Earthquake Occurrence in Geometrically Complex Systems

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Earthquake Occurrence in Geometrically Complex Systems

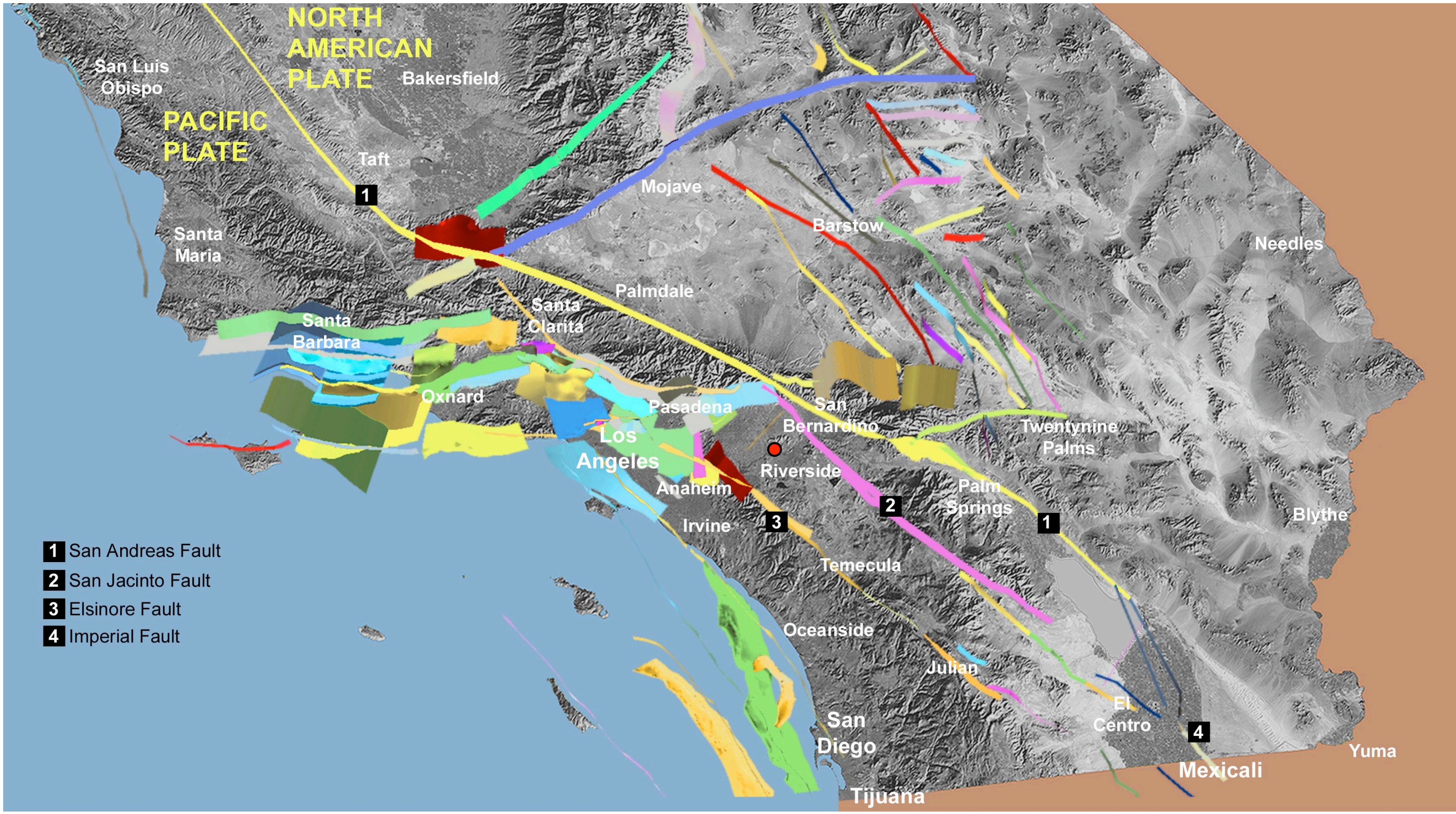
- Focus - Earthquakes and slip with non-planar faults and fault systems
- Principal result: Complex geometry introduces several new system-scale processes that do not operate with single planar faults or small arrays of planar fault segments → very strong affect on the characteristics of earthquake occurrence

Two related efforts are underway

1) Development of a large-scale earthquake simulation of earthquake in fault systems
    - Computationally fast, quasi-dynamic
    - 10^5-10^6 earthquakes M3.5-M8.0
    - Rate-state friction → clustering including foreshocks and aftershocks
    - Complex geometry

- Interactions of complex faults with embedding media
    - Off-fault stress relaxation and seismicity

Southern California Earthquake Center (SCEC) Community Fault Model



100km

Region ~ 600x 400km

Total fault length > 5000km

Fast fault system earthquake simulator

- Boundary elements - Okada
- ~35,000 fault elements (single processor G5)
  - Detailed representation of fault network geometry
  - Simulations of M3.5-8 for southern California
- 3D stress interactions
- Strike-slip, dip-slip and mixed mode fault slip
- Repeated Simulation of 10^5 - 10^6 events
- Basic elements of rate-state friction
  - Healing by log time
  - Time- and stress-dependent nucleation
  - Full representation of normal stress history effects
- Inputs
  - Fault slip rate (currently loading by backslip)
  - Rate-state parameters: *A, B,* (*Dc* does not enter equations)
  - Elastic modulii, shear wave speed β, stress intensity factor for rupture

Fast fault system earthquake simulator

- Computations are based on changes of fault sliding state using the method of Dieterich (1995)
  - 0 – Locked fault: aging by log time of stationary contact
  - 1 – Nucleating slip: analytic solutions with rate-state friction
  - 2 – Earthquake slip: quasi-dynamic – slip speed is fixed by shear impedance

$$\dot{\delta}_{EQ} = \frac{2\beta\Delta S}{G}$$

- No simultaneous equations to solve
  - During earthquakes slip, the initiation or termination of slip at an element requires one multiply and one divide operation to update stressing rate conditions at every element

$$\dot{S}_i = K_{ij}\dot{\delta}_j \text{ , where } K_{ij} = T_{ij} - \mu N_{ij}$$

  - Computation time scales by $N^{\sim 1}$ where N is the number of elements
  - 100,000 events with 30,000 fault elements ~ 12hrs

M8 event on fault with 10,000 fault elements

2x vertical exaggeration

QuickTime™ and a
GIF decompressor
are needed to see this picture.

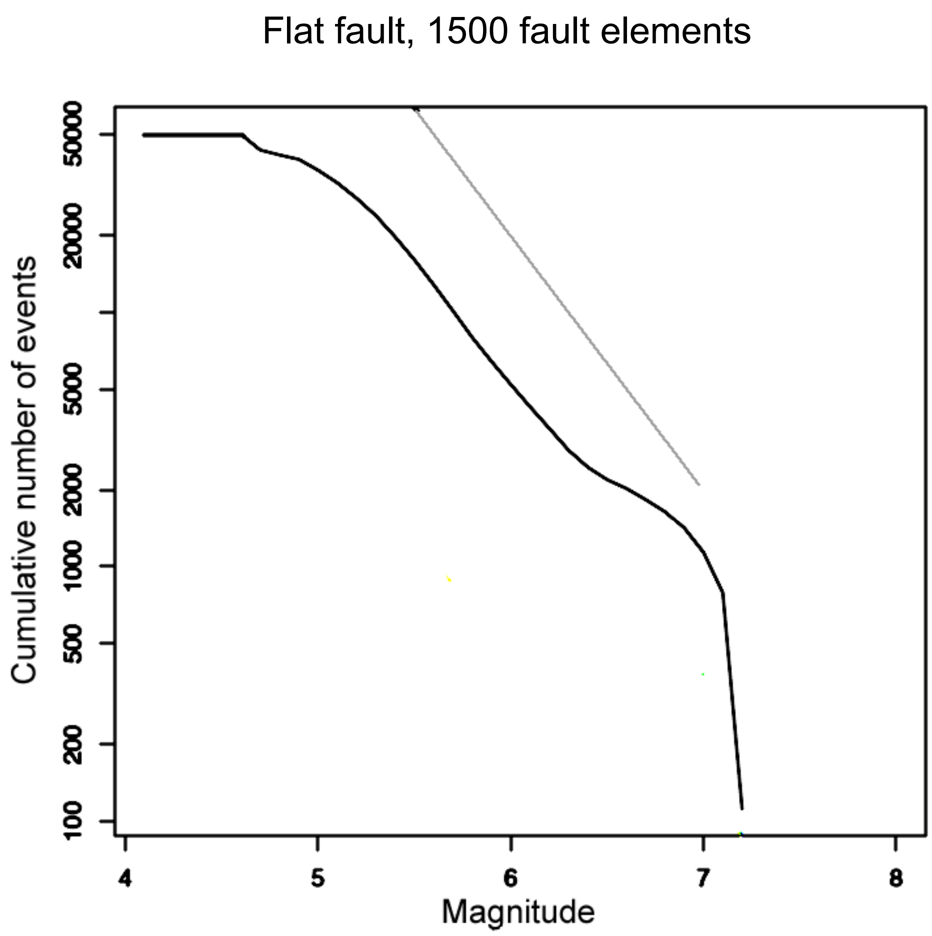
Simulation:

- 50,000 events, 10,000 elements
- M~4.0-8.0
- Implicit shear wave speed 3km/s
- Computation time ~ 60 minutes on Mac G5 using a single 2.2 GHz CPU

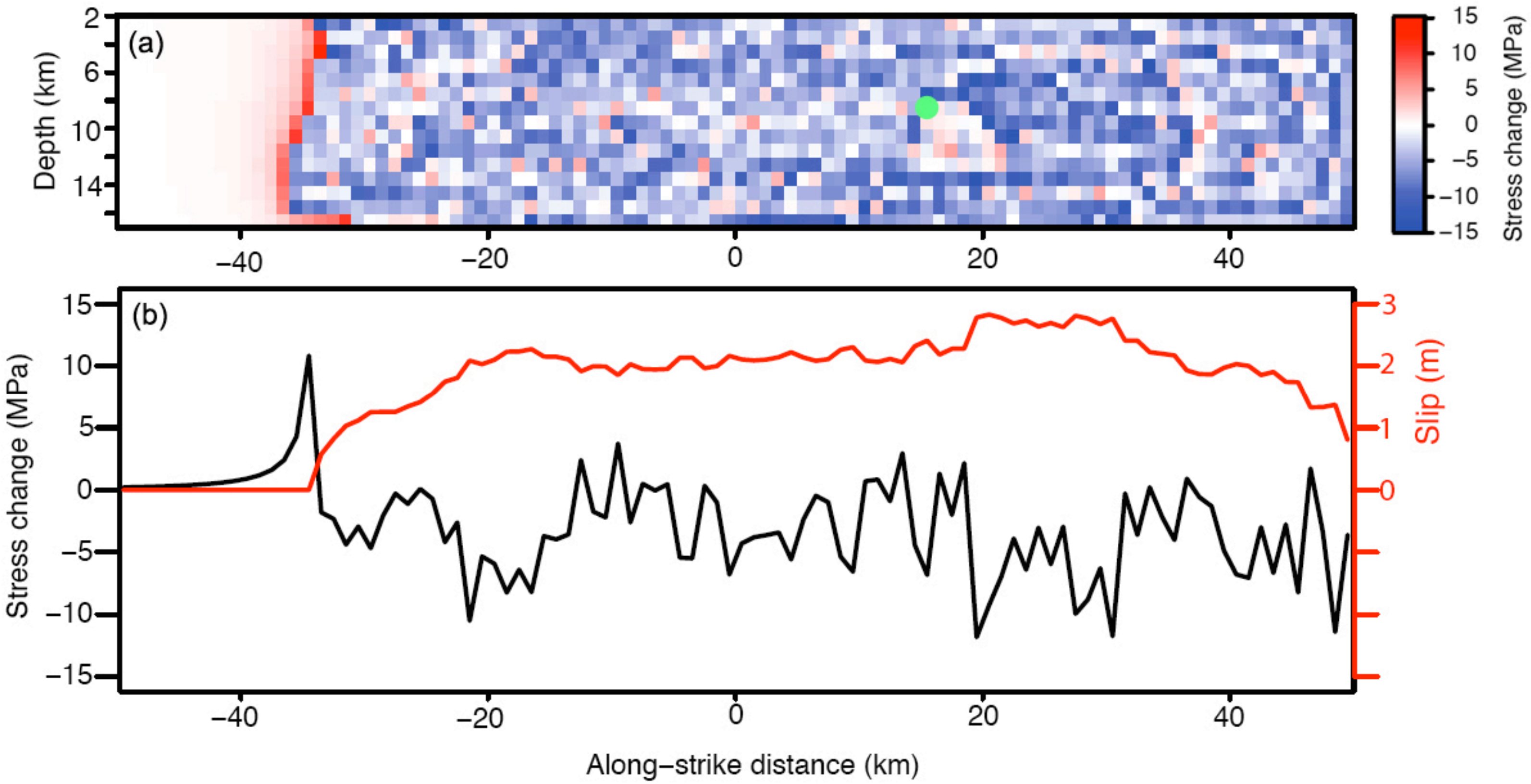
M8 events:

- Duration 215s, 204s
- Rupture speed 2.2–2.4 km/s

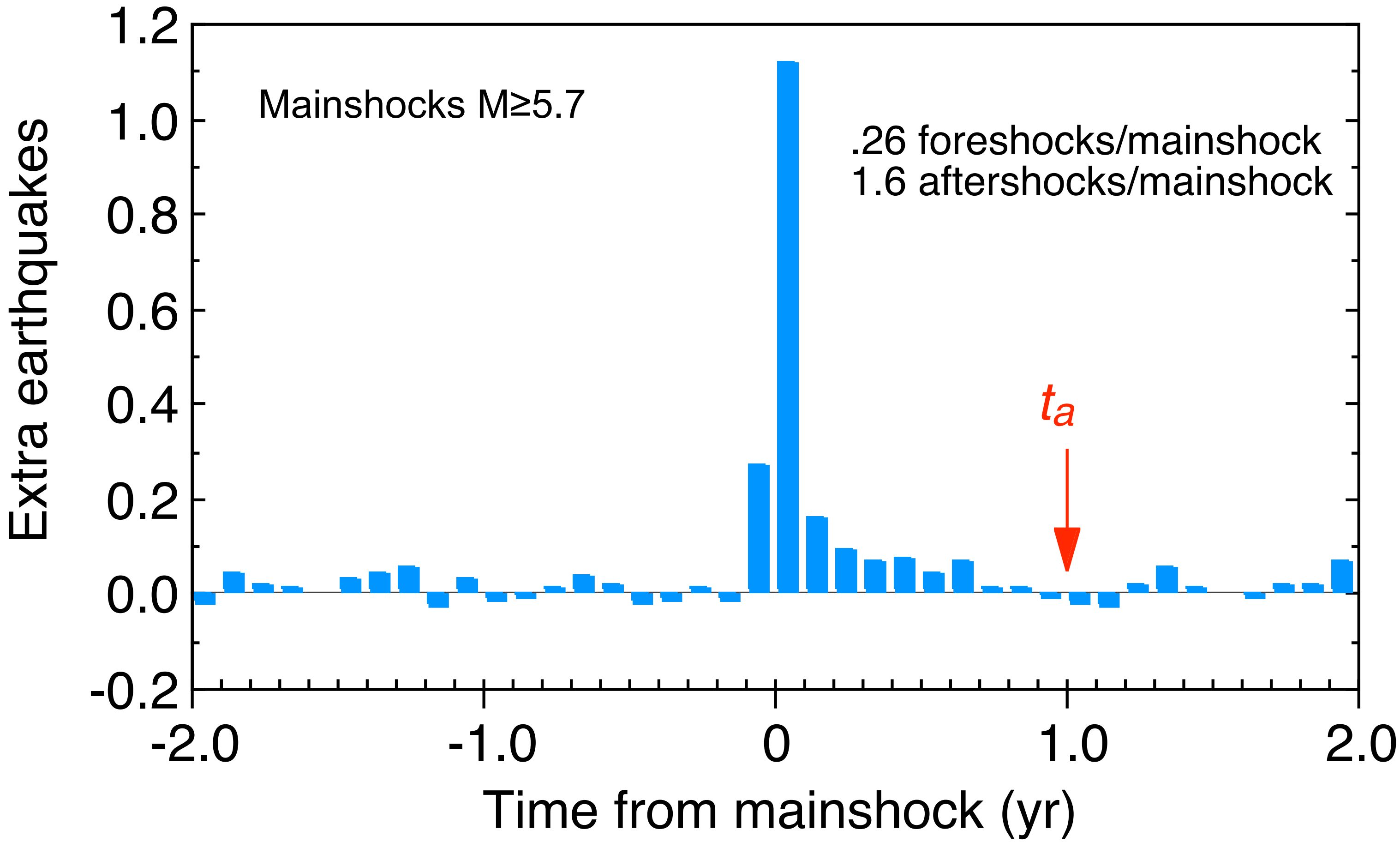
Magnitude – Frequency



Stress change and slip in a M7.1 earthquake



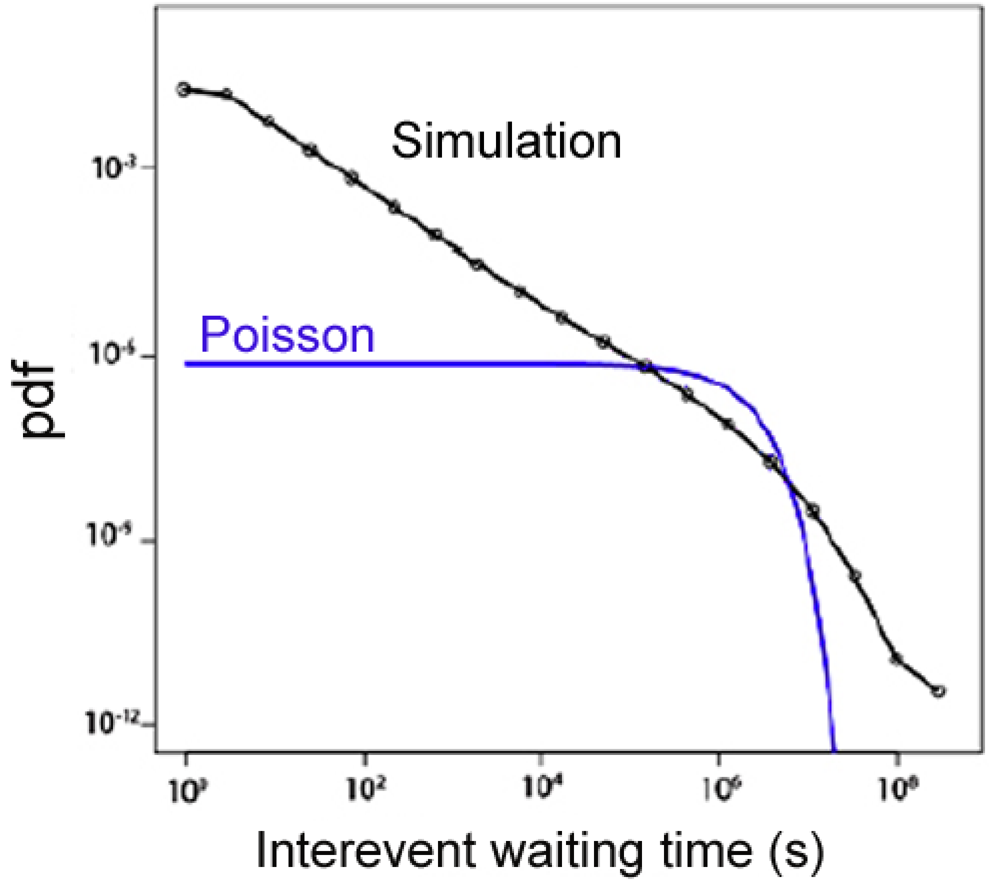
This event, which ruptured nearly the entire fault surface, was followed by M6.5, M5.4 and M6.3 events 64, 82 and 96 seconds, respectively following the mainshock. In a real earthquake this tight clustering might be interpreted as a single composite earthquake event.



Composite plot of earthquake clustering formed by stacking the records of seismic activity relative to mainshock times [from Dieterich, 1995]. Events in excess of the background rate, normalized by the number of mainshocks.

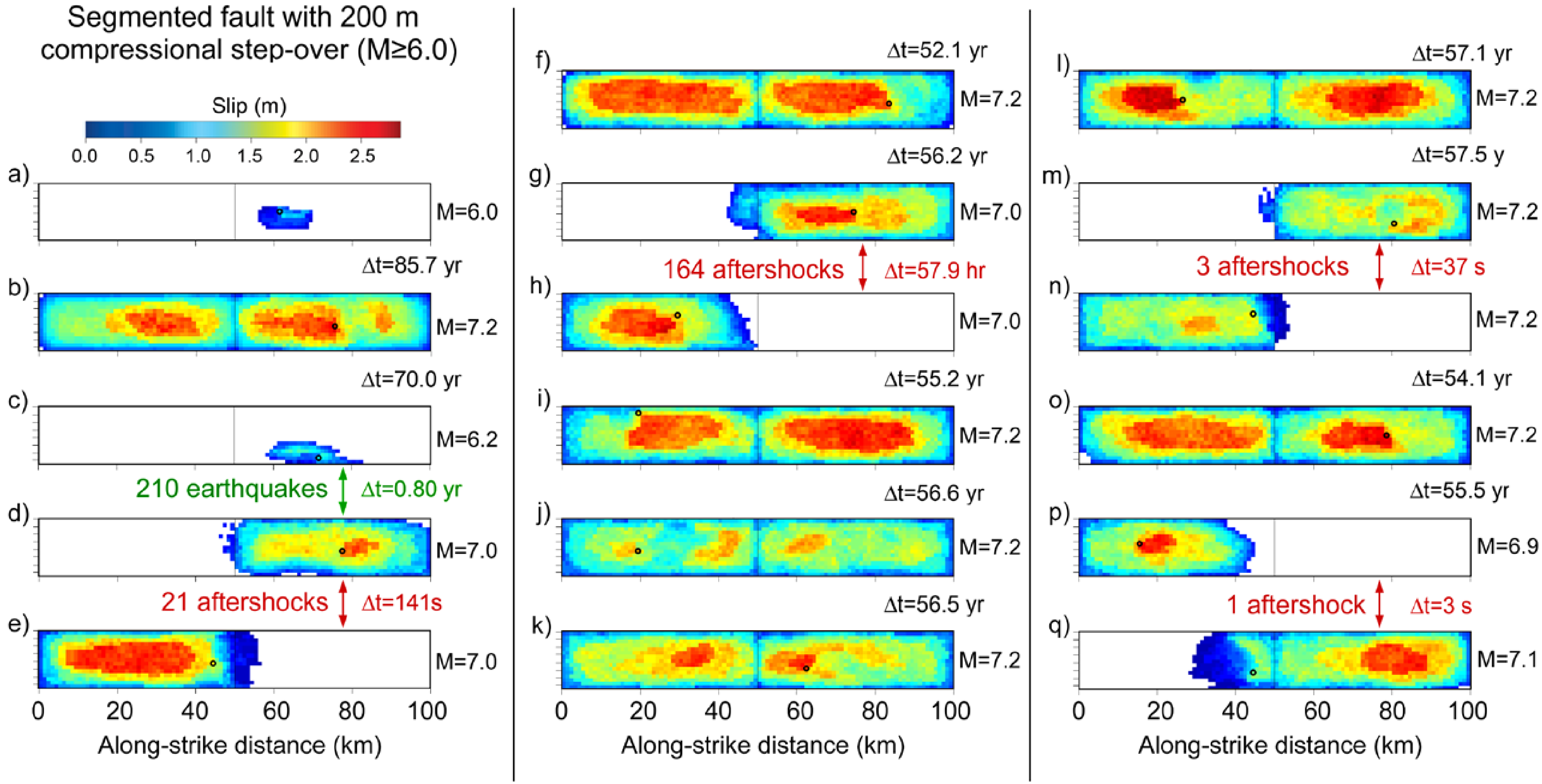
Clustering in synthetic catalog

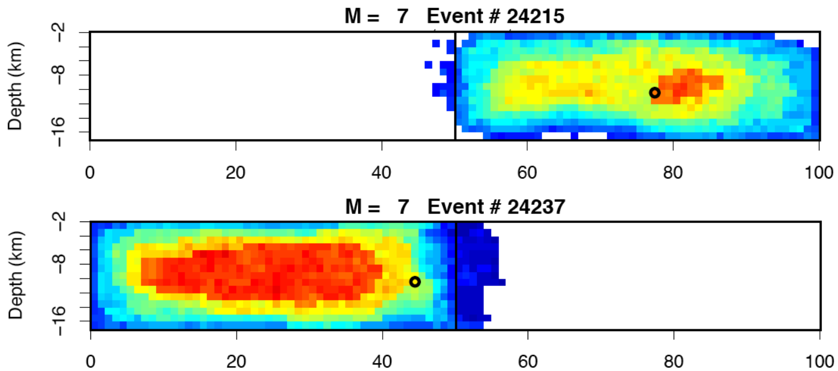
Single planar fault
All events (50,000), ~M4.3-7.2



Waiting-time distribution of events ≥7.0 are quasi-periodic with cov = 0.02 for single fault system. Aperiodicity of large increases with increasing numbers of faults

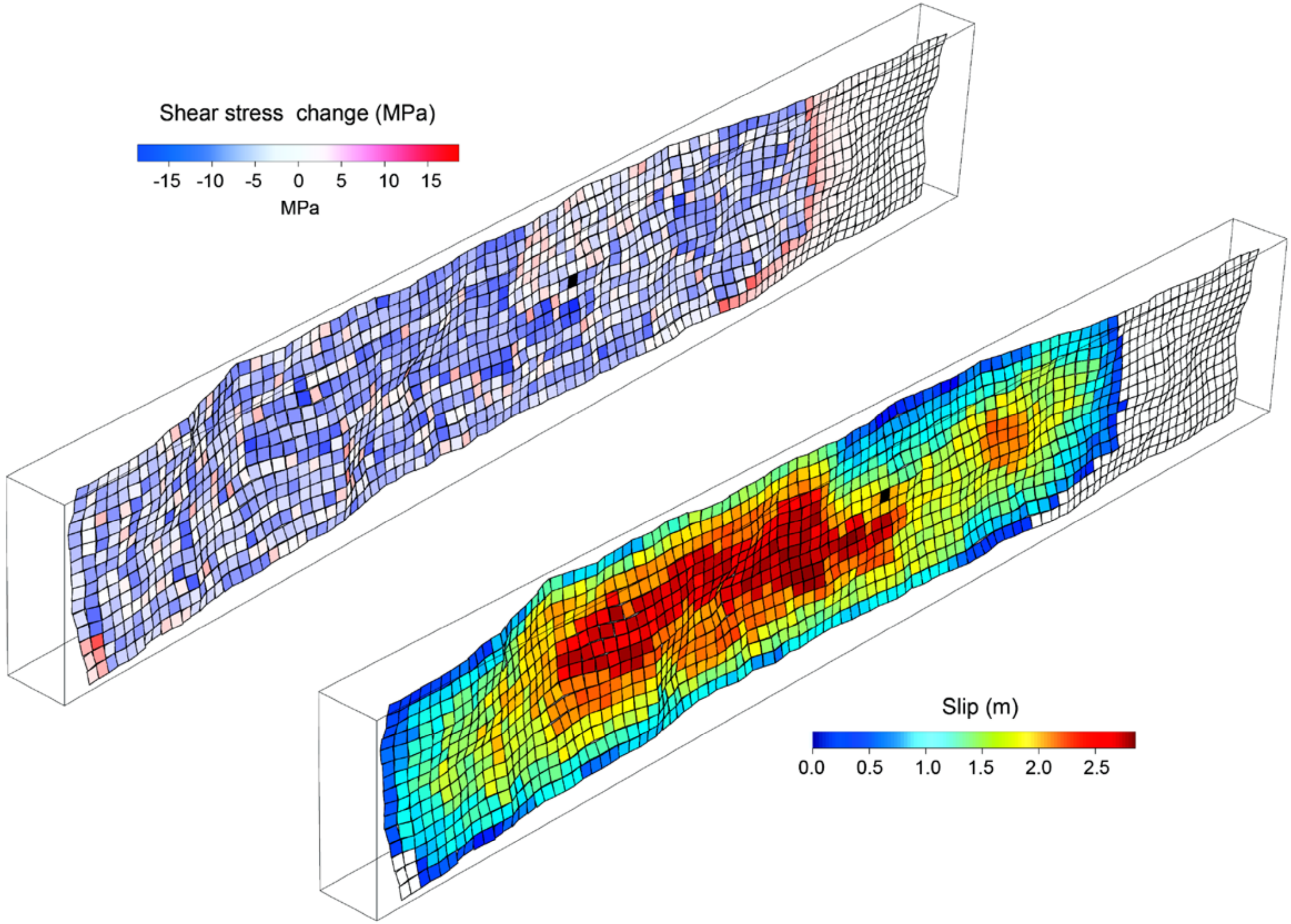
200 m Compressive Stepover
All events M≥6.0





- End of first M7 event – 27.9 s
- 21 aftershocks in interval between first and second M7 events
- Start of second M7 event – 169 s

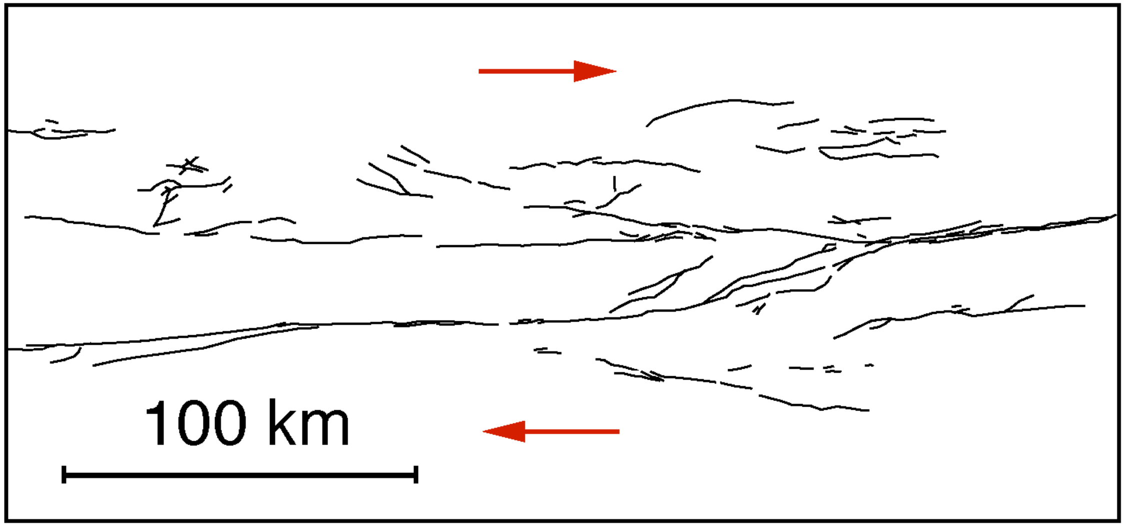
QuickTime™ and a
GIF decompressor
are needed to see this picture.



Slip and shear stress change for simulated M7.1 event on a fault with fractal fault roughness. Model is for strike-slip faulting (left-lateral) with 1,500 fault elements. This event was taken from a simulation with 50,000 earthquakes M3.5-M7.2. Nucleation occurred at the black element.

System-scale phenomena with complex geometries
Fault slip and off-fault seismicity

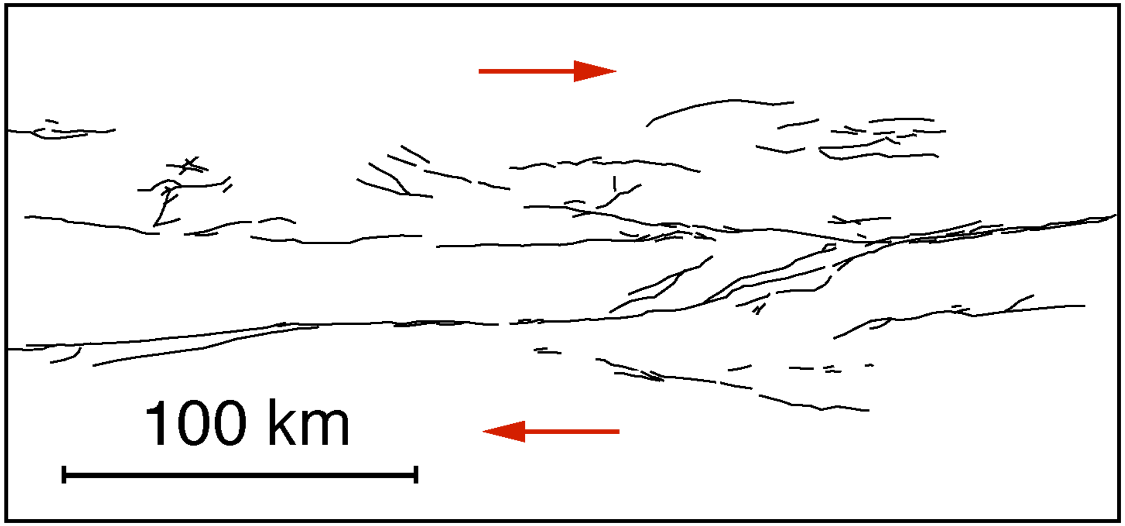
Individual faults exhibit approximately self-similar roughness



San Francisco Bay Region

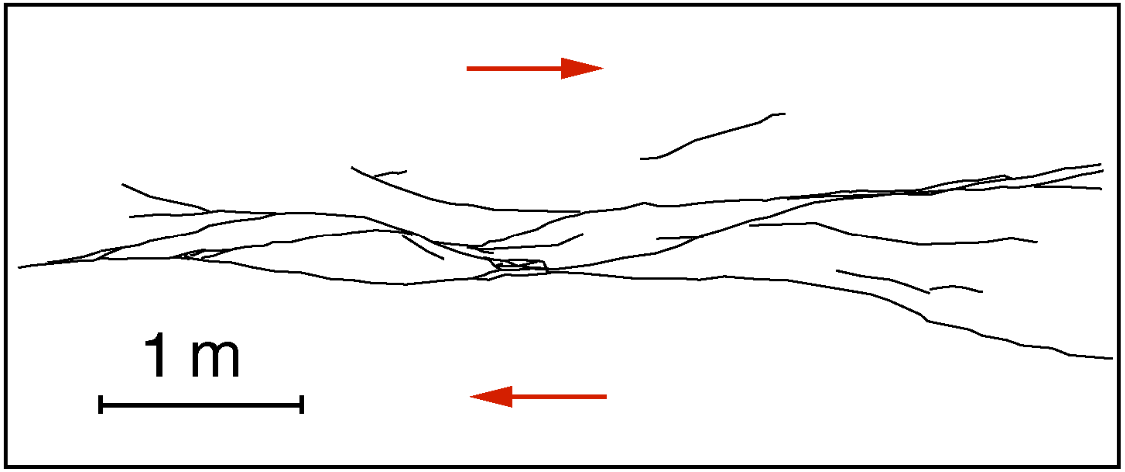
System-scale phenomena with complex geometries
Fault slip and off-fault seismicity

Individual faults exhibit approximately self-similar roughness



San Francisco Bay Region

Fault systems also appear to be scale-independent



Fault in the Monterrey Formation

Random Fractal Fault Model

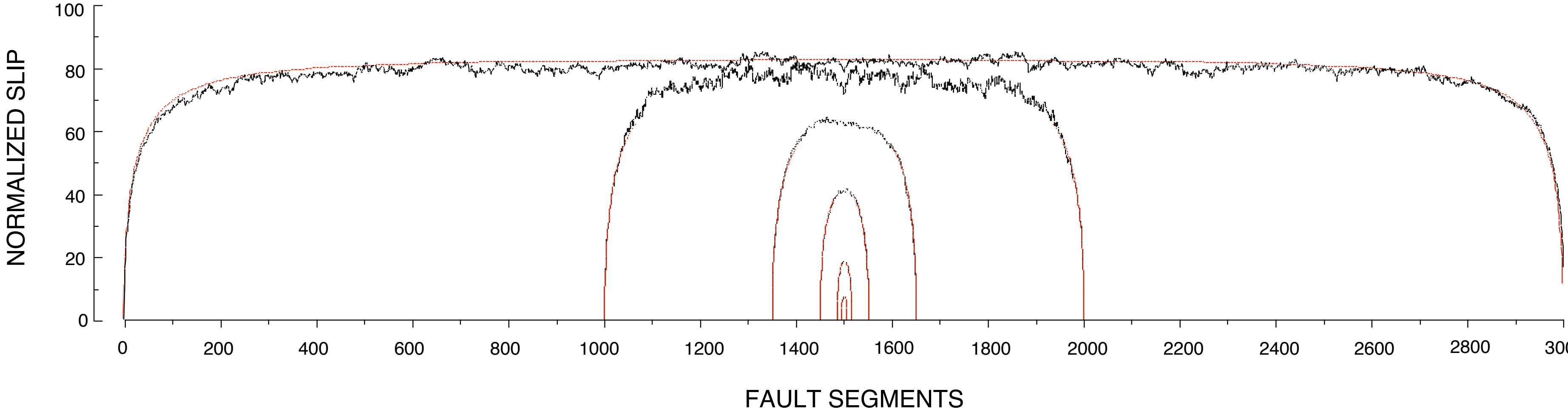
Solve for slip using boundary elements.
Simple Coulomb friction with μ = 0.6
Periodic B.C, or slip on a patch

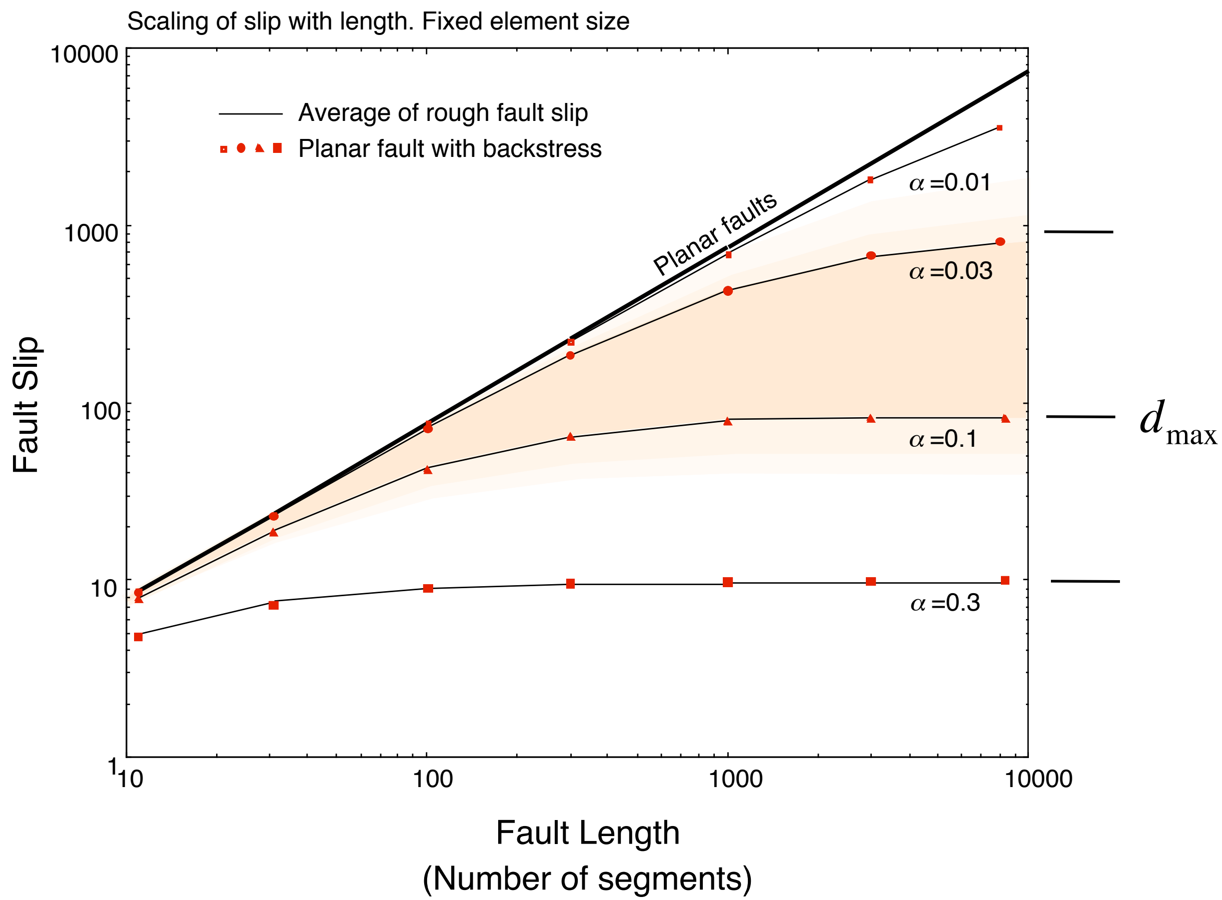
$$Ampl. \propto \beta l^H$$

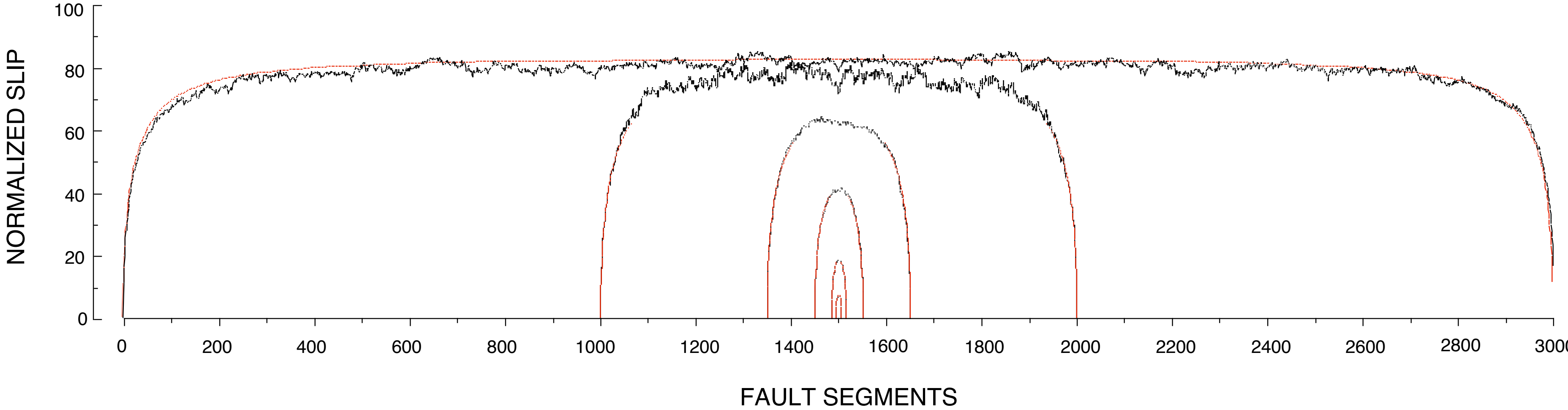
H = Hurst exponent

At reference length $l = 1$,

rms (slope) = β


NORMALIZED SLIP
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
FAULT SEGMENTS


Scaling of slip with length. Fixed element size
Average of rough fault slip
Planar fault with backstress
Planar faults
α =0.01
α =0.03
α =0.1
α =0.3
Fault Slip
10000
1000
100
10
1
10
100
1000
10000
Fault Length
(Number of segments)
$d_{\max}$

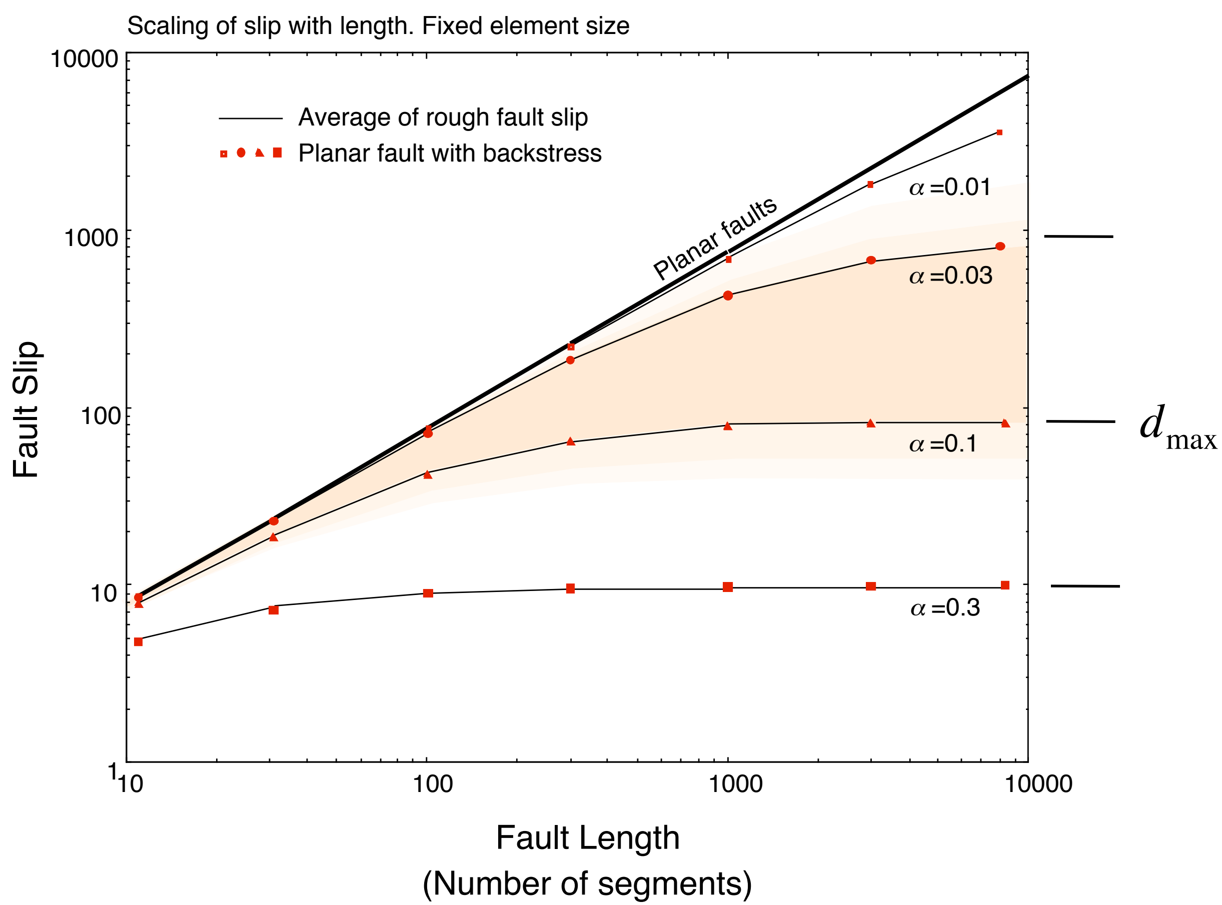


Backstress opposes slip and is proportional to slip. Slip saturates when the average backs stress S_{BACK} equals the stress that drives slip S_A

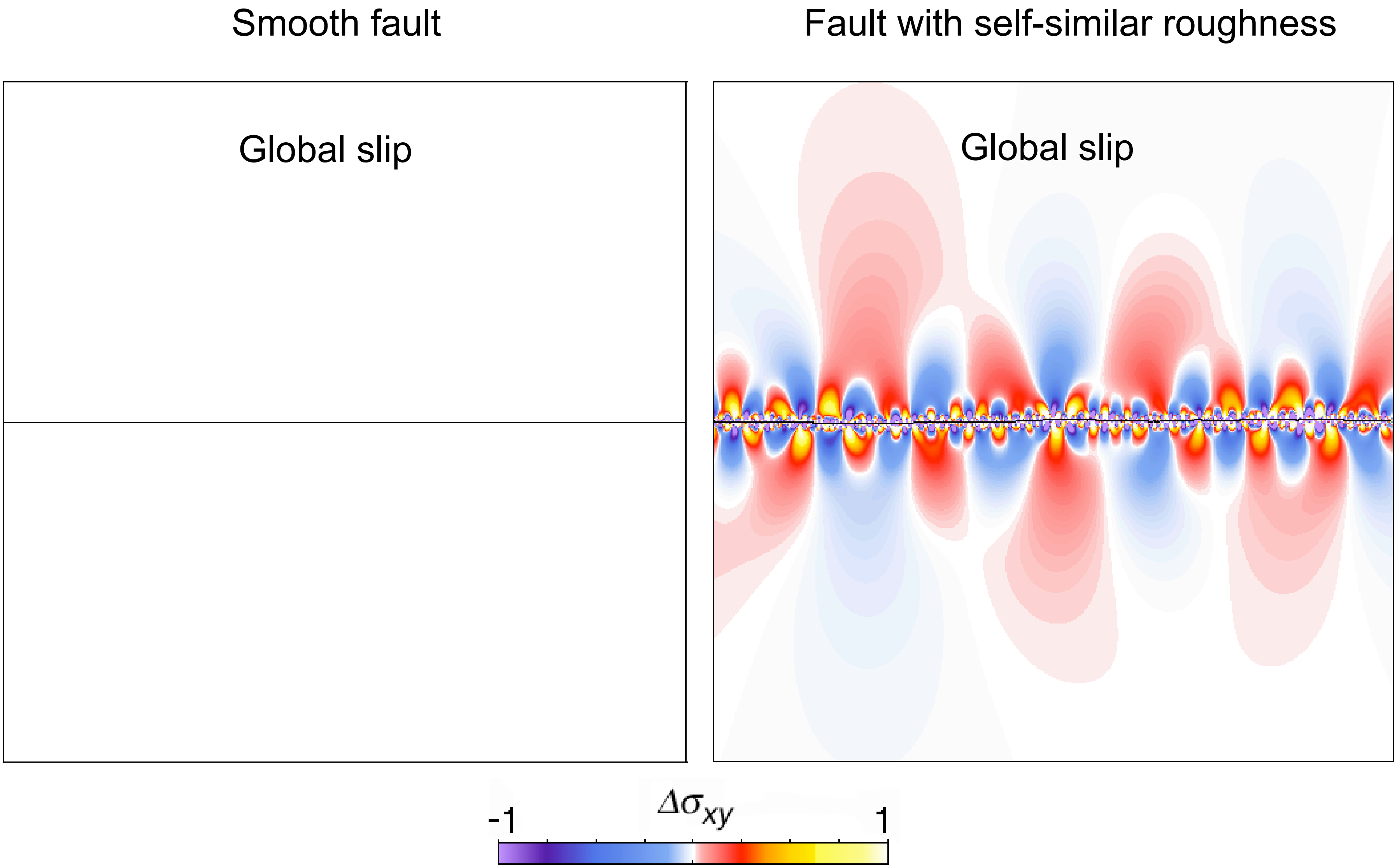
$$d_{\max} = c\beta^{-2}$$

$$S_{BACK} = S_A \frac{d}{\bar{d}_{MAX}}$$

$$S_{BACK} = \left(c\beta^2 S_A\right) d$$



Fault slip and stress changes



Yielding and Stress Relaxation

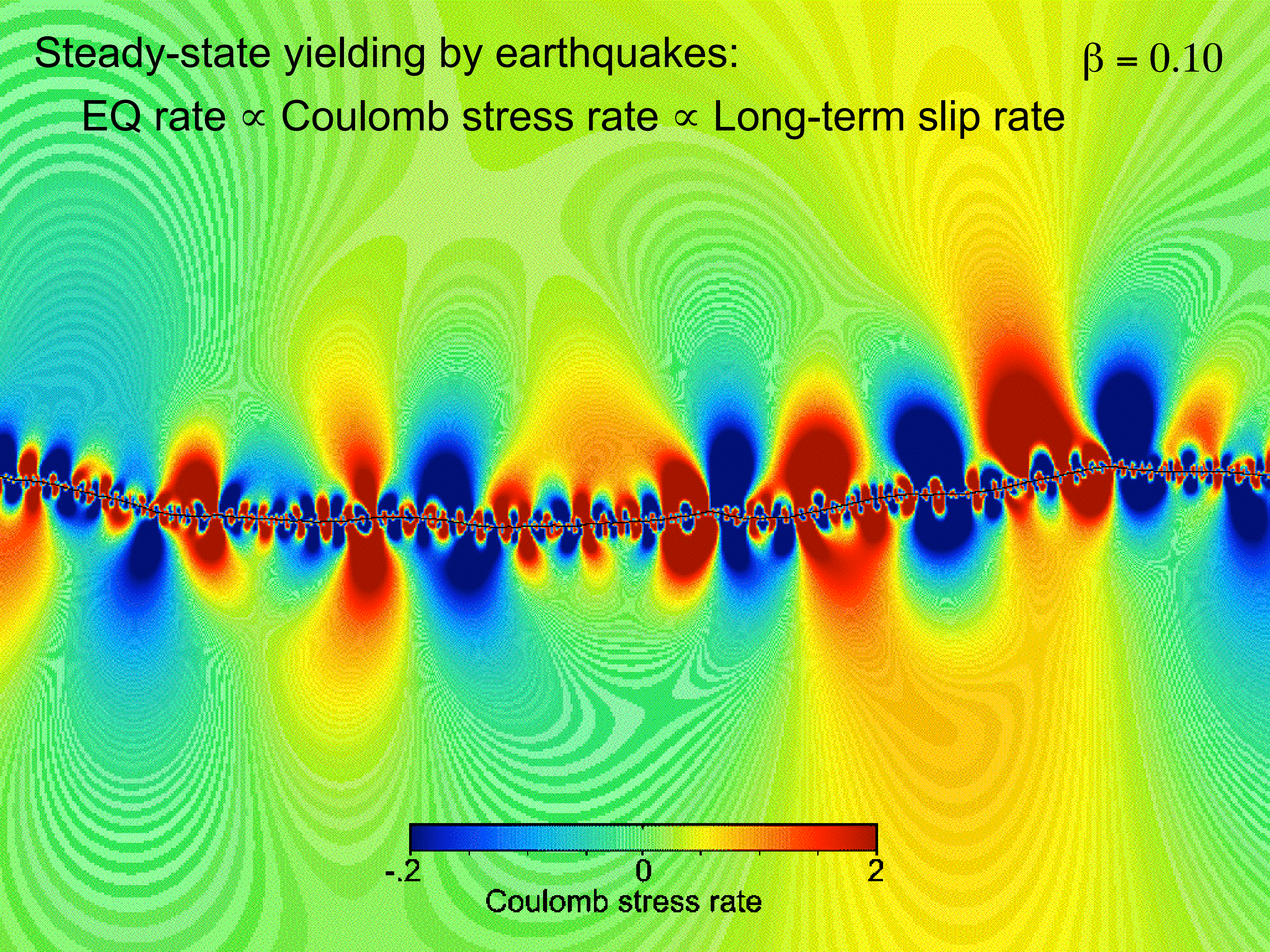
- Stresses due to heterogeneous slip cannot increase without limit - some form of steady-state yielding and stress relaxation must occur

$$RMS \;\; Slope \propto \beta l^{H-1}$$

Slope of 0.01 $\rightarrow$ shear strain ≈ 0.01, $\rightarrow$ brittle failure

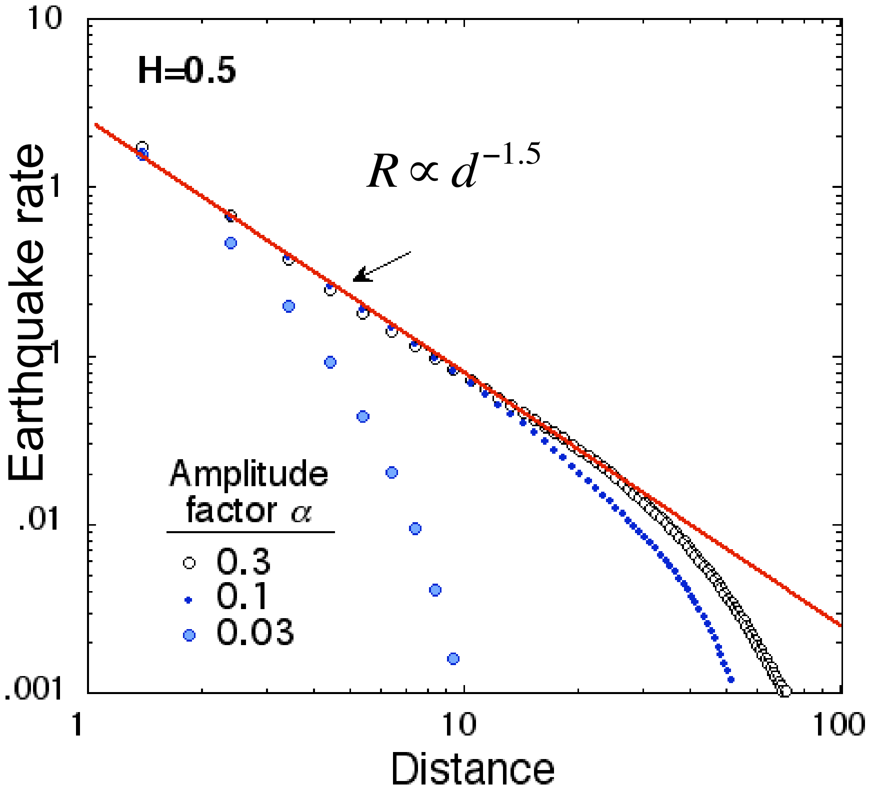
- In brittle crust, stress relaxation may occur by faulting and seismicity off of the major faults.
  - Ø Instantaneous failure and slip during earthquake
  - Ø Post-seismic – aftershocks
  - Ø Interseismic – background seismicity

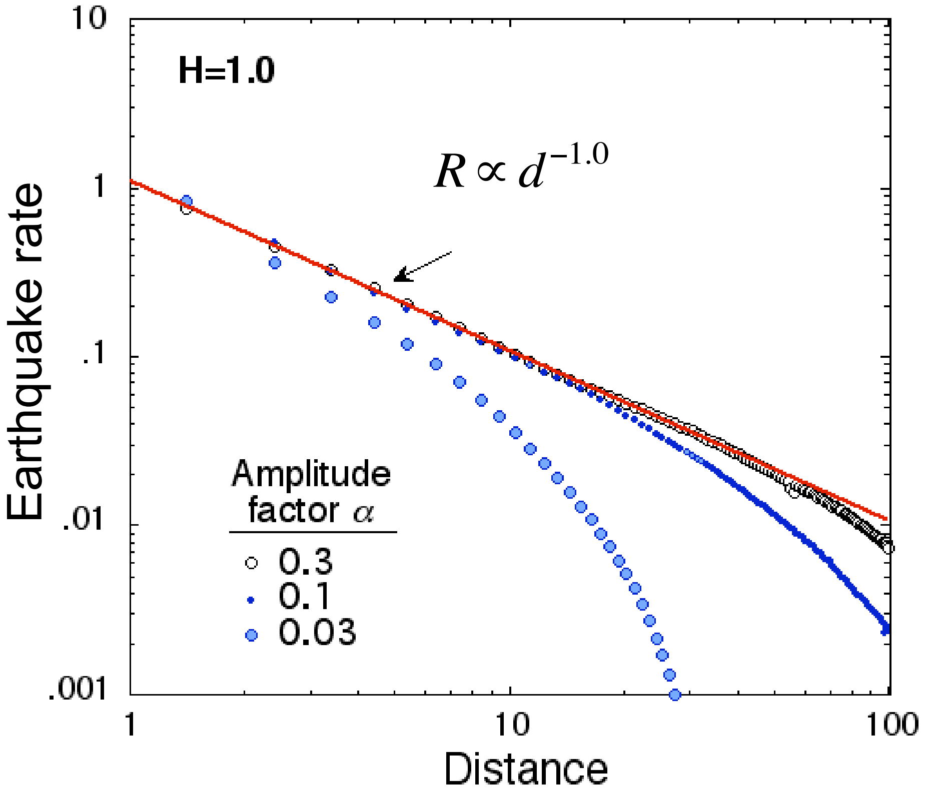
- Yielding will couple to the failure process, by relaxing the back stresses


Steady-state yielding by earthquakes:
EQ rate ∝ Coulomb stress rate ∝ Long-term slip rate
β = 0.10
-.2
0
2
Coulomb stress rate

Average long-term earthquake rate by distance from fault with random fractal roughness

- Stressing due to fault slip at constant long-term rate
- Model assumes steady-state seismicity at the long-term stressing rate, in regions where $\dot{S} > 0$



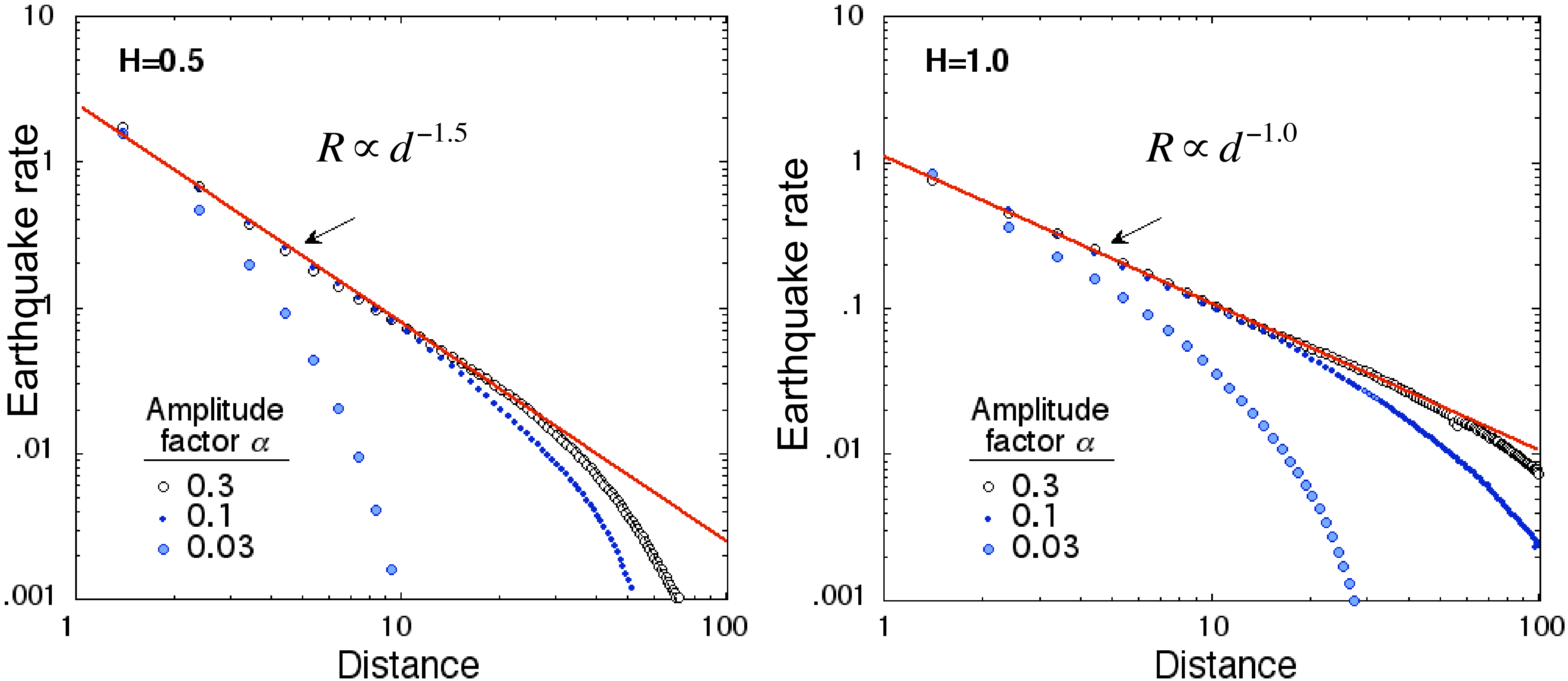


Average long-term earthquake rate by distance from fault with random fractal roughness

Scaling: $R \propto d^{-n}$, where $n = D - H$

$D = 2$ for 2D systems

$D = 3$ for 3D systems



Aftershocks
Earthquake rates following a stress step

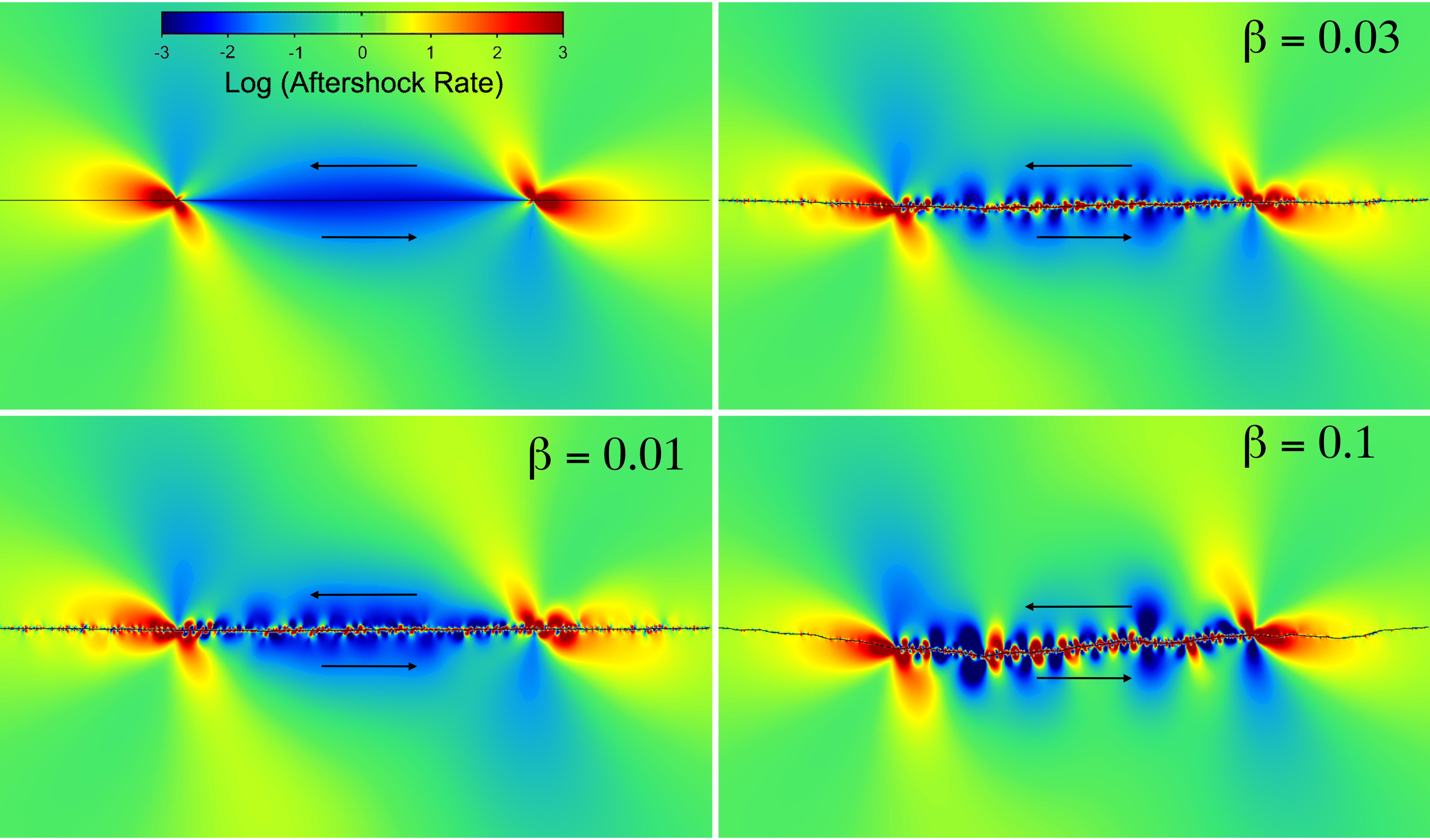
Earthquake rate $R = \dfrac{r}{\gamma \dot{S}_r}$, $d\gamma = \dfrac{1}{A\sigma}\left[dt - \gamma\, dS\right]$

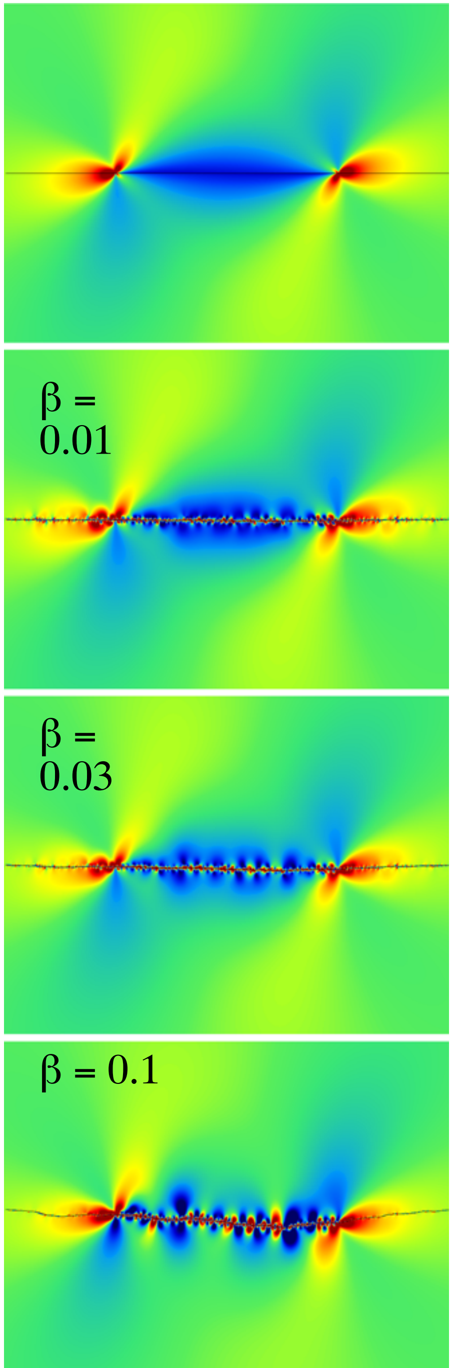
Following a stress step $R = \dfrac{r}{\left[\exp\left(\dfrac{-\Delta S}{A\sigma}\right) - 1\right]\left[\exp\left(\dfrac{-t}{t_a}\right)\right] + 1}$

Immediate aftershocks at *t*=0 $\dfrac{R}{r} = \left[\exp\left(\dfrac{\Delta S}{A\sigma}\right) - 1\right]$

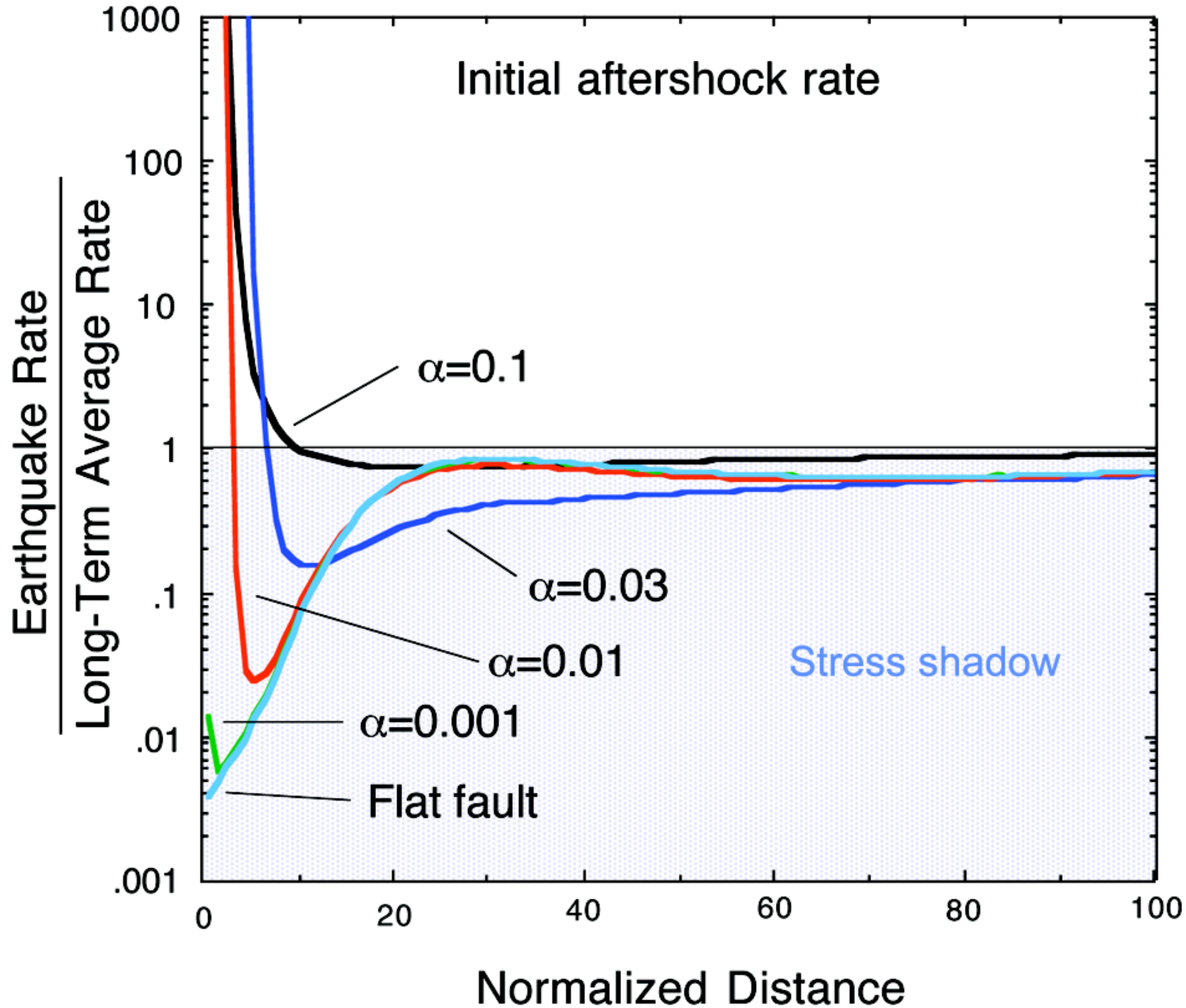
Dieterich, JGR (1994), Dieterich, Cayol, Okubo, Nature, (2000)

Initial Aftershock Rate / Background Rate





β = 0.01
β = 0.03
β = 0.1

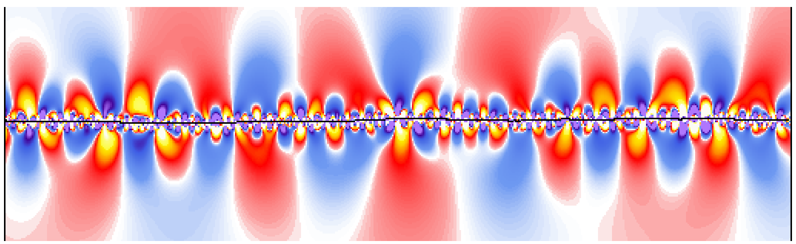


Initial aftershock rate
α=0.1
α=0.03
α=0.01
α=0.001
Flat fault
Stress shadow
Earthquake Rate
Long-Term Average Rate
Normalized Distance
1000
100
10
1
.1
.01
.001
0
20
40
60
80
100

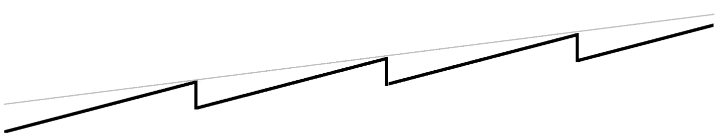
Rate-State Stress Relaxation

Concept for stress relaxation: Assume stresses fluctuate around a steady-state condition where the long-term growth of interaction stresses due to fault slip is balanced by off-fault yielding.

Change of stress during earthquake



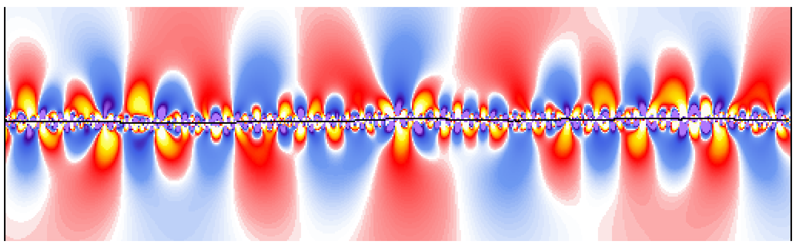
Elastic response



Rate-State Stress Relaxation

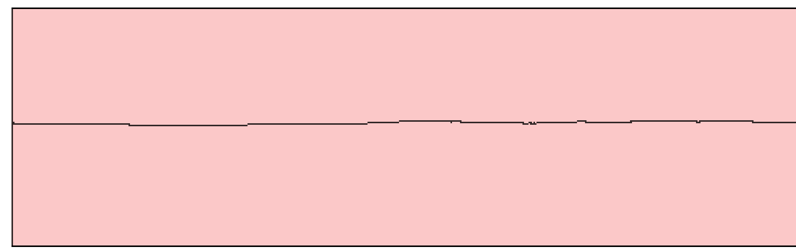
Concept for stress relaxation: Assume stresses fluctuate around a steady-state condition where the long-term growth of interaction stresses due to fault slip is balanced by off-fault yielding.

Change of stress during earthquake

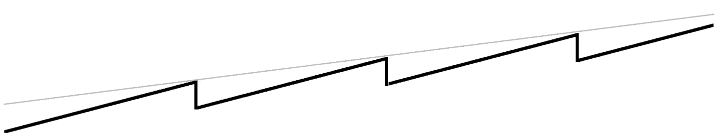


Δt

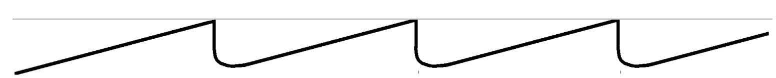
Relaxed state (+ tectonic stressing)



Elastic response



Elastic response
+
Rate - state relaxation



Rate-State Stress Relaxation

Relaxation rate is proportional to earthquake rate, $R \propto \dot{\sigma}$ where

$$R = \frac{r}{\gamma \dot{\tau}_r} \quad , \qquad d\gamma = \frac{1}{a\sigma}\left[dt - \gamma dS\right]$$

Relaxation rate of individual stress components

$$\dot{\sigma}_{ij}^{R} = \frac{C_{ij}}{\gamma_{ij}} \quad , \quad d\gamma_{ij} = \frac{1}{a\sigma}\left[dt - \Lambda_{ij}^{\pm}\gamma_{ij} d\sigma_{ij}\right]$$

$$\Delta\sigma_{ij}^{R}(t) = -C \int \frac{1}{\gamma_{ij}(t)} dt$$

Factors *C* and Λ vary spatially.

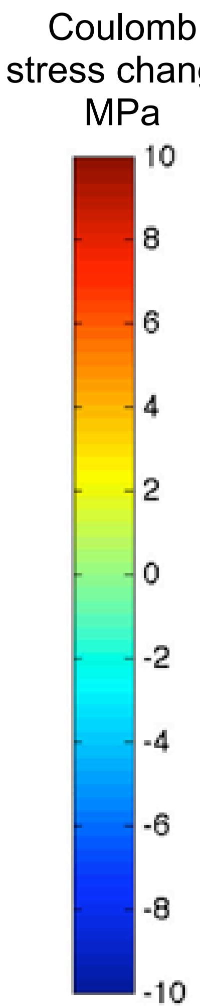
C is set to make net long-term stressing (from tectonic loading, fault slip, and off-fault relaxation) equal to zero.

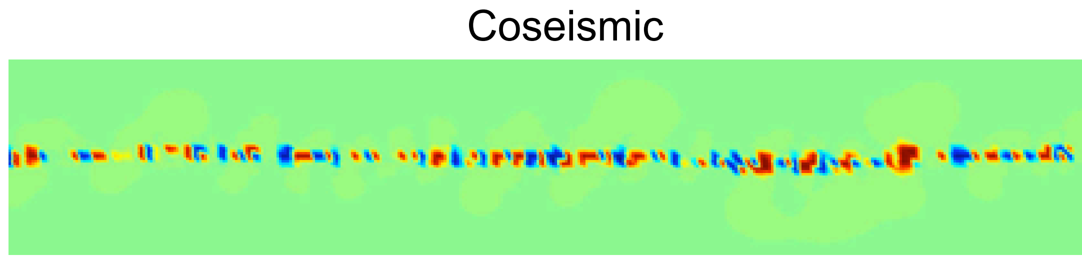
Λ is a sign function with values of ±1.

$\Lambda_{ij}^{\pm}$ = +1 if long-term slip → stress increase
-1 if long-term slip → stress decrease

Off-fault stress relaxation for a full earthquake cycle

t_a=11 yr, T=150 yr

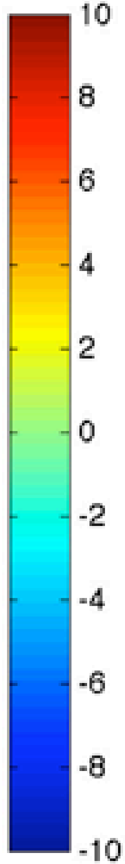




Off-fault stress relaxation for a full earthquake cycle

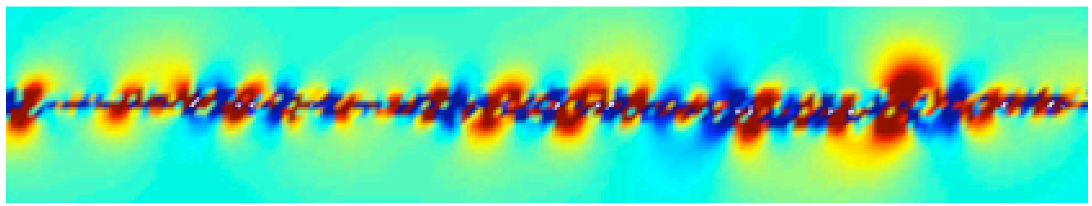
t_a=11 yr, T=150 yr

Coulomb stress change MPa



Coseismic

Aftershocks

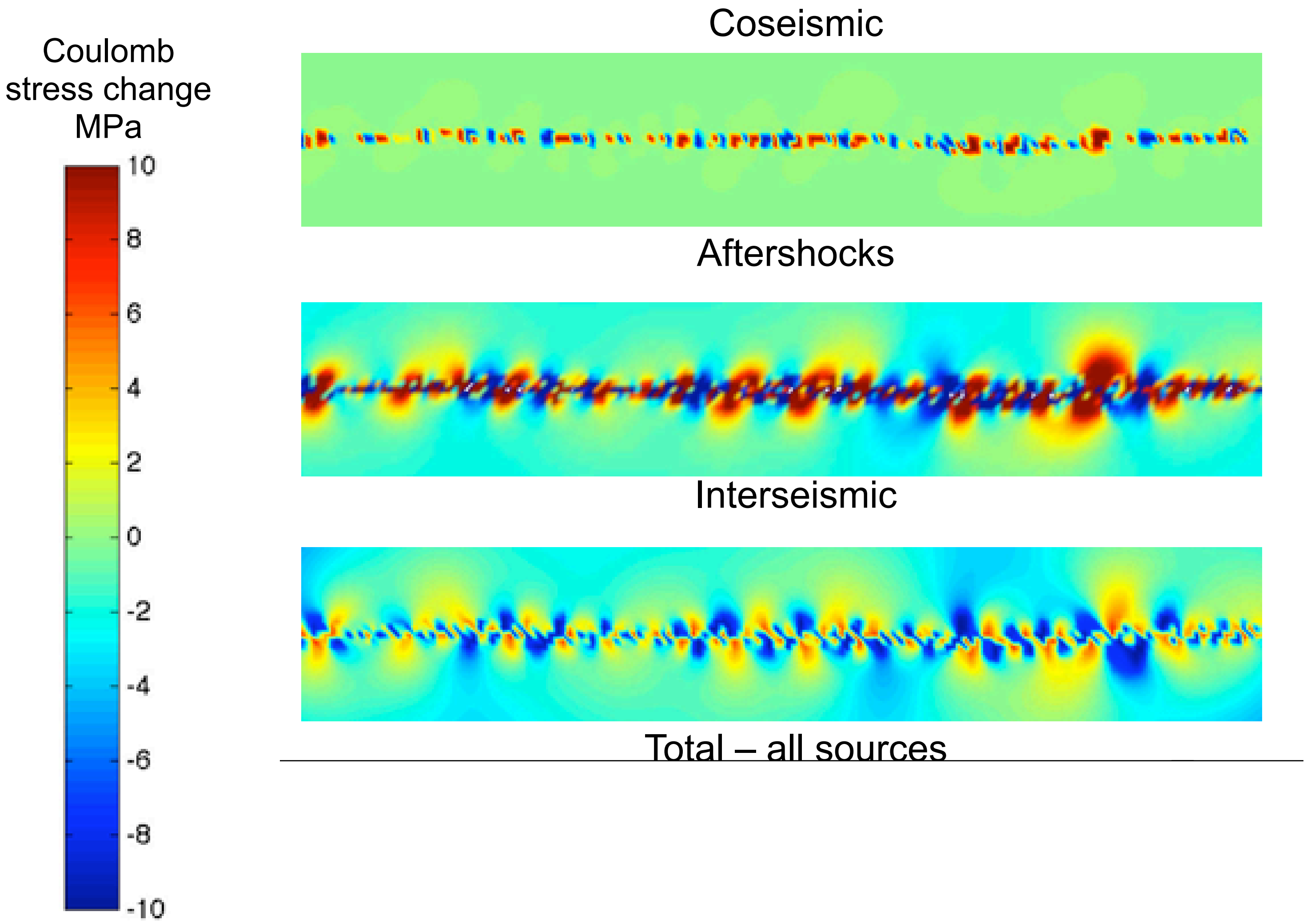


Interseismic

Total = all sources

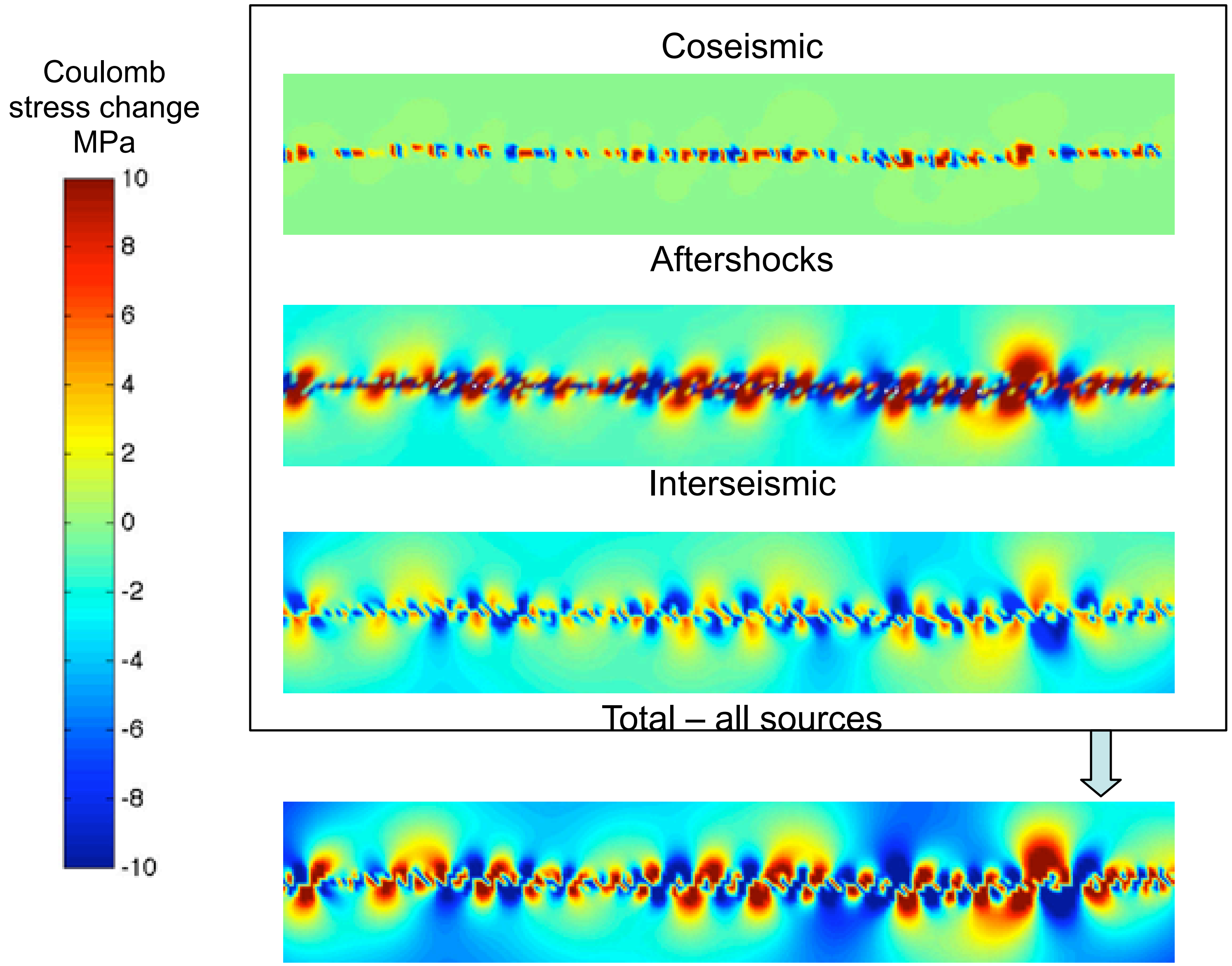
Off-fault stress relaxation for a full earthquake cycle

t_a=11 yr, T=150 yr



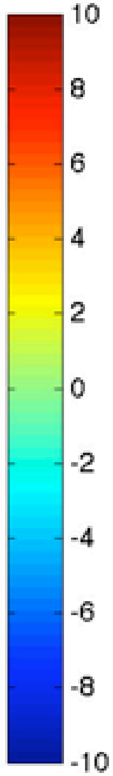
Off-fault stress relaxation for a full earthquake cycle

t_a=11 yr, T=150 yr

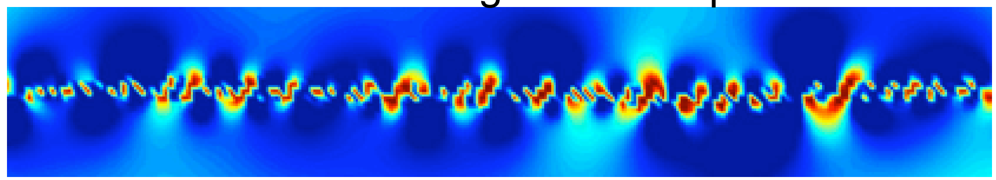


Stress change budget for a full earthquake cycle

Stress change MPa

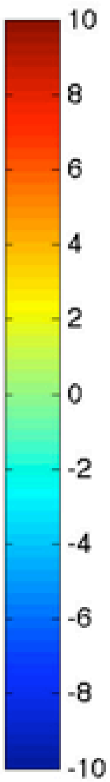


Stress change due to slip

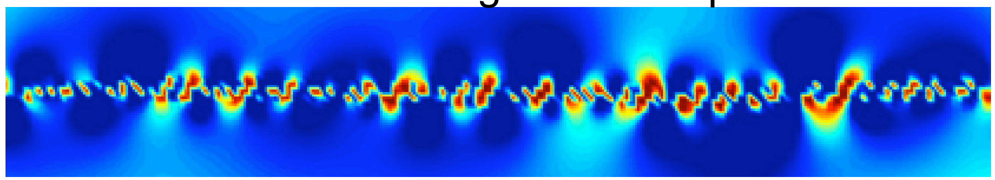


Stress change budget for a full earthquake cycle

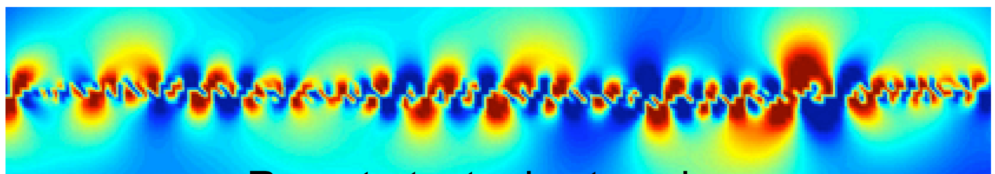
Stress change
MPa



Stress change due to slip

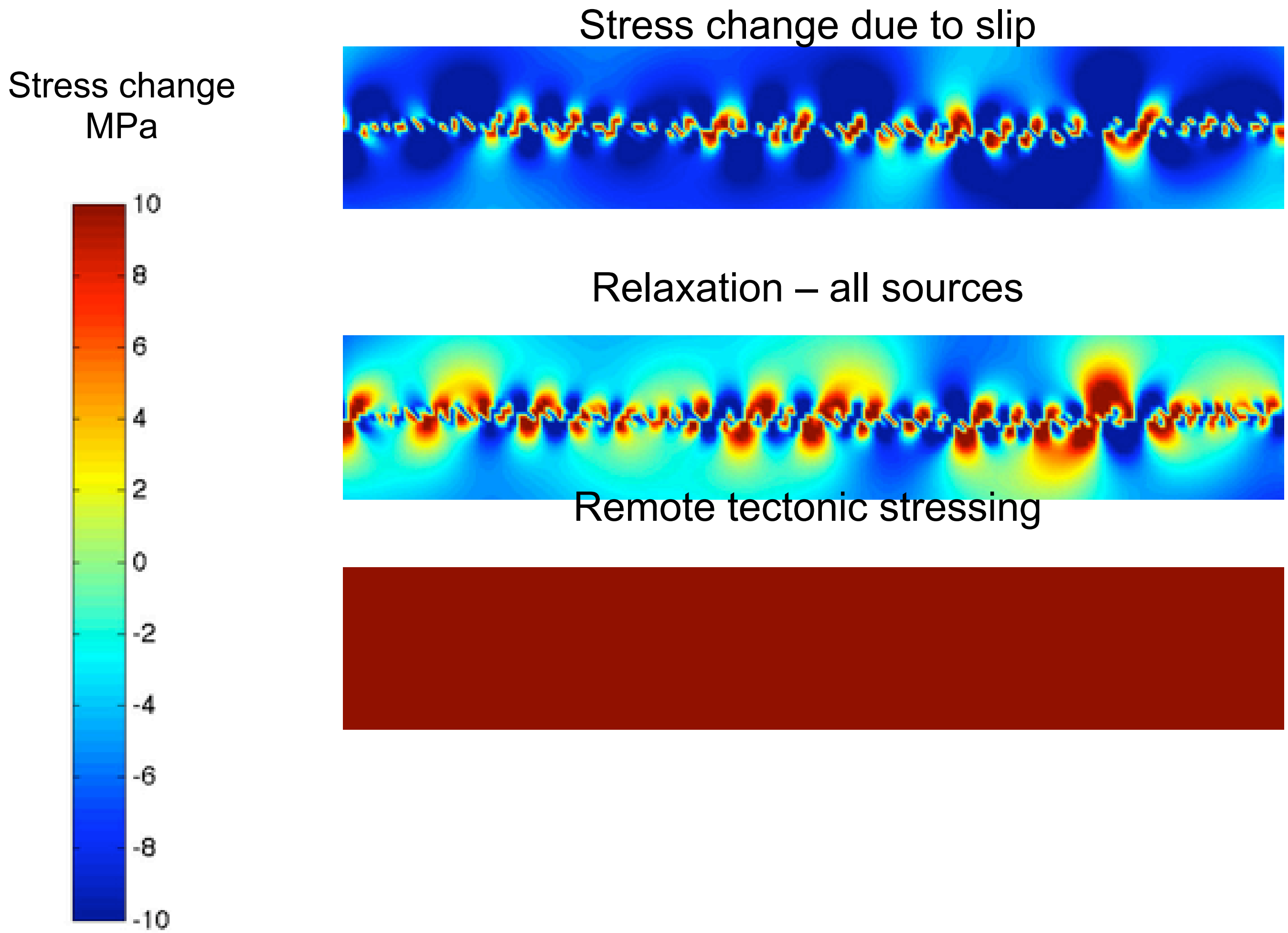


Relaxation – all sources

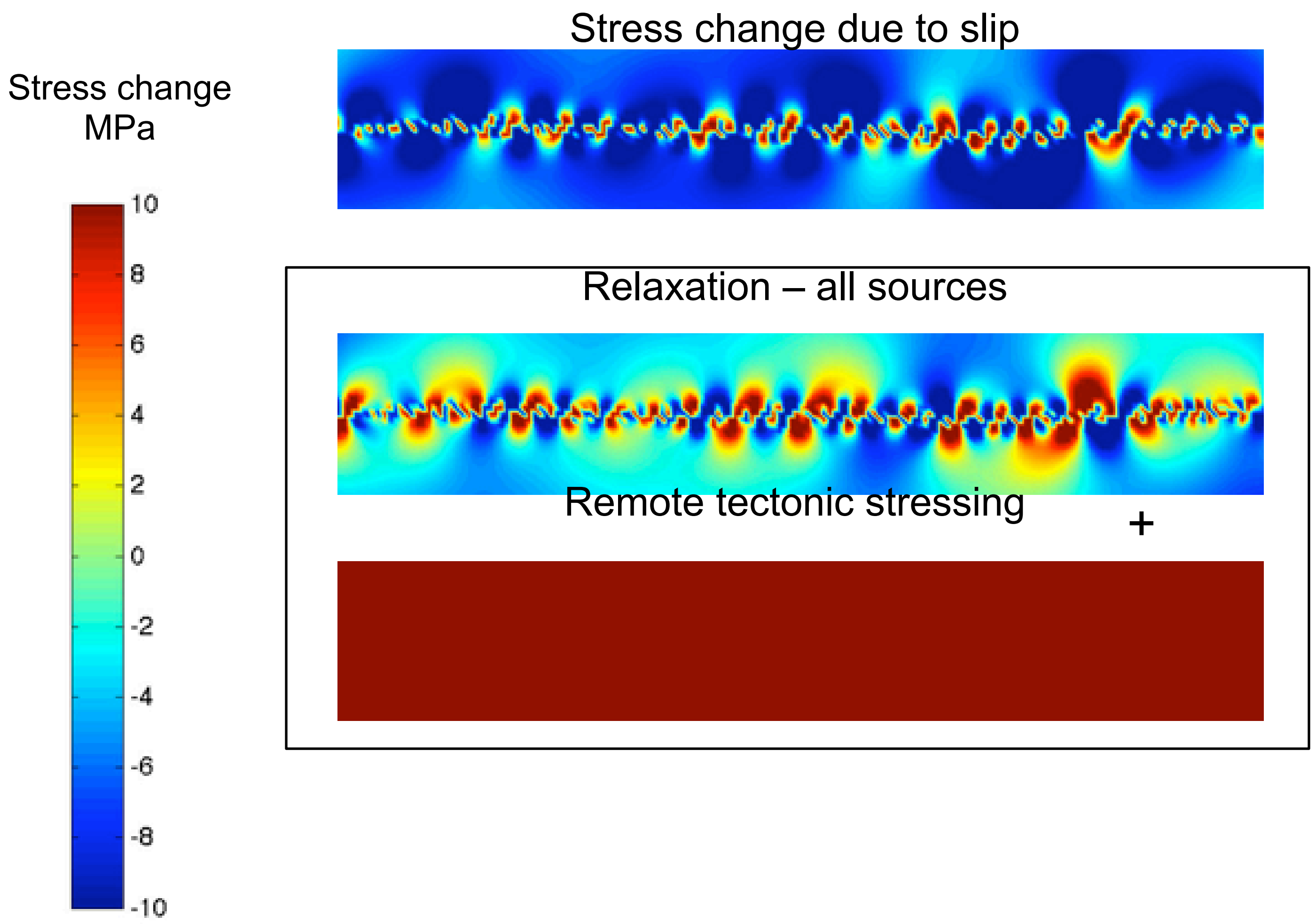


Remote tectonic stressing

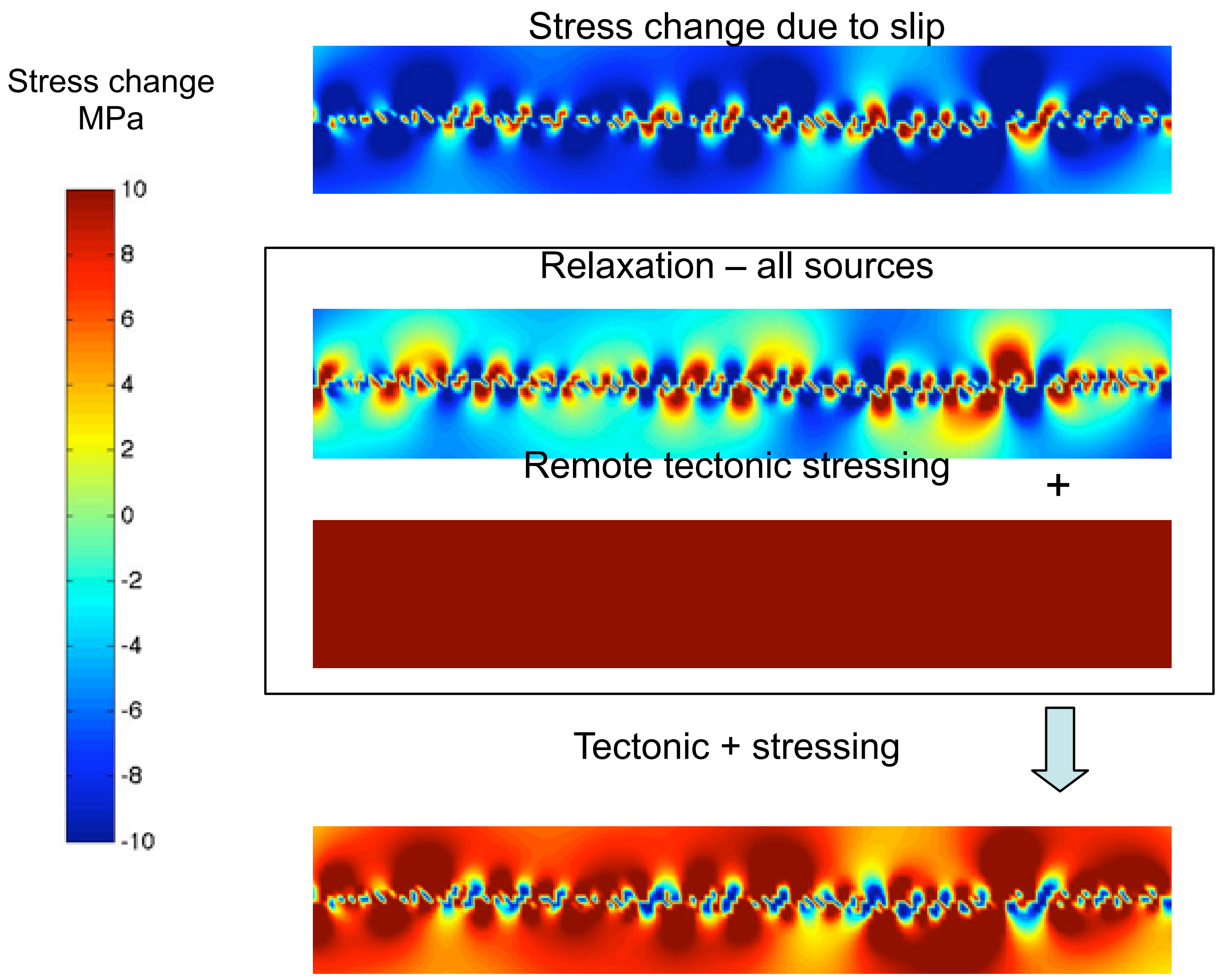
Stress change budget for a full earthquake cycle



Stress change budget for a full earthquake cycle

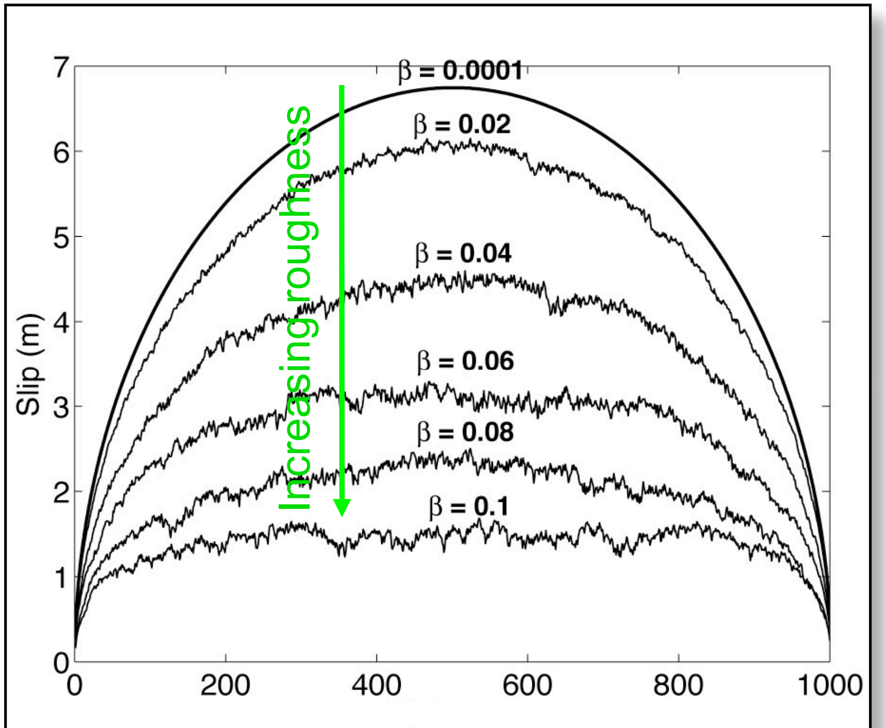


Stress change budget for a full earthquake cycle

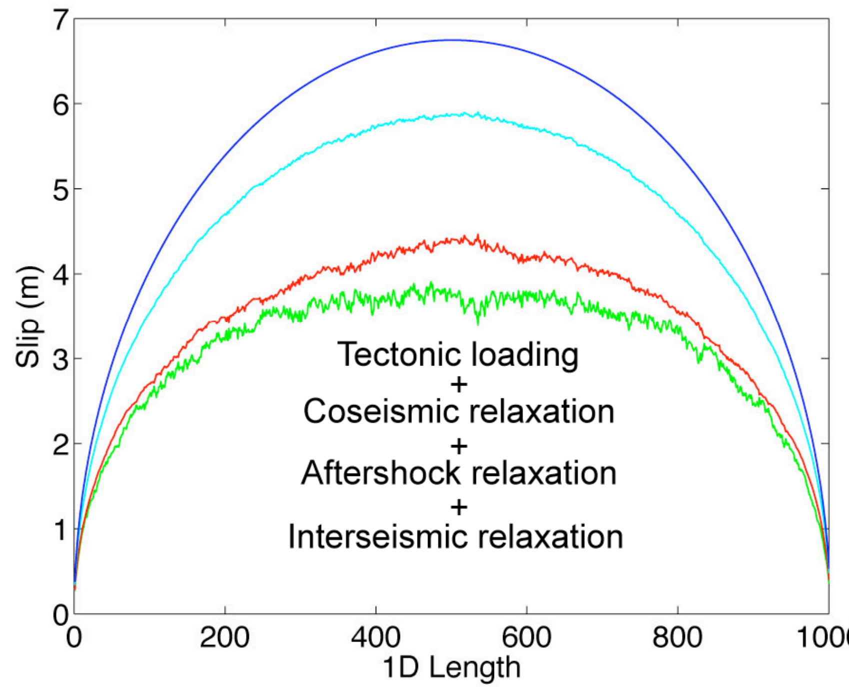


Fault Slip: Effects of Fault Roughness, Tectonic loading and Off-Fault Stress Relaxation

Slip due to remote tectonic loading
(no stress relaxation)

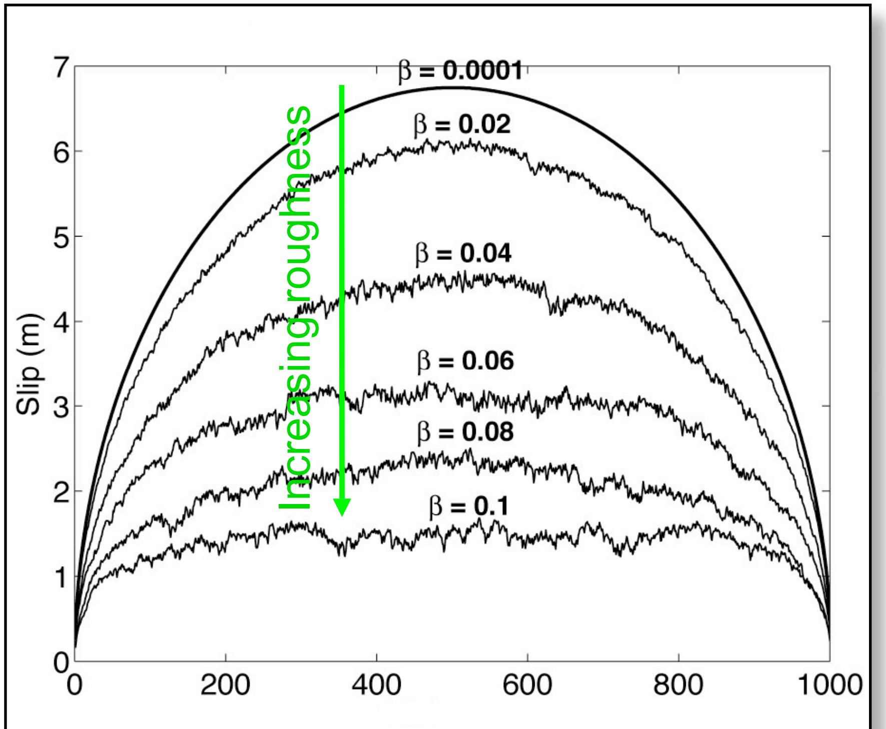


Remote loading
+
Off-fault relaxation (β=0.5)

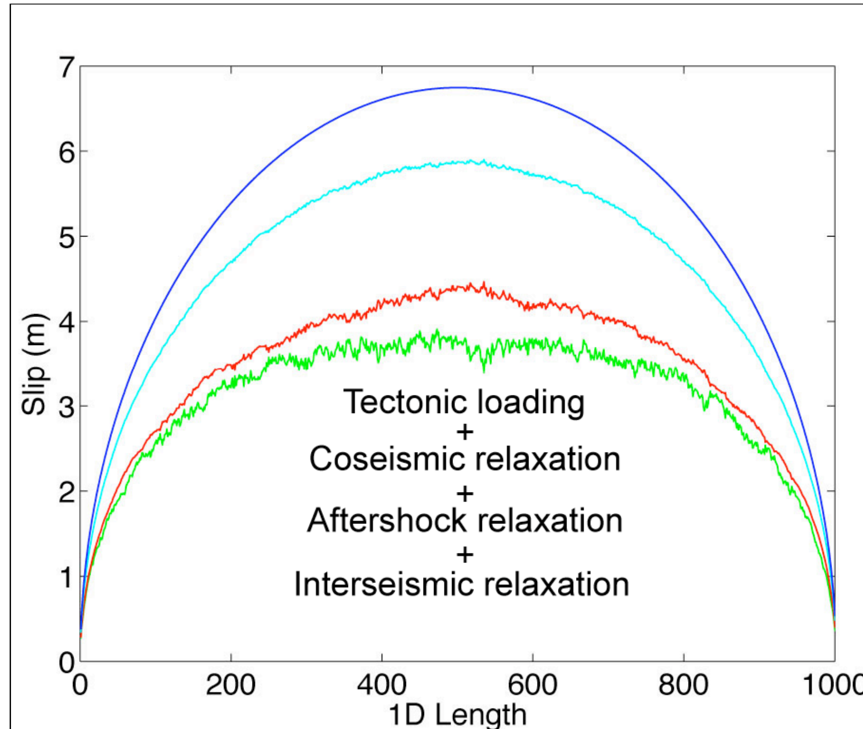


Fault Slip: Effects of Fault Roughness, Tectonic loading and Off-Fault Stress Relaxation

Slip due to remote tectonic loading
(no stress relaxation)

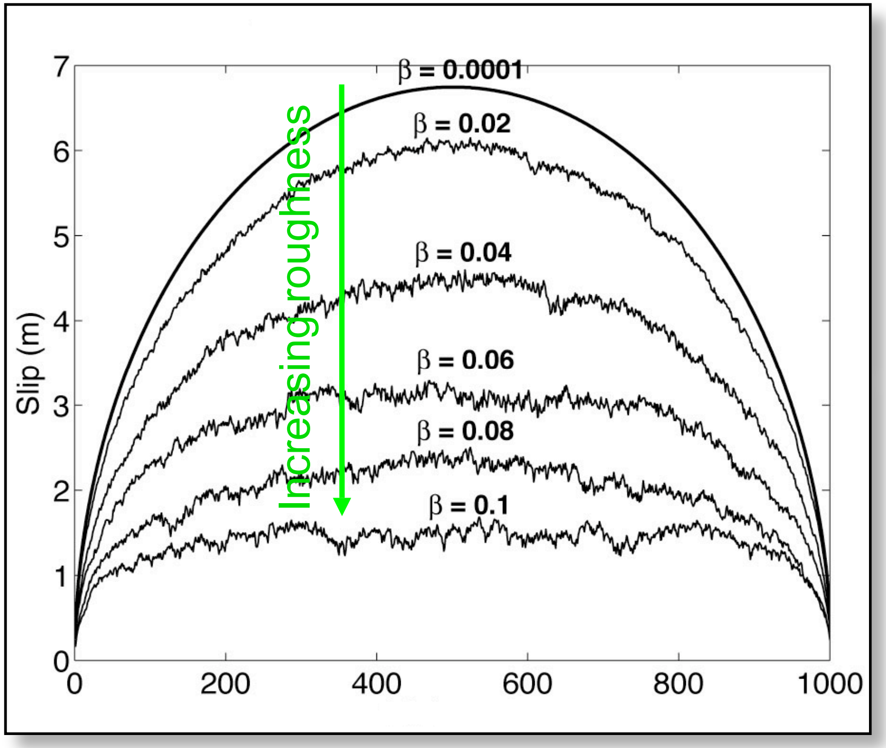


Remote loading
+
Off-fault relaxation (β=0.5)

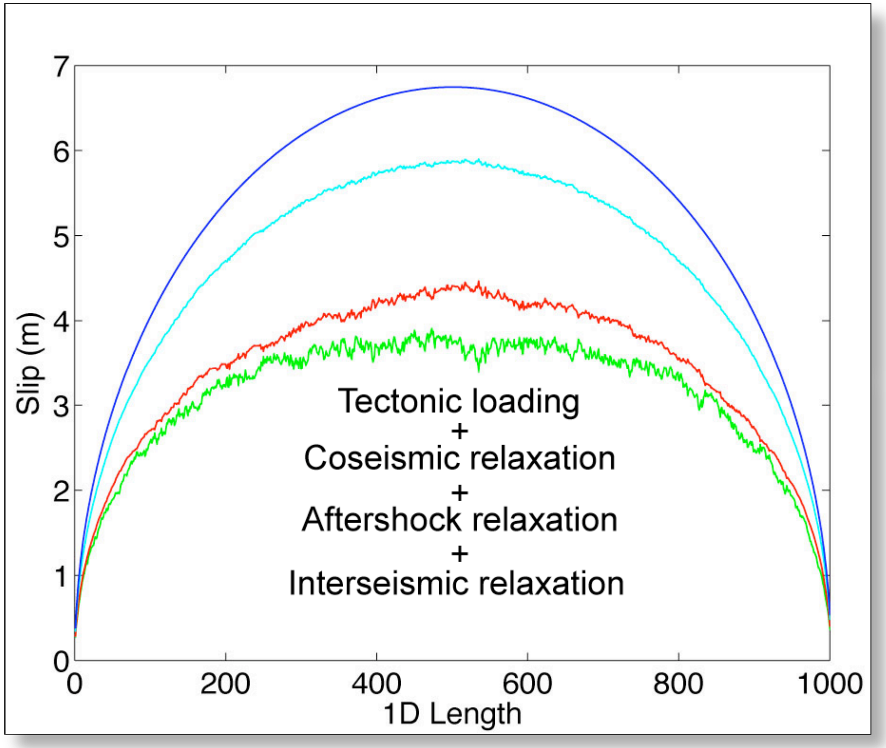


Fault Slip: Effects of Fault Roughness, Tectonic loading and Off-Fault Stress Relaxation

Slip due to remote tectonic loading
(no stress relaxation)

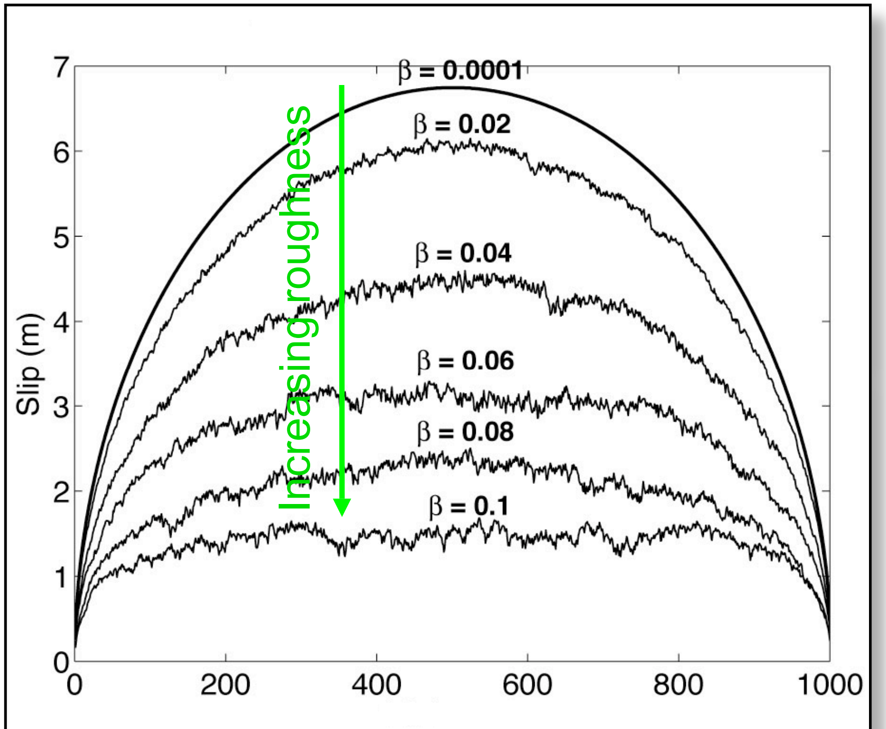


Remote loading
+
Off-fault relaxation (β=0.5)

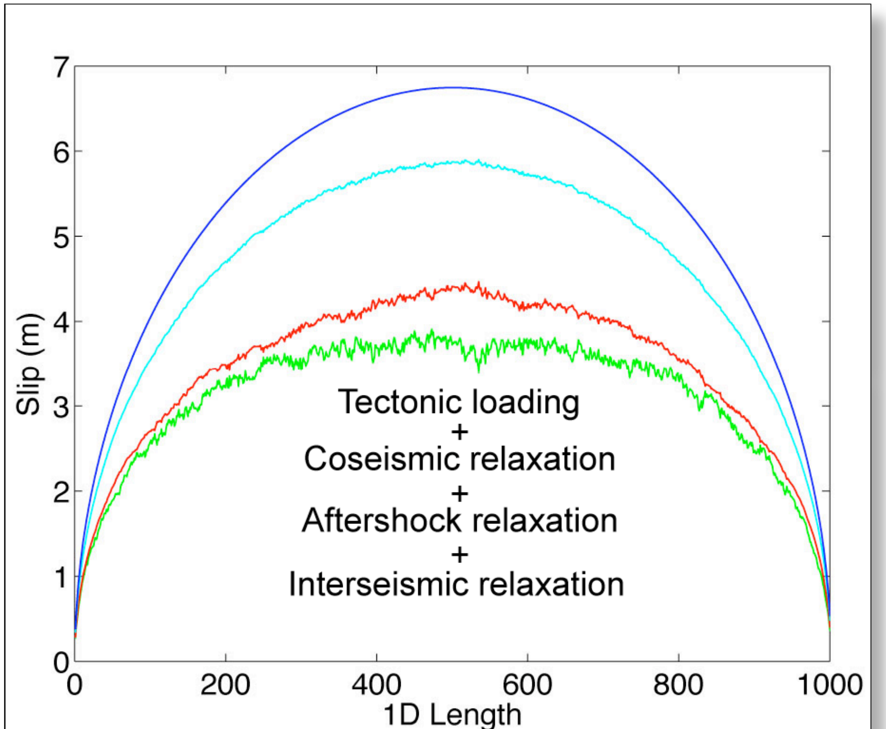


Fault Slip: Effects of Fault Roughness, Tectonic loading and Off-Fault Stress Relaxation

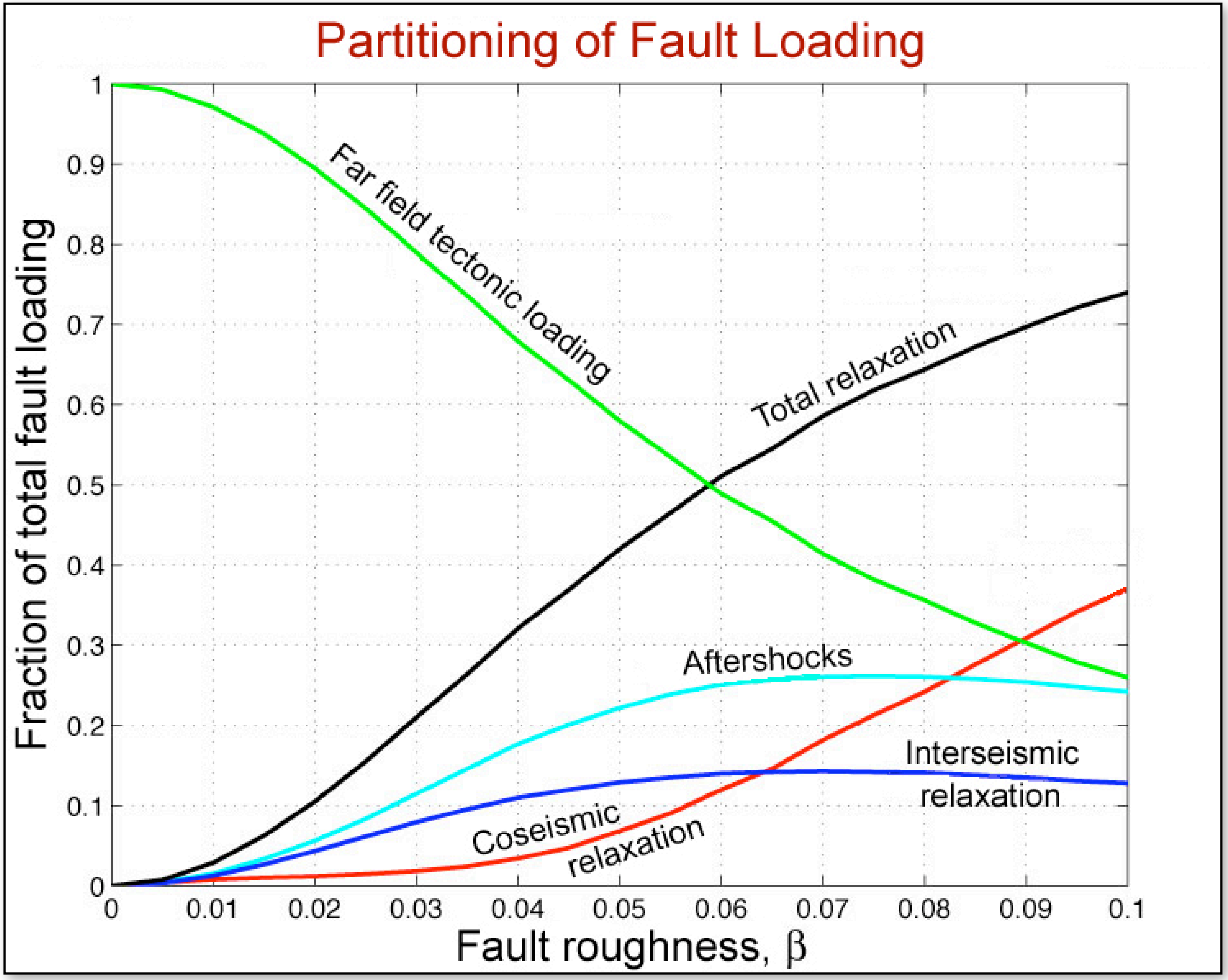
Slip due to remote tectonic loading
(no stress relaxation)



Remote loading
+
Off-fault relaxation (β=0.5)

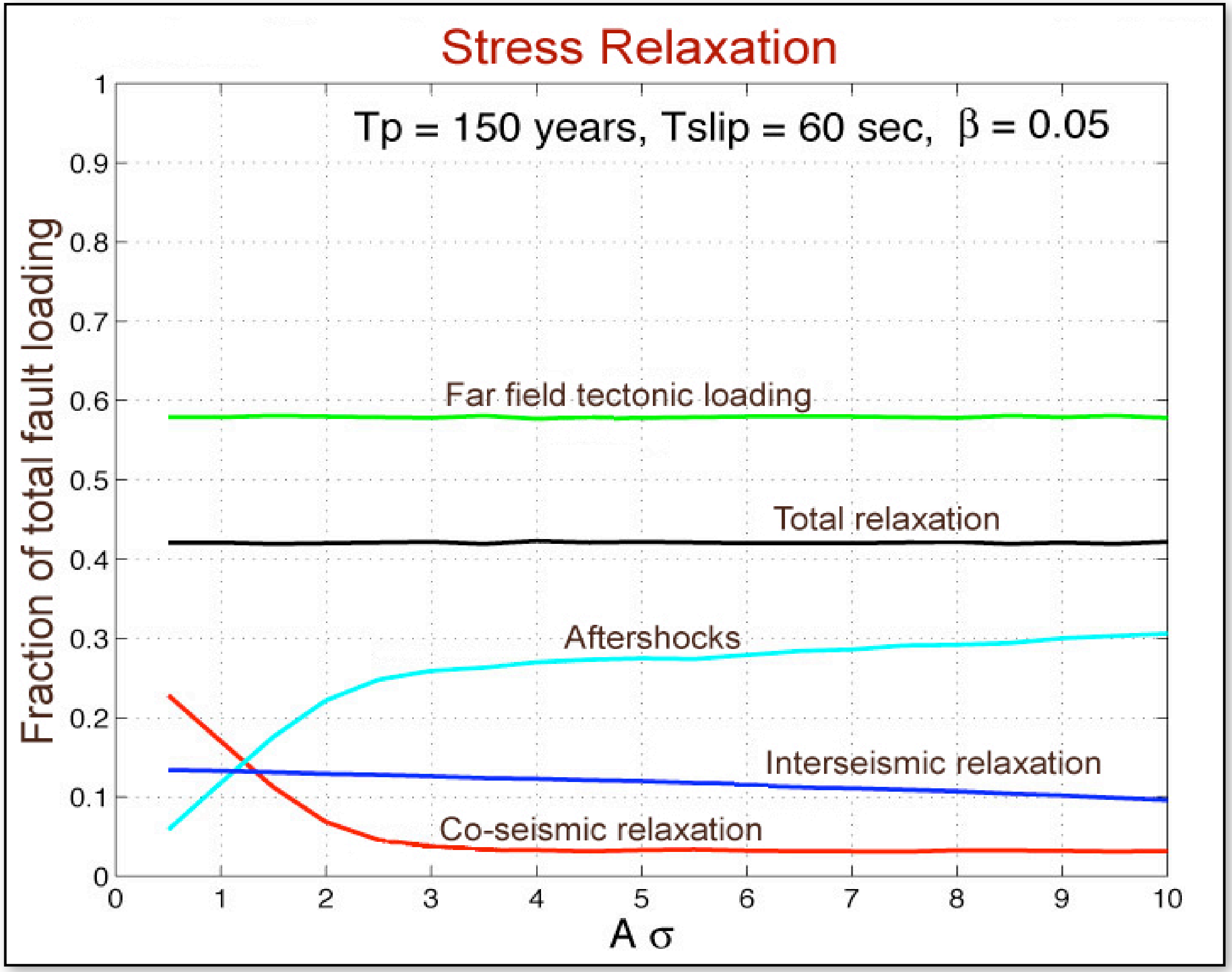


- Partitioning between far field loading and off-fault yielding is controlled by fault geometry

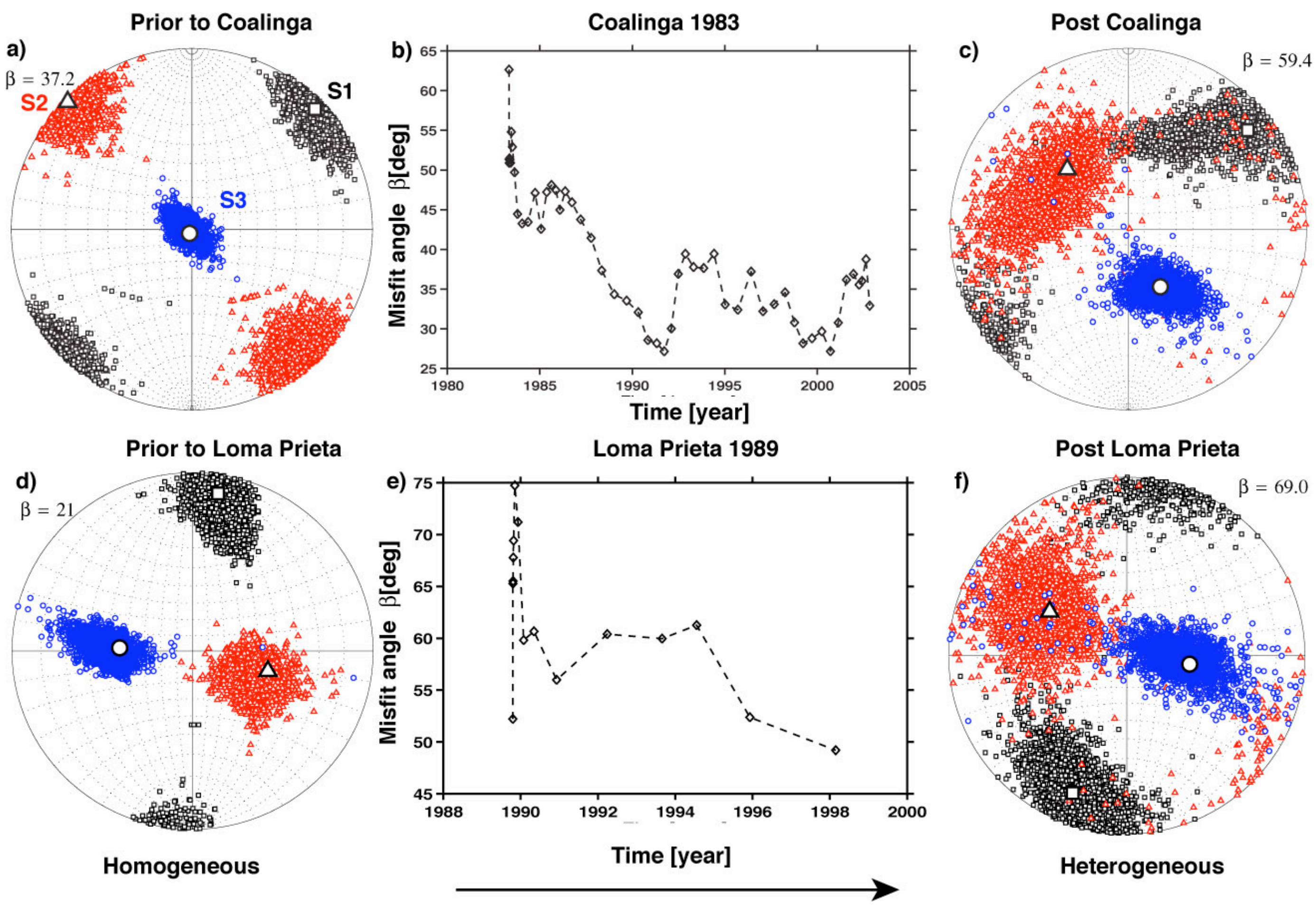


Asig=2 bar

- Partitioning among relaxation processes is controlled by Aσ



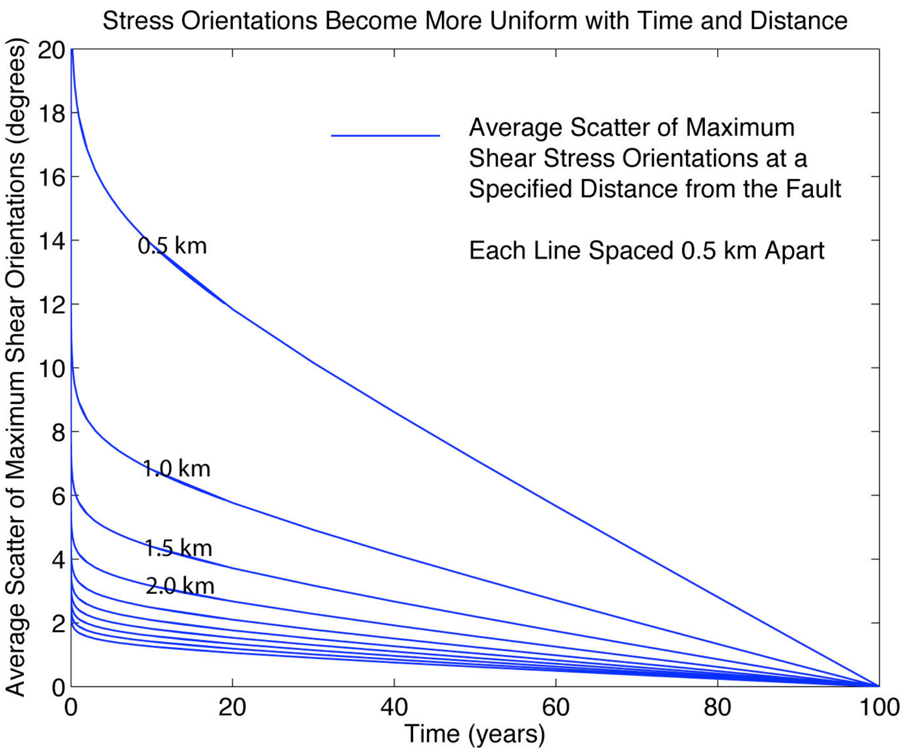
Evidence for Time Dependence of Stress Heterogeneity



Modified from (Woessner, 2005)

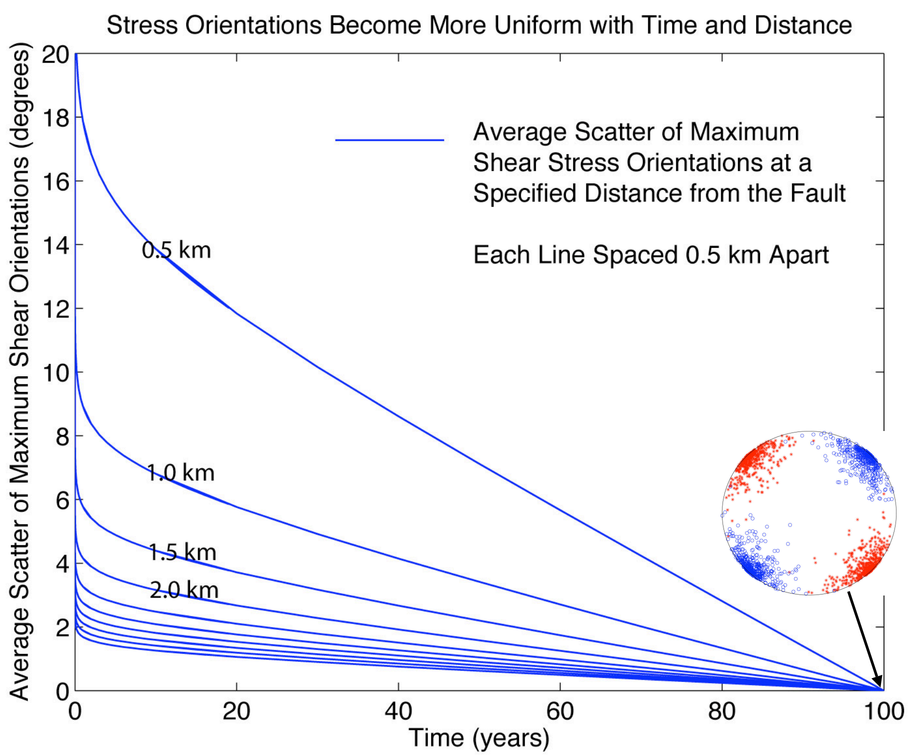
Decrease of Stress Heterogeneity with Time and Distance

(Background Deviatoric Stress = 100 bars)



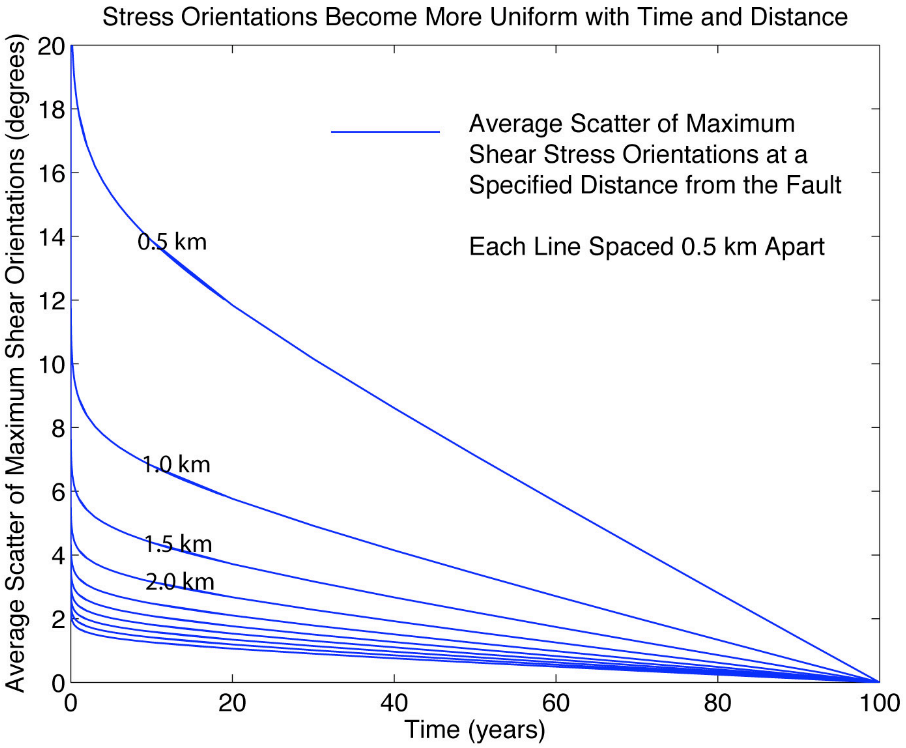
Decrease of Stress Heterogeneity with Time and Distance

(Background Deviatoric Stress = 100 bars)



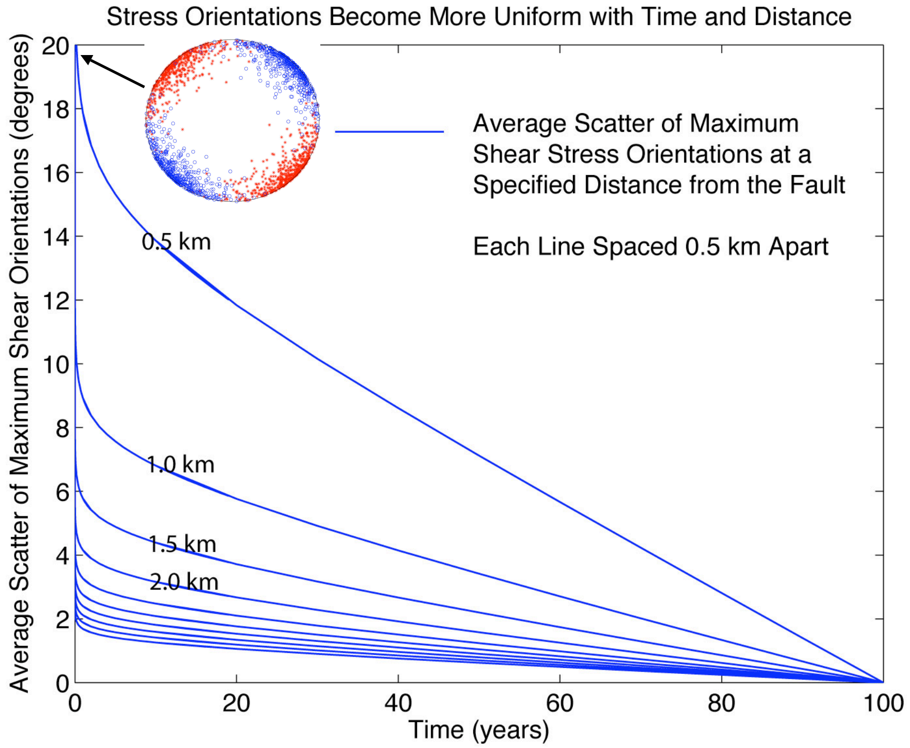
Decrease of Stress Heterogeneity with Time and Distance

(Background Deviatoric Stress = 100 bars)



Decrease of Stress Heterogeneity with Time and Distance

(Background Deviatoric Stress = 100 bars)



Decrease of Stress Heterogeneity with Time and Distance

(Background Deviatoric Stress = 100 bars)