"Effect of Brittle off-fault Damage on Earthquake Rupture Dynamics"

Harsha S. Bhat *ÉNS*

Marion Thomas (Oxford)

Raul Madariaga *ÉNS*
Alexandre Schubnel *ÉNS*
Ares J. Rosakis *CalTech*
Charlie Sammis *USC*

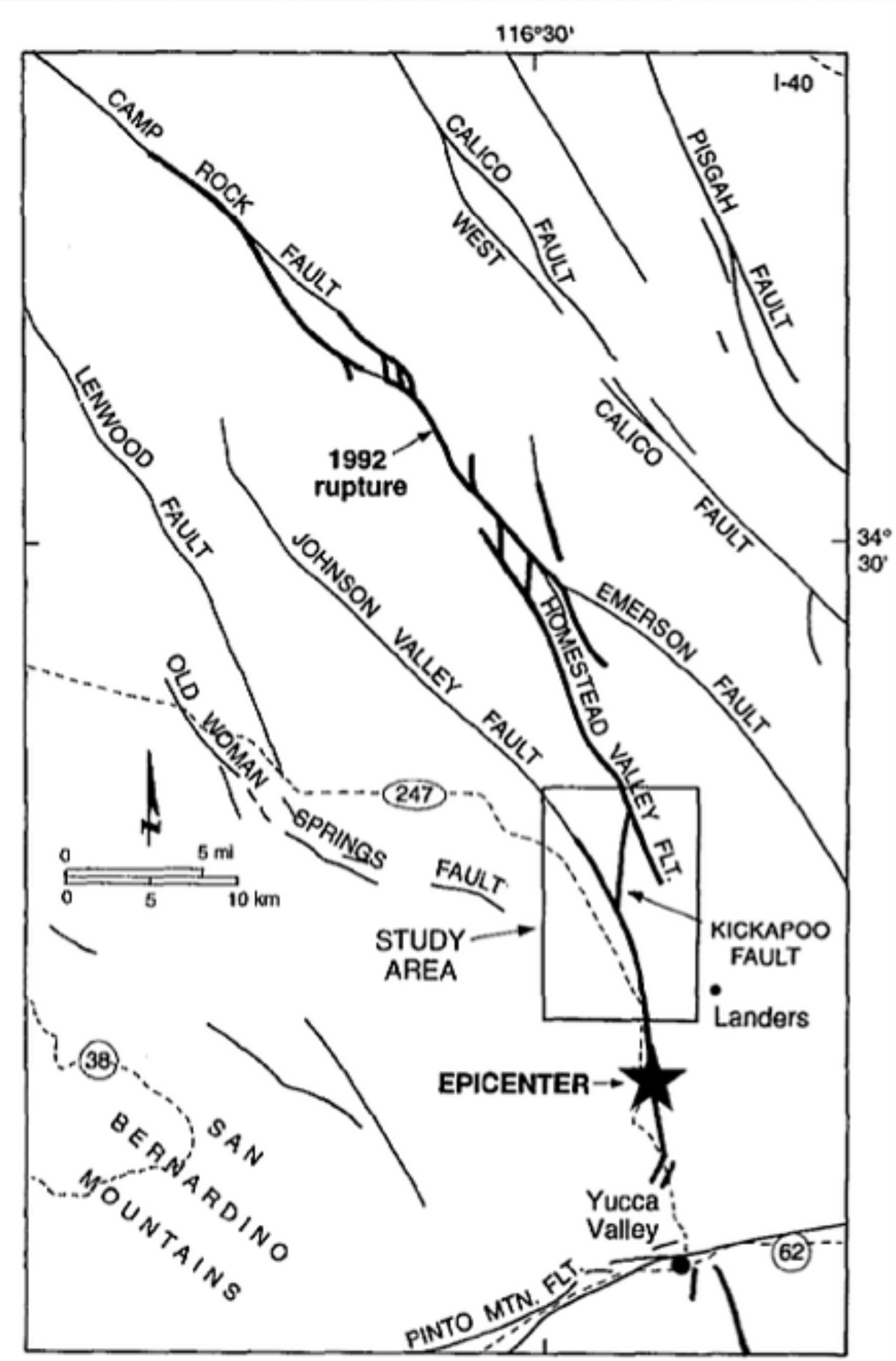
Complexity?

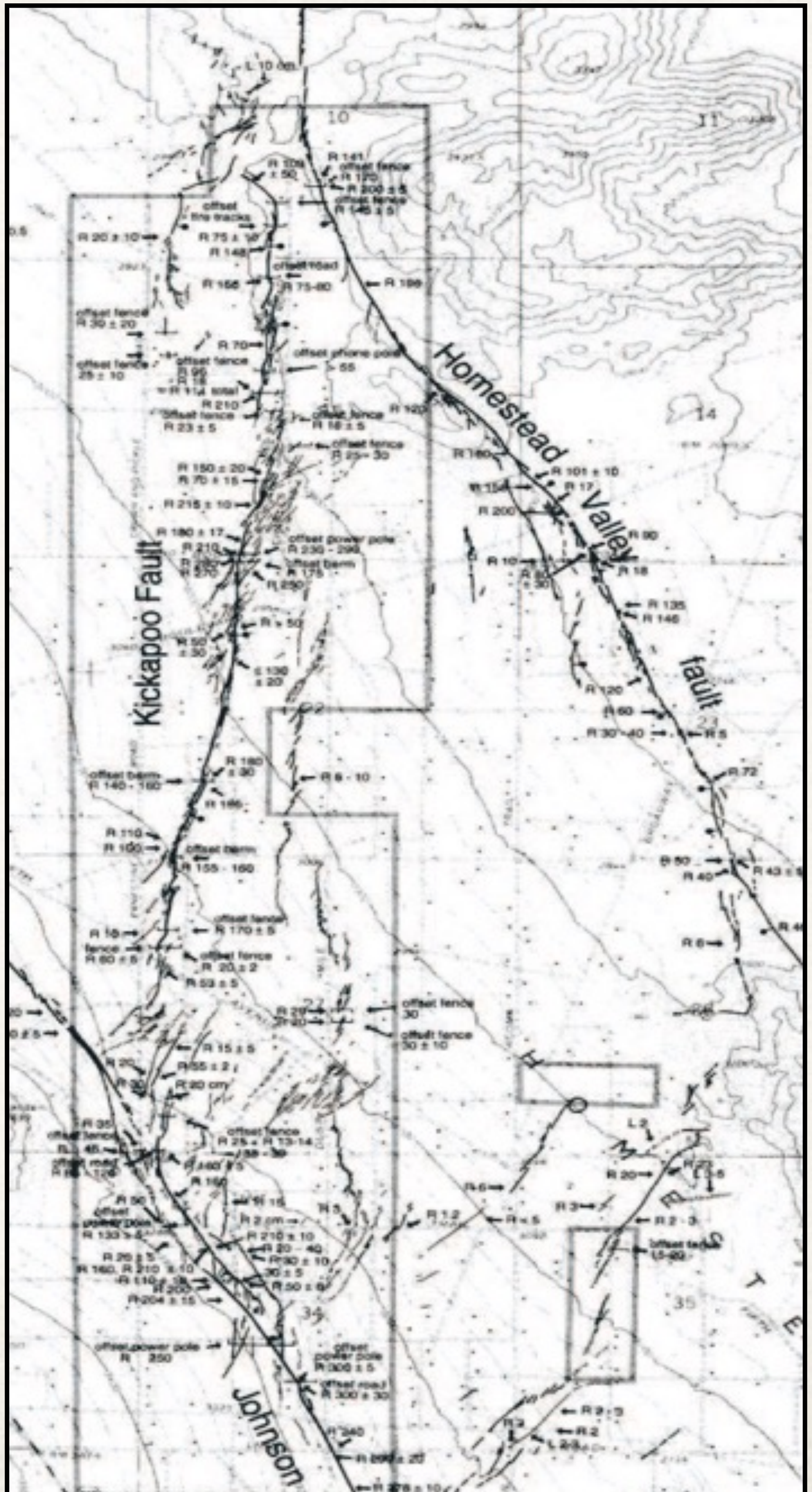
- ***Small Scale Geometric Complexities ("Off-fault damage")***
- ***Large Scale Geometric Complexities (branches, step-overs etc.)***
- **Structural** (hydro-mechanical complexity)
- **Loading** ($k^{-(1+H)}$ stress distribution…)
- **Friction** (R-S law, Flash Heating, Thermal Pressurisation, Thermal Decomposition, Dilatant Strengthening …)
    - ***Source (EQ, Slow EQ, LFE, VLFE, Tremors …)***
    - ***Speed (Migration, sub-shear, supershear …)***
    - ***Radiation (Spectral properties)***

Geometrical Complexities at Various Scales

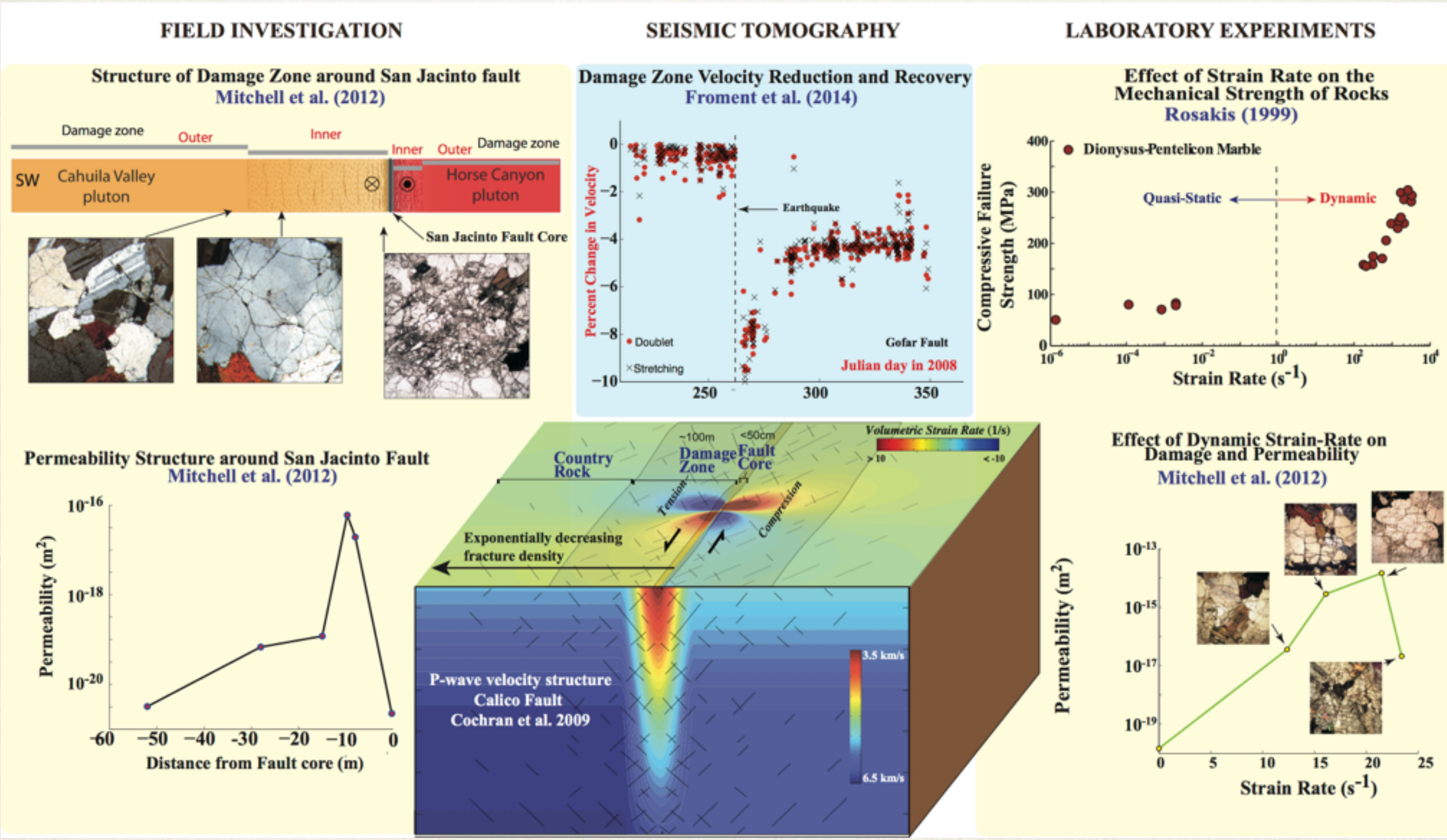
Mw 7.9 1992 Landers, California Earthquake

Sowers et al. 1994

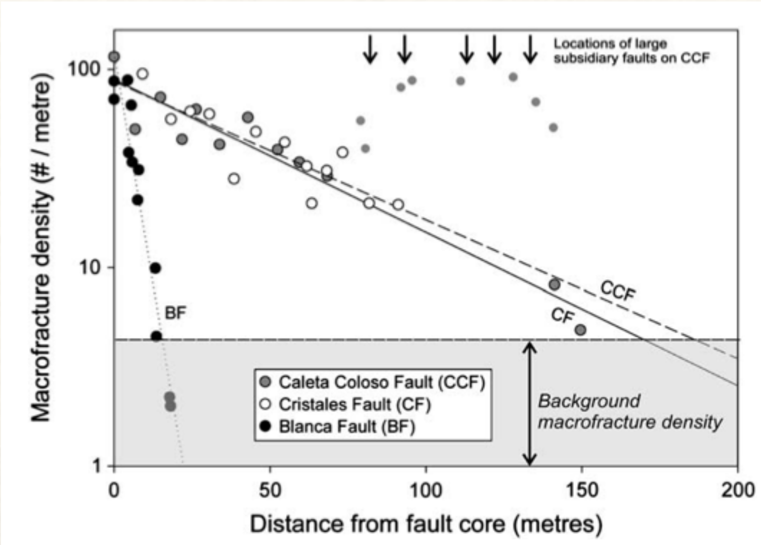




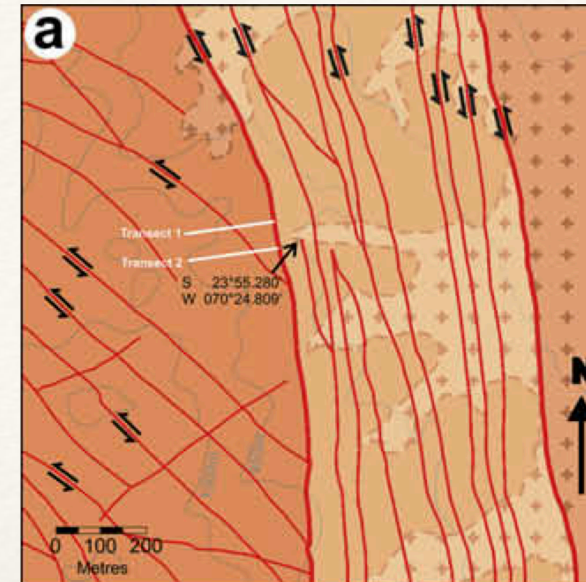
Zooming close to the fault plane : Hydro-Mechanical Complexities

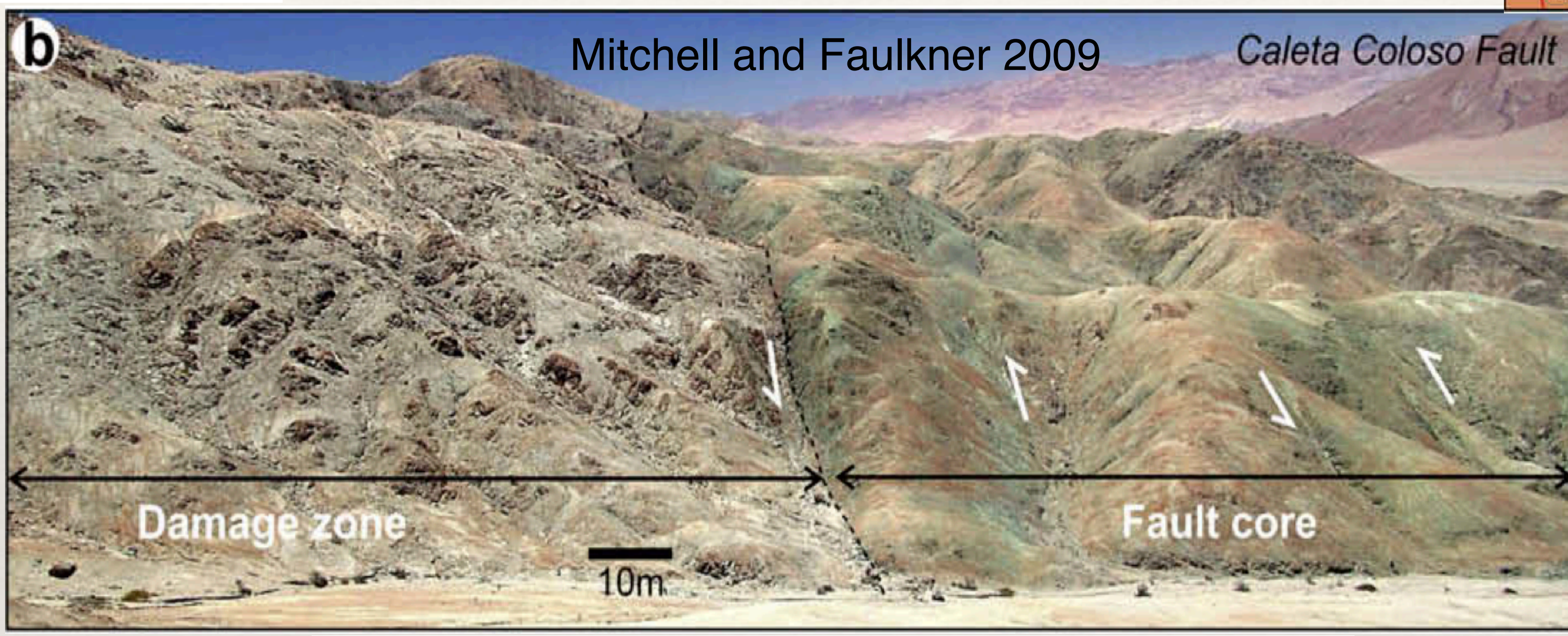


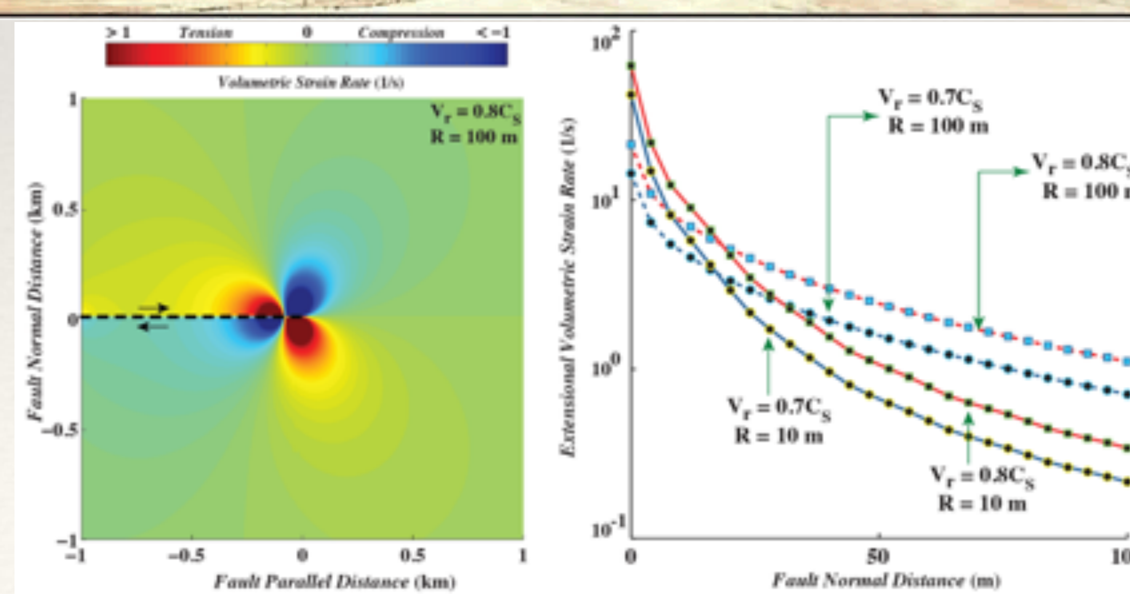
Modelling Earthquake Cycles : Missing ingredients



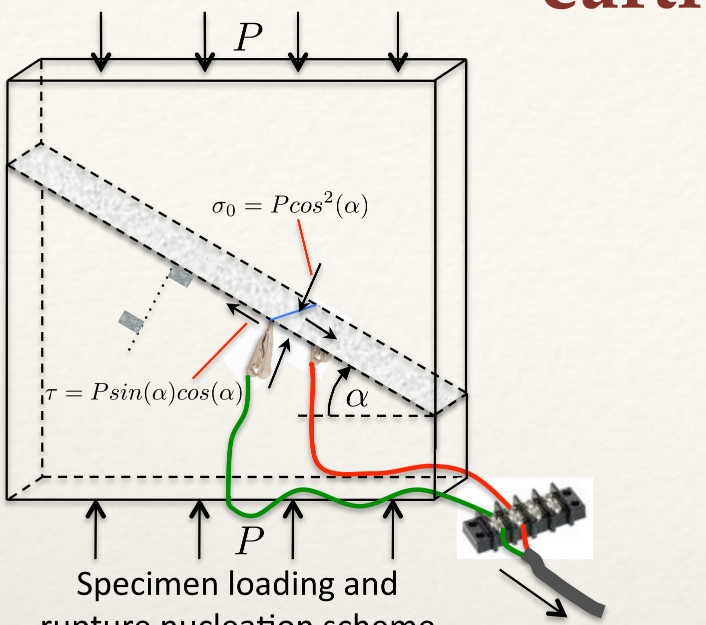
- *Small Scale Geometric Complexities ("damage")*
- *Large Scale Geometric Complexities (branches, step-overs etc.)*



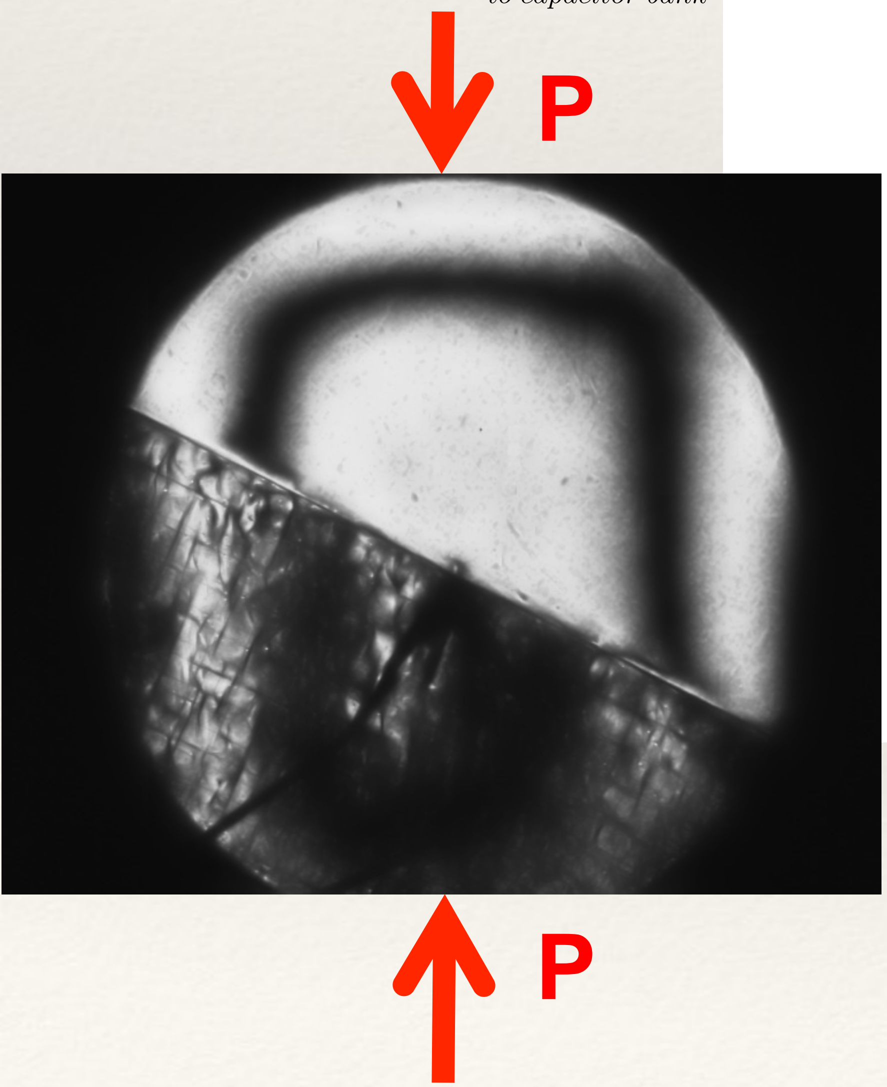


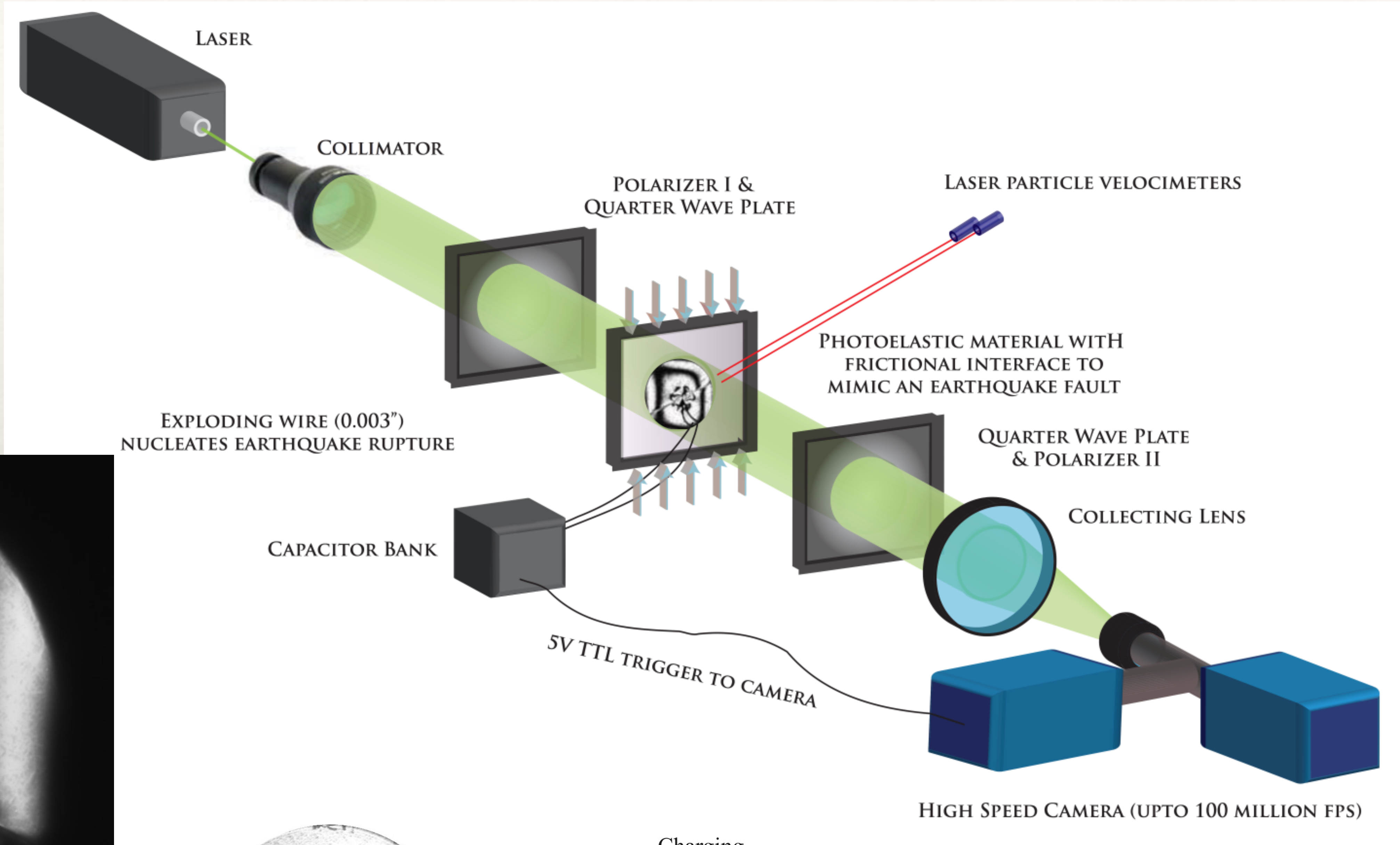


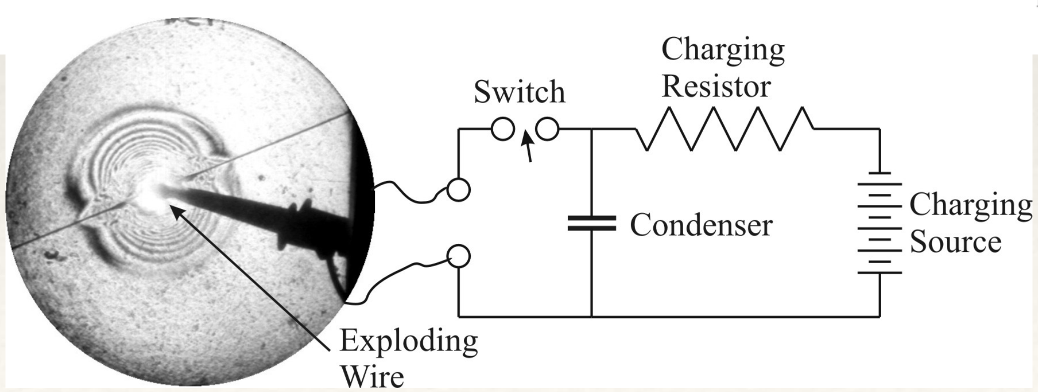
Role of off-fault damage (small scale geometric complexities) on a single earthquake rupture : Laboratory experiments



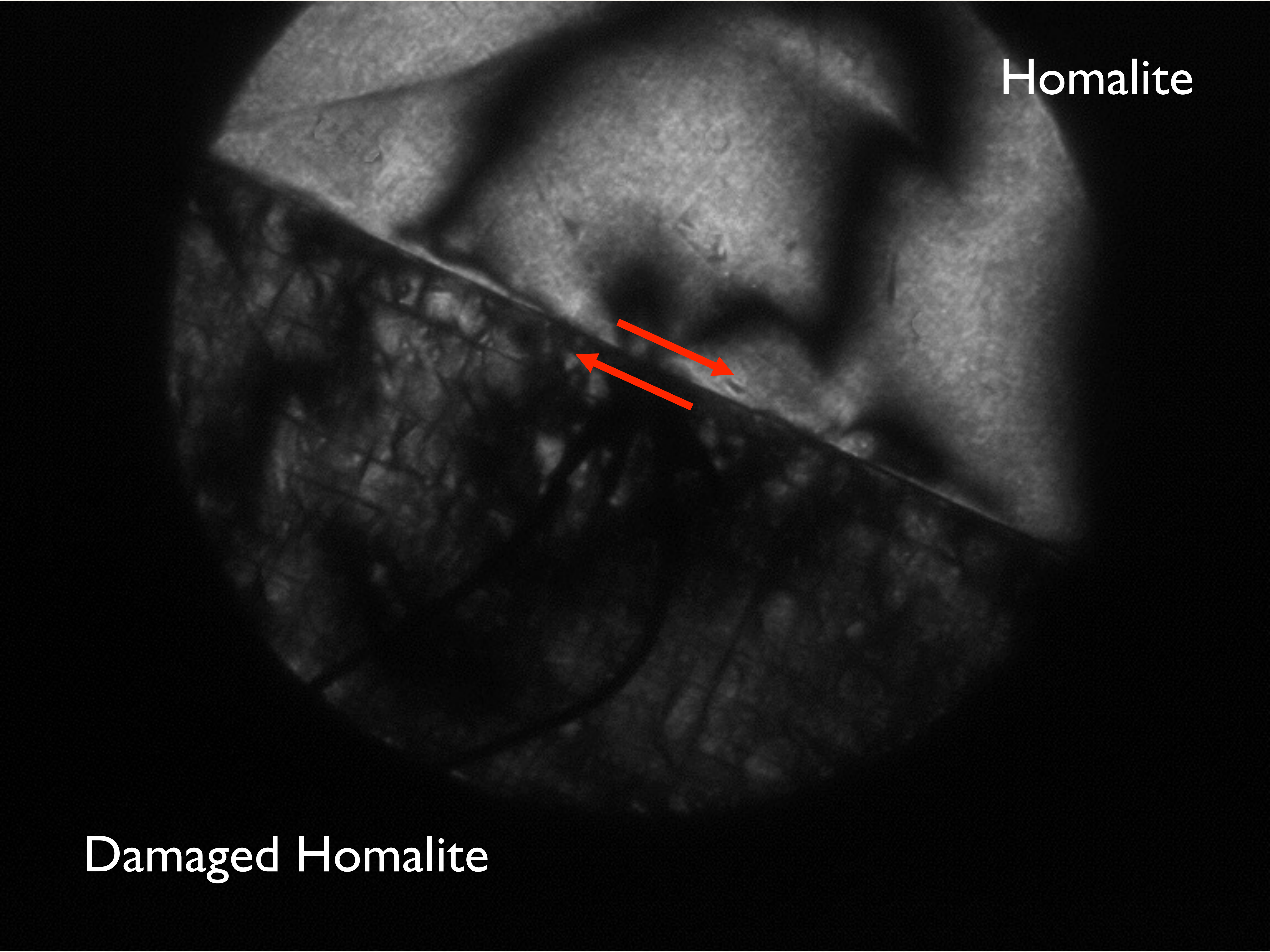
Specimen loading and rupture nucleation scheme



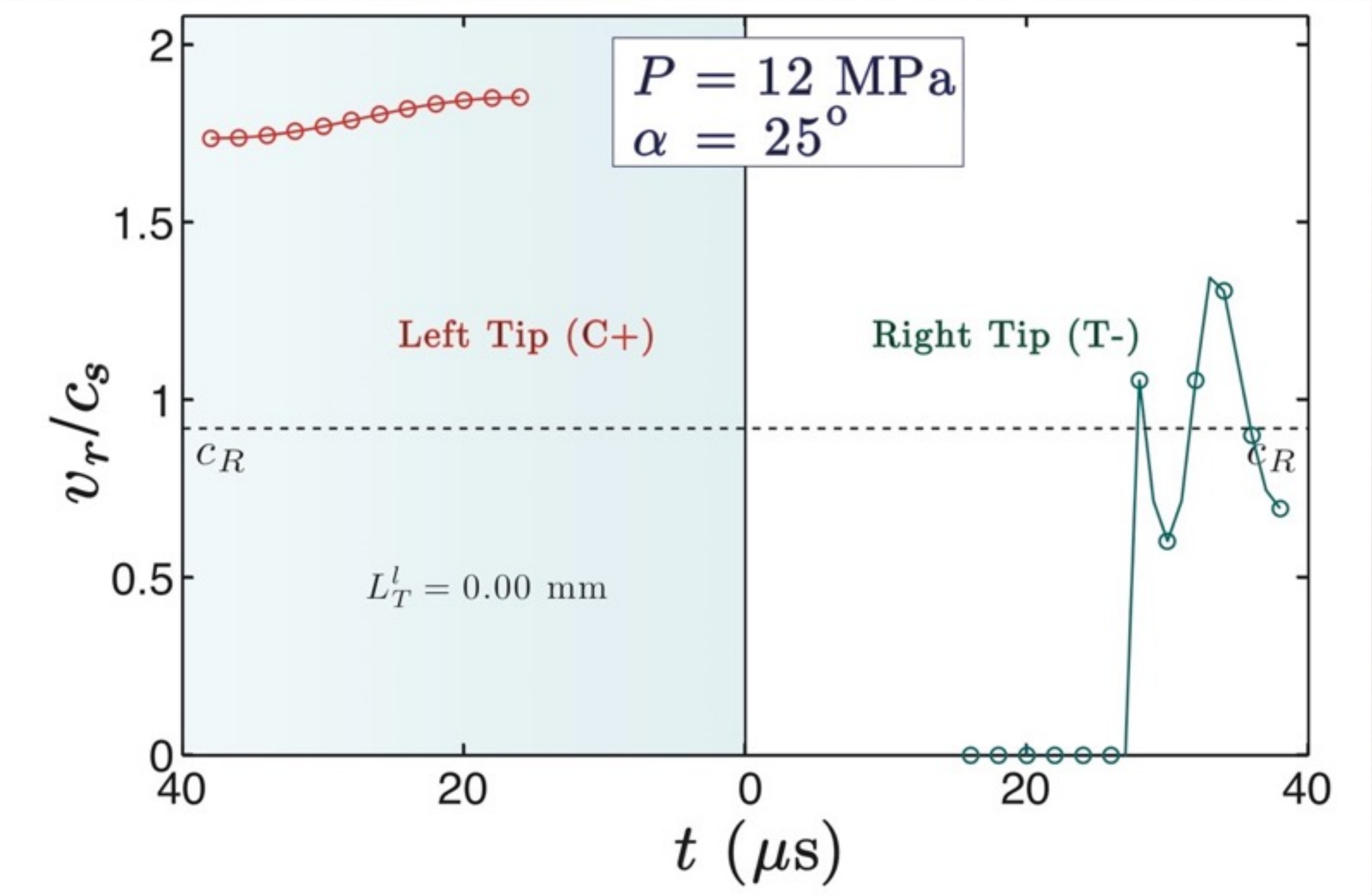




Bhat, Biegel, Rosakis and Sammis (2010) ; Biegel, Bhat, Sammis and Rosakis (2010)

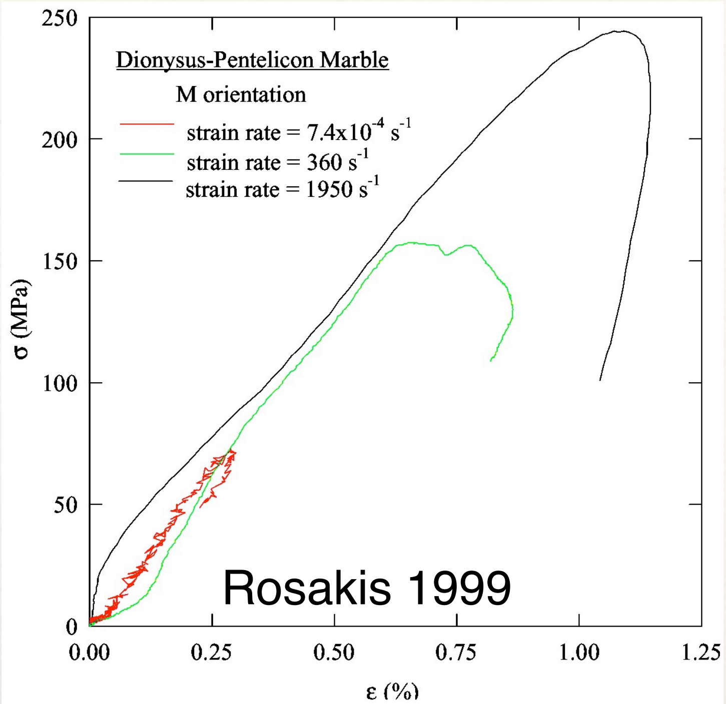

Homalite
Damaged Homalite

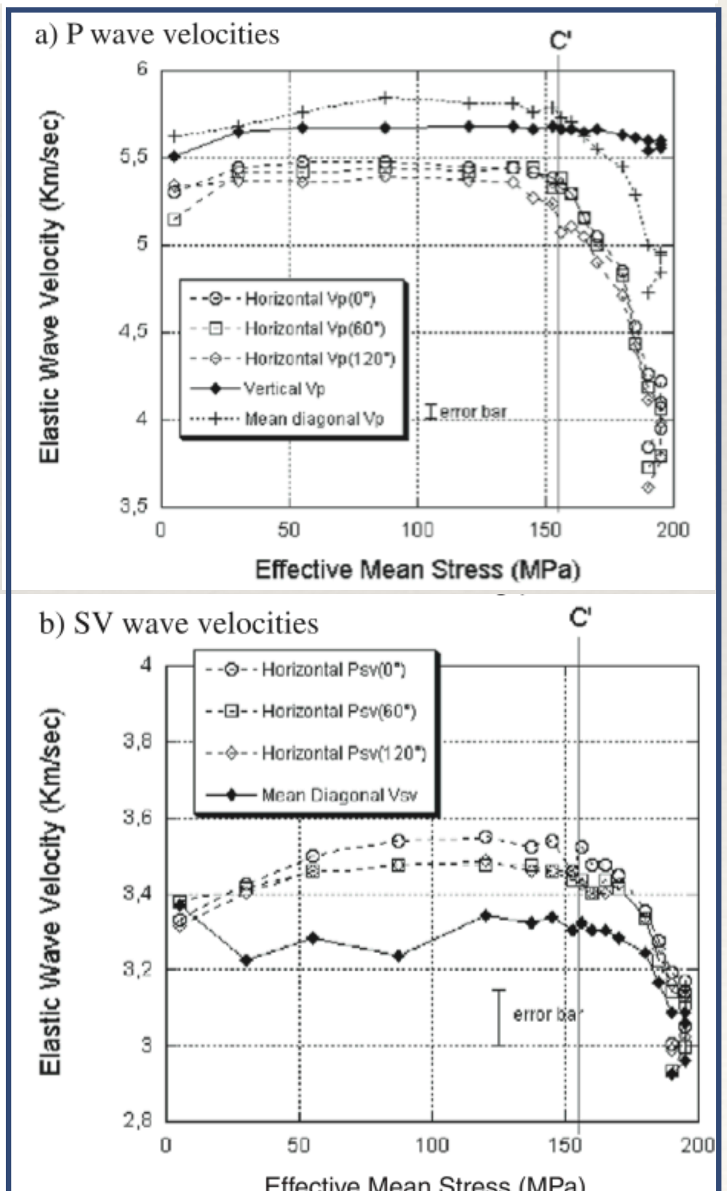
RUPTURE VELOCITY EVOLUTION
Homalite/Damaged Homalite

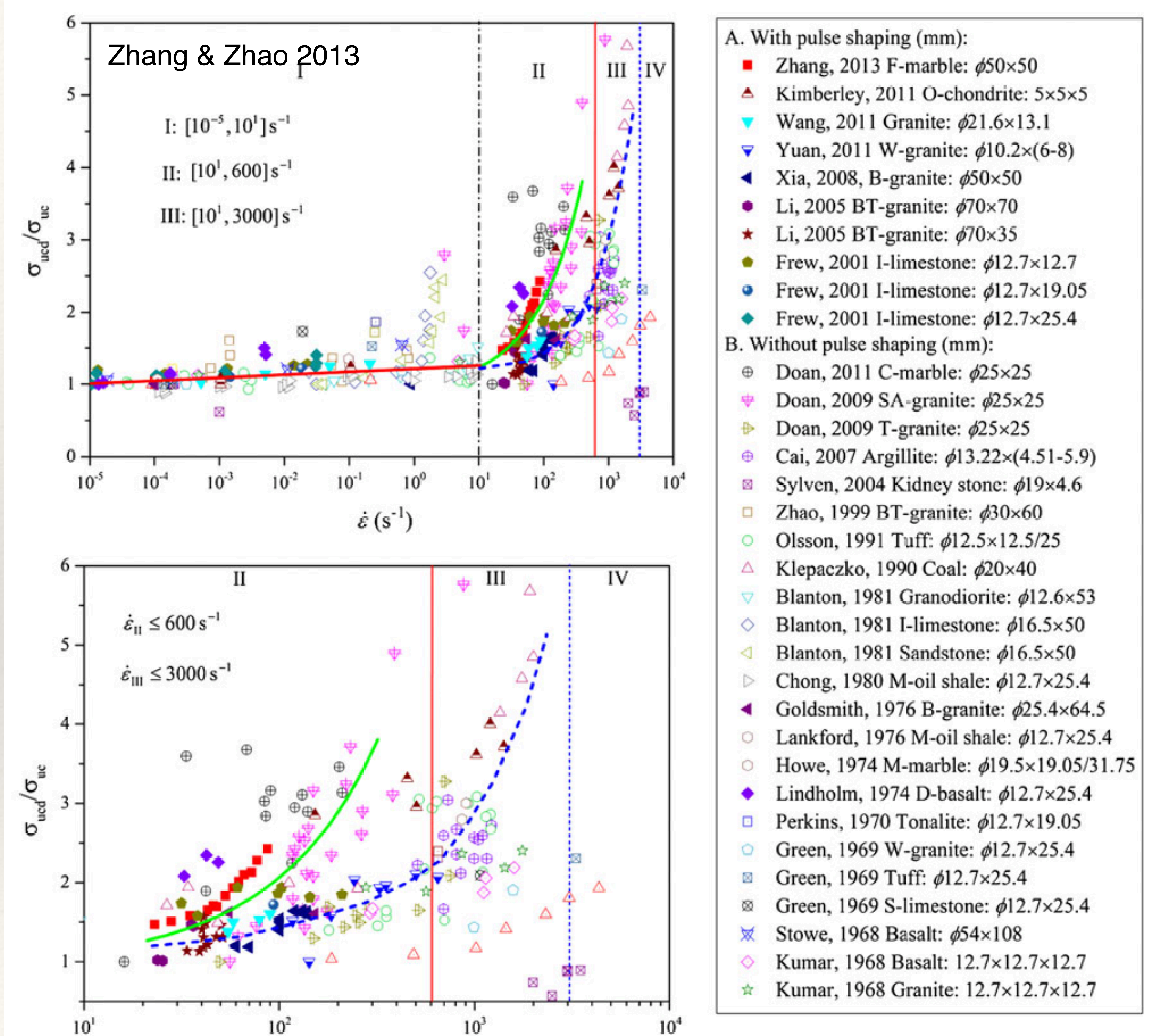


Bhat, Biegel, Rosakis and Sammis (2010) ; Biegel, Bhat, Sammis and Rosakis (2010)

Load and Loading rate dependency of brittle materials







Gueguen & Schubnel 2003

Incorporating Micro-Mechanics Based Rheology to Model Hydro-Mechanical Complexities

Micromechanical Damage Mechanics : General Idea

Coleman and Gurtin, 1967 ; Walsh 1965 ; Rice 1975 ; Budiansky and O'Connell, 1976

Let W be the Gibb's Free Energy density of a damaged solid whose damage "state" is characterized by D (scalar, vector or tensor). Then,

$$W = W^e(\bar{\sigma}) + N_v \Delta W^p(\bar{\sigma}, D)$$

Cracks, Voids, Dislocations etc.

Constitutive stress-strain relationship is given by,

$$\epsilon_{ij} = \frac{\partial W}{\partial \bar{\sigma}_{ij}} \qquad M_{ijkl} = \frac{\partial^2 W}{\partial \bar{\sigma}_{ij} \partial \bar{\sigma}_{kl}}$$

If the damaged solid solely consists of micro-cracks and Γ is the position along a microcrack describing its amount of local advance then the additional free energy due one crack is given by,

$$\Delta W^p = \frac{1-\nu^2}{E} \int_\Gamma \left\{ K_I^2 + K_{II}^2 + \frac{K_{III}^2}{(1-\nu)} - 2\gamma_s \right\} d\Gamma$$

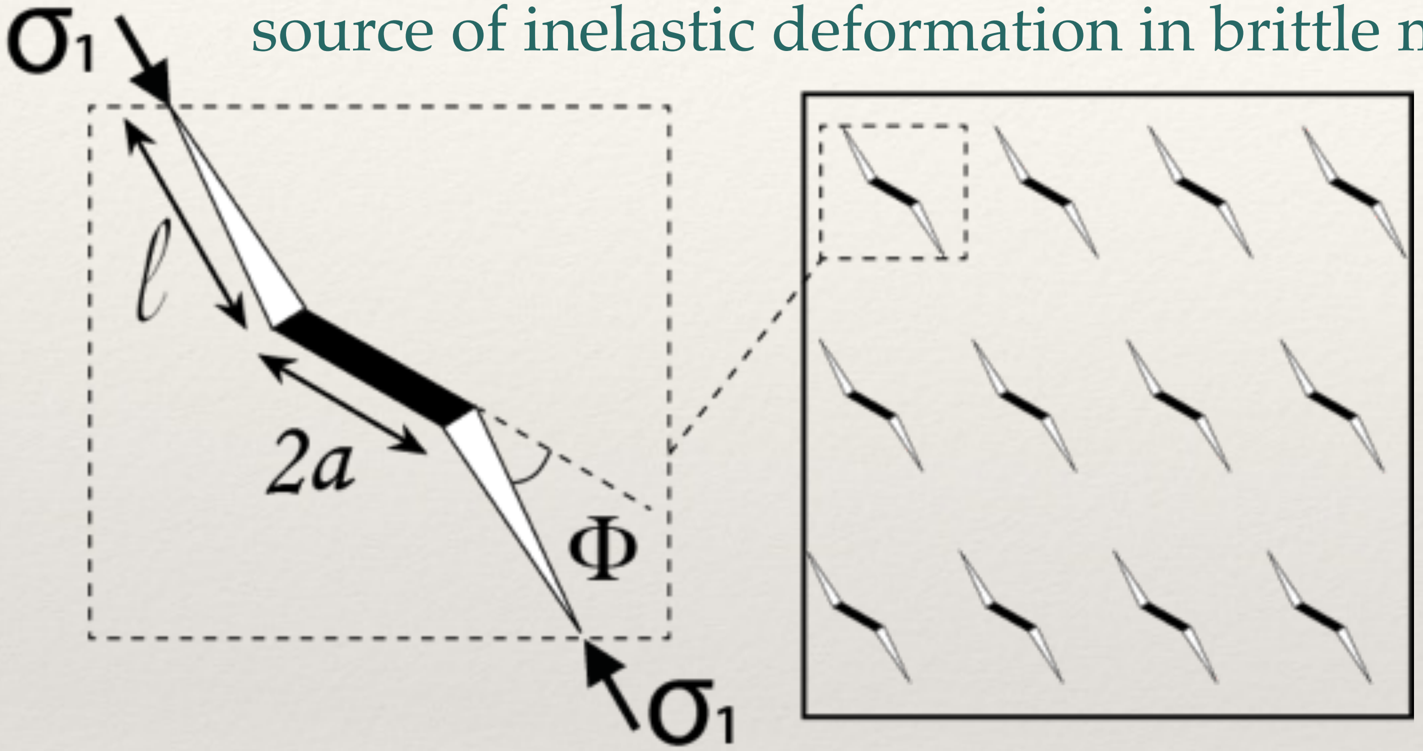
Energy Release Per Unit Crack Area

State Evolution Laws : $\dfrac{dD}{dt} = f(\sigma, \epsilon, \mathrm{History}, ...)$

Incorporating Micro-Mechanics Based Rheology to Model Hydro-Mechanical Complexities

Represent the medium surrounding faults as an isotropic elastic solid that contains pre-existing monosized flaws, here represented by penny-shaped cracks that grow as wing cracks.

Hypothesis: under compression, tensile growing cracks induced frictional sliding are the major source of inelastic deformation in brittle material (shallow depths).



Nv penny shaped cracks per unit volume

- optimally oriented from a Coulomb friction perspective
- grow as soon as the shear stress on crack faces overcome the Coulomb frictional resistance.

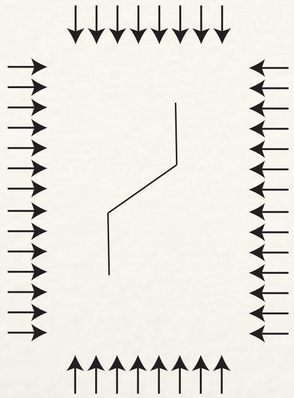
Initial damage:

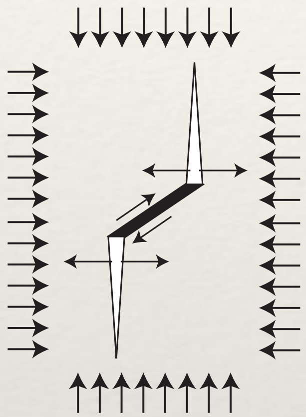
$$D_o = \frac{4}{3}\pi(\alpha a)^3 N_v$$

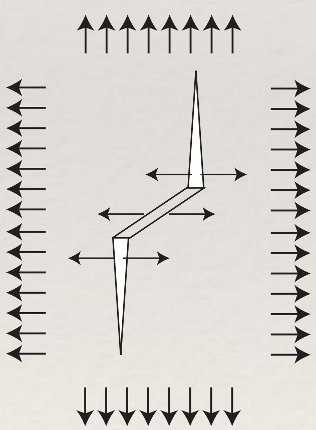
Damage when tensile wing-cracks have grown to length l:

$$D = \frac{4}{3}\pi(l + \alpha a)^3 N_v$$

Incorporating Micro-Mechanics Based Rheology to Model Hydro-Mechanical Complexities







Gibbs Free Energy of Damaged Solid

$$W(\sigma, D) = \underbrace{W^e(\sigma)}_{\text{elasticity}} + \underbrace{N v \Delta W^i(\sigma, D)}_{\text{inelasticity}}$$

Regime I : Linear Elastic (No Frictional Sliding)

$$W^e(\boldsymbol{\sigma}) = \frac{1}{4\mu}\left[2\tau^2 + \frac{3(1-2\nu)}{(1+\nu)}\sigma^2\right]$$

Regime II : Sliding Flaws and Growing Wing Cracks

$$W^e + \frac{1}{4\mu}\left[A_1\sigma + B_1\tau\right]^2$$

Regime III : Tensile Flaws

$$W^e + \frac{1}{4\mu}\left[C_1^2\sigma^2 + O_1^2\tau^2\right]$$

We can then derive the constitutive stress-strain relationship for a damaged solid

$$\epsilon_{ij} = \frac{\partial W}{\partial \bar{\sigma}_{ij}} \qquad M_{ijkl} = \frac{\partial^2 W}{\partial \bar{\sigma}_{ij} \partial \bar{\sigma}_{kl}}$$

$$\frac{dD}{dt} = \left(\frac{3D^{2/3}D_0^{1/3}}{\alpha a}\right) v$$

Incorporating Micro-Mechanics Based Rheology to Model Hydro-Mechanical Complexities

Elastodynamics : Converting Static K_I to a Dynamic K_I

Bhat, Rosakis and Sammis (2012)

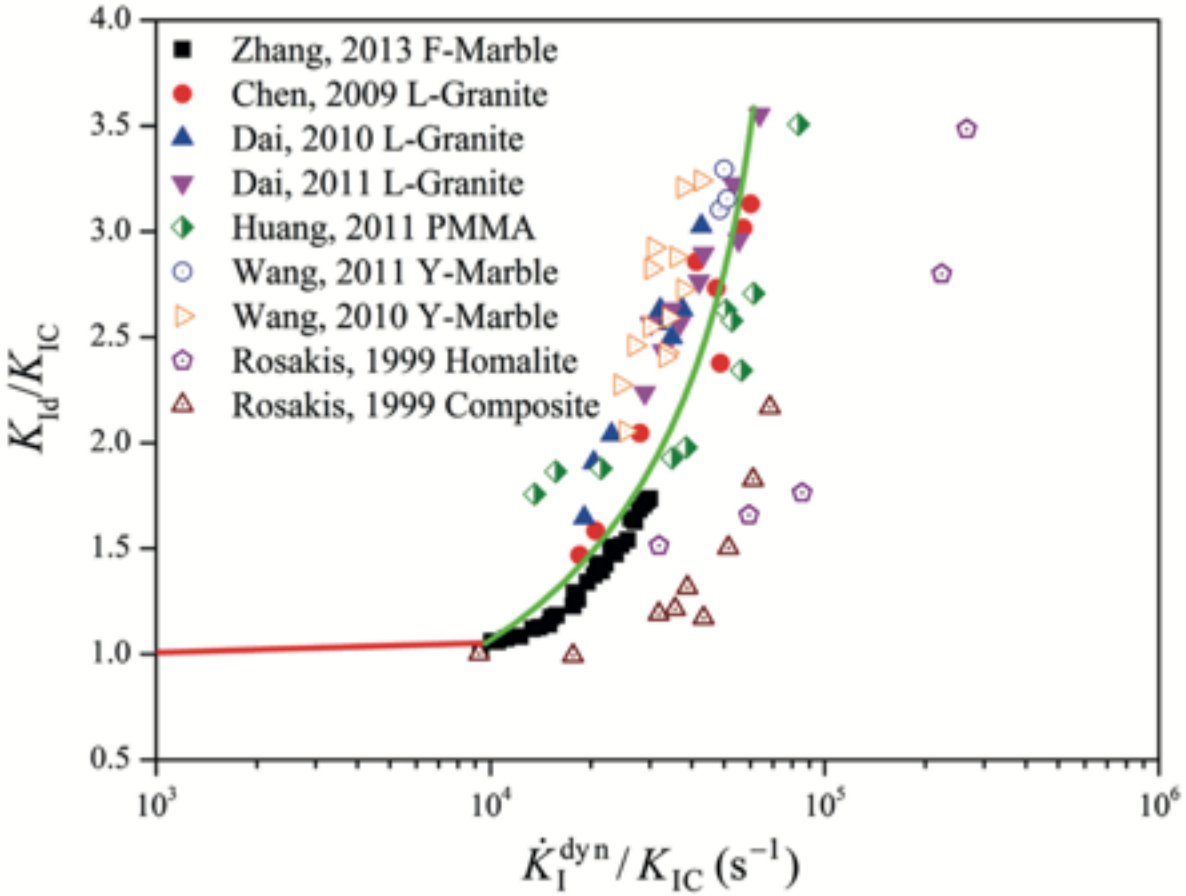
Freund (1973) showed that for an *unbounded body subjected to time independent loading*, the dynamic stress intensity factor at a running crack-tip can be expressed as a universal function of instantaneous crack-tip speed, *v(t)*, multiplied by the equilibrium stress intensity factor for the given applied loading and the instantaneous amount of crack growth i.e.

$$K_I^{AS,d}\left(v,\bar{\sigma},\bar{\tau},D\right) \approx \frac{(1-v/c_R)}{\sqrt{1-v/c_p}} K_I^{AS}\left(\bar{\sigma},\bar{\tau},D\right)$$

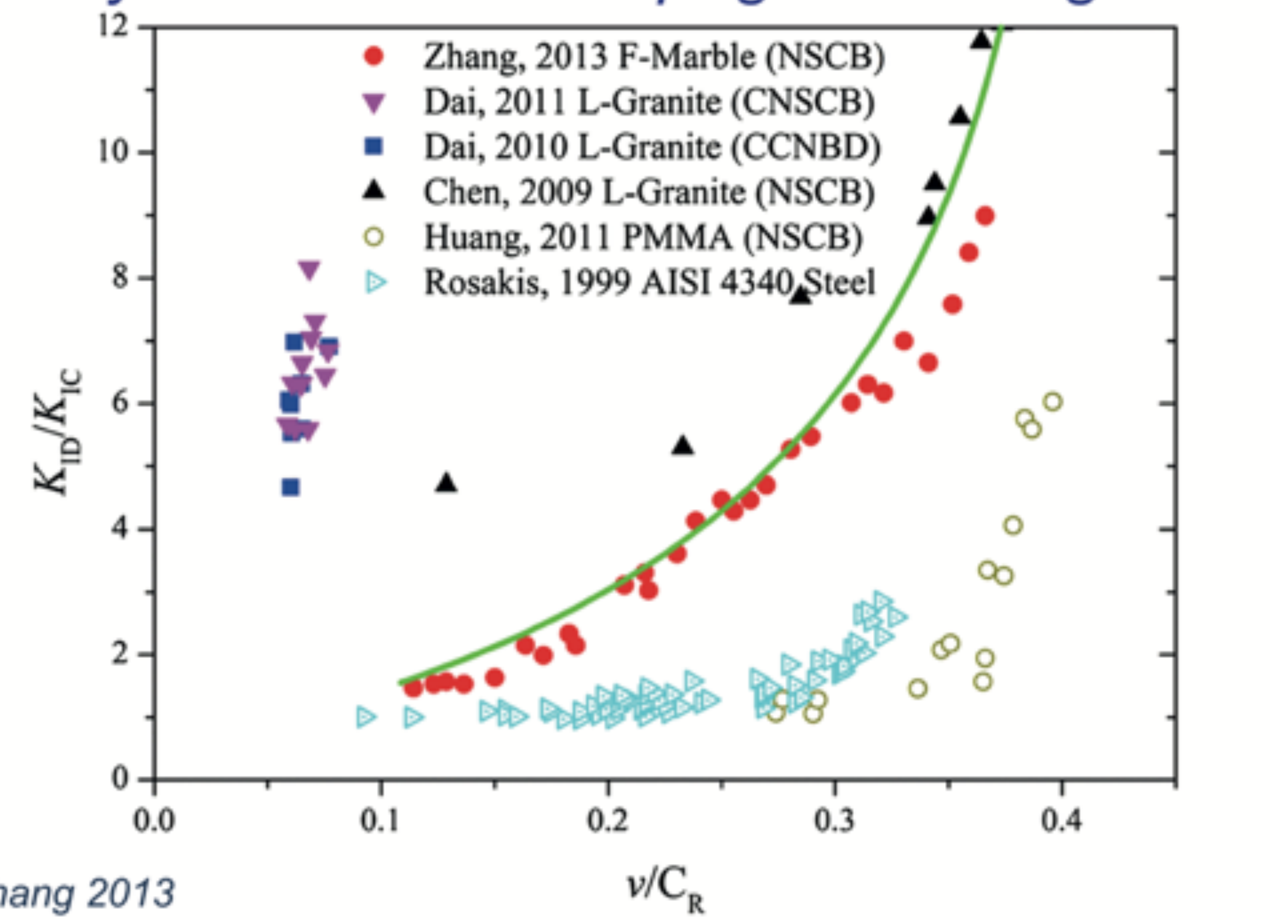
In doing this we make the explicit *assumption that the characteristic time associated with loading is much larger than the corresponding time associated with crack growth*

Incorporating proper micro-crack growth physics to capture dramatic strain-rate dependence of brittle materials

Dynamic Crack Initiation Toughness



Dynamic Crack Propagation Toughness



Zhao and Zhang 2013

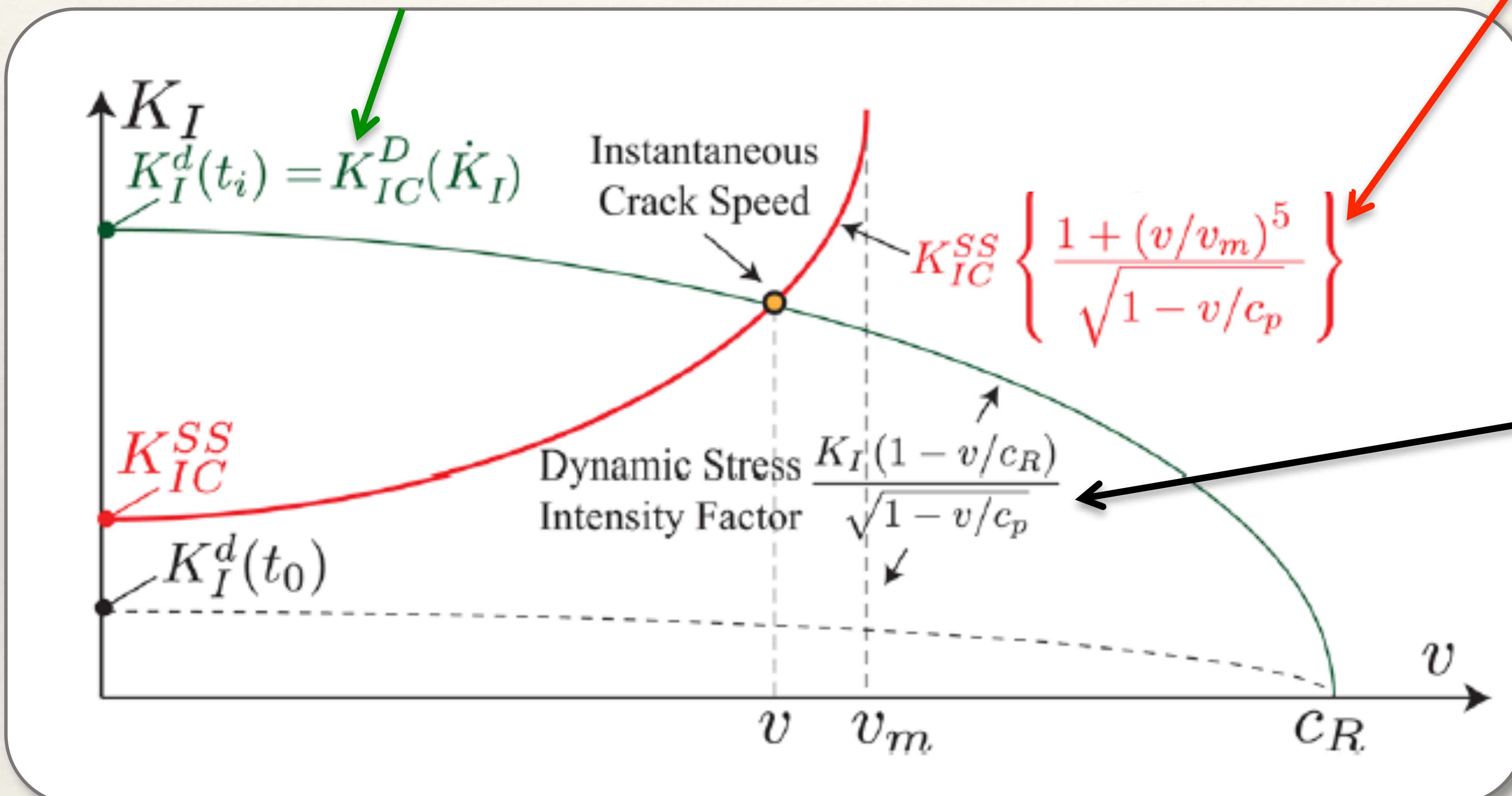
$$\frac{dD}{dt} = \left(\frac{3 D^{2/3} D_0^{1/3}}{\alpha a} \right) v$$

Laboratory Based, rate sensitive
Crack Growth Law

Incorporating proper micro-crack growth physics to capture dramatic strain-rate dependence of brittle materials

Dynamic Initiation Toughness
from experiment

Dynamic Propagation Toughness
from experiment



Stress Intensity Factor
from elasticity

Bhat, Rosakis and Sammis (2012)

Dynamic Damage Mechanics

- Constitutive time integration procedure implemented using finite/spectral element methods

Elastic Constants

E = 81GPa

ν = 0.32

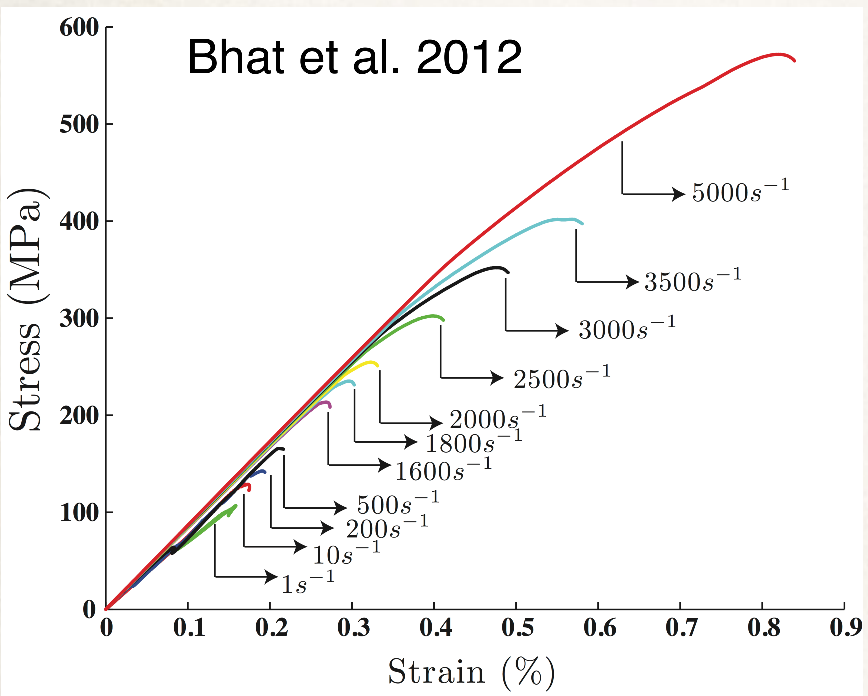
Fracture Parameters

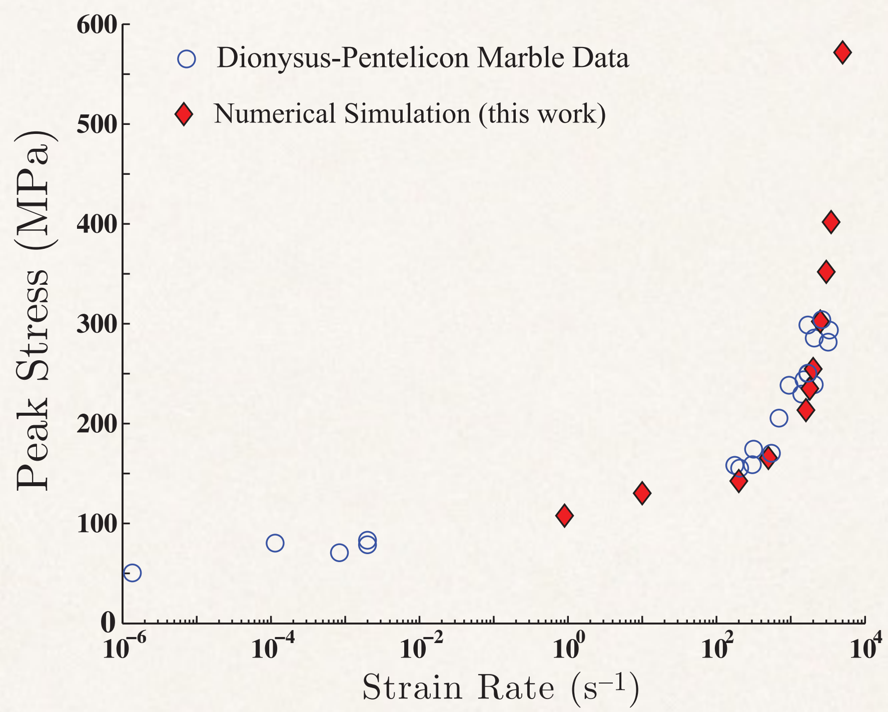
K_{IC} = 1.0 MPa-m$^{1/2}$

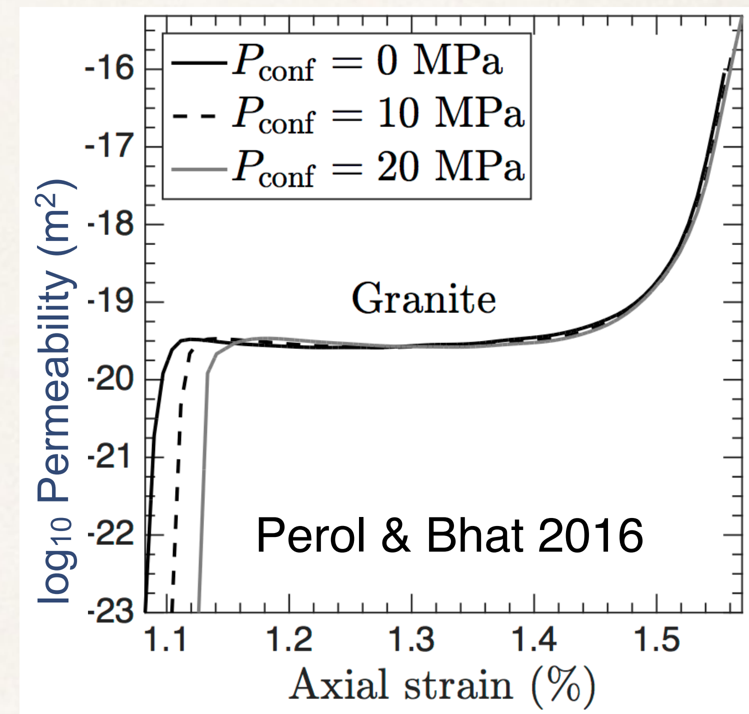
$v_m \approx 0.3c_R$= 990 m/s

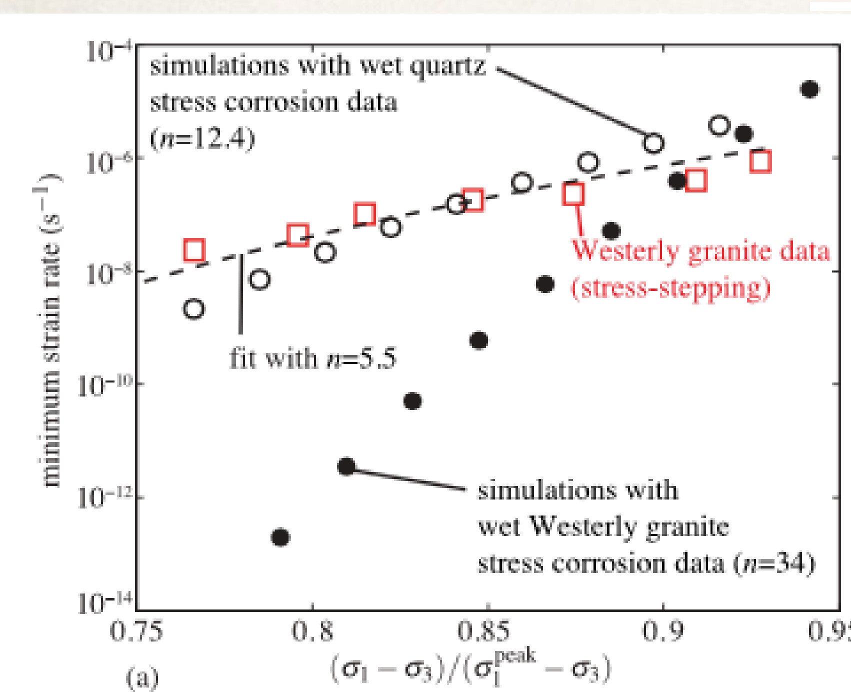
Determine flaw size and density from quasi-static strength data

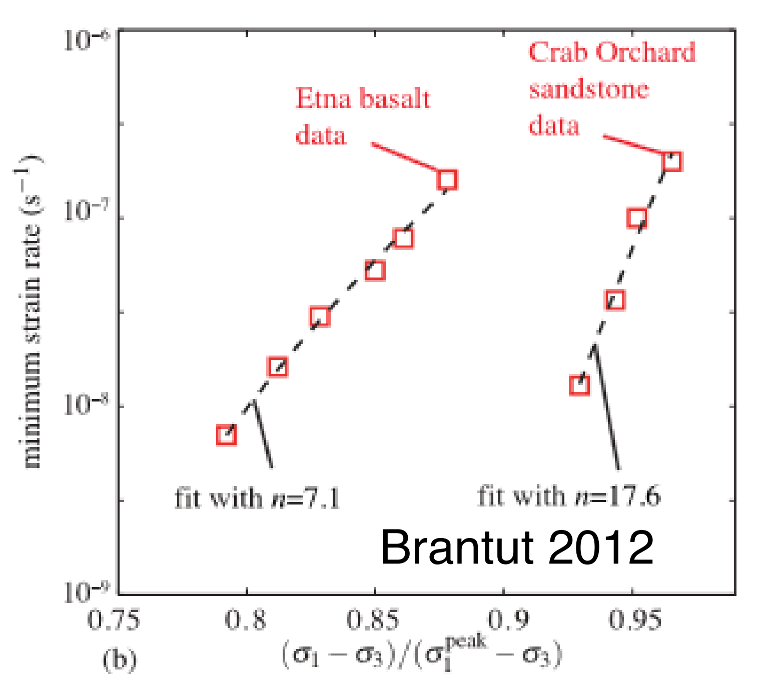
a = 0.5mm ; D_0 = 0.1

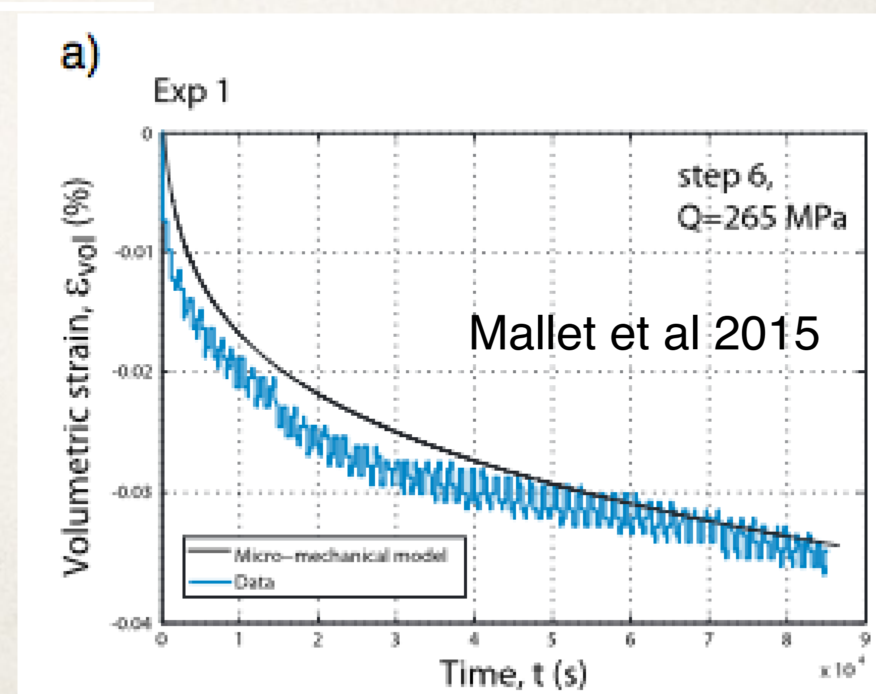






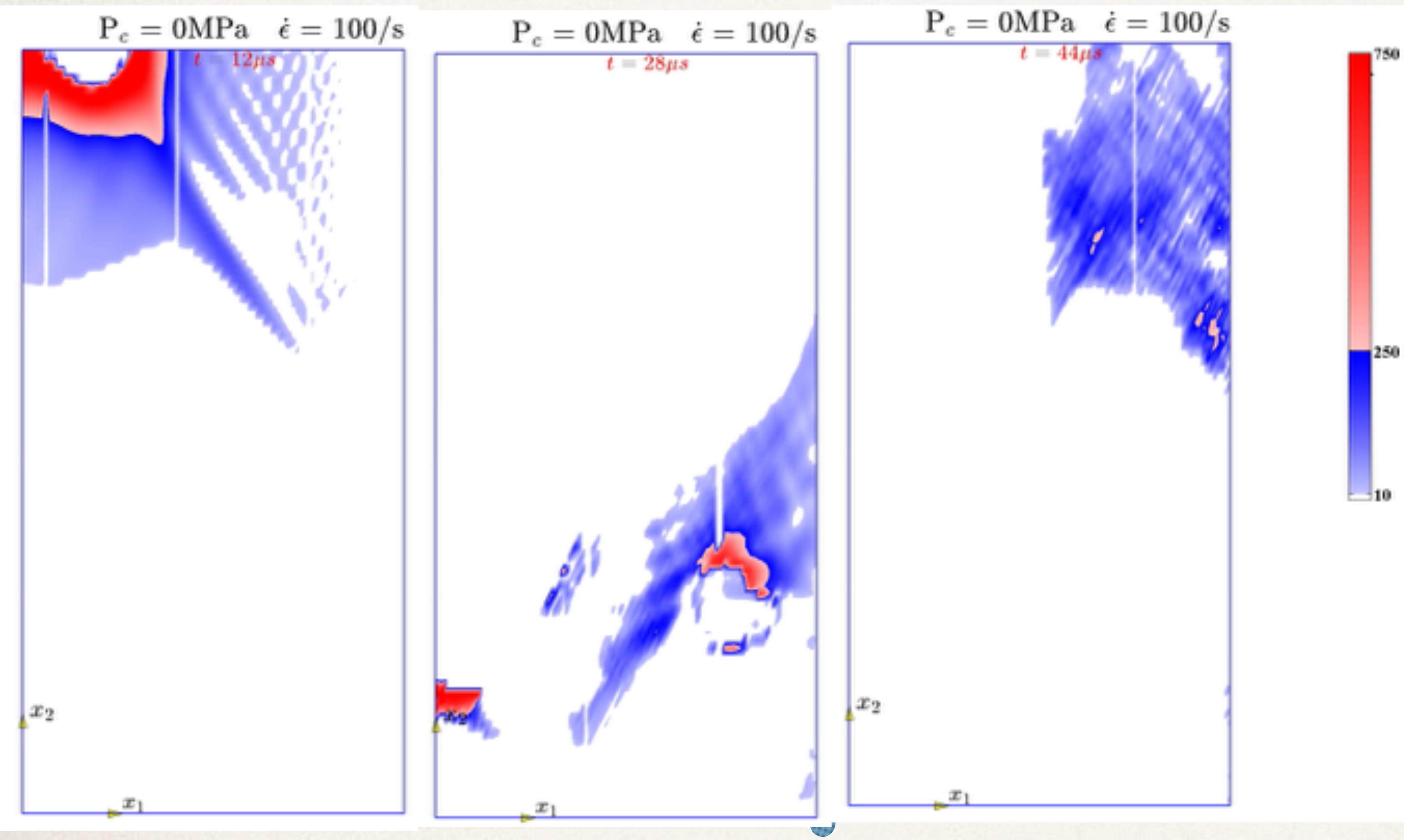




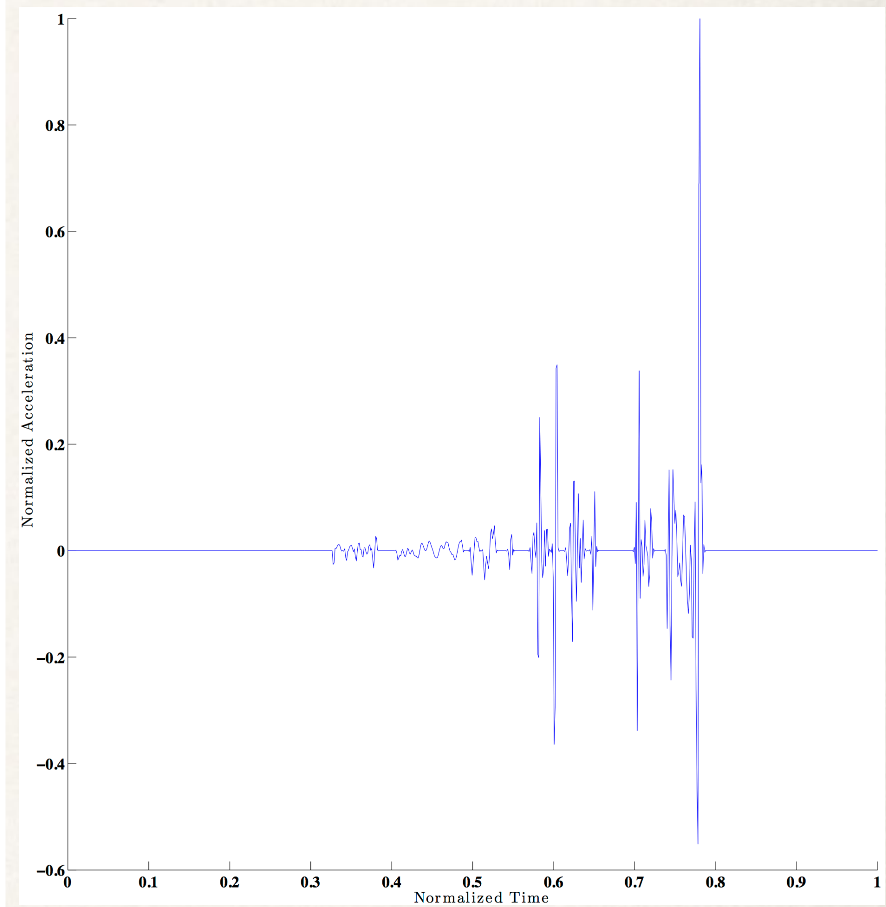


Dynamic Damage Mechanics (Acoustic Emission)

Evolution of micro-crack speed under uniaxial loading

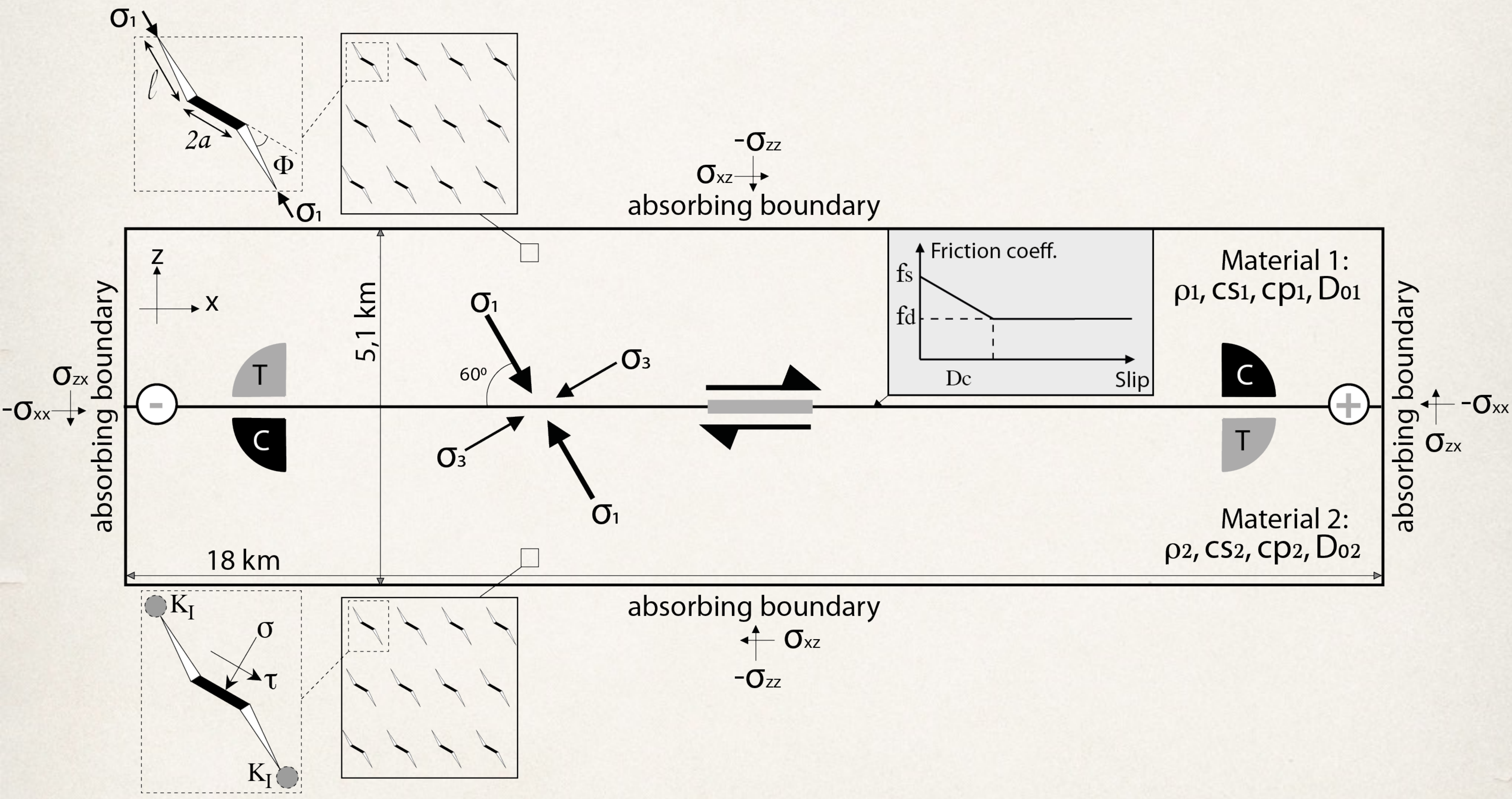


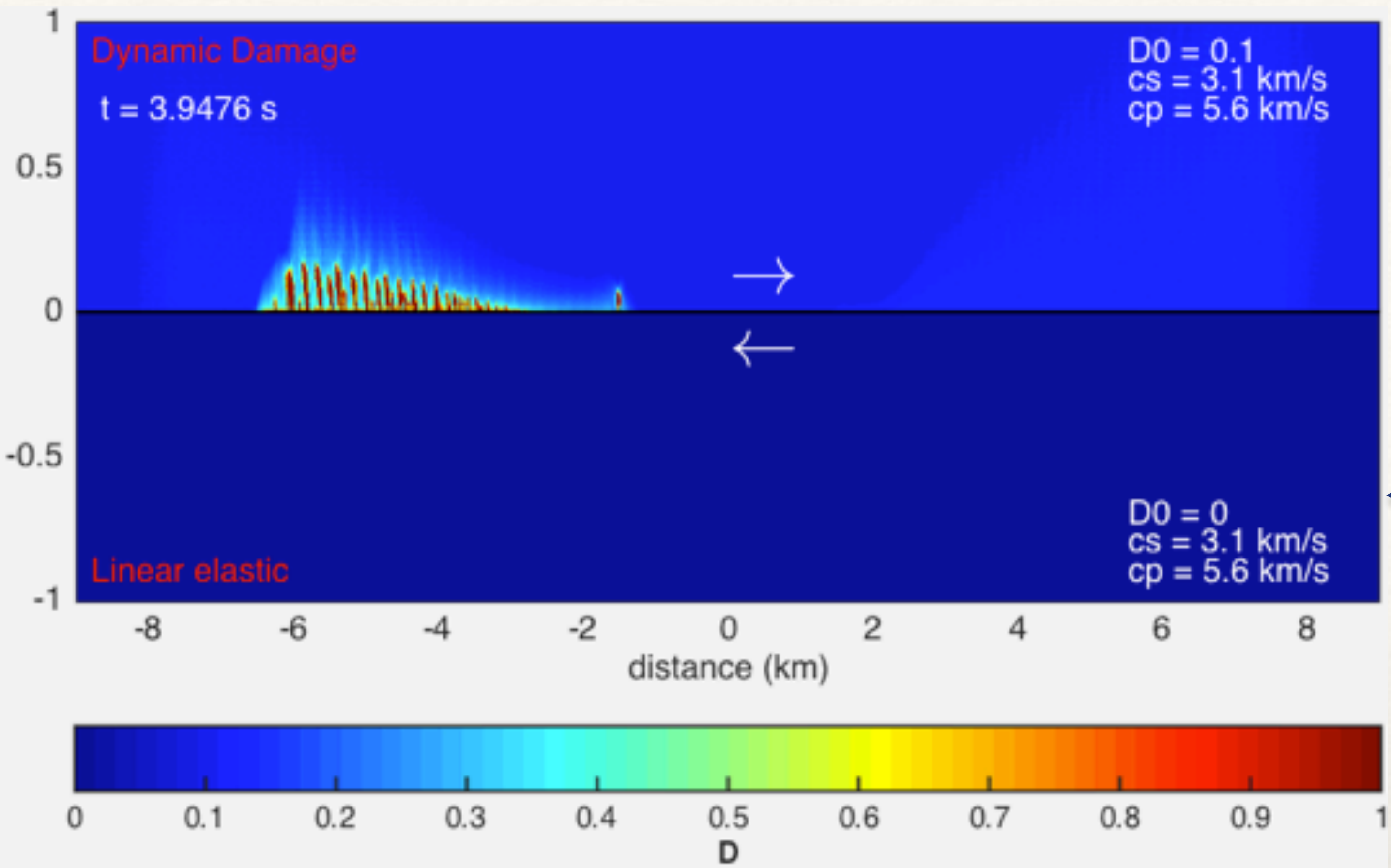
Normalised acceleration of a family of micro-cracks



Fully dynamic crack growth law allows for acceleration and deceleration of micro-cracks

Earthquake Rupture with Dynamic Off-Fault Damage

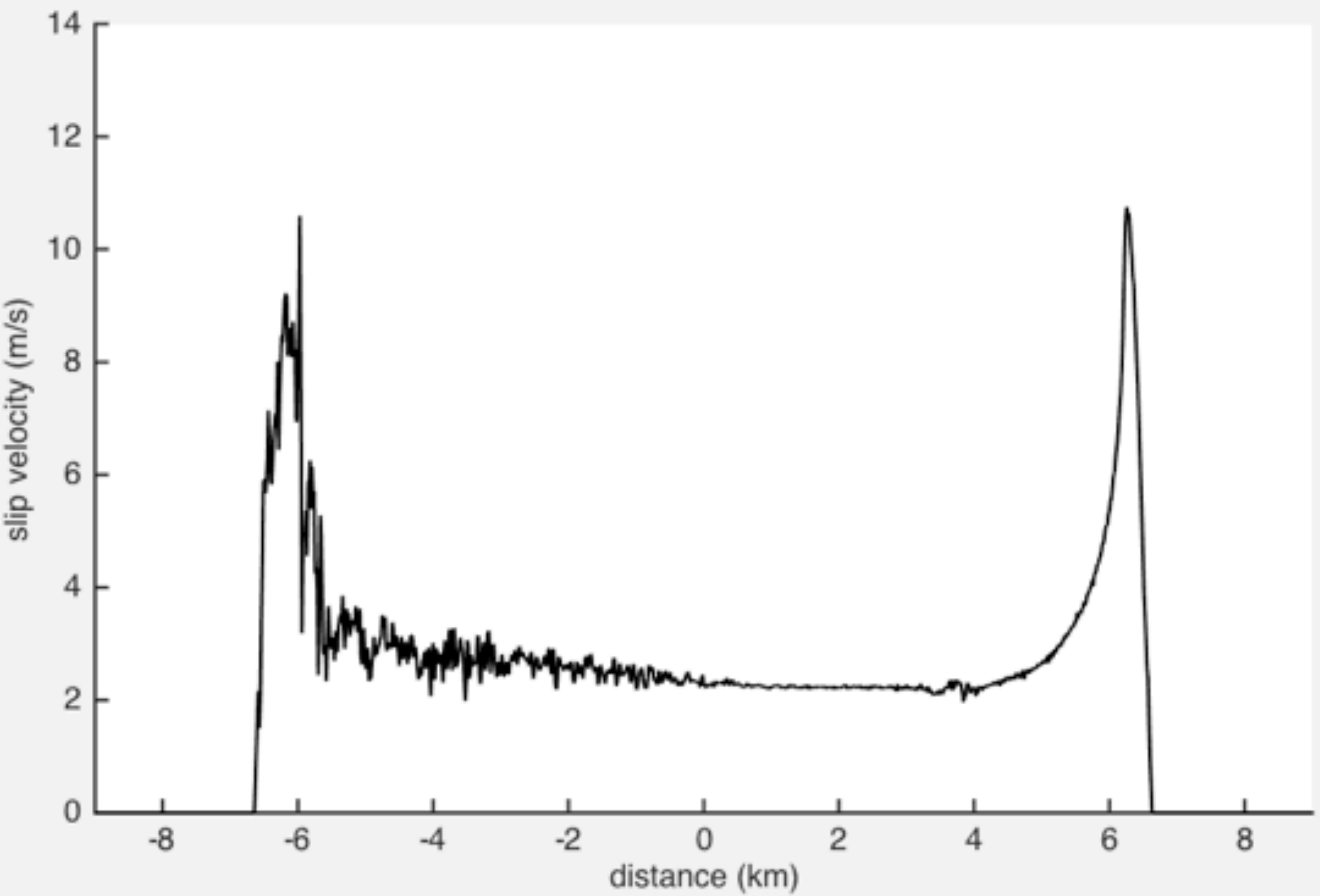




2D right-lateral fault inside an homogeneous medium (Granite), where damage is only occurring on one side.

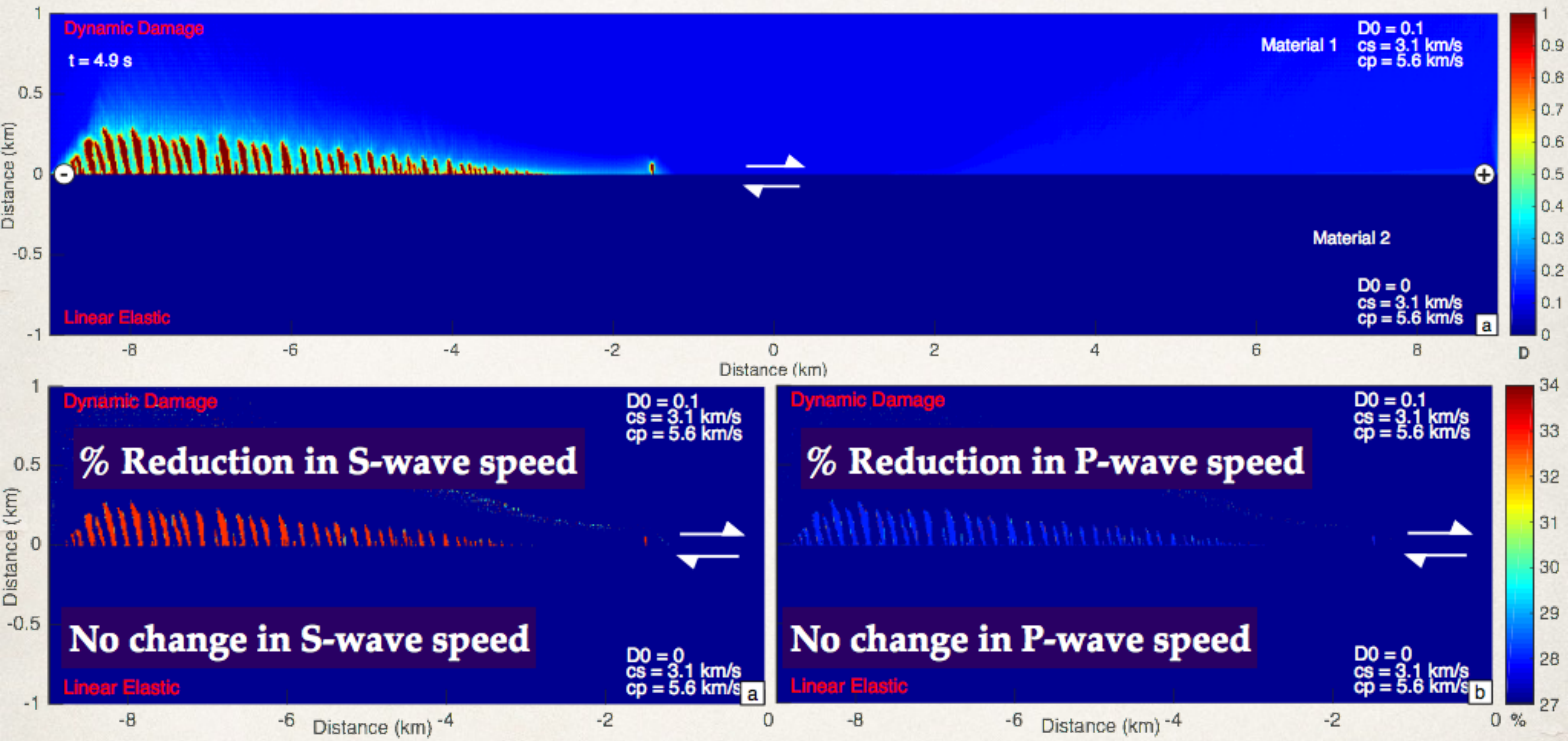
Evolution of the state parameter D that corresponds to the density of micro-cracks in the medium

D = 0 : Uncracked medium (linear elastic)
D = 1 : All cracks are connected (granular)



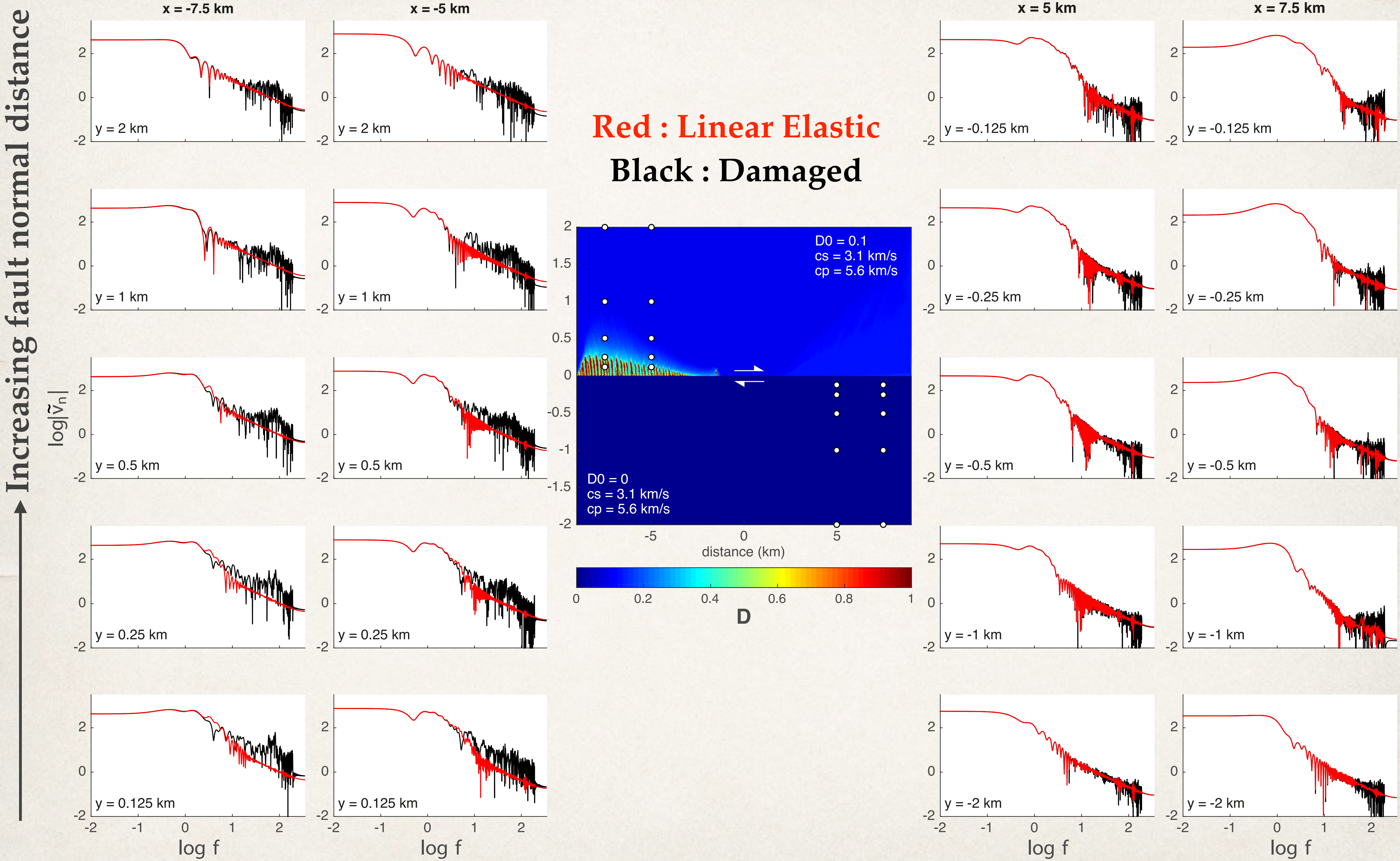
The slip velocity along the fault plane

Earthquake Rupture with Dynamic Off-Fault Damage



Earthquake Rupture with Dynamic Off-Fault Damage

Fault normal velocity Spectra



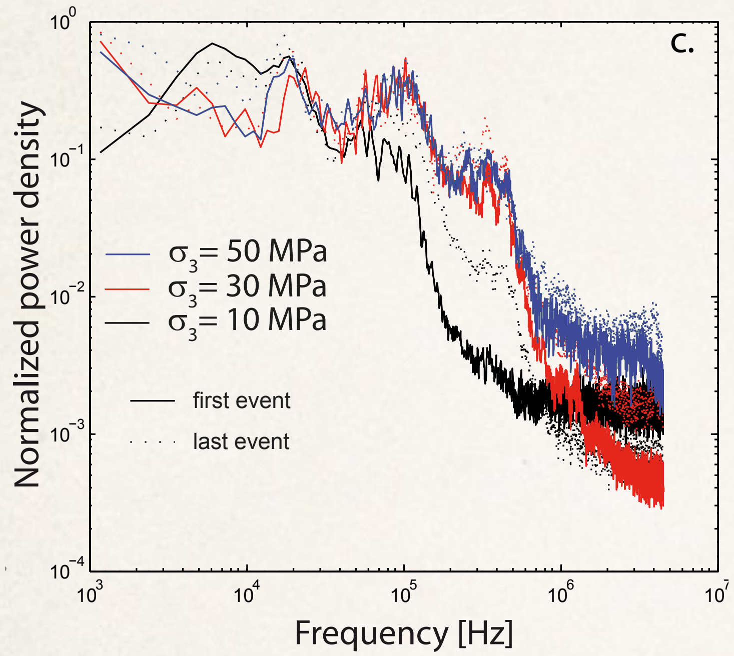
Damaged side

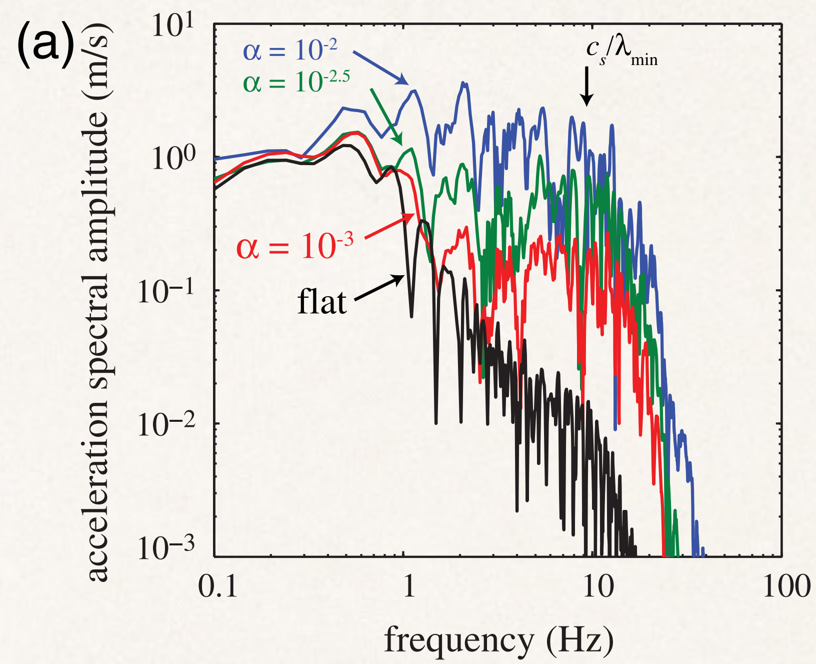
Undamaged side

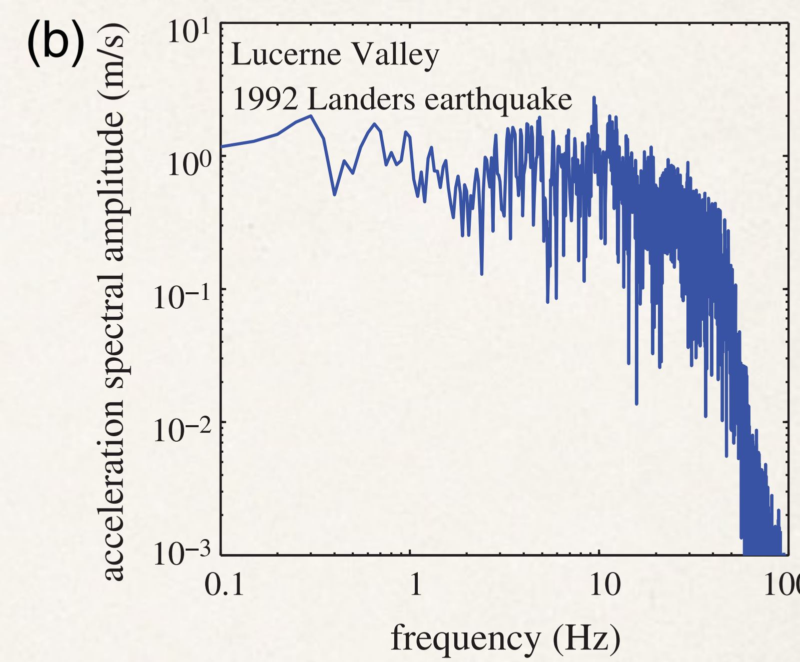
Earthquake Rupture with Dynamic Off-Fault Damage

Passelègue et al. 2016

Dunham et al. 2011



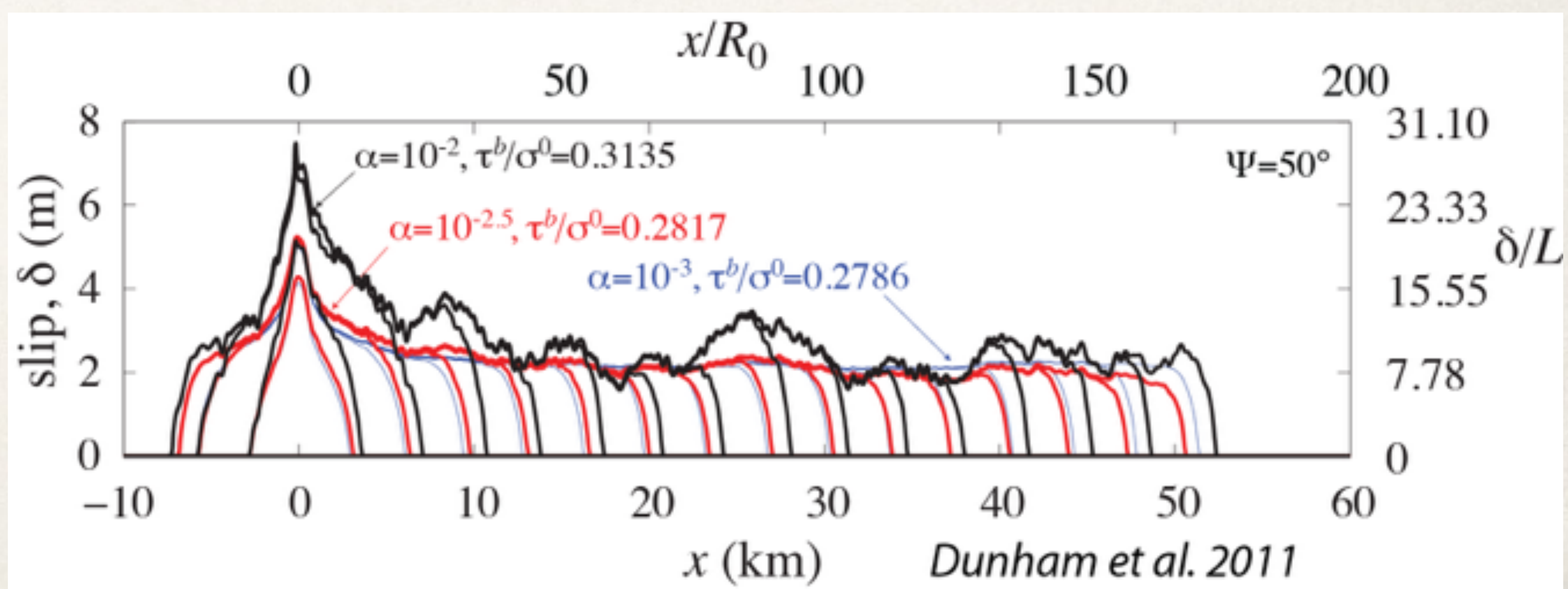




High frequency radiation from damage.
Lab experiments on saw cut westerly granite

High frequency radiation from self-affine fault roughness.
Numerical experiments

High frequency radiation from damage and/or self-affine fault roughness?
Field evidence



Conclusions and Perspectives

Physics based Micro-mechanical homogenisation of smaller scale geometric complexities (off-fault damage) allows/will allow us to capture :

1) Inter-play between on fault dissipation processes (friction) and off-fault dissipation processes (damage)
2) Dynamic evolution of the wave speeds in the medium (dynamic bi-material effect)
3) Generate high frequency radiation from a planar fault with uniform friction and stress
4) The coupling between larger scale geometric complexity and damage
5) The effect of permeability enhancement on post seismic response
6) Depth dependence of damage zone
7) Recovery of wave speeds due to crack healing