SLIP COMPLEXITY AND FRICTIONAL HETEROGENEITIES IN DYNAMIC FAULT MODELS

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Motivations

- Earthquakes are complex at all scales, both in slip on the fault surface and in the stress drop;
- First evidences in Das and Aki (1977a), Aki (1979), Day (1982);
- First attempts to model complexities were the “ asperity “ model of Kanamori and Stewart (1976) and the “ barrier “ model of Das and Aki (1977b);
- Madariaga (1979) showed that the seismic radiation from these models would be very complex;
- Bak et al. (1987) suggested that complexity must be due to the spontaneous organization of a fault that is close to criticality.

Goals

The slip complexity on a fault may arise from:

- Numerical artefacts and spurious pollutions of the solutions due to violation of stability and convergency conditions or grid dispersion;
- Effects of heterogeneous distribution of initial stress;
- Inhomogeneities in the mechanical and rheological properties of the fault (expressed in terms of heterogeneity of frictional parameters);
- Modifications of governing equation;
- Coupling of two modes of propagation in a *truly* 3 – D earthquake model;
- Interactions with other active faults;
- Geometrical complexity, non – planarity, fault segmentation and branching;
- Different and competing physical mechanisms occurring within the cosesimic temporal scale, like thermal pressurization, rock melting, mechanical lubrication, ductile compaction of gouge, etc..

Statement of the problem and methodology

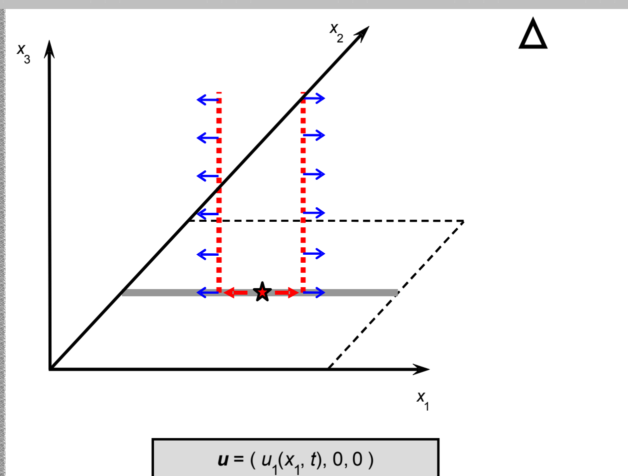
We solve *fully* dynamic, spontaneous problem (the fundamental elasto–dynamic equation), without body forces **f**

$$\rho \ddot{U}_i = \sigma_{ij,j} + f_i$$

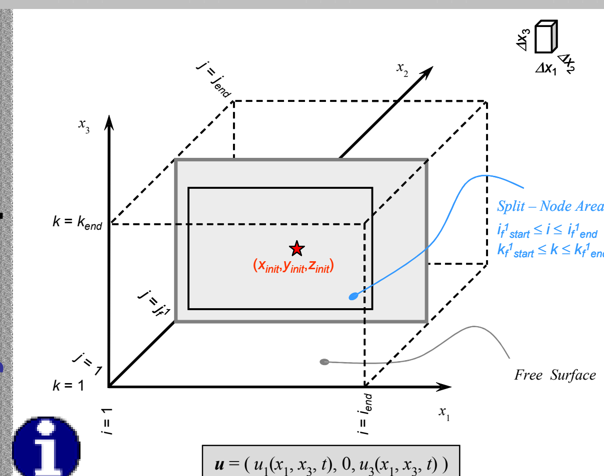
We consider 2–D pure in–plane (or mode II) problem, for which solutions (for instance the fault slip, i. e. the particle displacement discontinuity) are in the form: $\mathbf{u} = (u_1(x_1,t), 0, 0)$ …

… and *truly* 3–D problem, for which solutions are: $\mathbf{u} = (u_1(x_1,x_3,t), 0, u_3(x_1,x_3,t))$

2 – D problem



***truly* 3 – D problem**



The spatial computational domain is discretized using equilateral triangles in 2–D problems and cubic building blocks in 3–D one. The medium is linearly elastic except that in the fault plane …

… that obeys to the Fault Boundary Condition, i. e. to the governing law, that relates the fault friction τ to some physical observables. In general is:

$$\tau = \mu(u, v, \Psi, T, H, \lambda_c, h, g, C_e)\ \sigma_n^{eff}(\sigma_n, p_{fluid})$$

where μ is the friction coefficient and σ_n^{eff} the effective normal stress.

Slip – weakening law (Barenblatt

$$\tau = \begin{cases} \left[\mu_u - (\mu_u - \mu_f)\dfrac{u}{d_0} \right] \sigma_n^{eff} & , u < d_0 \\ \mu_f \sigma_n^{eff} & , u \geq d_0 \end{cases}$$

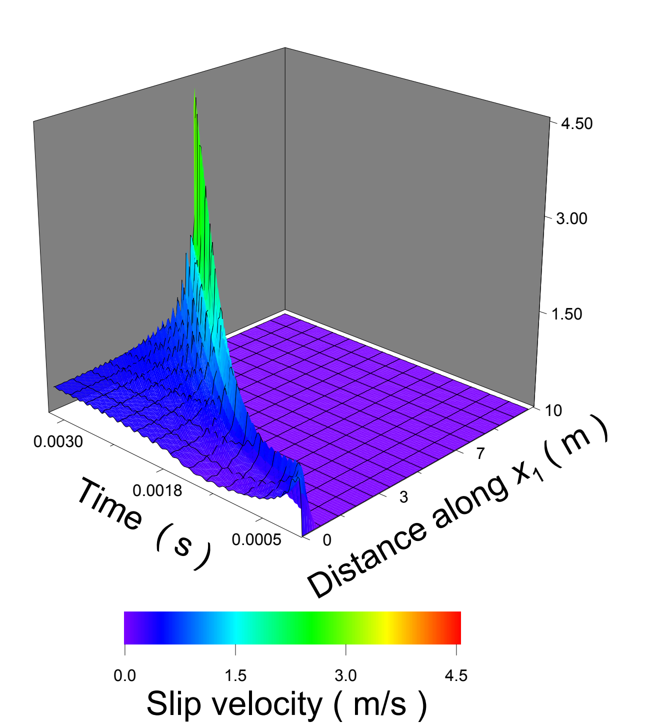
$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + b \ln\left(\dfrac{\Psi v_*}{L} \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \dfrac{\Psi v}{L} - \left(\dfrac{\alpha_{LD}\Psi}{b \sigma_n^{eff}} \right) \dfrac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{eff} \end{cases}$$

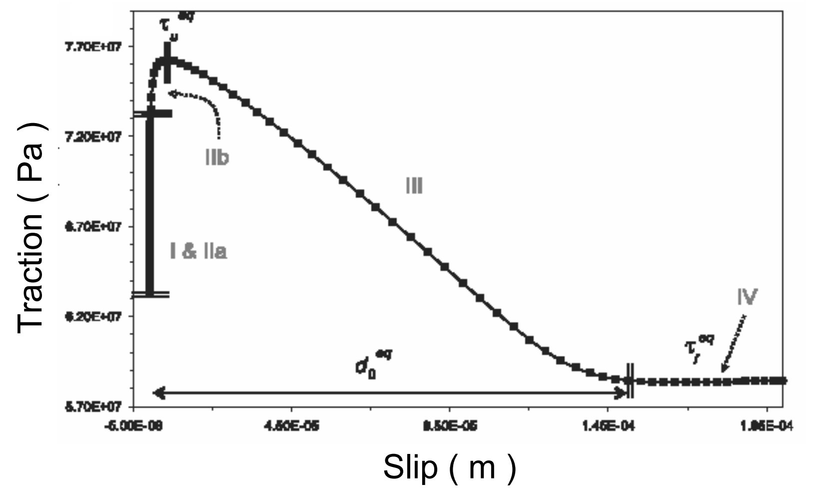
An explicit displacement discontinuity is assumed between the two sides of the fault: **Traction–at–Split–Nodes** scheme (Day, 1982a, 1982b; Andrews, 1999)

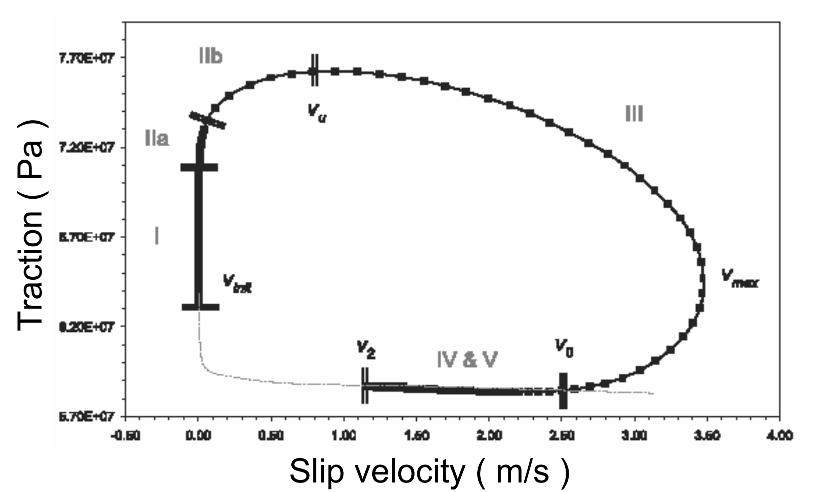
The numerical details and the implementations of constitutive equations is given in Bizzarri et al. (2001, GJI, *144, 656-678*) and in Bizzarri and Cocco (2005a, Ann. Geophys, *48*, 2, 279-299)

Dynamic rupture propagation

2-D





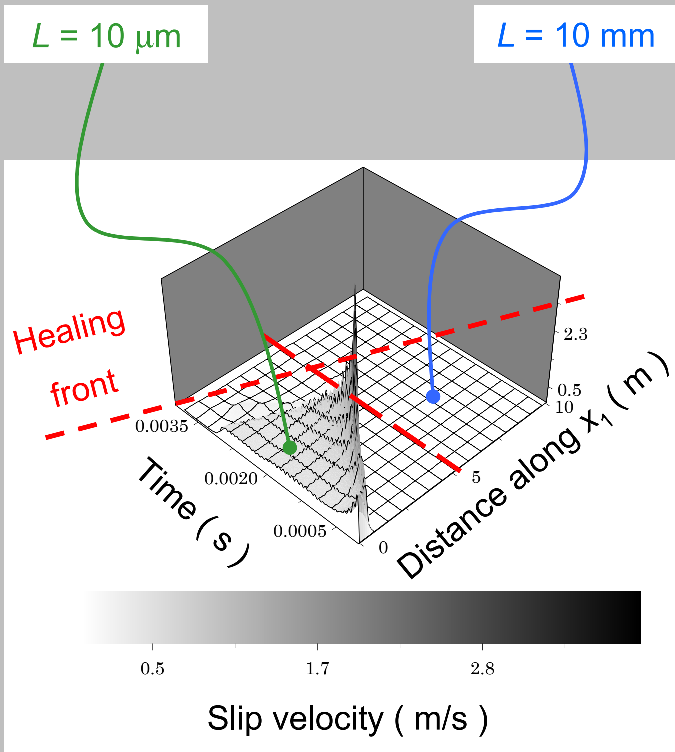


$$
\begin{cases}
\tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} \right) + b \ln\left(\dfrac{\Psi \, v_*}{L} \right) \right] \sigma_n \\
\dfrac{\mathrm{d}}{\mathrm{d}\,t} \Psi = 1 - \dfrac{\Psi \, v}{L}
\end{cases}
$$

Bizzarri and Cocco (2003, *JGR*, 108, B8, 2373)

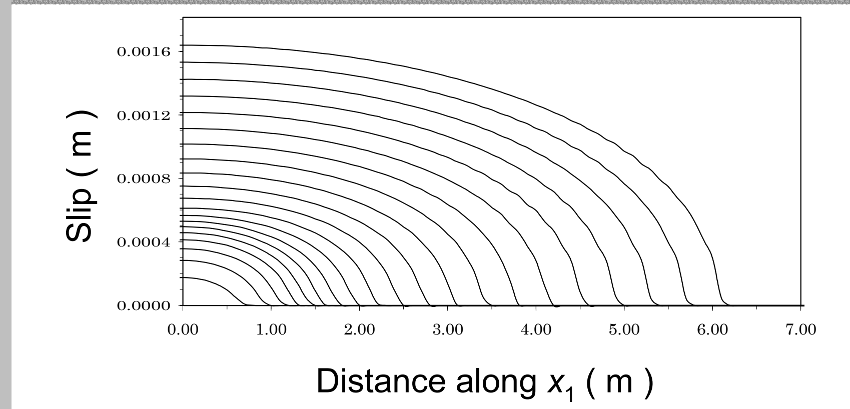
Barrier – healing with DR law

2-D

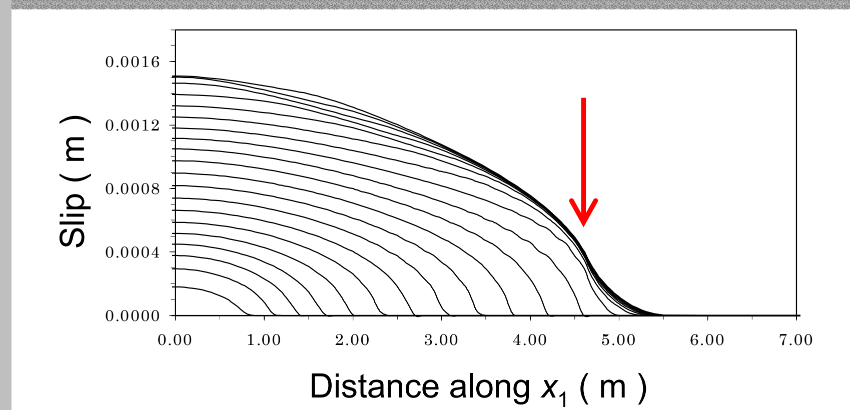


Bizzarri et al. (2001, *GJI*, 144, 656-678)

Crack like (homogeneous – reference)

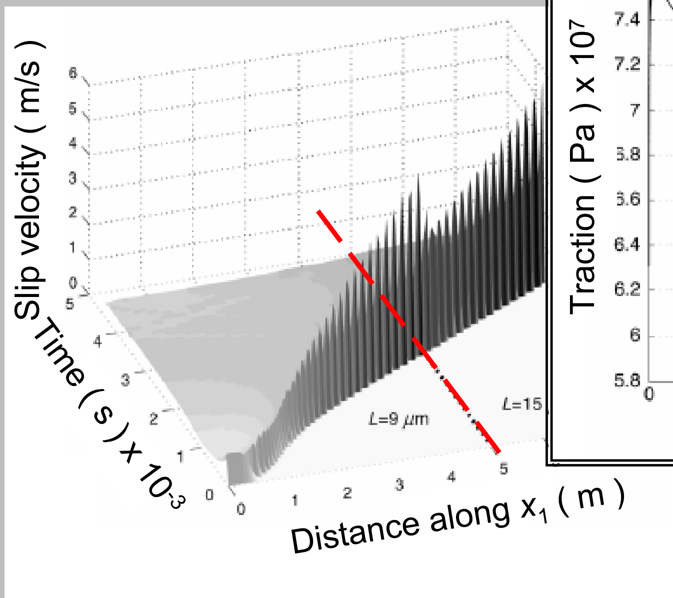


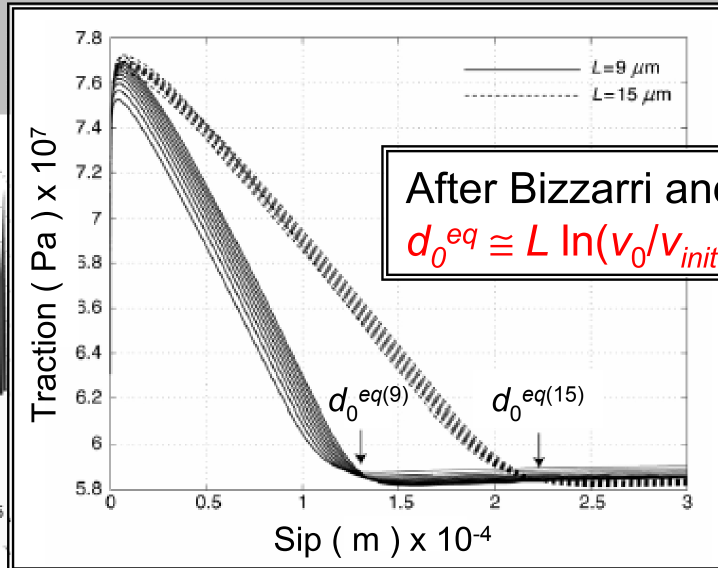
Barrier – healing (*L* heterogeneous)



2-D

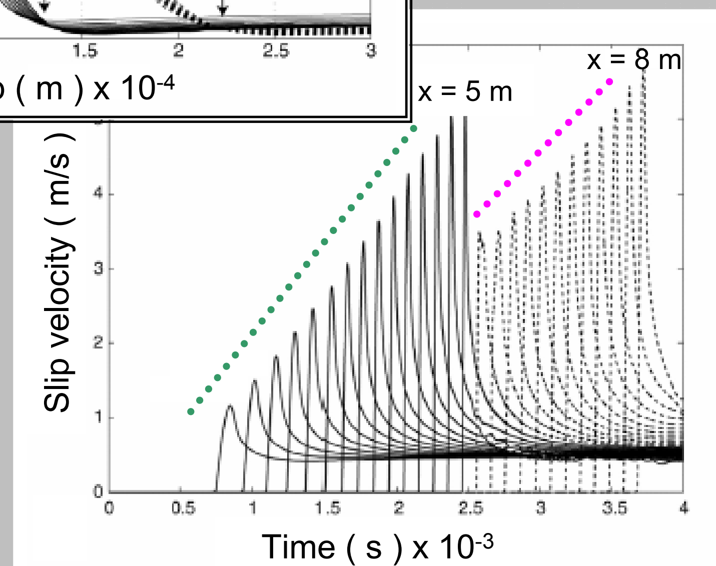
Heterogeneity of parameter *L*





After Bizzarri and Cocco (2003):

$d_0^{eq} \cong L \ln(v_0/v_{init})$

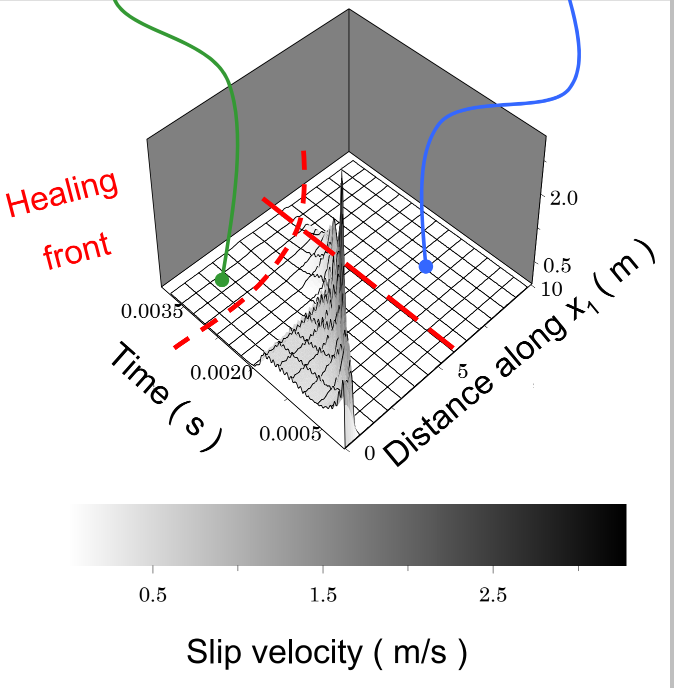


Tinti, Bizzarri, Cocco (2005, *Ann. Geophys.*, 48, 2, 327-345)

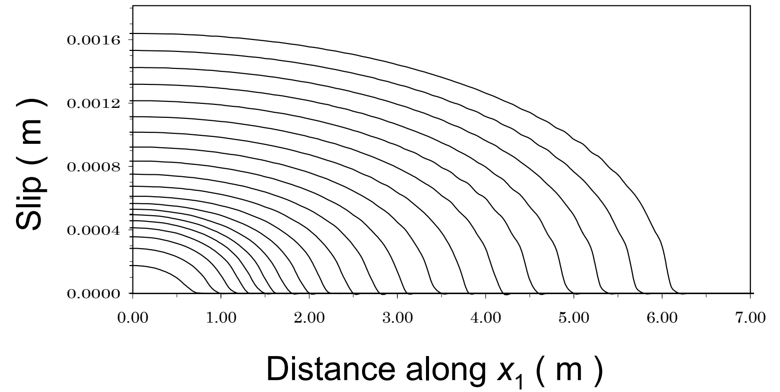
Heterogeneity of parameters *a* and *b* #1

Velocity Weakening
a = 0.012, *b* = 0.016

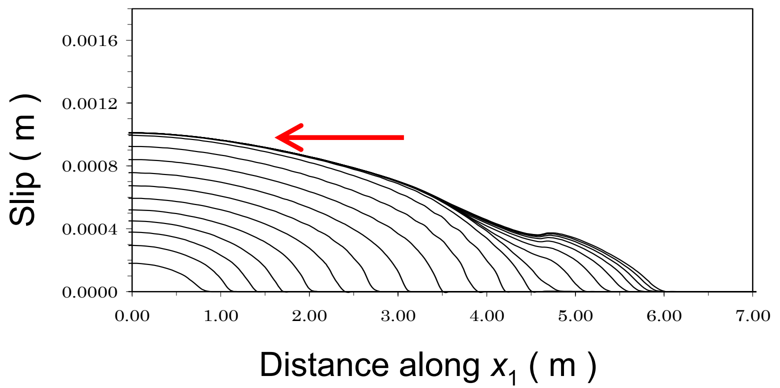
Velocity Strengthening
a = 0.015, *b* = 0.012



Crack like (homogeneous – reference)



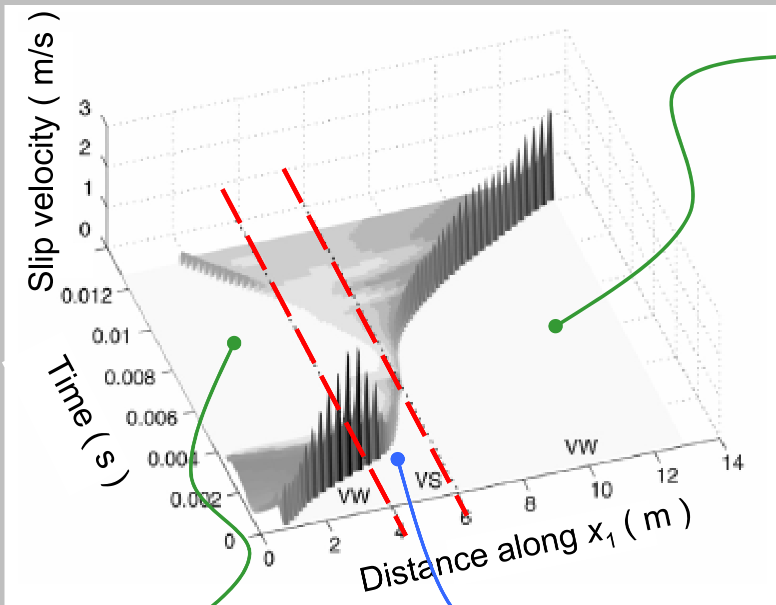
Slip pulse (*a* and *b* heterogeneous)



Bizzarri et al. (2001, *GJI*, 144, 656-678)

Heterogeneity of parameters *a* and *b* #2

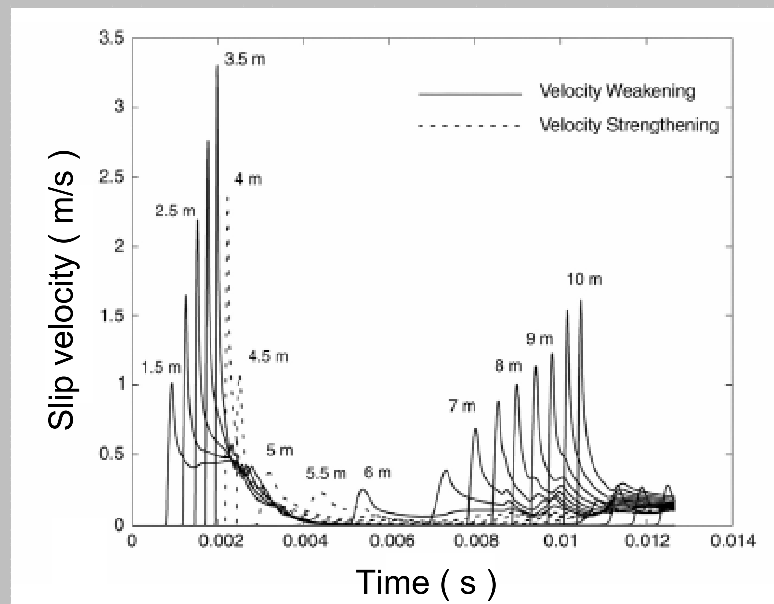
2-D



Velocity Weakening
a = 0.014, *b* = 0.016

Velocity Weakening
a = 0.012, *b* = 0.016

Velocity Strengthening
a = 0.015, *b* = 0.013

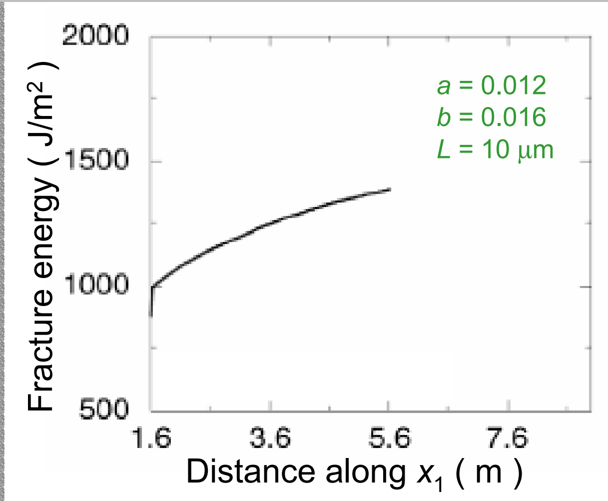


Tinti, Bizzarri, Cocco (2005, *Ann. Geophys.*, 48, 2, 327-345)

Implications for fracture energy

2-D

Crack like (homog.)



In the location **x** on the fault plane we estimate the " Fracture Energy " accordingly to the formula (e. g. Ida, 1972):

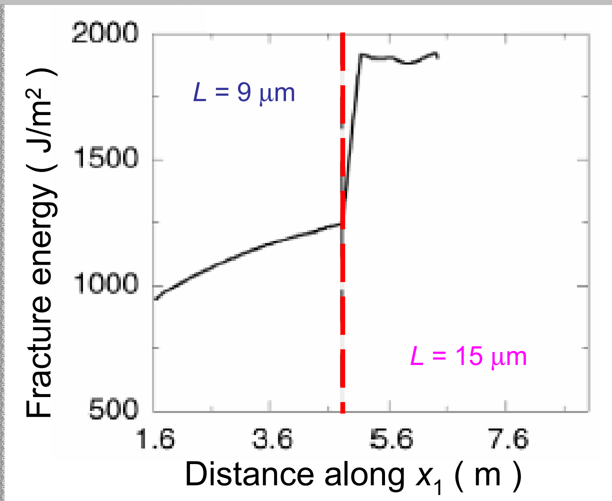
$$E_G(\mathbf{x}) = \frac{1}{2} \int_0^{d_0^{eq}} \left(\tau(\mathbf{x},t) - \tau_f^{\,eq}(\mathbf{x}) \right) \mathrm{d}\,u$$

but

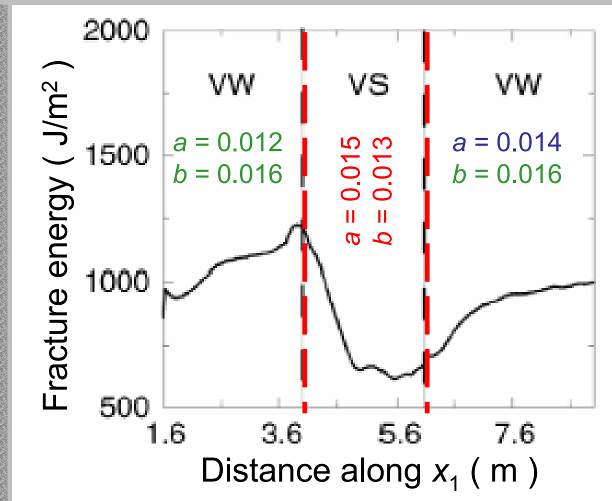
Is Fracture Energy Surface Energy ?

Remember ***POSTER S41B–0997*** *by Pittarello, Di Toro, Bizzarri, Pennacchioni, Hadizadeh*

***L* heterogeneous**



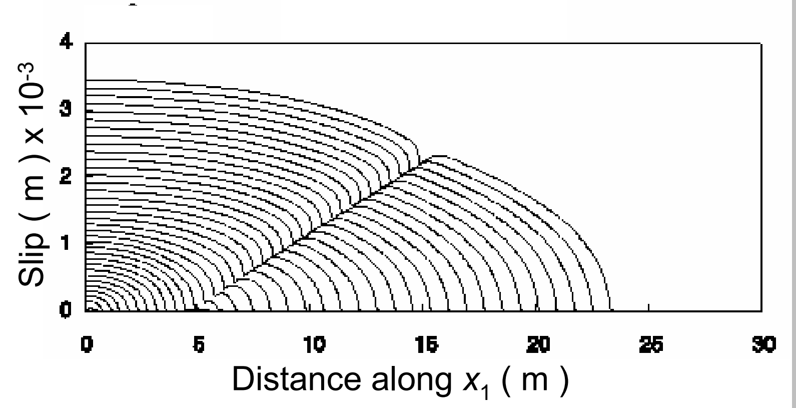
***a, b* heterogeneous**



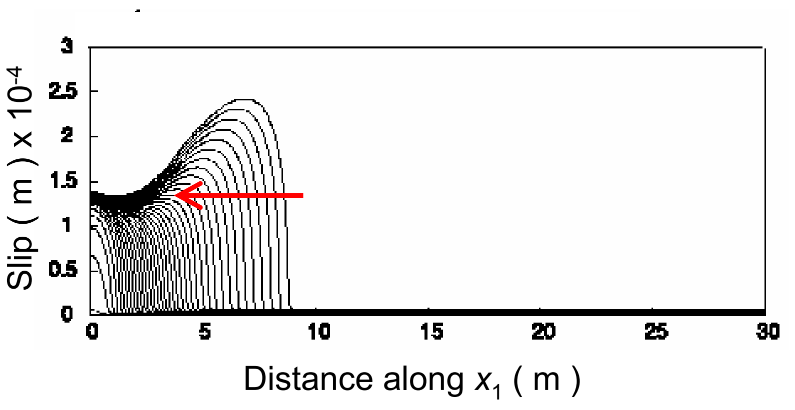
Effects of evolution law #1

2-D

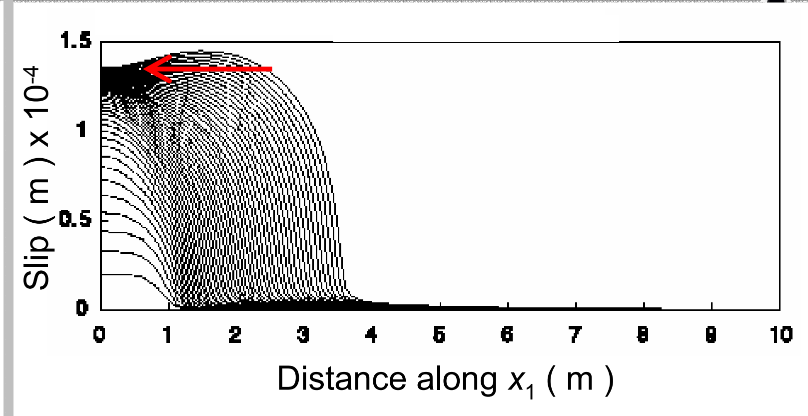
Dieterich – Ruina (ageing) law



Carlson evolution law



Perrin evolution law

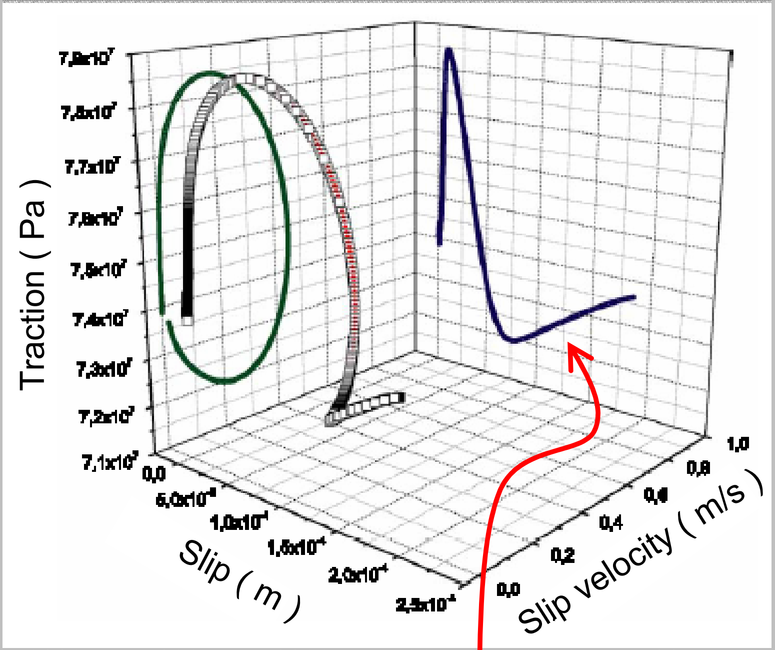


Cocco, Bizzarri, Tinti (2004, *Tectonophys.*, 378, 241-262)

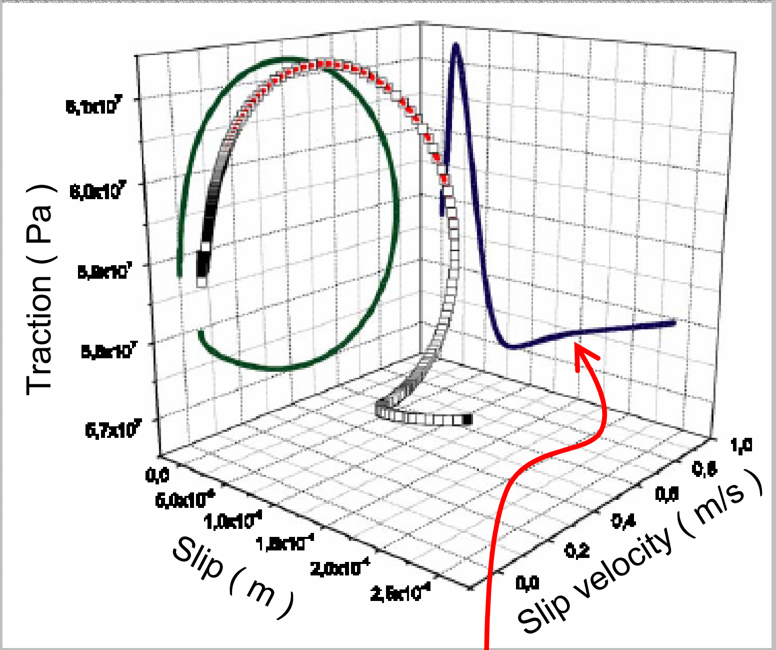
Effects of evolution law #2

2-D

Carlson evolution law



Perrin evolution law

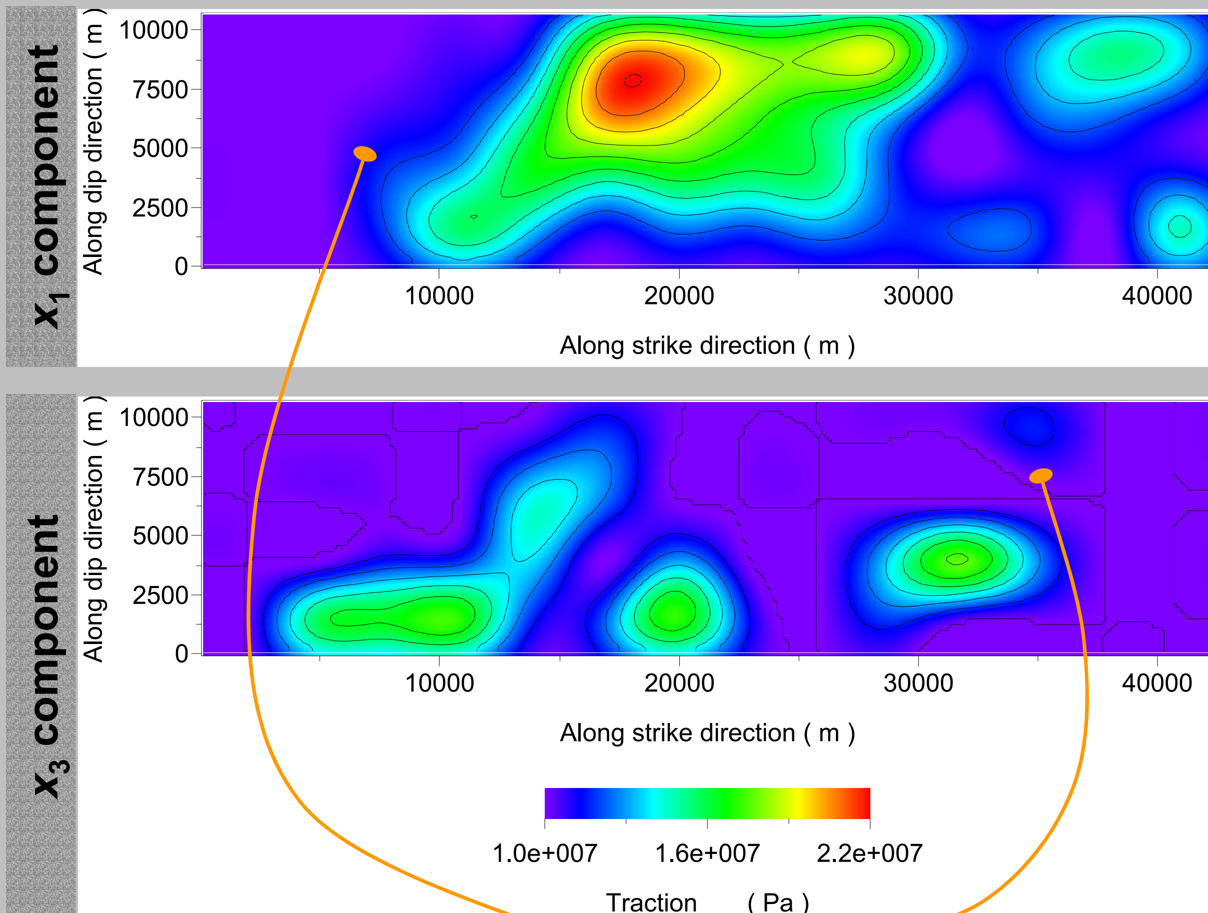


Fast re – strengthening

Fast re – strengthening

Cocco, Bizzarri, Tinti (2004, *Tectonophy.*, 378, 241-262)

The rake variation #1



$$\mathrm{T}_0(x_1, x_3) \equiv \mathrm{T}(x_1, x_3, 0) = (T_1(x_1, x_3, 0), 0, T_3(x_1, x_3, 0))$$

$$\mathcal{T}_0 = \mathrm{T}_0 + \Sigma_0$$

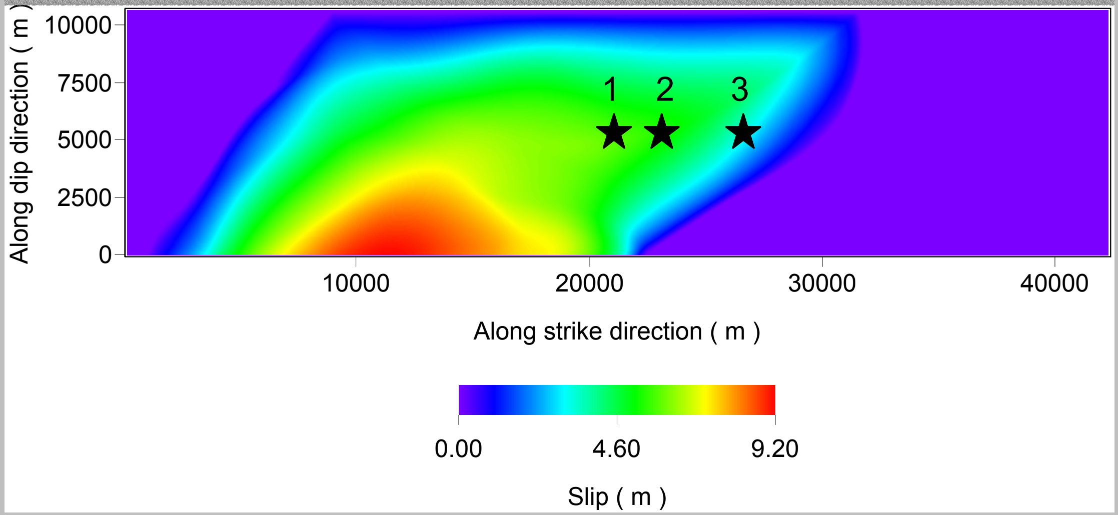
Normal Traction →

$$\Sigma_0(x_1, x_3) \equiv \Sigma(x_1, x_3, 0) = -\sigma_n^{eff}\,\hat{\mathbf{n}} = (0, -30\ \mathrm{MPa},\ 0)$$

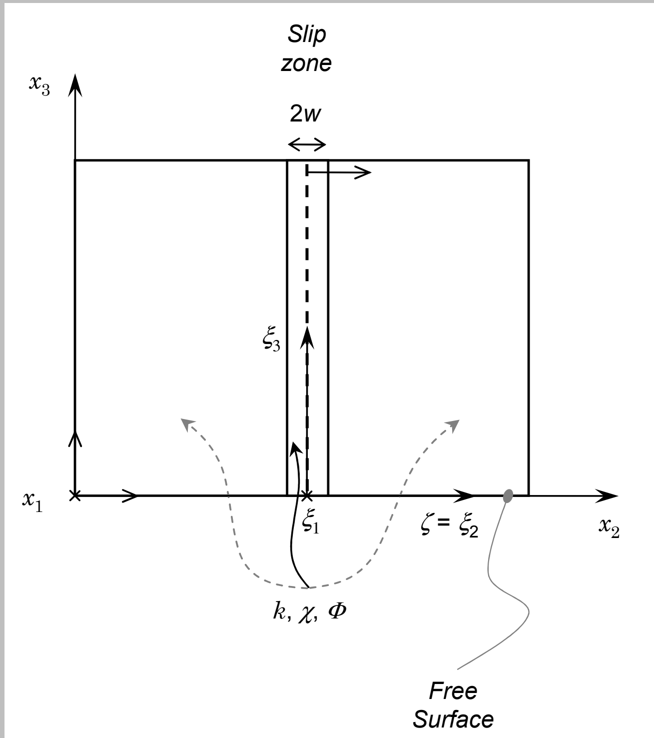
Total Traction

The rake variation #2

Fault slip time snapshots – Linear SW assumed



Thermal pressurization of fluids #1



1 – D Fourier’ s heat conduction equation:

$$\frac{\partial}{\partial t}T = \chi \frac{\partial^2}{\partial \zeta^2}T + \frac{1}{c}q$$

Coupling of temperature T with pore fluid pressure p_{fluid}:

$$\frac{\partial}{\partial t}p_{fluid} = \frac{\alpha_{fluid}}{\beta_{fluid}}\frac{\partial}{\partial t}T - \frac{1}{\beta_{fluid}\Phi}\frac{\partial}{\partial t}\Phi + \omega \frac{\partial^2}{\partial \zeta^2}p_{fluid}$$

where χ is the thermal diffusivity, c the heat capacity for unit volume, α_{fluid} the coefficient of thermal expansion, β_{fluid} the compressibility coefficient, Φ the porosity and $\omega = k/\eta_{fluid}\beta_{fluid}\Phi$ the hydraulic diffusivity (being k the permeability of the medium and η_{fluid} the dynamic fluid viscosity). Analytical solutions at $\zeta = 0$ are:

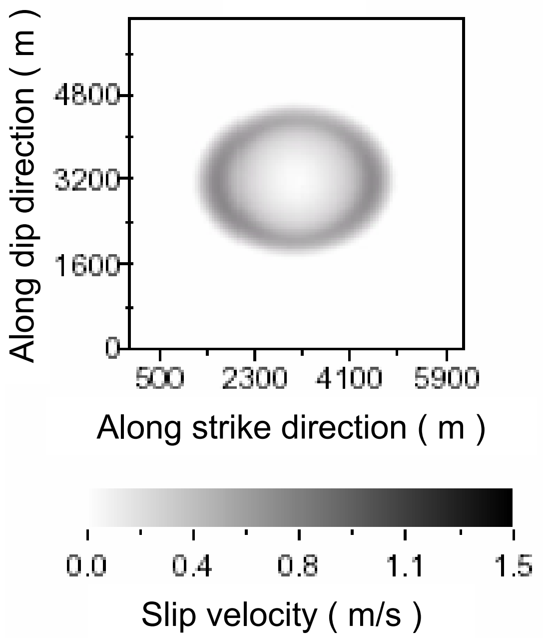
$$T^{wf}(\xi_1,\xi_3,t) = T_0^f + \frac{1}{2cw(\xi_1,\xi_3)}\int_0^{t-\varepsilon} \mathrm{d}t' \,\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right)\tau(\xi_1,\xi_3,t')v(\xi_1,\xi_3,t')$$

$$\tilde{p}_{fluid}^{wf}(\xi_1,\xi_3,t) = p_{fluid_0}^{f} + \frac{\gamma}{2w(\xi_1,\xi_3)}\int_0^{t-\varepsilon}\mathrm{d}t' \left\{ -\frac{\chi}{\omega-\chi}\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\chi(t-t')}}\right) + \frac{\omega}{\omega-\chi}\mathrm{erf}\left(\frac{w(\xi_1,\xi_3)}{2\sqrt{\omega(t-t')}}\right) \right\}$$
$$\left\{ \tau(\xi_1,\xi_3,t')v(\xi_1,\xi_3,t') - \frac{2w(\xi_1,\xi_3)}{\gamma}\frac{1}{\beta_{fluid}\Phi(t')}\frac{\partial}{\partial t'}\Phi(\xi_1,0,\xi_3,t') \right\}$$

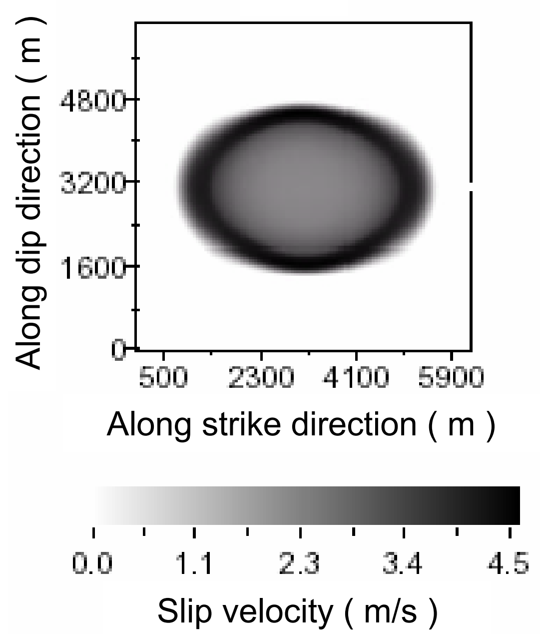
Bizzarri and Cocco (2005c, 2005d, *JGR*, submitted June 2005)

Thermal pressurization of fluids #2

Dry fault (σ_n^{eff} = const)



Wet fault (σ_n^{eff} varies)



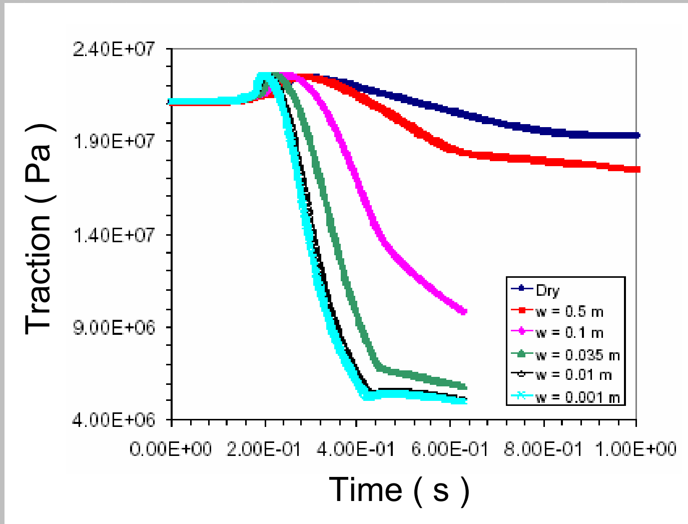
$$\tau = \left[\mu_* + a \ln\left(\frac{v}{v_*}\right) + b \ln\left(\frac{\Psi v_*}{L}\right) \right] \sigma_n$$

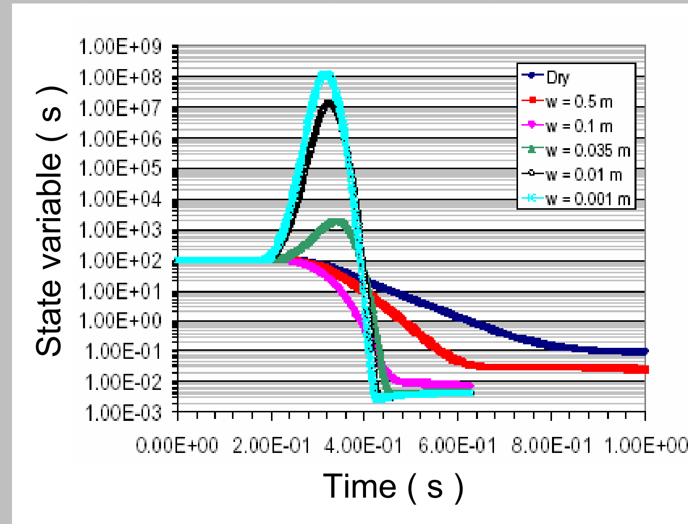
$$\frac{\mathrm{d}}{\mathrm{d}t}\Psi = 1 - \frac{\Psi v}{L}$$

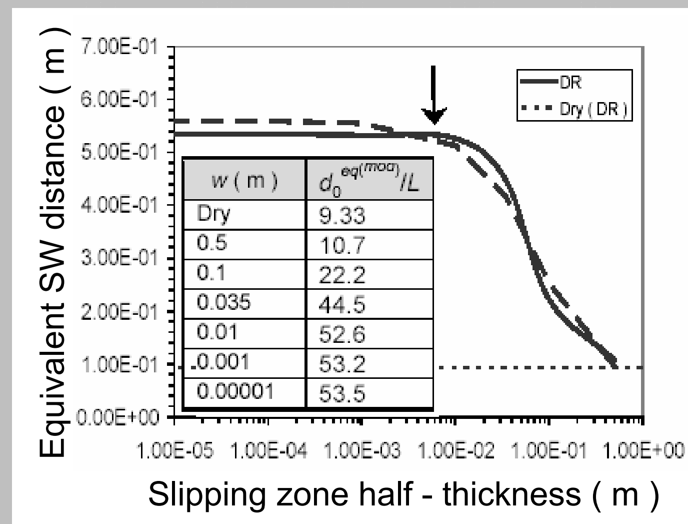
Dry fault

Bizzarri and Cocco (2005c, 2005d, *JGR*, submitted June 2005)

Thermal pressurization of fluids #3







Bizzarri and Cocco (2005c, 2005d, *JGR*, submitted June 2005)

Conclusions

- ✓ Spatial heterogeneities in the constitutive parameters make us able to simulate different behaviors, like barrier – healing and self – healing pulses;
- ✓ The regularization of the governing laws is an alternative to have self – healing;
- ✓ Slip complexity may arise considering a heterogeneous initial stress and rake rotation during the rupture propagation;
- ✓ The inclusion of the so – called second – order physical effects, like thermal pressurization of pore fluid, changes the traction evolution within the cohesive zone and the rupture shape.

Thank you!

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Support Slides:
Parameters, Notes, etc.

To not be displayed directly. Referenced above.

Why " *truly* " 3 – D ?

Remembering the dimensionality of the problem:

2 – D Mode II (pure in – plane): $\mathbf{u} = (u_1(x_1,t), 0, 0)$

2 – D Mode III (pure anti – plane): $\mathbf{u} = (0, u_2(x_1,t), 0)$

3 – D Mixed mode: $\mathbf{u} = (u_1(x_1,t), u_2(x_1,t), 0)$

3 – D having only one non null component: $\mathbf{u} = (u_1(x_1,x_2,t), 0, 0)$

Truly 3 – D: $\mathbf{u} = (u_1(x_1,x_2,t), u_2(x_1,x_2,t), 0)$

DIETERICH IN REDUCED FORM WITH HEALING

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v_*}{v} + 1 \right) + b \ln\left(\dfrac{\Psi v_*}{L} + 1 \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t} \Psi = \dfrac{\gamma_{fh} - \Psi}{t_{fh}} - \dfrac{\Psi v}{L} \end{cases}$$

γ_{fh} = 1 s

t_{fh} is the time for healing (slip duration)

Evolution law proposed by *Nielsen et al. (2000)* and by *Nielsen and Carlson (2000)*. Used in this form by *Cocco et al. (2004)*

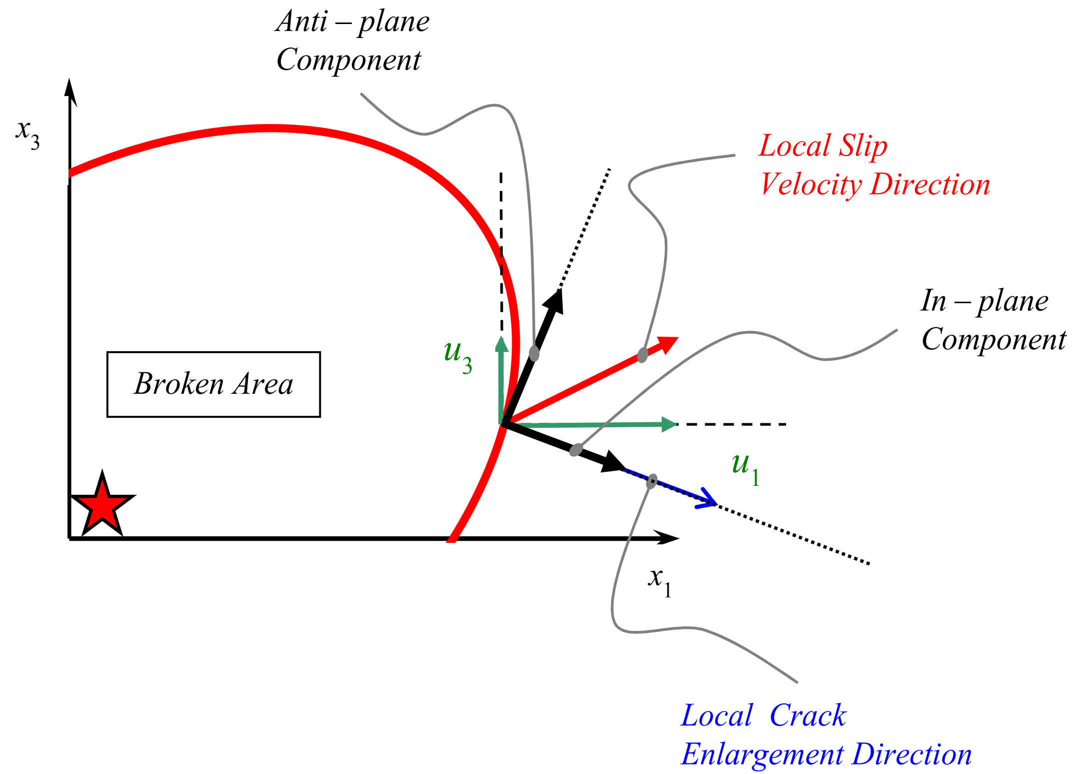
DIETERICH IN REDUCED FORM REGULARIZED

$$\begin{cases} \tau = \left[\mu_* - a \ln\left(\dfrac{v + v_*}{v + v_r} \right) + b \ln\left(\dfrac{\Psi \left(v - v_r\right)}{L} + 1 \right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t} \Psi = 1 - \dfrac{\Psi \left(v + v_r\right)}{L} \end{cases}$$

v_r is a regularization fault slip velocity

Perrin et al. (1995), Cocco et al. (2004)

Coupling of two modes of propagation. The rake variation



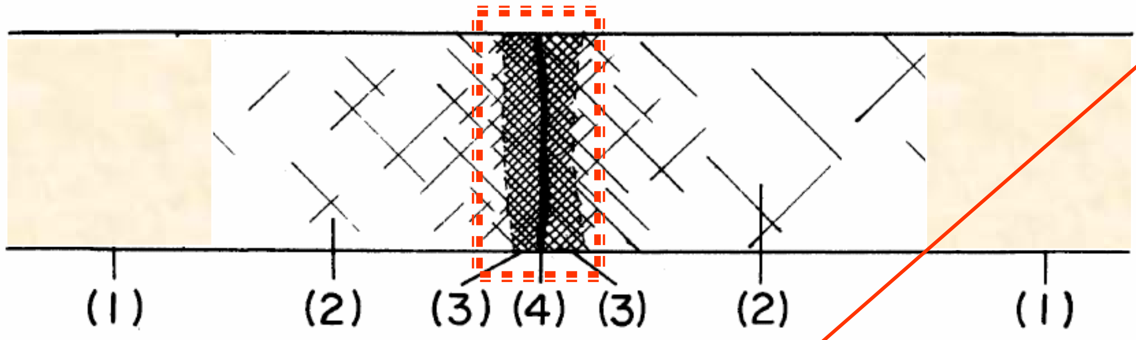
Bizzarri and Cocco (2005a, *Ann. Geophys.*, 48, 2, 279-299)

Initial stress is based on the Hartzell and Heaton (1983) Imperial Valley Earthquake model:

http://www.seismo.ethz.ch/srcmod/Eventpages/s1979IMPERIhart.html

Non – laminar fault model

Internal Structure of Principal Faults of the North Branch San Gabriel Fault



1) Undeformed Host Rock

Fault Zone {
2) Damaged Host Rock
3) Foliated Zone
4) Central ultracataclasite layer } Fault Core

Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

30 - 100 m (Damage ≈ *highly cracked rock*)

1 - 10 m (*foliated gouge* or *gouge*)

10s - 100s mm (containing the ***principal slipping zone***, *which* is *much thinner*, typically < 5 mm)

Chester, Evans and Biegel, *J. Geoph. Res.,*1993
Sibson, BSSA, 2003
Chester and Chester, SSA, SCEC meetings 2004