Computational Infrastructure for Geodynamics Webinar
May 20, 2022

Fault-size-dependent Fracture Energy, Seismogenesis, Cascading Rupture on Multi-Scale Fault Networks

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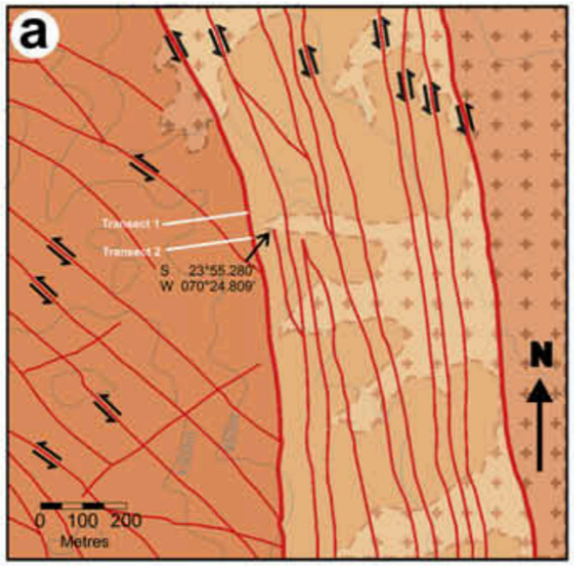
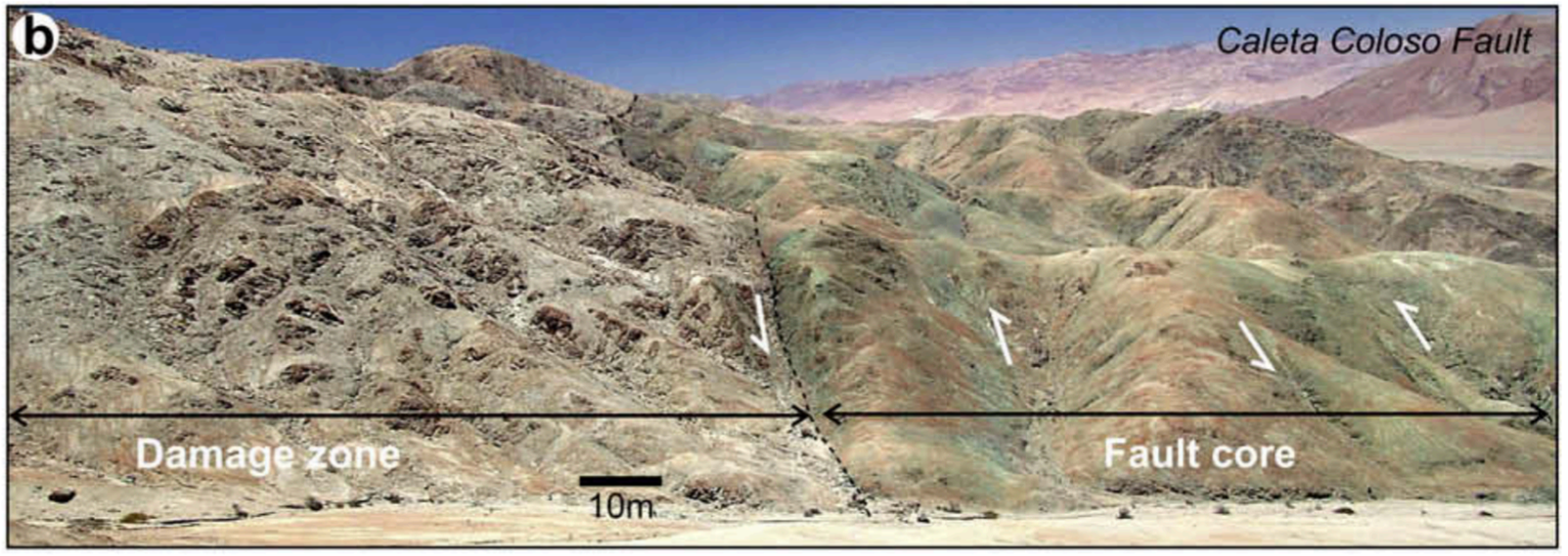
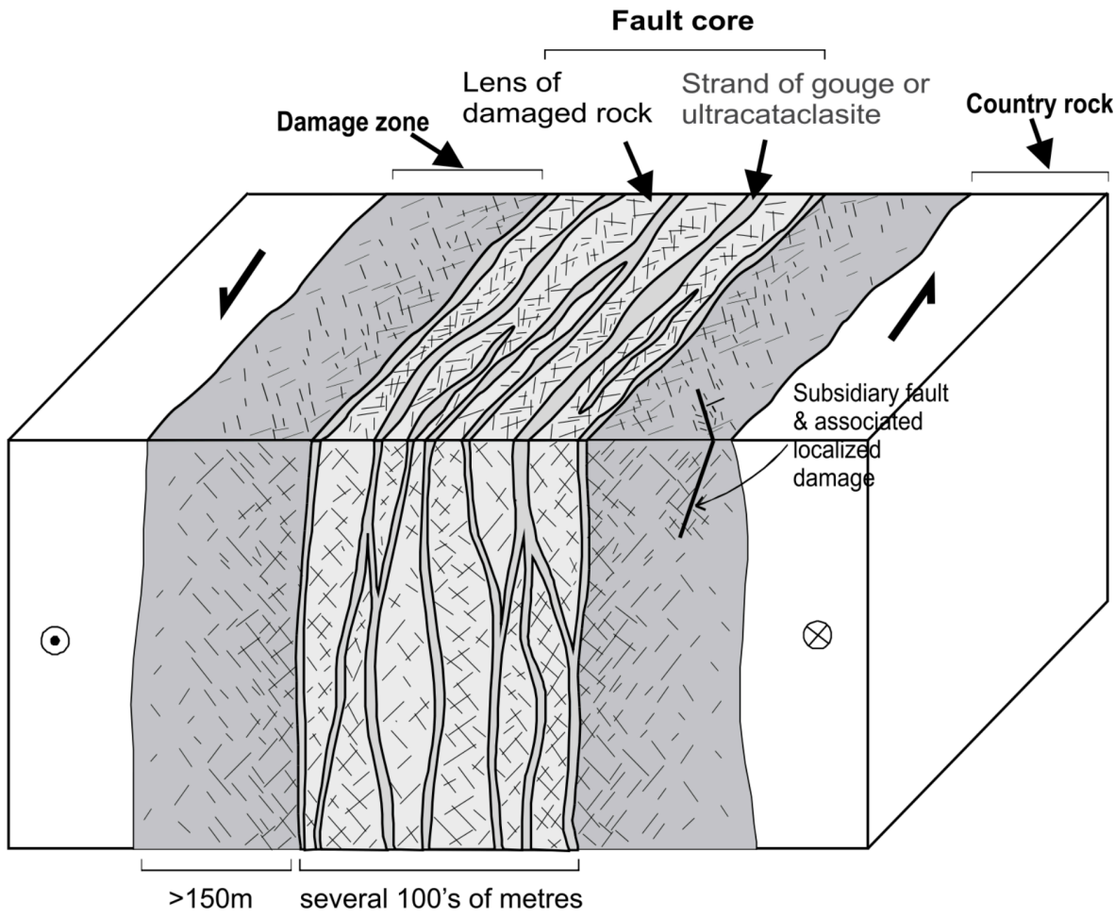
Faults and Seismicity on All Scales

Mitchell and Faulkner JSG 2009, Faulkner et al JSG 2010

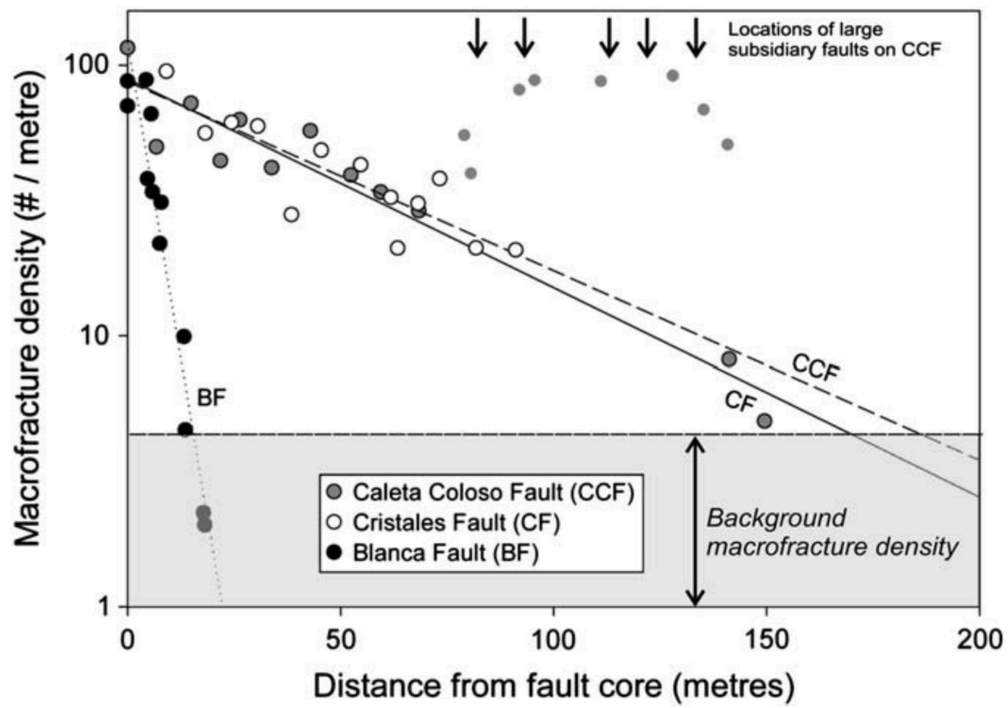






Fault Damage Zone (FDZ) ~ 100's meters

Multiscale, conjugate system fractures:
from *micro-fractures* to *macro-fractures* to *subsidiary faults* with maximum size commensurate with the thickness of FDZ



Faults and Seismicity on All Scales

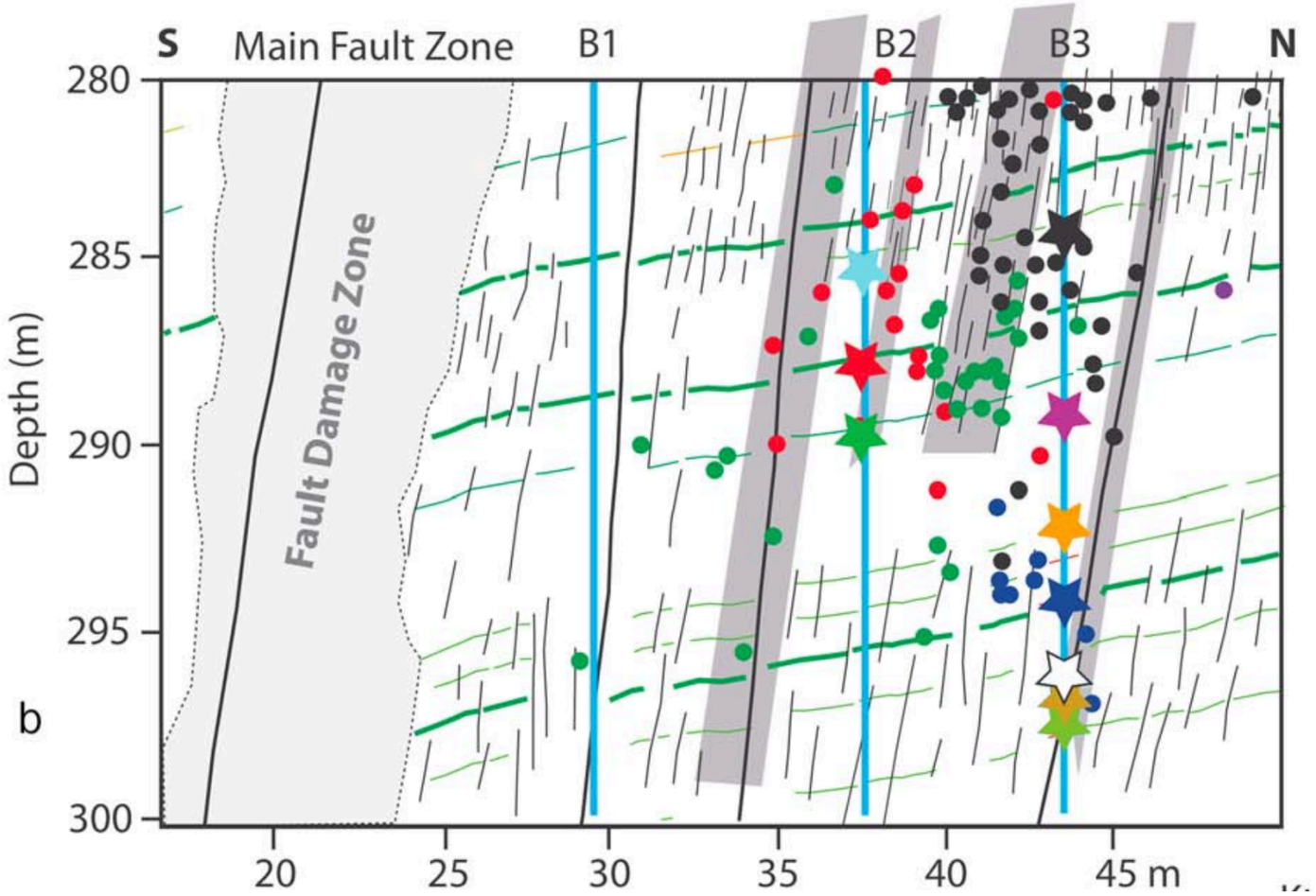
AGU PUBLICATIONS

JGR

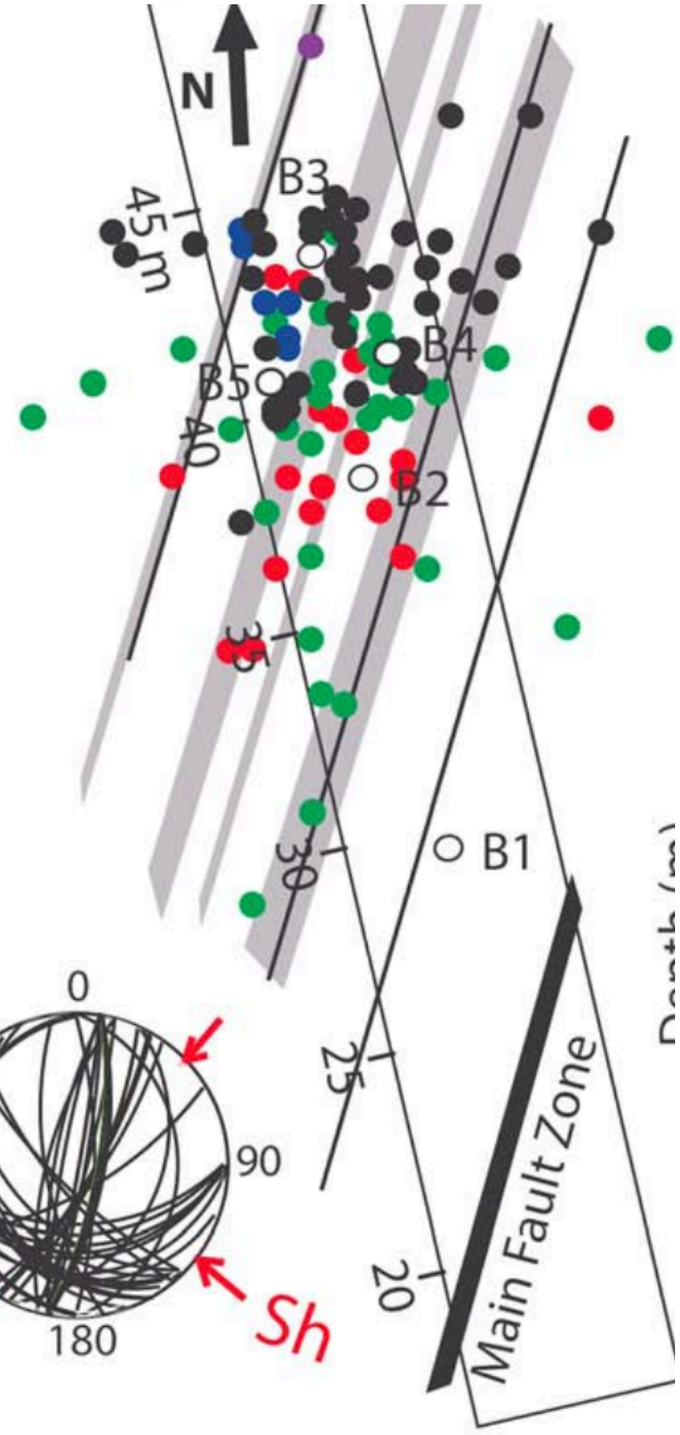
Geophysical Research: Solid Earth

Aseismic Motions Drive a Sparse Seismicity During Fluid Injections Into a Fractured Zone in a Carbonate Reservoir

Laure Duboeuf[1], Louis De Barros[1], Frédéric Cappa[1,2], Yves Guglielmi[3], Anne Deschamps[1], and Simon Seguy[4]



Map View



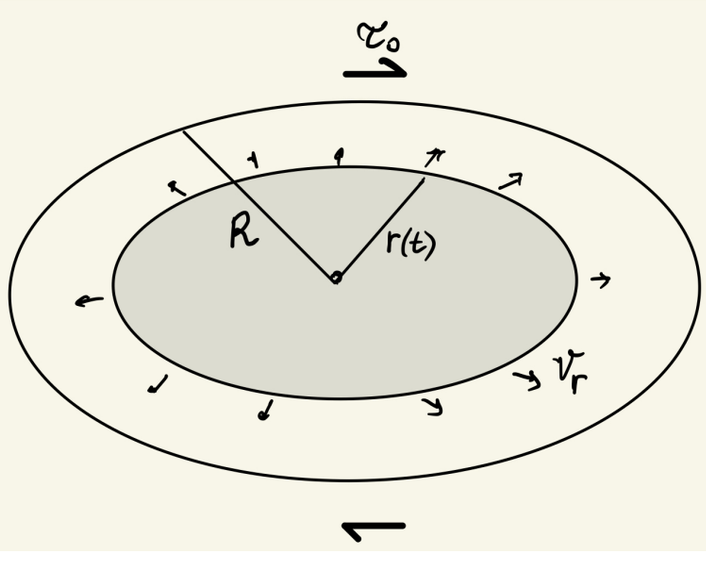
Fault Fracture Energy and Seismogenesis Concepts

Classical Fracture Energy = mechanical work to break the fault strength from the *peak* value at the onset of slip to the *residual* weakened value at large enough slip

$$G_c = \int_0^{\delta \gg D_c} (\tau - \tau_r) d\delta \quad \sim (\tau_p - \tau_r) D_c$$

D_c = slip distance over which the weakening is accomplished

Fault is **seimogenic** if the ***rate*** at which the elastic ***energy*** of the prestressed bulk can be ***released*** to the rupture front (*ERR*) can match the fault fracture energy G_c, i.e. ***ERR = G_c***



r(t) = rupture front,
R = fault size or max rupture size

$$ERR = g(v_r)\, ERR_0(r), \qquad ERR_0(r) = C_0 \frac{\Delta\tau^2\, r}{2\mu}$$

$g(v_r)$ - dependence on rupture speed, $g(0)=1$ and $g(c_s)=0$ [Madariaga 1976; Ida 2002]

$\Delta\tau = \tau_o - \tau_r$ = stress drop
($C_0 \sim 1$ geometry const.)

Define ***critical size*** [Andrews 1976]

$$R_c = \frac{2\mu G_c}{C_0 \Delta\tau^2}$$

Dynamic rupture requires
Seismogenic Index = $ERR_0(R) / G_c = R/R_c > 1$

[see also related concept of rupture potential, Weng and Ampuero NGeo 2020]

Seismological Inference of Fracture Energy

Potential energy release per unit ruptured fault surface
[e.g. Kanamori and Heaton 2000]

$\Delta W = (\tau_0 + \tau_1)\,\delta/2 = E_s + G + F$

E_s = radiated energy, G = fracture energy, and
$F = \tau_d\,\delta$ = frictional heat

Fracture energy can be written as

(1) $G = G' + (\Delta\tau_d - \Delta\tau)\,\delta$

where energetic quantity [Abercrombie and Rice GJI 2005]

(2) $G' = \Delta\tau\,\delta/2 - \tau_a\,\delta$

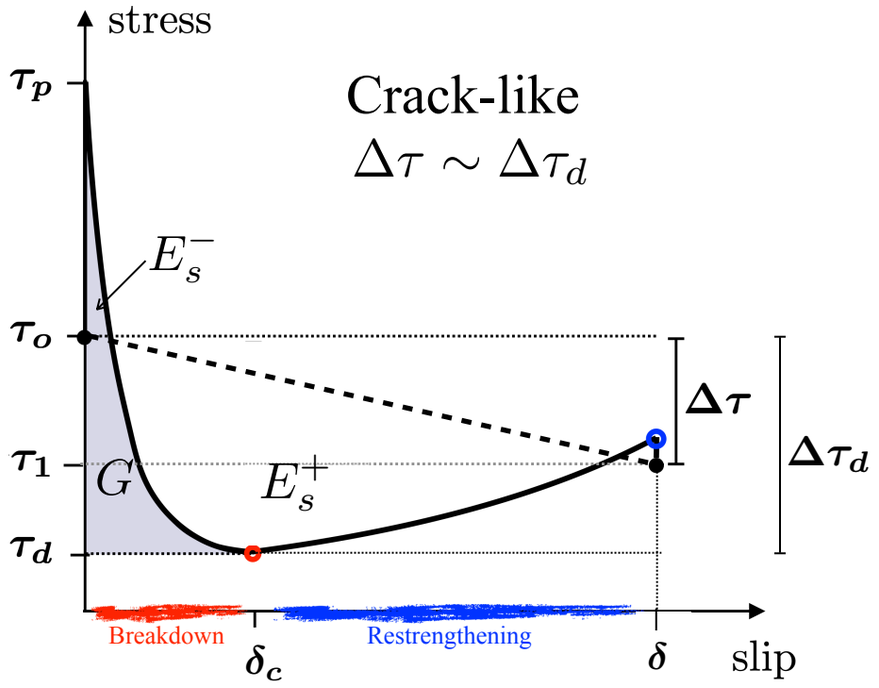
is the part of the fracture energy inferred from seismologically observable *static stress drop* $\Delta\tau = \tau_0 - \tau_1$, apparent stress $\tau_a = \mu E_s/M_0$, and slip δ.

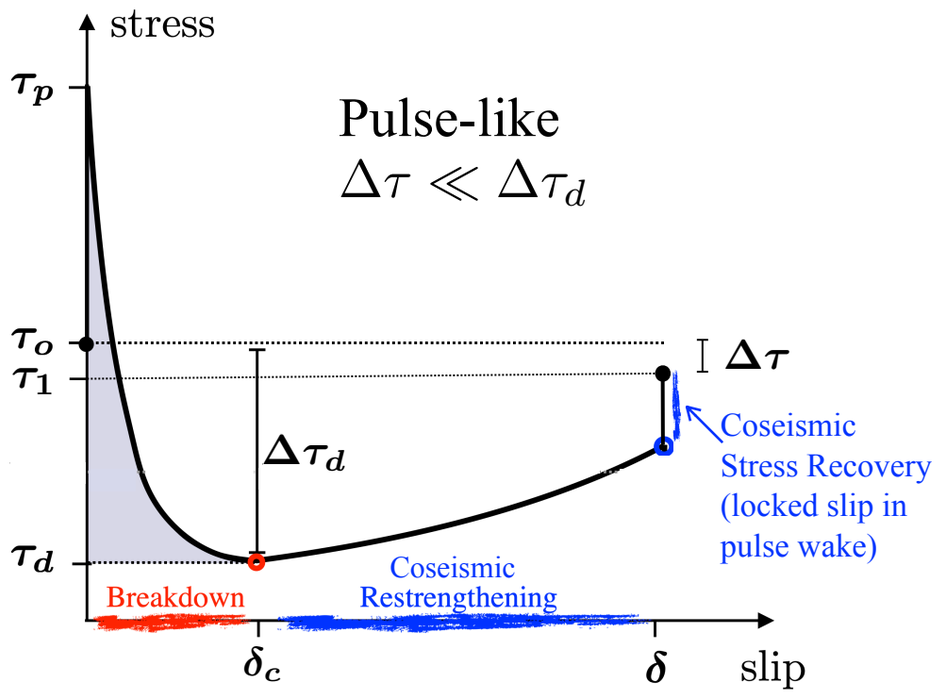
Maximum dynamic stress drop $\Delta\tau_d$, or coseismic re-strengthening $\Delta\tau_d - \Delta\tau$, required to estimate full fracture energy G, Eq. (1), **cannot be inferred from seismic data.**

WHAT TO DO?

Crack-like ruptures: G = G'
if can neglect co-seismic restrengthening

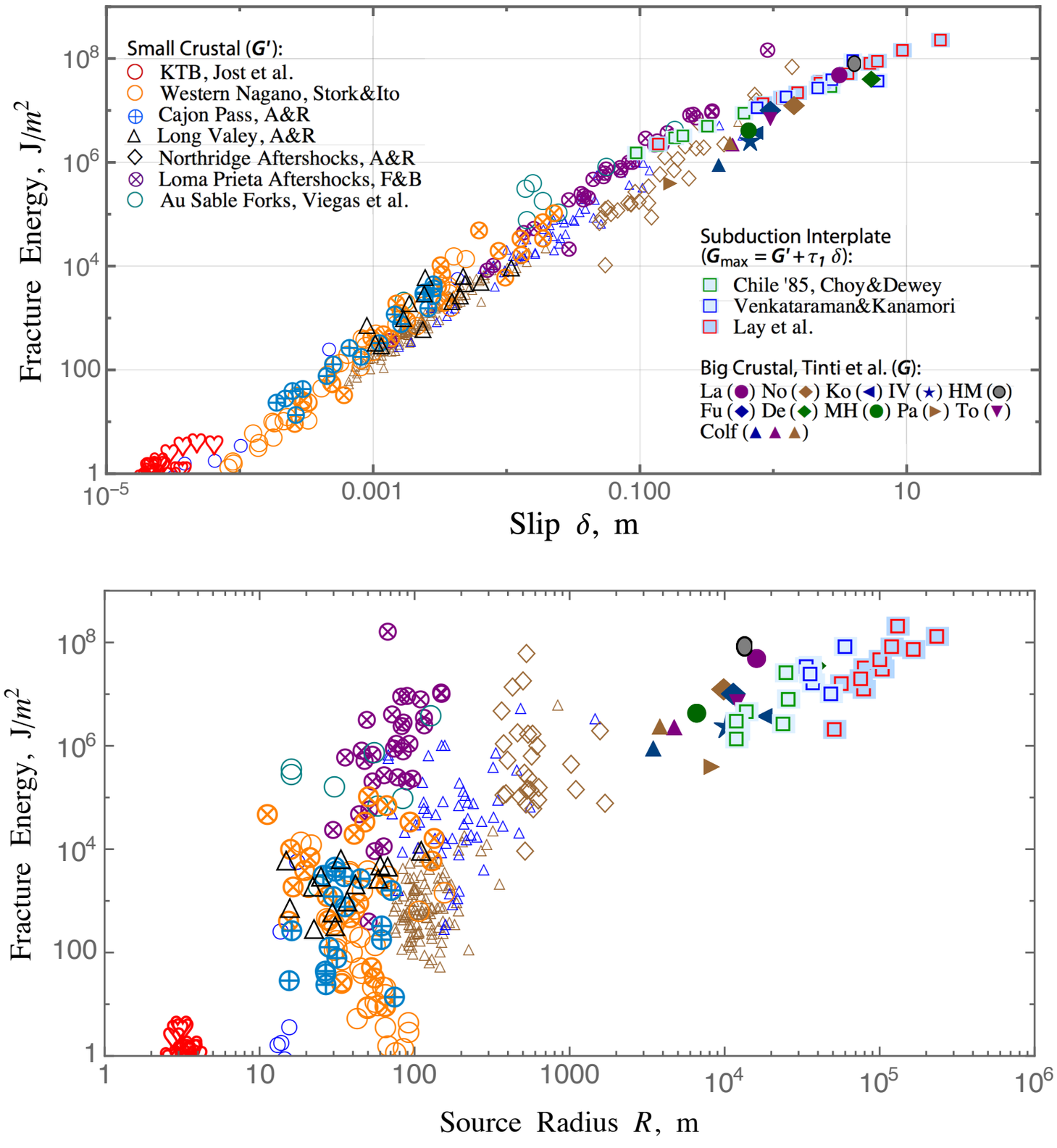
Pulse-like ruptures: $G = G' + \tau_1\delta$
if nearly full weakening $\tau_d = 0$ (large EQs) followed by nearly full restrengthening in the wake of the pulse





Inferred Fracture Energy vs. Event Slip vs. Event Size

Viesca and Garagash NGeo 2015, compilation from various sources



- Fracture Energy G increases with both event slip and event size on all scales

  WHY?

- Hypothesis 1: $\Delta G(\delta)$
  due to ***continuing*** thermal ***weakening with co-seismic slip*** on all scales (possibly fault-invariant)
  [Rice JGR 2006; Garagash JGR 2012; Viesca and Garagash NGeo 2015]

- Hypothesis 2: $G_c(R)$
  Fracture energy is a fault property, a ***function of fault size*** / maturity / total fault accrued slip
  [e.g. Scholz et al. JGR 1993]

- Alternative hypothesis [Ke, McLaskey, Kammer NComm 2022]: assuming fault prestress heterogeneity scaling with fault size can also explain the observations

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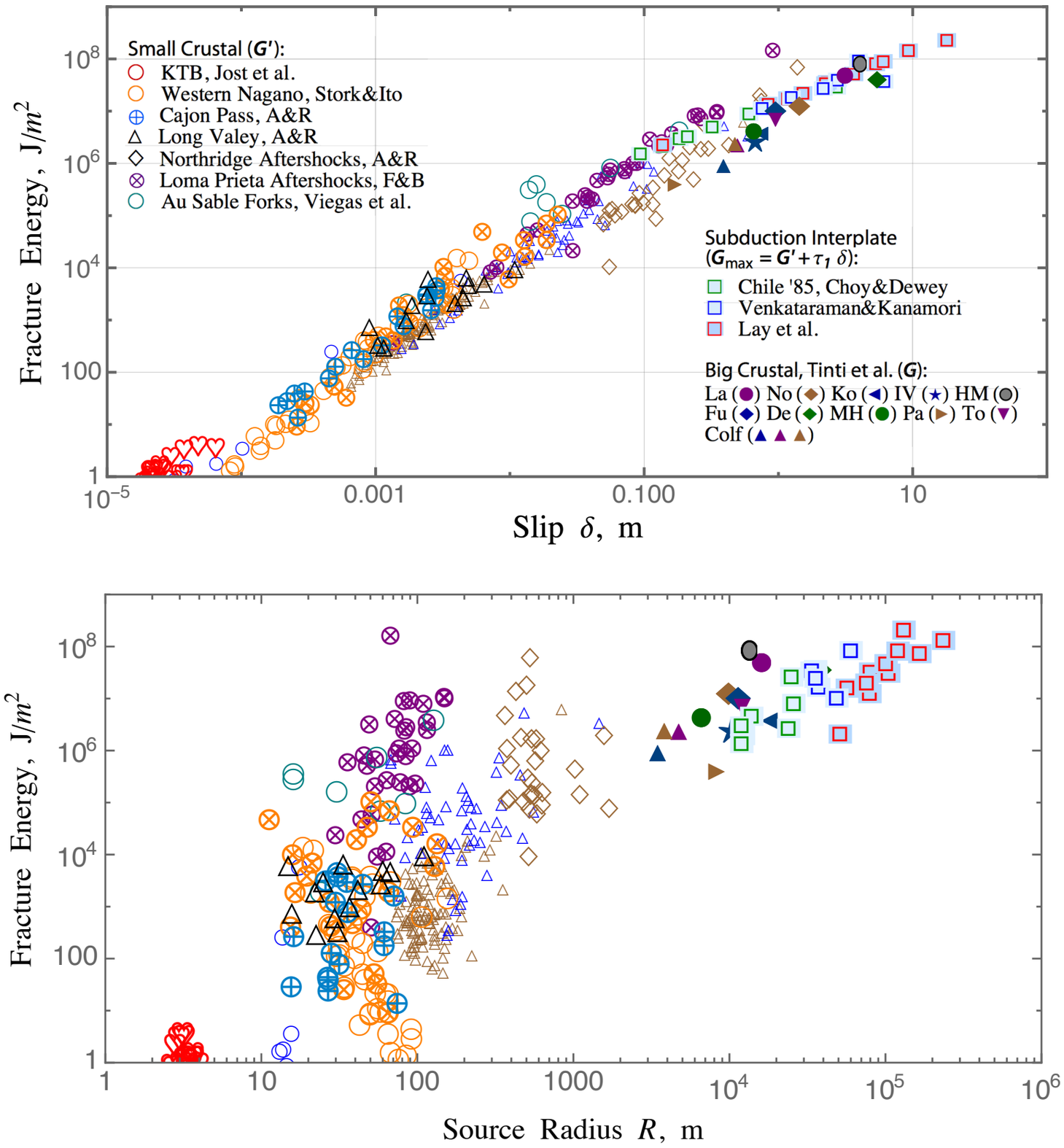

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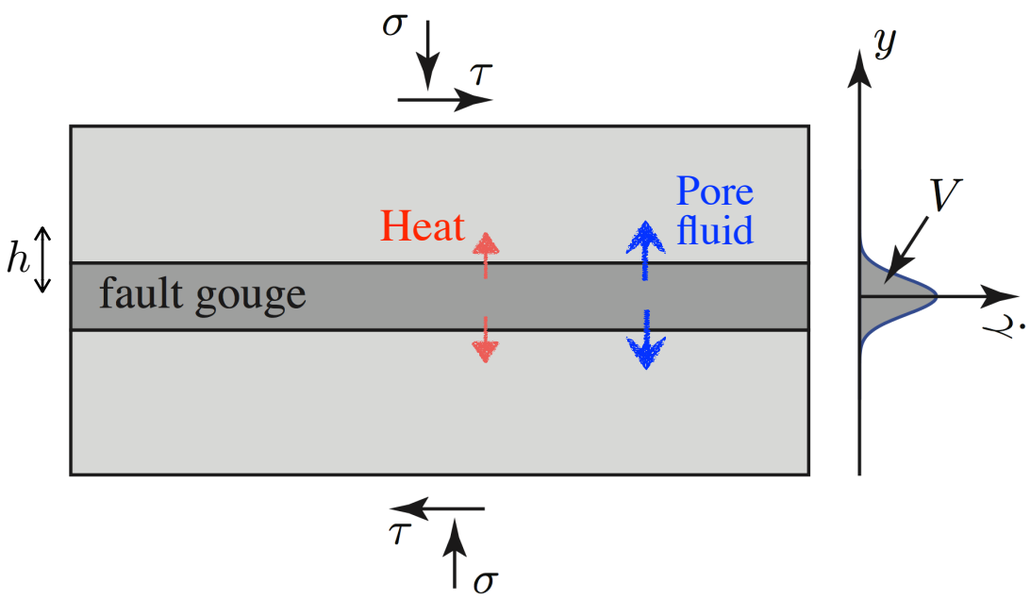
Thermal Pressurization (TP) of Pore Fluid due to Shear Heating of Fault

as candidate mechanism of ***continuing weakening with co-seismic slip*** **(Hypothesis 1)**



Inside actively deforming gouge, temperature and pore pressure evolve as

$$\frac{\partial T}{\partial t} = \frac{\tau\dot{\gamma}}{\rho c} + \alpha_{th}\frac{\partial^2 T}{\partial y^2} \qquad \frac{\partial p}{\partial t} = \Lambda\frac{\partial T}{\partial t} + \alpha_{hy}\frac{\partial^2 p}{\partial y^2}$$

where strain rate $\dot{\gamma}$ follows an assumed Gaussian distribution with effective width h; ρc is the heat capacity; α_{th} and α_{hy} are the thermal and hydraulic diffusivities; and Λ is the thermal pressurization coefficient of the gouge.

For a given history of τ and V, p at $y = 0$ is

$$p = p_0 + \frac{\Lambda}{\rho c h}\int_0^t \tau(t')V(t')\mathcal{K}\left(\frac{t-t'}{T^*};\frac{\alpha_{hy}}{\alpha_{th}}\right)dt'$$

where T^* is a timescale for diffusion $\quad T^* = \dfrac{h^2}{4\alpha} \quad \alpha = (\sqrt{\alpha_{hy}} + \sqrt{\alpha_{th}})^2$

Thermal pressurization operates with **two limiting regimes**:

(1) Diffusion of pore fluid and heat is negligible (undrained-adiabatic conditions, or simply "undrained"), in which case $\mathcal{K} = 1$ [Lachenbruch 1980]

For the effective normal stress $\bar{\sigma} = (\sigma - p)$, shear strength obeying $\tau = f\,\bar{\sigma}$, and constant σ and f, strength evolves as

$$\tau = f\bar{\sigma}_0 \exp(-\delta/\delta_c) \quad \text{with} \quad \delta_c(f) = \frac{\rho c h}{f\Lambda} \qquad \text{(1b)}$$

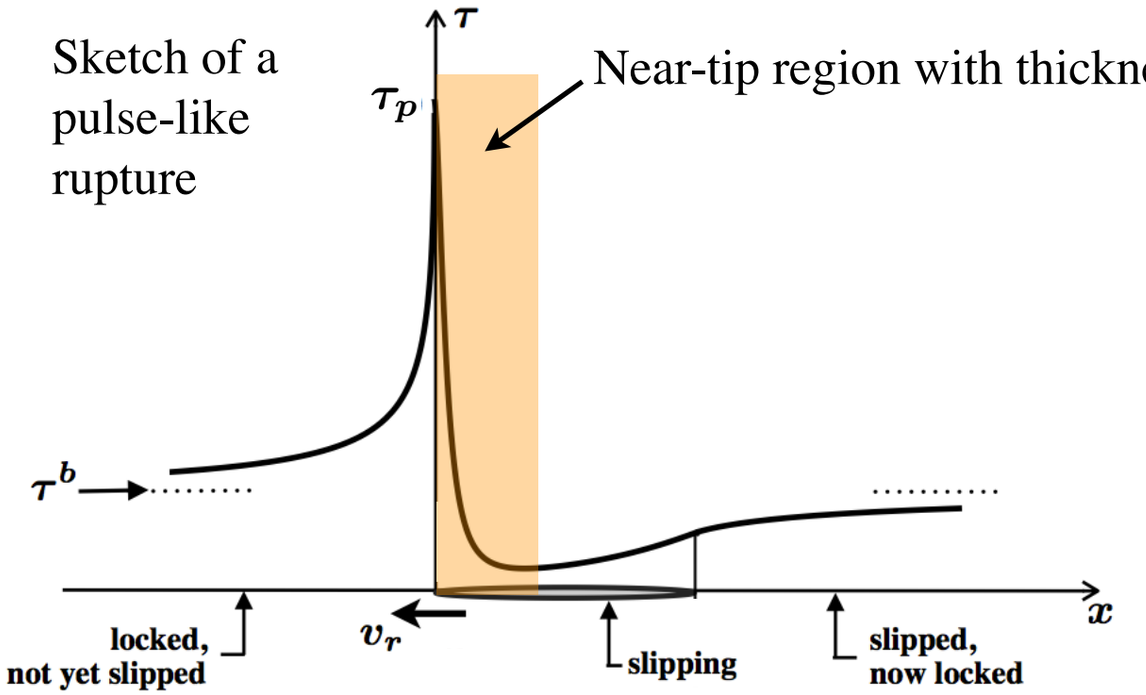
(2) Diffusion is to such an extent that shear heating of finite gouge effectively reduces to slip on a plane, and $\mathcal{K} = 1/\sqrt{\pi(t-t')/T^*}$ [Mase and Smith 1987; Rice 2006; Rempel and Rice 2006]

Here, strength retains explicit dependence on the history of τ and V $\quad \tau = f\bar{\sigma}_0 - \dfrac{f\Lambda}{2\rho c\sqrt{\alpha}}\displaystyle\int_0^t \frac{\tau(t')V(t')}{\sqrt{\pi(t-t')}}dt' \qquad \text{(2)}$

Examining Weakening Near the Front of a Dynamic Rupture Driven by TP

The near-rupture-front region, where the weakening is localized, can be modelled as a ***semi-infinite shear crack*** steadily propagating at the instantaneous velocity v_r **[Garagash, JGR 2012; Viesca and Garagash, NGeo 2015]**

Sketch of a pulse-like rupture



Near-tip region with thickness $\sim \ell_*$, where elastodynamic equation is approximated as

$$\frac{\tau-\tau_\infty}{\tau_*}=\frac{1}{2\pi}\int_0^\infty \frac{V(x')}{V_*}\frac{dx'}{x'-x} \qquad \left(\frac{V}{V_*}=\frac{d\delta/\delta_*}{dx/\ell_*}\right) \qquad (3)$$

with corresponding stress, slip, length, and slip-rate scales are from:

	Residual strength, τ_∞	Strength drop, τ_*	Slipscale, δ_*
Undrained TP	0	$f_w\bar{\sigma}_0$	$\delta_c=(\rho c/f_w\Lambda)\,h$
"Drained" TP	0	$f_w\bar{\sigma}_0$	$L^*=(\rho c/f_w\Lambda)^2\,(4\alpha/V_*)$

Length and slip-rate scales are $\ell_*=(\bar{\mu}/\tau_*)\delta_*$ and $V_*\equiv(\tau_*/\bar{\mu})v_r$
(apparent elastic modulus $\bar{\mu}=\mu\sqrt{1-(v_r/c_s)^2}$, mode III)

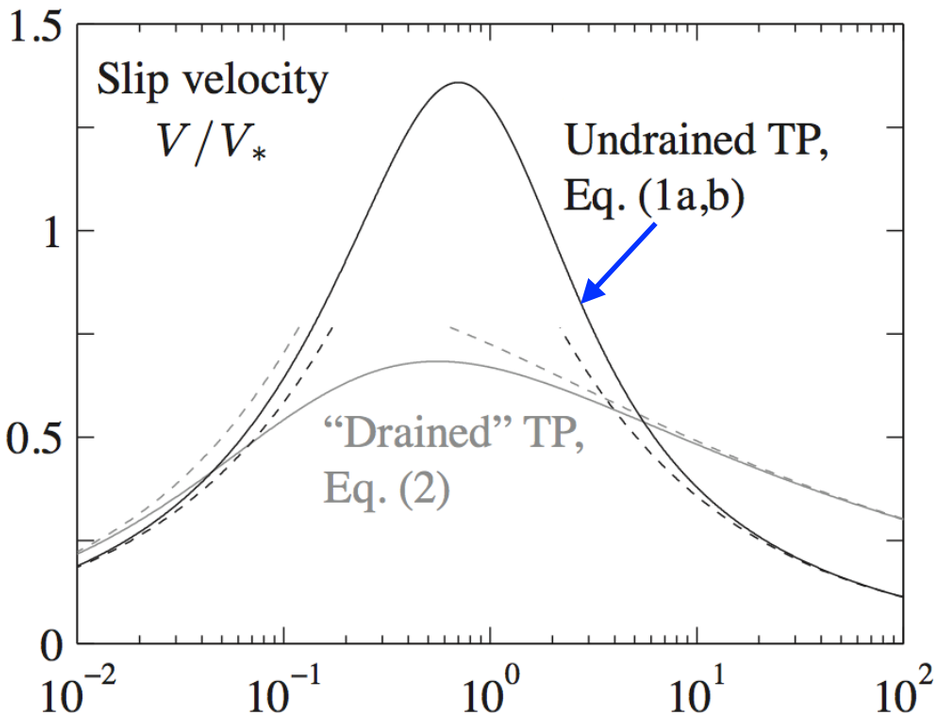
Fault strength, allowing for multiple weakening mechanisms: $\tau=f\,\bar{\sigma}$, where effective stress and friction follow

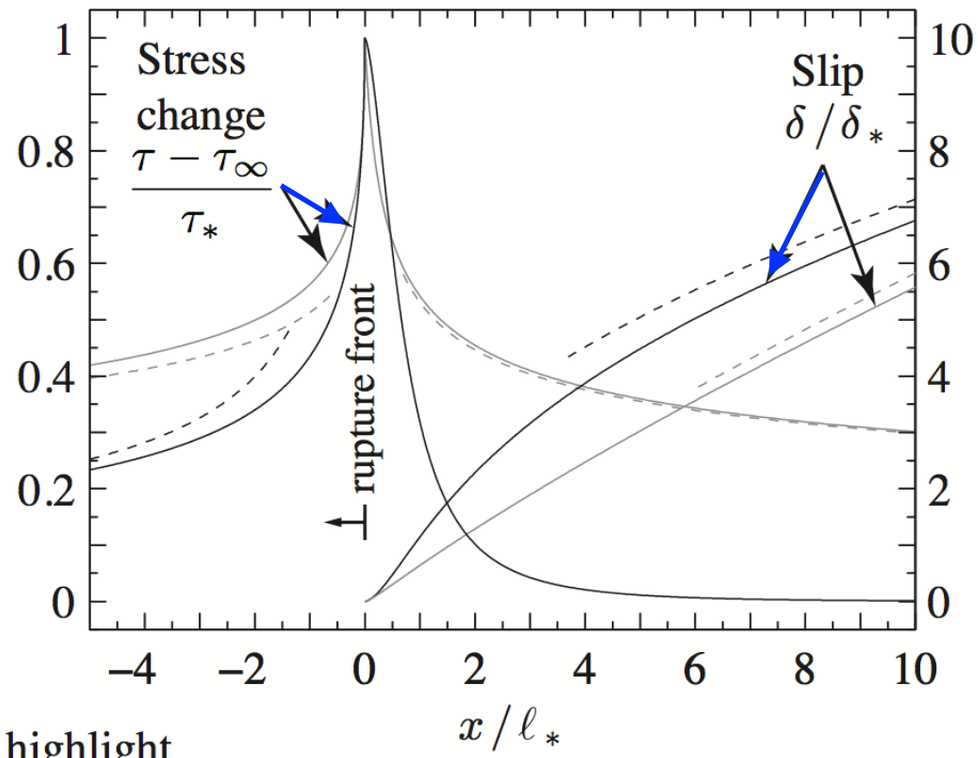
$$\frac{\bar{\sigma}}{\bar{\sigma}_0}=1-\frac{\delta_*}{\delta_c(f_*)}\int_0^x \frac{\tau(x')}{\tau_*}\frac{V(x')}{V_*}\mathcal{K}\left(\frac{x-x'}{\ell_*}\frac{\delta_*}{\delta_d};\frac{\alpha_{hy}}{\alpha_{th}}\right)\frac{dx'}{\ell_*} \qquad (\delta_d=T^*V_* \text{ such that } L^*/\delta_c=\delta_c/\delta_d;\ \tau_*=f_*\bar{\sigma}_0)$$

$$\frac{df}{d(x/\ell_*)}=-\frac{\delta_*}{L}\frac{V}{V_*}[f-f_{ss}(V)]\,,\quad f(0)=f_p$$

End-Members (small and large slip) of Thermal Pressurization

Undrained TP (1a,b): $\dfrac{\tau - \tau_\infty}{\tau_*} = \exp\left(-\dfrac{\delta}{\delta_*}\right)$ **"Drained" TP (2):** $\dfrac{\tau}{\tau_*} = 1 - \displaystyle\int_0^x \frac{\tau(x')}{\tau_*}\frac{V(x')}{V_*}\frac{dx'}{\sqrt{\pi \ell_* (x - x')}}$





(Dashed lines highlight asymptotic behavior)

Exponential weakening (1a,b):

Far from the crack tip ($x \gg \ell_*$), the solution corresponds to the classical fracture mechanics singularity:

$V = (K v_r/\bar{\mu})\sqrt{2/\pi x}$ where the stress intensity factor K is expressible as $K = \sqrt{2\bar{\mu}G}$ } → $\dfrac{V}{V*} = 2\sqrt{\dfrac{\ell_*}{\pi x}}$

in terms of the fracture energy [Palmer and Rice, 1973], $G = \int_0^\infty (\tau - \tau_\infty)d\delta = \tau_* \delta_*$

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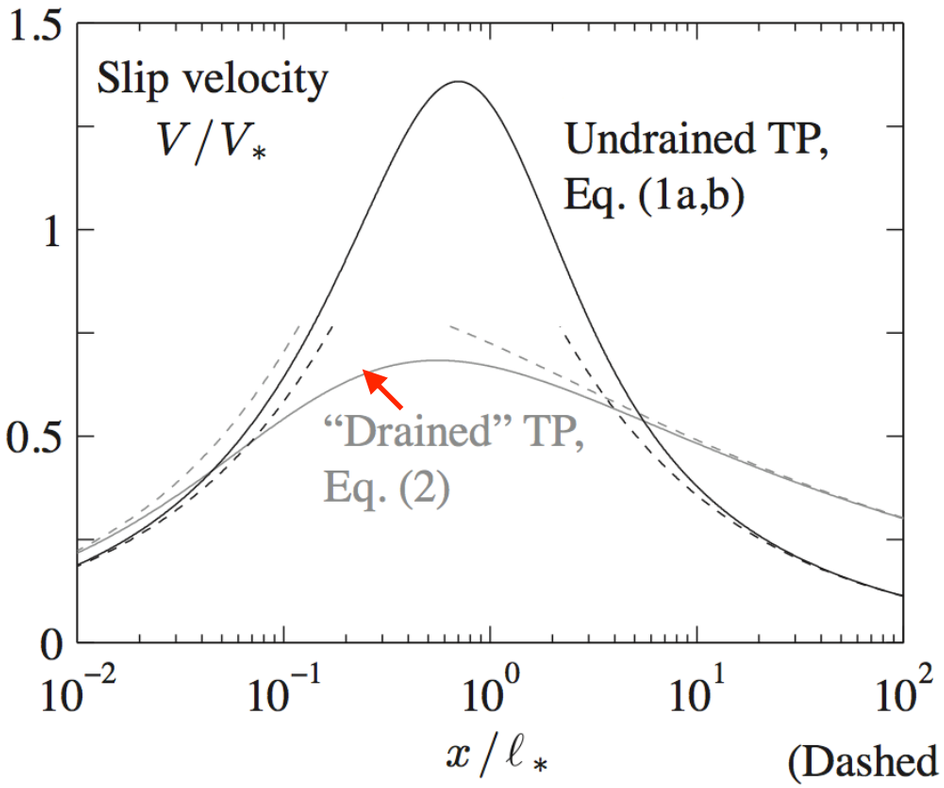
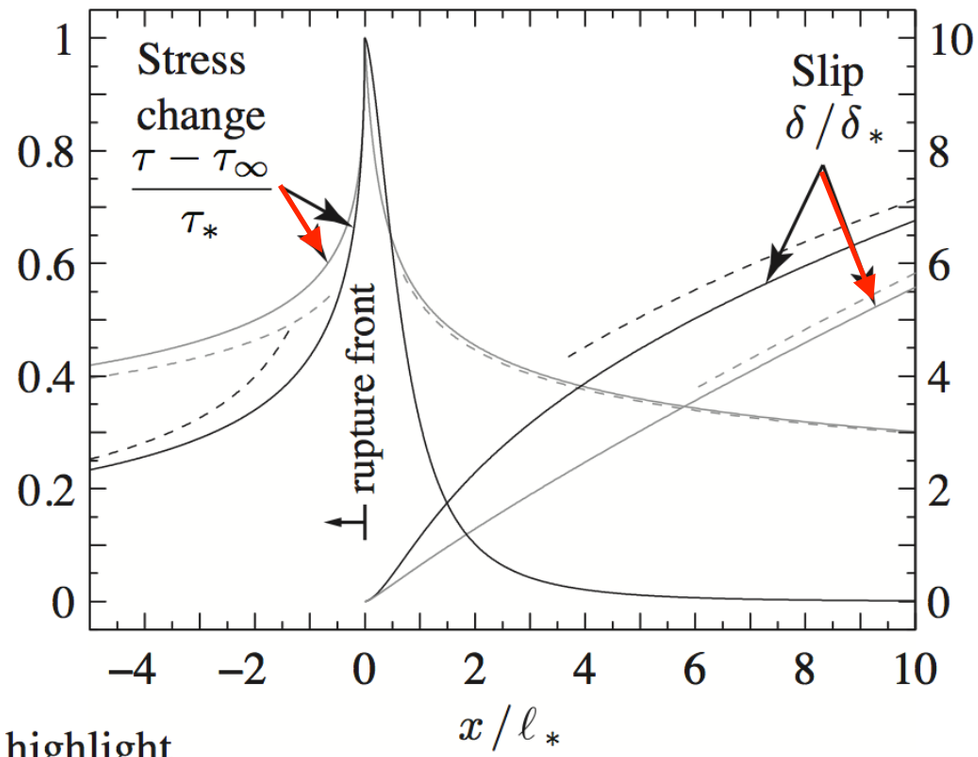




(Dashed lines highlight asymptotic behavior)

Slip-on-a-plane TP (2):

Here, for $(x \gg \ell_*)$, slip velocity follows a much weaker singularity: $\dfrac{V}{V_*} = \sqrt{2}\left(\dfrac{\ell_*}{\pi x}\right)^{1/4} - \dfrac{\pi}{\Gamma(1/4)^2}\sqrt{\dfrac{2\ell_*}{x}}$ and stress is not constant, rather slowly falls off as: $\dfrac{\tau}{\tau_*} = \dfrac{1}{\sqrt{2}}\left(\dfrac{\ell_*}{x}\right)^{1/4}$

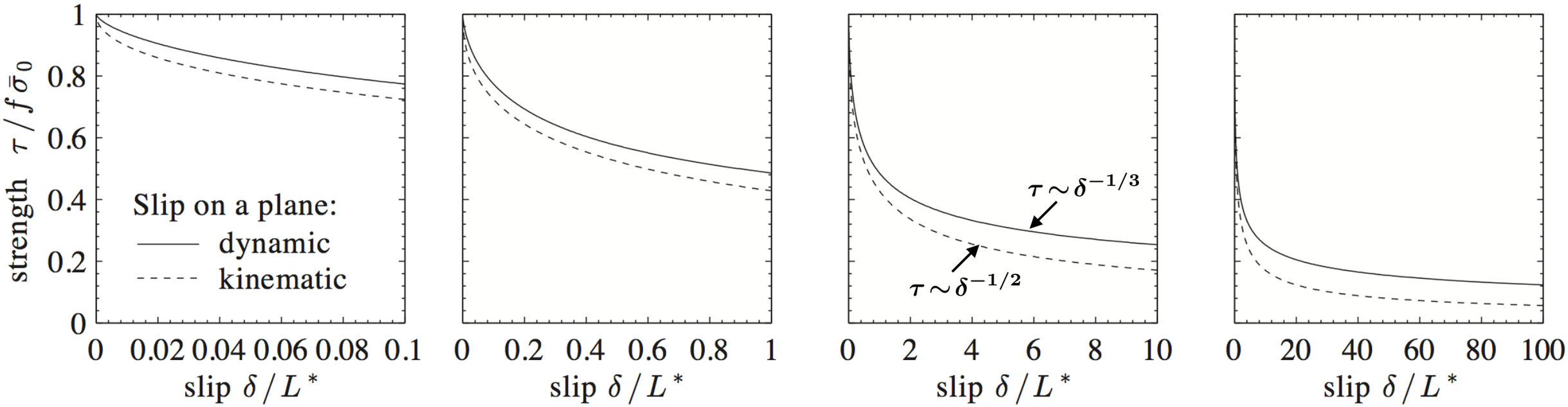
These imply a stress-slip relation at large slip of $\dfrac{\tau}{\tau_*} = \left(\dfrac{3\pi}{2}\dfrac{L_*}{\delta}\right)^{1/3}$

Note: predicted continuing dynamic power-law weakening with slip differs from d kinematic solution for (const) imposed slip rate [Rice 2006], for which $\tau \sim (1/\delta)^{1/2}$

End-Members (small and large slip) of Thermal Pressurization

Slip-on-a-plane TP (2):

Comparison of the complete slip-weakening curves for true dynamic vs. kinematically-imposed [Rice, 2006] slip-on-a-plane:

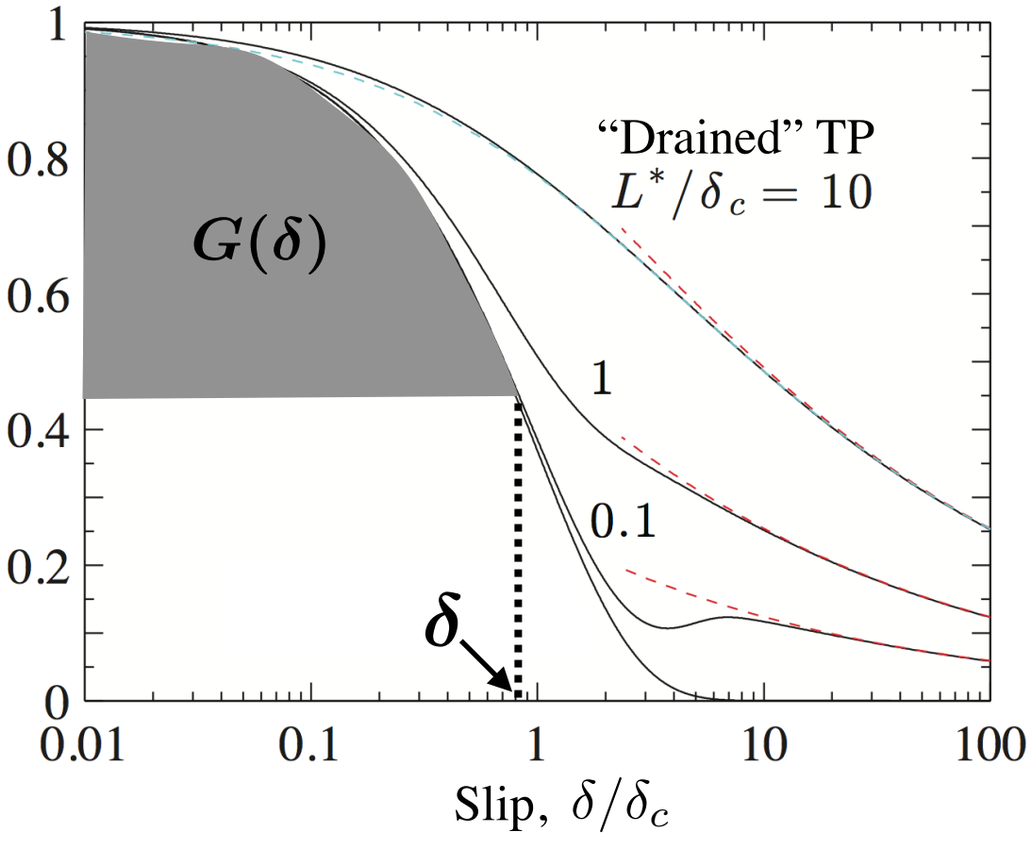


Slow, fractional power-law weakening of strength with slip implies no well-defined "end" to weakening, and strictly diverging fracture energy. For such a case of incomplete weakening, a useful alternative definition of fracture energy [Ida 1972; Palmer and Rice 1973] is $G(\delta) = \int_0^{\delta} [\tau(\delta') - \tau(\delta)] d\delta'$.

This implies $G \sim \delta^{2/3}$ for "drained" thermal pressurization under dynamic slip (and $G \sim \delta^{1/2}$ for kinematically-imposed slip).

Complete Solution (from small to large slip) of TP Weakening

Parameter L^*/δ_c measures the efficiency of drainage of pore fluid and heat away from fault gouge



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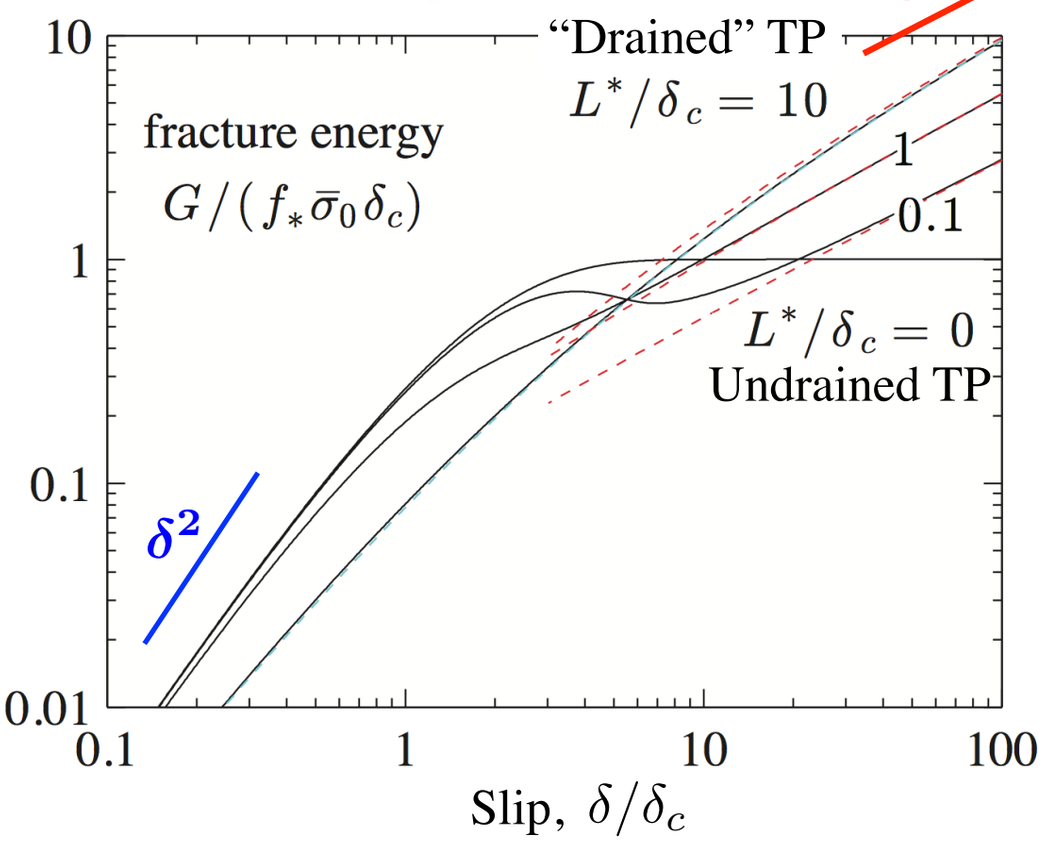
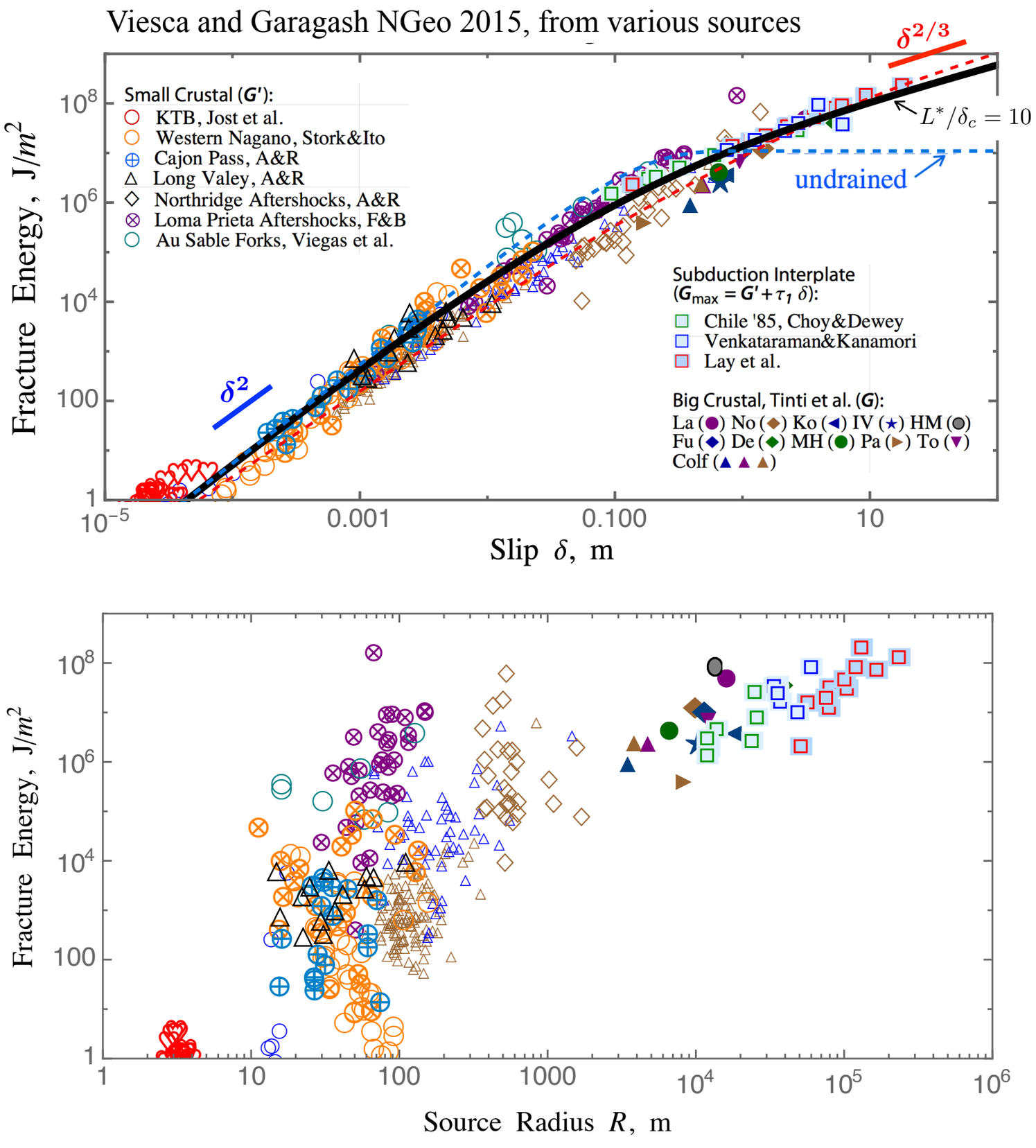


$$\frac{L^*}{\delta_c} = \frac{\rho c}{f_w \Lambda} \frac{4\alpha}{hV_*}$$

$$V_* = (f_w \bar{\sigma}_0 / \bar{\mu}) v_r$$

Inferred Fracture Energy vs. Event Slip vs. Event Size



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  [Rice JGR 2006; Garagash JGR 2012; Viesca and Garagash NGeo 2015]

- Hypothesis 2: $G_c(R)$
  Fracture energy is a fault property, a ***function of fault size*** / maturity / total fault accrued slip
  [e.g. Scholz et al. JGR 1993]

- Hypothesis 1+2: $G_c(R) + \Delta G(\delta)$
  Weakening processes cascade with 'small-slip' fracture energy (a fault property) followed by continuing weakening, 'large-slip' fracture energy (fault-invariant)

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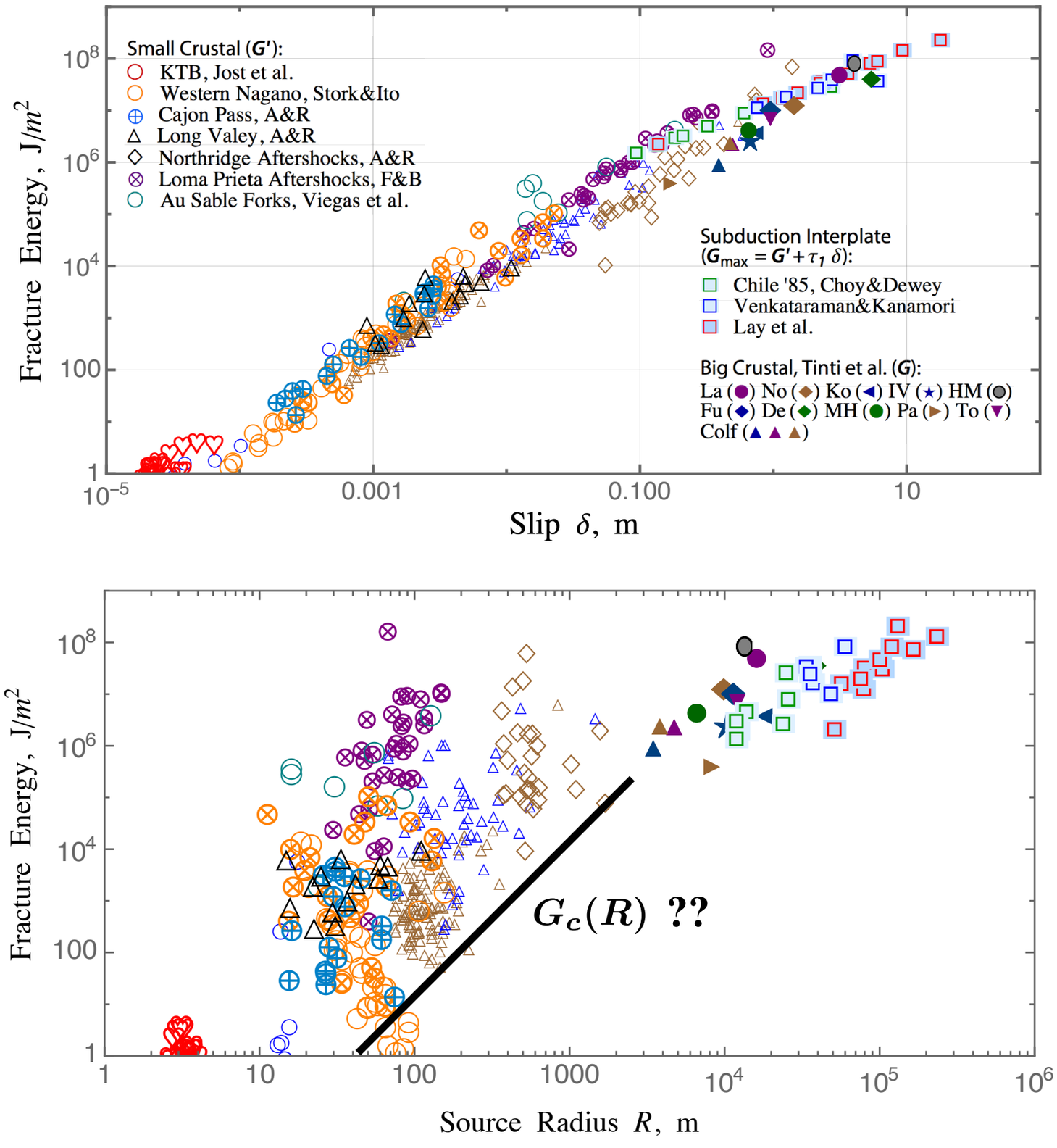
Viesca and Garagash NGeo 2015, compilation from various sources



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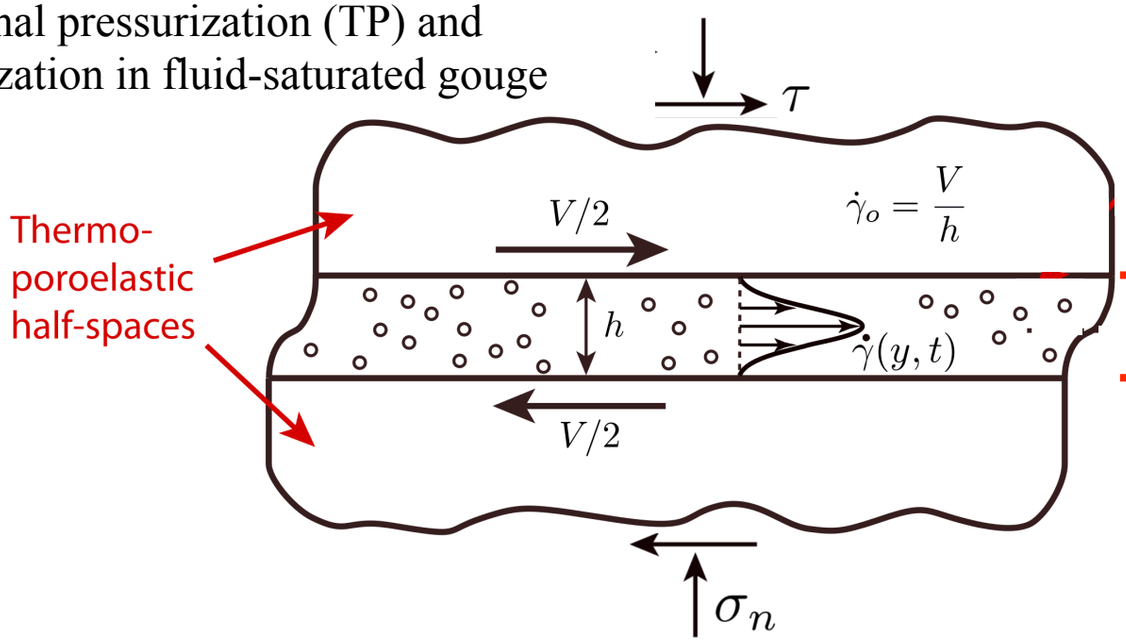
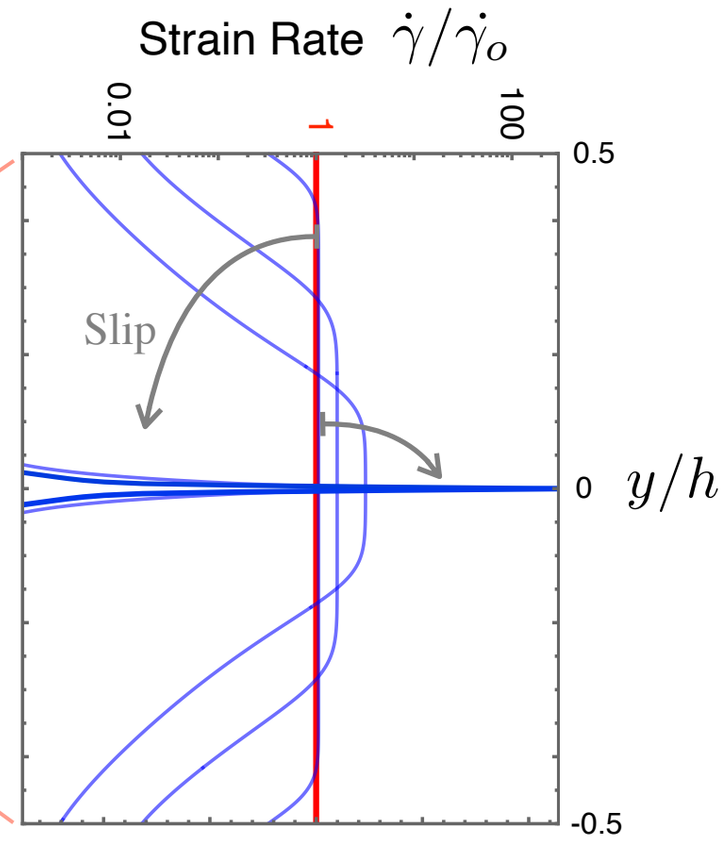
Example of Fracture Energy Decomposition $G = G_c + \Delta G(\delta)$

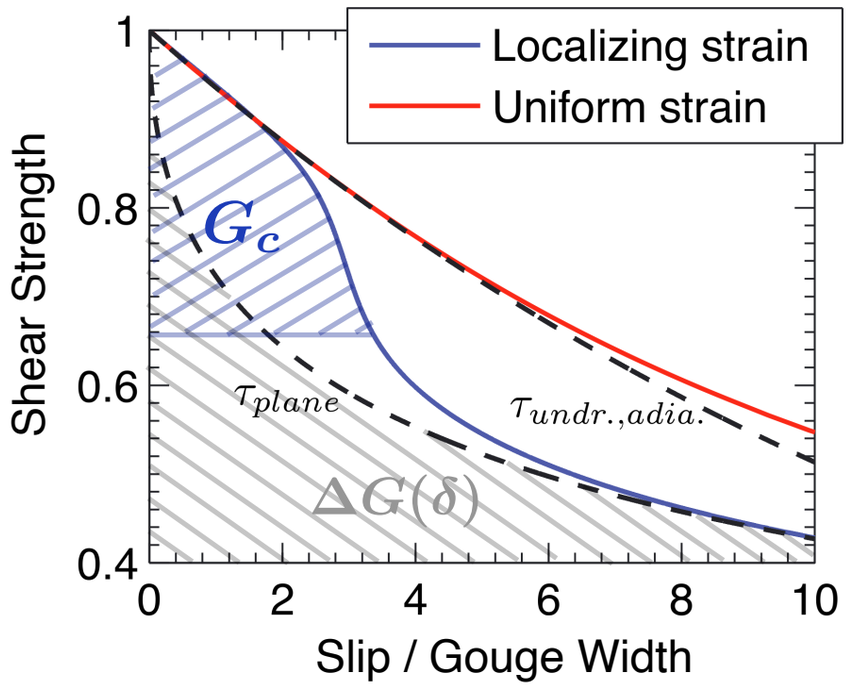
Localization of initially distributed slip (G_c)
followed by continuous TP weakening with slip (ΔG)

Platt, Rice & Rudnicki, JGR 2014
Thermal pressurization (TP) and
localization in fluid-saturated gouge





Gouge layer
of width *h*



Strain localization over ***slip*** distance ~ ***gouge width*** defines minimum fracture energy (***fault property***):

$$G_c \sim (\tau_p - \tau_{plane}(\delta_c)) \times \delta_c, \quad \delta_c \sim h$$

Subsequent ***continuing*** TP weakening on a 'plane'

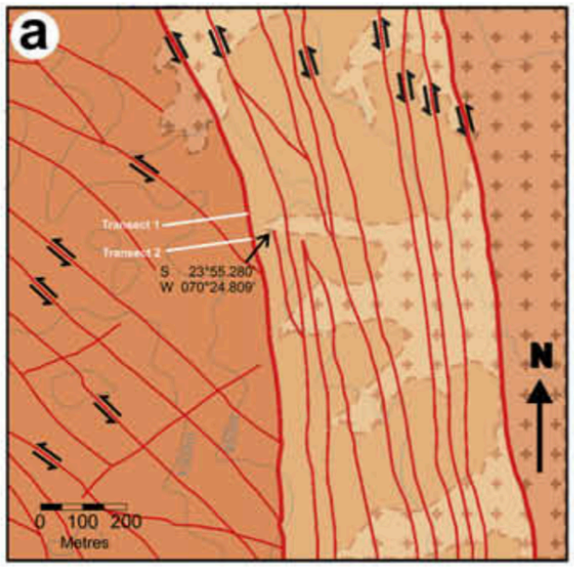
$$\Delta G(\delta) = \int_0^\delta (\tau_{plane}(s) - \tau_{plane}(\delta))ds \propto \delta^{2/3}$$

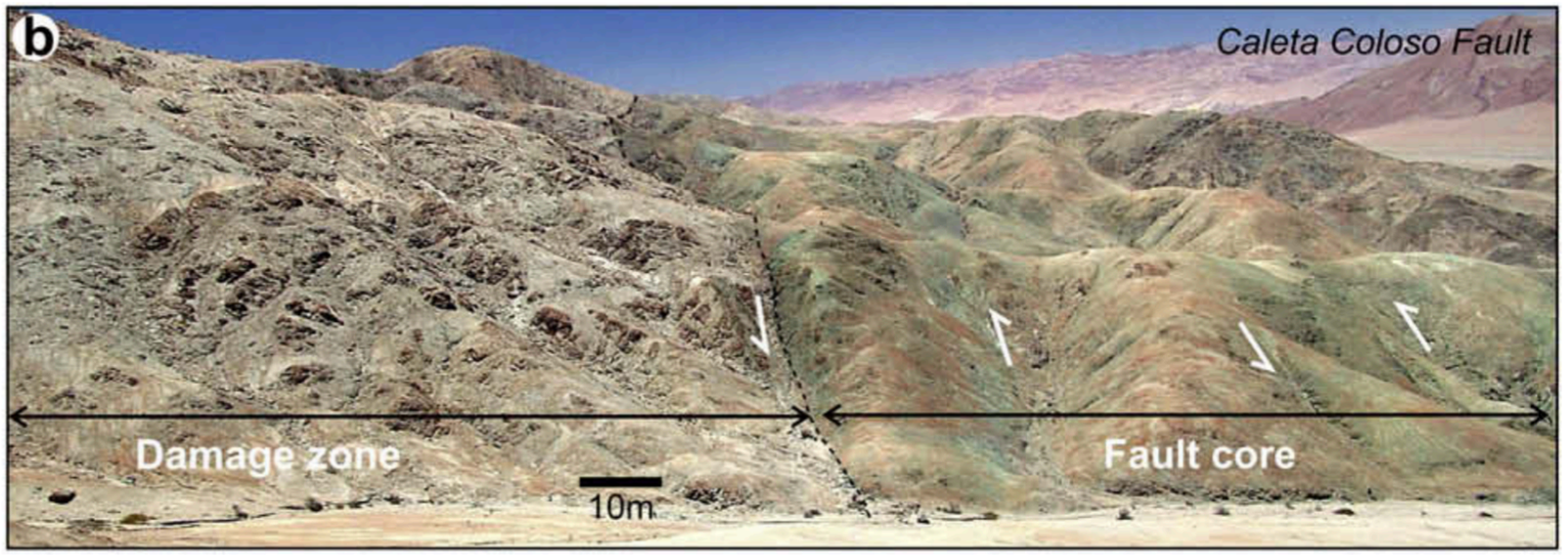
Viesca and Garagash, NGeo 2015

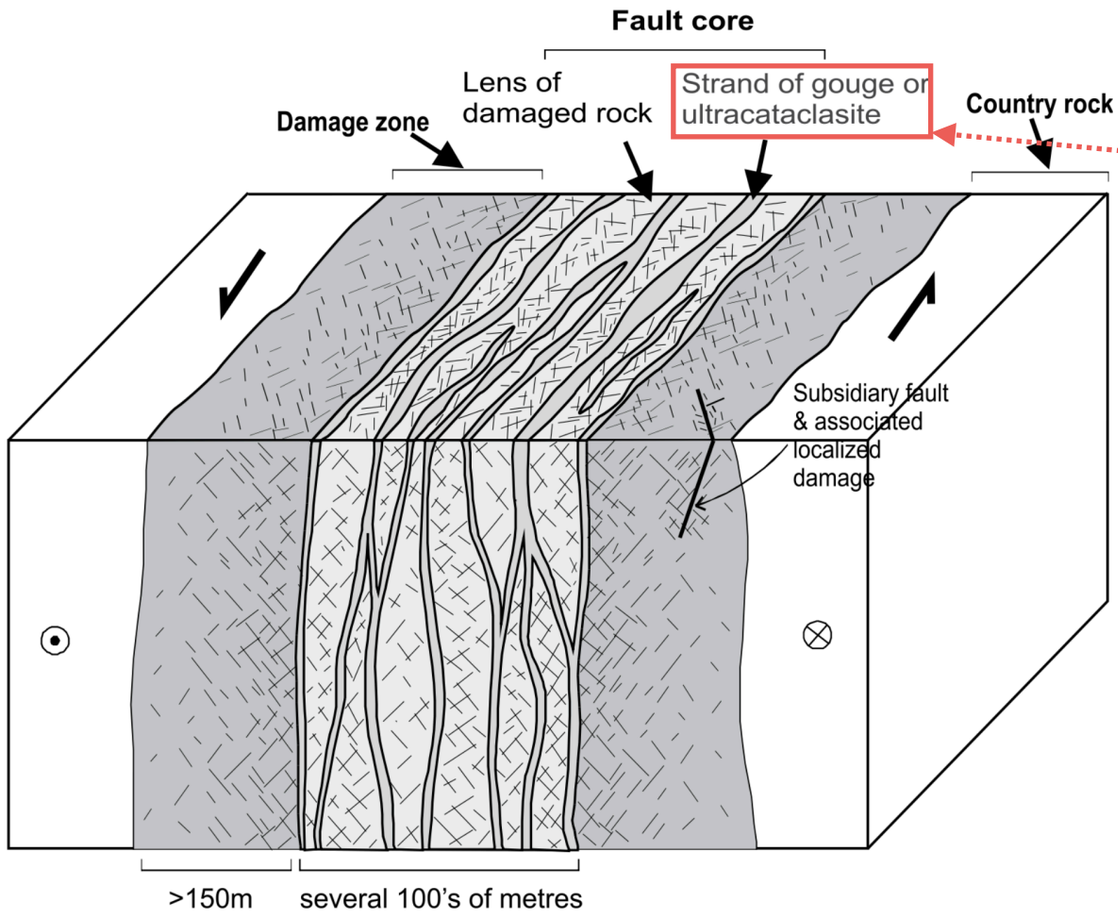
Alternative initial (localizing) and continuing (localized) weakening mechanisms: flash heating [Brantut and Viesca GRL 2017; Paglialunga et al EPSL 2022], thermal decomposition [Platt et al, JGR 2015]

Structure of a Large Fault

Mitchell and Faulkner JSG 2009, Faulkner et al JSG 2010







Candidate **Principal Slip Zone (PSZ)** ~ 0.5 m

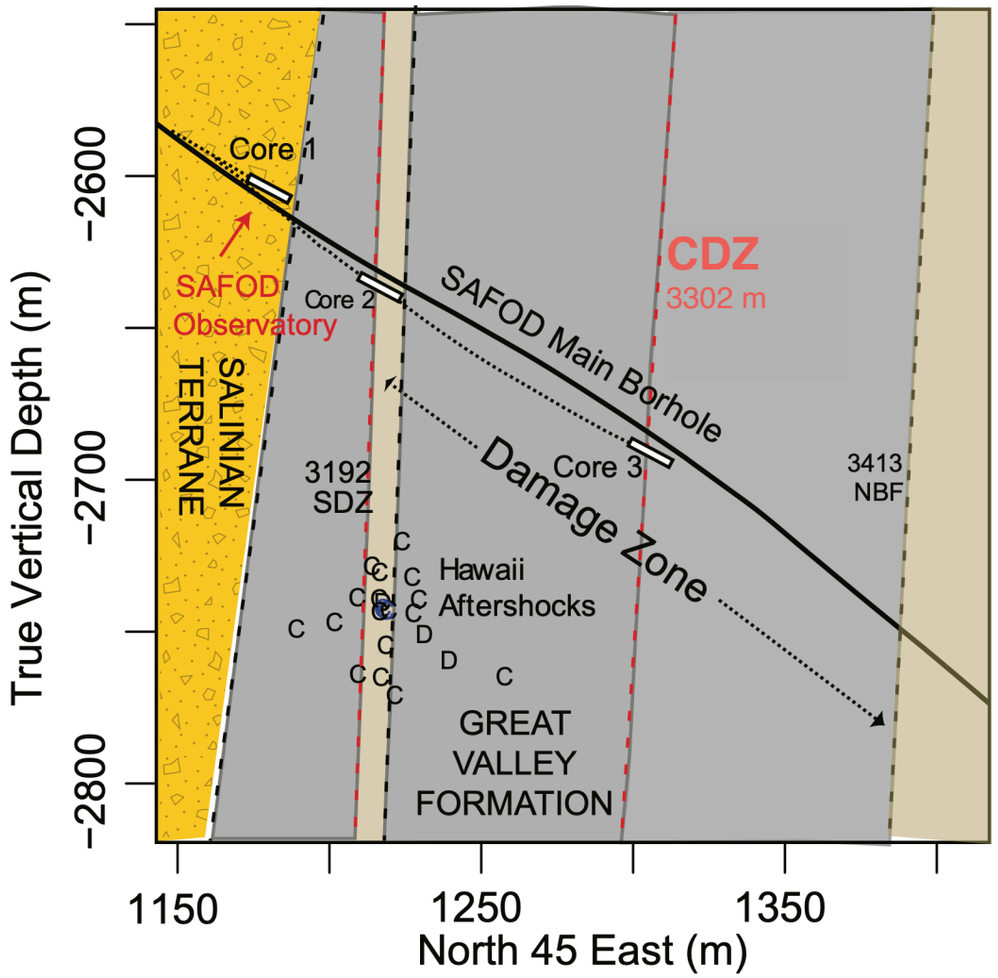
(if initially distributed slip, while can co-seismically localize to ~ mm)

Fault Damage Zone (FDZ) ~ 100's meters

Multiscale, conjugate system fractures:
from *micro-fractures* to *macro-fractures* to *subsidiary faults* with maximum size commensurate with the thickness of FDZ

Example: Principle Slip Zone San-Andreas Fault at SAFOD

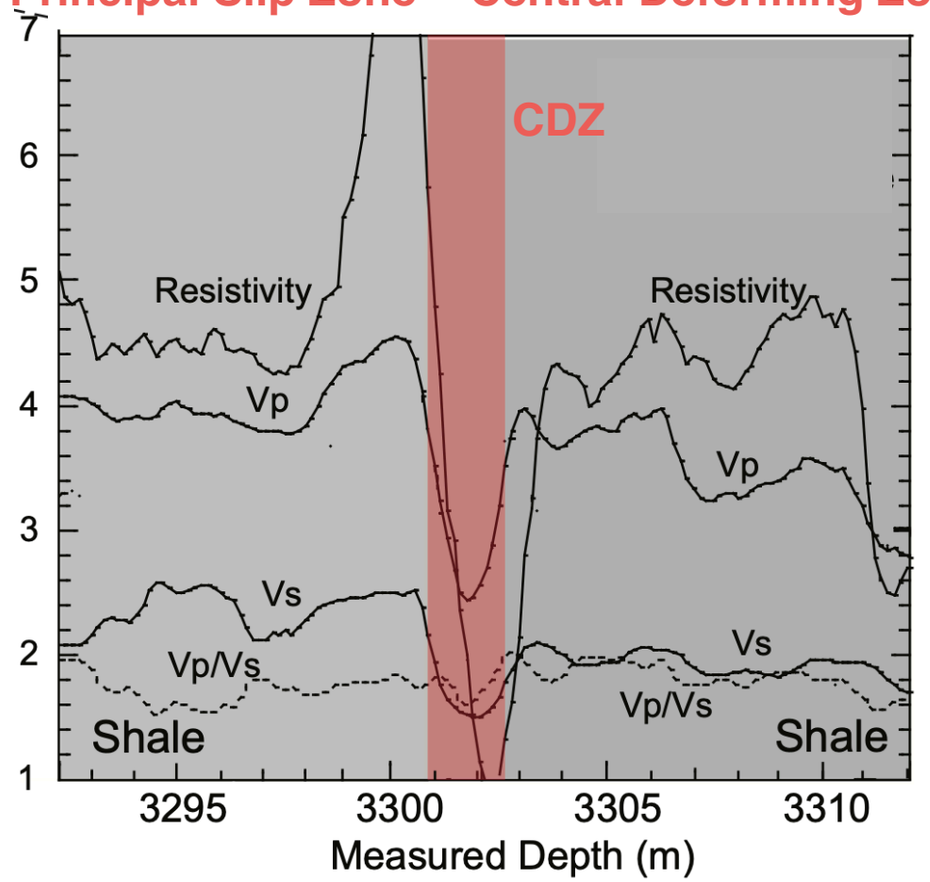
Zoback, Hickman & Ellsworth, Sci. Drill. 2010

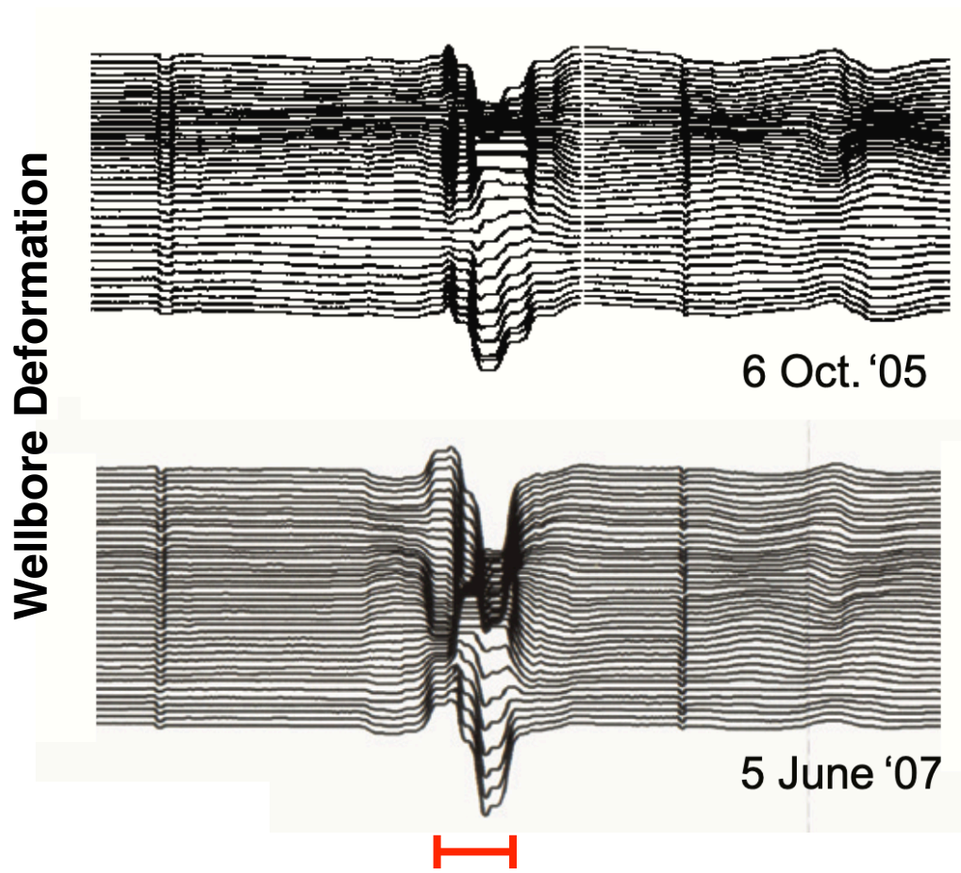


Fault minimum dimension R ~ crust thickness 25 km

Slip distance to localize shear strain,
δ_c ~ few meters

Principal Slip Zone - 'Central Deforming Zone'

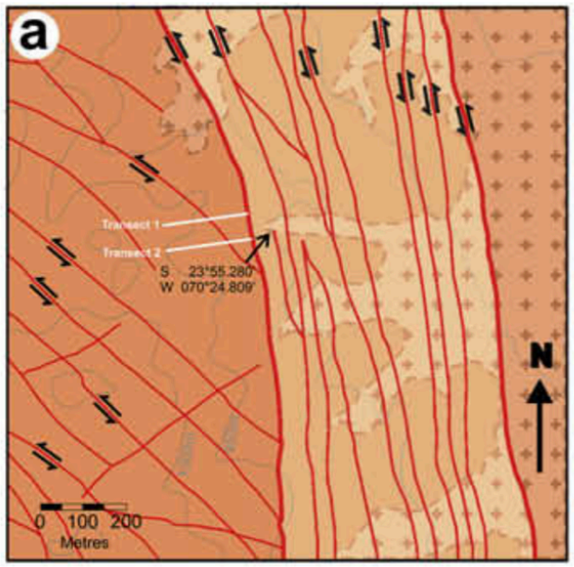


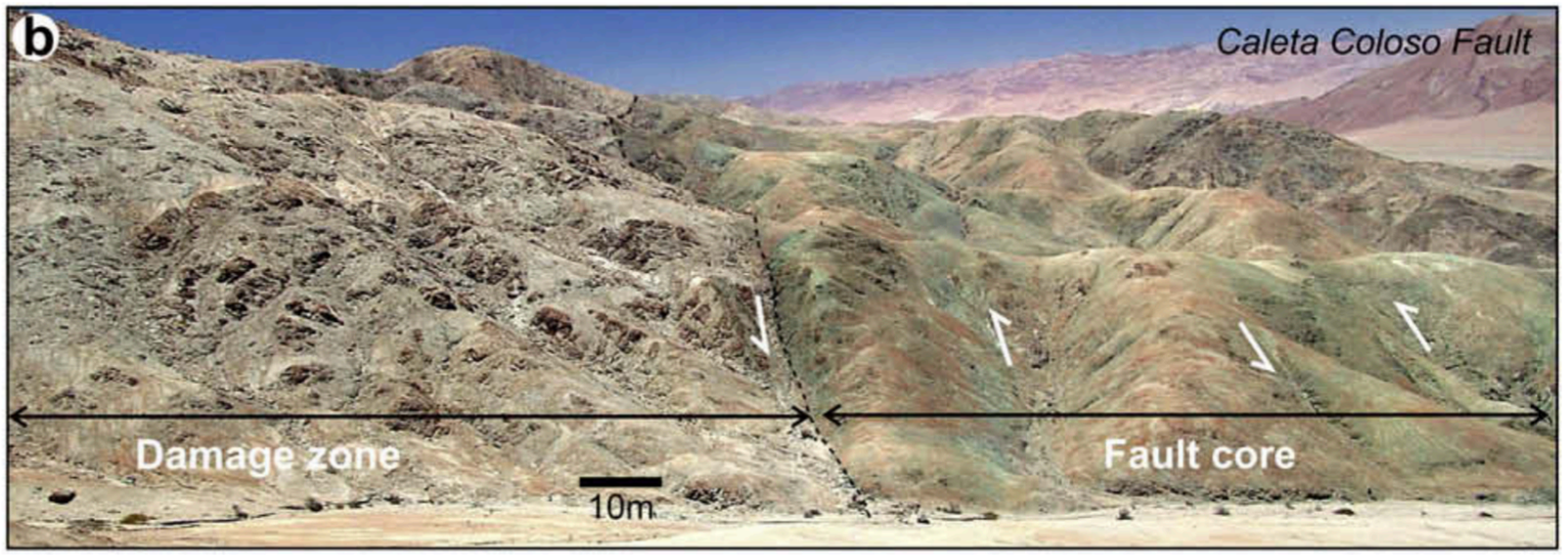


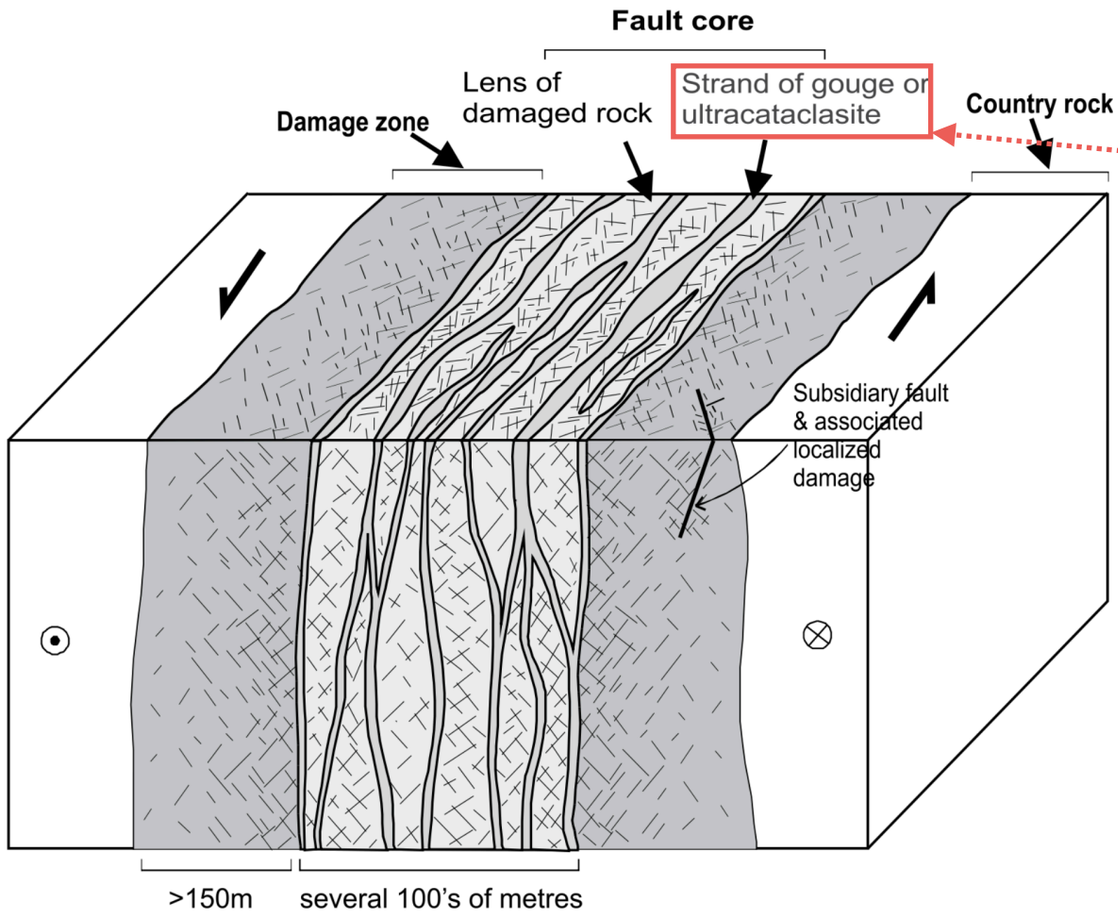
Principal Slip Zone, h ~ 1.5 meters

Structure of a Large Fault

Mitchell and Faulkner JSG 2009, Faulkner et al JSG 2010







Candidate **Principal Slip Zone (PSZ)** ~ 0.5 m

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Multiscale, conjugate system fractures:
from *micro-fractures* to *macro-fractures* to *subsidiary faults* with maximum size commensurate with the thickness of FDZ

Multi-scale fractures/faults in FDZ can also slip, one at a time, producing microseismicity, or perhaps as a dynamic cascade

What is the scaling of principal slip zone thickness with fault/fracture size?

Scaling Conjecture:
Principle Slip Zone vs Fault Damage Zone vs Fault Size
(capped by crust thickness)

Fault Damage Zone ~ 2 (Total Fault Slip)
[Savage and Brodsky JGR 2011]

Total Fault Slip ~ 3 10^{-3} (Fault Size R)
[Scholtz et al JGR 1993; Gudmundson JSG 2000]

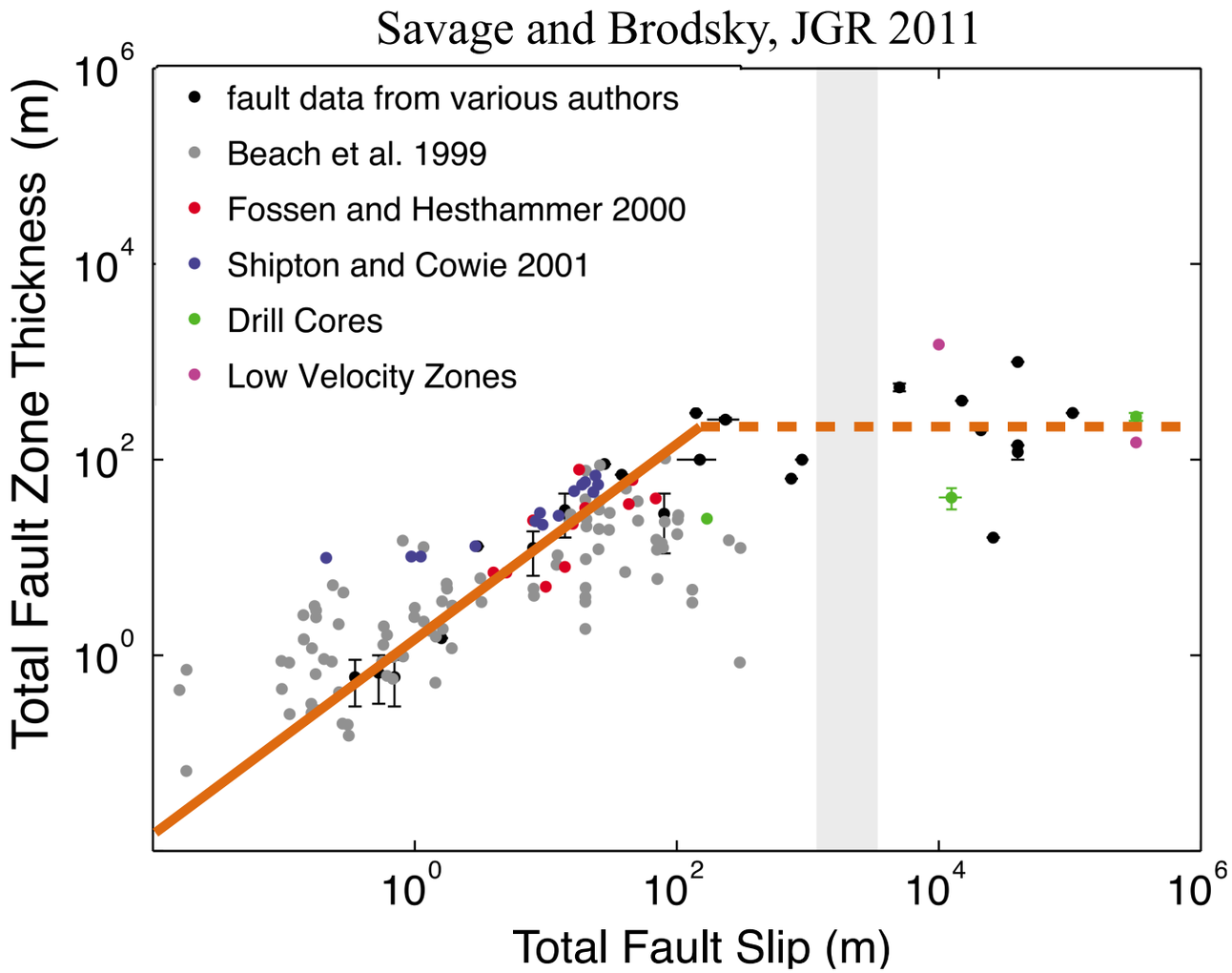
(Principal Slip Zone h) / Fault Damage Zone ~ 0.5 / 100
[e.g. Mitchell and Faulkner JSG 2009]

⬇

(Principal Slip Zone h) ~ 3 10^{-5} (Fault Size R)

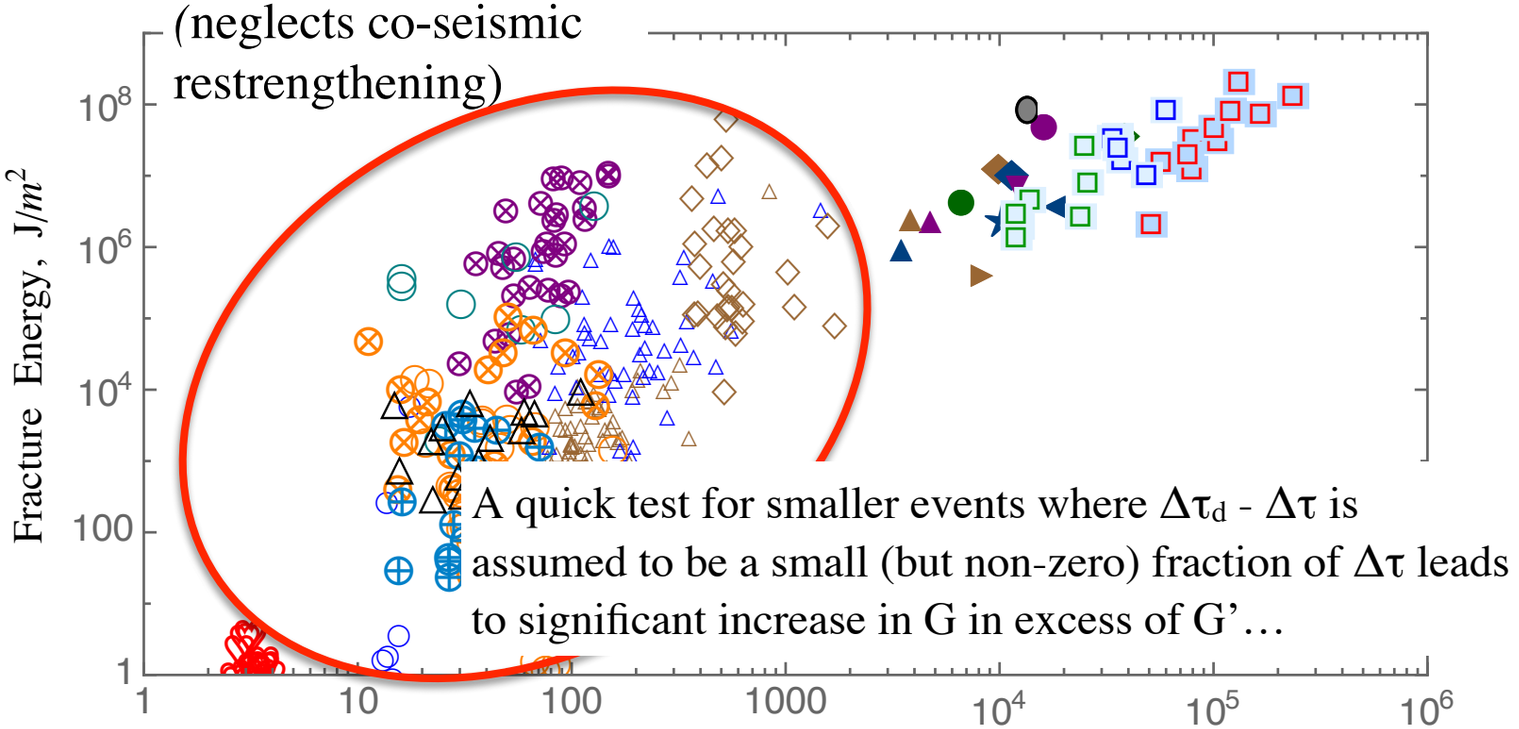
Recall, slip distance to localize shear strain, $\delta_c \sim h$

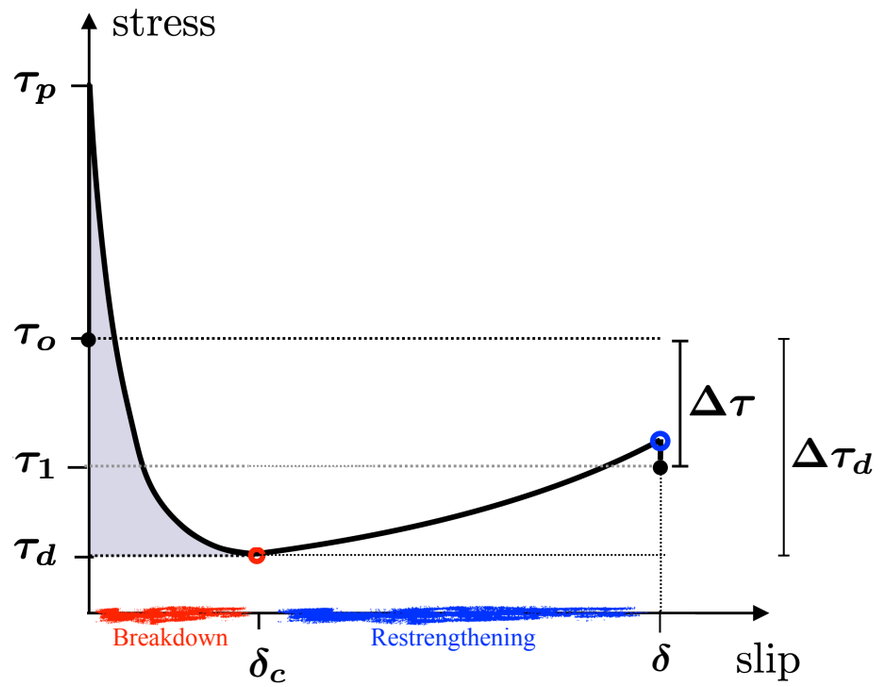
Does this imply that corresponding minimum fracture energy G_c also scales linearly with fault size?



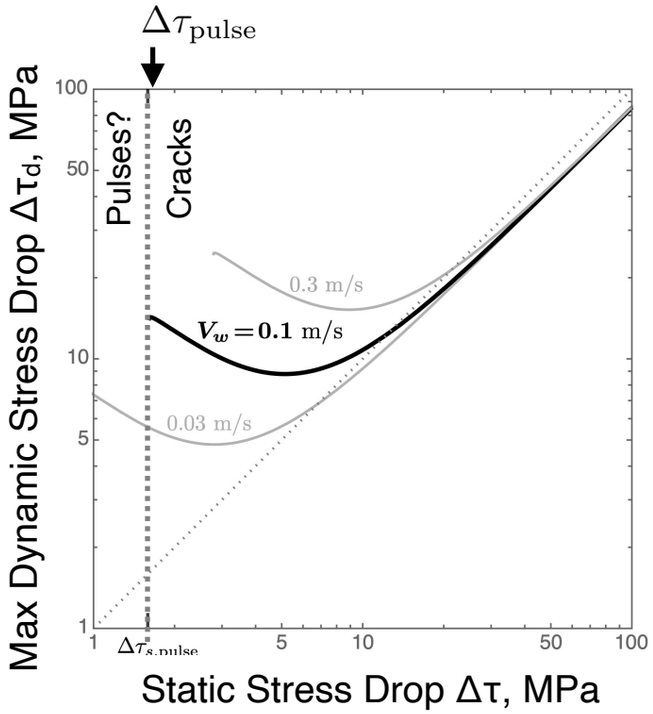
Revisit Inferred Fracture Energy for Smaller Events

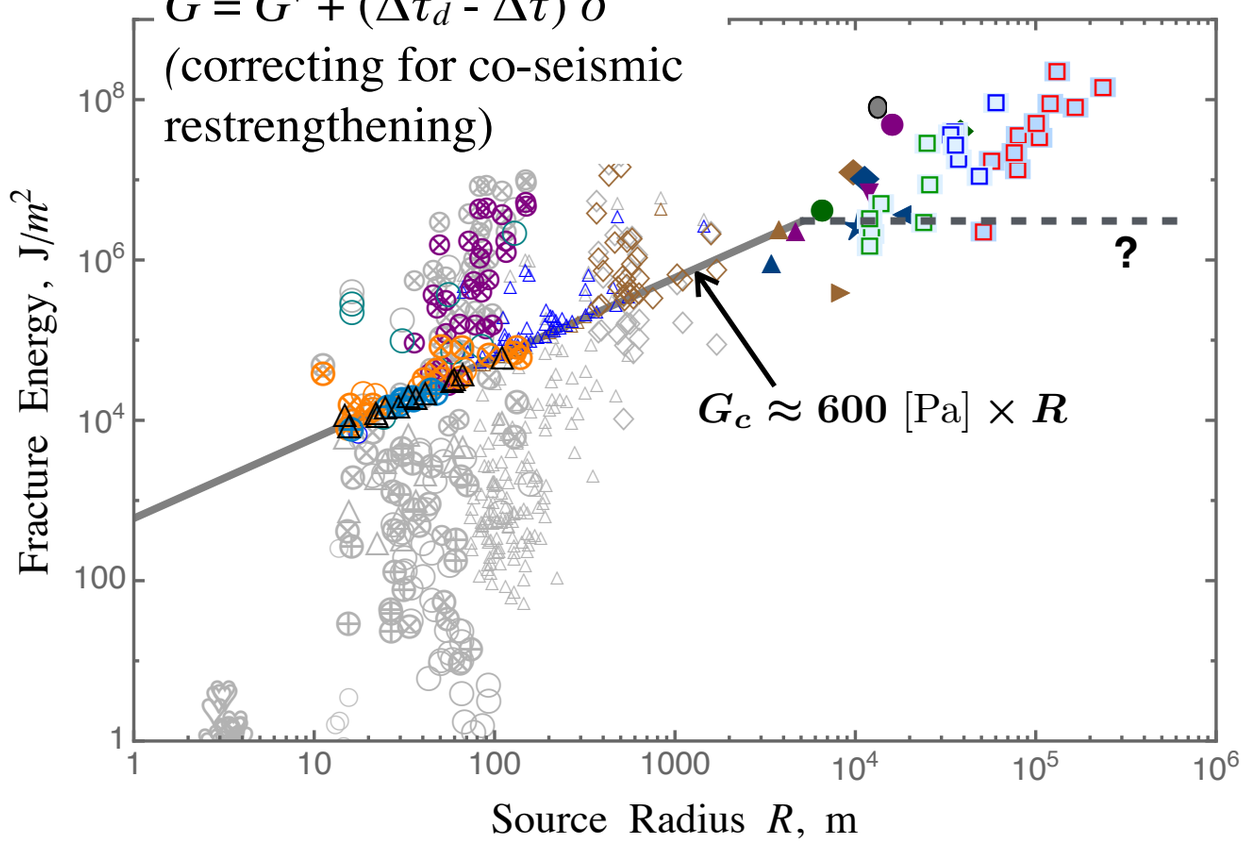
$G = G' + (\Delta\tau_d - \Delta\tau)\,\delta$
(neglects co-seismic restrengthening)





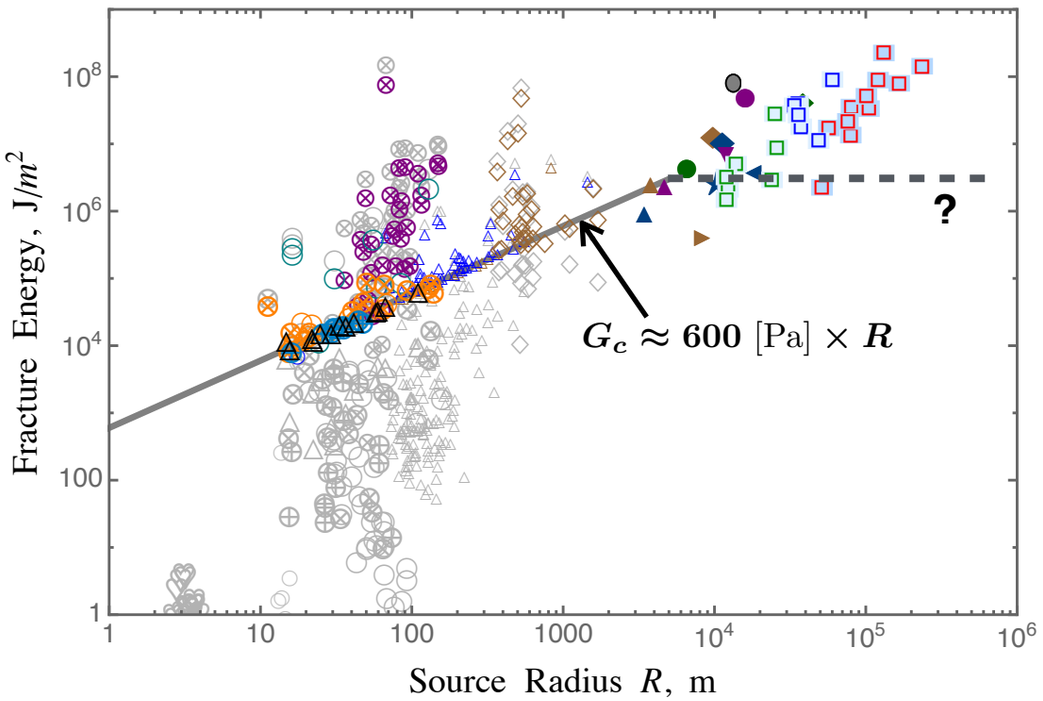
A physics-based model for the fault friction (rate/state friction with flash-heating at high slip velocity $V>V_w$) allows to evaluate co-seismic restrengthening in a circular crack-like rupture propagation and relate $\Delta\tau_d$ to $\Delta\tau$





Seismologically Inferred Small Slip Fracture Energy and Application to a Multi-scale 3D Dynamic Rupture Model

We use the emergent **linear scaling of the minimum fracture energy G_c with fault size to model** mechanically viable composite earthquake ruptures occurring as **a cascade over networks of faults/fractures** of very different sizes.

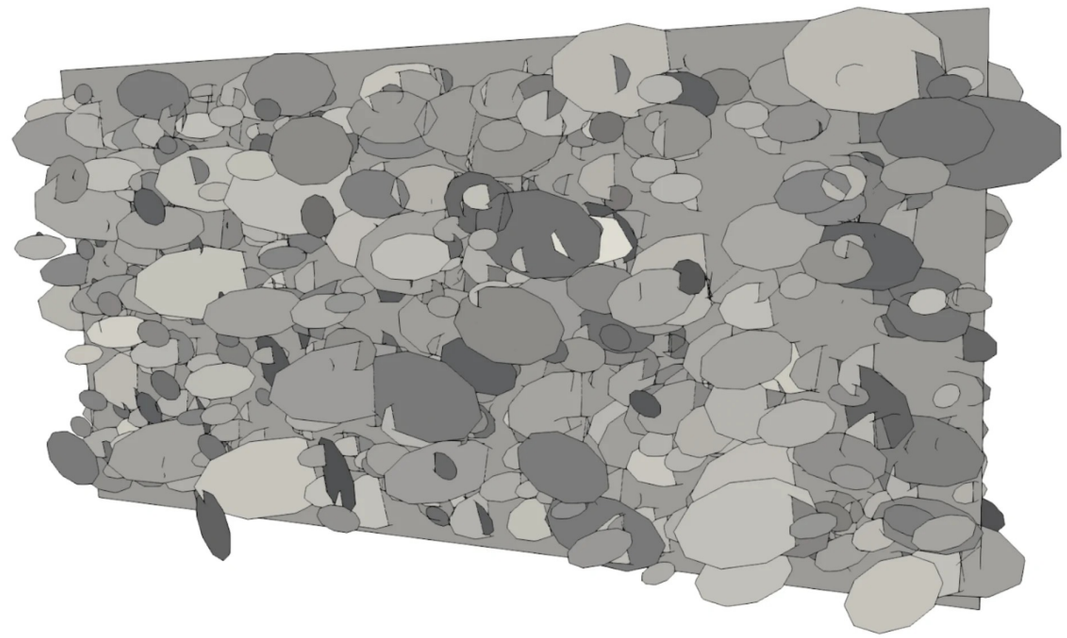


Side view: **Strike Slip Fault** embedded in **Damage Zone** consisting **~ 700 fractures** ***of two conjugate families***

[e.g. numerical observations of co-seismic damage by Okubo et al JGR'19, Gabriel et al PTRS'21, field observations of Faulkner et al 2010]

Fault 8 km by 4 km

Fractures ~ 100 - 500 meters

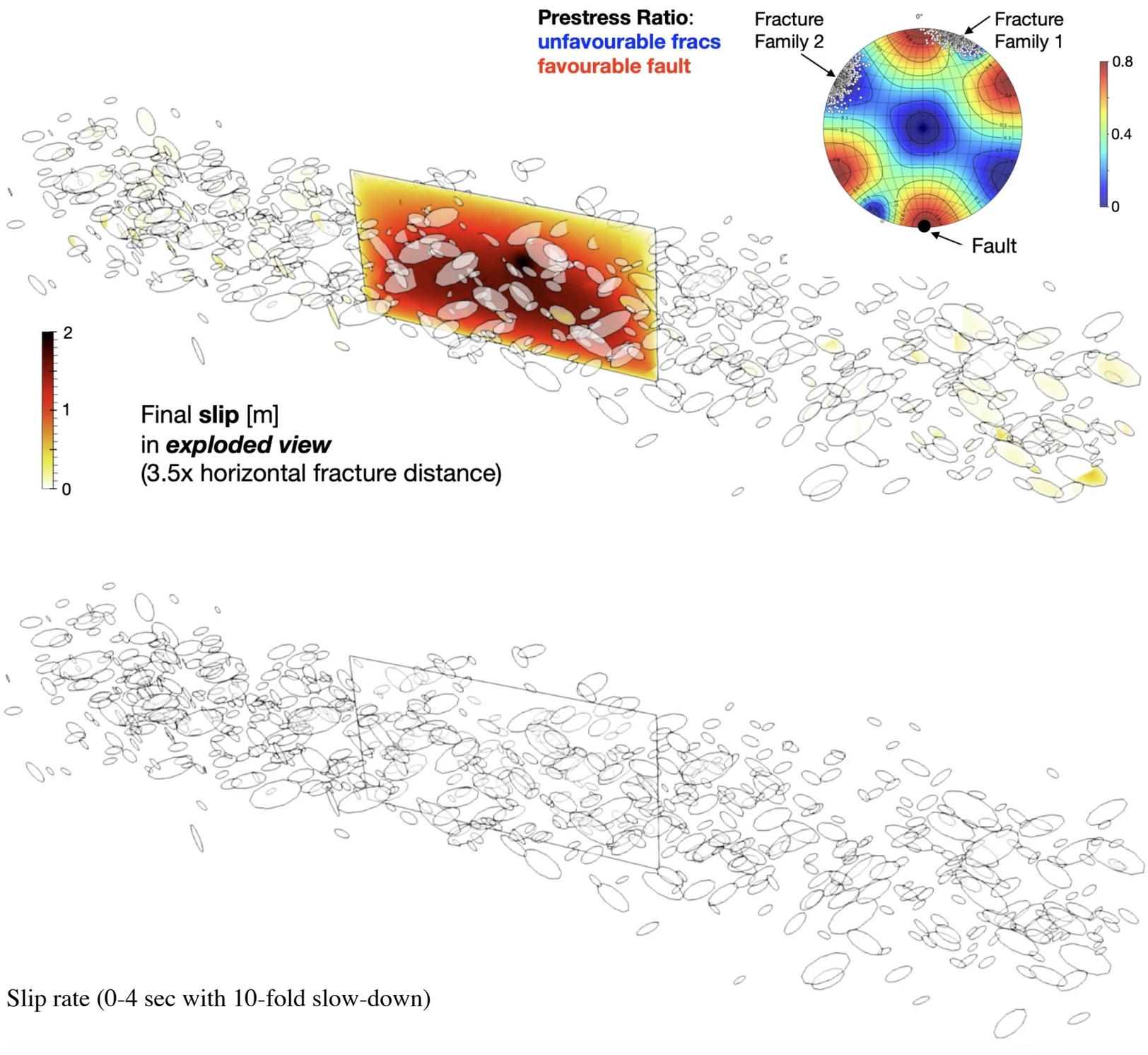


Palgunadi et al. (AGU'21 S22A-04) for further details on a) the fault/fracture-network model construction, b) parametrization, c) implementation in the open-source software SeisSol; as well as e) in-depth exploration of the cascading behaviour as a function of regional stress orientation (prestress) and different (listric) fault geometry

Palgunadi, Gabriel, Garagash, Mai [EGU/AGU 2021]

3D Dynamic Modeling of Cascading Slip Across Fractured Fault Zone: Dynamic Interaction of main fault rupture and off-fault fractures

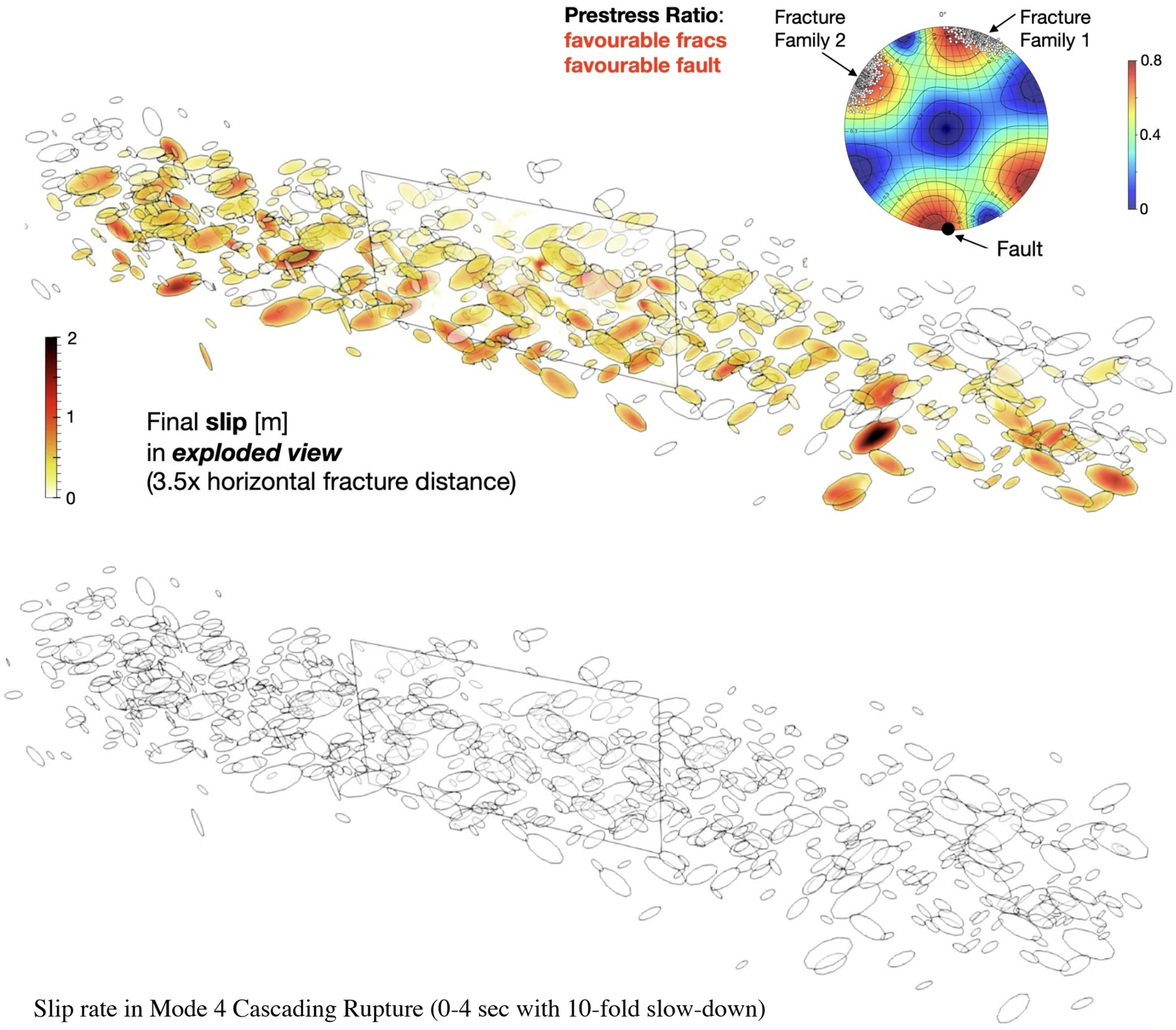
'Classical' Earthquake Rupture
on well-oriented **main fault** activating poorly-oriented fractures in the damage zone (off-fault slip)



Slip rate (0-4 sec with 10-fold slow-down)

3D Dynamic Modeling of Cascading Slip Across Fractured Fault Zone: "Mode 4"

New 'Mode 4' Earthquake Rupture
cascading on well-oriented **multi-scale fractures in the damage zone** (*without* main fault activation)



Slip rate in Mode 4 Cascading Rupture (0-4 sec with 10-fold slow-down)

We identify the following **"mode 4" characteristics:**

1) Potential signatures in seismological observations of cascading slip in a fractured damage zone include

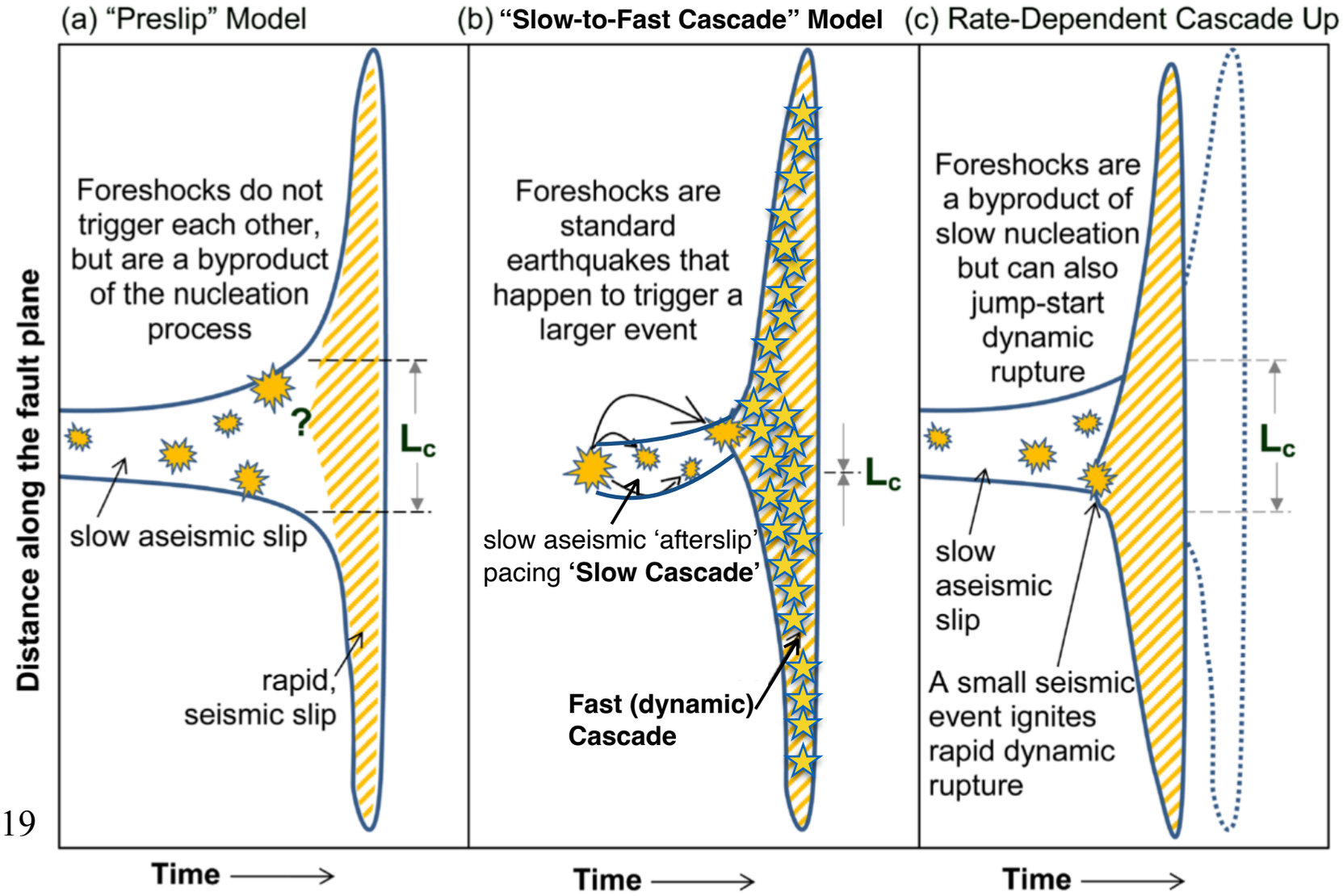
- misaligment of focal mechanism with the fault trace
- naturally limited apparent rupture (cascading) speed - such earthquake can not accelerate to the limiting speed due to rupture branching/ jumping slow-down from one fracture to the next
- complex moment-rate release (intermediate-to-high frequency content)

2) fracture cascading rupture effectively suppresses main fault rupture

Summary

- Seismically Observable Fracture Energy can be decomposed into a fault-size-dependent, small-slip part and potentially fault-invariant, large-slip part increasing continuously with co-seismic slip
- Seismogenesis (nucleation of dynamic slip on a fault) likely defined by the small-slip fracture energy
- Proposed scaling of the minimum fracture energy with fault size allows for seismicity on all scales
- Composite dynamic ruptures on faults embedded in fractured damage zone: a) main fault rupture inducing off-fault seismic slip; b) cascading dynamic rupture on fractures in the damage zone with/ without rupture of the main fault

- Can an EQ be a 'disguised' fast fracture cascade in the damage zone ?
- E.g., 'slow cascade' leading to 'fast cascade'



Modified from McLaskey 2019