Size Dependence of Strength in Materials with Self-organized Critical Pre-stress

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Poster tomorrow morning S51D-1780

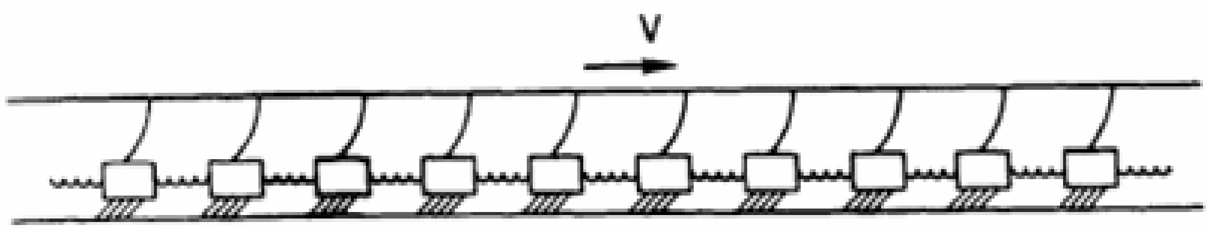
Many faults have very thin primary deformation zones, with no significant evidence of melting. Therefore the sliding friction must have been either very low, or the sliding must have been very slow.

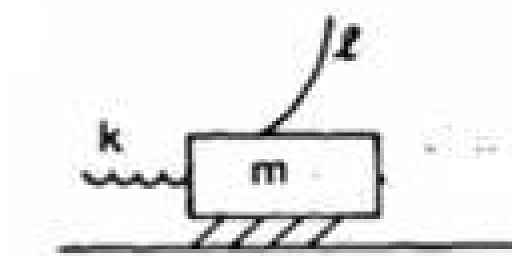
Transmission line fault in Pacoima Canyon, S. Calif. 300 m strike-slip total offset.

High-speed Friction

- Rapid transition from Coulomb static friction ($\mu \approx 0.7$) to low sliding friction ($\mu < 0.1$)
- Leads to localized and unsteady ruptures in the form of slip pulses (Aagaard and Heaton, 2008)
- For discrete 3-d dynamic simulations that are compatible with a friction law, the number of calculations scales as $(1/\Delta L)^5$
- For 50 km domain, grid spacing of 100 m is feasible with current supercomputers … grid spacing of 1 m requires a computer that is 10^{10} times faster

Spring-block slider with velocity dependent friction

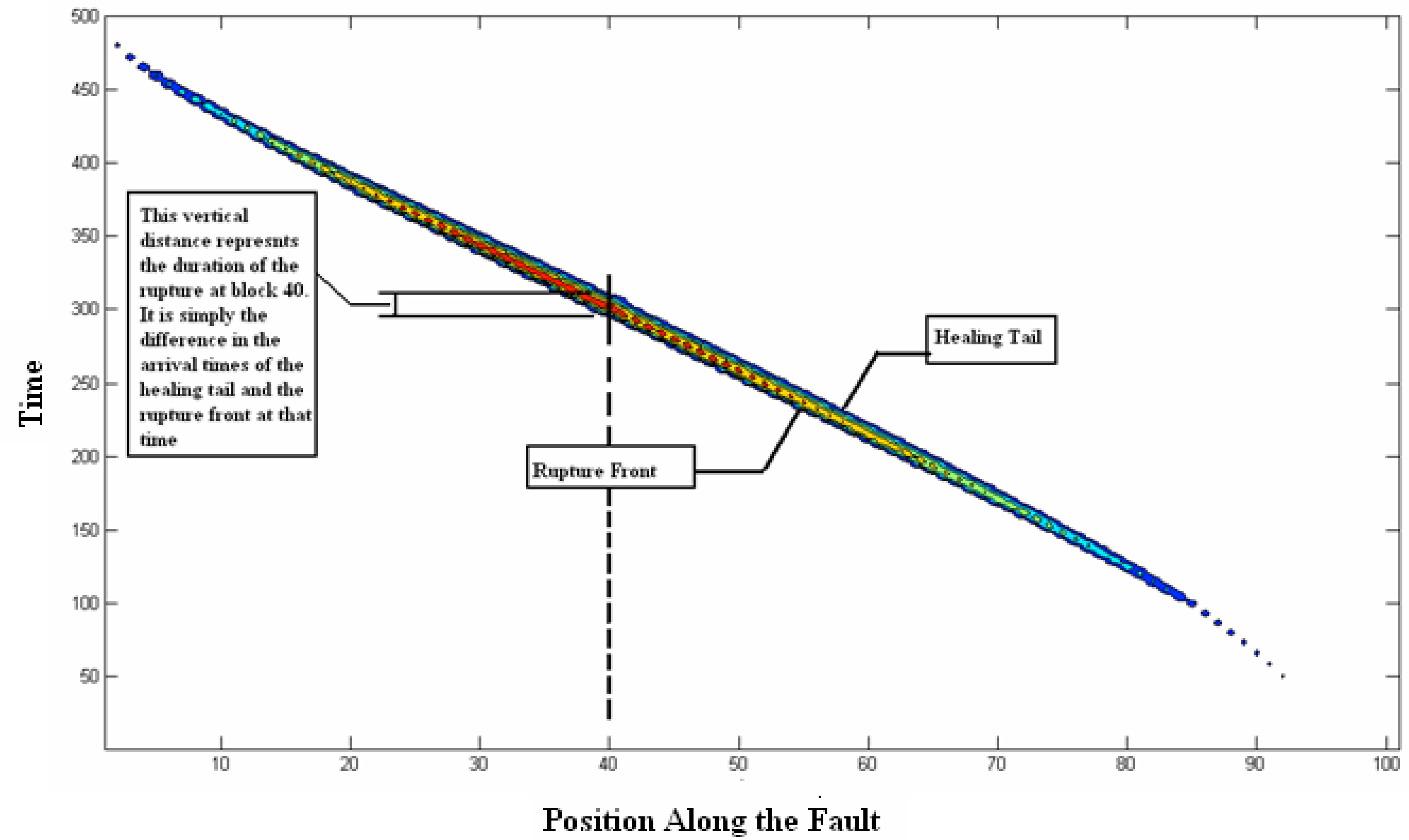




$$\mu \equiv \frac{1}{1+b\dot{u}}$$

- When coil springs become stiff, then all masses move in unison, few small events
- When leaf springs become stiff, then masses move independently, many tiny events

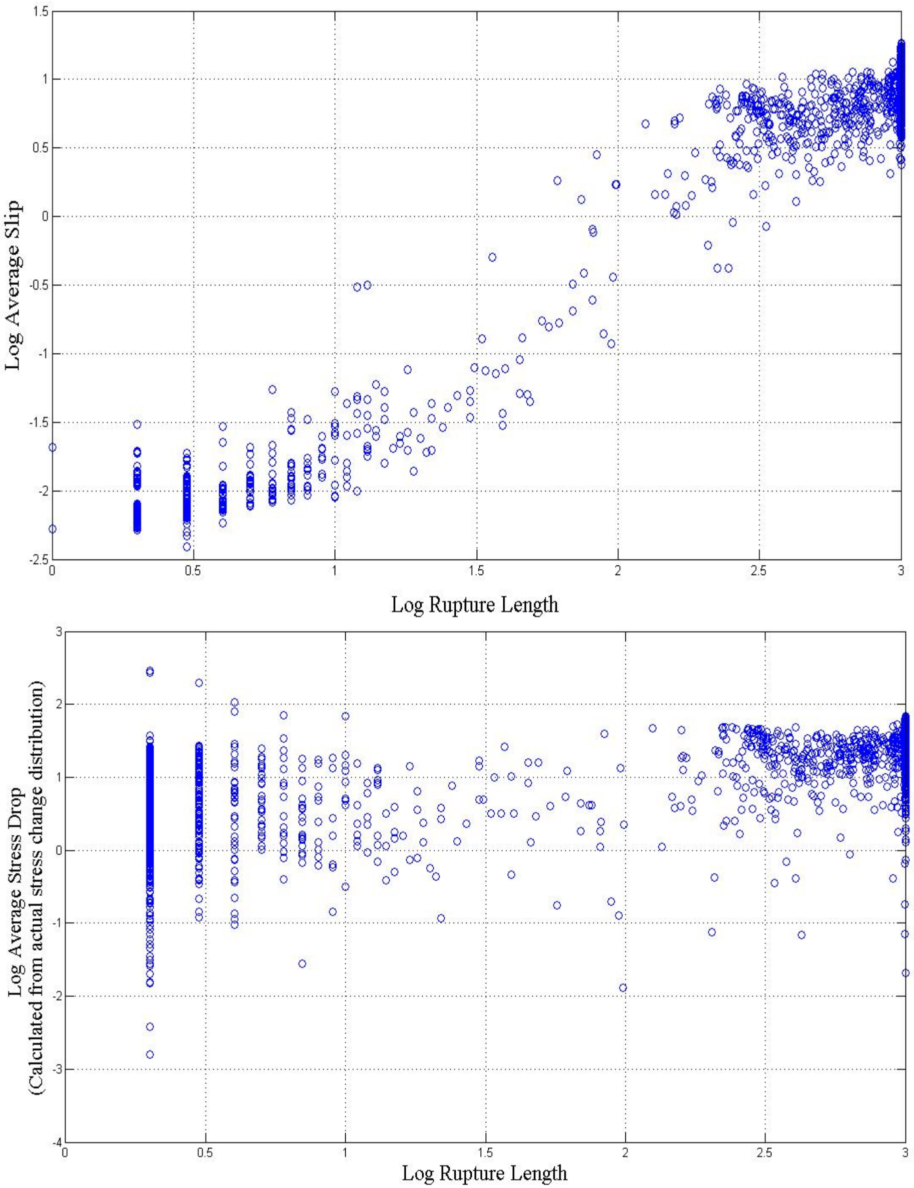
Rupture is comprised of unsteady slip pulses … event size distribution is a power law



There are no stable steady-state solutions

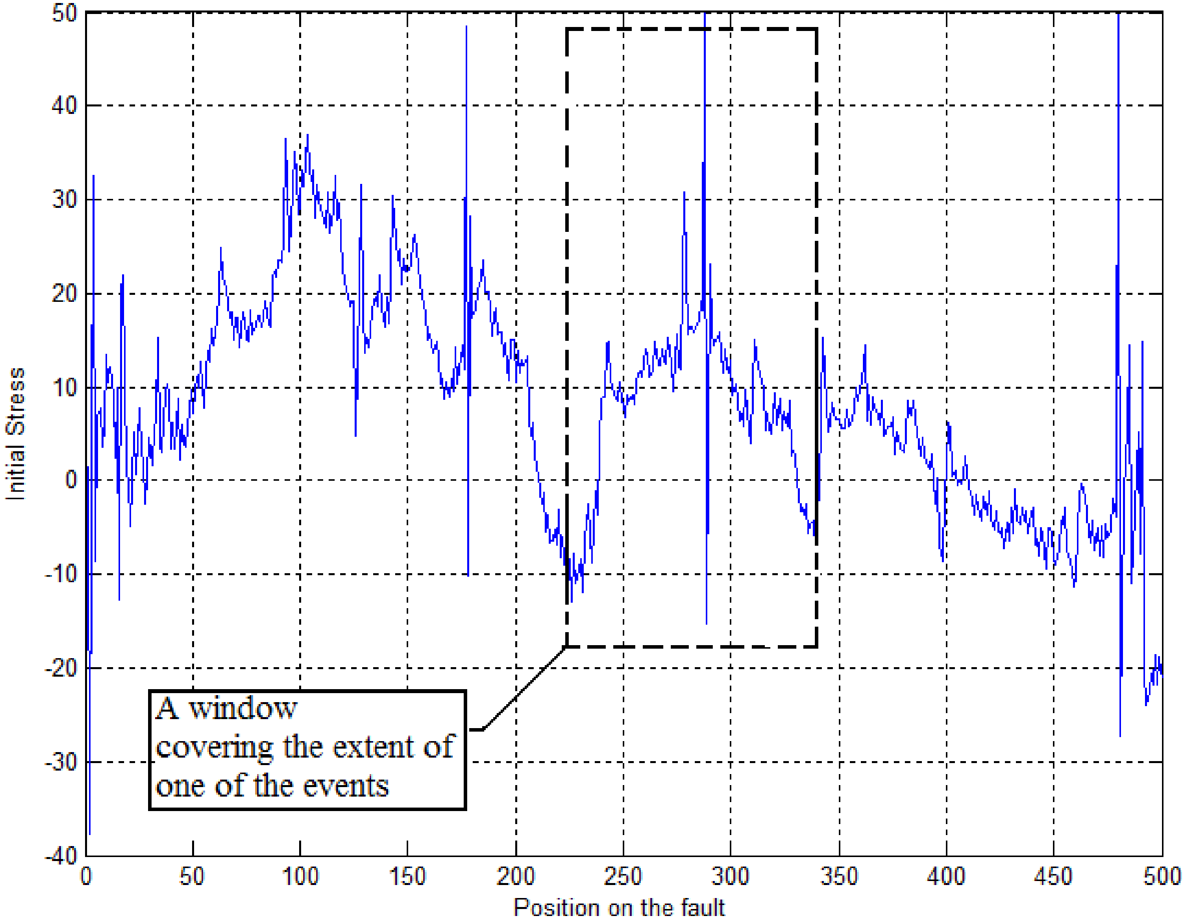
- Slip velocity depends of the amplitude of the slip pulse, so friction decreases with the size of the slip pulse
- For a given constant pre-stress, there is only one unique amplitude slip pulse that does not grow or diminish as it propagates
- If the pulse is infinitesimally larger, then friction drops and the pulse amplitude grows exponentially.
- If the system is allowed to evolve naturally, then events of all length scales occur and the system evolves into a critical state that is heterogeneous

Chaotic Ruptures at all Length Scales

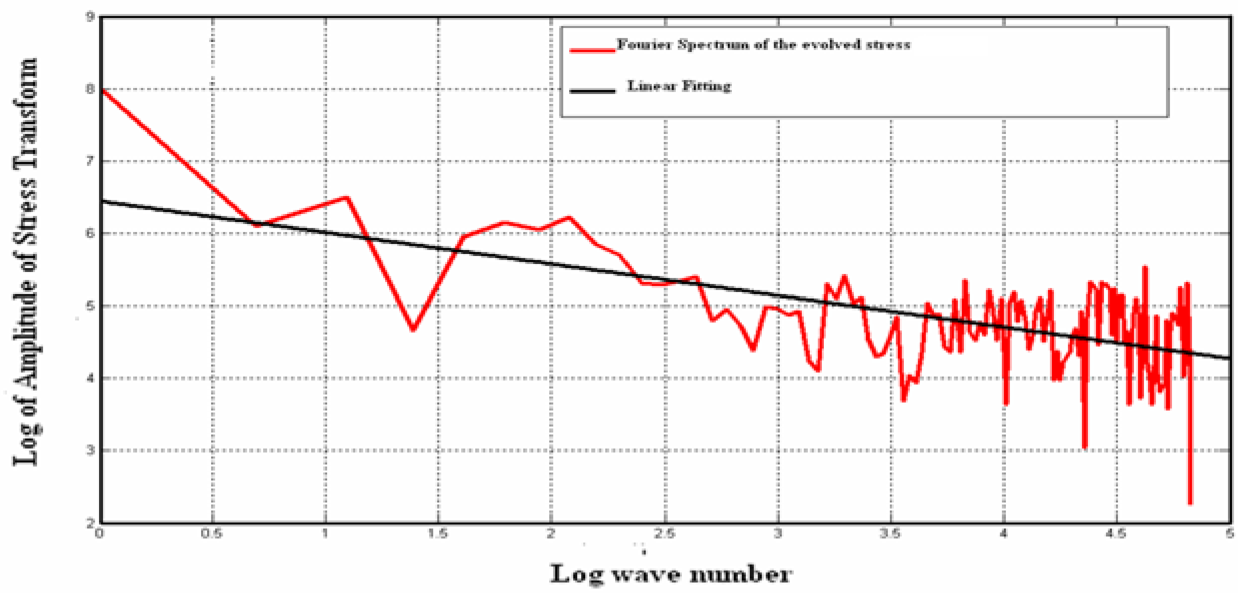


- Not truly fractal because of length scale introduced by ratio of spring stiffnesses
- Stress drops are determined by the dynamics and are **not** a local property of the friction

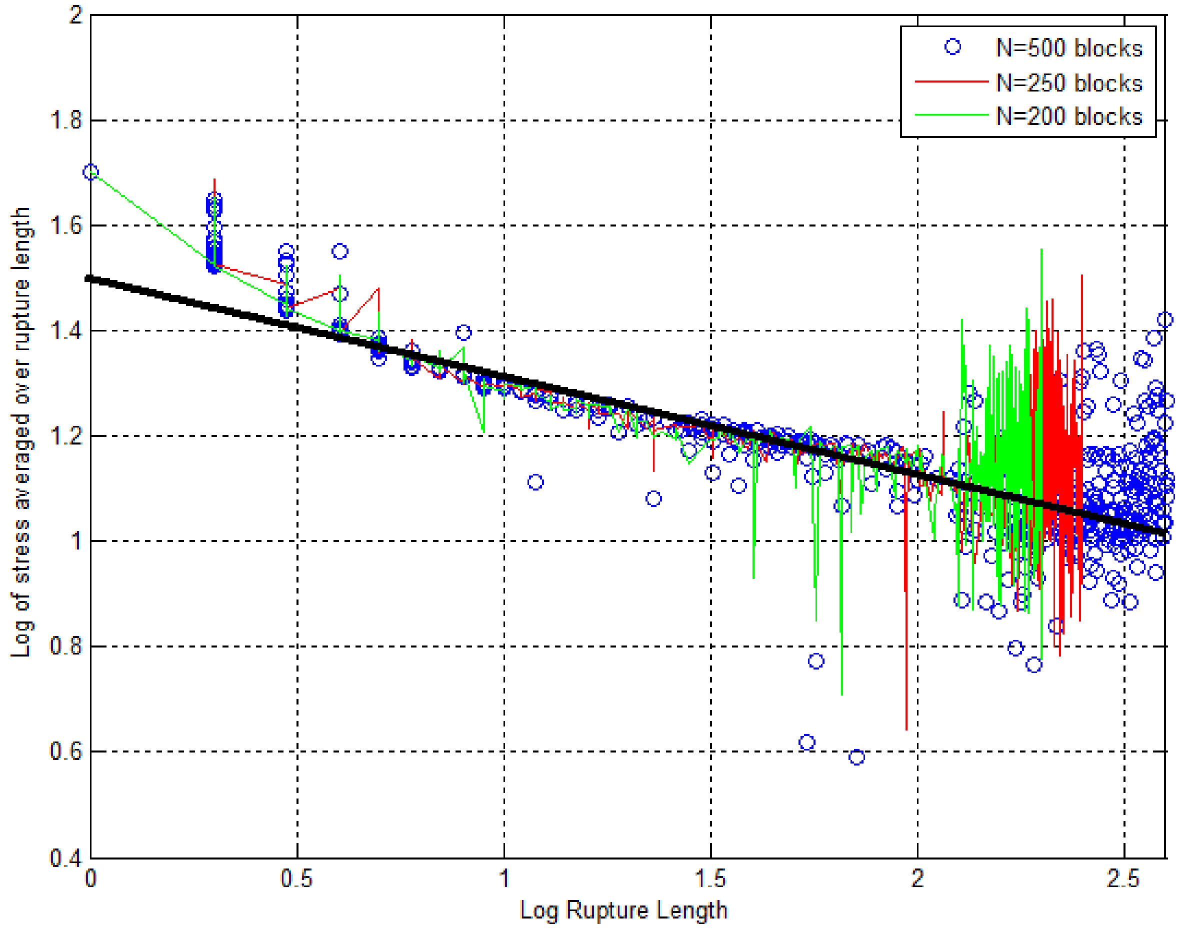
Stress evolves into a spatially heterogeneous distribution



Stress wavenumber spectrum evolves into a power law … at least over a range of length scales



Stress-based Strength = average stress over rupture strength α (rupture length) $^{-0.2}$



Earthquake Energy Balance

$$\Delta W = E_F + E_G + E_R$$

$\Delta W \equiv$ change in potential energy

$E_F \equiv$ frictional sliding work on fault plane

$E_G \equiv$ inelastic work off the fault

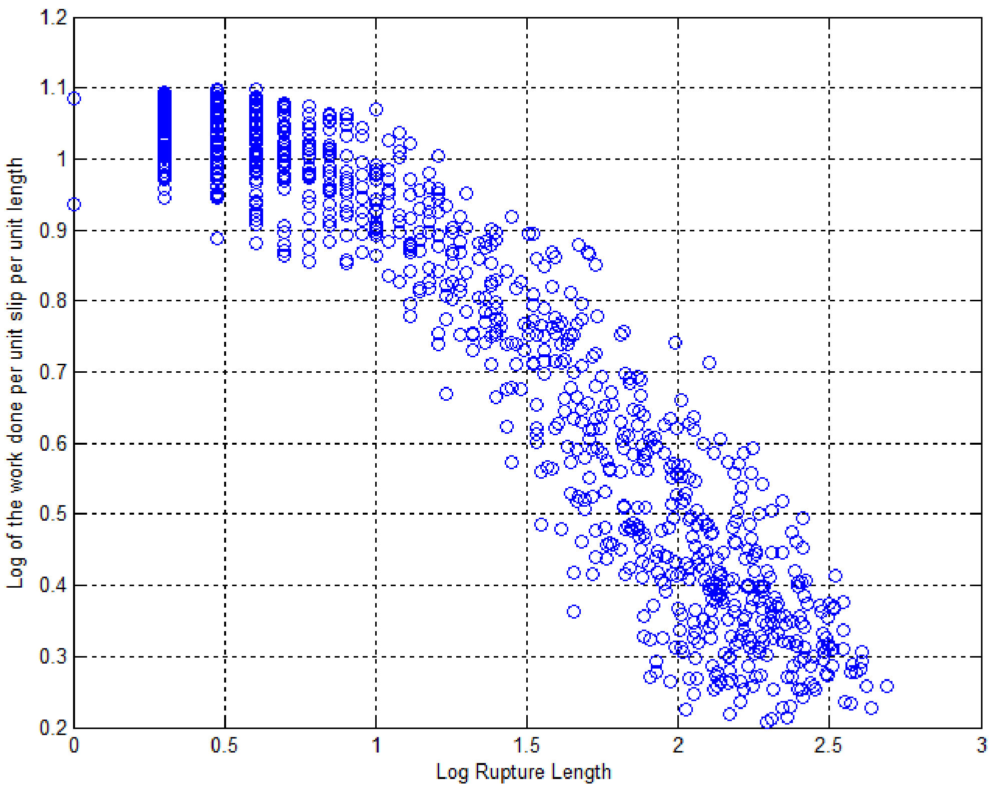
(plasticity at crack tip)

$E_R \equiv$ radiated wave energy

By estimating E_F, E_G, and E_R, we can estimate ΔW .

Work-based strength $\equiv \Delta W / (\text{area} \bullet \text{slip})$

work-based strength = work / slip
strength α (rupture length) $^{-0.5}$



Events with large slips have lower frictions and require less work per unit slip

Conclusions

- Materials that are in a self-organized critical state of stress have strengths that decrease with increasing length scale
- Energy based measures of strength can have a different (stronger) scale dependence than strength based on average pre-stress
- There will be endless confusion among earth scientists until consistent definitions of strength are agreed upon