Slip of Faults of Non-Planar Faults: Implications for Modeling of Fault Systems

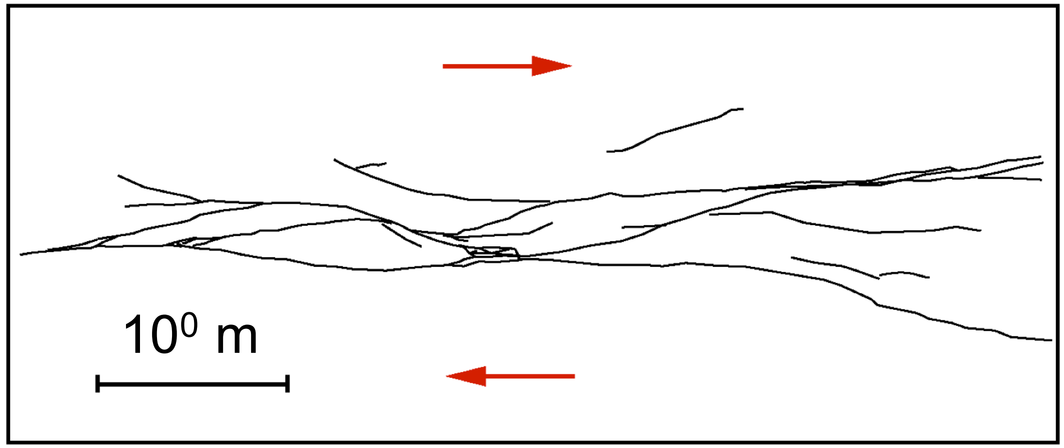
Jim Dieterich

USGS, Menlo Park CA

USGS

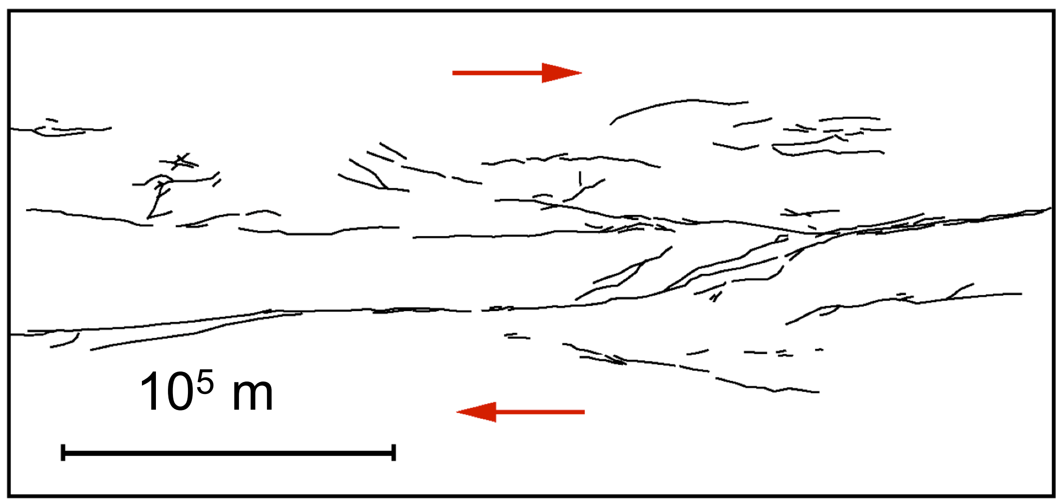
Fault geometry

Individual faults exhibit approximately self-similar roughness



Fault in the Monterrey Formation

Fault systems also appear to be scale-independent



San Francisco Bay Region

Physics-based modeling of earthquake occurrence in fault systems

Understanding earthquake processes

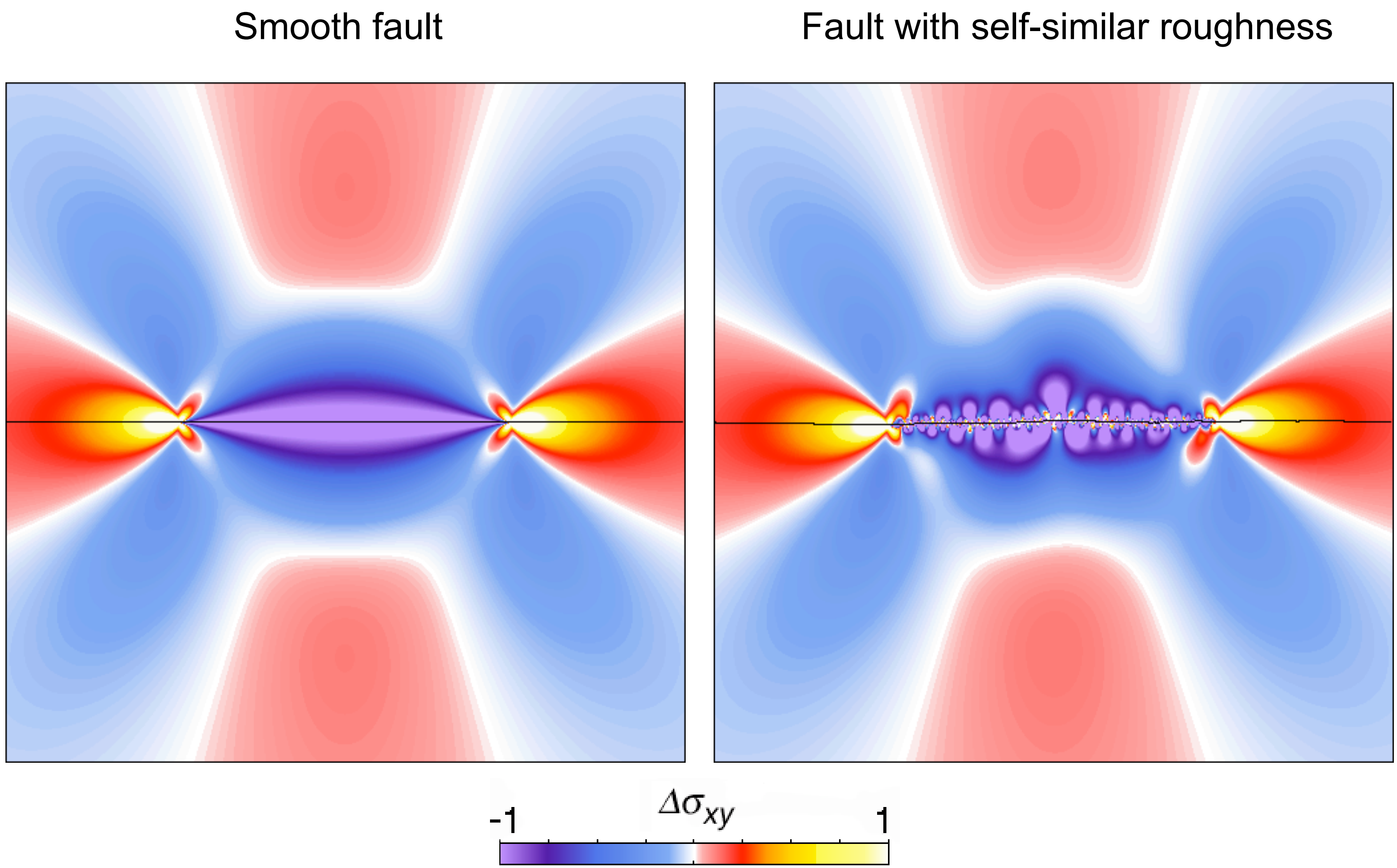
Earthquake occurrence forecasts and probabilities

Some challenges

- Description of fault of fault system geometry
- Computational – extreme range of geometric scales and magnitudes
- Complex geometry involves processes that do not operate in planar fault models
    - Scaling – model resolution is important
    - Stress relaxation – faulting and seismicity

Random Fractal Fault Profiles

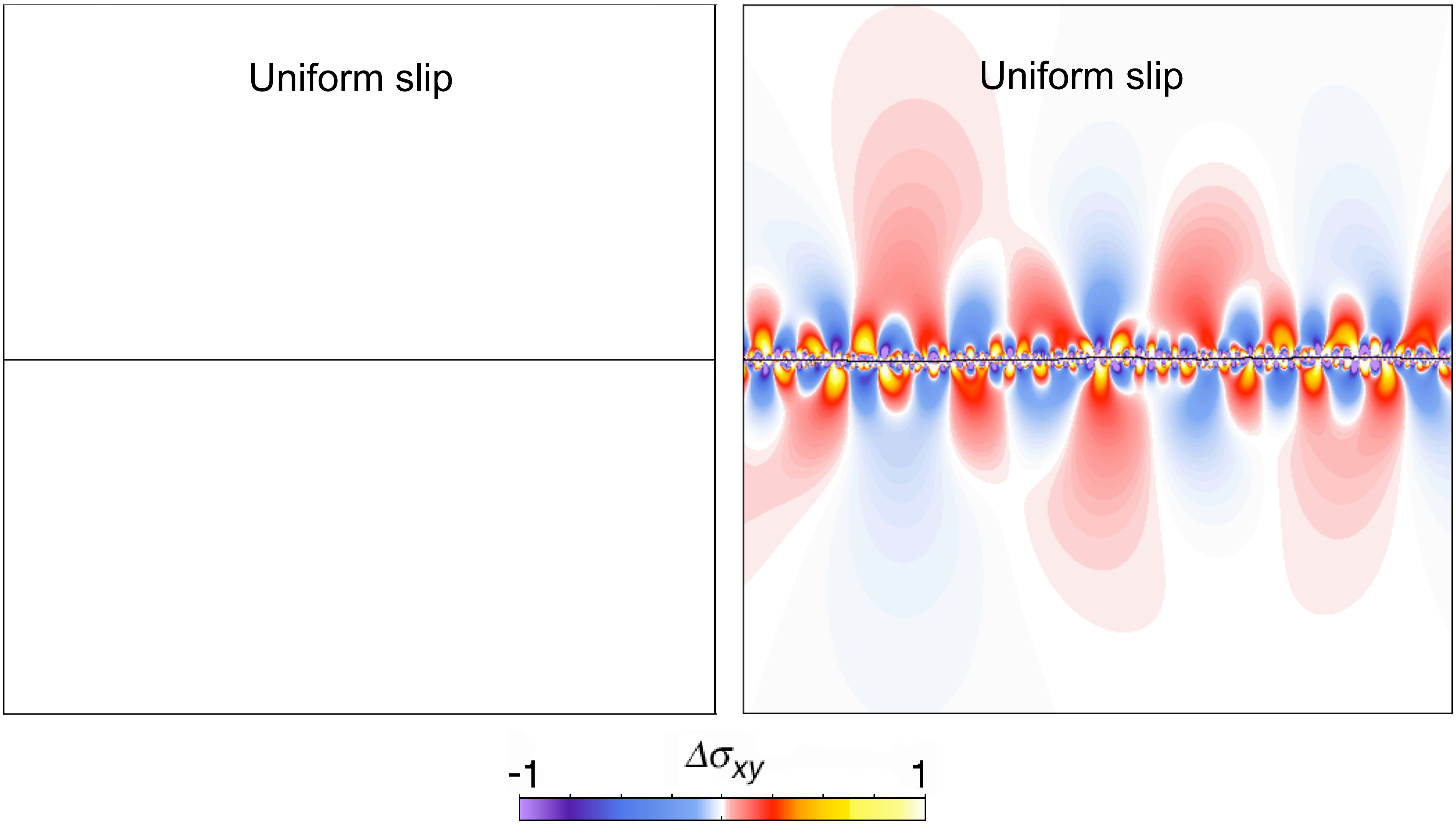
Fault slip and stress changes



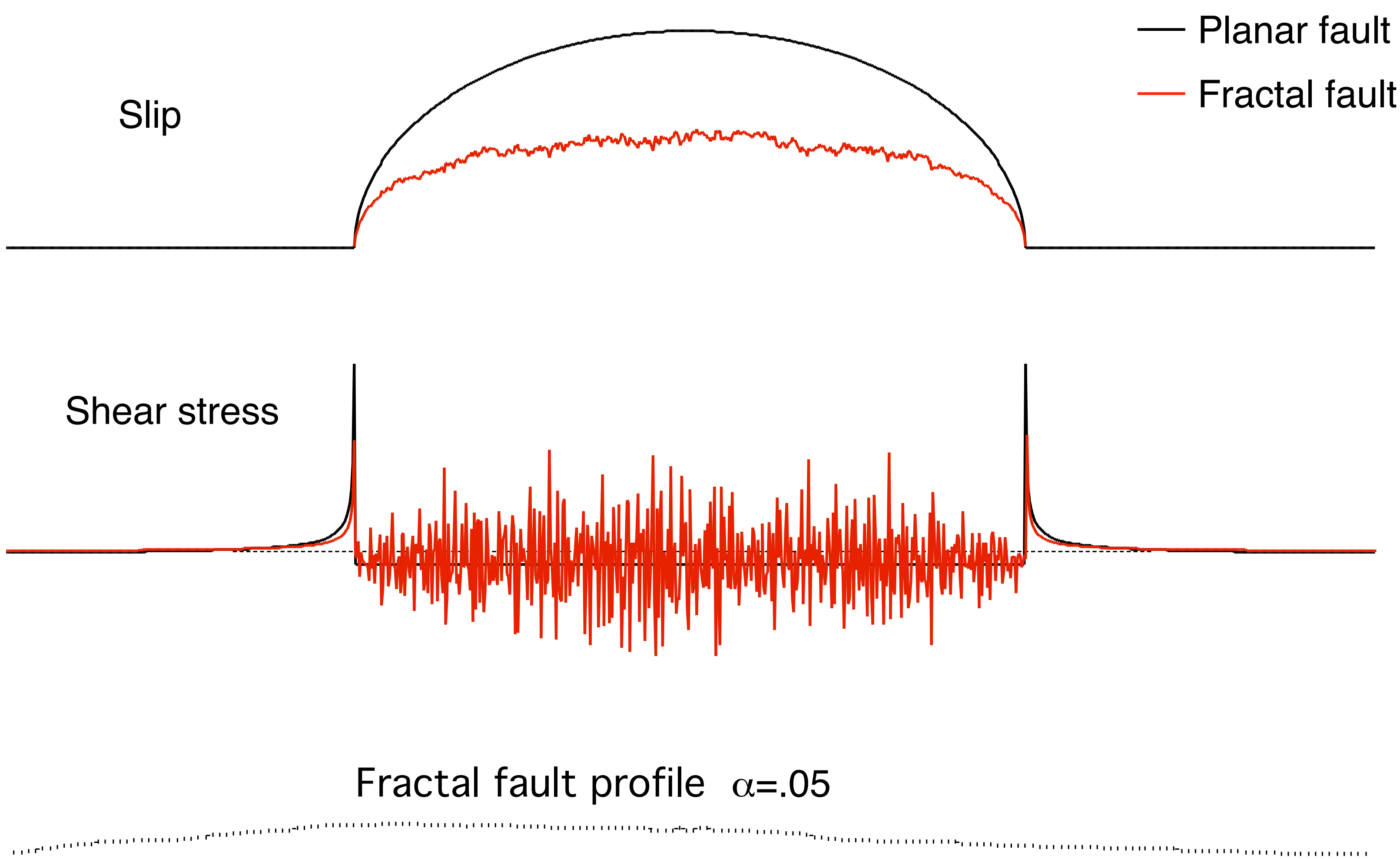
Fault slip and stress changes

Smooth fault

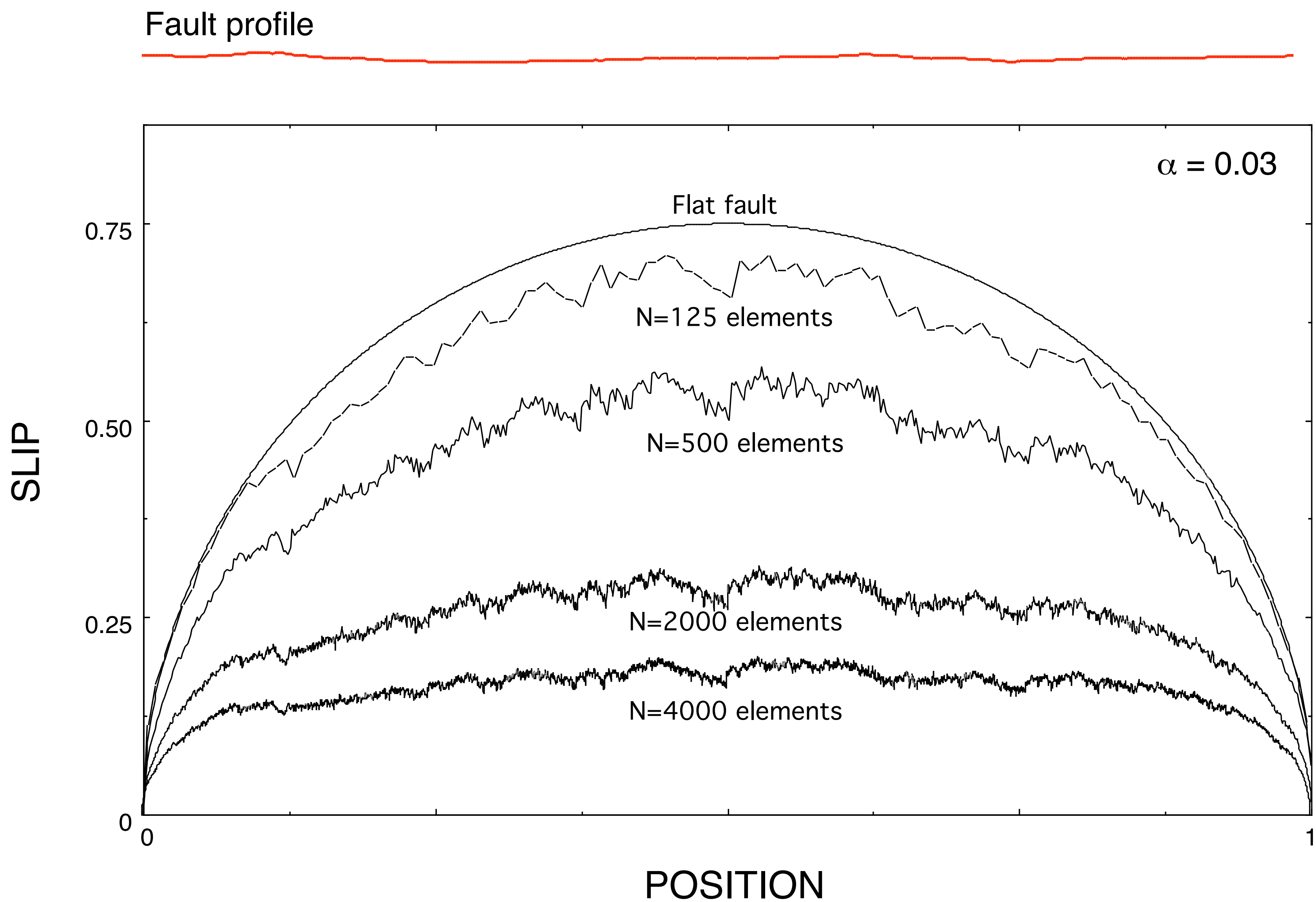
Fault with self-similar roughness



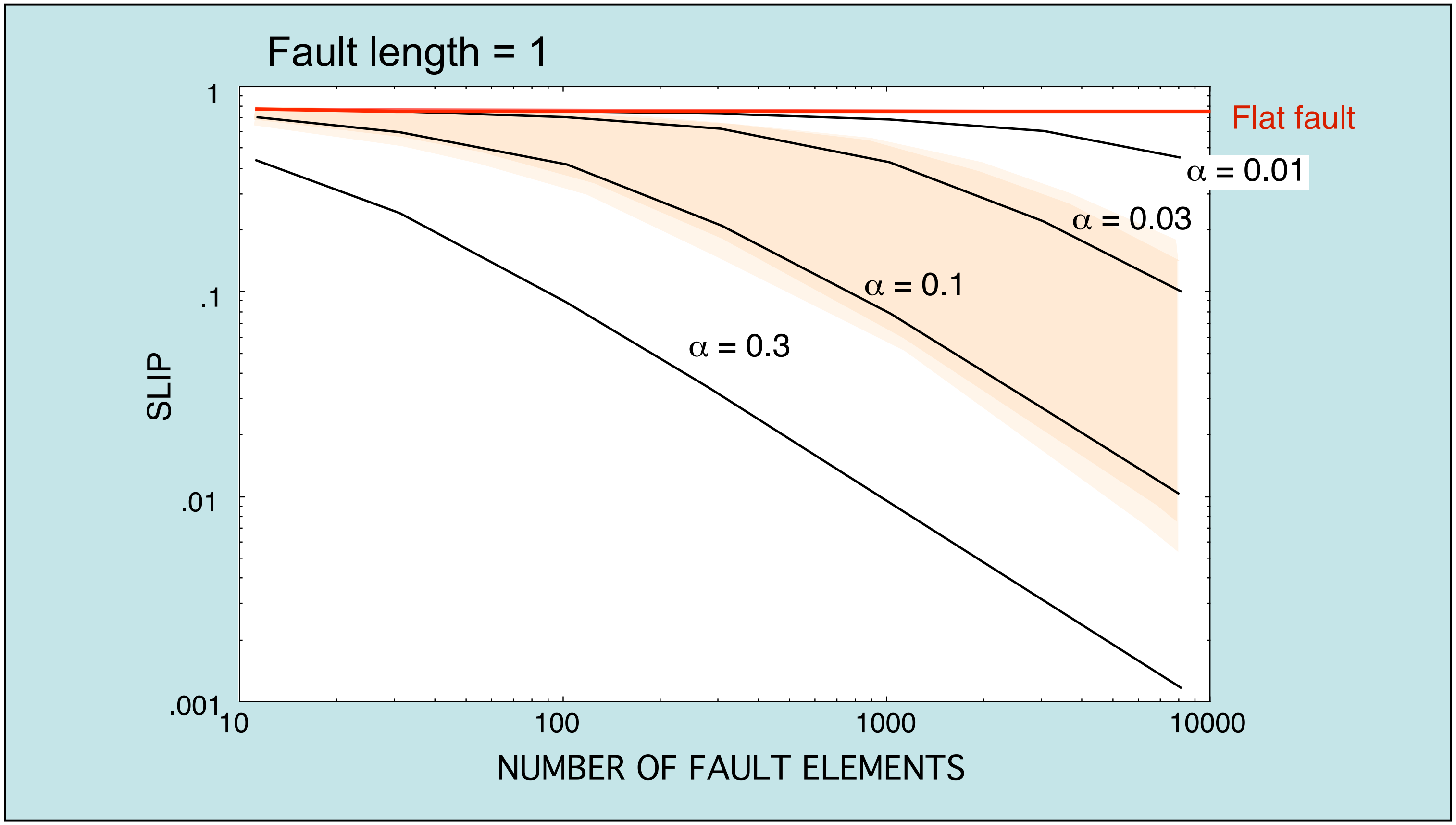
Slip of a fault patch

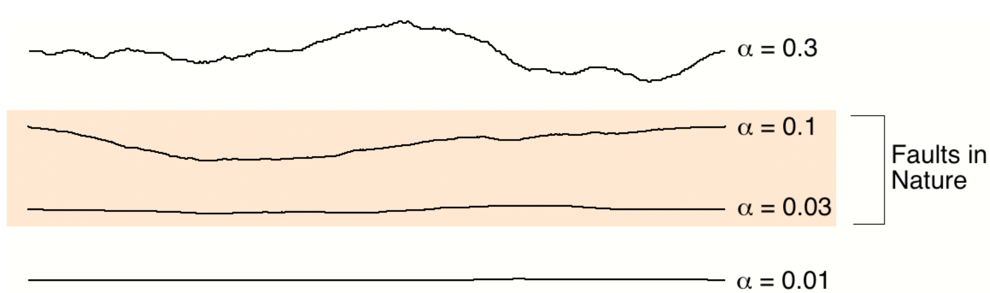


Effect of model resolution

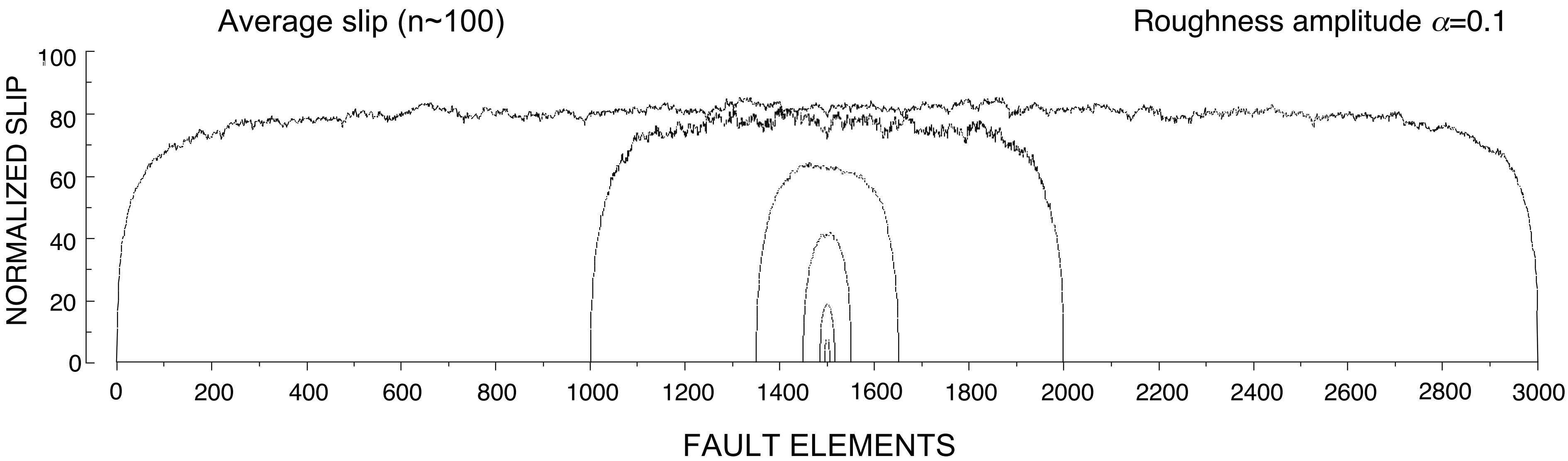


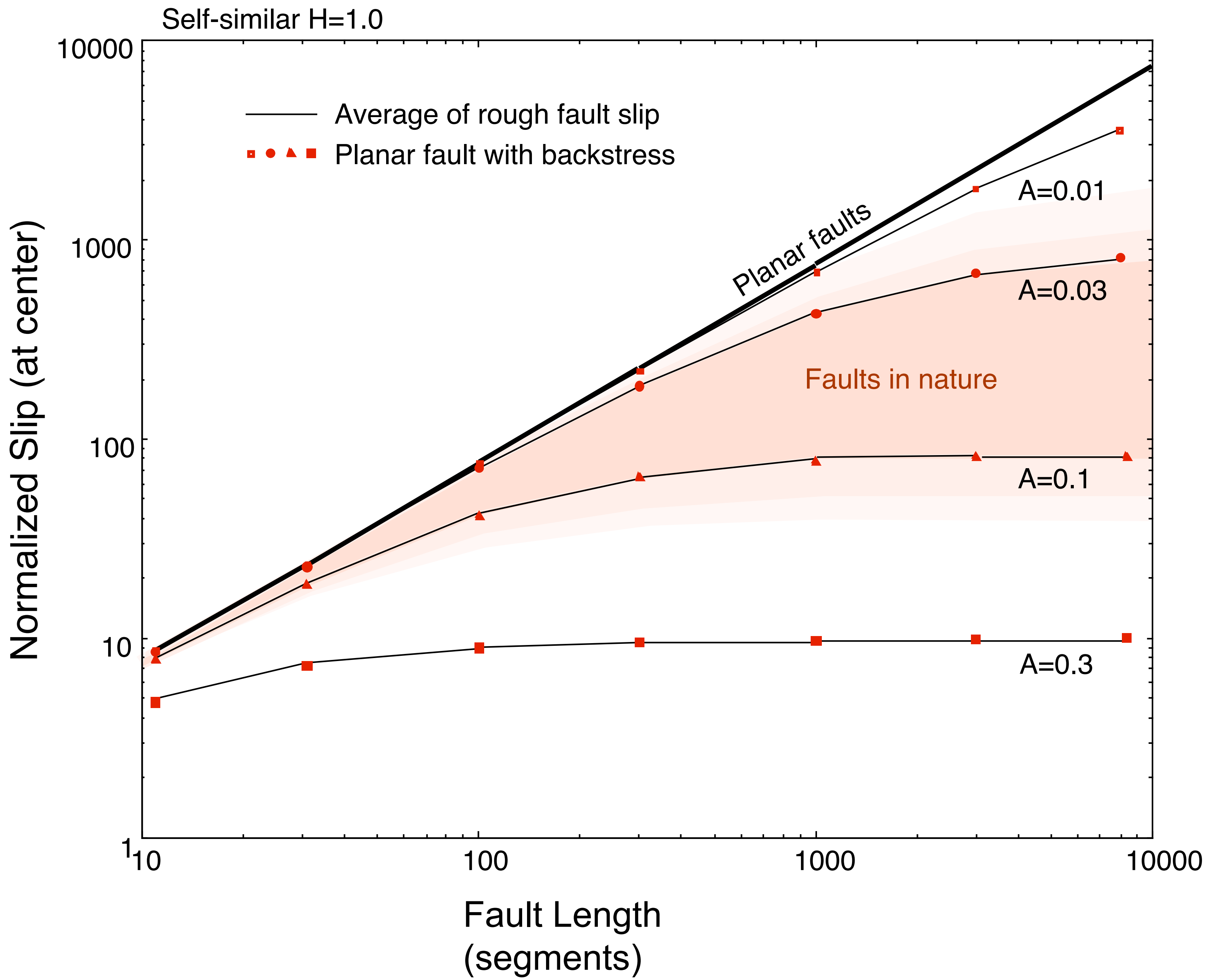
Dependence of slip on number of fault elements used to resolve geometry





Non-linear scaling of slip with fault length

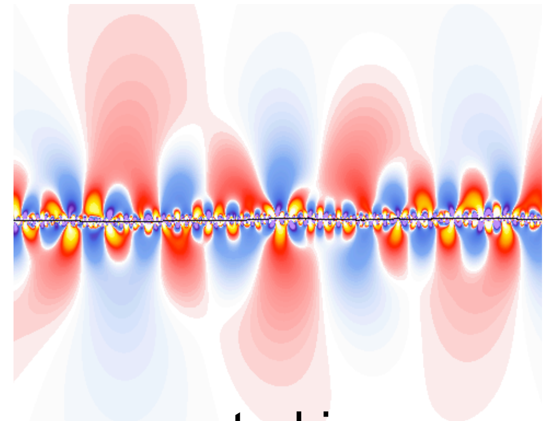



Self-similar H=1.0
Average of rough fault slip
Planar fault with backstress
Planar faults
A=0.01
A=0.03
Faults in nature
A=0.1
A=0.3
Normalized Slip (at center)
10000
1000
100
10
1
10
100
1000
10000
Fault Length
(segments)

Origin of non-linear scaling and model scale-dependence

Geometric complexity forms barriers to slip

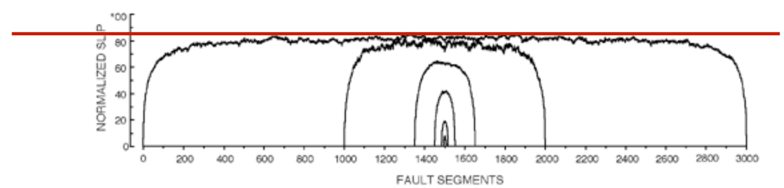
Elastic strain energy increases with slip and requires greater work to slide.



Increased strain energy due to fault complexity can be represented in planar fault models as an elastic back-stress that increases with slip

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

$\bar{d}_{MAX}$

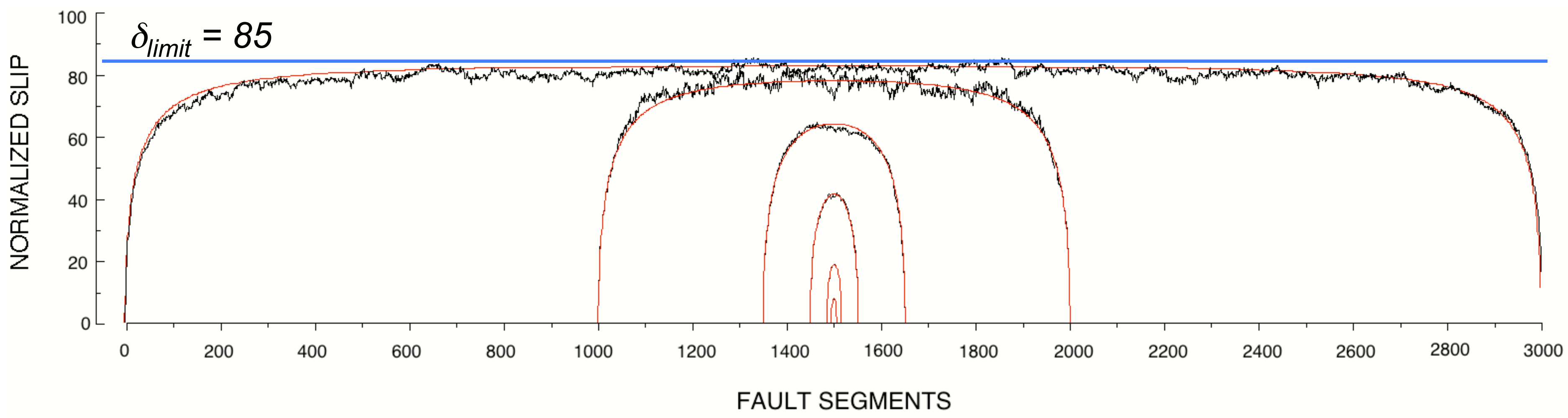


where, $\bar{d}_{MAX}$ is maximum slip at the applied stress S_E

Non-linear scaling of slip with fault length

Average slip on non-planar faults n~100

Planar fault model with elastic back stress

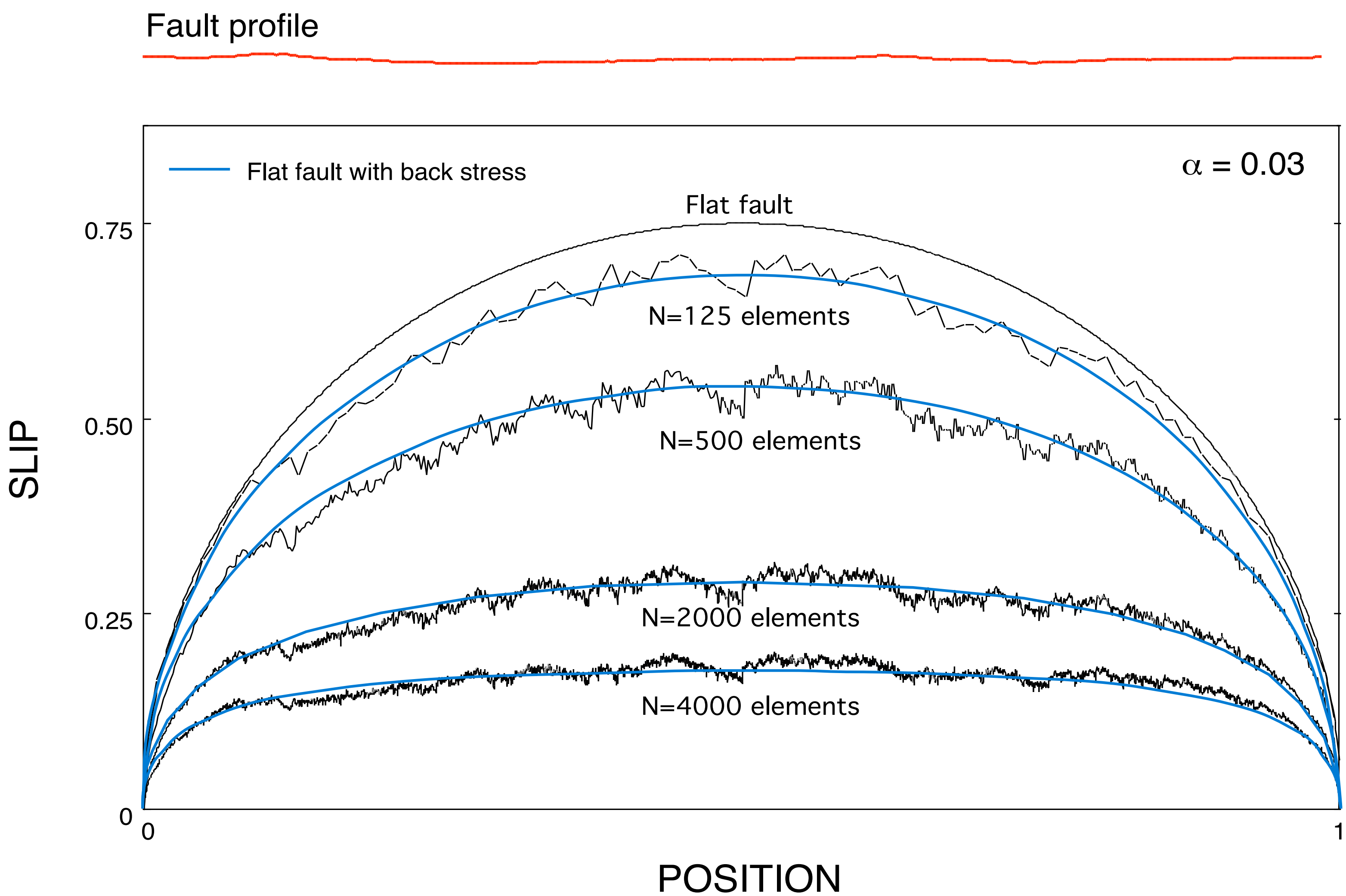


Roughness amplitude = .1

Back-stress also depends on number of fault elements N

for scaling with fixed L=1

$$S_{BACK} = \frac{NG}{\bar{\delta}_{\ell MAX}} d$$



Is the non-linear scaling applicable to faults?

Arises from work required to increase the elastic strain energy

In 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

Speculation:

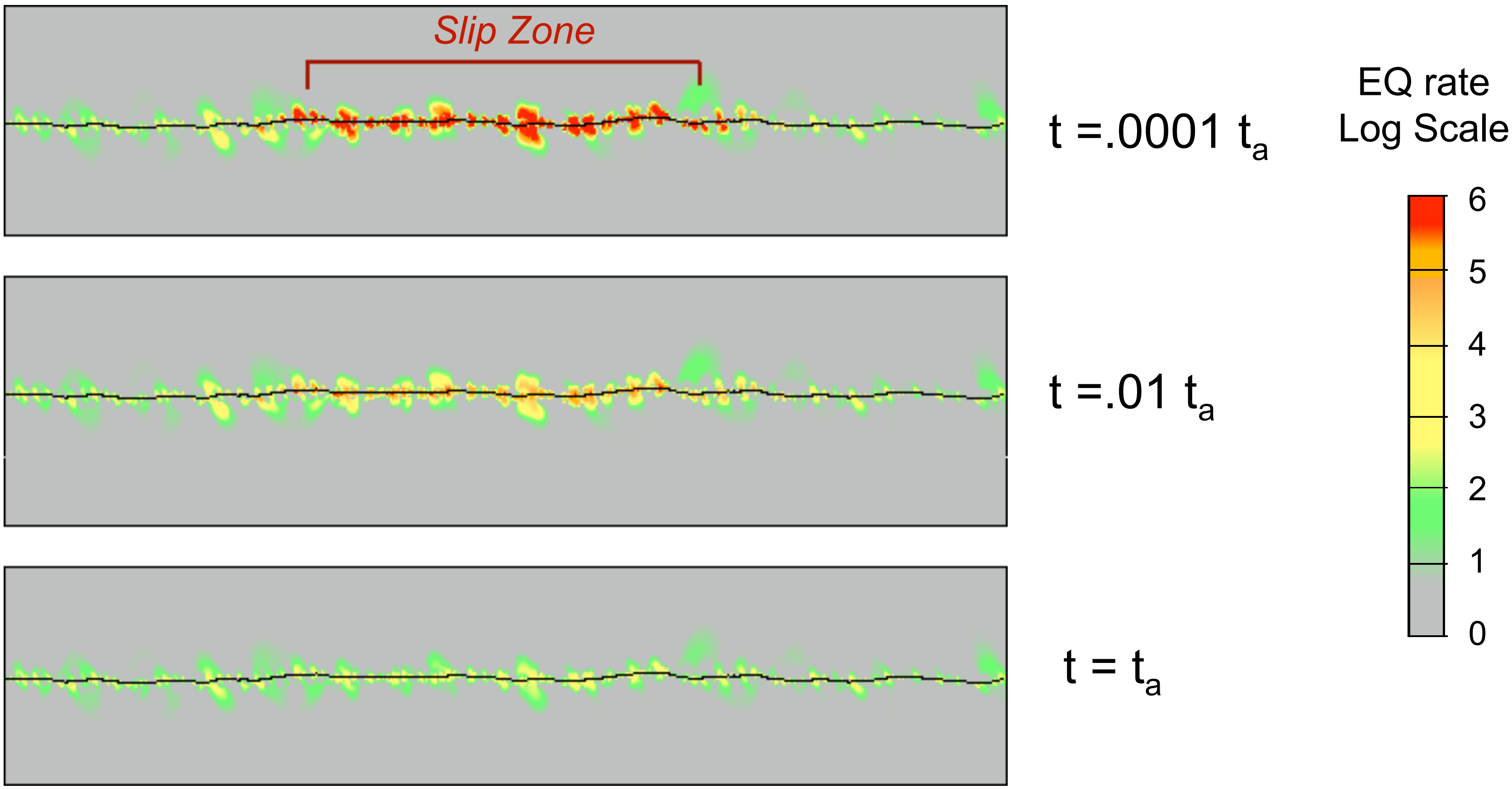
Non-linear scaling may not operate if stress dissipation is simultaneous with slip on main fault. This means earthquake source processes are much more complicated than current models

Non-linear scaling of earthquake slip will operate if stress dissipation is time-dependent following earthquake

Stress relaxation: Seismicity following slip

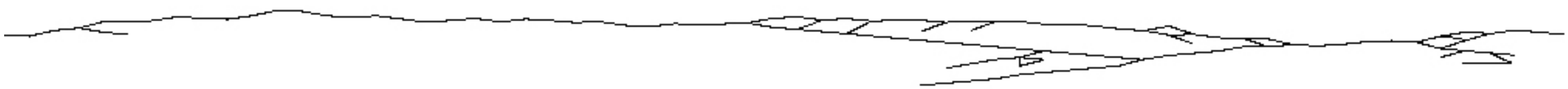
State-dependent formulation Dieterich (1994)

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

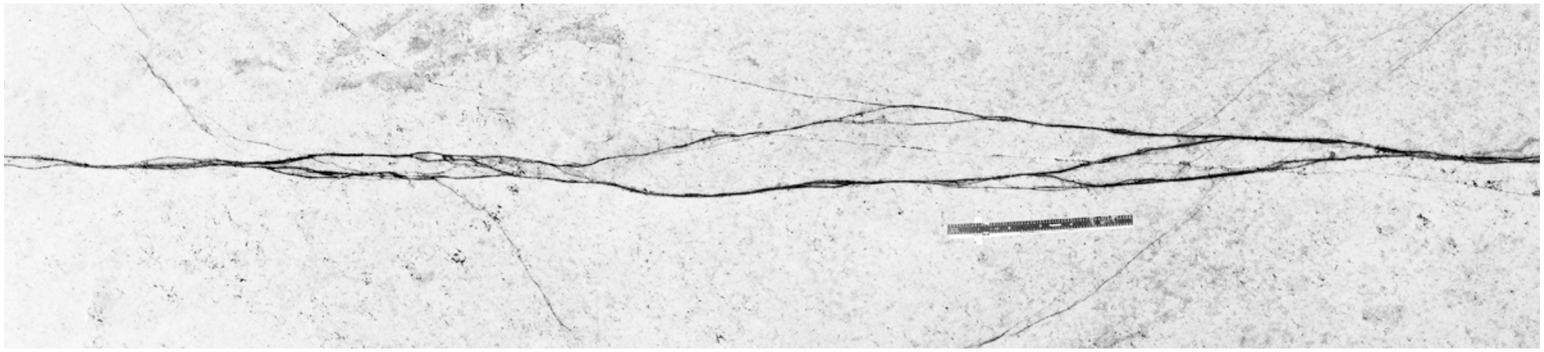


Stress relaxation: Secondary fault formation

Simulation of secondary fault generation



Fault in Entrada sandstone



Conclusions – Complex fault geometry

- Complex fault geometry results in heterogeneous slip and stresses

- Complex fault geometry
  –> Retards slip compared to planar faults
  –> Leads to non-linear scaling of slip with L in purely elastic models
  –> Results depend on model resolution size. Serious issues for large scale simulations of earthquakes in fault systems

- In nature stress heterogeneity cannot increase without limit.
  –> Characteristics of stress relaxation are important
  –> New methods are needed for simulation of off-fault seismicity and stress relaxation.