- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

How the Coulomb Stress Change is Calculated

Stress Rise Drop

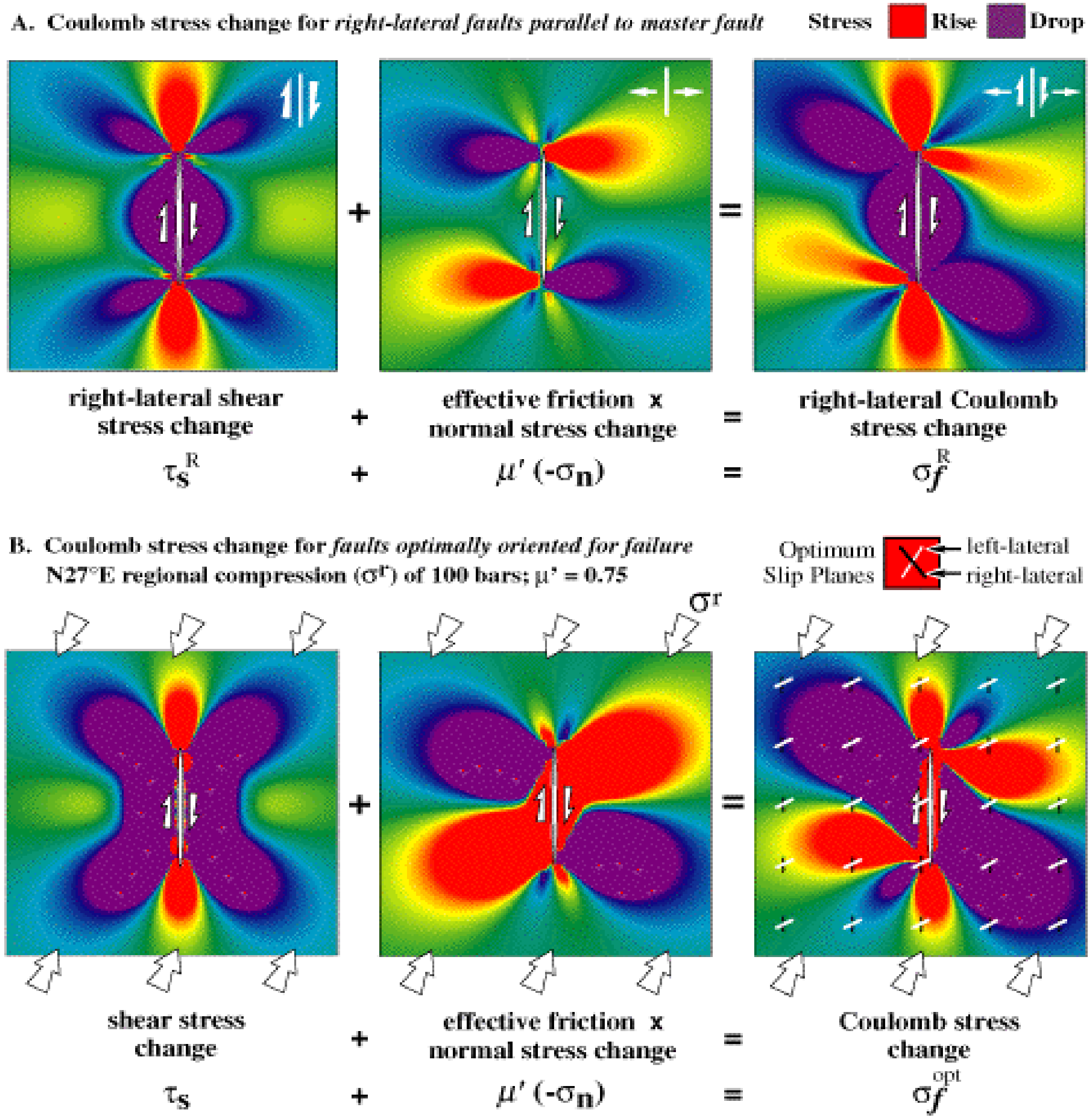


Shear stress change	+	Friction coefficient **x** normal stress change	=	Coulomb failure stress change
$\Delta\tau_s$	+	$\mu' \, (\Delta\sigma_n)$	=	$\Delta\sigma_f$

- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

Coulomb stress change due to strike slip earthquakes



Effet de la chute de contraintes

+

Effet de la contrainte régionale

Coulomb stress imparted by mainshocks

Source fault

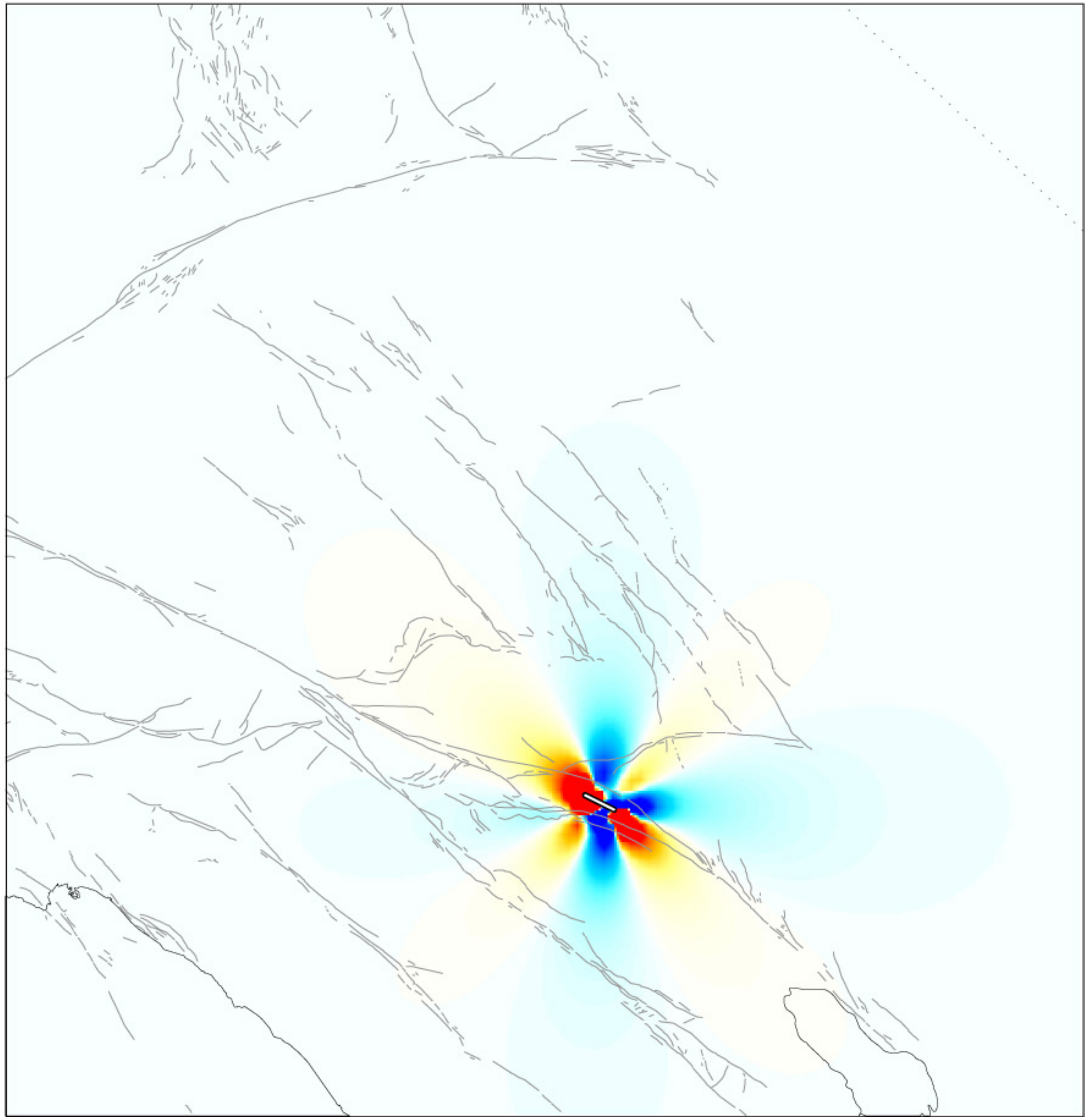
Distance (km)

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)

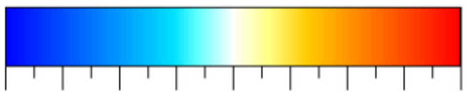
Coulomb stress imparted by mainshocks

Source fault

Distance (km)

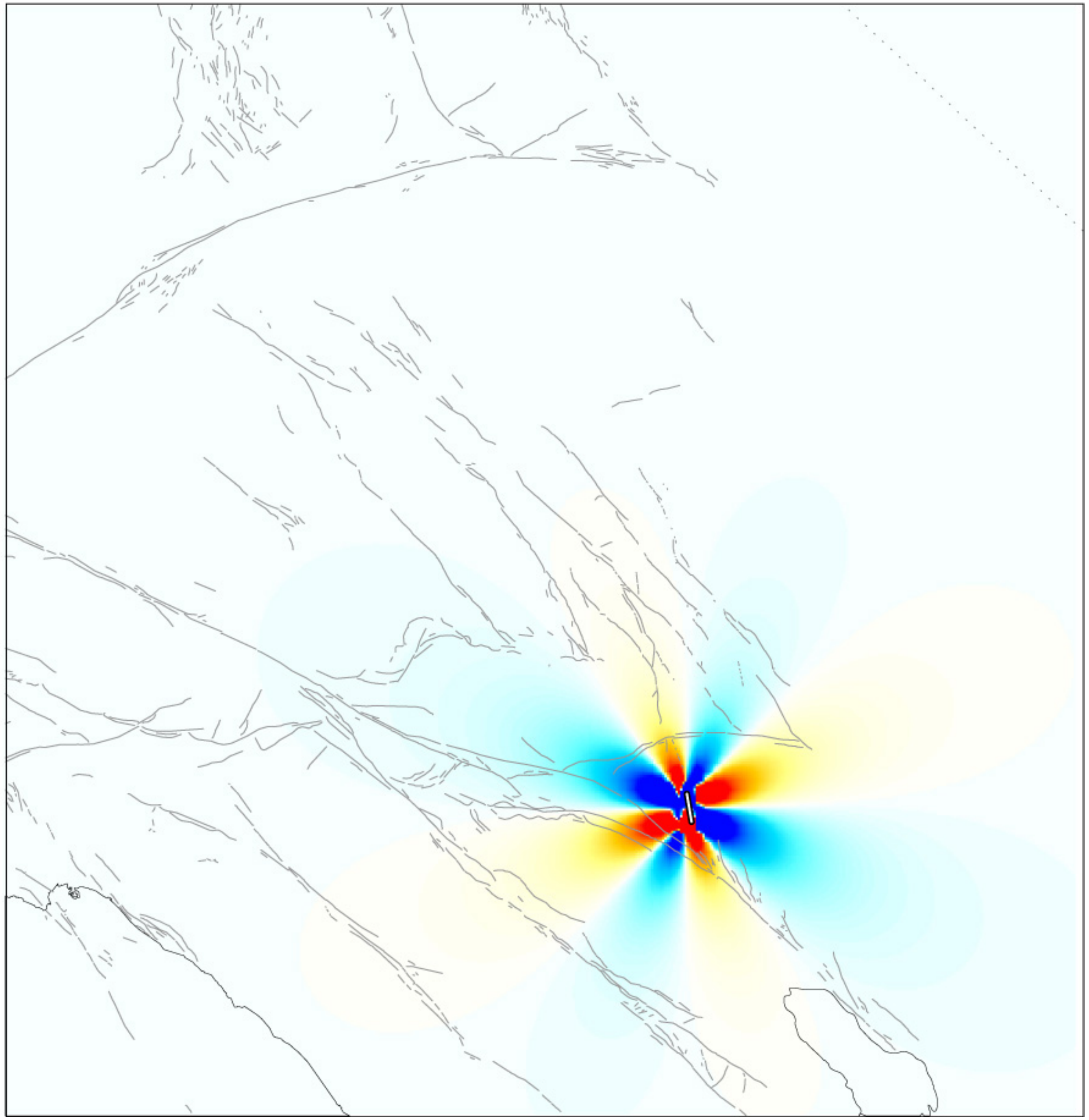
0 50 100

Coulomb stress change (bars)



-1.0 -0.5 0.0 0.5 1.0

1992 **M**=6.2 Joshua Tree



from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

Source fault

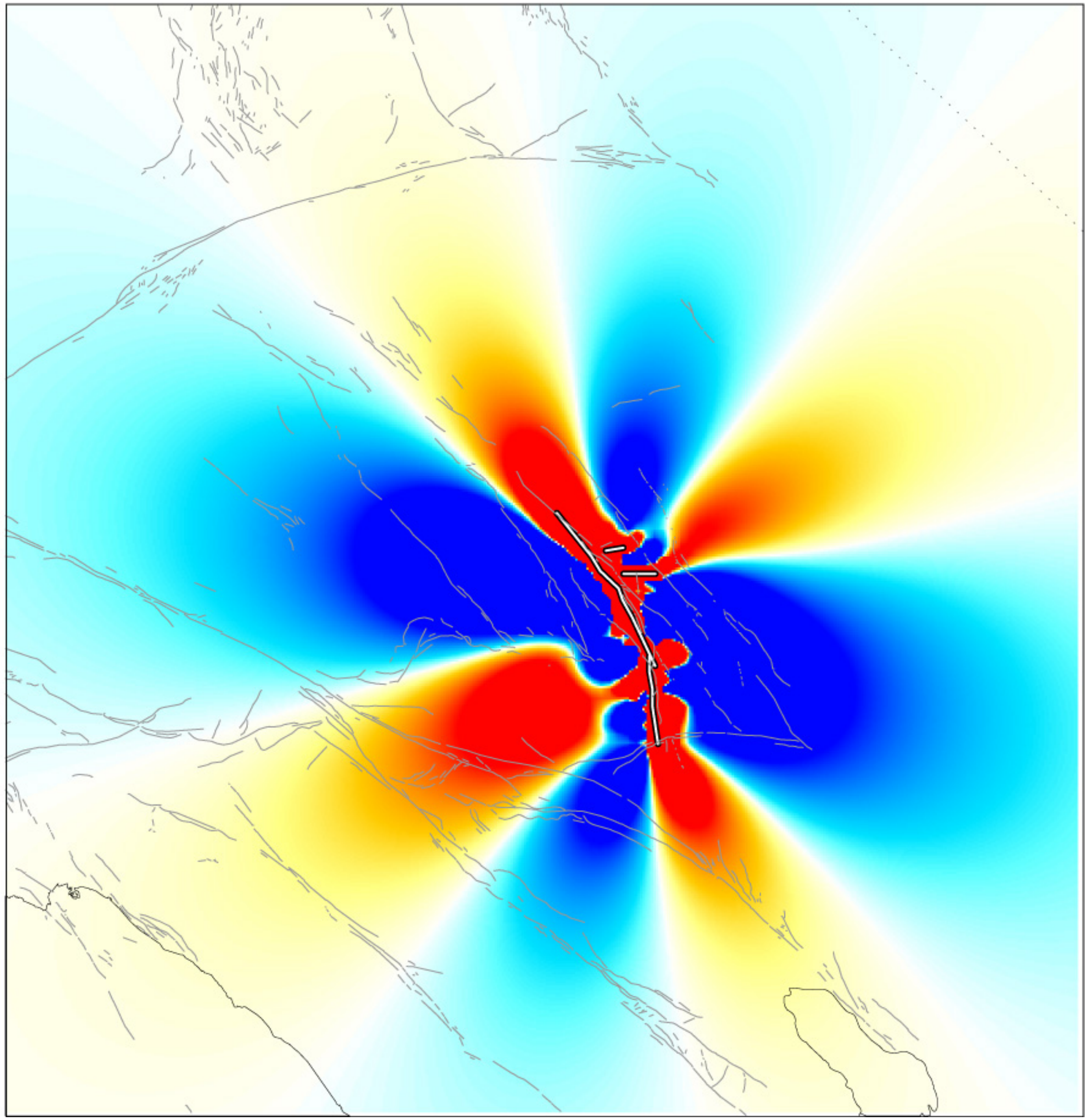
Distance (km)

0 50 100

Coulomb stress change (bars)

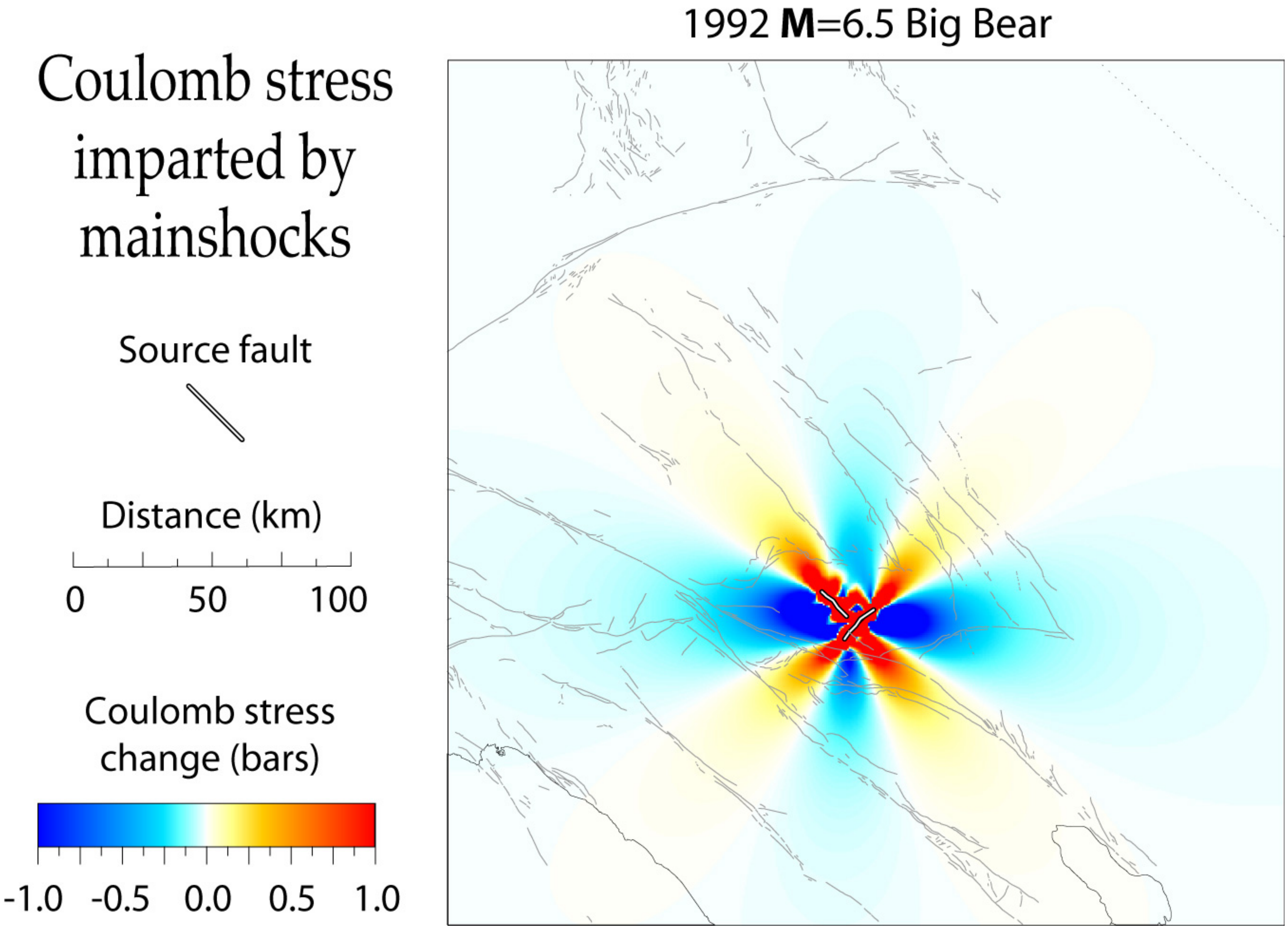
-1.0 -0.5 0.0 0.5 1.0

1992 **M**=7.4 Landers



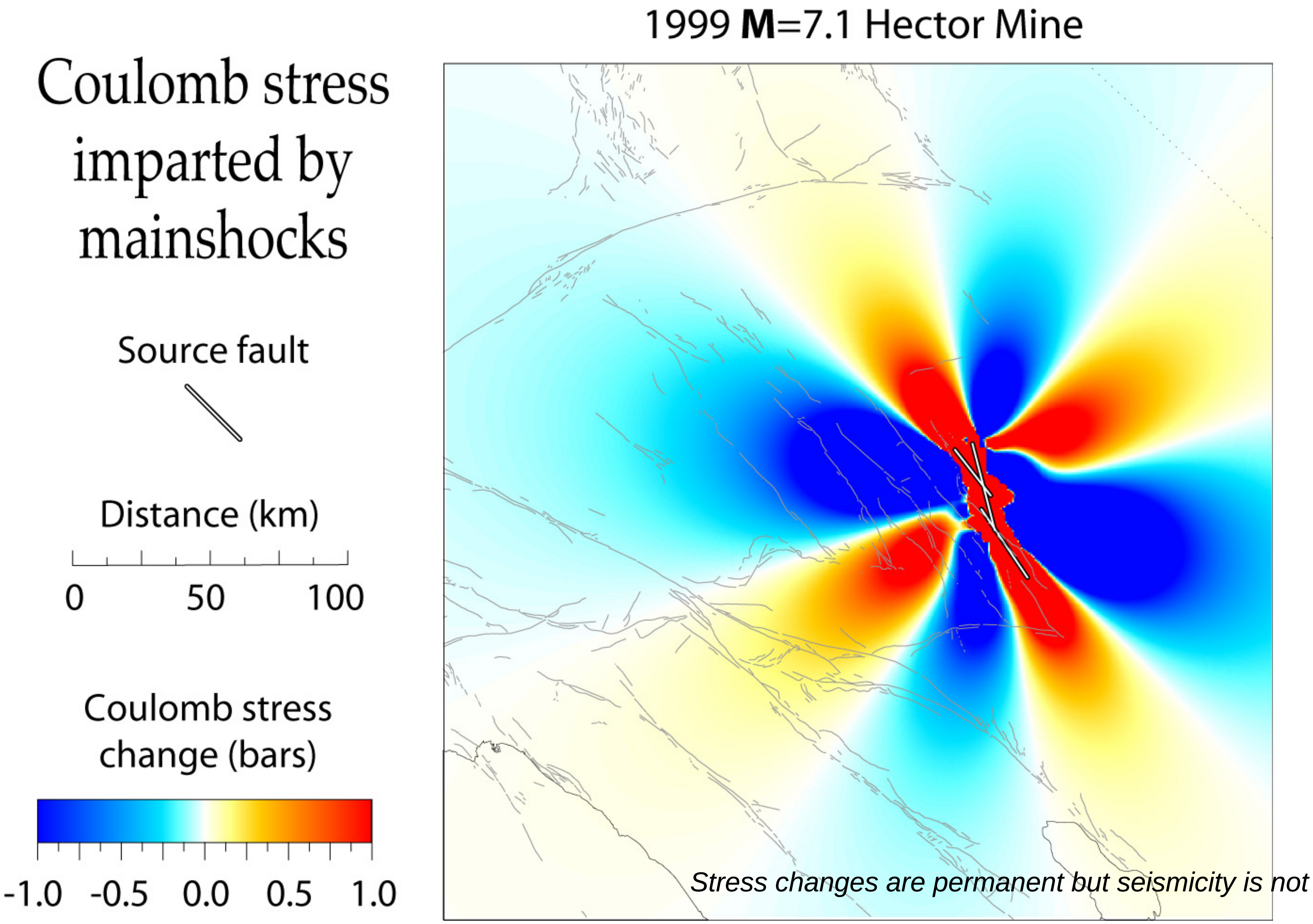
from Todal et al (JGR, 2005)

Coulomb stress imparted by mainshocks

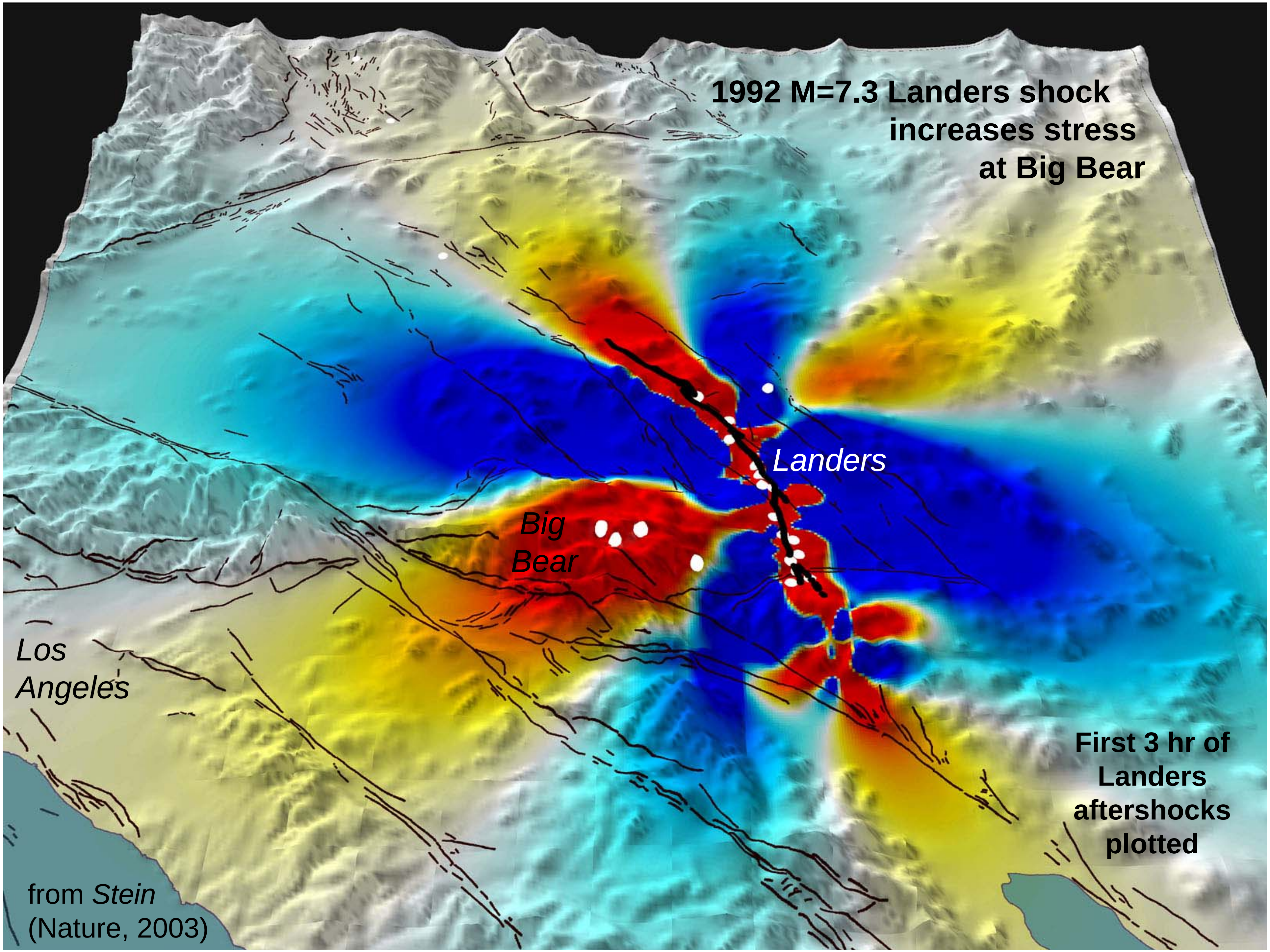


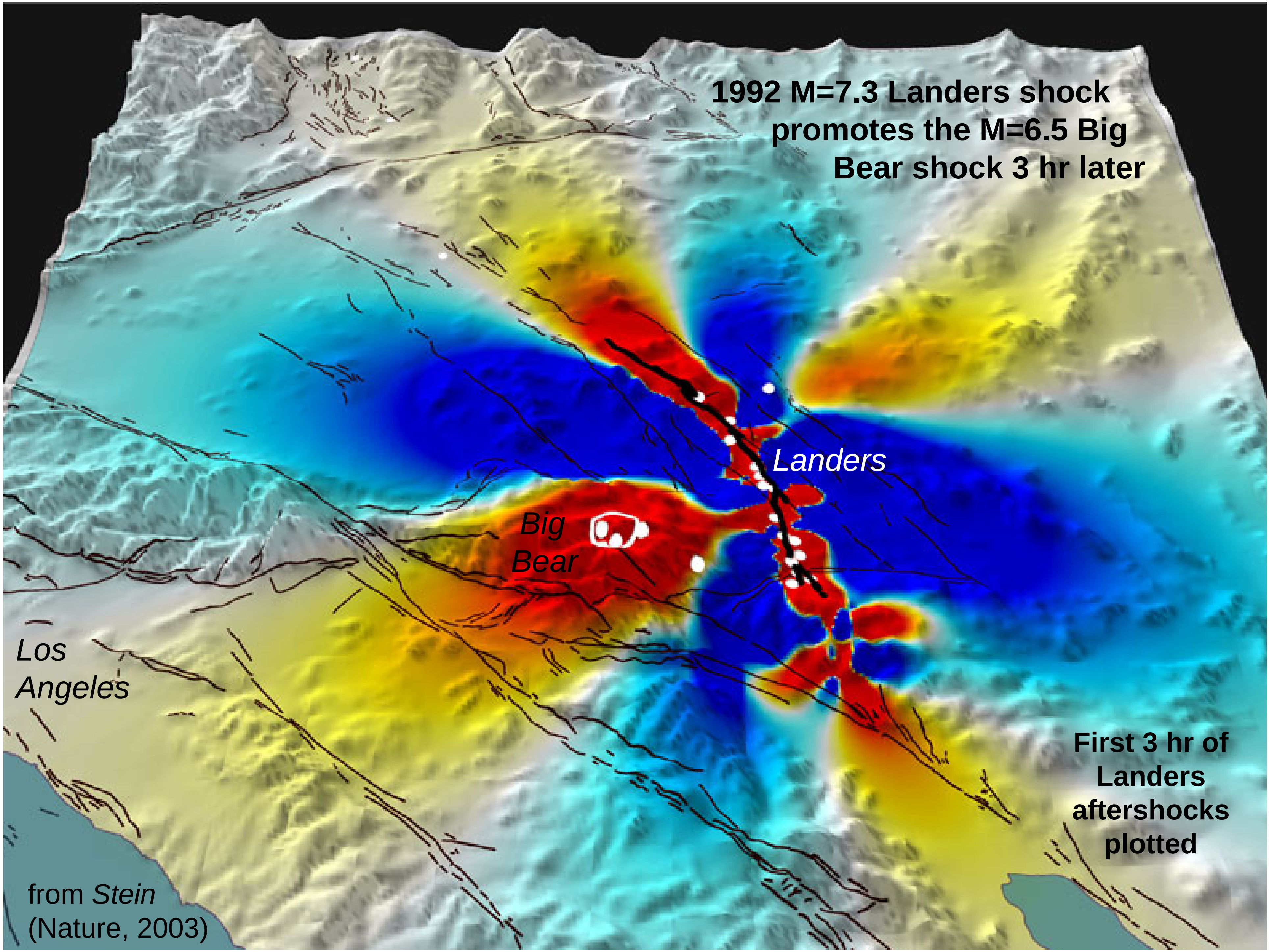
from Todal et al (JGR, 2005)

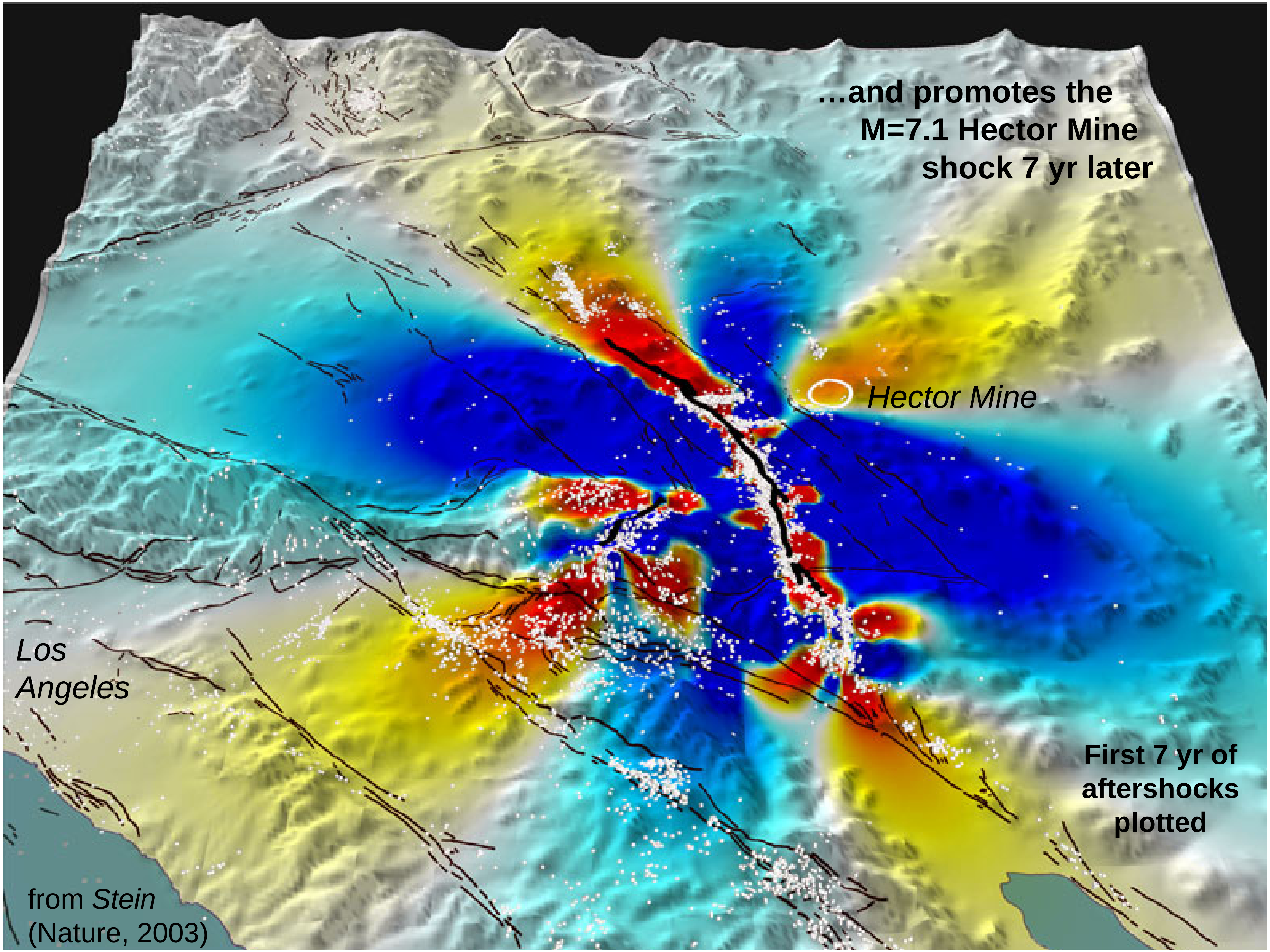
Coulomb stress imparted by mainshocks



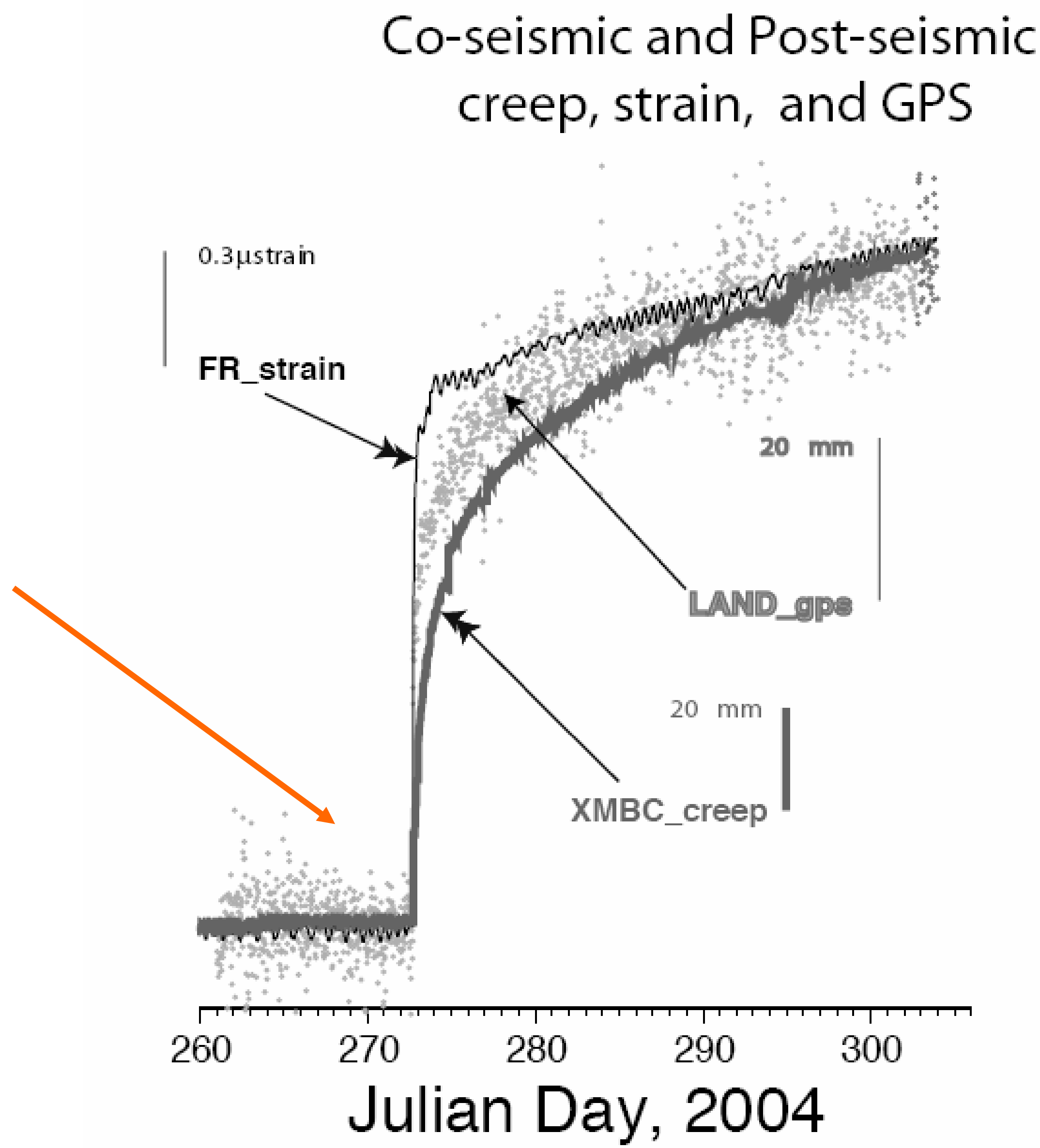
from Todal et al (JGR, 2005)


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)

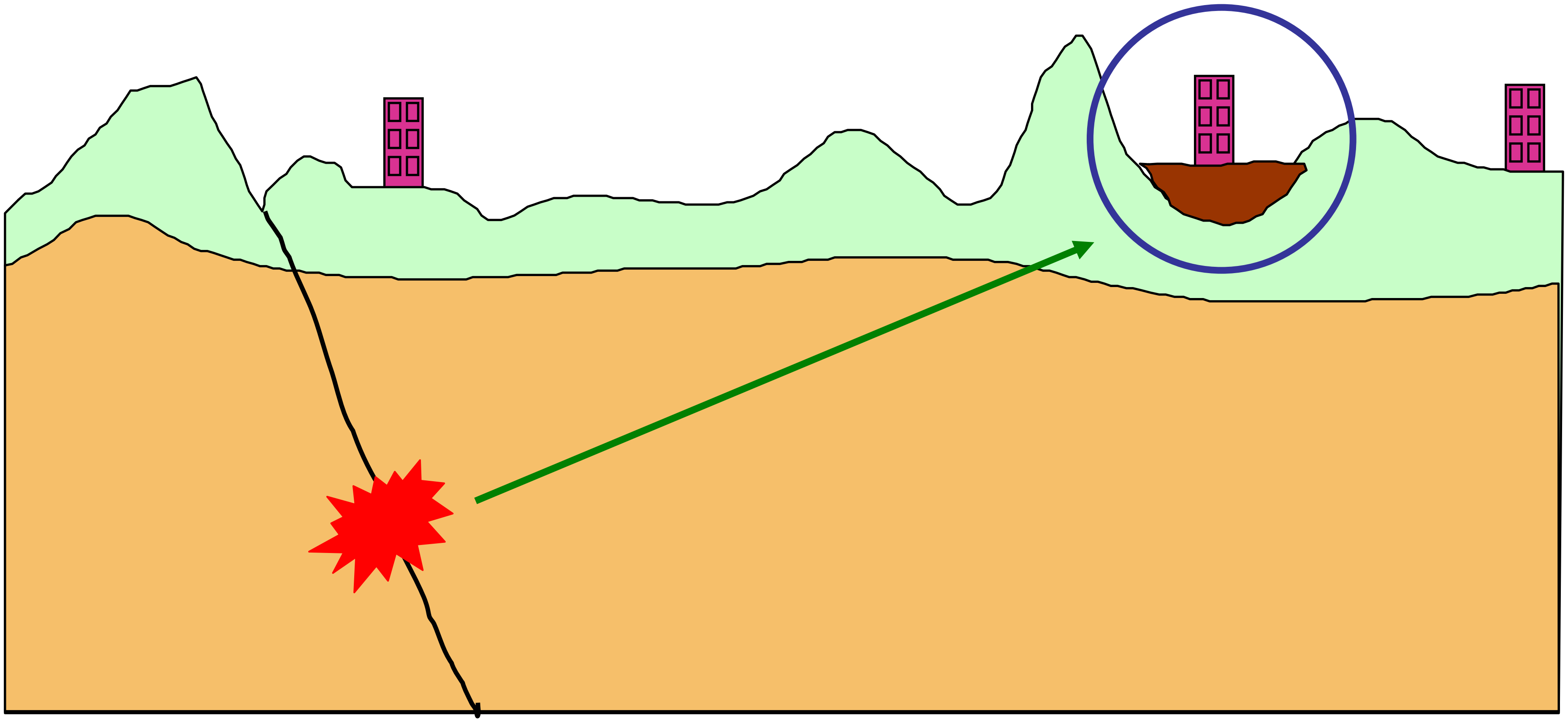
No precursor



Implications des lois d'échelle pour l'accélération du sol

Ground motion evaluation

Source + Path + Site



Une méthode d'estimation du mouvement sismique simple et très utilisée : la loi d'atténuation

$$\log\left(PSA(f)\right) = \boxed{a(f)\cdot M} + \boxed{b(f)\cdot R - \log(R)} + \boxed{c(i,f)}$$

Source	Magnitude
Parcours	Distance
Site	Caractéristiques du sol