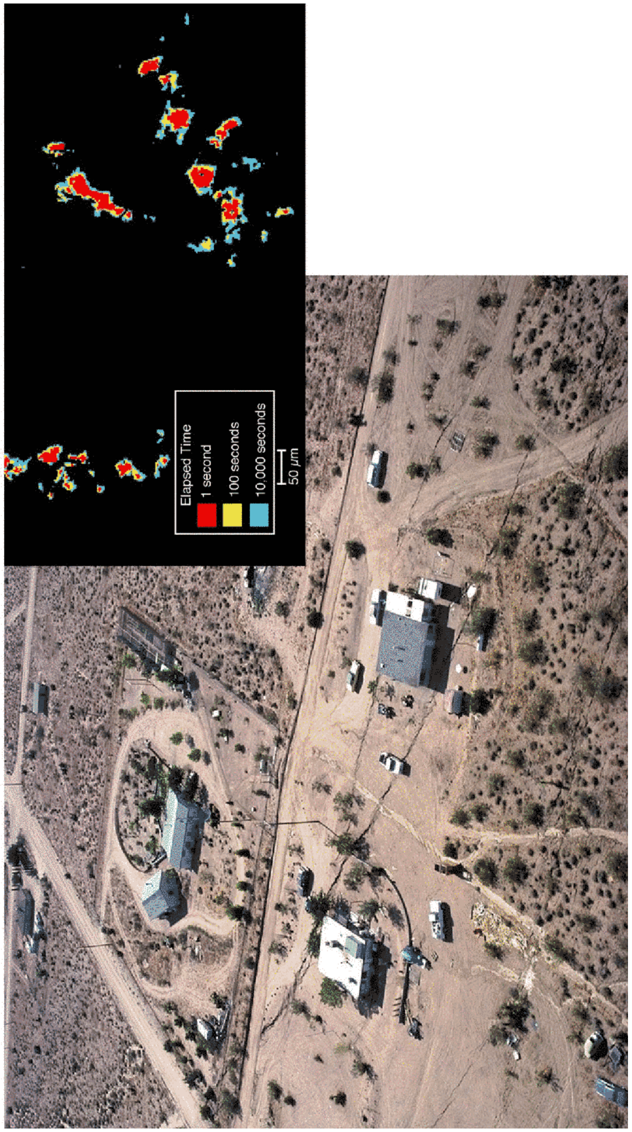
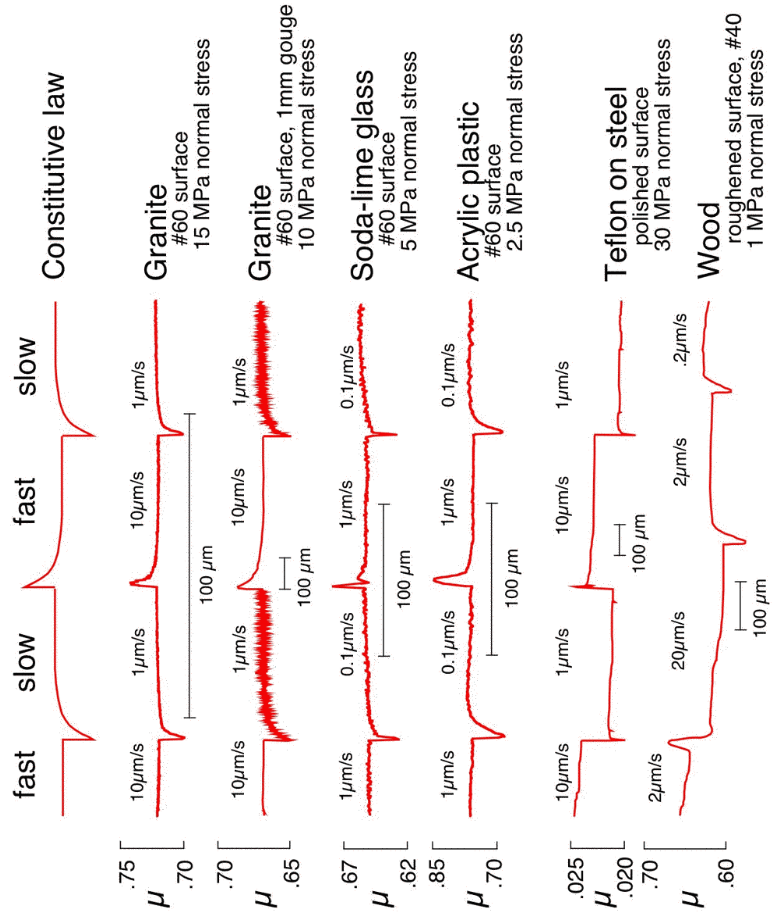
Macroscopic friction and earthquakes

Jim Dieterich, UC Riverside





Rate- and state-dependent friction

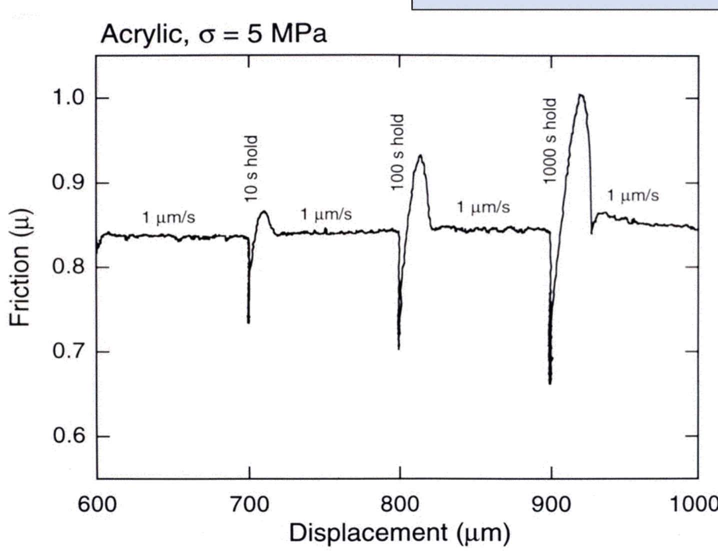
$$\frac{\tau}{\sigma} = \mu = \mu_0 + A\ln\left(\frac{V}{V^*}\right) + B\ln\left(\frac{\theta}{\theta^*}\right)$$

$$d\theta = dt - \frac{\theta}{D_c}d\delta - \frac{\alpha\theta}{B\sigma}d\sigma$$

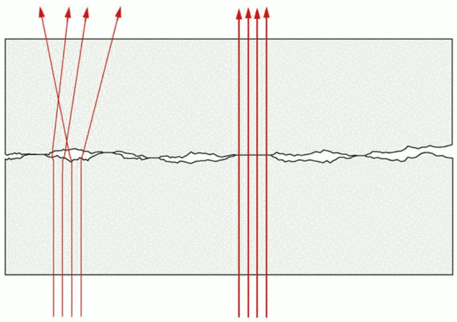
Slide – hold – slide experiments

$$\frac{\tau}{\sigma} = \mu = \mu_0 + A\ln\left(\frac{V}{V^*}\right) + B\ln\left(\frac{\theta}{\theta^*}\right)$$

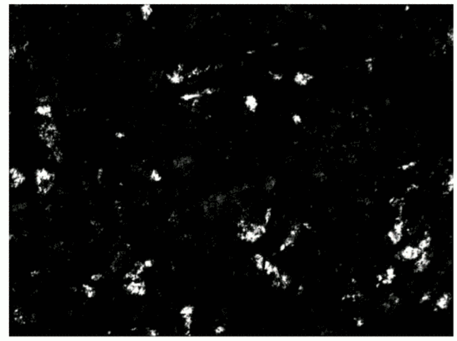
$$d\theta = dt - \frac{\theta}{D_c}d\delta - \frac{\alpha\theta}{B\sigma}d\sigma$$



Imaging contacts during slip



Schematic magnified view of contacting surfaces showing isolated high-stress contacts. Viewed in transmitted light, contacts appear as bright spots against a dark background.



Acrylic surfaces at 4MPa applied normal stress

Apparatus for viewing contacts during slip

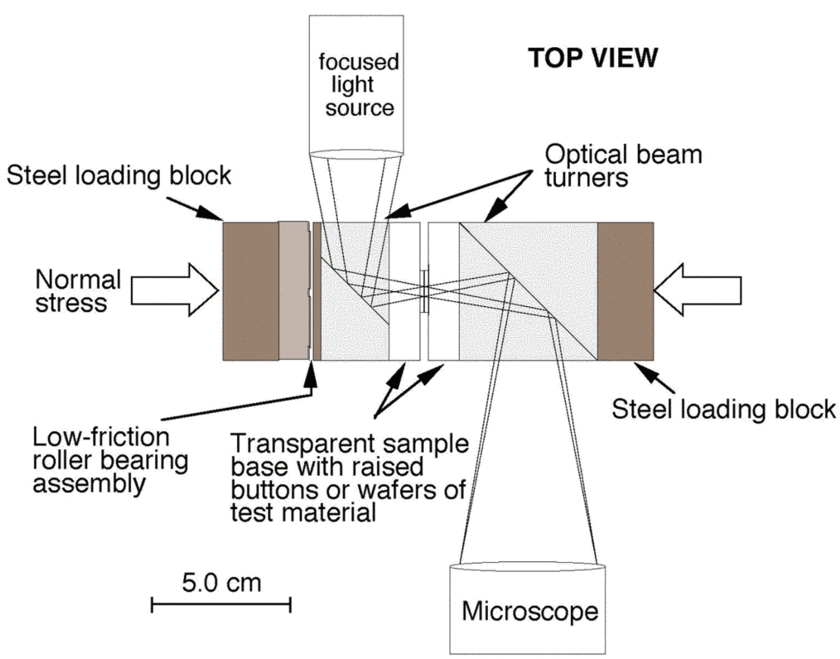
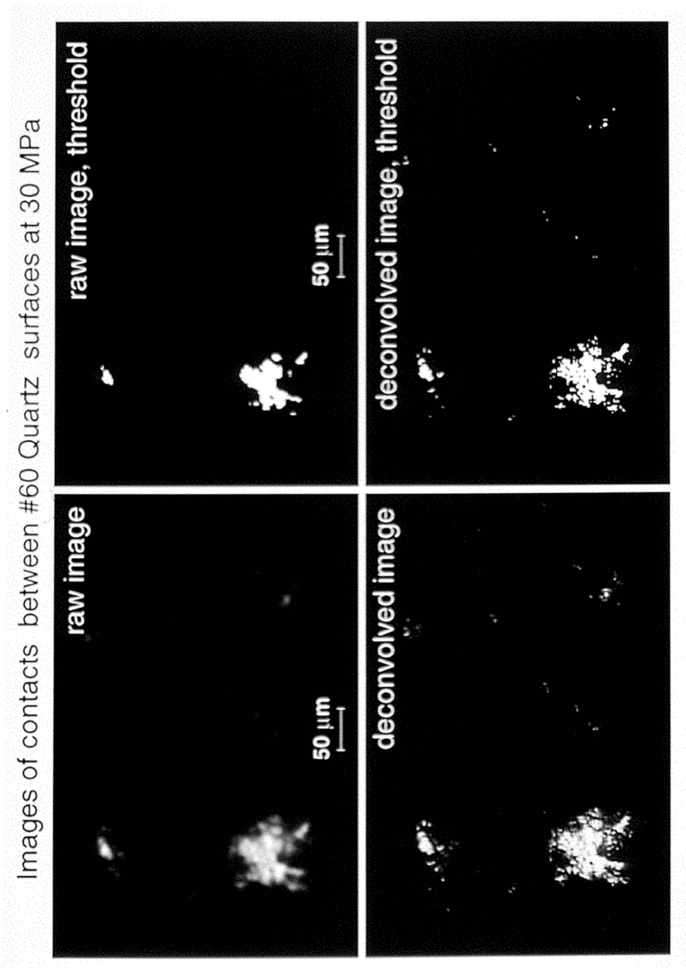
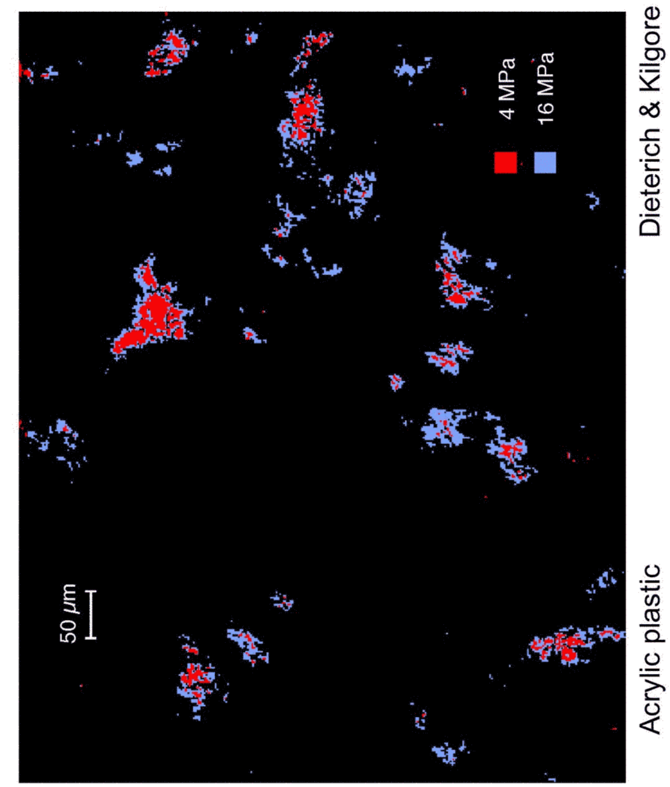


Image Processing

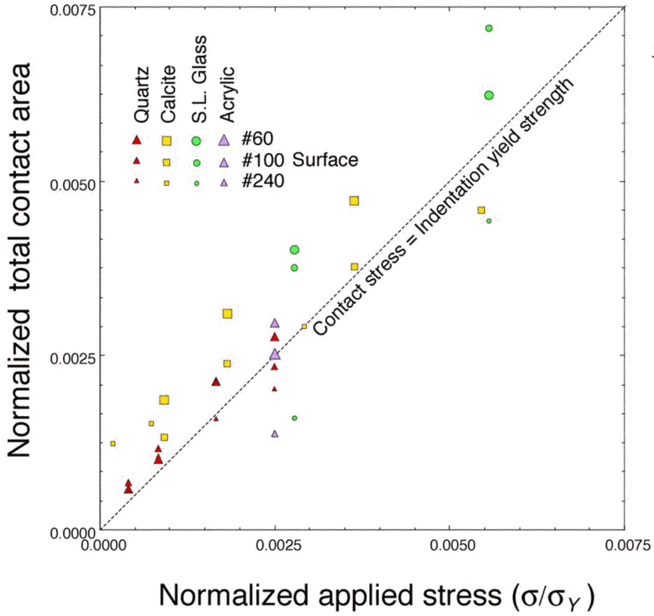
Images of contacts between #60 Quartz surfaces at 30 MPa



Change of contact area with normal stress

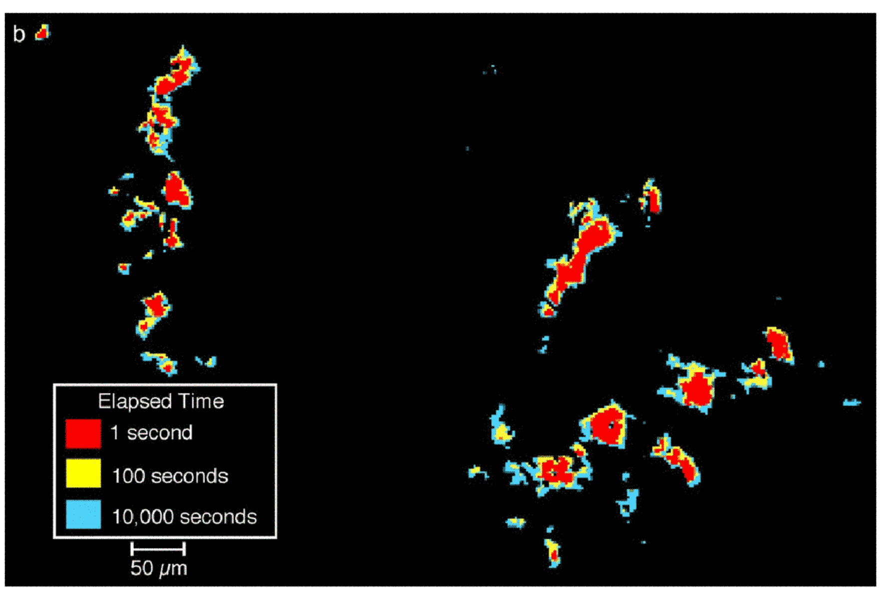


Contact stresses



Indentation yield stress, σ_y	
Acrylic	400 MPa
Calcite	1,800 MPa
SL Glass	5,500 MPa
Quartz	12,000 MPa

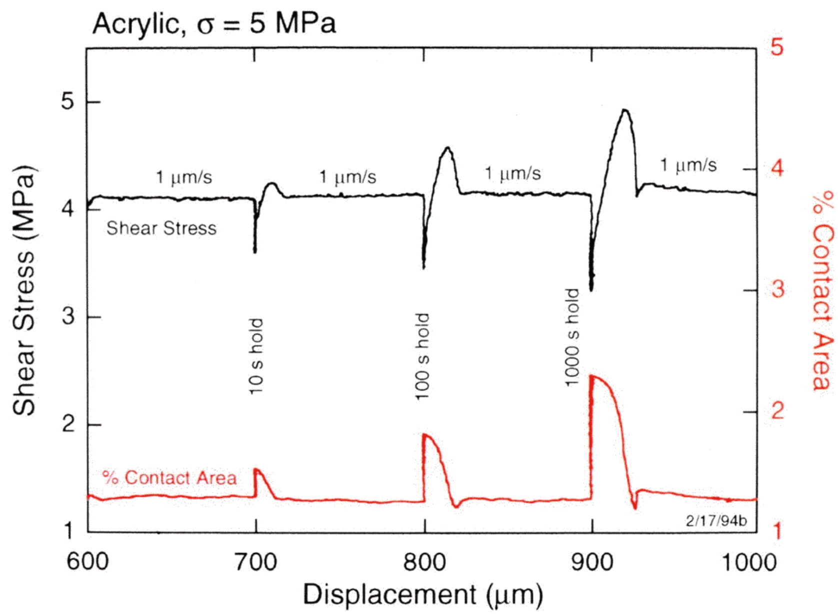
Increase of contact area with time



Acrylic plastic

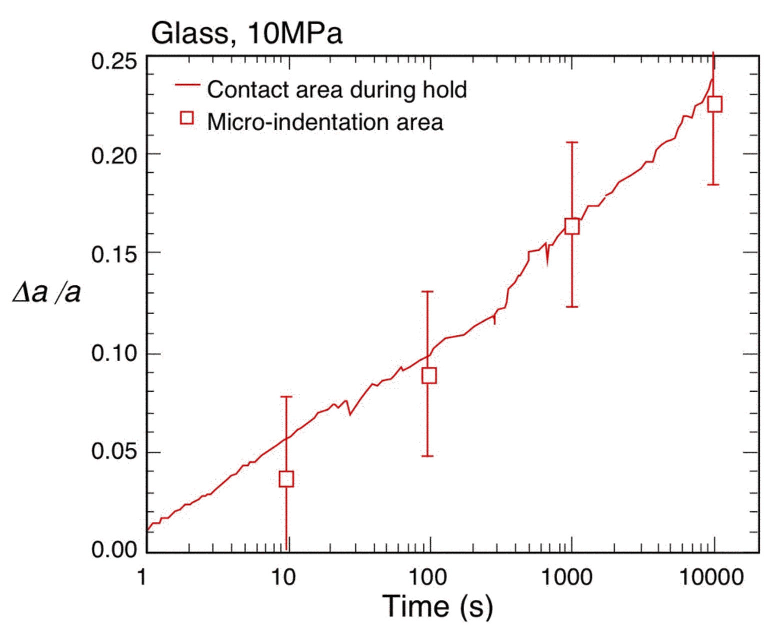
Dieterich and Kilgore, PAGEOPH, 1994

Time dependent friction & contact area



Dieterich and Kilgore, PAGEOPH, 1994

Contact area during hold



Dieterich and Kilgore, PAGEOPH, 1994

Interpretation of friction terms

Bowden and Tabor adhesion theory of friction

Contact area: area = $c\sigma$

c=1/ indentation yield stress
g=shear strength of contacts

Shear resistance: τ = (area) (g), $\tau/\sigma = \mu = cg$

Time and rate dependence of contact strength terms

Indentation creep: $c(\theta) = c_1 + c_2\ln(\theta)$

Shear of contacts: $g(V) = g_1 + g_2\ln(V)$

$$\mu = c_1 g_1 + c_1 g_2 \ln(V) + c_2 g_1 \ln(\theta) + \boxed{c_2 g_2 \ln(V+\theta)}$$

$$\mu = \mu_0 + A\ln(V) + B\ln(\theta)$$

(Drop the high-order term)

Slip instabilities – earthquake nucleation

Required:

Rate weakening at ss. $\mu_{ss} = const. + (A-B)\ln(V)$

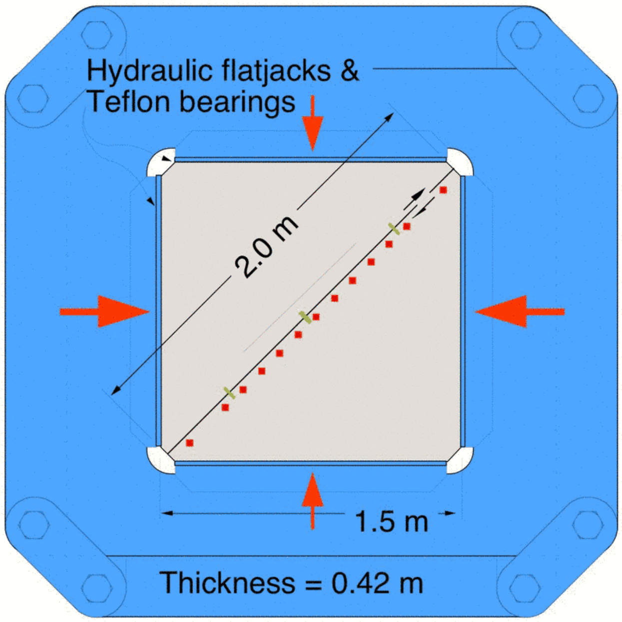
Critical stiffness: $K_c = \dfrac{\sigma\xi}{D_c}$

For slip on a fault patch, effective stiffness is given by elastic crack solution $K = \dfrac{\Delta\tau}{d} = \dfrac{G\eta}{L}$

Equating with critical stiffness: ($L>L_c$ for instability) $L_c = \dfrac{D_c G\eta}{\sigma\xi}$

(η is crack geometry factor, $\eta \sim 1$)

Large-scale biaxial test of L_c



Minimum fault length for unstable slip

$$L_c = \frac{D_c G \eta}{\sigma \xi}$$

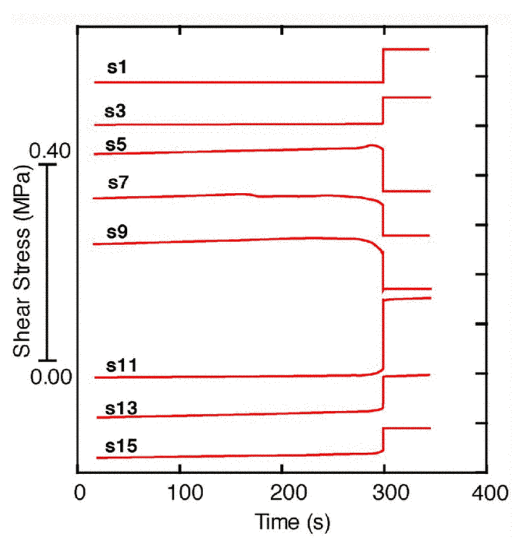
$L_c = .75$ m

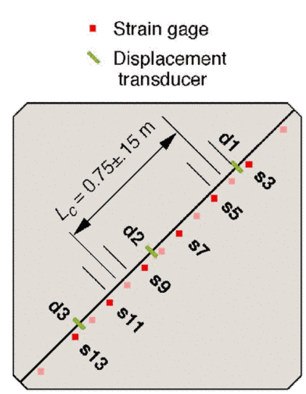
- $G = 15000$ MPa
- $\eta = 0.5$
- $D_c = 2\ \mu$m
- $\sigma = 5$ MPa
- $\xi = .4B = 0.004$

Strain gage

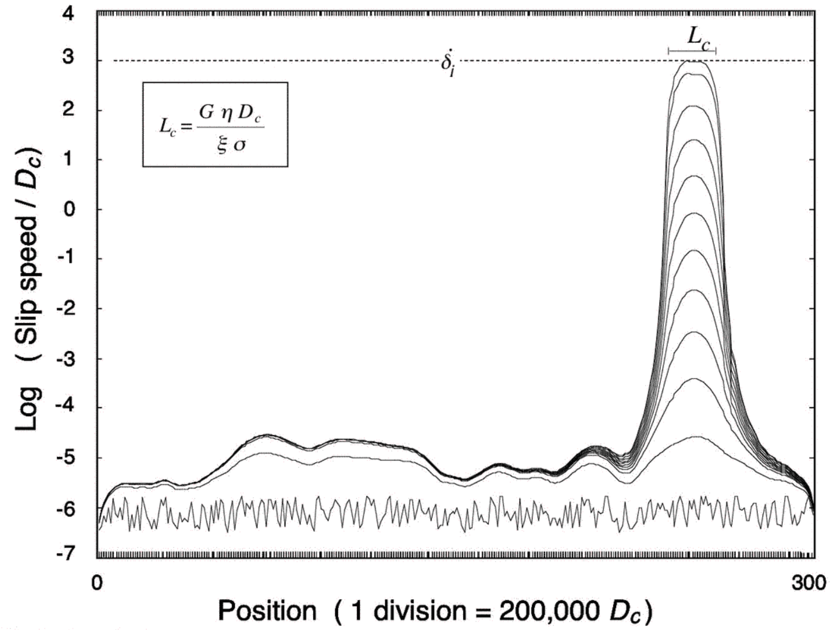
Displacement transducer

Confined Unstable Slip



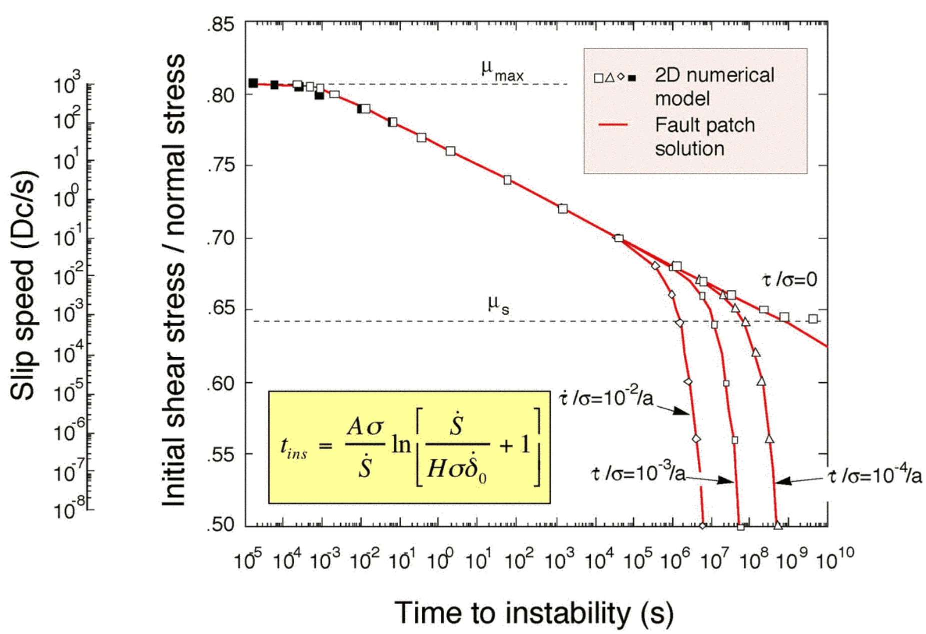


Earthquake nucleation – heterogeneous normal stress



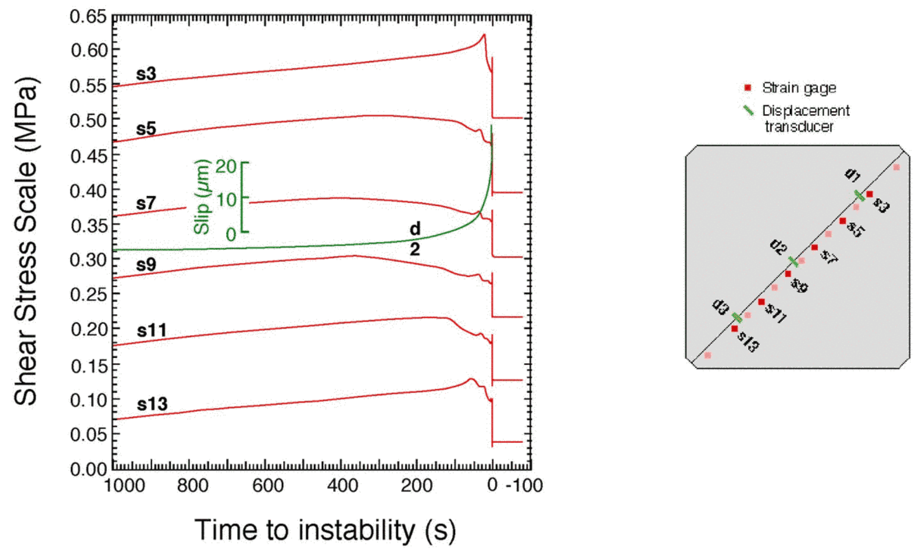
Dieterich, 1992, *Tectonophysics*

Time to instability

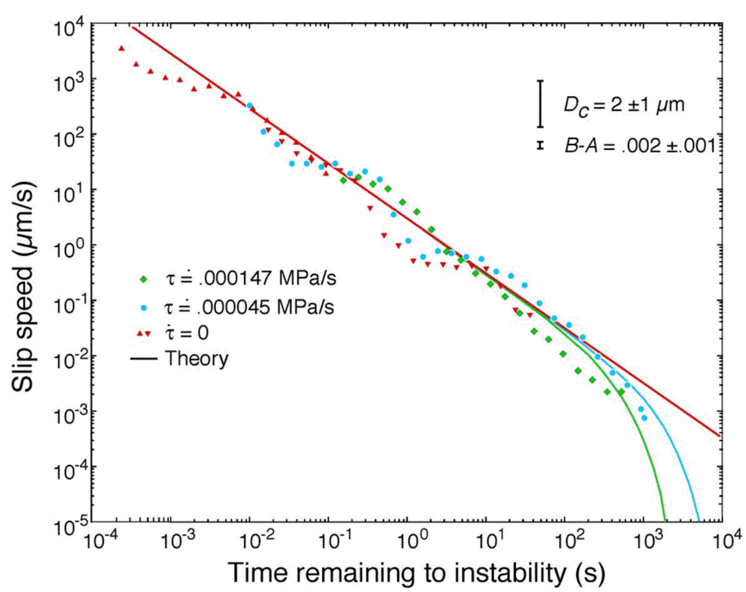


Dieterich, 1992, *Tectonophysics*

Accelerating slip prior to instability



Time to instability - Experiment and theory

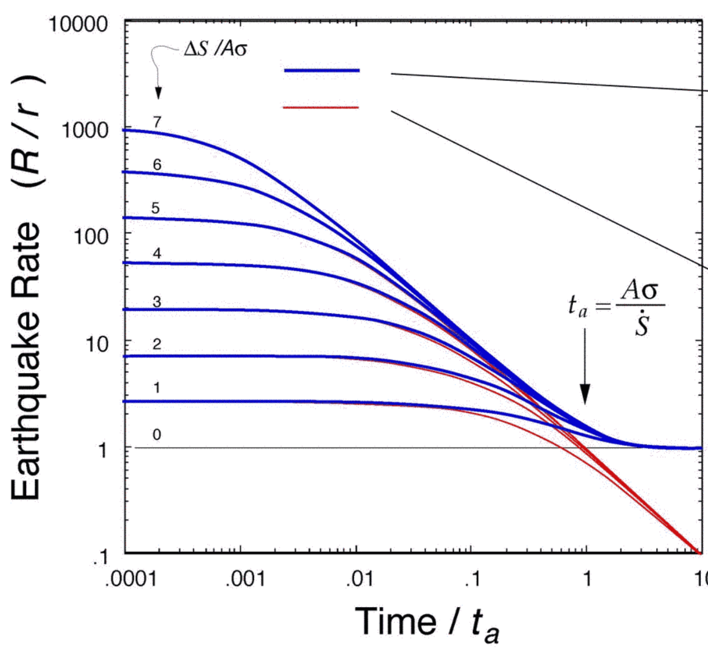


Formulation for earthquake rates

Earthquake rate $R = \frac{r}{\gamma \dot{\tau}_r}$, $d\gamma = \frac{1}{A\sigma}\left[dt - \gamma d\tau + \gamma\left(\frac{\tau}{\sigma} - \alpha\right)d\sigma\right]$

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

Earthquake rates following a stress step



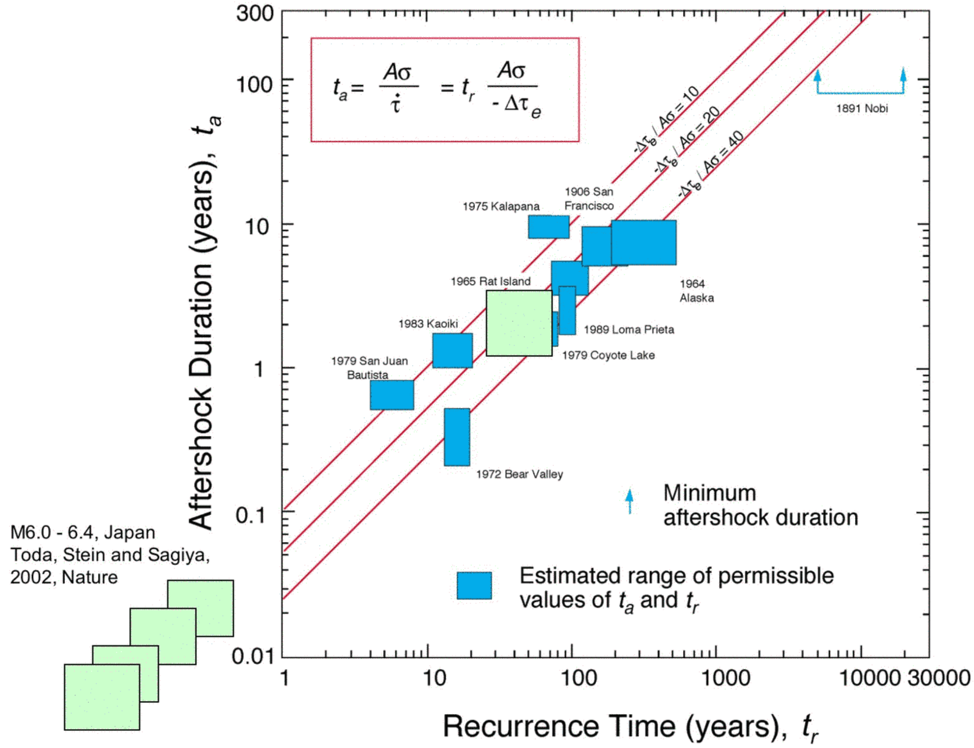
$$R = \frac{r}{1 + \left[\exp\left(\frac{-\Delta S}{A\sigma}\right) - 1\right]\exp\left(\frac{-t}{t_a}\right)}$$

Omori's Law: $R = \frac{a}{b + t}$

$a = r\, t_a$

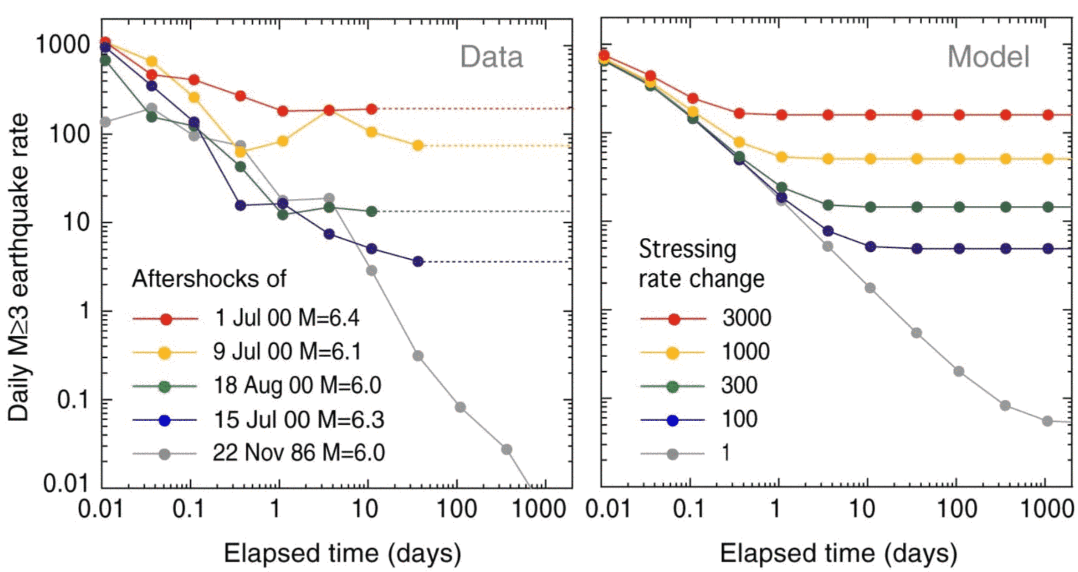
$b = t_a \exp\left[\frac{-\Delta S}{A\sigma}\right]$

Aftershock duration



Short duration aftershock sequences

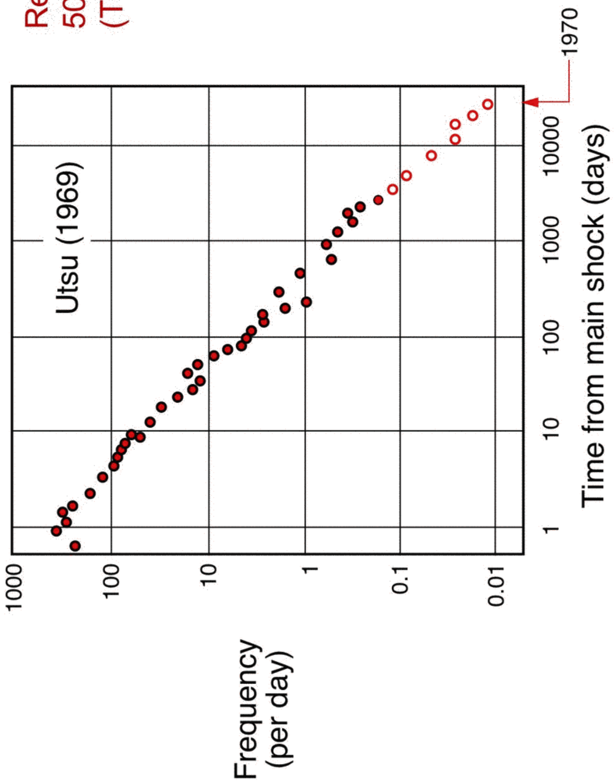
Izu Islands swarm in 2000:
7,000 M≥3 and 5 M≥6 earthquakes



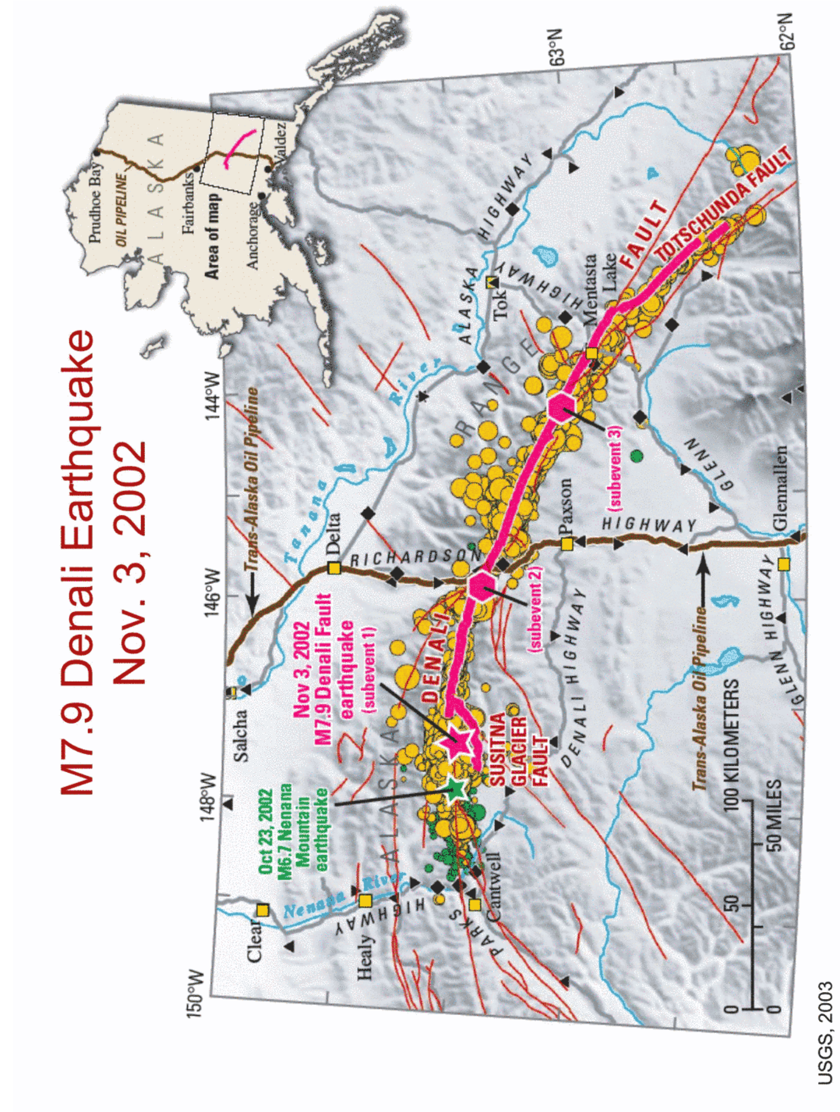
Toda, Stein and Sagiya, 2002, Nature

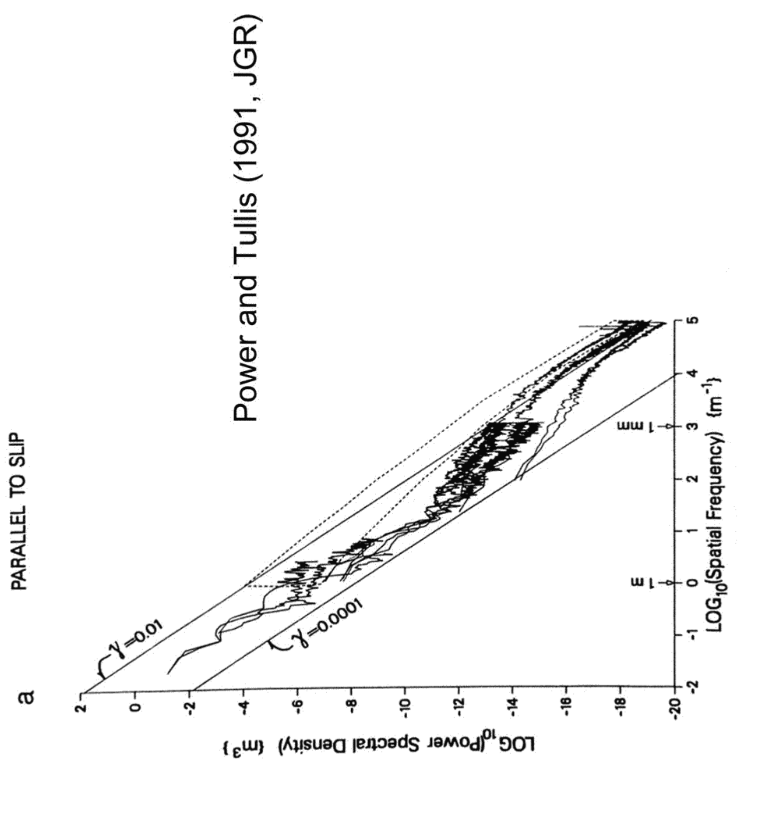
Nobi Earthquake, Oct 28, 1891

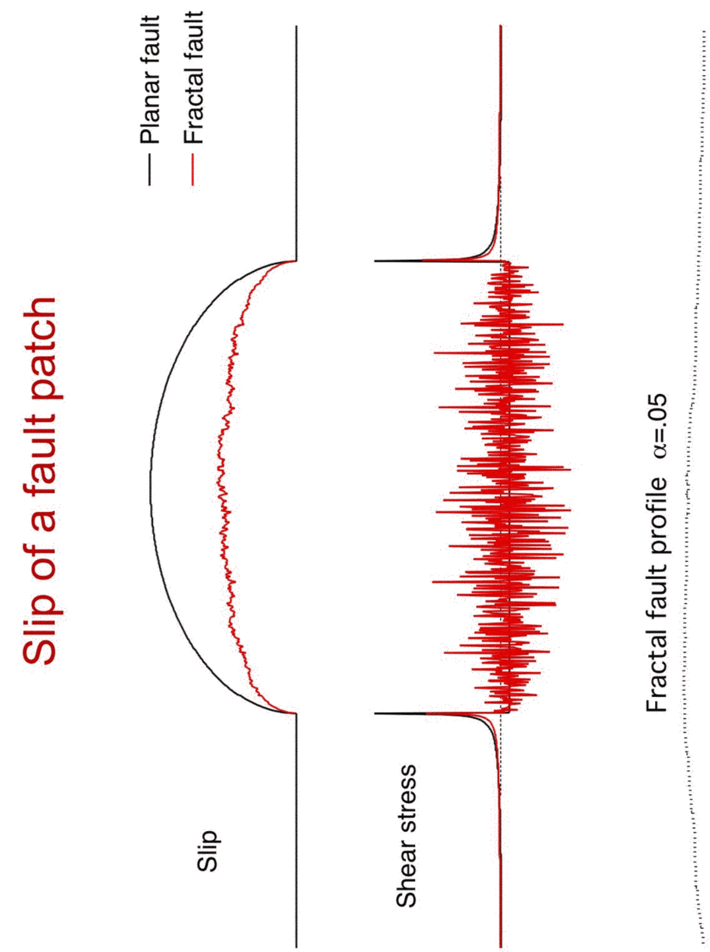
Recurrence:
5000 – 20000yr
(Tsukuda, 1983)



M7.9 Denali Earthquake Nov. 3, 2002

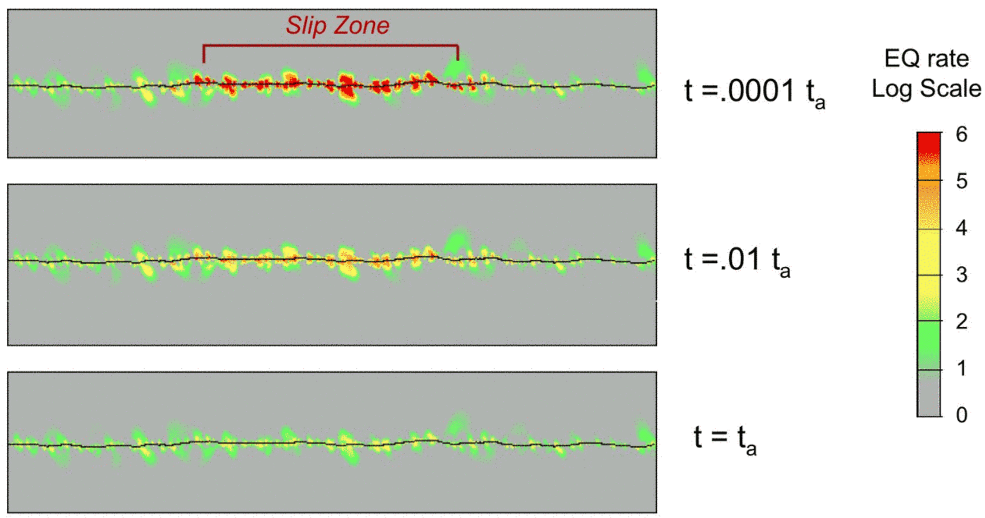



Power and Tullis (1991, JGR)
PARALLEL TO SLIP
a
γ=0.01
γ=0.0001
LOG10(Power Spectral Density) (m3)
LOG10(Spatial Frequency) (m-1)
1 m
1 mm

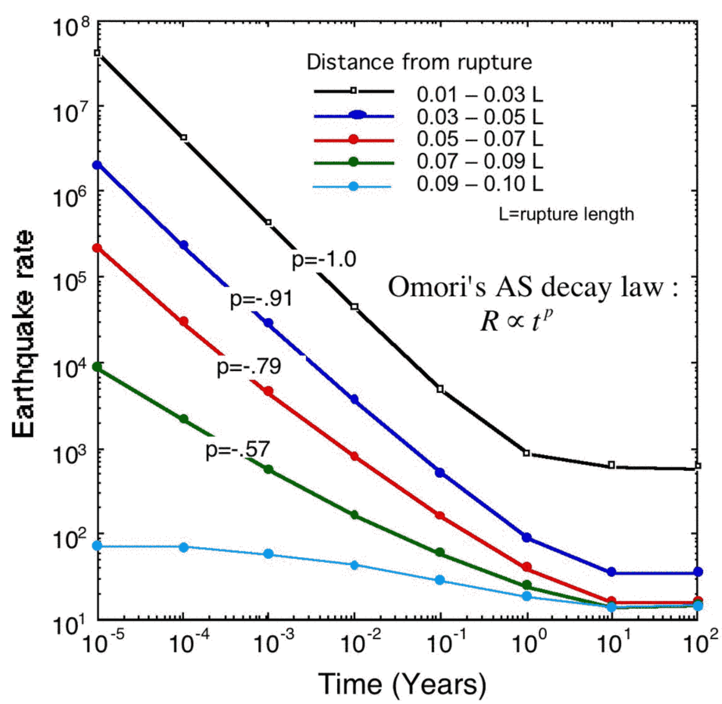

Slip of a fault patch
Planar fault
Fractal fault
Slip
Shear stress
Fractal fault profile α=.05

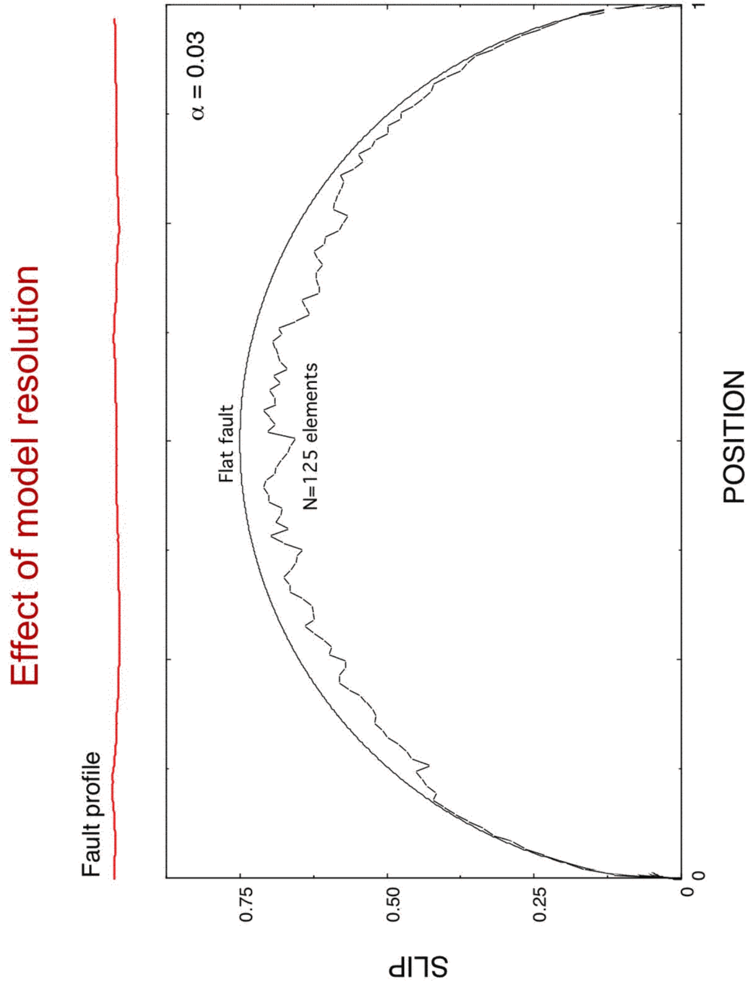
Stress relaxation: Seismicity following slip

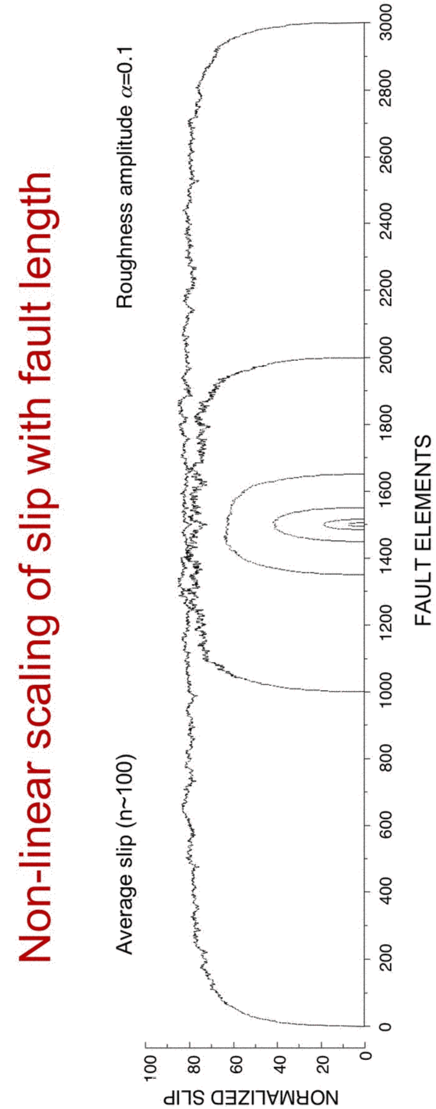
Earthquake rate $R = \dfrac{r}{\gamma \dot{S}_r}$ $\qquad d\gamma = \dfrac{1}{A\sigma}\left[dt - \gamma\, dS\right]$

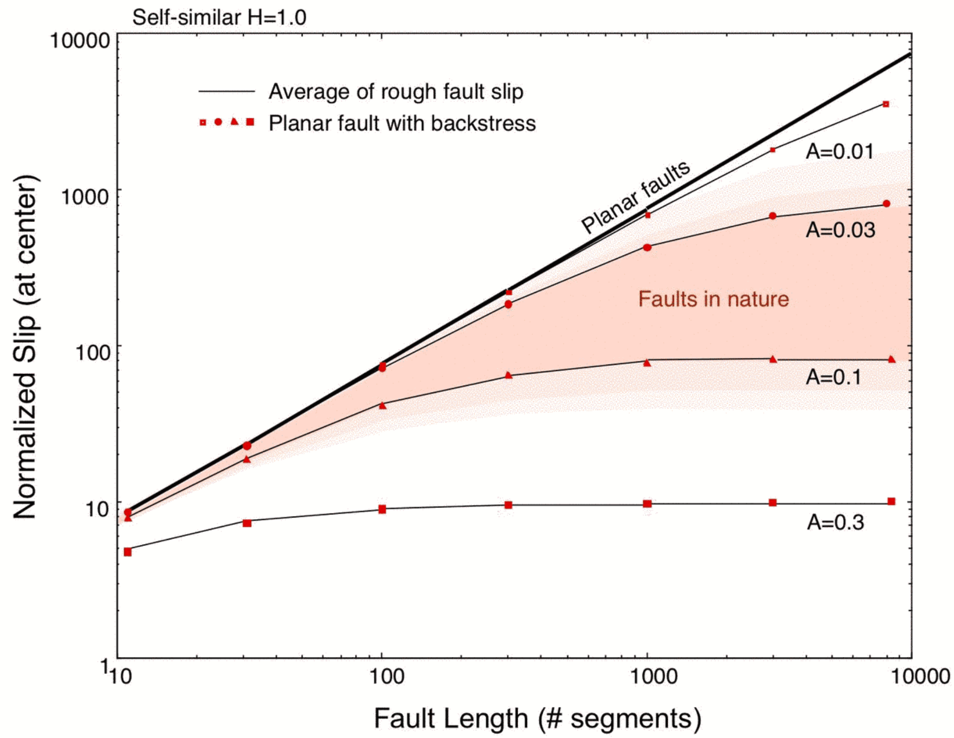


Aftershock rates as function of distance

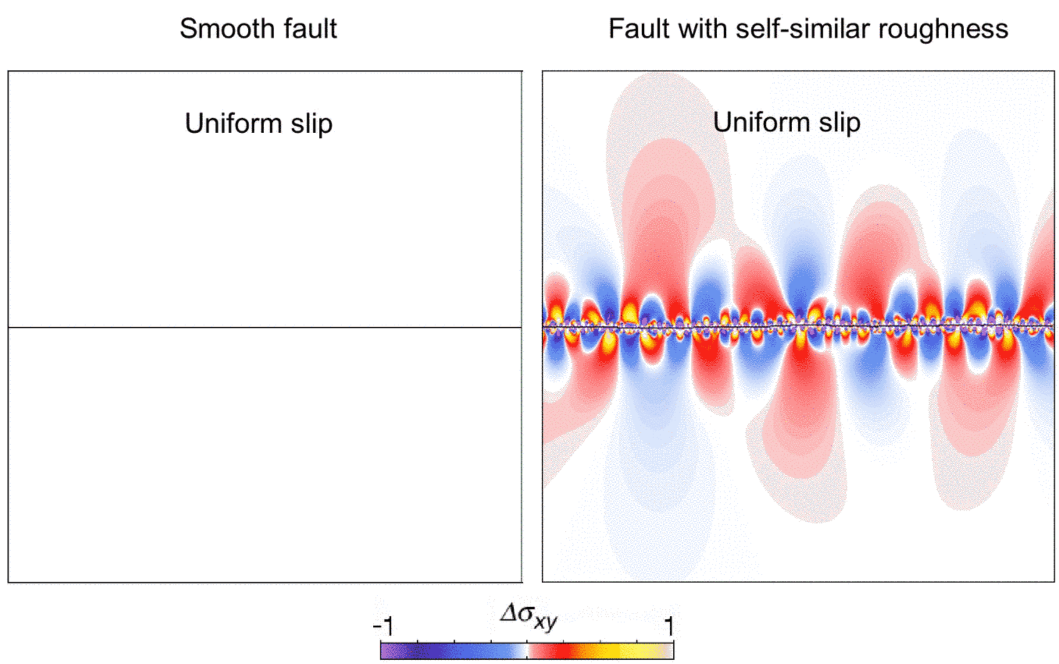



Effect of model resolution
Fault profile
α = 0.03
Flat fault
N=125 elements
SLIP
0.75
0.50
0.25
0
0
1
POSITION

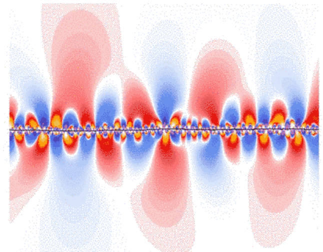

Non-linear scaling of slip with fault length
Average slip (n~100)
Roughness amplitude α=0.1
NORMALIZED SLIP
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
FAULT ELEMENTS



Fault slip and stress changes



Origin of non-linear scaling and model scale-dependence



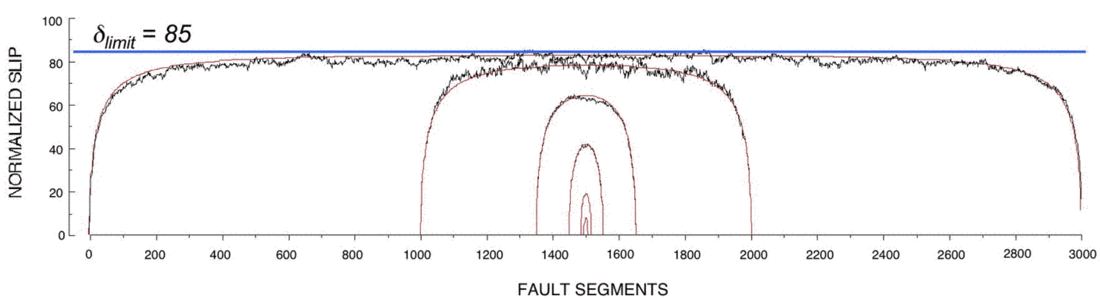
Geometric complexity inhibits to slip

Elastic strain energy increases with slip and requires greater work to slide.

Non-linear scaling of slip with fault length

Average slip on non-planar faults n~100

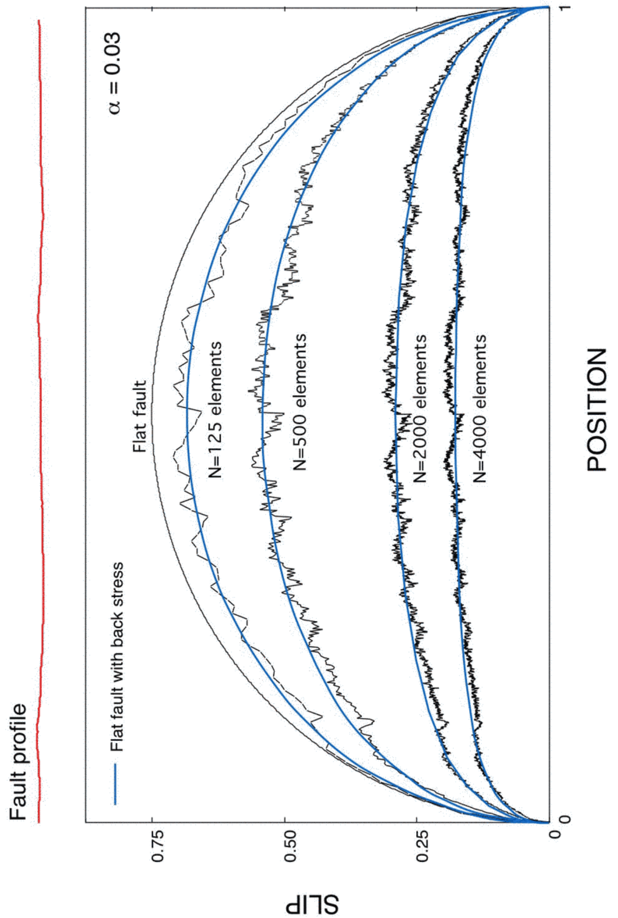
Planar fault model with elastic back stress



Roughness amplitude = .1

Back-stress also depends on number of fault elements N

for scaling with fixed L $\qquad S_{BACK} = \frac{NG}{\delta_{\ell MAX}} d$



Is the non-linear scaling applicable to faults?

Arises from increase of the elastic strain energy

In purely elastic models strain energy increases without limit

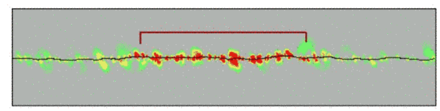
Real materials: limit to stresses and elastic strain energy
- Bulk yielding
- Slip on secondary faults or off-fault seismicity

Truncation of roughness at small wavelengths (by wear) may reduce but not eliminate the effect

Stress relaxation and off-fault seismicity
Mechanisms and modeling

1) Bulk Aseismic bulk yielding: Viscoelasticity
   - Aseismic stress release at complexities between fault slip events (Nielsen and Knoppoff, 1998; Duan and Oglesby, 2005)

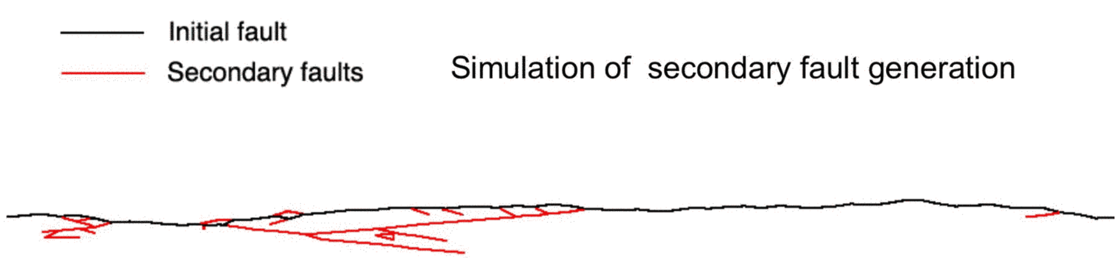
2) <u>Seismicity rate simulations using the state-dependent rate eqn's</u>
   - Simulates off-fault seismicity between fault slip events
   - Could be adopted to co-seismic represent co-seismic stress release
   - Appropriate time and stress dependence

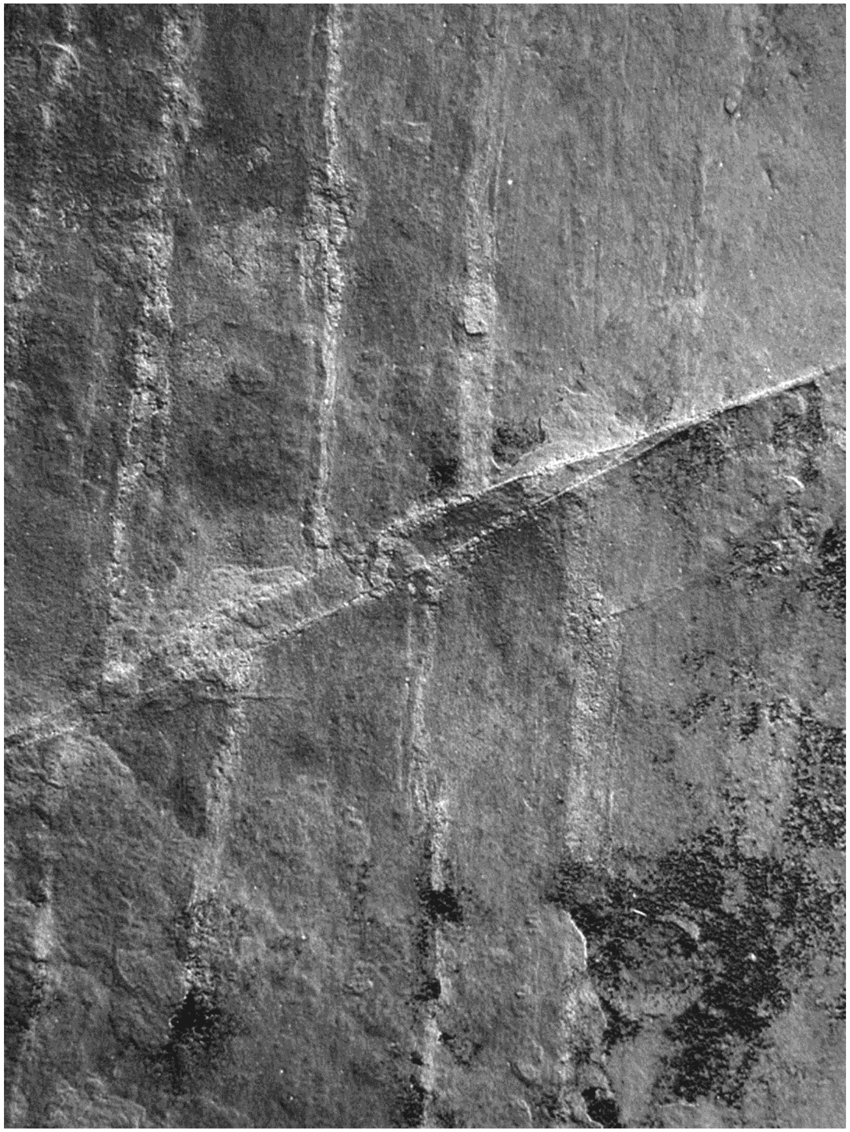


3) <u>Secondary faulting</u>
   - Permits coseismic and interseismic stress relaxation
   - Complicated simulation to generate secondary faults
   - Finite model cannot fully represent off-fault seismicity

Stress relaxation: Secondary fault formation

Simulation of secondary fault generation

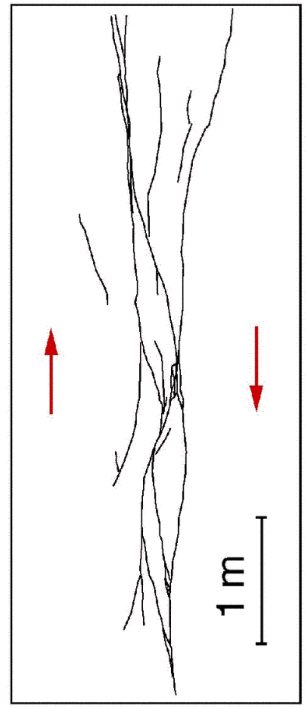




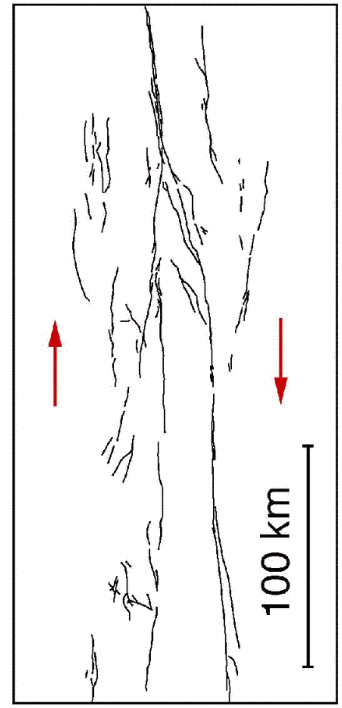
Fault geometry

Individual faults exhibit approximately self-similar roughness (fractal dimension~1).

Fault systems also appear to be scale-independent



Fault in the Monterrey Formation



San Francisco Bay Region