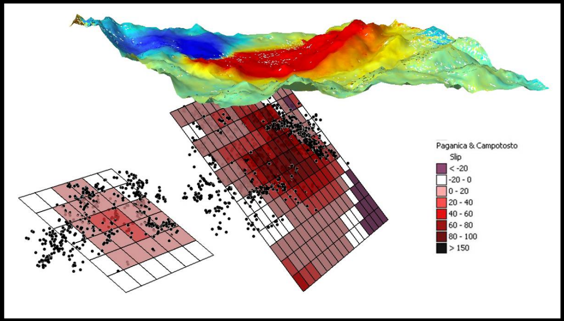
ECGS Workshop 2012
Earthquake source physics on various scale
Luxembourg, October 3-5, 2012



Stress drop variability and dynamic fault weakening for extended earthquake sources

Cocco Massimo and Elisa Tinti
Istituto Nazionale Geofisica e Vulcanologia, Rome
Department of Seismology and Tectonophysics
massimo.cocco@ingv.it elisa.tinti@ingv.it

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Key Talking Points

1. Reconciling seismological measurements, geological observations and the key findings of laboratory experiments

2. Model dependence. Estimated parameters are model dependent and they do not allow us to distinguish the processes controlling dynamic fault weakening

3. Scale dependence: implications for self-similarity

Focus: Fault Zone Physical Processes during Seismic Slips

- How does *shear stress* (τ) vary with *slip* (δ) during earthquakes?

  (Focus is on *large* slip, *e.g.*, $\delta > 0.1$ m, well beyond slips of order 0.01 mm to 0.5 mm at which events are thought to *nucleate*)

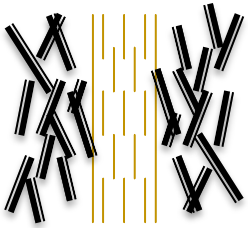
- What *physical mechanism* of weakening during slip?

  (Argued here: *Different physical mechanisms can control dynamic weakening each of which has its own spatial and temporal length scales*)

- What *fracture energy* (G) is implied by the τ *vs.* δ relation?

  (Important because *seismological fracture energy* is different from fracture energy *in fracture mechanics*)

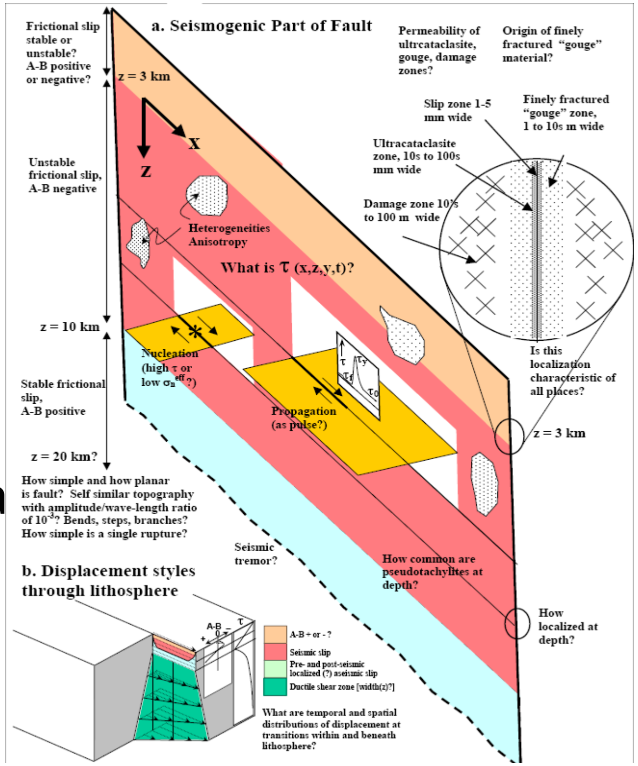
(1) Lessons from geological observation



- Fault zone structure is complex:
  - **volumetric** versus **surface** processes
- Complex damage zones: energy loss outside the slip zone. $G' = W_b = W_{on} + W_{off}$ $V_{peak} \leq V_{\mathrm{limit}}$
  - Impact on fracture energy and peak slip velocity.
- Structure of the fault core
  - impact on hydraulic and thermal properties
- Principal slipping zones (strain localization)
  - have a finite, although small, thickness
  - and are geometrically complex.

(1) Lessons from seismology

- Seismological investigations rely on a **phenomenological** description of source parameters
- We measure **global** source parameters
  - M_o, E_R, σ_a, $\mathbf{D_{av}}^{100\%}$, Fault Area: A=L•W, M_L
- We measure **macroscopic** parameters (on a virtual mathematical plane of zero thickness)
  - $\Delta\sigma_s(\xi)$, $\Delta\sigma_d(\xi)$, $\Delta\tau_b(\xi) = \tau_y(\xi) - \tau_o(\xi)$, $V_r(\xi)$,
  - $D_{tot}(\xi)$, $\mathbf{D_{mean}}^{\neq\%}$, D_{max}, $V_{peak}(\xi)$



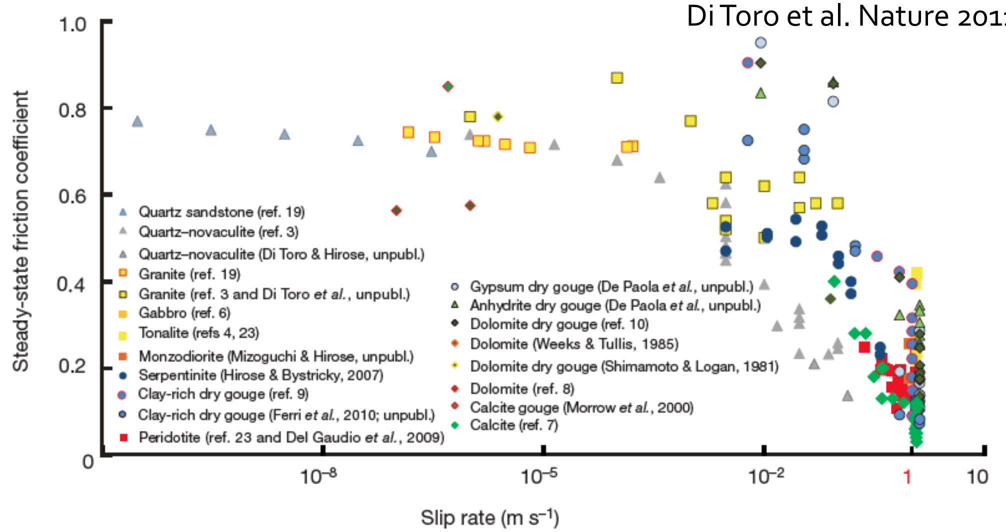
from Dahelm Workshop report (2005)

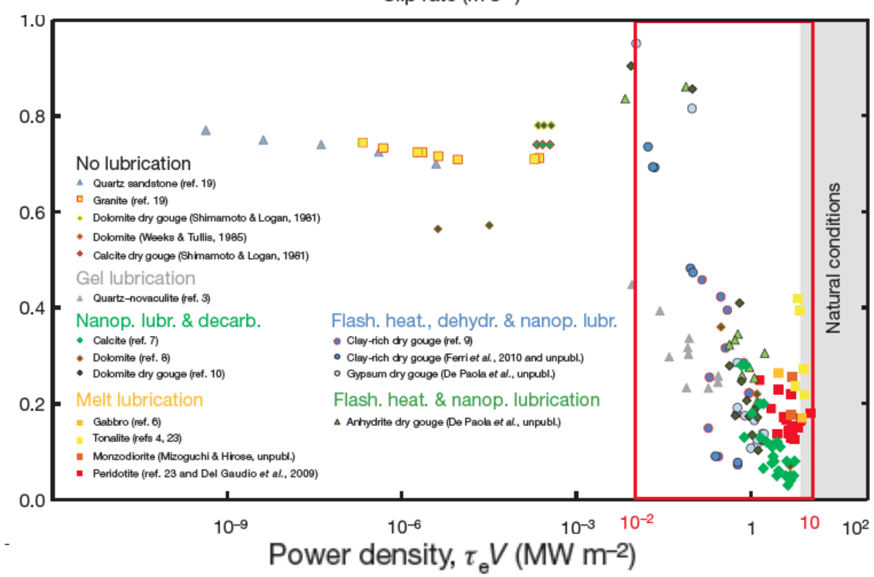
- We measure integral quantities
  - Breakdown Work W_b or seismological fracture energy G'

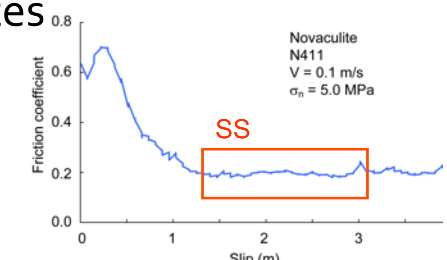
(1) Lessons from Lab experiments

- Lab experiments show dynamic fault weakening
- Efforts are still needed to bridge the gap between natural and experimental faults
- HVFE have the advantage of:
  - produce similar experimental and natural fault products
  - generate similar mechanical work estimates

Di Toro et al. Nature 2011





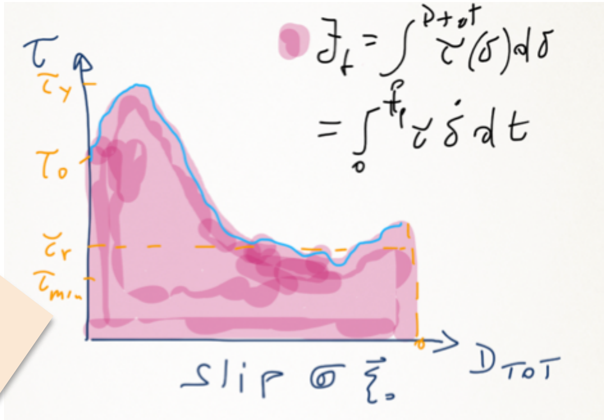


Di Toro et al., Nature, 2004.

Dynamic Fault Weakening

Physical intuition of scale dependence

fracture + friction = Dynamic weakening



Flash Heating

Thermal Pressurization

Porosity & permeability evolution

Melting

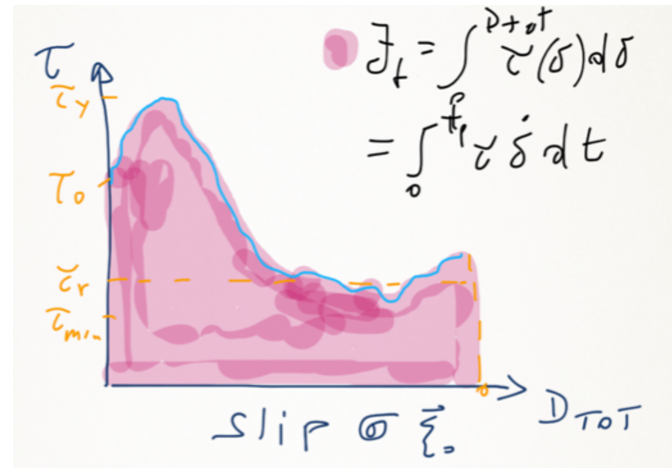
Abrasion & Wear

Physical Processes (≠ length scales)

Outcome of scale dependent processes

The Macroscopic Frictional Work

We have defined the macroscopic frictional work as the irreversible part of mechanical work, which is the work that does not go into elastic strain energy and kinetic energy, and it is partitioned into surface energy and heat (here for heat we mean all the distinct dissipative mechanisms such as high frequency stress waves, plastic deformation on- and off-fault)

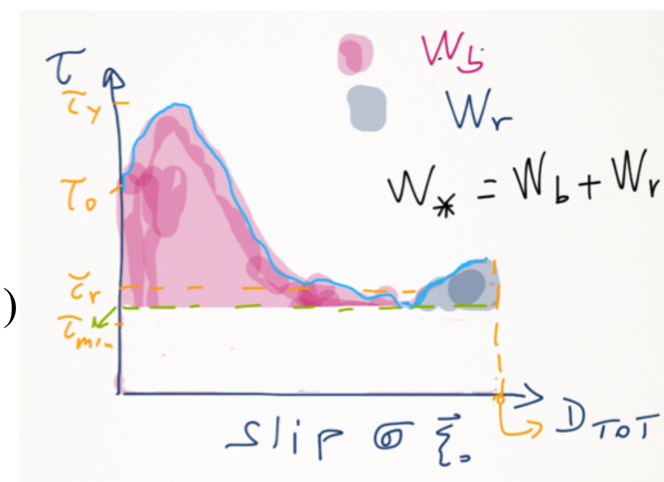


Work Rate $\tau_i \Delta\dot{u}_i = \cancel{2\gamma} + \Delta q$

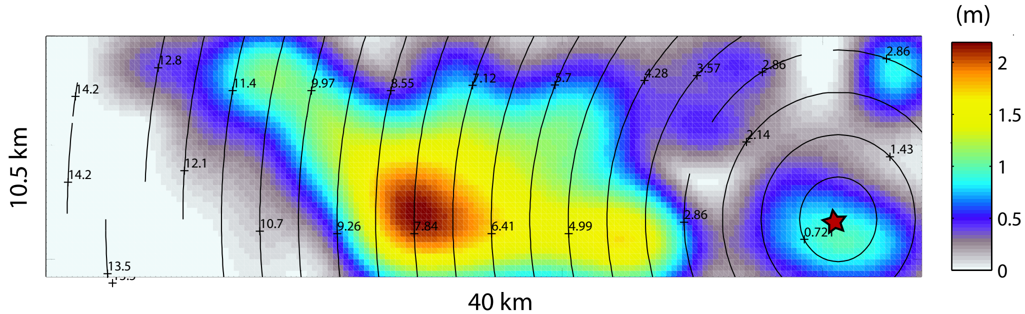
Frictional Work $\Im(\vec{\xi}) = \int_0^{t_m} \tau_i \Delta\dot{u}_i\, dt = \int_o^{D_t} \tau_i\, d(\Delta u_i)$

Total Frictional Work $\Delta E_\Sigma = \iint_\Sigma dS \int_0^{t_m} \tau_i \Delta\dot{u}_i\, dt = \iint_\Sigma dS \int_o^{D_t} \tau_i\, d(\Delta u_i)$

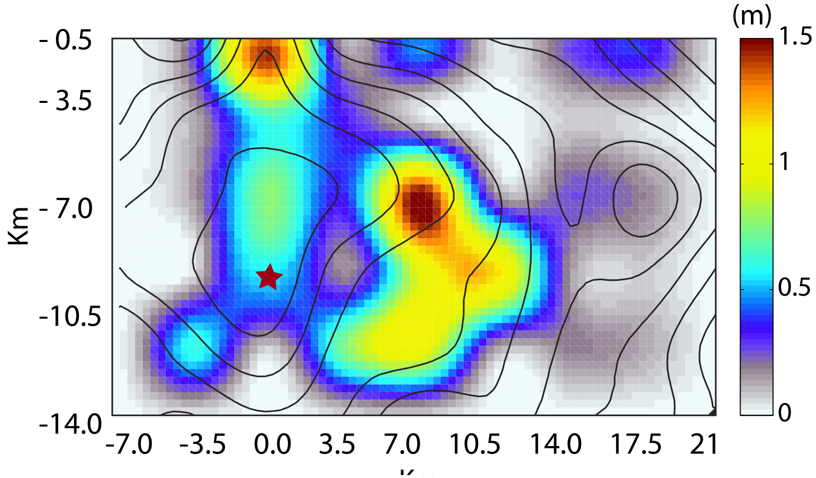
Breakdown Work $W_b = \int_0^{T_b} \left(\vec{\tau}(t) - \vec{\tau}_{\min}\right) \cdot \dot{\vec{\delta}}(t)\, dt$



Kinematic rupture models imaged from geophysical data inversions

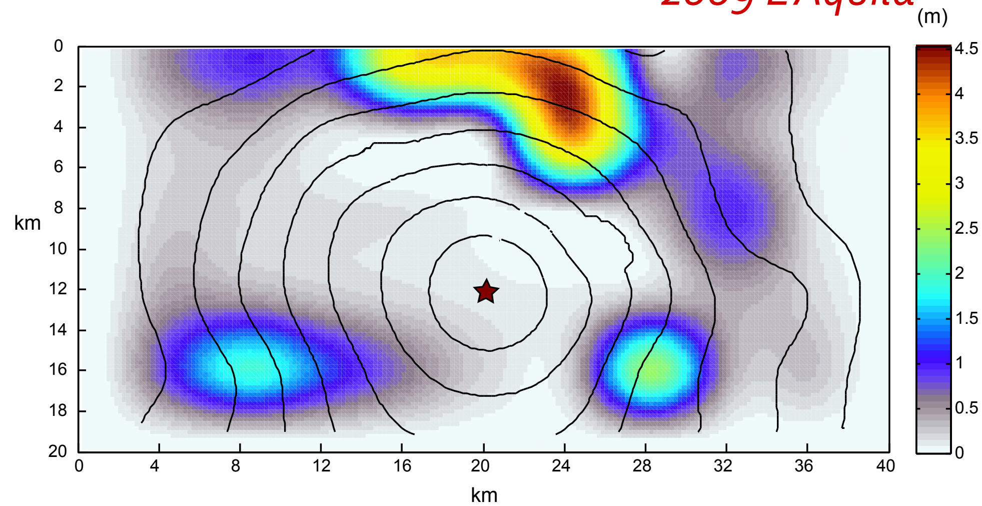


1979 Imperial Valley



2009 L'Aquila

Rupture histories are used to constrain the traction evolution and to infer dynamic rupture parameters as well as seismological fracture energy.



2000 Western Tottori

Estimates of dynamic parameters for real earthquakes

We infer the traction change evolution on the fault plane by using the rupture history

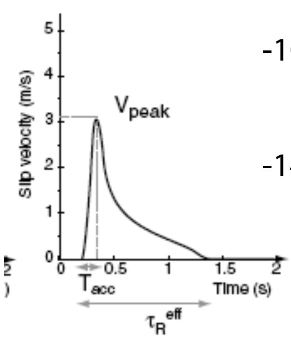
We solve the Elastodynamic equation using the slip velocity history as a boundary condition on the fault

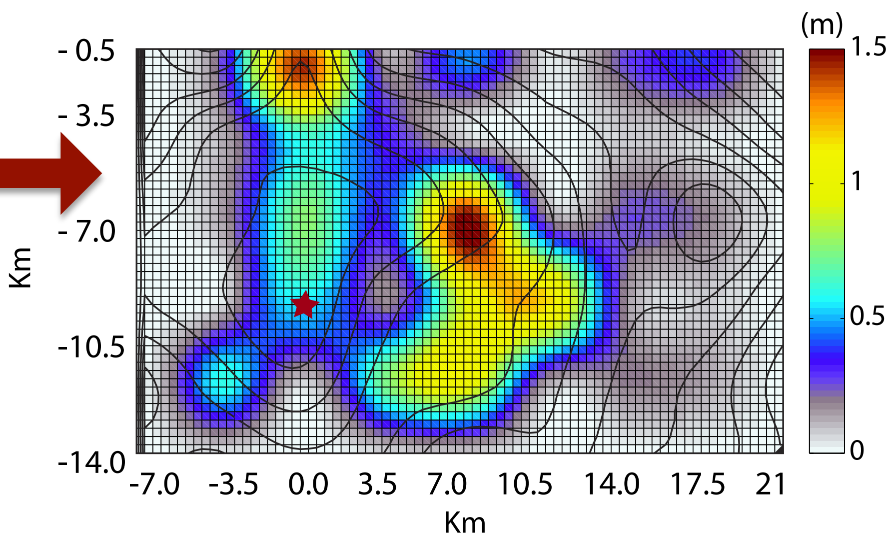
$$\sigma(x,t) = -\frac{\beta}{2\mu}\Delta\dot{u}(x,t) + \iiint \Delta\dot{u}(\xi,\tau)\mathrm{K}(x-\xi,t-\tau)\,d\xi\, d\tau$$

Fukuyama & Madariaga (1998)

$$\Delta\dot{u}(\xi,t) = \dot{f}(t - t_r(\xi)) \cdot d(\xi)$$

Slip Velocity time history on the fault





example: Slip distribution and rupture time from kinematic inversion

[Piatanesi, Tinti, Cocco & Fukuyama, GRL, 2004]
[Tinti, Fukuyama Piatanesi & Cocco, BSSA, 2005]
[Tinti, Spudich, Cocco, JGR, 2005]

Reconstructing stress evolution

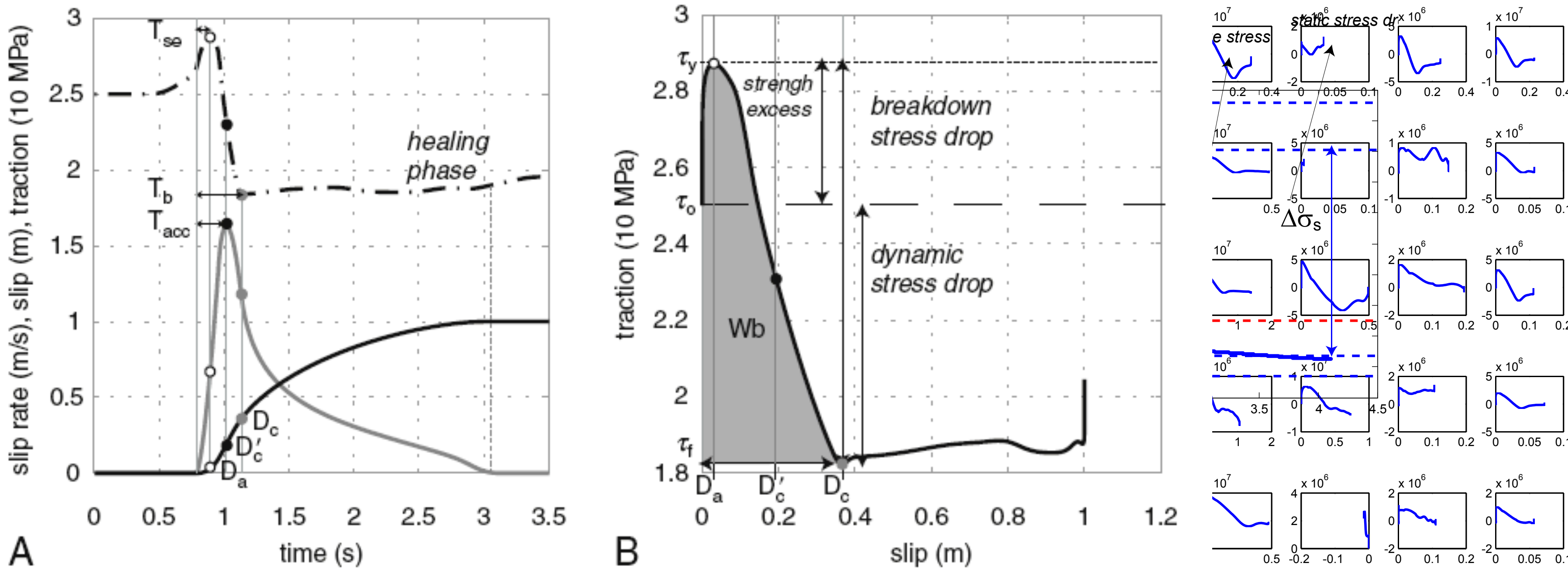
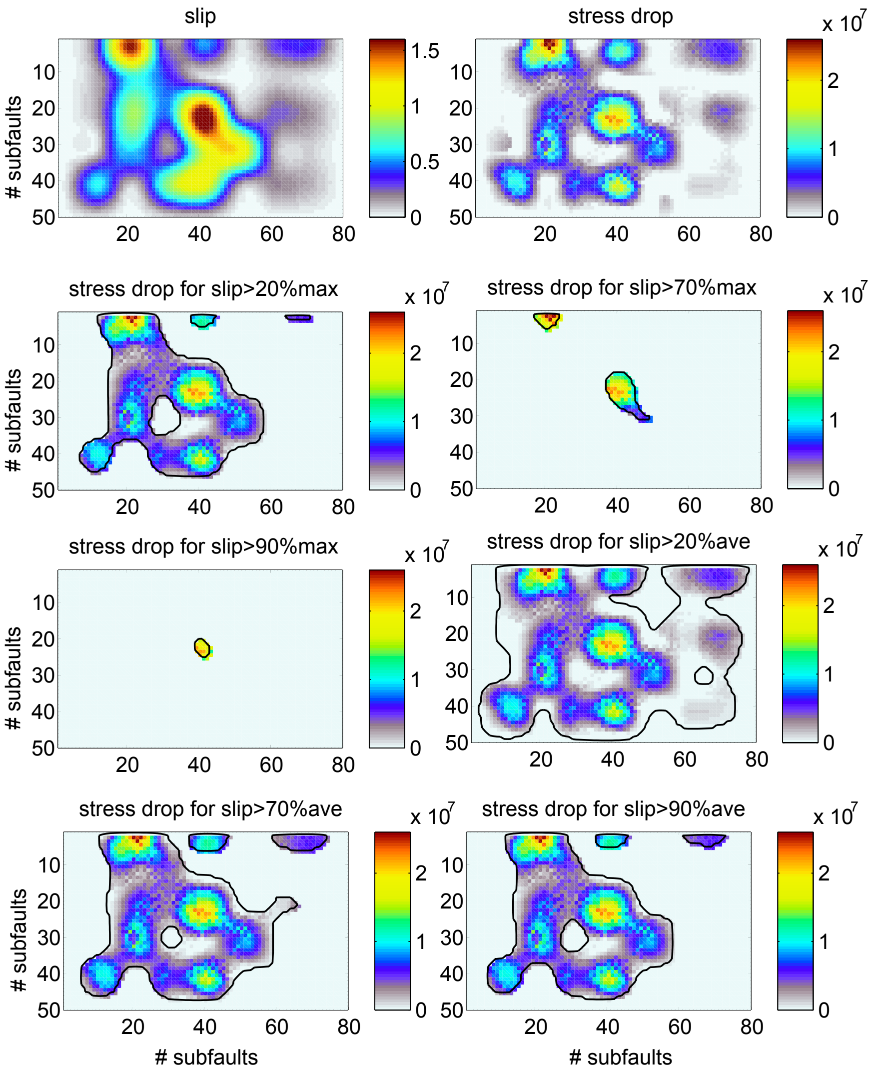


FIGURE 1 (a) Comparison of slip velocity, slip, and traction time histories at a target point on a fault plane using a smoothed Yoffe function as a source time function. Black solid circles indicate the time of peak slip velocity (T_{acc}) and the gray solid circles indicate the end of weakening (T_b). (b) Corresponding traction versus slip behavior; the same circles of panel a are used to indicate the parameters D_a, D'_c, and D_c.

Cocco M., E. Tinti, C. Marone & A. Piatanesi (2009),

Averaging on the fault plane

- For a scale-independent model we can average local estimates of stress drop on different fault portions
- These different average values yield a variability up to a factor 5 in stress drop
- Including k^{-2} heterogeneities and assuming scale-independence confirms and partially enhance such variability



(2) Model Dependence

- Stress drop can be inferred from
  - Seismic moment and source radius
  - Brune stress drop: ground acceleration high frequency plateau
  - Rupture history through quasi-dynamic models

➢ Stress drop estimates are strongly model dependent

$$r = C\frac{\beta}{f_c} \qquad \Delta\sigma = \frac{7}{16}\frac{M_0}{r^3} \qquad M_0 f_c^3 \cong const \propto \Delta\sigma$$

(Equations derived assuming circular source with constant rupture velocity)

➢ Stress drop from quasi-dynamic models varies on the fault plane and averaging is allowed only for scale-independent models

Scaling of breakdown work with slip

$$\tau(\delta) = \tau_* + C\delta^n$$

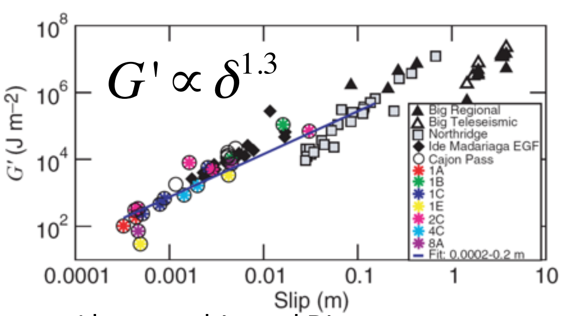
$$W_b = G' = \frac{\partial \tau}{\partial \delta} = Cn\delta^{n-1}$$

$$\tau(\delta) = \tau_r + \Delta\tau_b \exp(-\alpha\delta / \delta_1)$$

A power law?

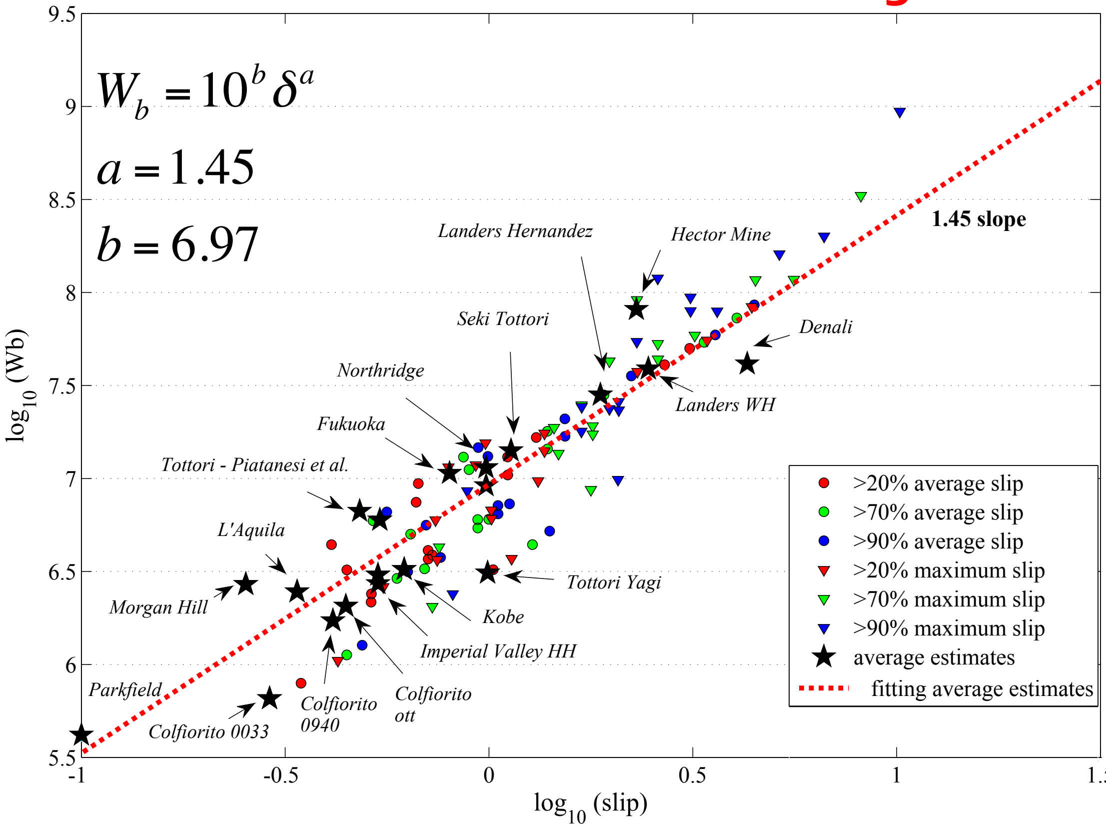
Good for scale-dependence?

$$G' = \Delta\tau_b \delta_1$$



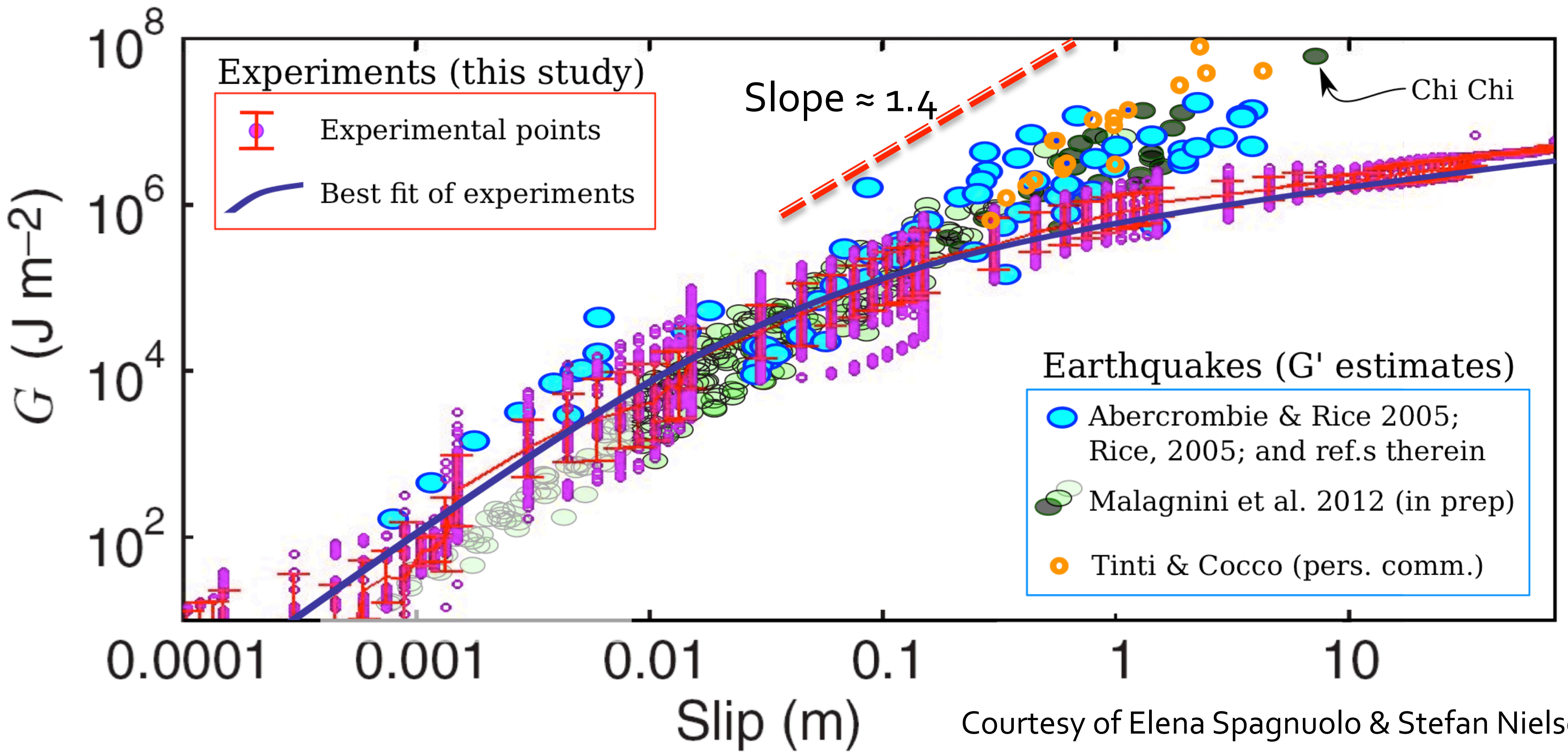
Abercrombie and Rice 2005

Breakdown Work Scaling



Regression computed using average values

Comparison with lab estimates



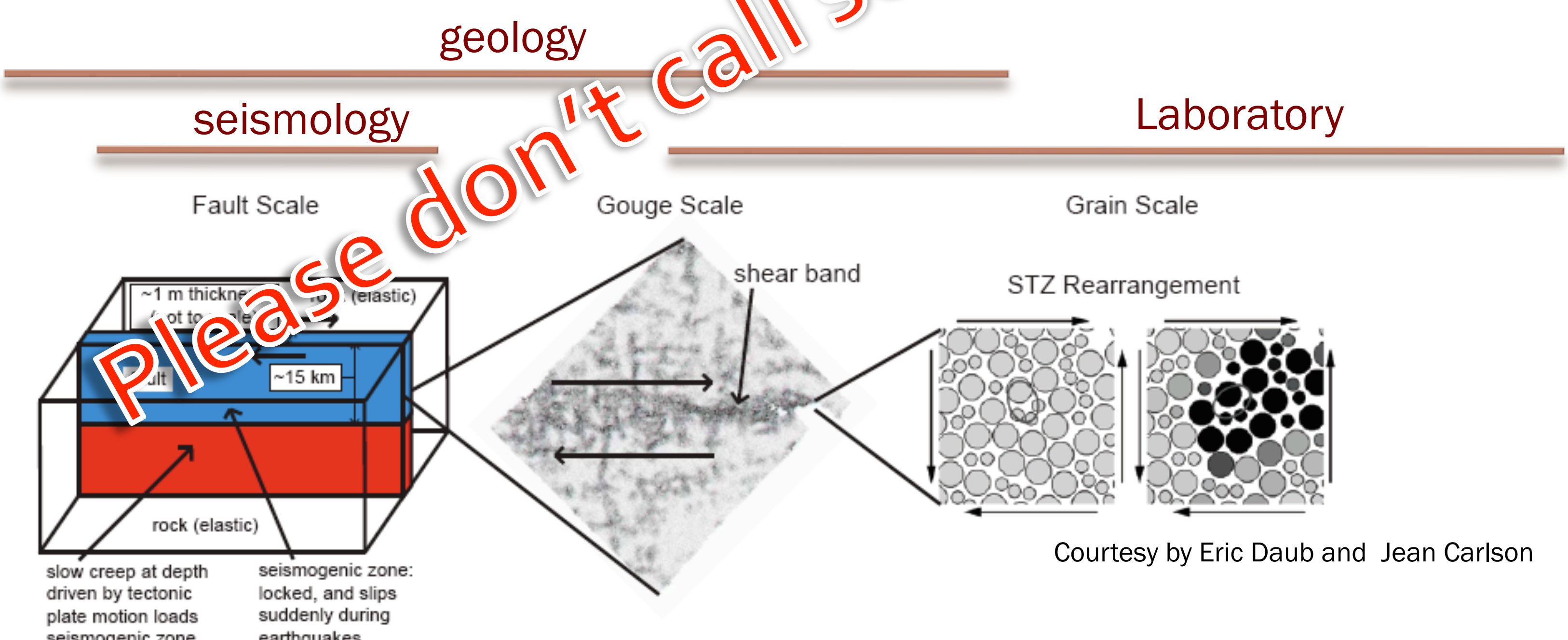
Courtesy of Elena Spagnuolo & Stefan Nielsen

Nielsen et al. 2012. See Friday morning talk.

(3) Scale dependence

- In a scale-dependent model, averaging is not allowed and we should apply a physically coherent approach to deal with different lengths-scales.
- Asserting self-similarity of earthquake ruptures implies that we have established a hierarchy among length-scale parameters characterizing each process and that a single length-scale dominates the others.
- Such a demonstration has never been achieved so far!

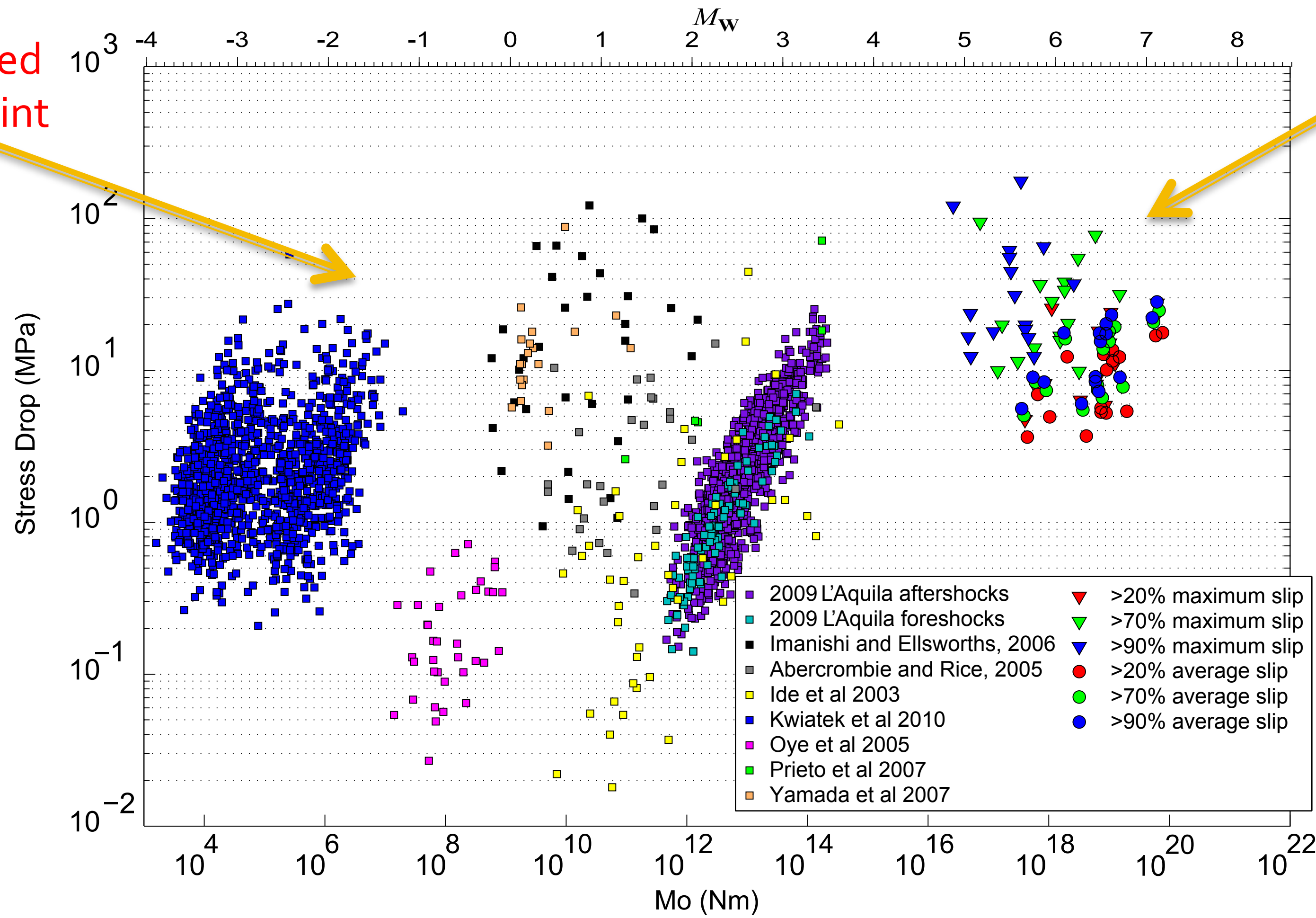
Please don't call self-similarity



Daub, E. G., and J. M. Carlson, Friction, Fracture, and Earthquakes, Ann. Rev. Cond. Matter Phys. 1, 397-418 (2010).

Stress drop scaling with seismic moment

Estimated from point source models



Averaged from Extended sources

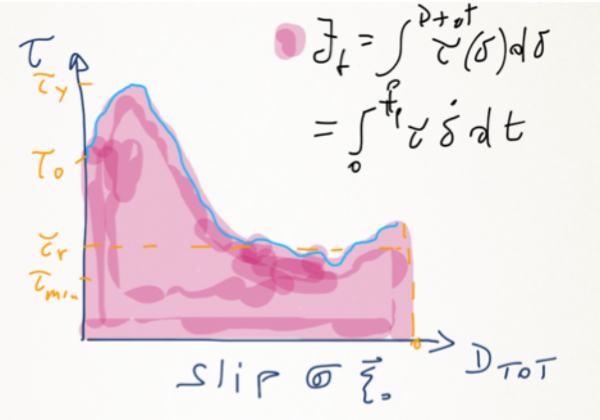
Conclusions

- We need a next generation of laboratory derived constitutive laws, which will allow us to study individual physical processes and understanding scale dependence
- Our estimates of source parameters have a large variability and are strongly model dependent
- Paradoxes might be created by ill-posed physical questions
- Are we sure that self-similarity in earthquakes is formulated in a physically coherent way?

Earthquake size is not a constitutive length scale parameter!

Dynamic Fault Weakening

Physical intuition of scale dependence



Which length-scale dominates for corroborating self-similarity?

Flash Heating

$$\tau = g_1(\delta, \dot{\delta}, \vartheta, p, T, \omega, \kappa, \psi_i, L_1)$$

Thermal Pressurization

$$\tau = f_2(\delta, \dot{\delta}, \vartheta, p, T, \omega, \kappa, \psi_i, L_2)$$

Porosity & permeability evolution

$$\tau = g_3(\delta, \dot{\delta}, \vartheta, p, T, \omega, \kappa, \psi_i, L_3)$$

Melting

....

Abrasion & Wear

$$\tau = g_n(\delta, \dot{\delta}, \vartheta, p, T, \omega, \kappa, \psi_i, L_n)$$