Dynamical, Material, and Geometrical Heterogeneities in Earthquake Models

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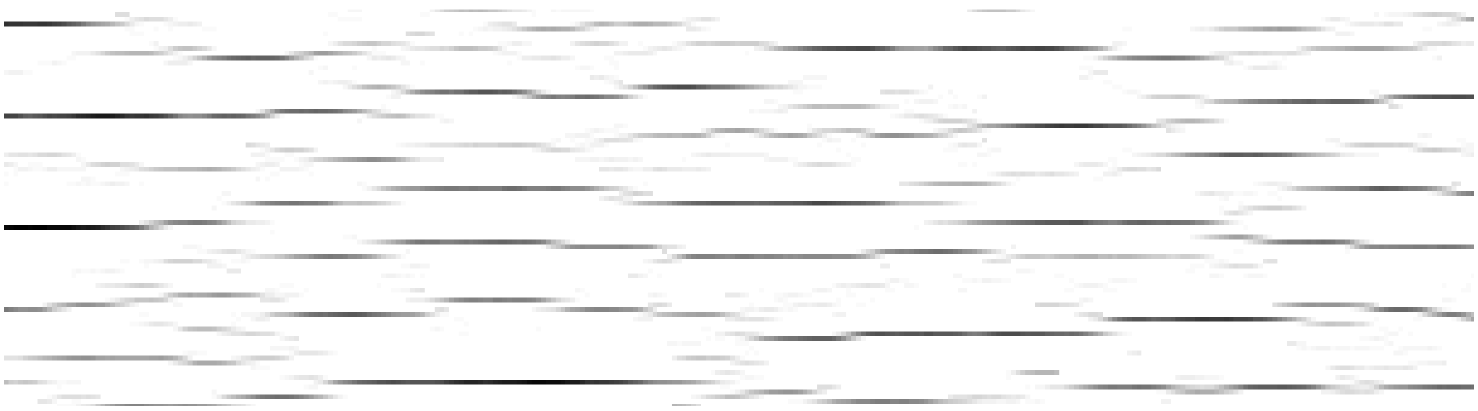
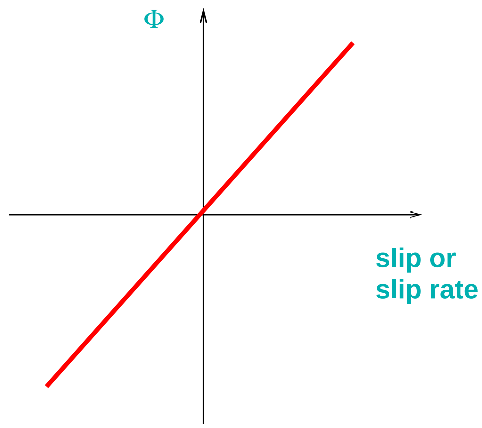
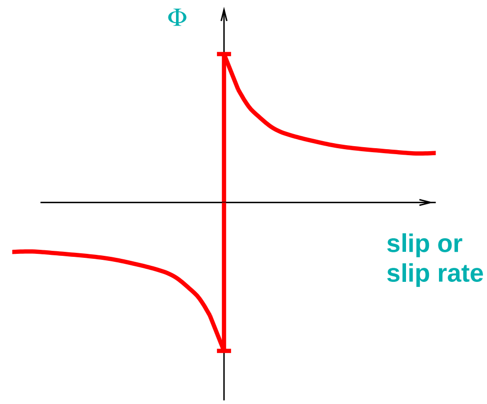


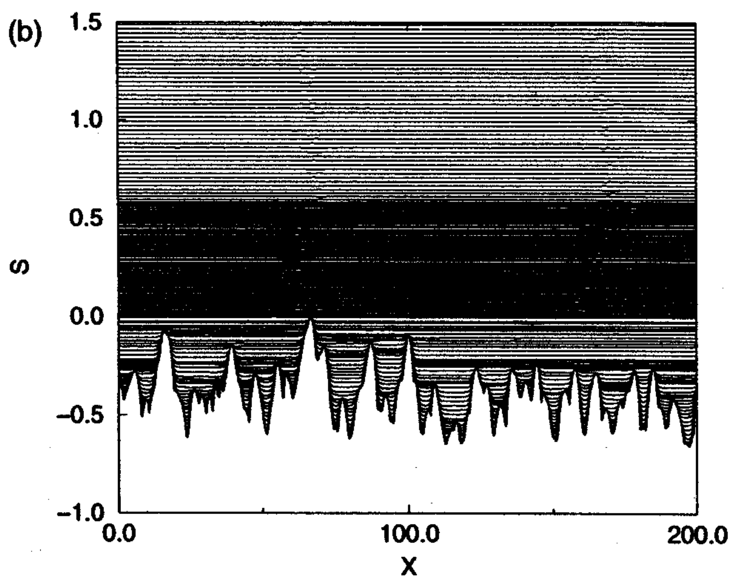
Frictional weakening $\longrightarrow$ complexity

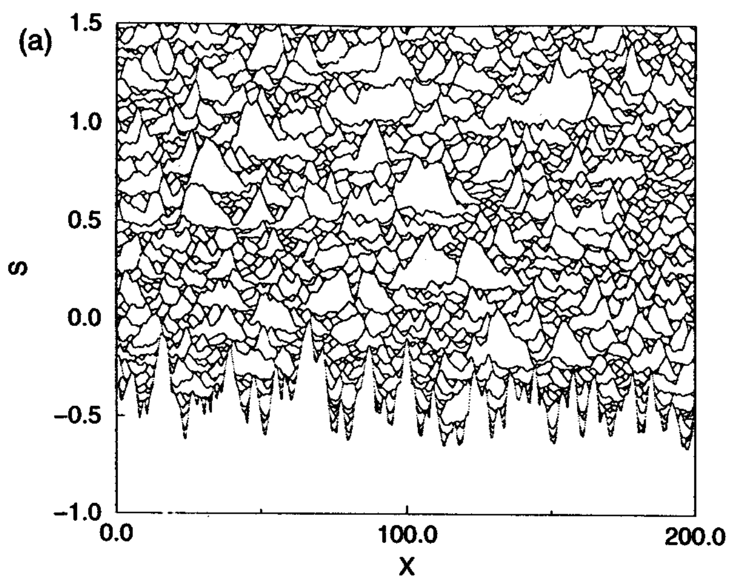




strengthening $\longrightarrow$ periodic

weakening $\longrightarrow$ complexity





Frictional weakening from frictional heating

$$\Phi = N\mu$$

$$\mu = \begin{cases} [-\mu_0 \, , \; \mu_0] & \frac{\partial S}{\partial t} = 0; \\ -\mu_0(1-\sigma) \, , \; \mu_0(1-\sigma) & \frac{\partial S}{\partial t} < 0 \, , \; \frac{\partial S}{\partial t} > 0 \end{cases}$$

$$N = N_0 - \alpha Q$$

$$\frac{\partial Q}{\partial t} = -\gamma Q + \Phi \frac{\partial S}{\partial t}$$

$\gamma \ll 1 \longrightarrow$ slip weakening:

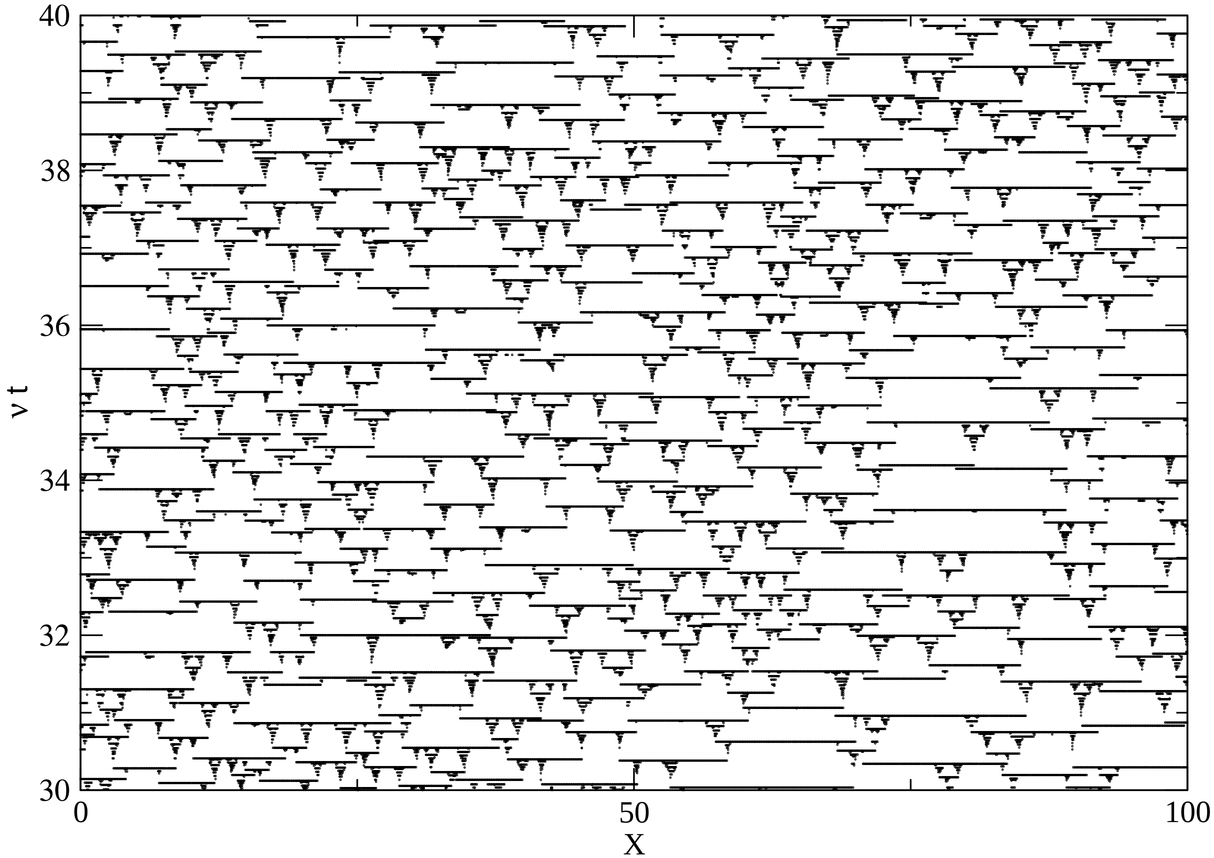
$$\Phi = N_0 \mu e^{-\alpha\mu(S-S_0)}$$

$\gamma \gg 1 \longrightarrow$ velocity weakening:

$$\Phi = \frac{N_0\mu}{1+\frac{\alpha}{\gamma}\mu\frac{\partial S}{\partial t}}$$

[Shaw, 1995]

Uniform Fault



- Complex attractor:

  Large event complexity generally;

  small event complexity near critical weakening values

Material Heterogeneities:

Strength Heterogeneities

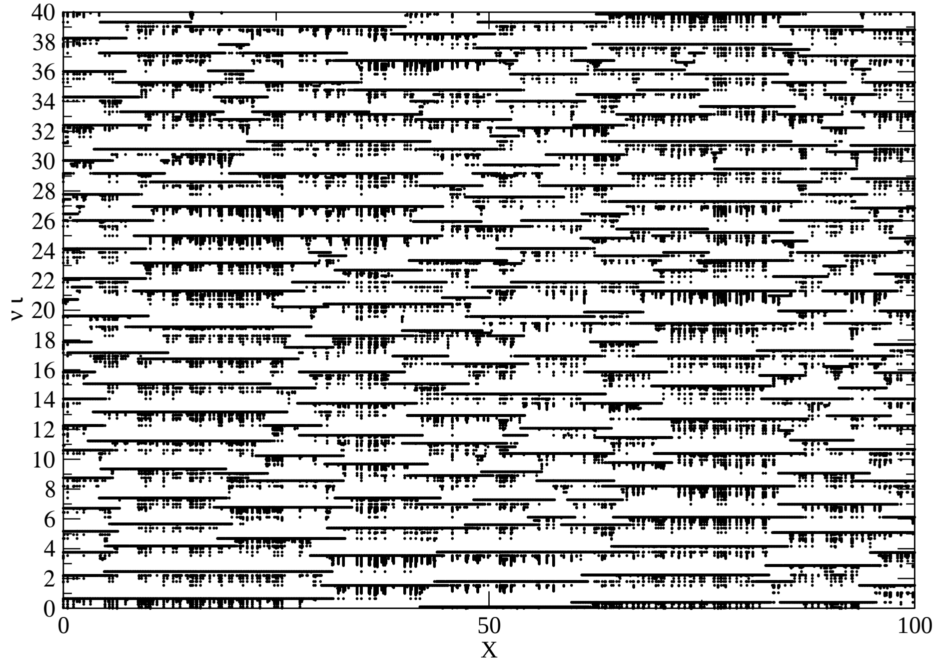
$$\Phi \longrightarrow a(x) + (1 + n(x))\Phi$$

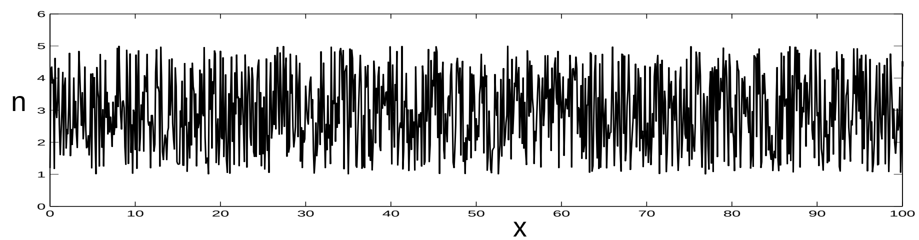
Φ friction

$a(x)$ additive strength [*Invariance*]

$n(x)$ multiplicative strength

Multiplicative strength heterogeneities

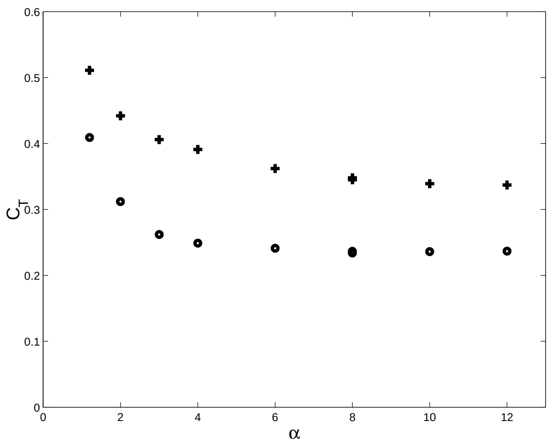


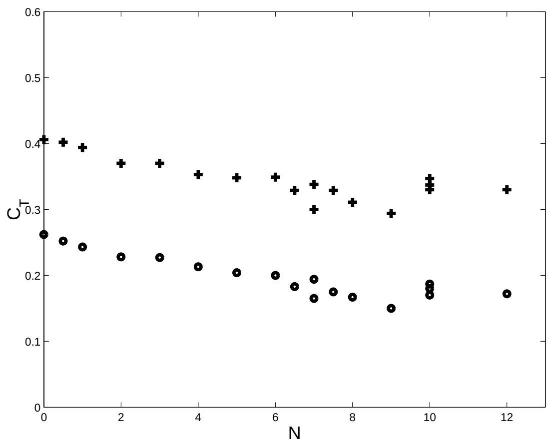


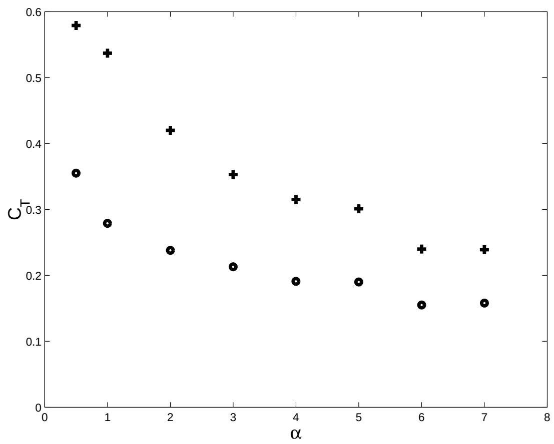
- pinning of behaviors in space

Variation of large event repeat times

$$C_T \equiv \frac{\sqrt{<T^2> - <T>^2}}{<T>} = \frac{\text{standard deviation}}{\text{mean}}$$







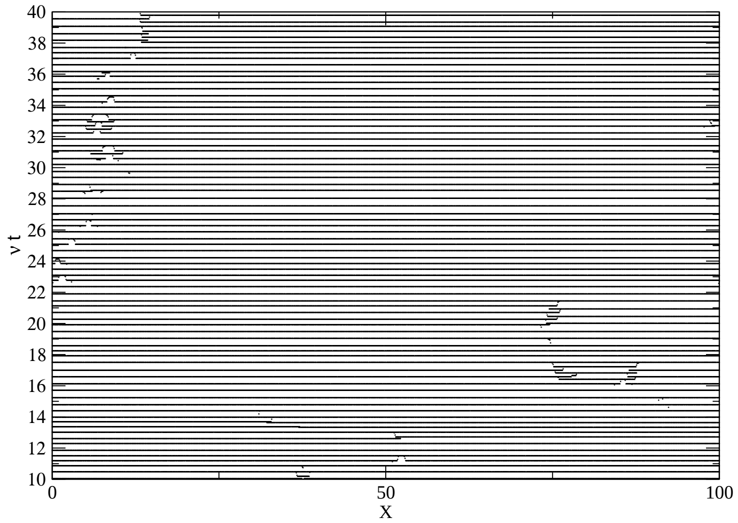
$n = 0$, varying α

varying n

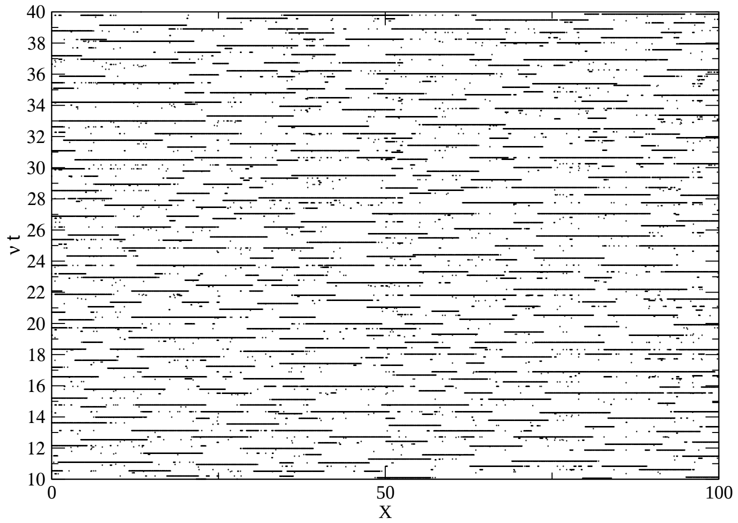
$n = 4$, varying α

- Heterogeneities reduce variation for complex attractor but do not kill it

Time dependent strength drop



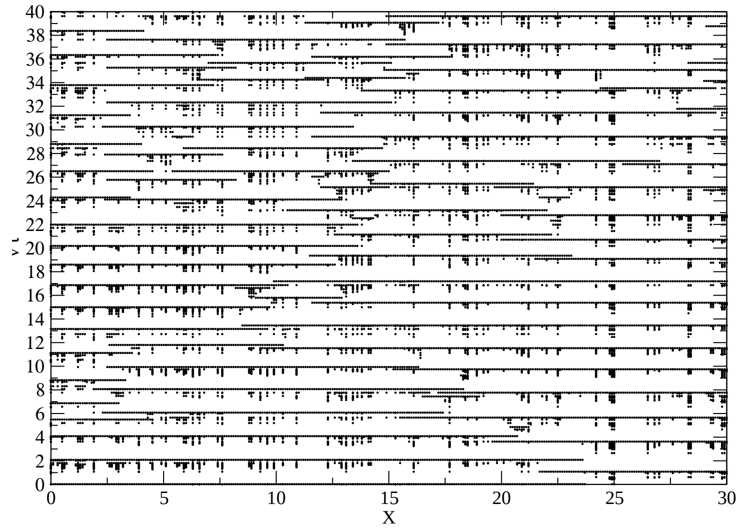
uniform fault

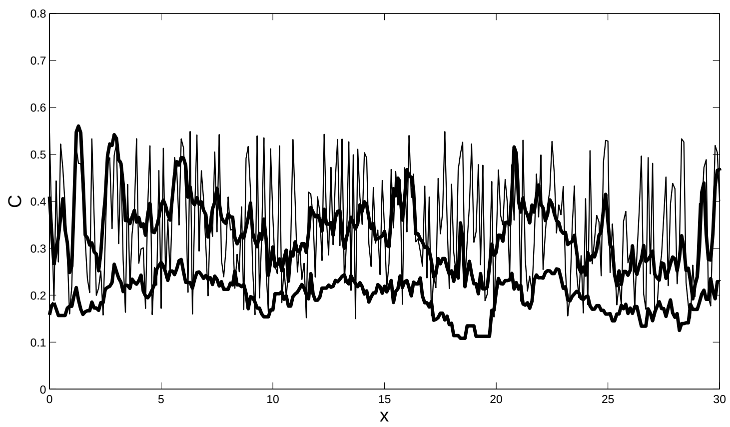


heterogeneous fault

- Heterogeneities increase variation for simple attractor

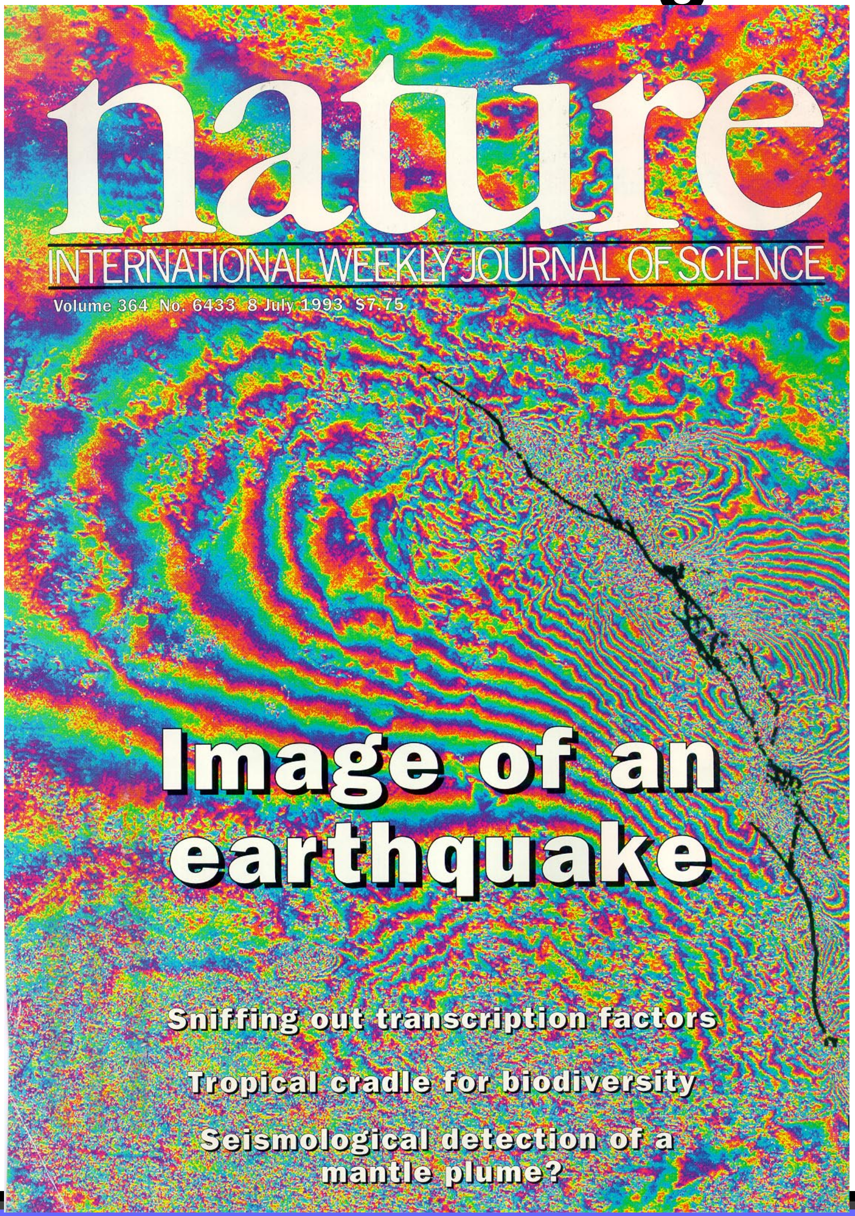
Spatial Dependence of Variation

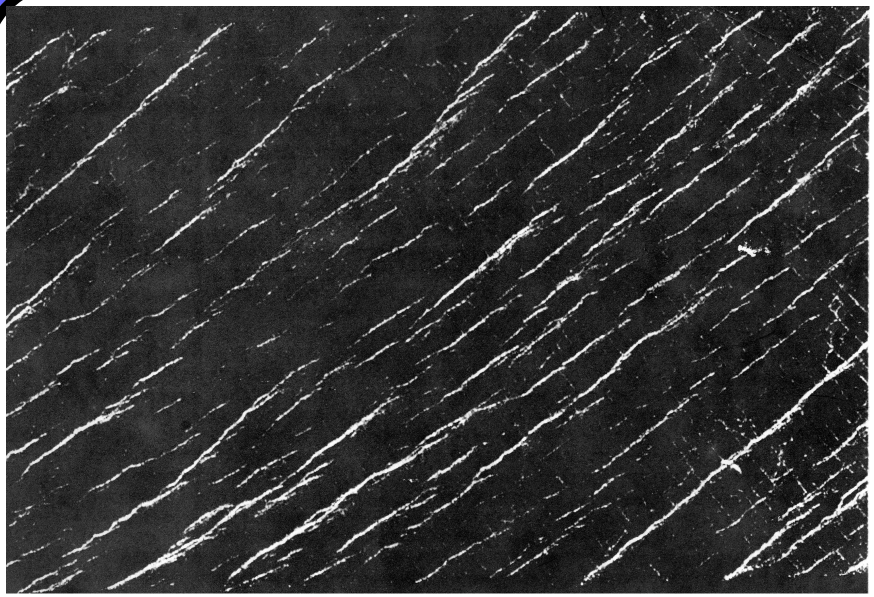




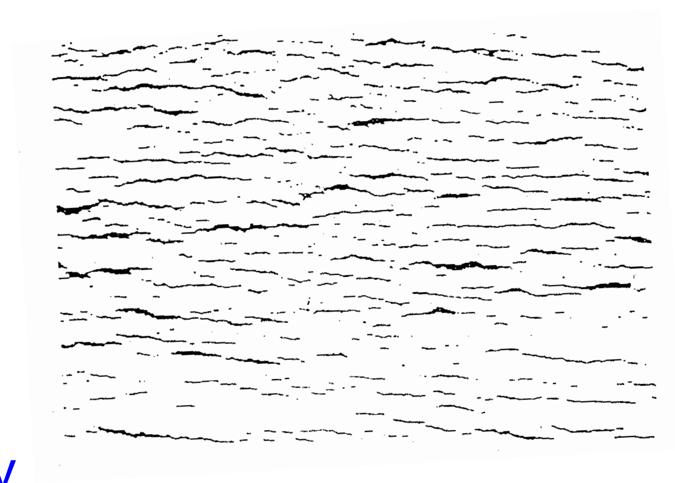
- Higher variation of large event repeat times at low strength drops

Geometrical Heterogeneities

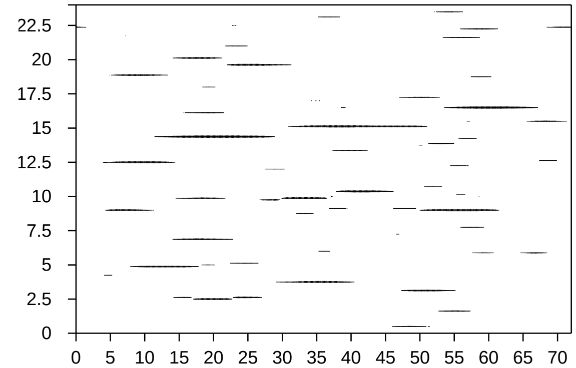


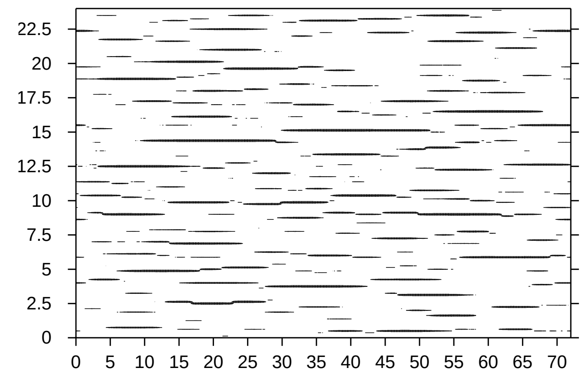


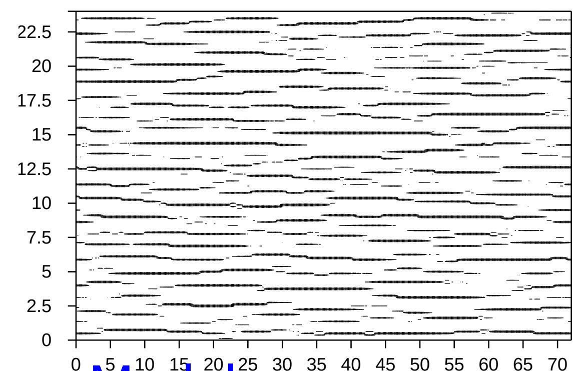
Venus



Clay

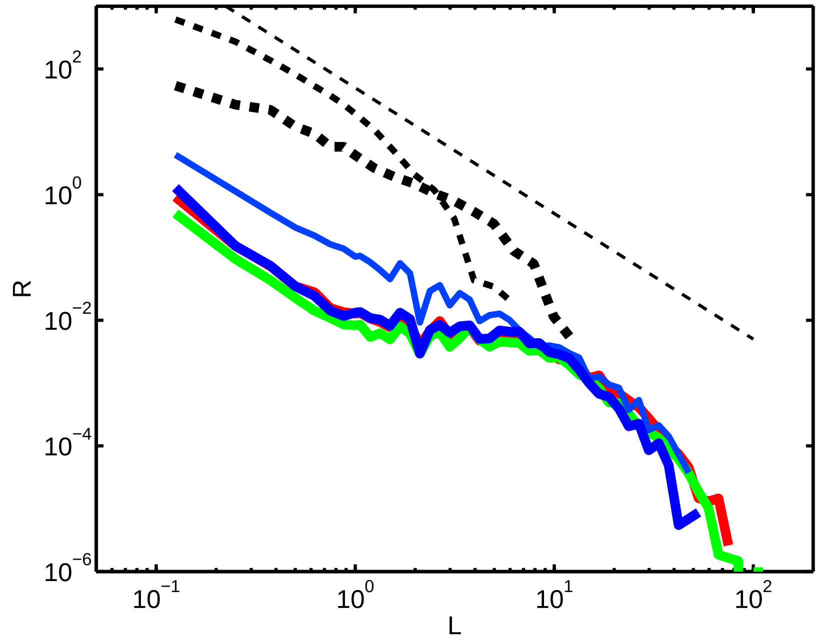


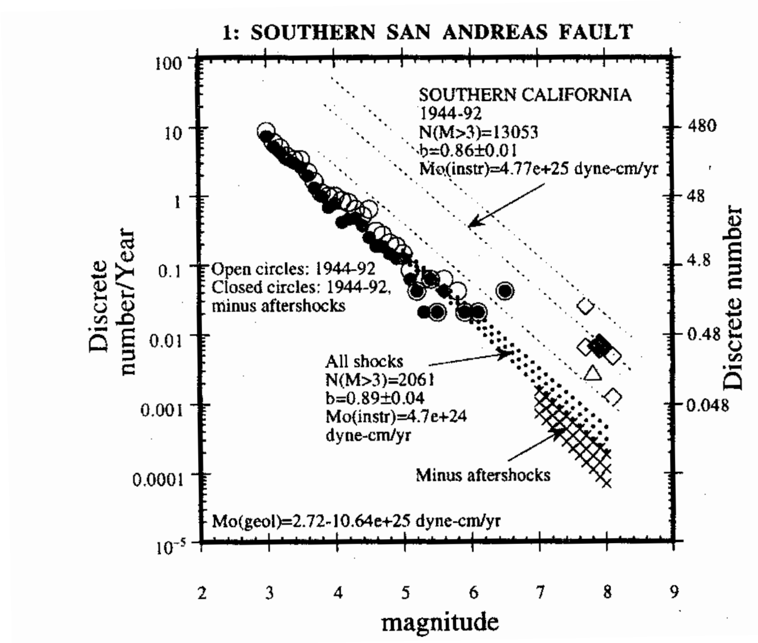




Model

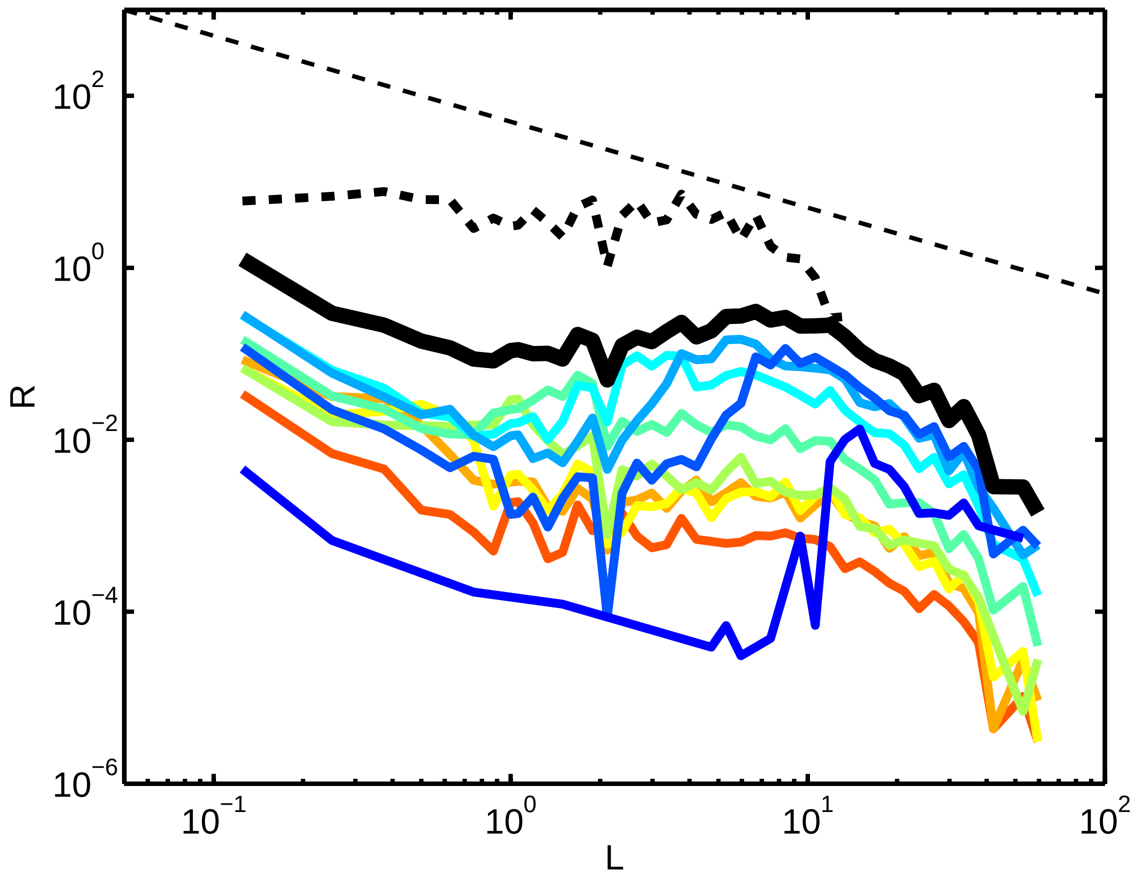
Distribution of sizes





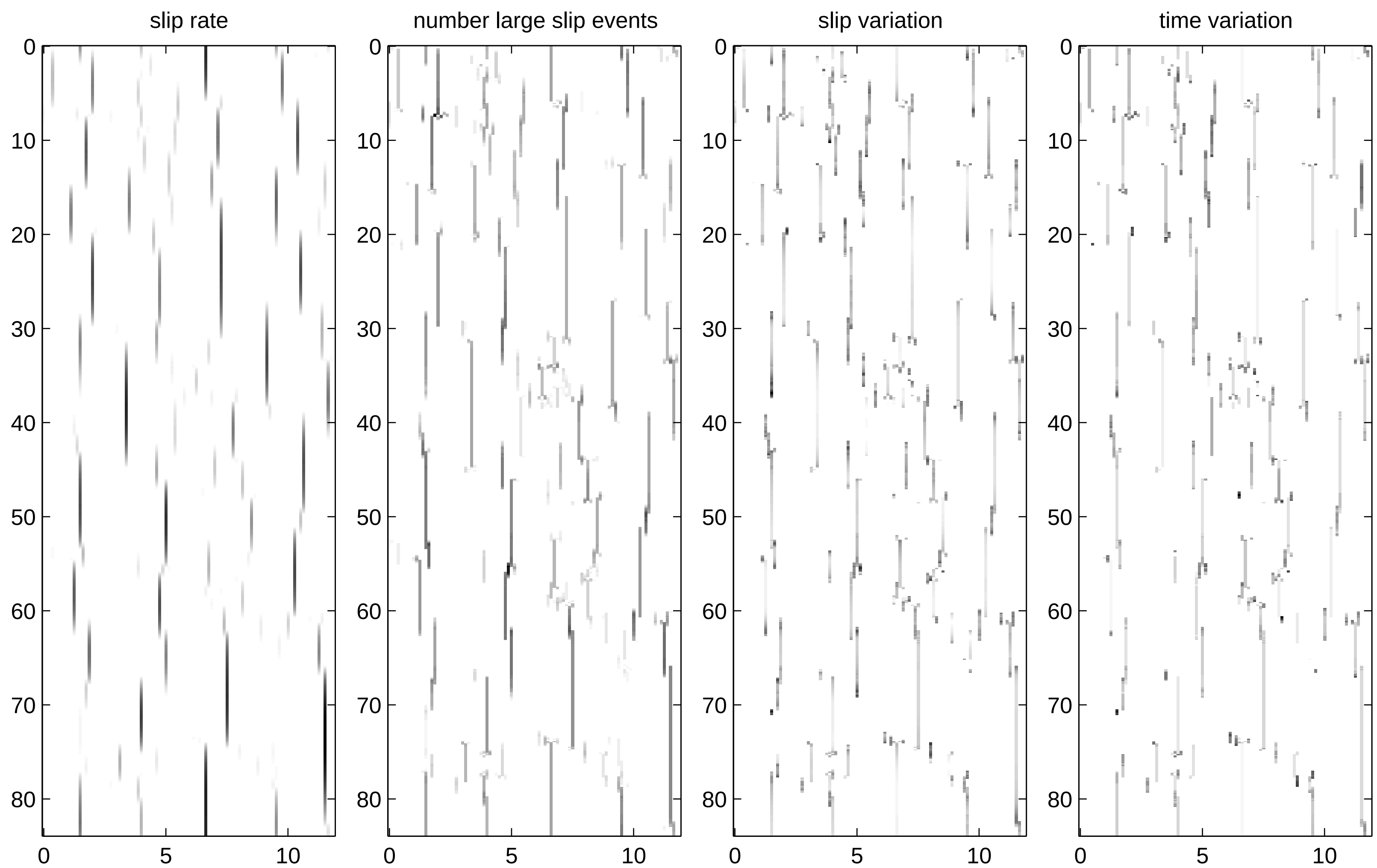
- Large events occur above extrapolated small event rate
- Large events dominate net slip
- Distribution of sizes depends on fault geometry
  but is not simple scaling of distribution of faults
- Friction secondary effect relative to geometry

Distribution of sizes of events on fault segments

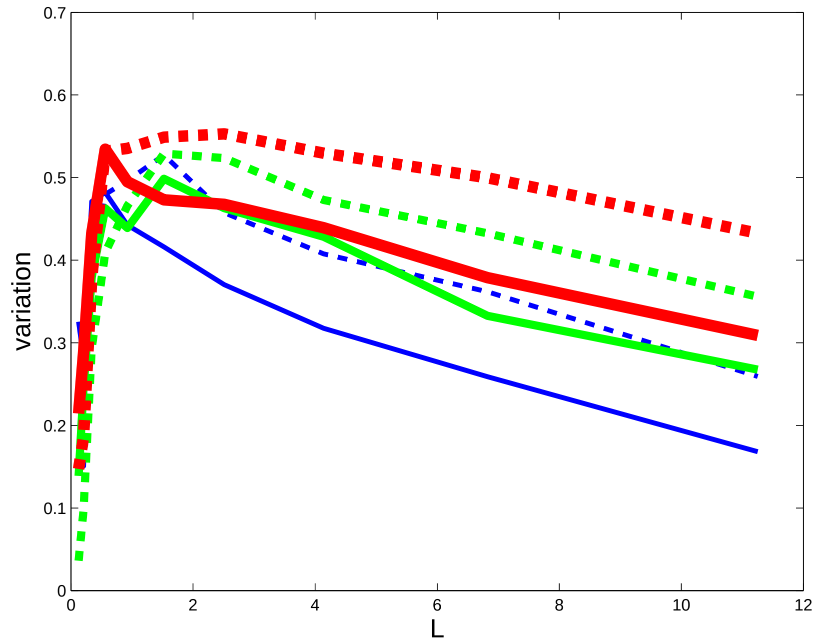


- Modified Segmentation Hypothesis: Segment length typical lengthscale, but also power law smaller events and cascades of longer ruptures

Variation of large events



Segment length dependence of variation

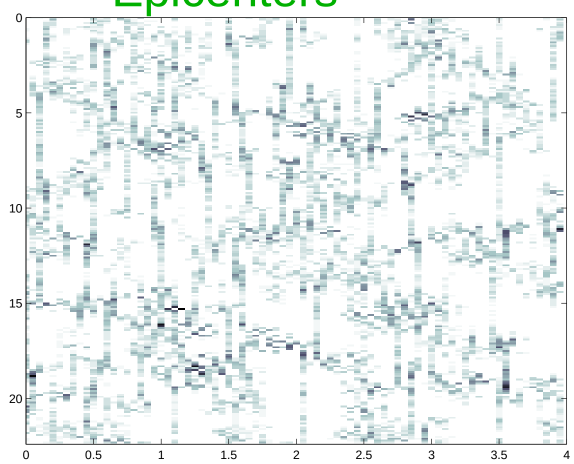


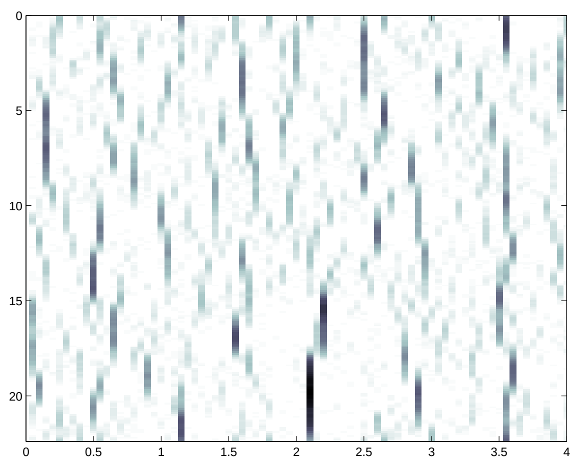
- Longest segments have lower variation
- Slip variation generally greater than Time variation
- velocity slip time weakening have different variation

Epicenters & Slip

Model

Epicenters

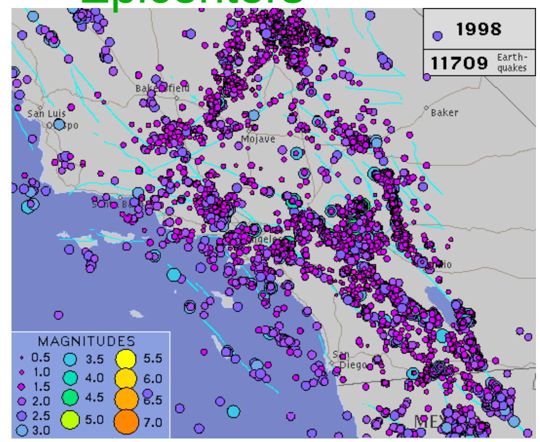


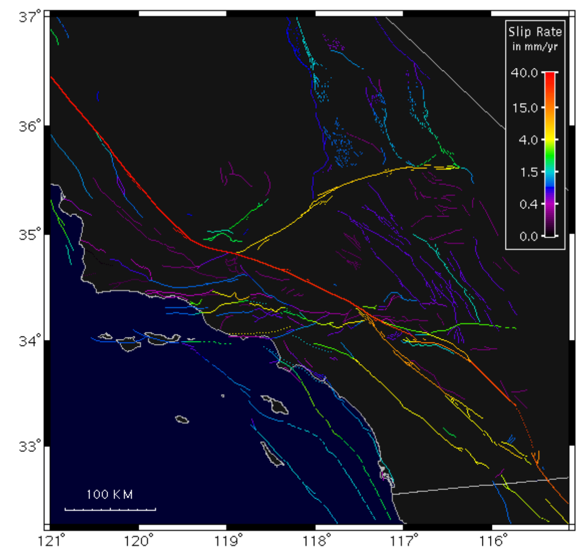


Slip

Southern California

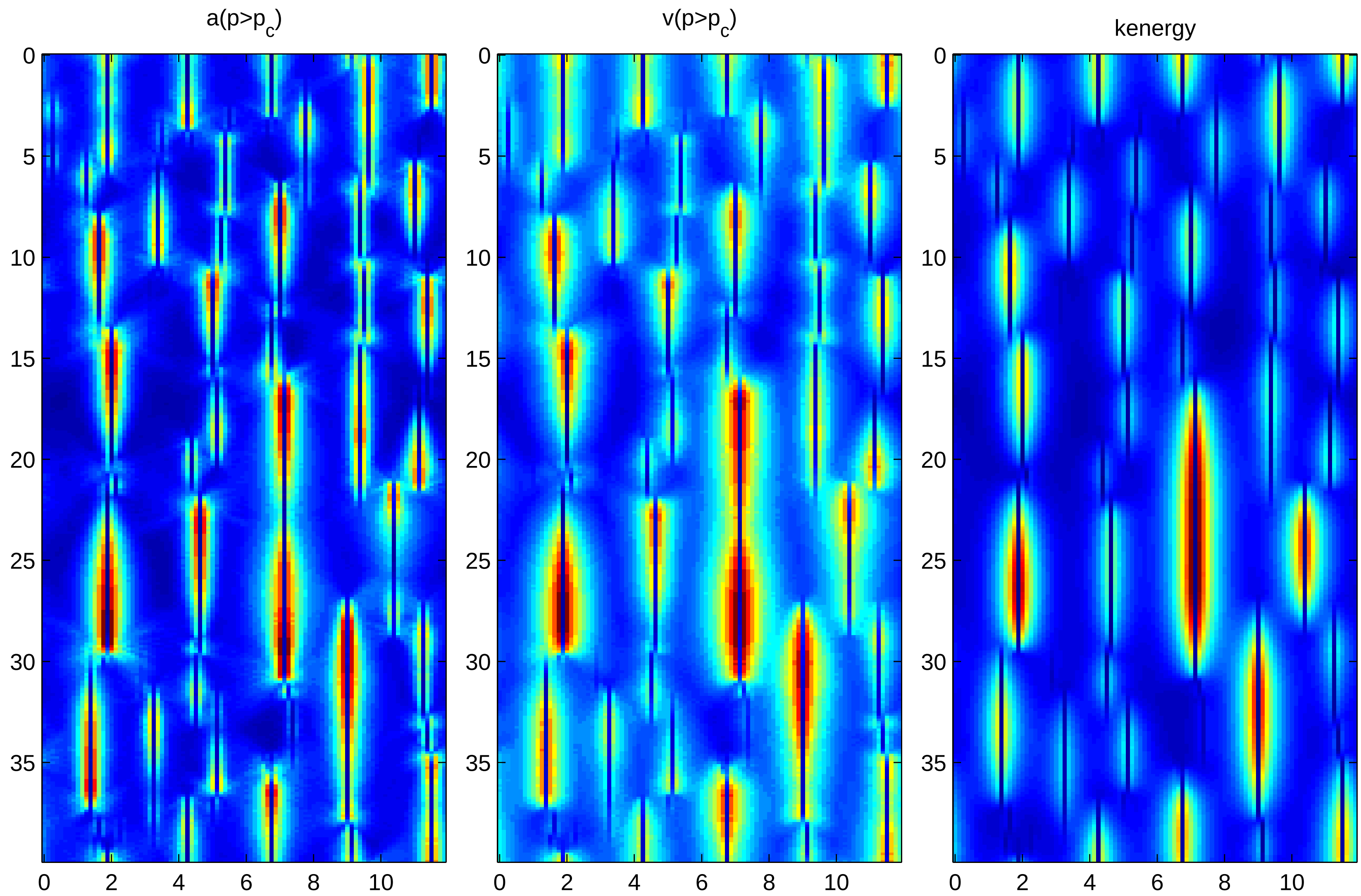
Epicenters





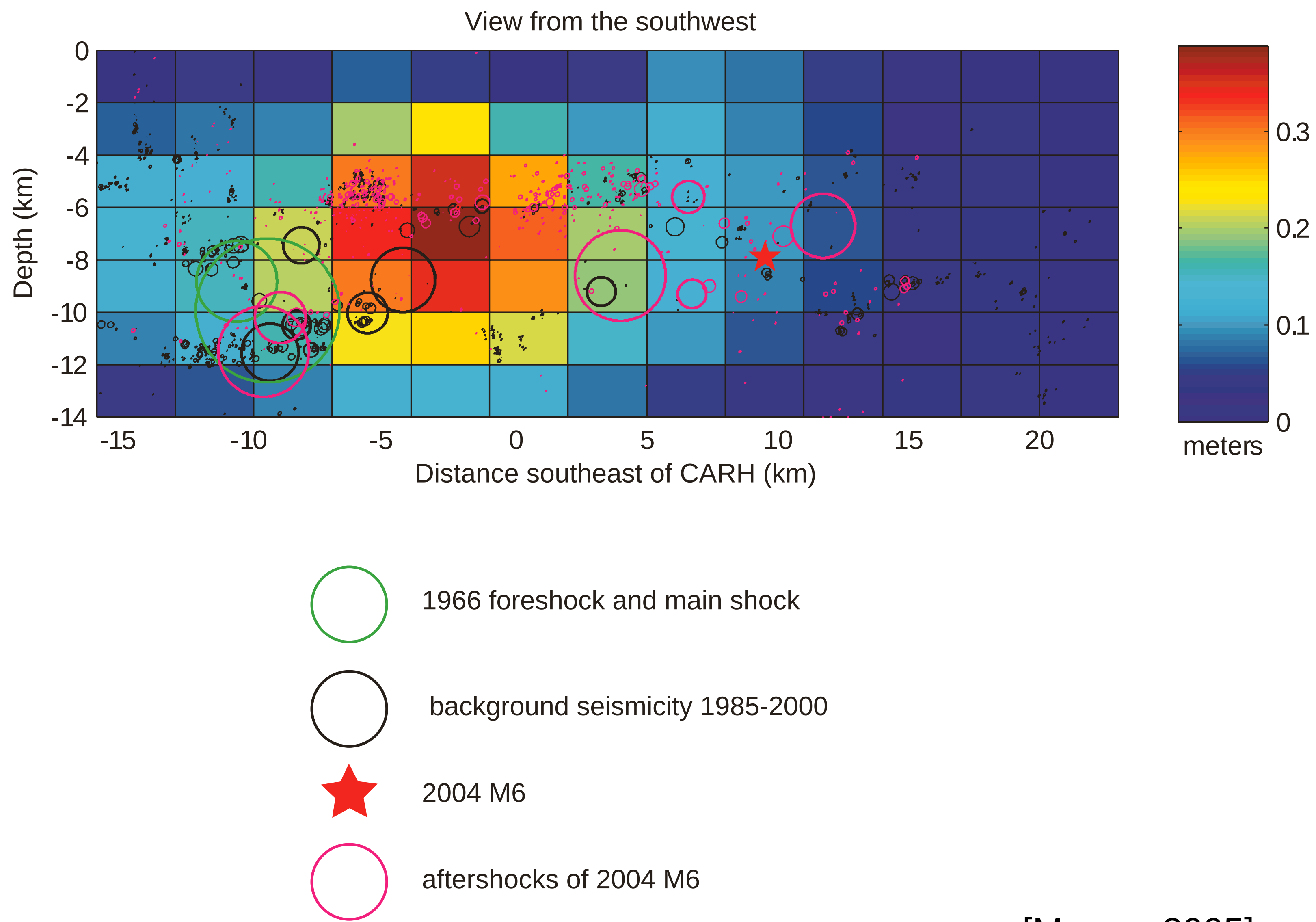
Fault slip rate

Geometry & Shaking



peak acceleration   peak velocity   kinetic energy

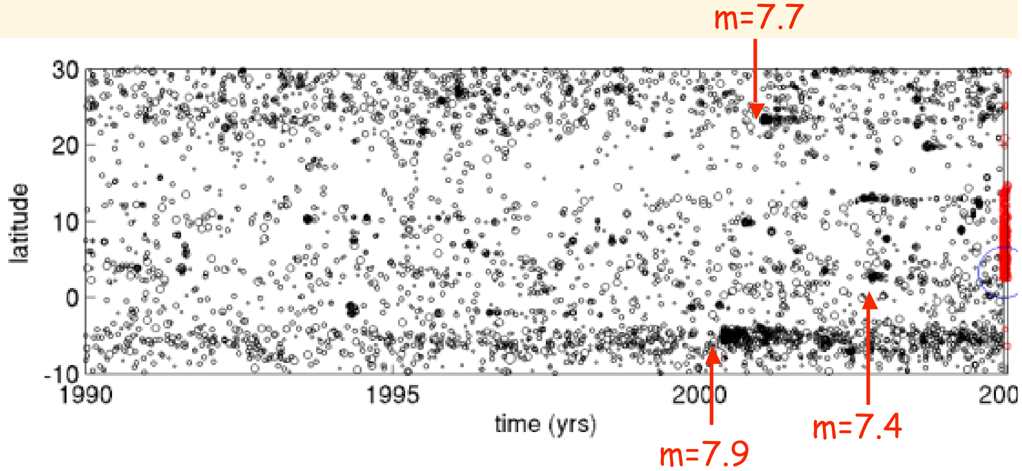
Persistence: 2004 M6.0 Parkfield

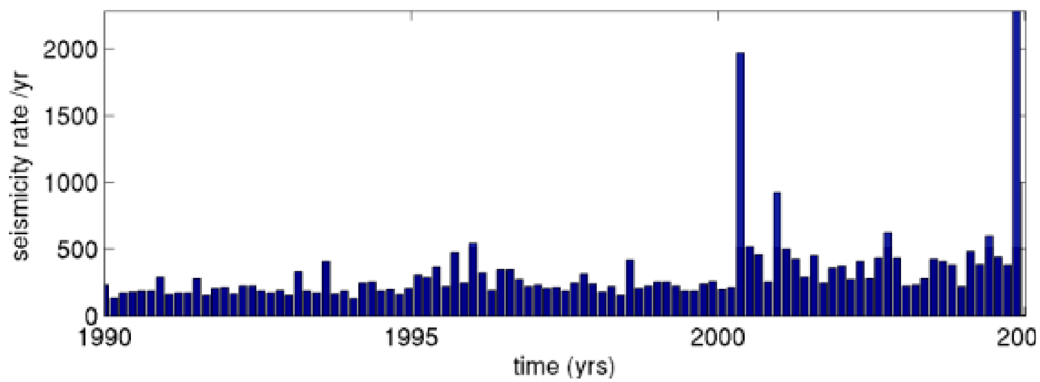


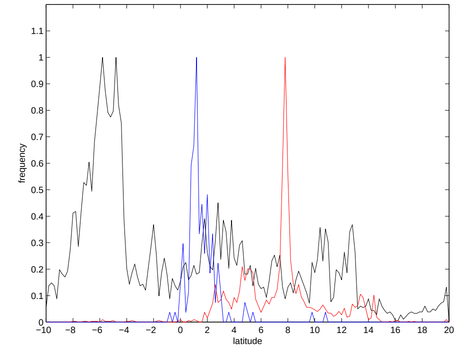
[Murray, 2005]

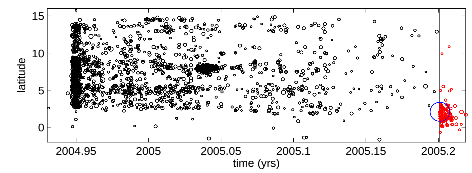
Persistence: Largest Earthquake 2004 M9.0 Sumatra

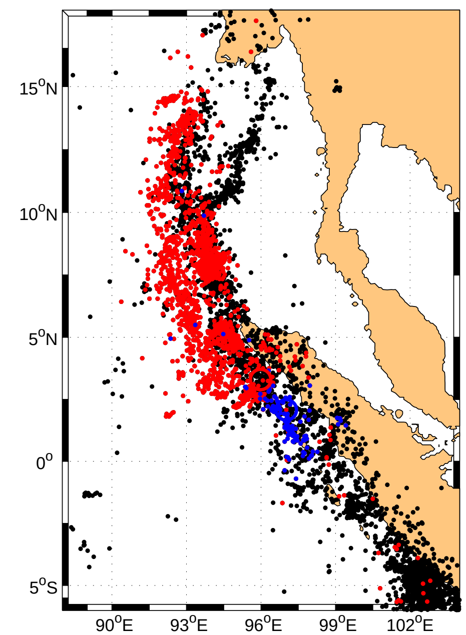
Sumatra seismicity, before & after











[Helmstetter, 2005]

Conclusions

- Dynamical Heterogeneities enough to make it complex, but constitutive equations giving sufficient stress heterogeneity not yet found (e.g. aftershocks on fault plane)
- Spatial persistence of small events with strong quenched heterogeneities
- Geometry more important than friction for sizes; friction does matter for some other measures
- Segment ends play important role in initiating and terminating ruptures
- Many questions remain on interaction of dynamical and geometrical heterogeneities