An attempt to reconcile friction experimental measurements with seismological observations

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with the guest participation of:

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European Research Council
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Università degli Studi di Padova

Objectives

- **Measure fracture energy G from high-velocity friction experiments**
- **Estimate fracture energy G' from earthquakes**
- **Compare the two**

- **And, if lucky, generate a big fight**

Old ideas, new data

- Palmer & Rice, 1973:

  equivalence between *fracture energy* and integration of the post-failure stress-displacement curve

- Teng-Fong Wong, 1983:

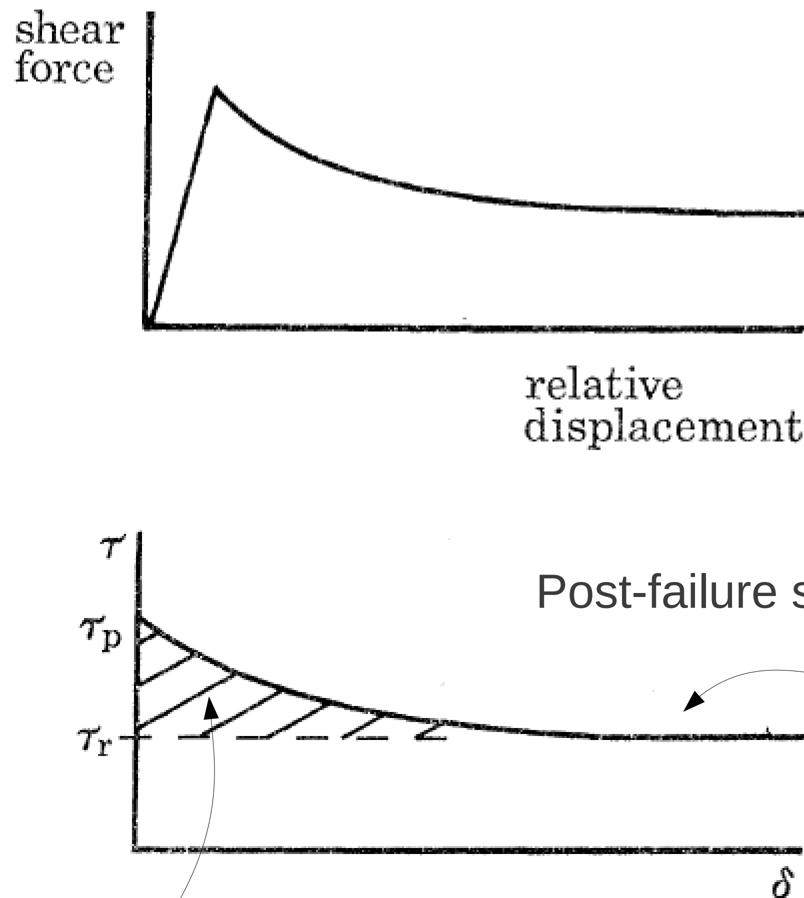
  Extrapolate laboratory rock-mechanical measures of fracture energy G to earthquakes

- High velocity friction experiments

  Hirose & Shimamoto 1995; Di Toro & al. 2006; Nielsen & al. 2008, ...

- Earthquake data estimates

  Abercrombie & Rice, 2005; Mori et al. 2003; Ide et al, 2003; Kanamori et al. 1993, 2003; McGarr 2000; Venkataraman et al. 2000, 2002, ...



Post-failure stress curve

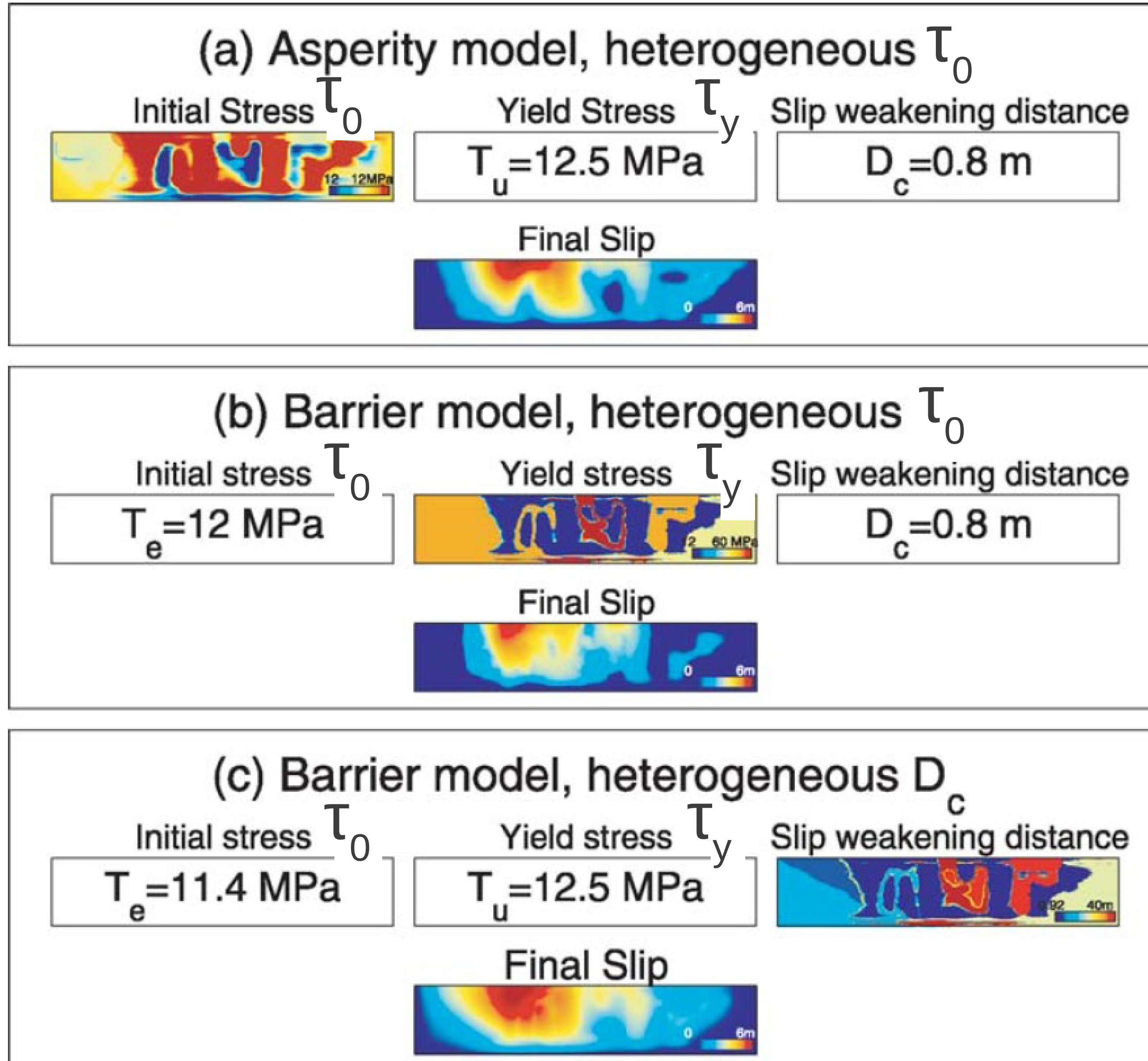
Fracture energy or G

From Palmer and Rice, 1973

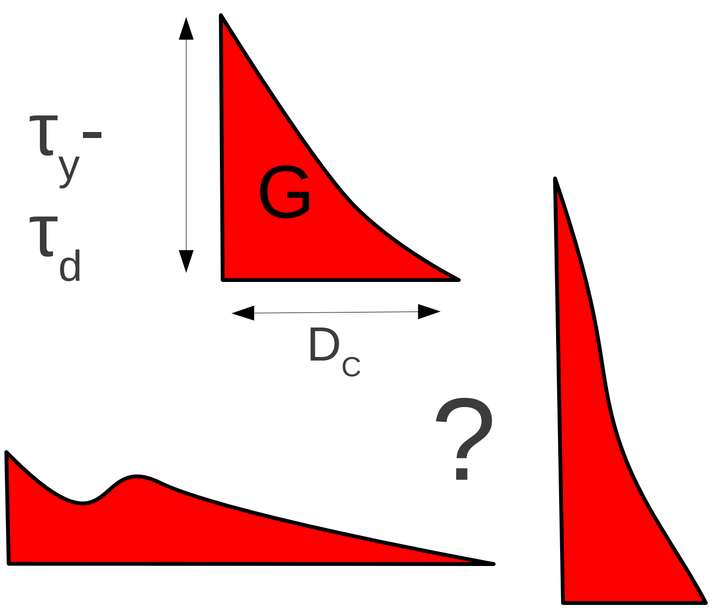
"Lacking detailed knowledge of
the rupture process, the value of G is the
minimum amount of information required for any
meaningful modeling of the source dynamics".

T.-F. Wong (1982)

Resolution of dynamic parameters

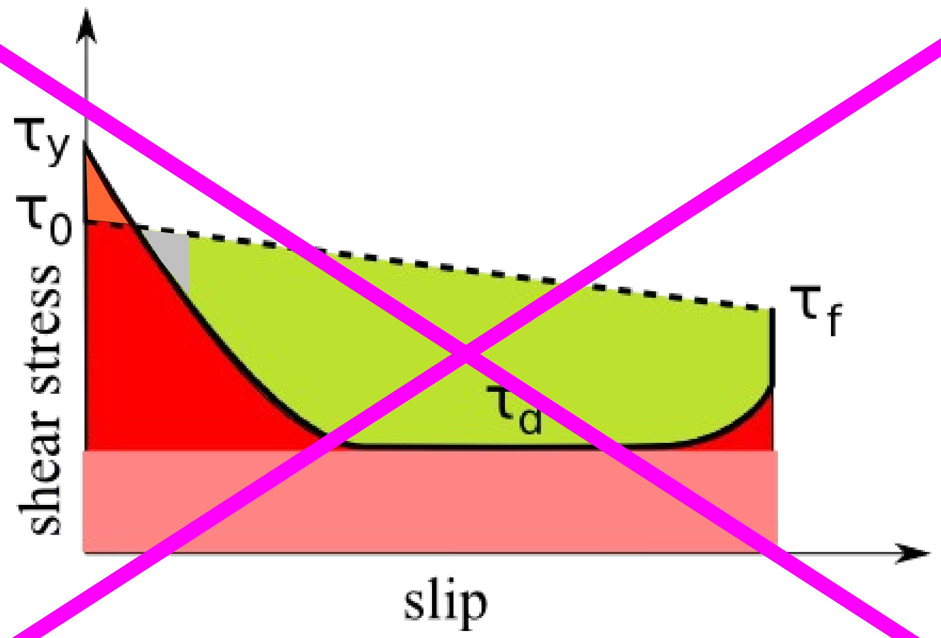


$$G \approx \tfrac{1}{2} D_C (\tau_y - \tau_d)$$



From Peyrat, Olsen & Madariaga 2004

Energy balance

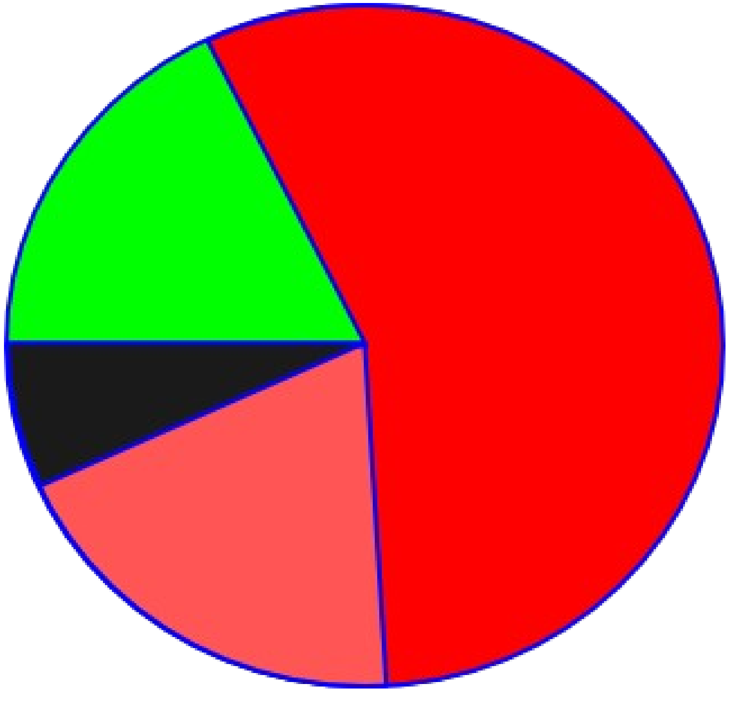


Censored...

Energy balance

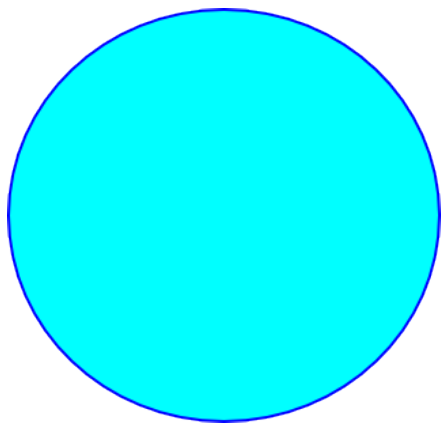
From Knopoff, Kostrov, Dahlen, Kanamori...

To the pie-chart energy balance!

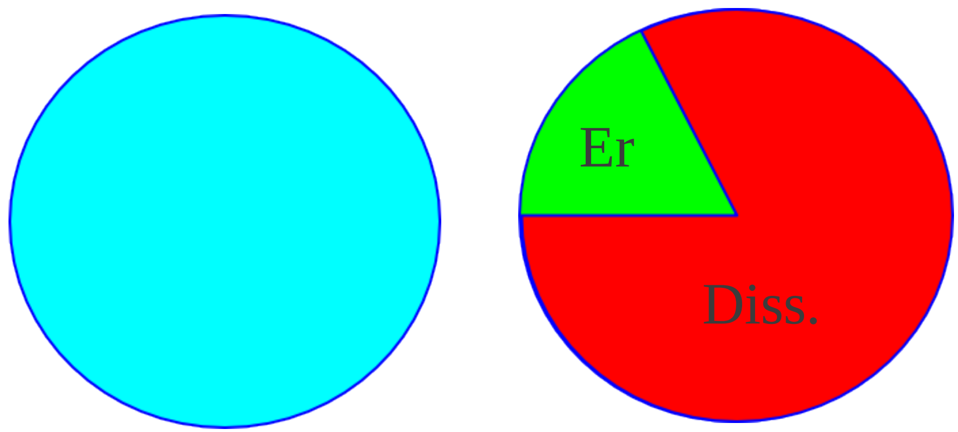


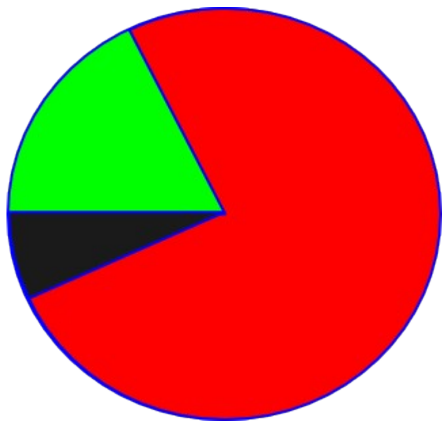
Total released potential energy

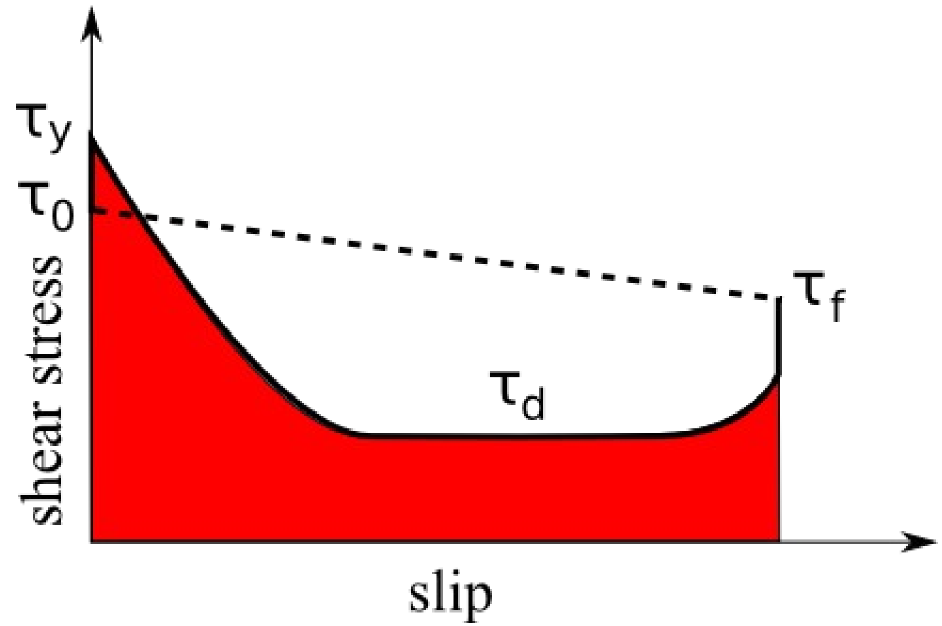
$$\Delta W = \frac{1}{2} \int_{\Sigma} \left(\tau^{0}{}_{ij} + \tau^{f}{}_{ij} \right) \Delta u_i \, \nu_j \, d V$$



$$\Delta W = \frac{1}{2}\int_{\Sigma}\left(\tau^{0}{}_{ij} + \tau^{f}{}_{ij}\right)\Delta u_i\, \nu_j\, d V \qquad = \qquad Er + Diss.$$

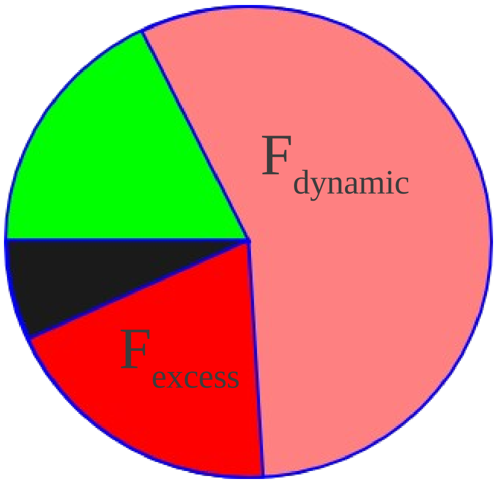


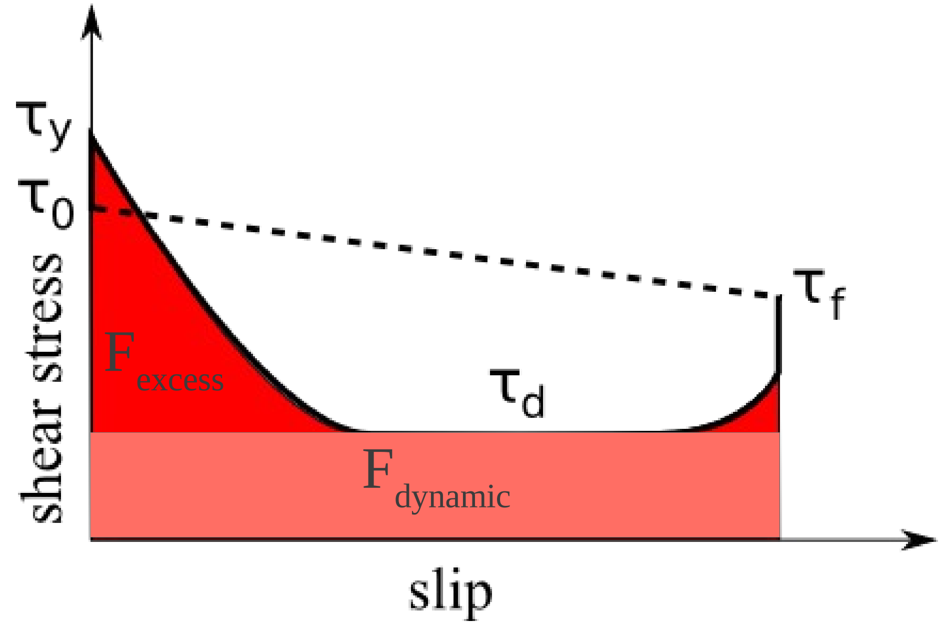




$$\Delta W = \overbrace{\underbrace{\int_{\Sigma} 2\gamma_{\mathrm{eff}}\, dS}_{\text{Originally, “singular terms” (but rather damage In the general sense)}} + \underbrace{\int_{t_0}^{t_1} dt \int_{\Sigma(t)} \sigma_{ij}\, \Delta \dot{u}_i\, \nu_j\, dS}_{\text{Friction}}}^{\text{Dissipation}} - \overbrace{\int_{t_0}^{t_1} dt \int_{S_0} \sigma_{ij}\, \dot{u}_i\, n_j\, dS}^{\text{Er}}$$

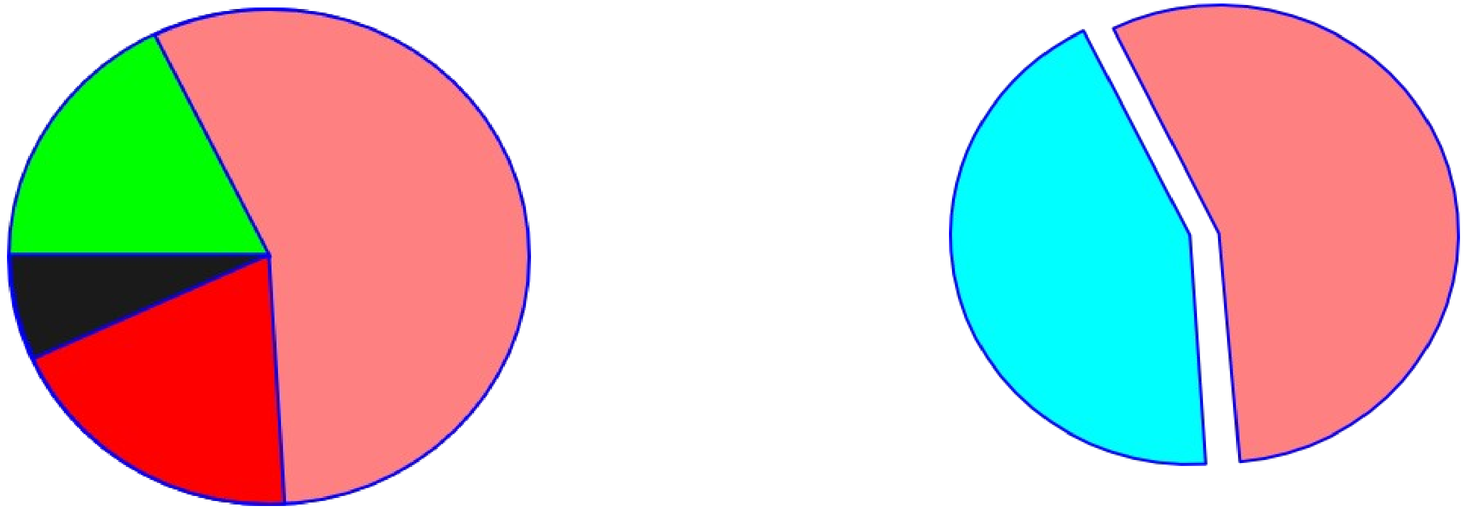
Radiated energy
(waves)



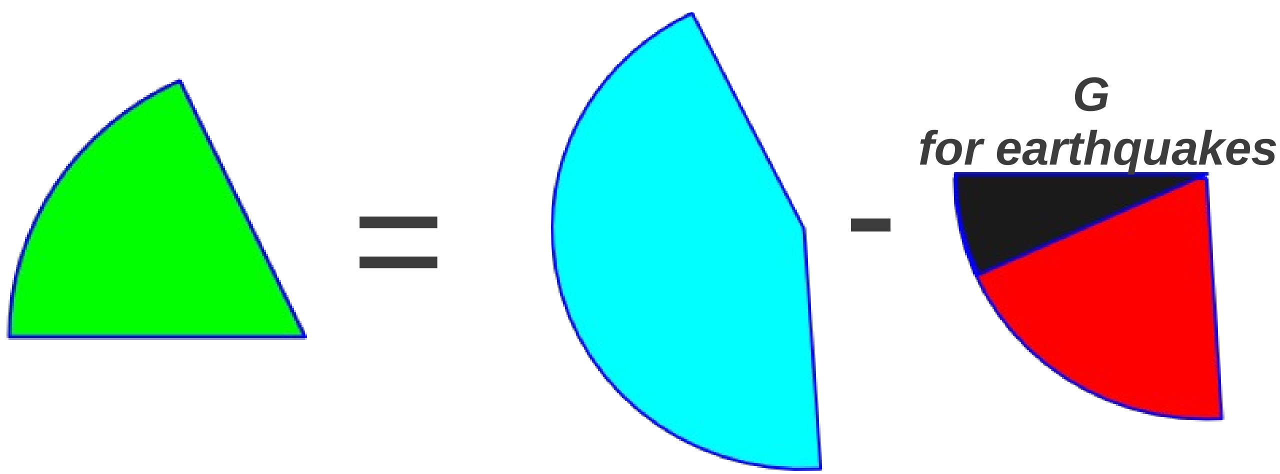


$$F = \underbrace{\int_{t_0}^{t_1} dt \int_{\Sigma(t)} \sigma_{ij}^{d} \Delta \dot{u}_i \nu_j \, dS}_{F_{\text{dynamic}}} + \underbrace{\int_{t_0}^{t_1} dt \int_{\Sigma(t)} \sigma_{ij}^{e} \Delta \dot{u}_i \nu_j \, dS}_{F_{\text{excess}}}$$

Work of:

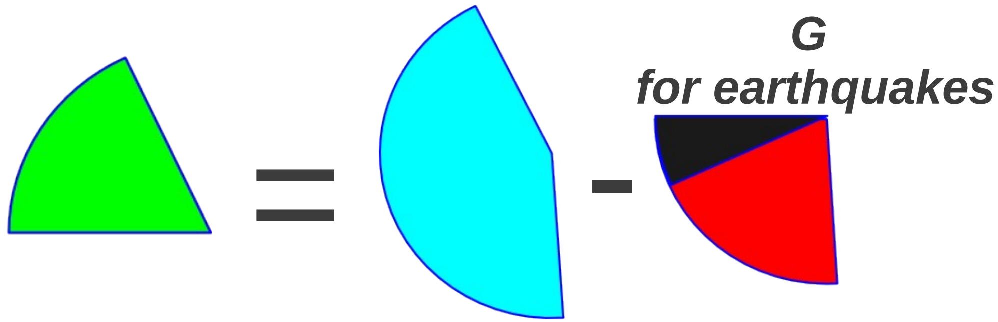


Only if dynamic and final stress are the same, we can write:

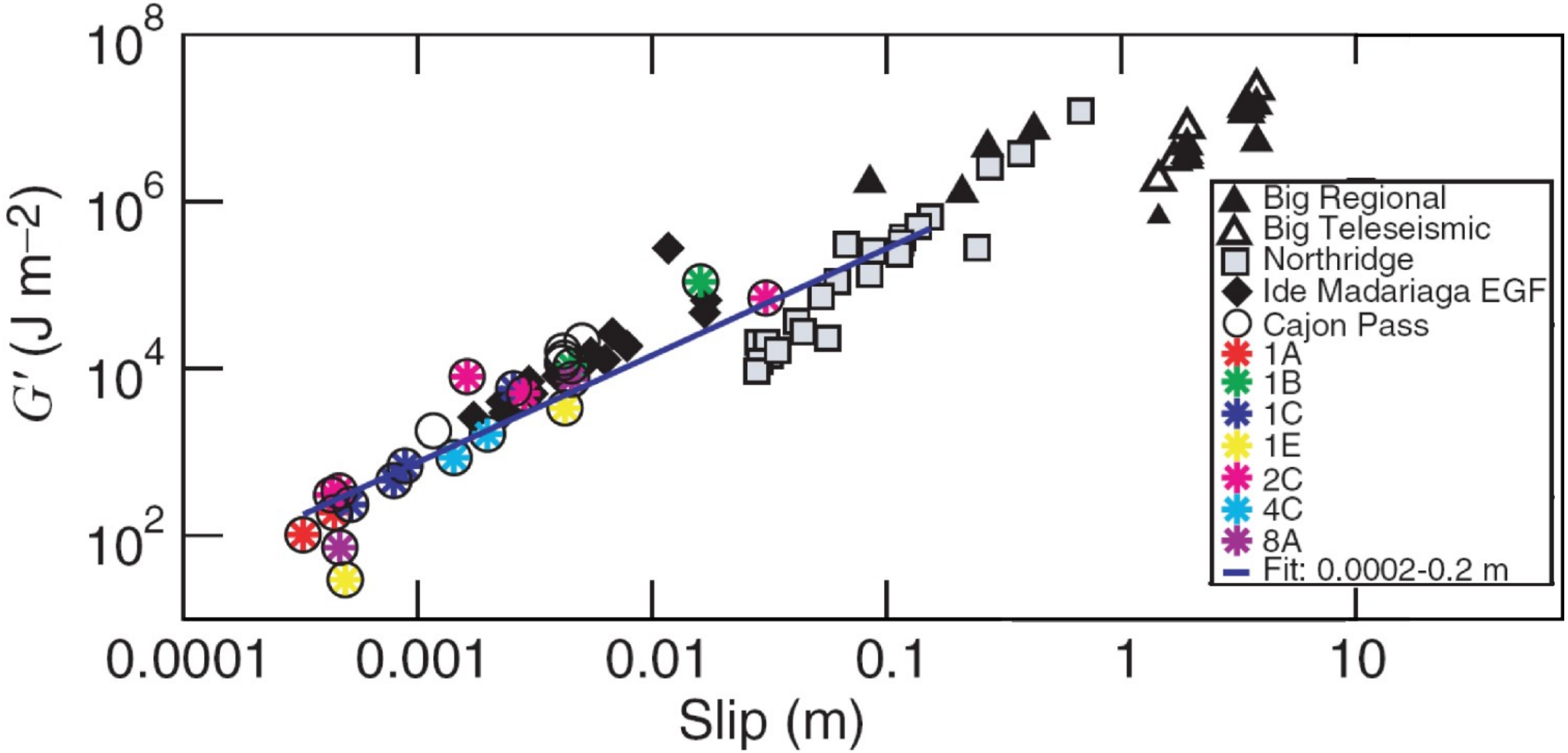


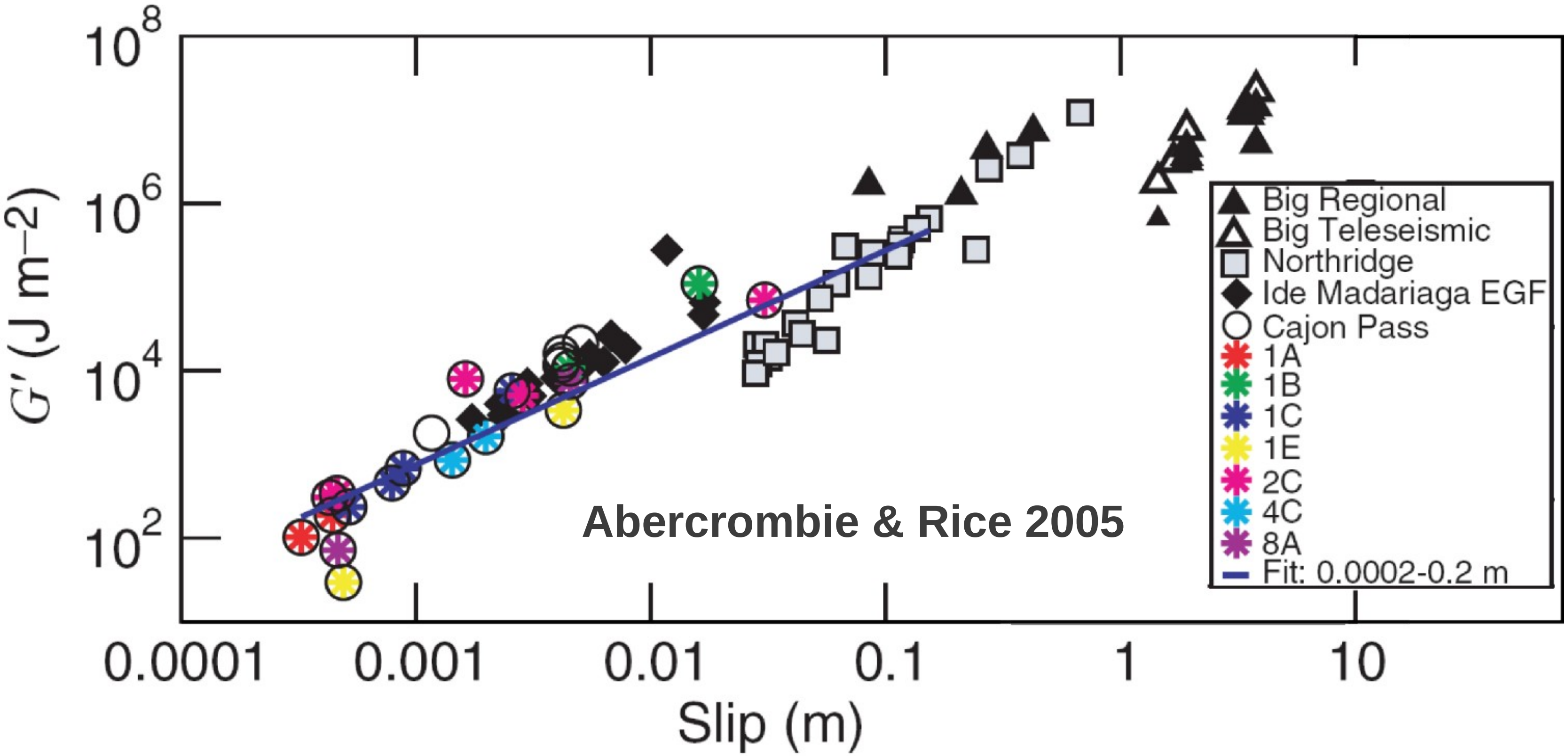
$$E_{\mathrm{R}} = \frac{1}{2}\int_{\Sigma} (\sigma_{ij}^{0} - \sigma_{ij}^{1})\,\Delta u_i \nu_j\, dS - \left(\int_{\Sigma} 2\gamma_{\mathrm{eff}} dS + \int_{t_0}^{t_1} dt \int_{\Sigma(t)} \dot{\sigma}_{ij}^{\mathrm{e}} \Delta u_i \nu_j\, dS.\right)$$

Kostrov, 1974 *revisited*

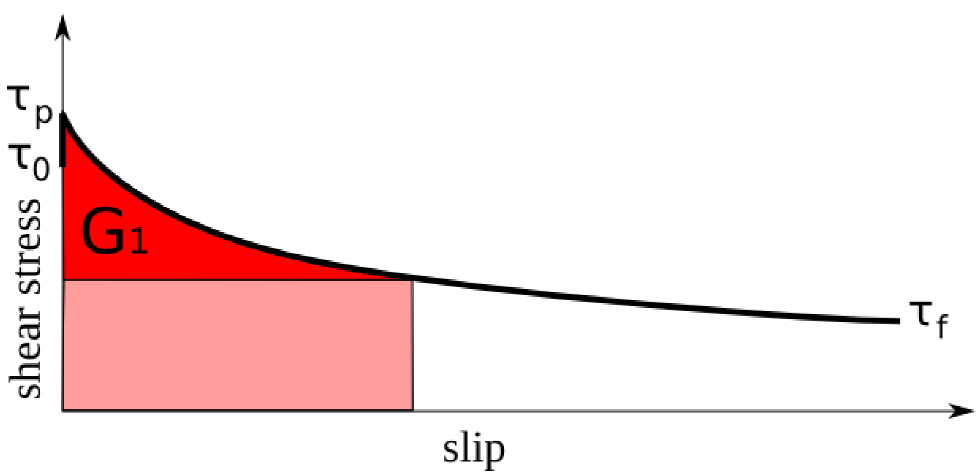


Abercrombie & Rice 2005

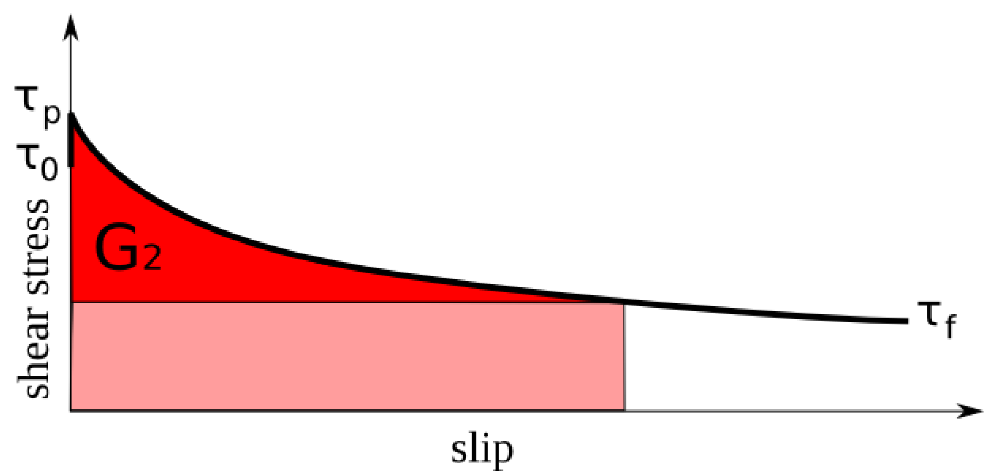




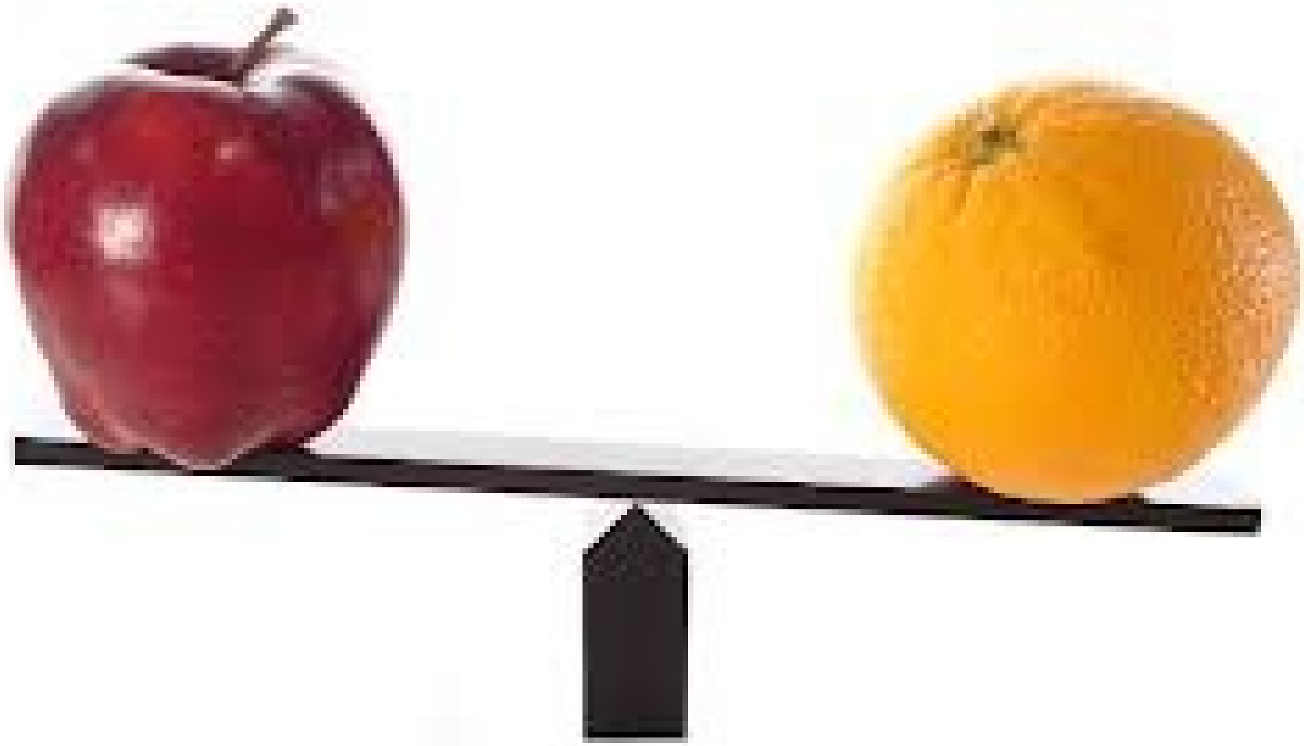
10^8
10^6
10^4
10^2
G' (J m−2)
0.0001
0.001
0.01
0.1
1
10
Slip (m)
Abercrombie & Rice 2005
Big Regional
Big Teleseismic
Northridge
Ide Madariaga EGF
Cajon Pass
1A
1B
1C
1E
2C
4C
8A
Fit: 0.0002-0.2 m

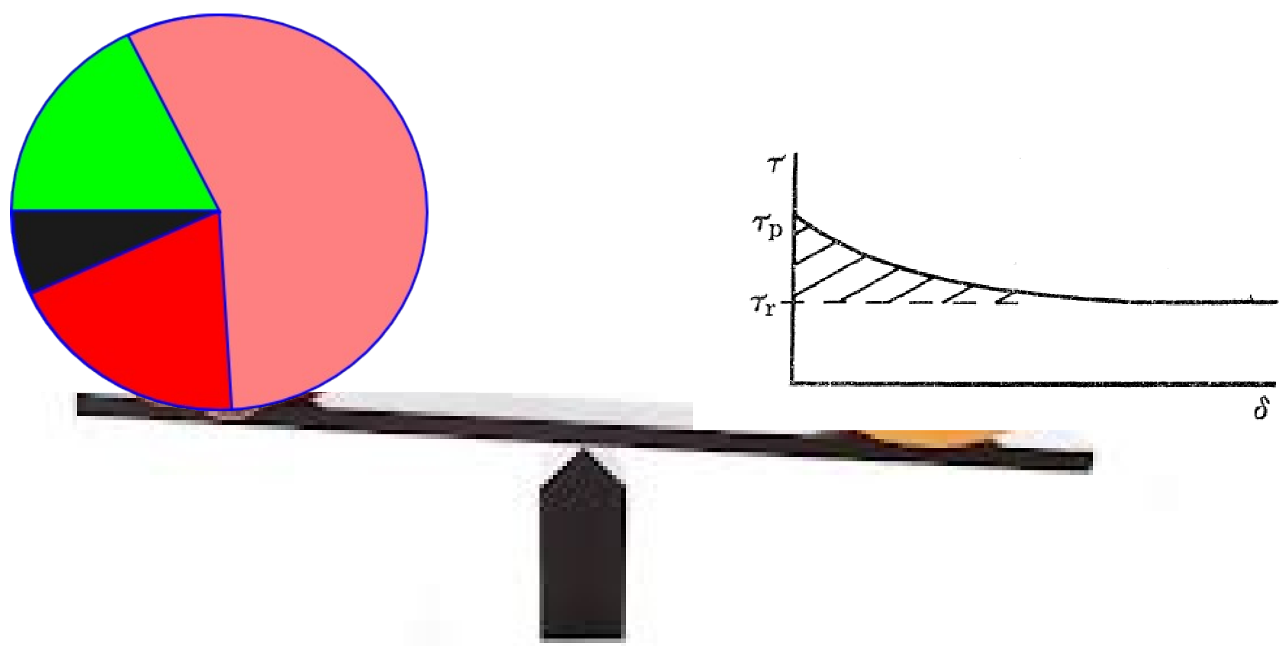


τ_p
τ_0
shear stress
G_1
τ_f
slip



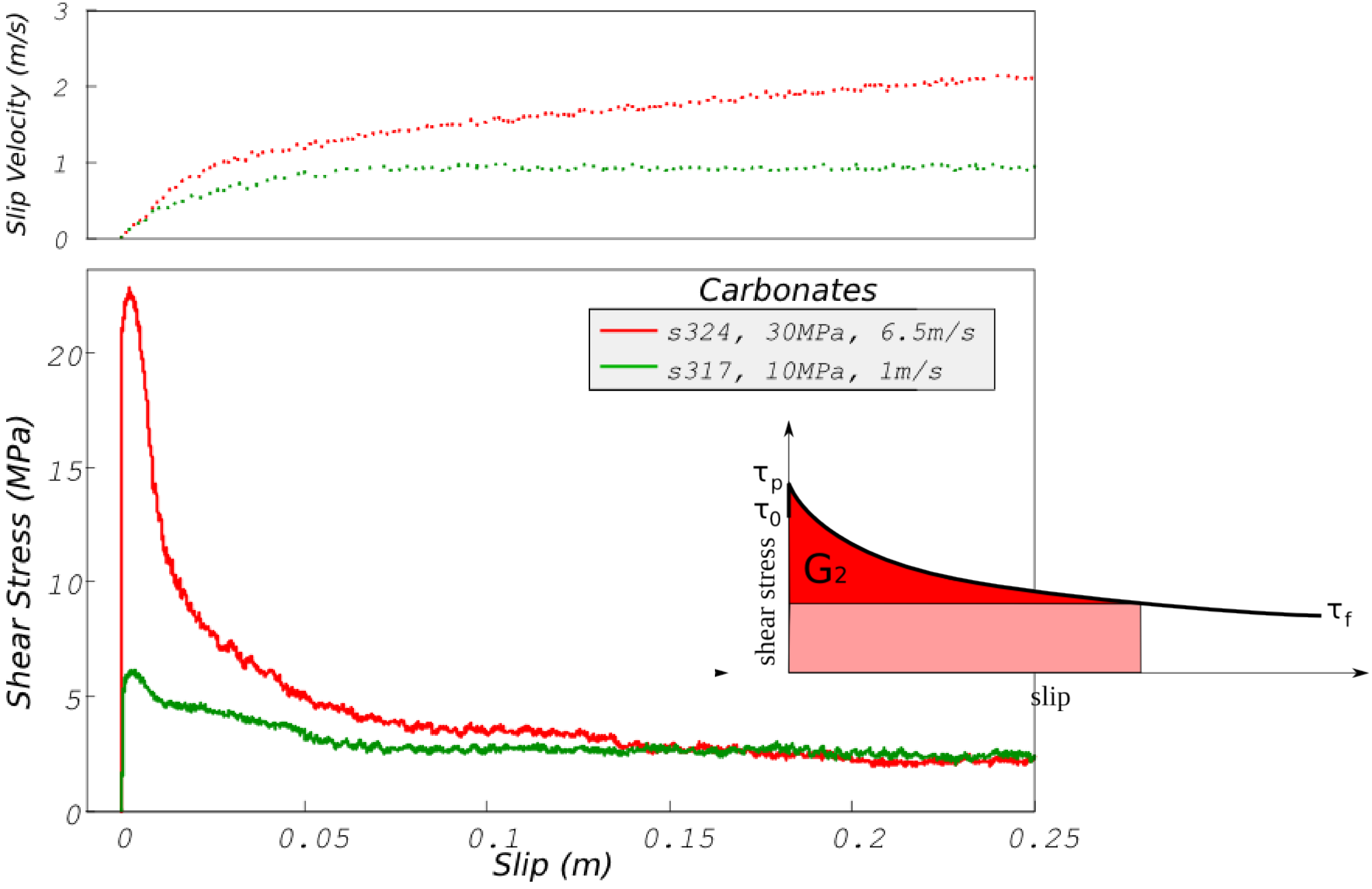
τ_p
τ_0
shear stress
G_2
τ_f
slip

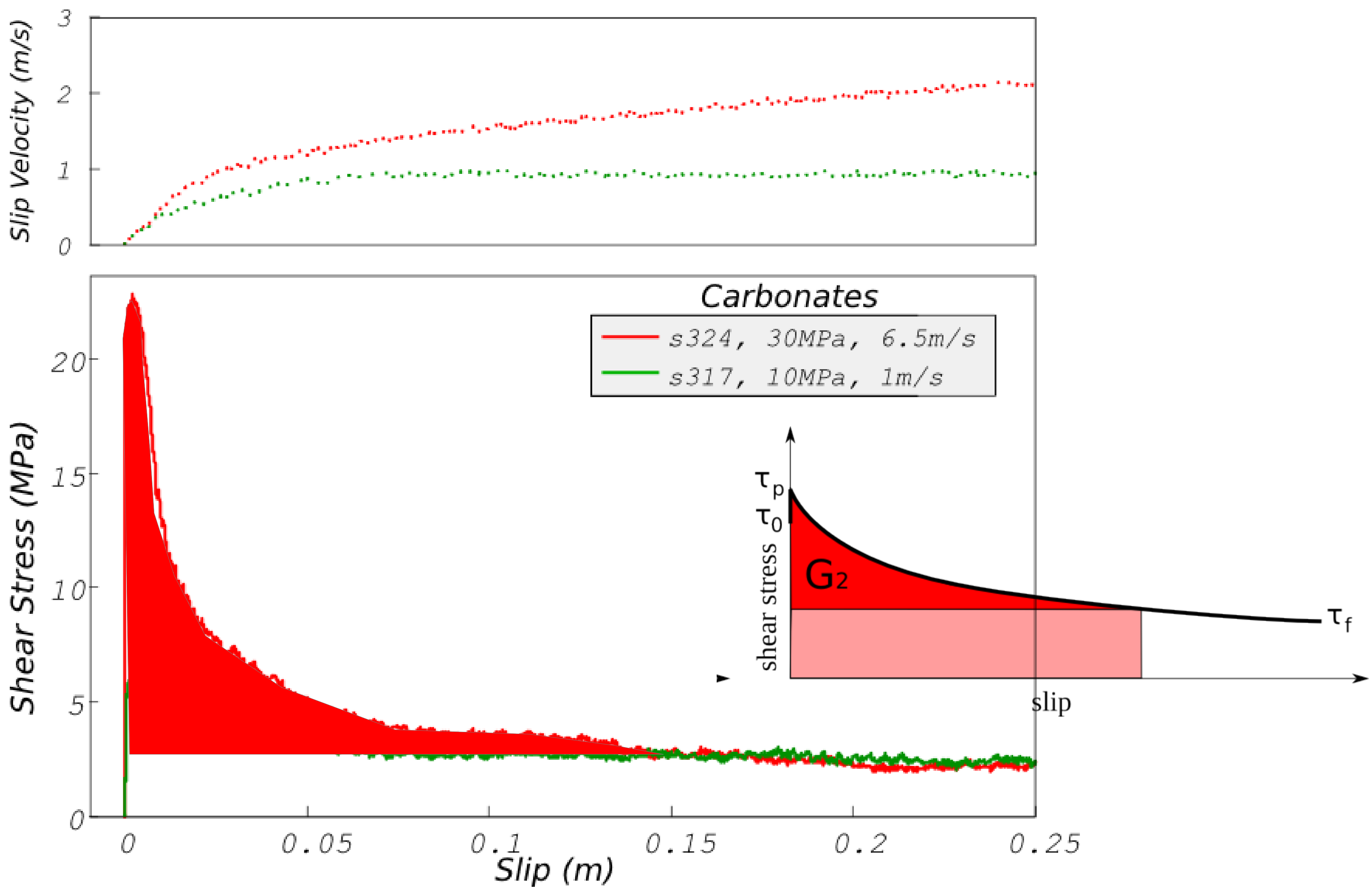




PS:Thanks to R. Abercrombie for introducing fruit in the discussion on wednesday

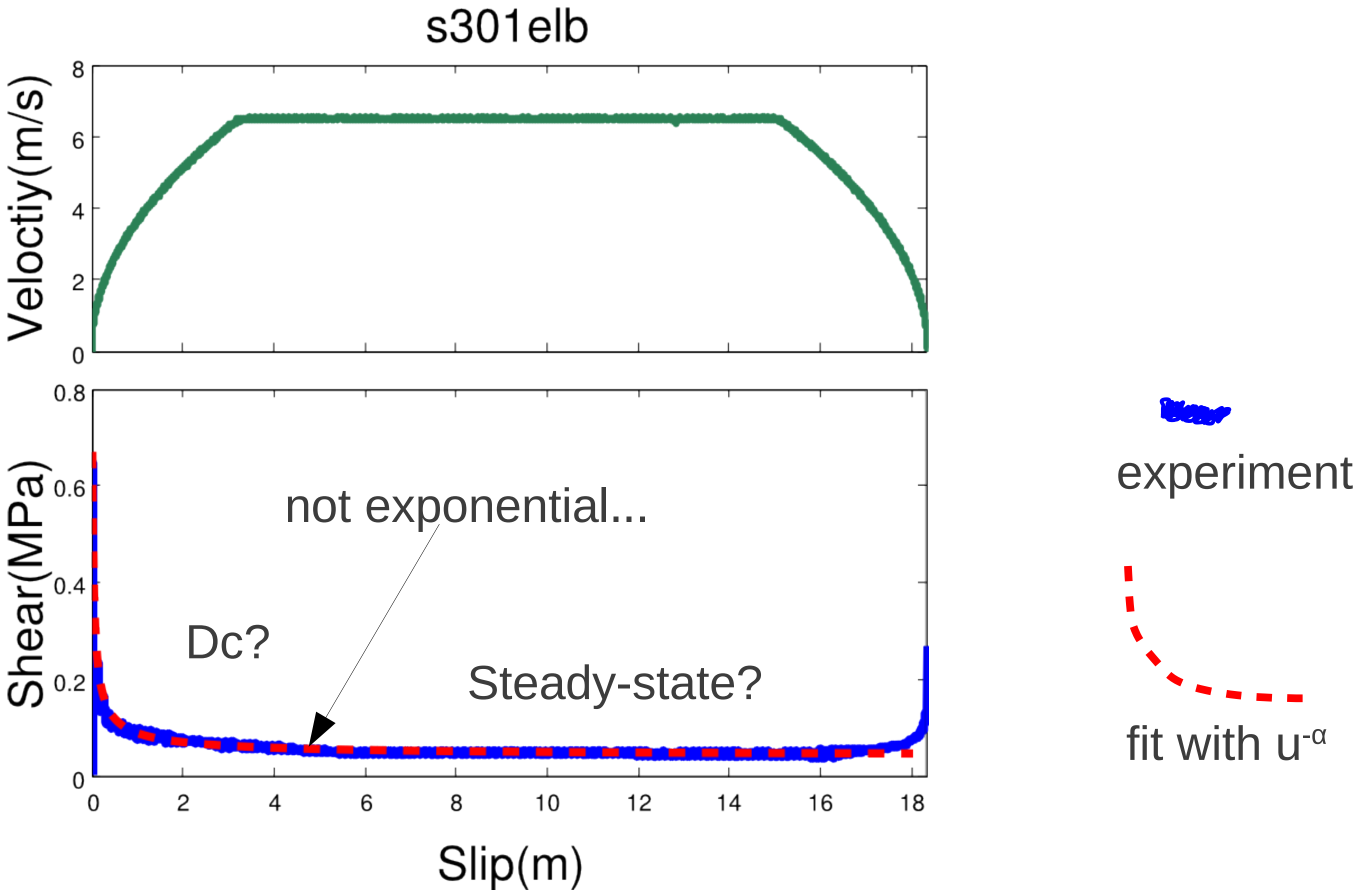
Let's go to the lab...





Slip Velocity (m/s)
3
2
1
0
Carbonates
s324, 30MPa, 6.5m/s
s317, 10MPa, 1m/s
Shear Stress (MPa)
20
15
10
5
0
0
0.05
0.1
0.15
0.2
0.25
Slip (m)
τp
τ0
shear stress
G2
τf
slip

Weakening and Dc



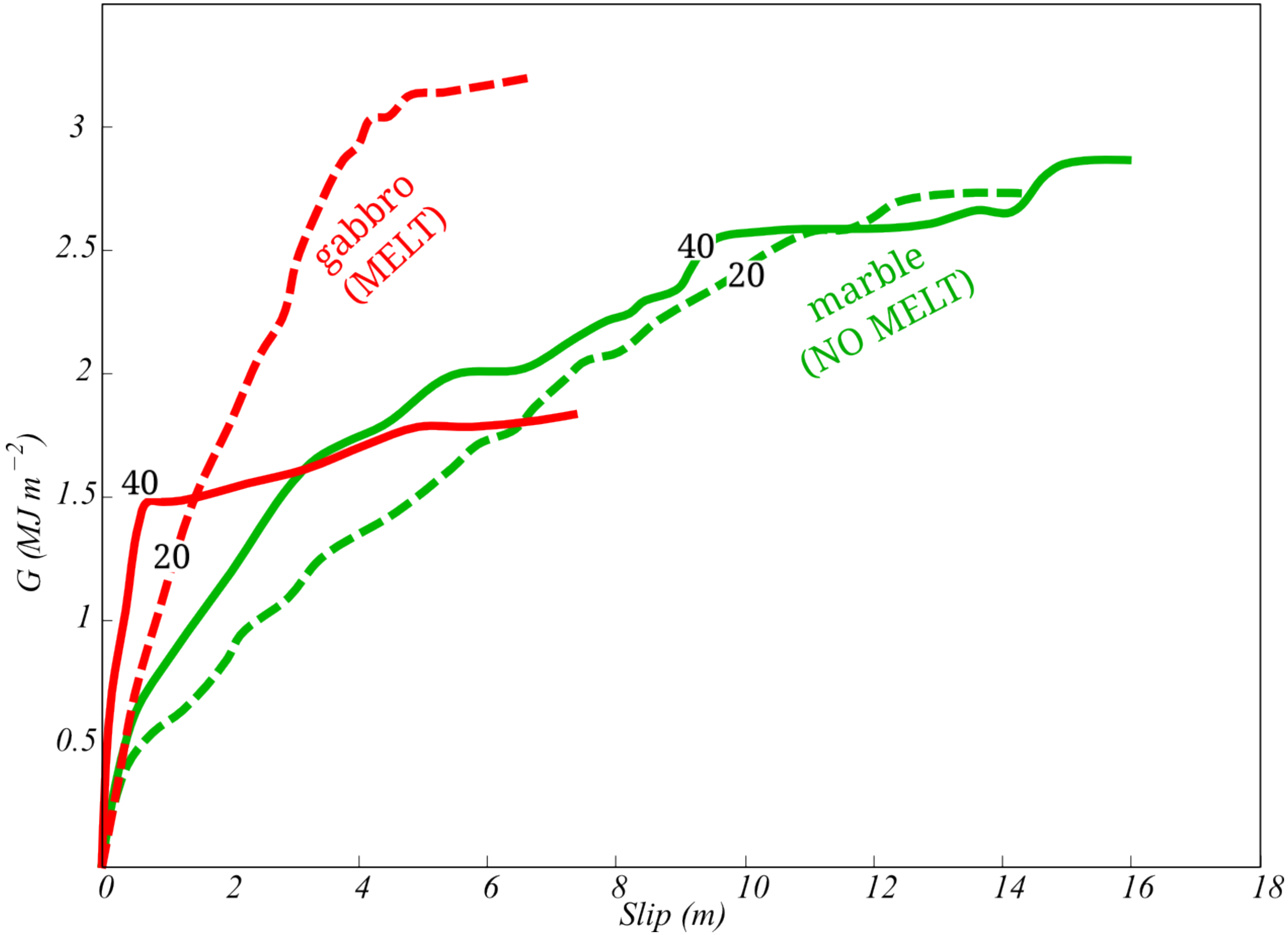
Problems:
1) Dc is highly dependent on definition and measuring technique
2) Dc is meaningless if the weakening is a sort of *powerlaw*
3) Dc cannot be compared directly to earthquake observation

$$\tau = A\,(\mathrm{u} - \mathrm{u}_0)^{-\alpha} + \tau_{ss}$$

$$G = \frac{A\;\mathrm{u}_0^{1-\alpha}}{\alpha - 1} - \frac{A\;\mathrm{u}_0\,(\mathrm{u} + \mathrm{u}_0)^{-\alpha}}{\alpha - 1} - \frac{A\;\mathrm{u}\;\alpha\,(\mathrm{u} + \mathrm{u}_0)^{-\alpha}}{\alpha - 1}$$

$$\left.\begin{aligned} \tau &\approx A\,\mathrm{u}^{-\alpha} + \tau_{ss} \\[2em] G &\approx C_1\;\mathrm{u}^{1-\alpha} \end{aligned}\right\} \quad u \gg u_0$$

G & steady-state for carbonatic or silicatic rock

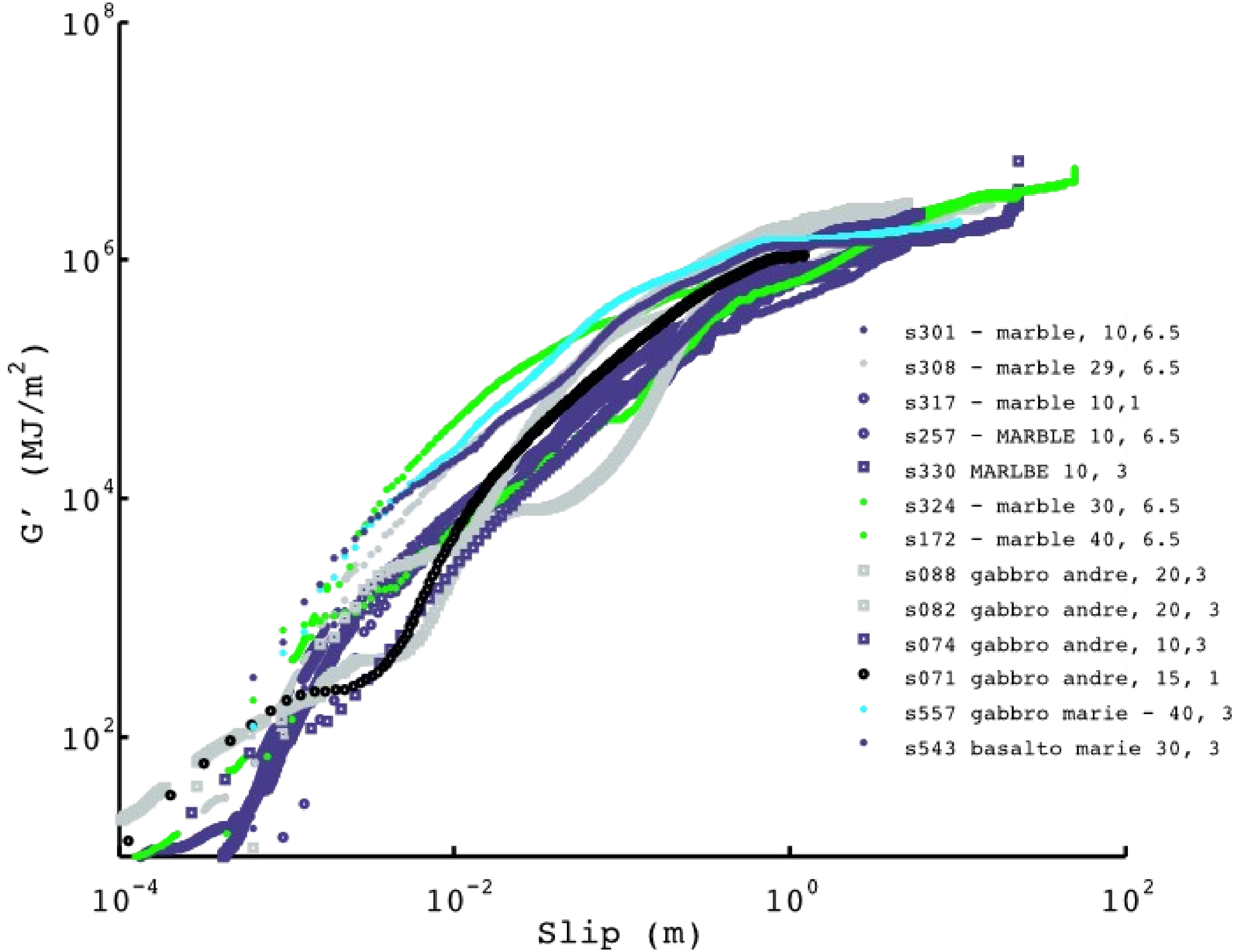


The big picture?

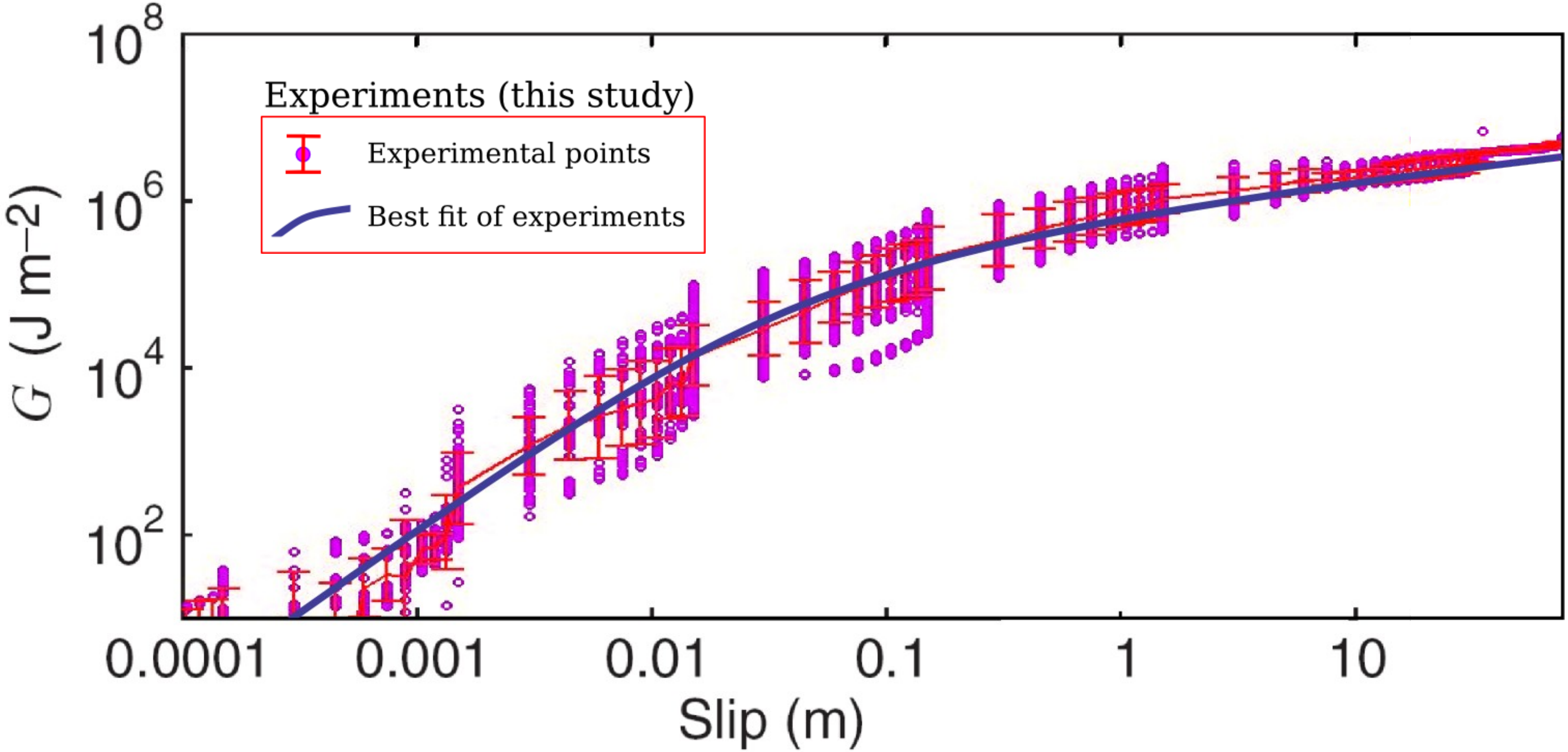
How to apply this to earthquakes?

Beyond the variability, let us seek for an "average" scaling on large intervals of slip

(in log log scale,
all birds of a feather flock together)



G' (MJ/m^2)
10^8
10^6
10^4
10^2
10^{-4}
10^{-2}
10^0
10^2
Slip (m)
s301 - marble, 10,6.5
s308 - marble 29, 6.5
s317 - marble 10,1
s257 - MARBLE 10, 6.5
s330 MARLBE 10, 3
s324 - marble 30, 6.5
s172 - marble 40, 6.5
s088 gabbro andre, 20,3
s082 gabbro andre, 20, 3
s074 gabbro andre, 10,3
s071 gabbro andre, 15, 1
s557 gabbro marie - 40, 3
s543 basalto marie 30, 3



Experiments (this study)
Experimental points
Best fit of experiments
10^8
10^6
10^4
10^2
G (J m^{-2})
0.0001
0.001
0.01
0.1
1
10
Slip (m)

Malagnini et al. 2012 (in prep):

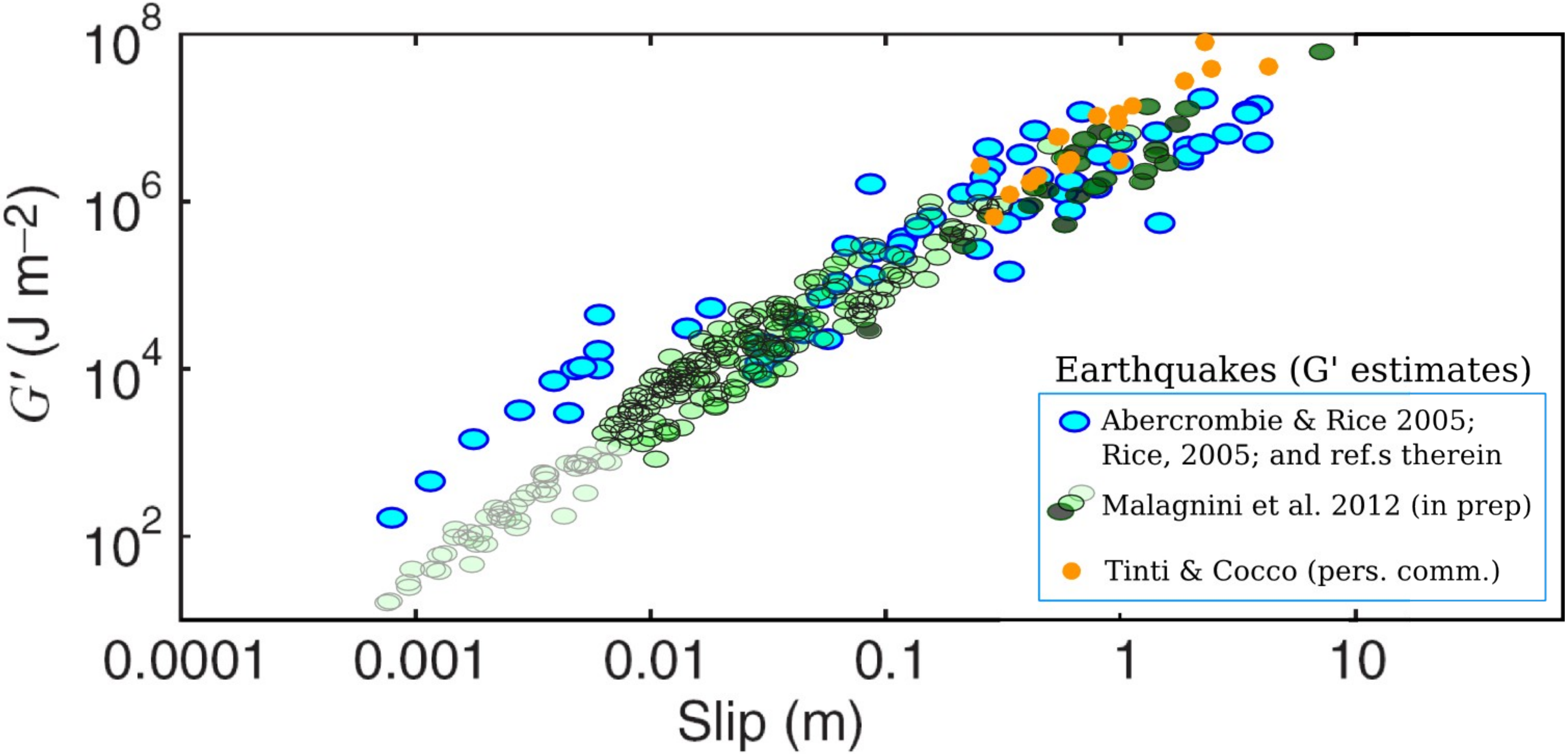
Northridge 1994 + afts.
HectorMine 1999
Tottori 2000
Parkfield 2004
Aquila 2009 + afts.
SanGiuliano 2002
Oklahoma 2011
Virginia 2011
Noto-Hanto 2007
Niigata 2004
Iwate 2008
Honshu 2011
Fukuoka 2005
Chuetsu 2004
Baja
Aqaba 1995
San Simeon 2003
Colfiorito 1997
Wells
Chi Chi 1999
Ferrara 2012 + afts

Abercrombie & Rice 2005, Rice 2005 and references therein (Mori et al. 2003; Ide et al, 2003; Kanamori et al. 1993, 2003; McGarr 2000; Venkataraman et al. 2000, 2002):

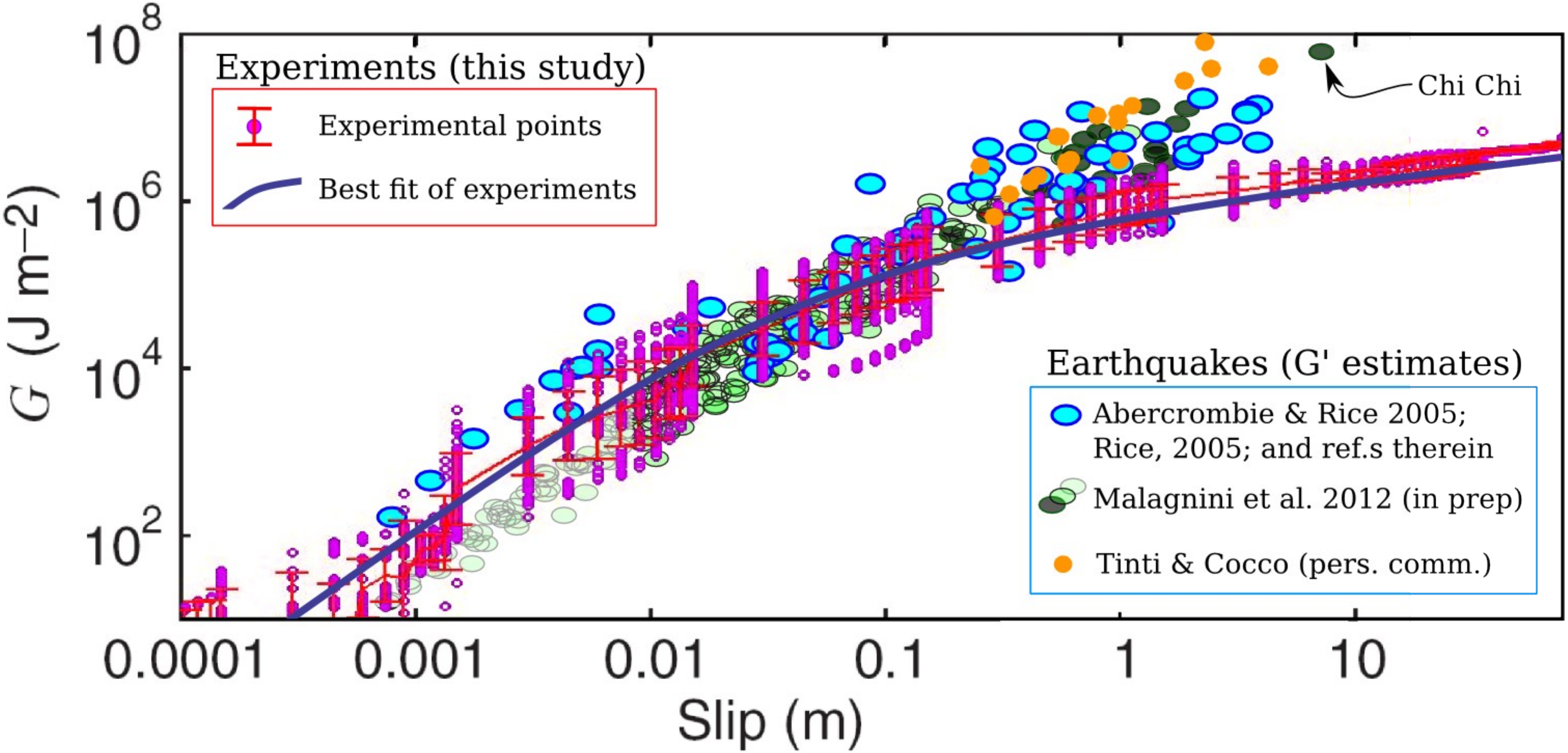
Northridge 1994 + afts.
Hector Mine 1999
Tottori 2000
Landers 1992
Imperial Valley 1971 + afts.
Colfiorito 1997
Kobe 1995
Sierra Madre 1991
Loma Prieta 1989
Miochacan 1985
San Fernando 1971
Borah Peak 1983
North Palm Springs 1996

Tinti & Cocco (per. Com.)

Northridge 1994
Hector Mine 1999
Tottori 2000
Landers 1992
Imperial Valley 1971
Colfiorito 1997
Kobe 1995
Parkfield 2004
L'Aquila 2009
Fukuoka
Morgan Hill
Denali
Seki

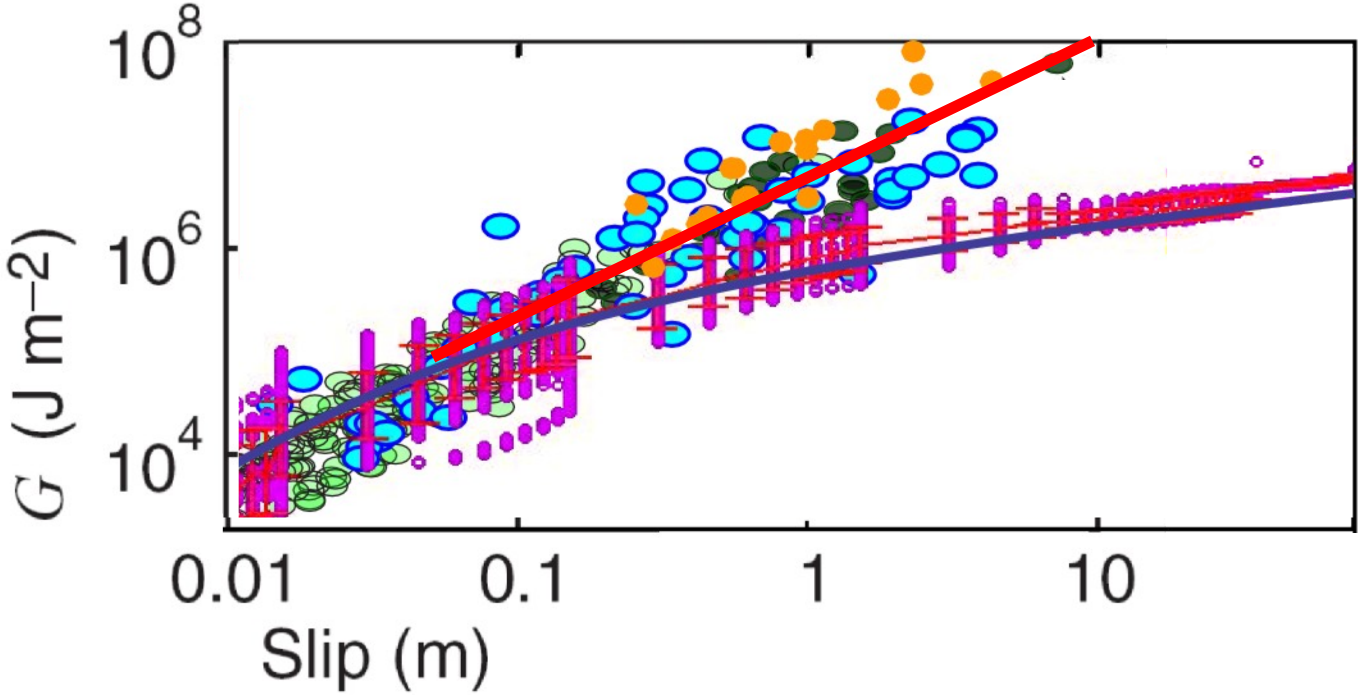


10^8
10^6
10^4
10^2
G' (J m^{-2})
0.0001
0.001
0.01
0.1
1
10
Slip (m)
Earthquakes (G' estimates)
Abercrombie & Rice 2005; Rice, 2005; and ref.s therein
Malagnini et al. 2012 (in prep)
Tinti & Cocco (pers. comm.)

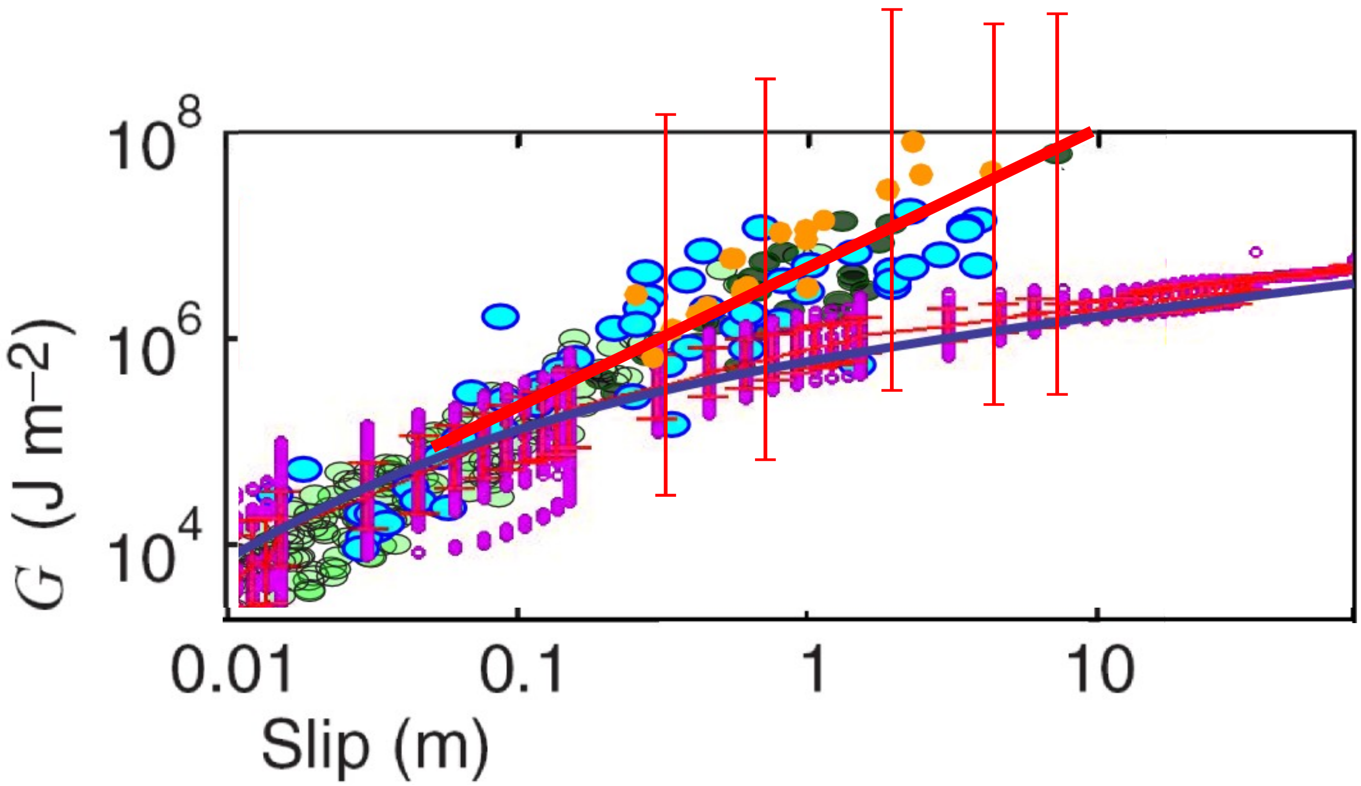


Experiments (this study)
Experimental points
Best fit of experiments
Earthquakes (G' estimates)
Abercrombie & Rice 2005;
Rice, 2005; and ref.s therein
Malagnini et al. 2012 (in prep)
Tinti & Cocco (pers. comm.)
Chi Chi
G (J m−2)
10^8
10^6
10^4
10^2
0.0001
0.001
0.01
0.1
1
10
Slip (m)

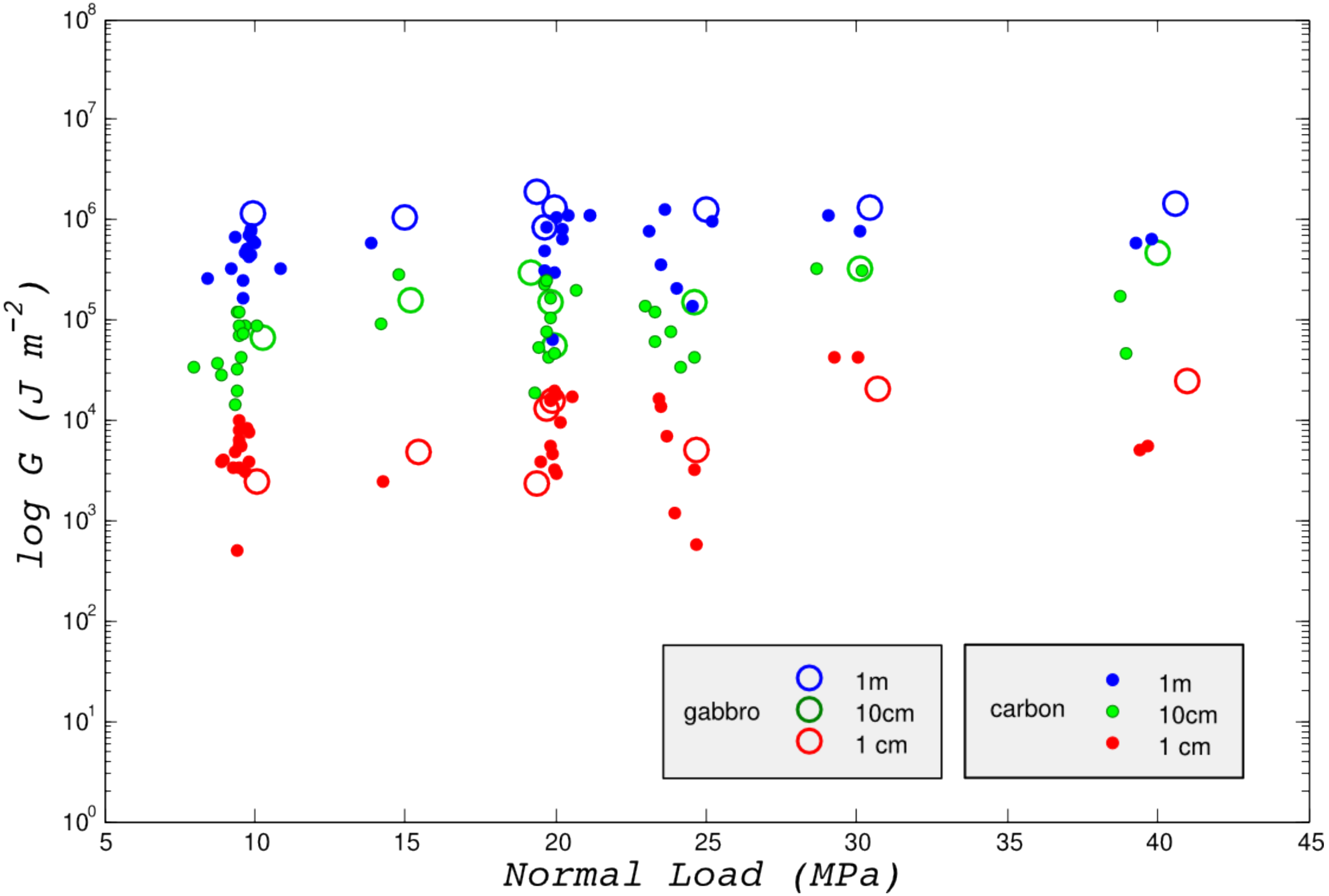
Is there a misfit at slip ≥ 0.1m
and
how to interpret it?



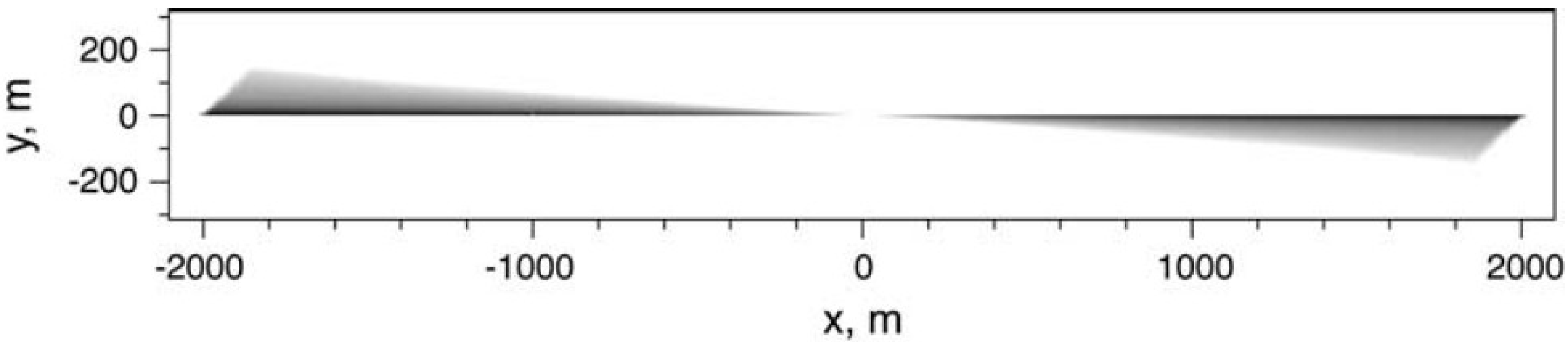
Error bar (?) of Es estimates?



Normal stress upscaling?
Probably not...



Off-fault damage
(1) damage zone increasing with L
$G \propto U$



Andrews 2005

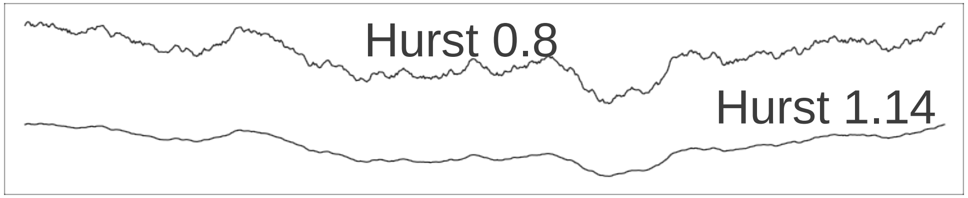
Off-fault damage (2) non-planarity and off-fault strain

Additional work of elastic strain in the surrounding volume of a non-planar, self-affine fault

$$G_r \propto w_{el.} \propto \quad E\ U^{2H-1}$$

(H=Hurst exponent)

$H = 0.8 \rightarrow G \propto U^{0.6}$
$H = 1.0 \rightarrow G \propto U$
$H = 1.14 \rightarrow G \propto U^{1.28}$



Conclusions

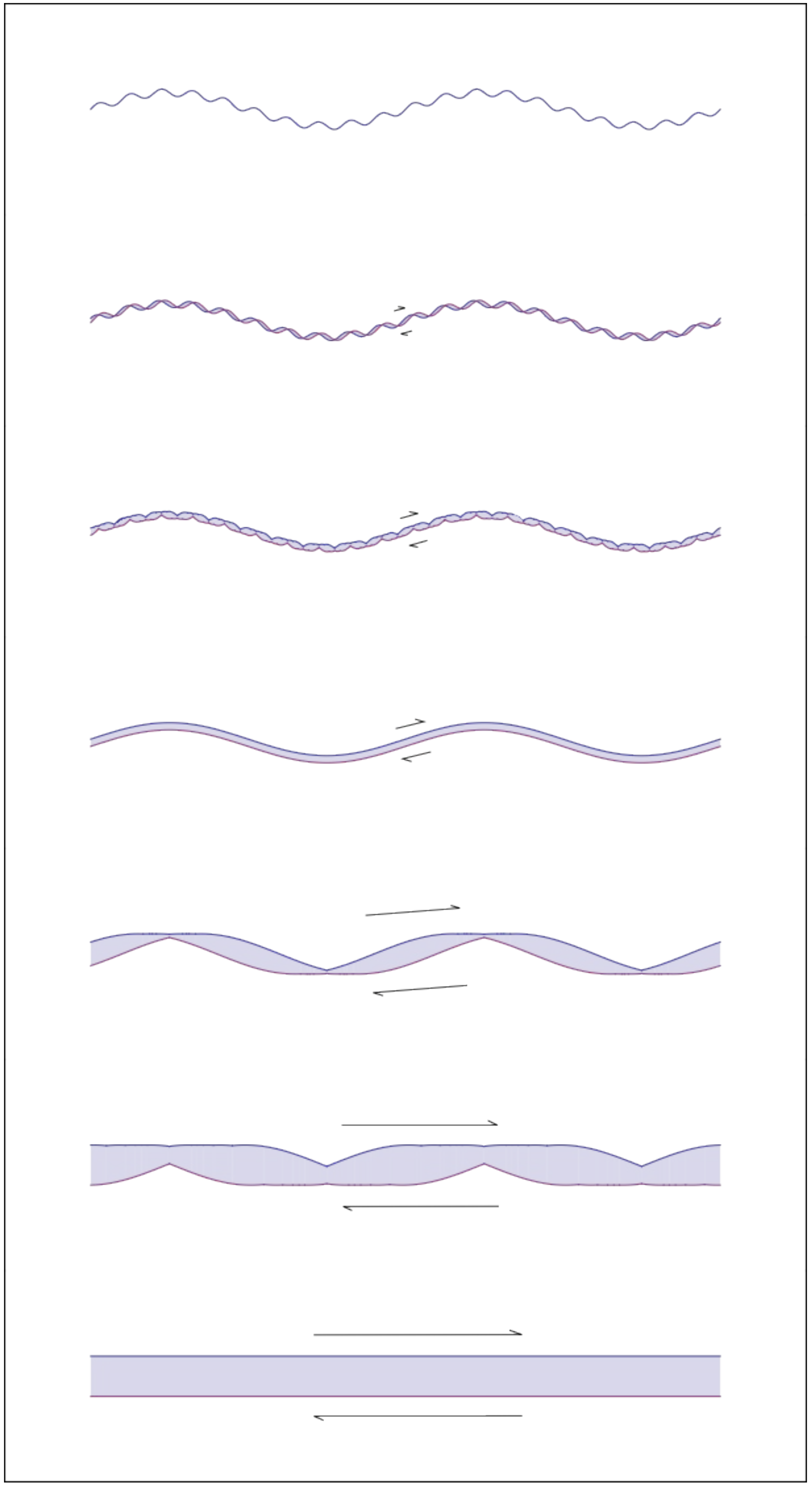
Up to slip ≈ 30 cm:
G from frictional dissipation alone shows a distribution with slip compatible with estimates of G' from real earthquakes

At slip > 30 cm:
G (friction) and G'(eq.) diverge G'>G

Extra dissipation sources in real eq: off-fault damage due stress concentration or to non-planarity of the fault.

Upscaling and homogenization issues (we compare global behavior to local behavior)

If we believe these estimates then G'-G can give us a measure of non-frictional dissipation during earthquakes



Stress and strain due to slip on a sinusoidal fault:

$$\sigma_{\mathrm{ij}}(x,y) = \quad E\left(a + b\frac{2\pi y}{\lambda}\right)\frac{h\mathrm{u}}{\lambda^2}\, g(2\pi x/\lambda)\exp(-2\pi y/\lambda)$$

$$\varepsilon_{\mathrm{ij}}(x,y) = \quad \left(c + d\frac{2\pi y}{\lambda}\right)\frac{h\mathrm{u}}{\lambda^2}\, g(2\pi x/\lambda)\exp(-2\pi y/\lambda)$$

Work of elastic strain for u ~ λ:

$$d\mathrm{w} = \sigma_{ij} d\varepsilon_{ij} = \sigma_{ij}(\mathrm{u})\ \varepsilon'_{ij}(\mathrm{u})\ du$$

Self-affine surface with Hurst exponent H:

$$h = \gamma\ \lambda^H$$

$$d\mathrm{w} \propto E\ h^2\ \mathrm{u}/\lambda^3\ d\mathrm{u}$$

$$\mathrm{w} \propto \int_{u=0}^{u=\lambda} E\ h^2\ \mathrm{u}/\lambda^3\ d\mathrm{u}$$

$$\mathrm{w} = {}^1\!/_4\ \pi^3\gamma^2(2-\nu)\ E\ U^{2H-1}$$

$$\text{for}\ \ U = 1\ \ \mathrm{m}\ \ \text{we obtain}\ \ \mathrm{w} \approx 2.5\ 10^8\ \ \mathrm{J\ m^{-2}}$$

For a self-affine fault topography:

$$\rho_h(k) = \mathrm{c}\ k^{-H-\frac{1}{2}}$$

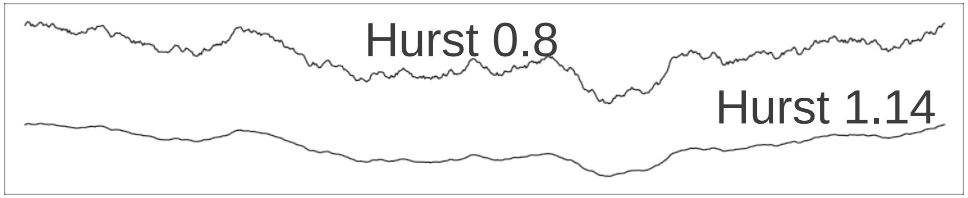
Wavenumber k

Integration over wavenumbers:

$$\mathrm{w} \propto E \int_{2\pi/U}^{\infty} k^{-2H}\ dk$$

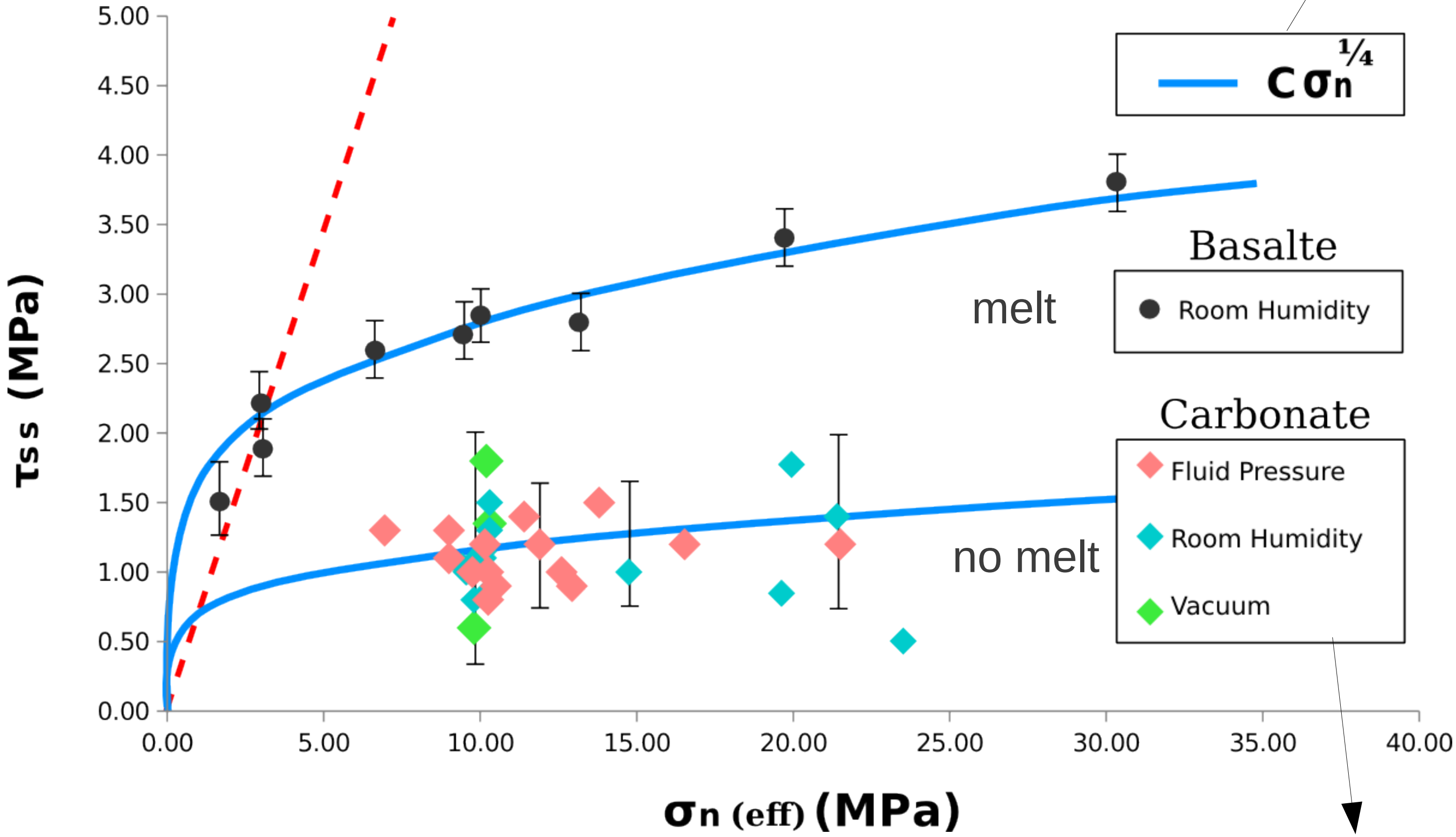
$$G_r \propto \mathrm{w} \propto E\, U^{2H-1}$$

H= 0.8 → $G \propto U^{0.6}$
H= 1.0 → $G \propto U$
H=1.14 → $G \propto U^{1.28}$



Lubrification

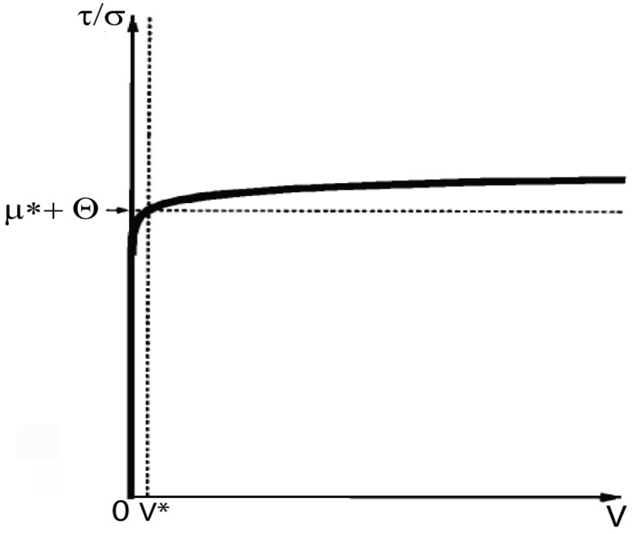
Modèle théorique
Friction melt
Nielsen et al 2008

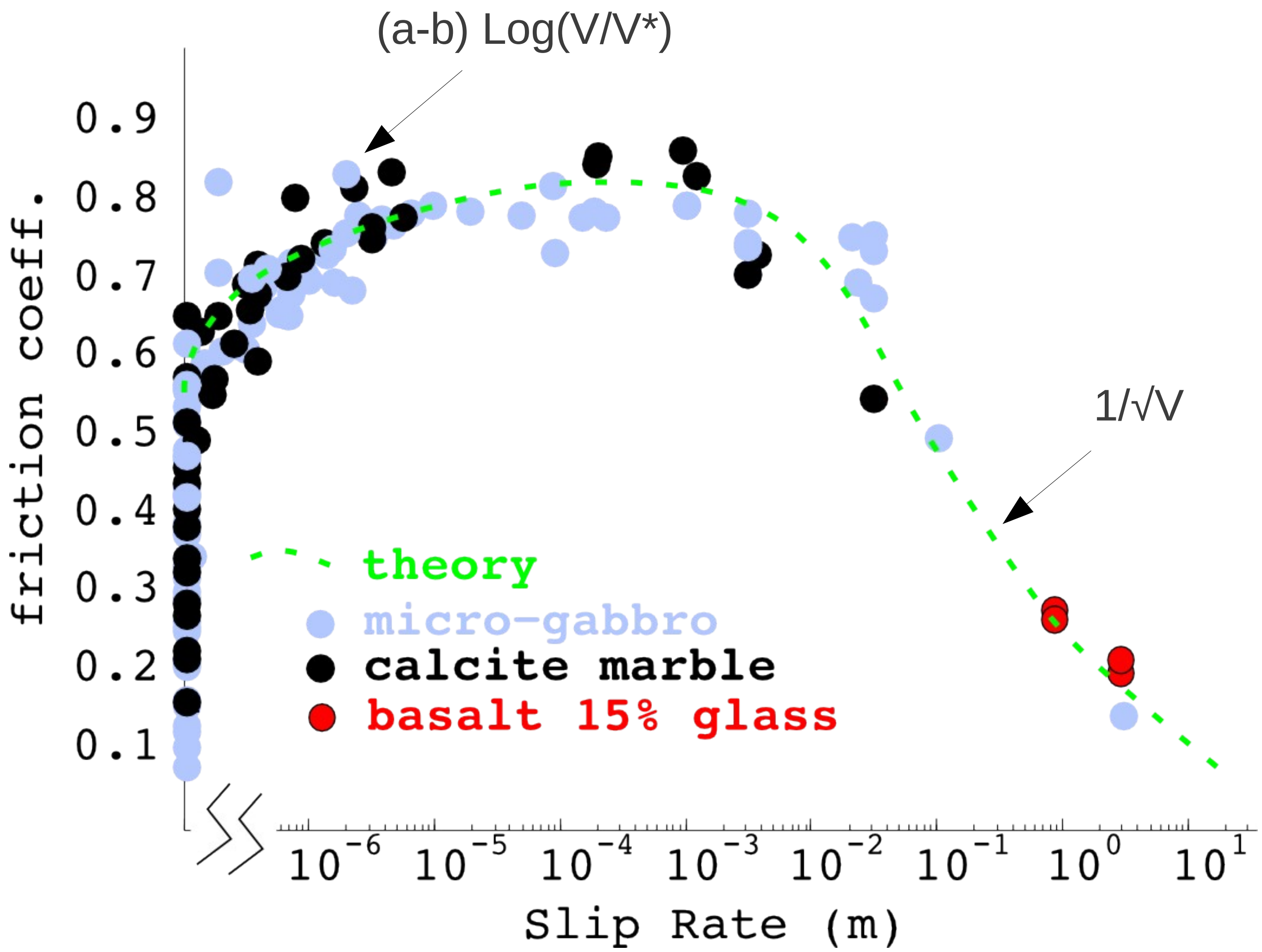


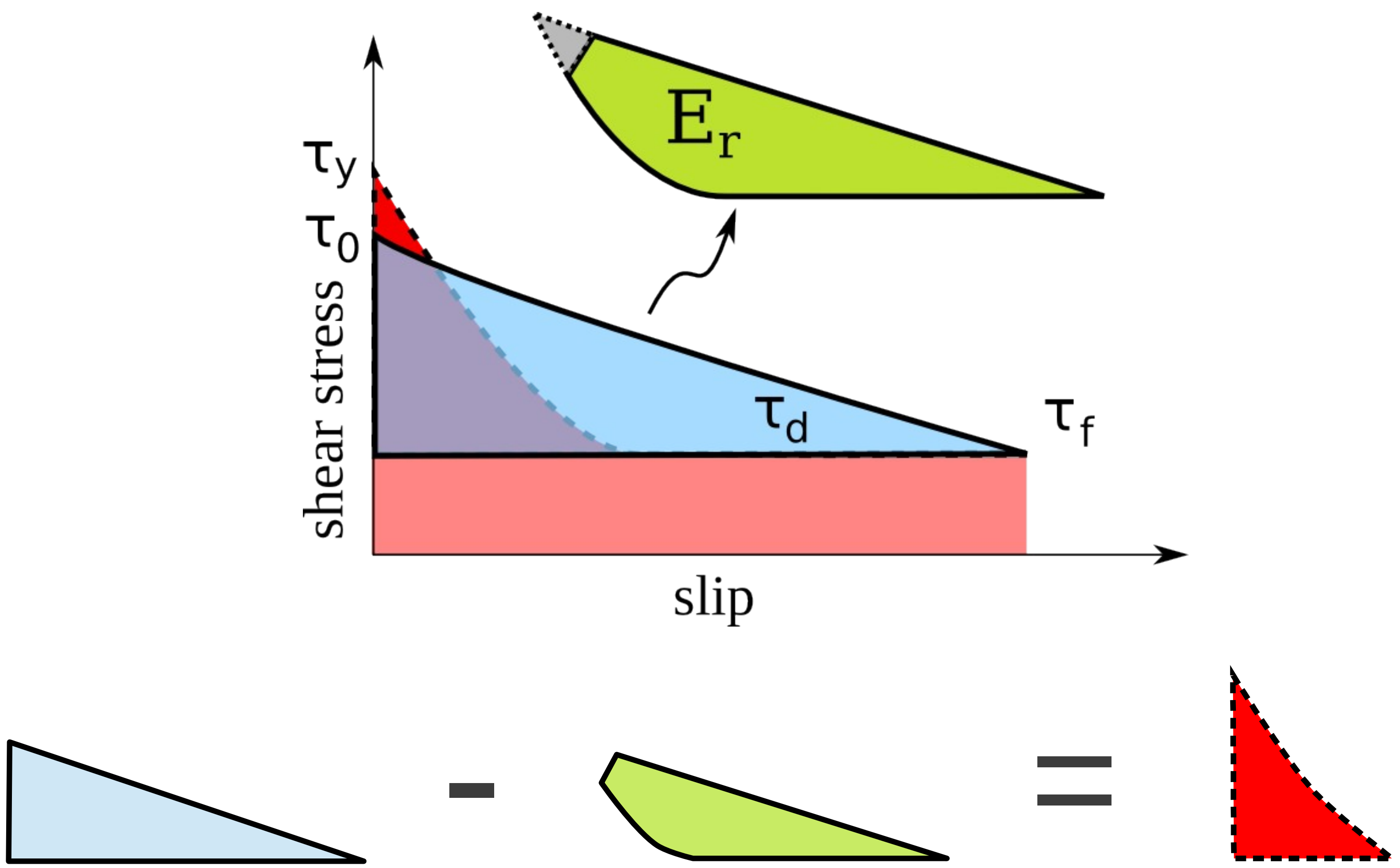
Pas de modèle
Théorique
solide

Transition stable/instable

état stationnaire

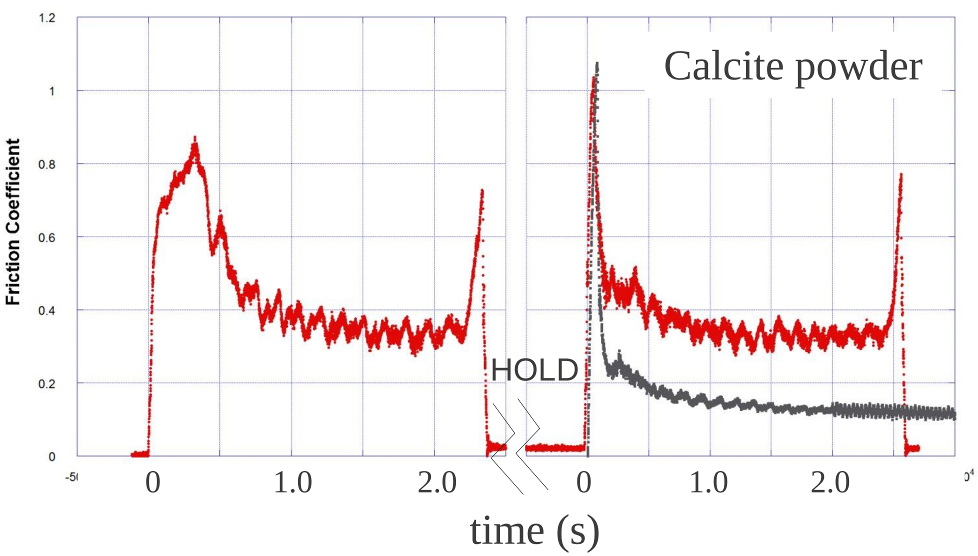


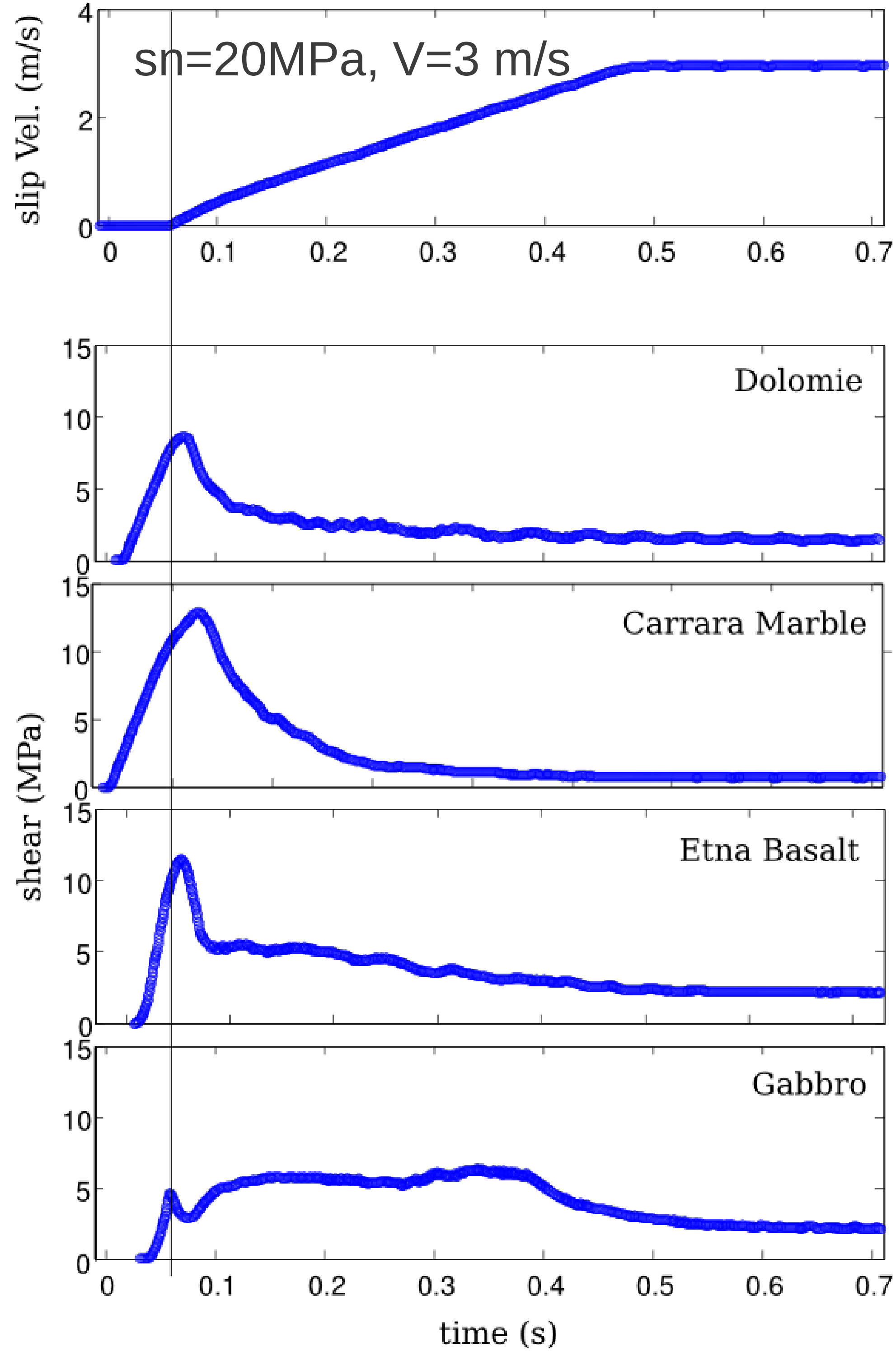




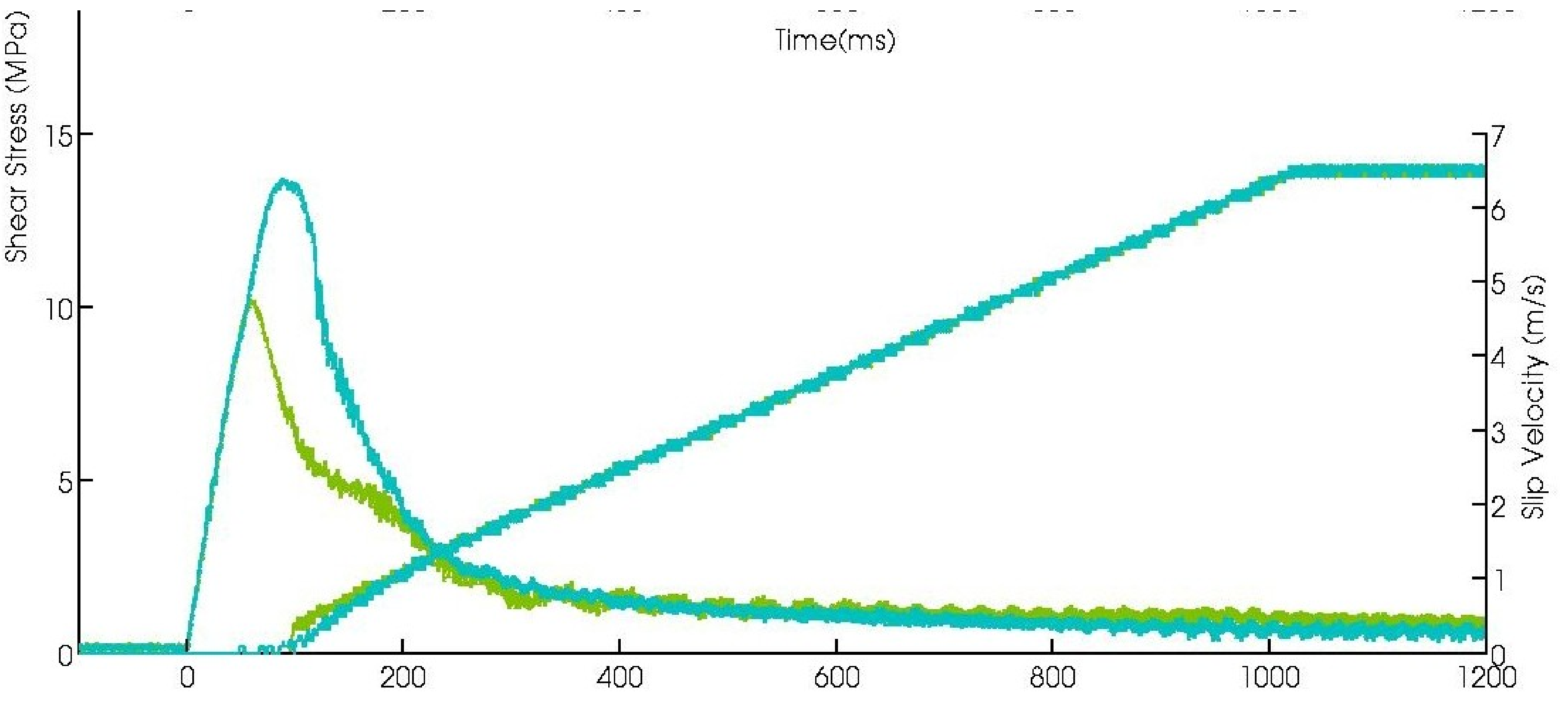
E$_r$
τ$_y$
τ$_0$
shear stress
τ$_d$
τ$_f$
slip

Various lithologies





Calcite and Dolomite



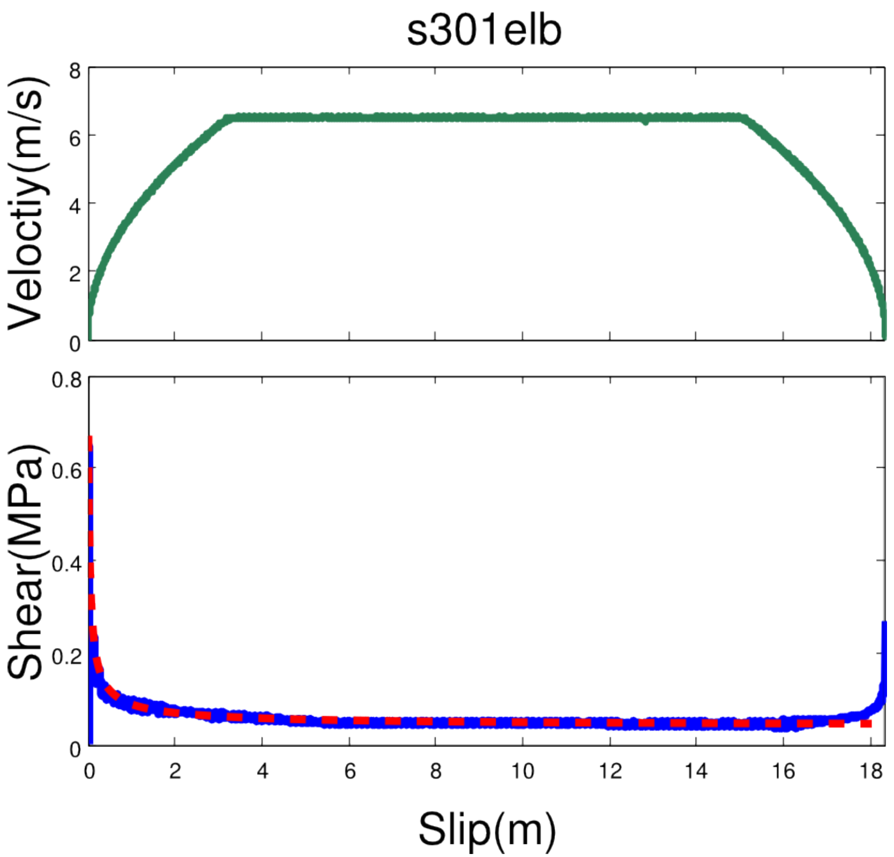
Spagnuolo et al., in preparation

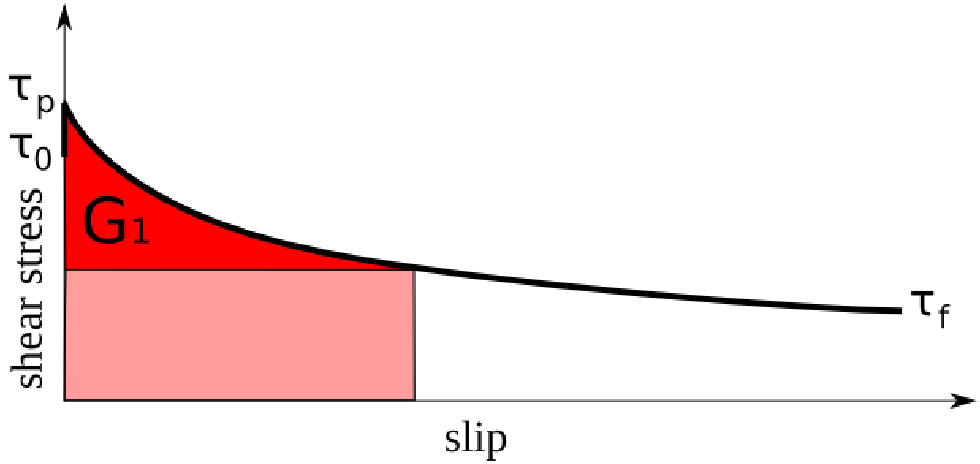
To do

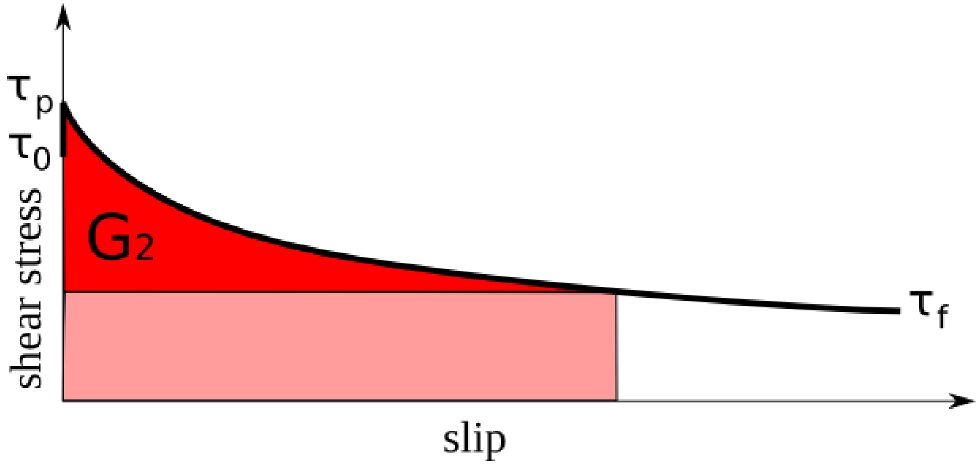
Add data from Tinti et al.
Experimental examples
Difficulties in defining Dc in experiments
Different G curves
Off fault dissipation
Fault roughness and H
Powerlaw fit and integration: equations
Rice's fit with therm. press. Model
Normal stress dependence
Velocity load time history
Total stress drop / large stress drop?

Weakening and G

...how to get rid of details







G

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